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

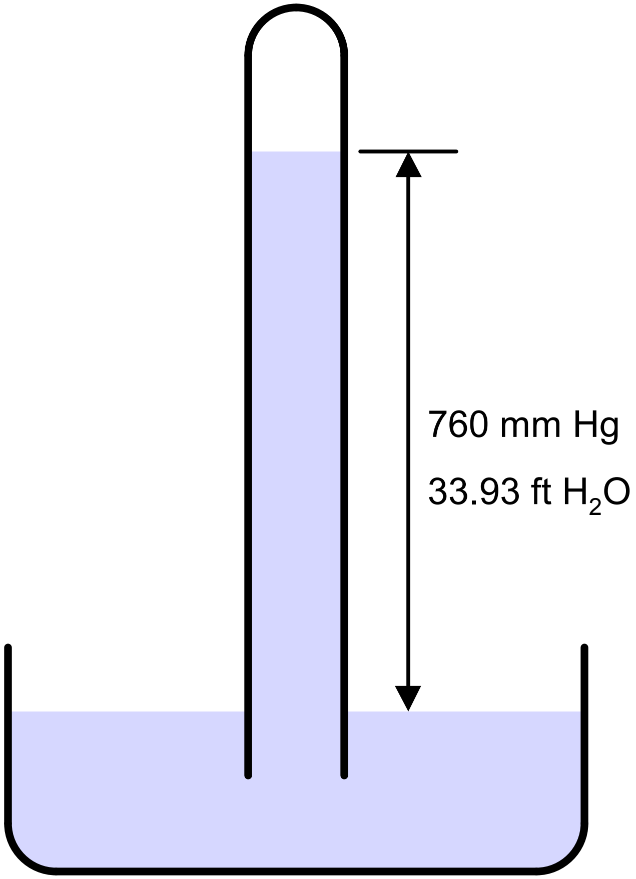
Ultra-High Vacuum

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. H_2O
  - 33.9324 ft. H_2O

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	1.4×10^{-2}
Helium	He	0.0005	4.0×10^{-3}
Krypton	Kr	0.0001	8.7×10^{-4}
Hydrogen	H_2	0.00005	4.0×10^{-4}
Xenon	Xe	0.0000087	6.6×10^{-5}
Water	H_2O	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

$$PV = N_m RT$$

$$PV = N k_B T$$

$$P = n k_B T$$

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, $P = \frac{1}{3} nm\overline{v^2} = nk_B T$ $\qquad \frac{1}{2} m\overline{v^2} = \frac{3}{2} k_B T$
- 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:

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

  - 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:

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

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

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

Distribution Functions - 3

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

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

- Normalized distribution function for velocity magnitude (Gaussian):

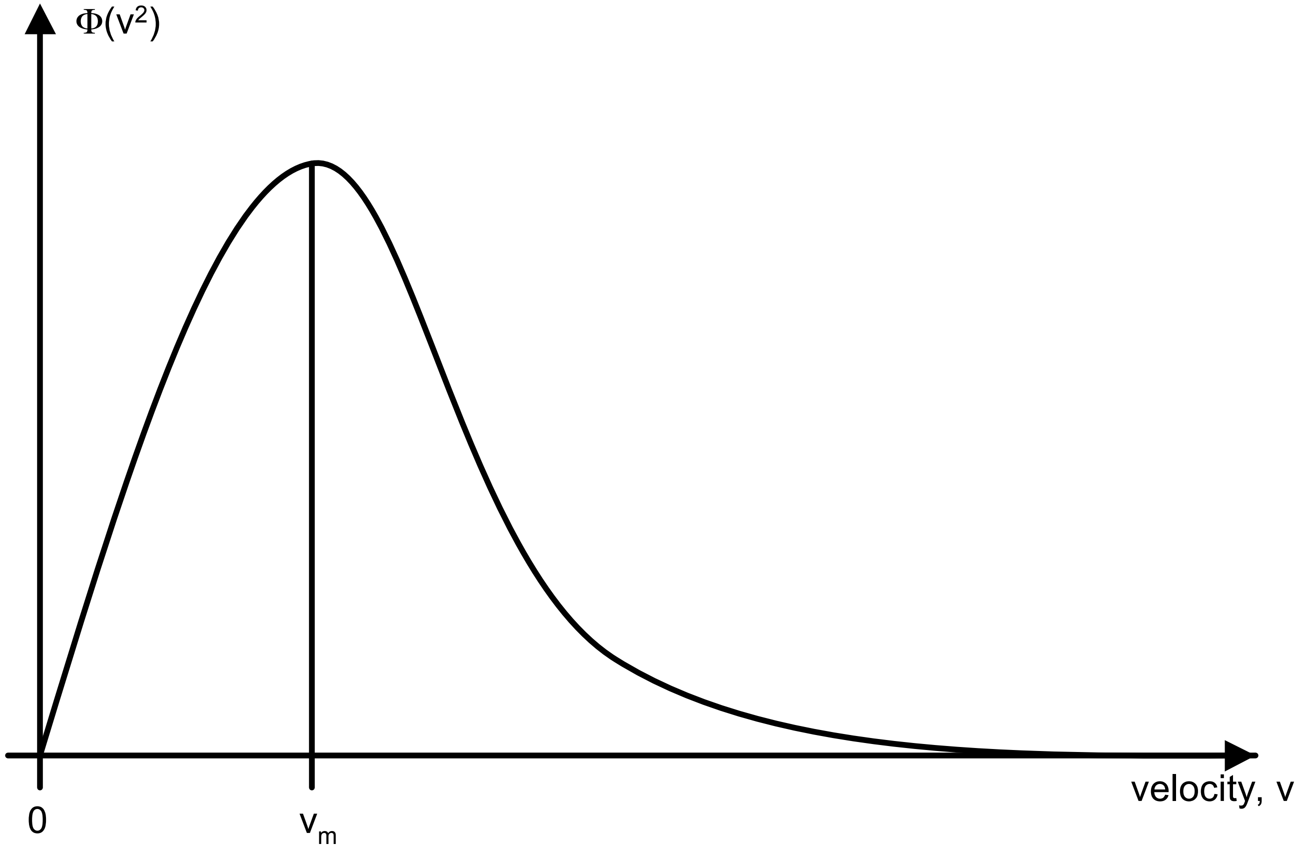
$$\psi(v^2) = \left(\frac{m}{2\pi k_B T}\right)^{3/2} \exp\left(-\frac{m v^2}{2 k_B T}\right)$$

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

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

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

$$d^2N_{vx} = \frac{N}{V} A v_x \,\phi(v_x^2)\, dv_x dt$$

integrate: $\displaystyle\int_0^\infty v_x\,\phi(v_x^2)\,dv_x = \left(\frac{k_BT}{2\pi m}\right)^{1/2}$

⇒

$$\frac{dN_i}{Adt} = \frac{N}{V}\left(\frac{k_BT}{2\pi m}\right)^{1/2} = \left(2\pi m k_B T\right)^{-1/2} P$$

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:

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

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

- Free Molecular Flow
  - Knudsen's equation:

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

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

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

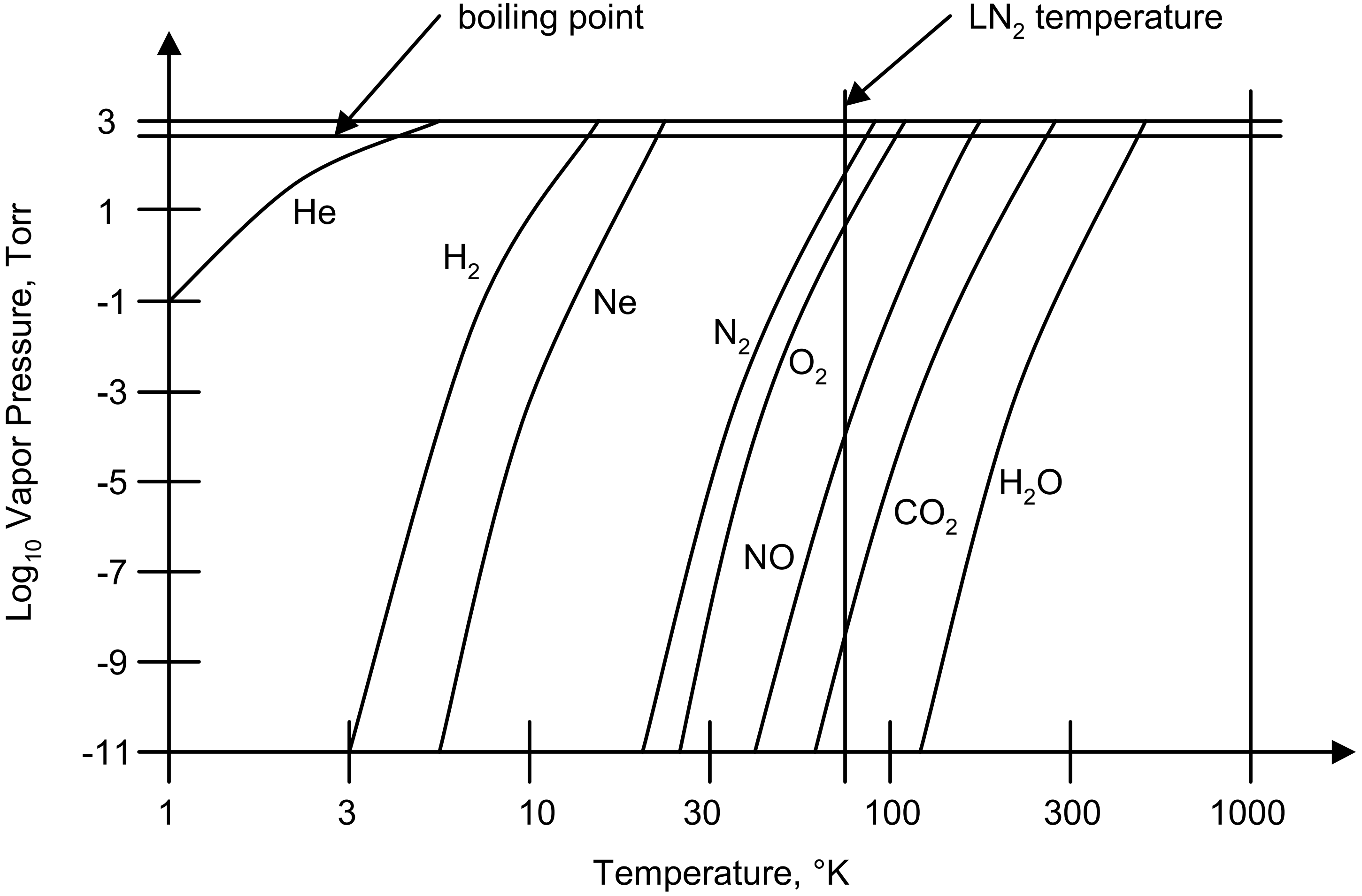
For common gases, {H_2O, He, CO_2, CH_4, Ar, O_2, N_2, H_2}, at T = 300 K:

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

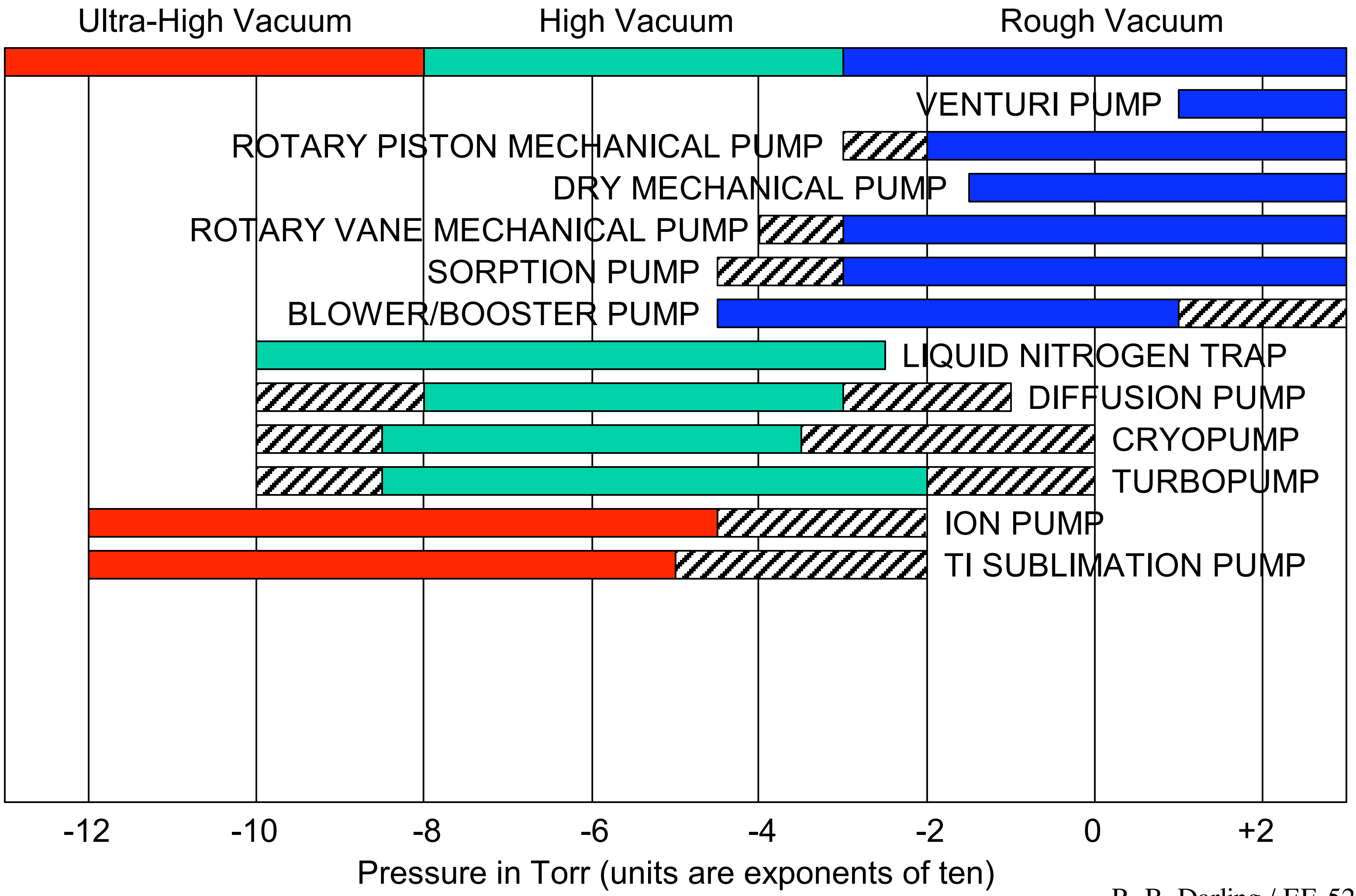
Gas Throughput

- $Q = PS$
- 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



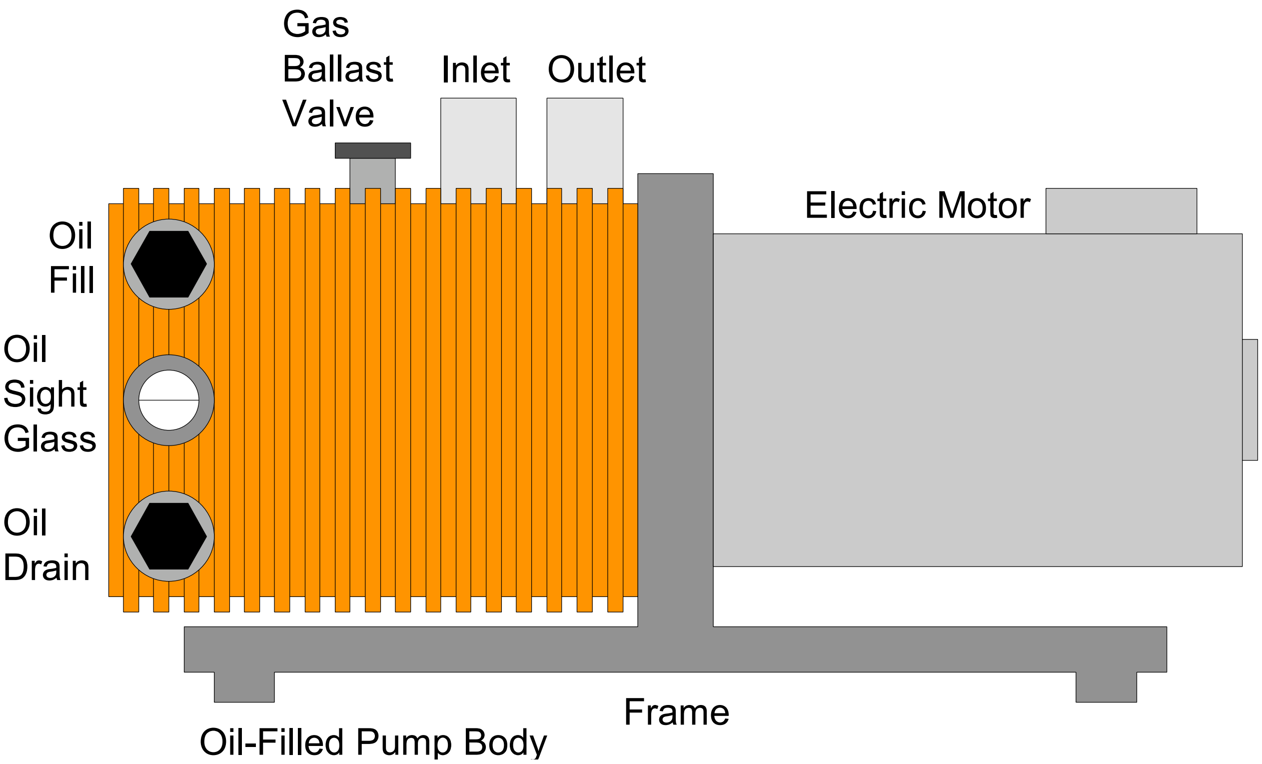
Vacuum Pump Pressure Ranges



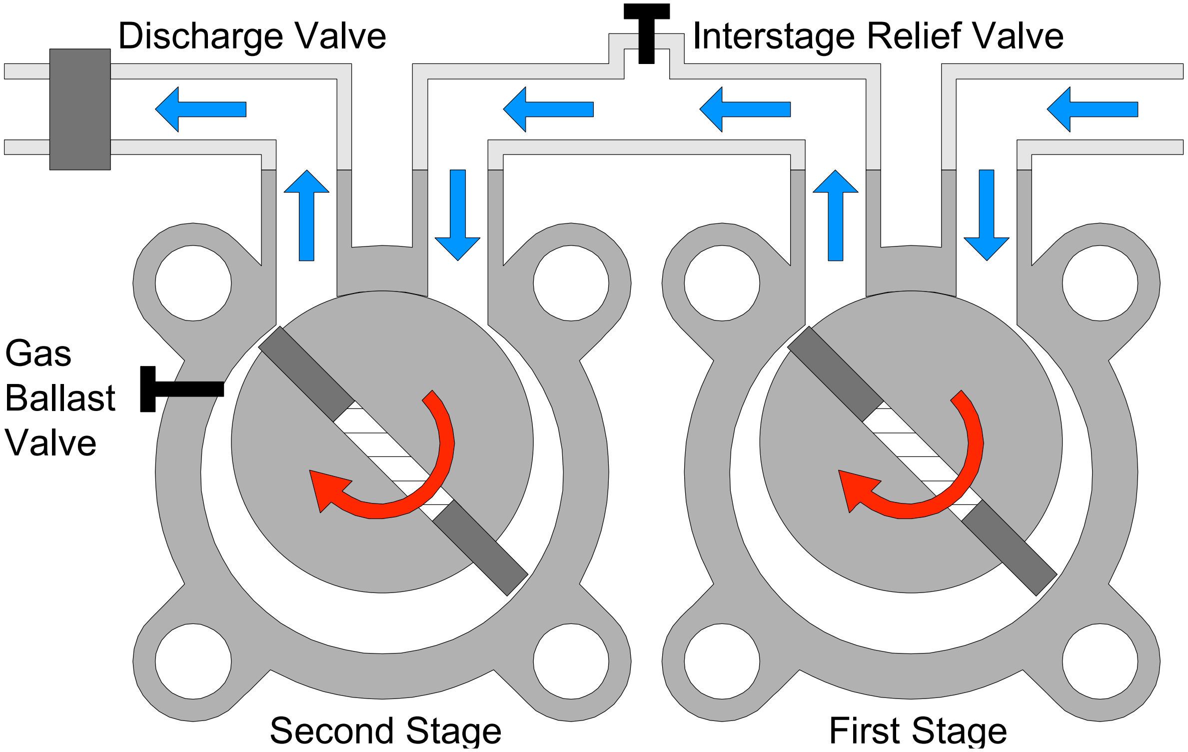
Vacuum Pumps

- 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



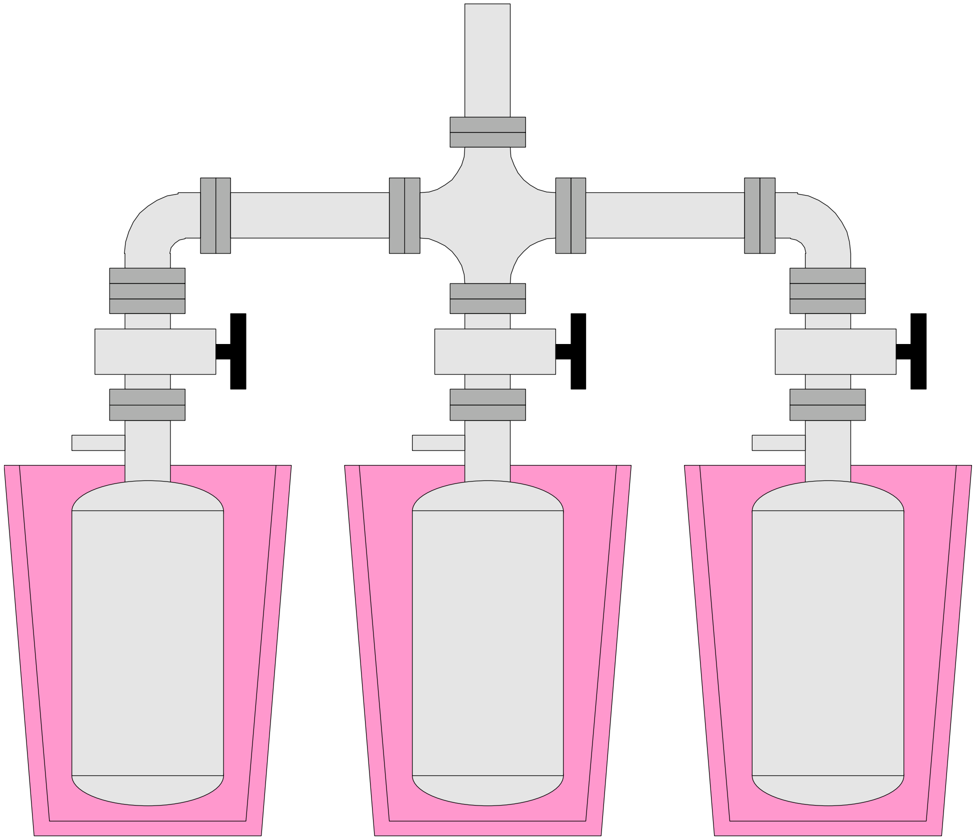
Rotary Vane Mechanical Pumps - 3

- 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)

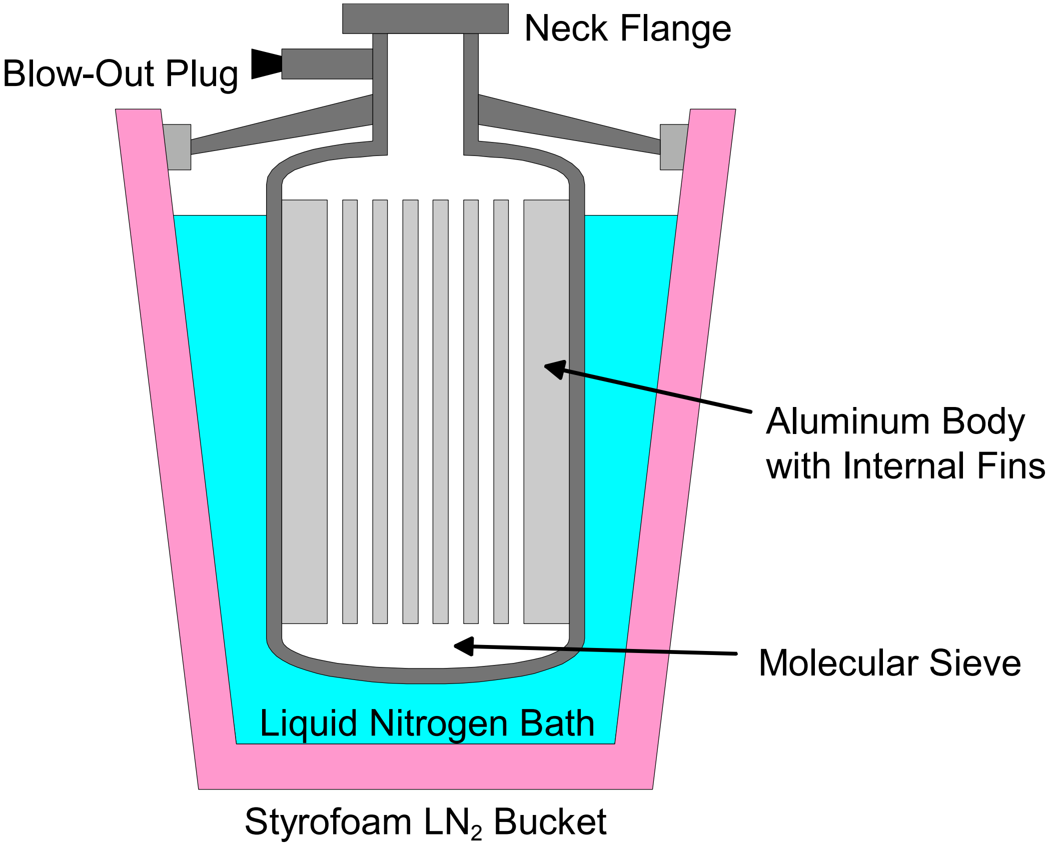
Rotary Vane Mechanical Pumps - 4

- 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



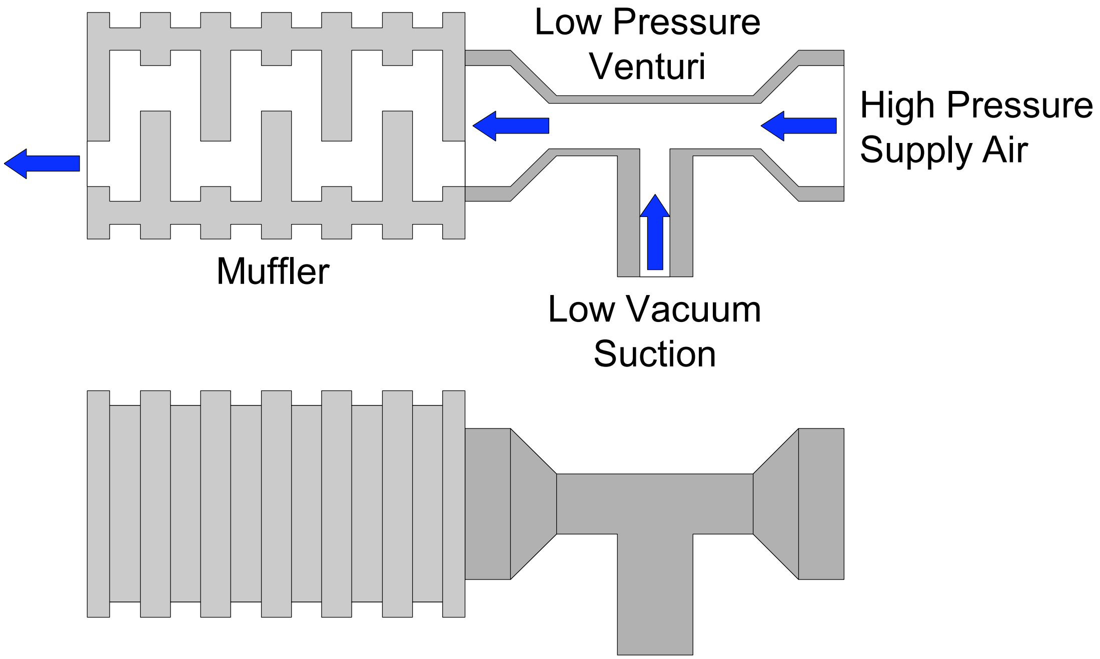
Sorption Pumps - 2



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.

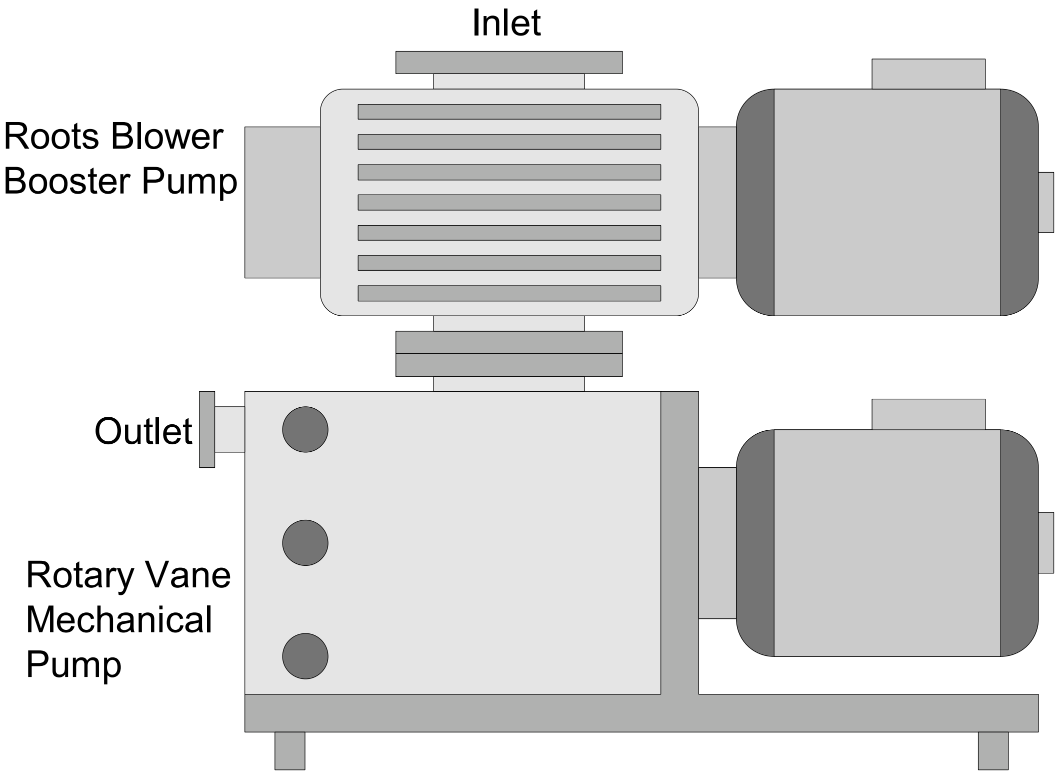
Venturi Pumps - 1



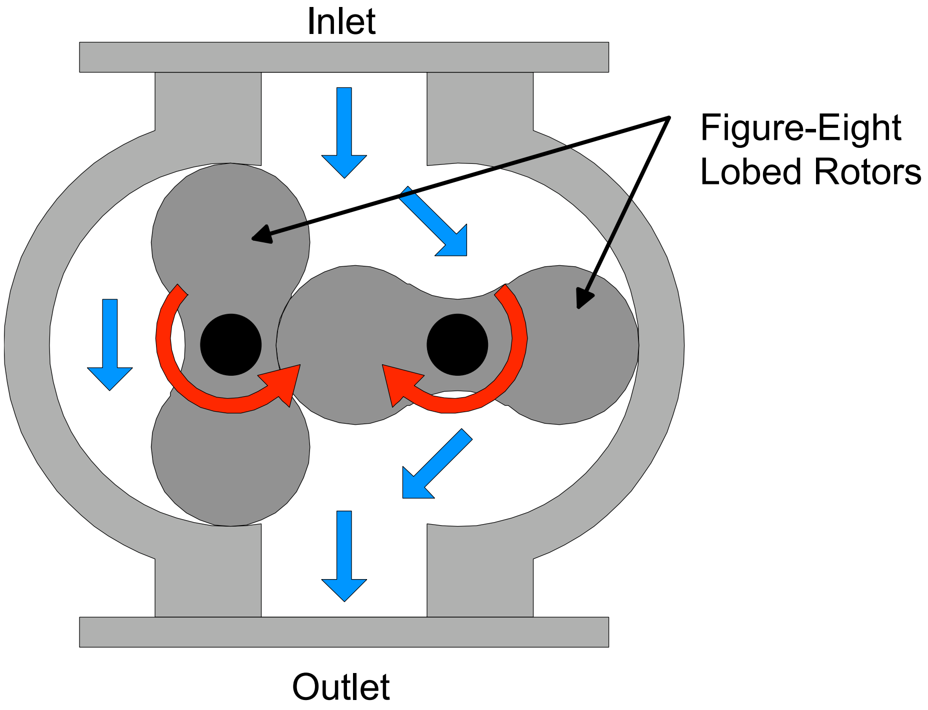
Venturi Pumps - 2

- 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



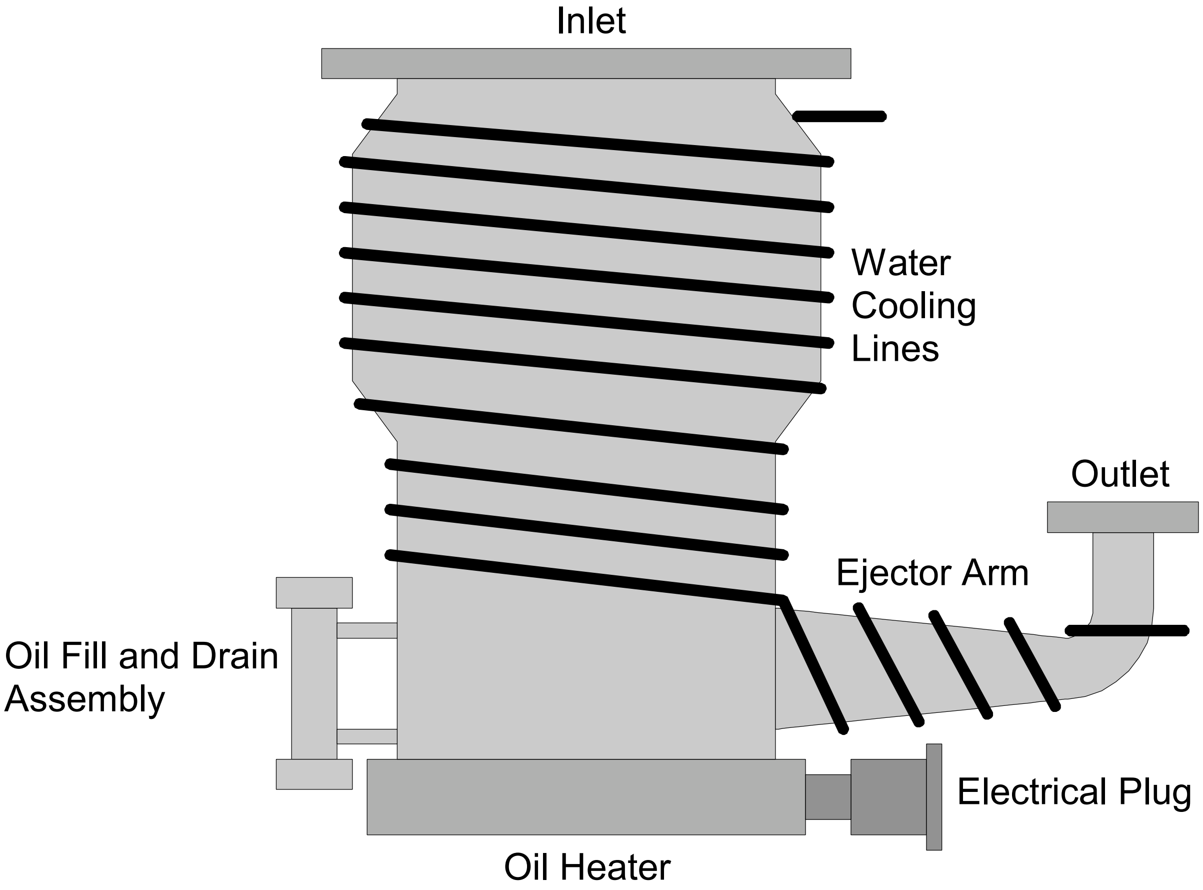
Roots Blowers / Booster Pumps - 2



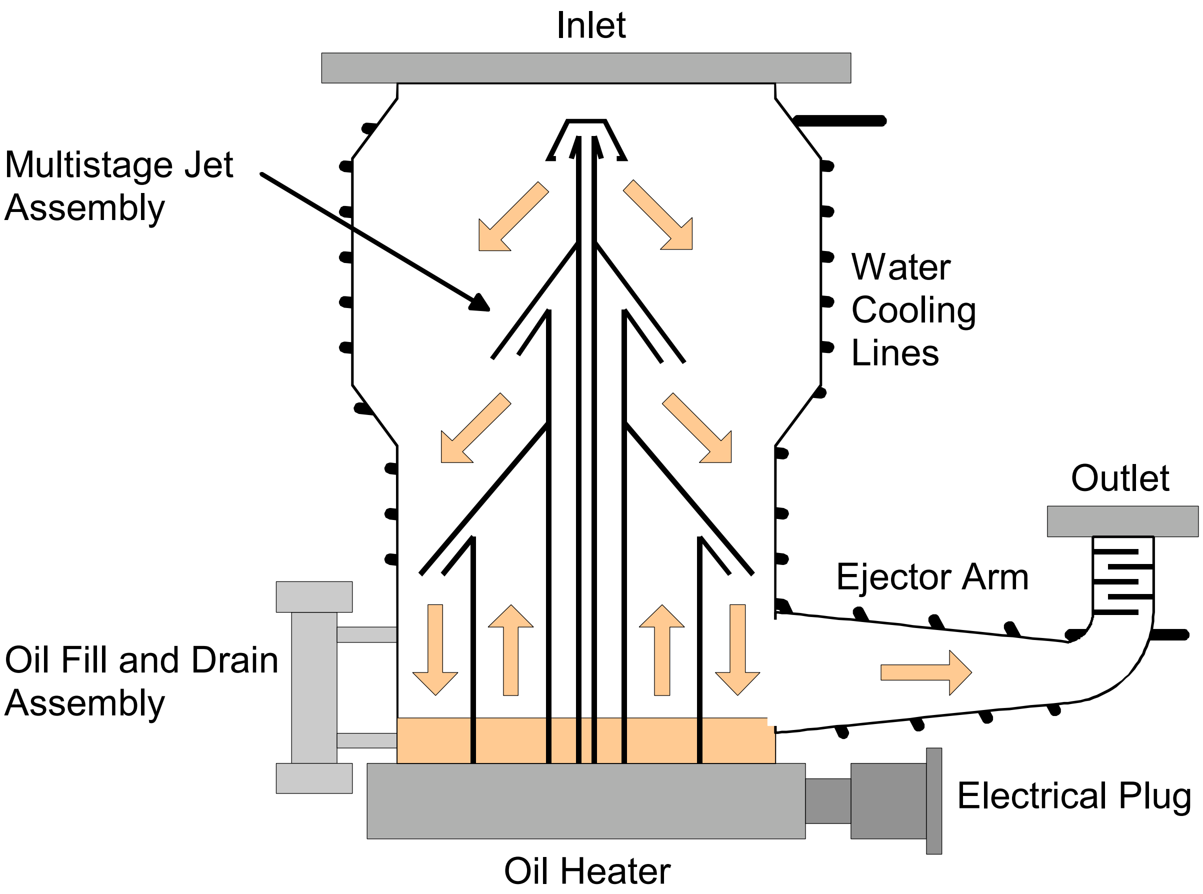
Roots Blowers / Booster Pumps - 3

- 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.

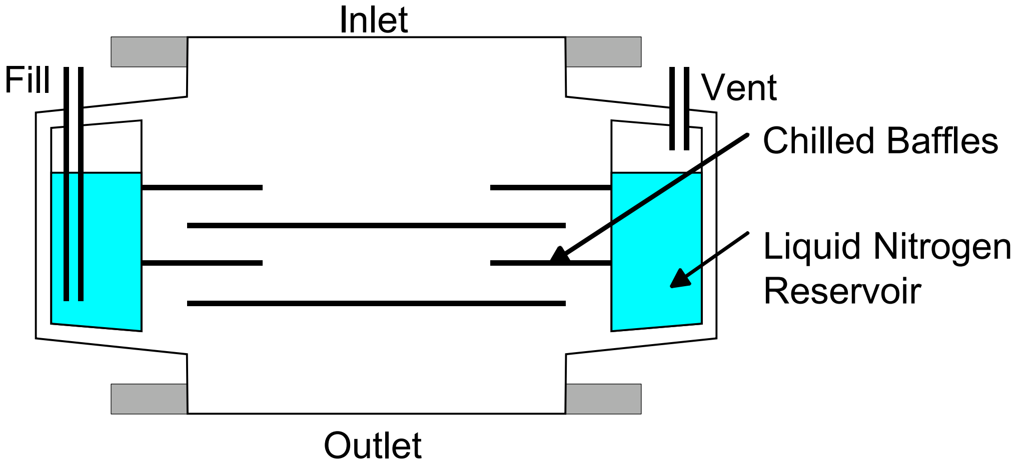
Diffusion Pumps - 4

- 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

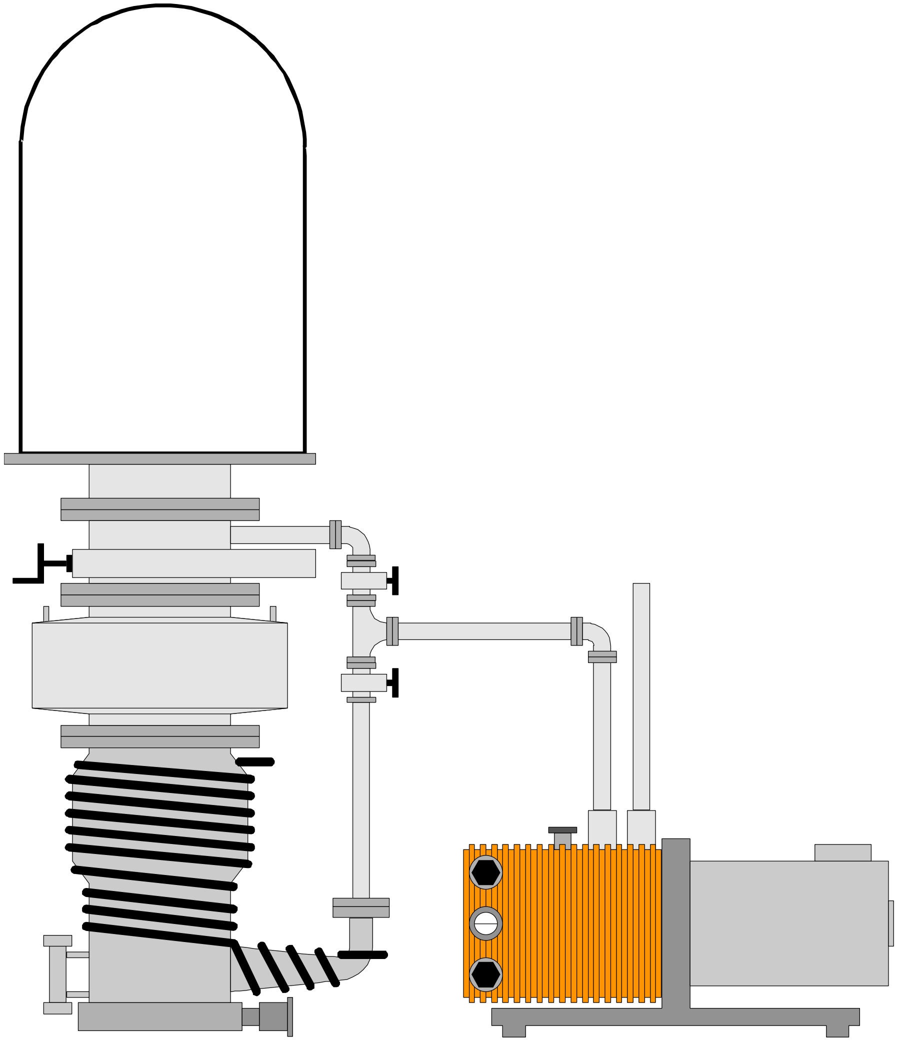
Liquid Nitrogen Traps / Baffles - 1



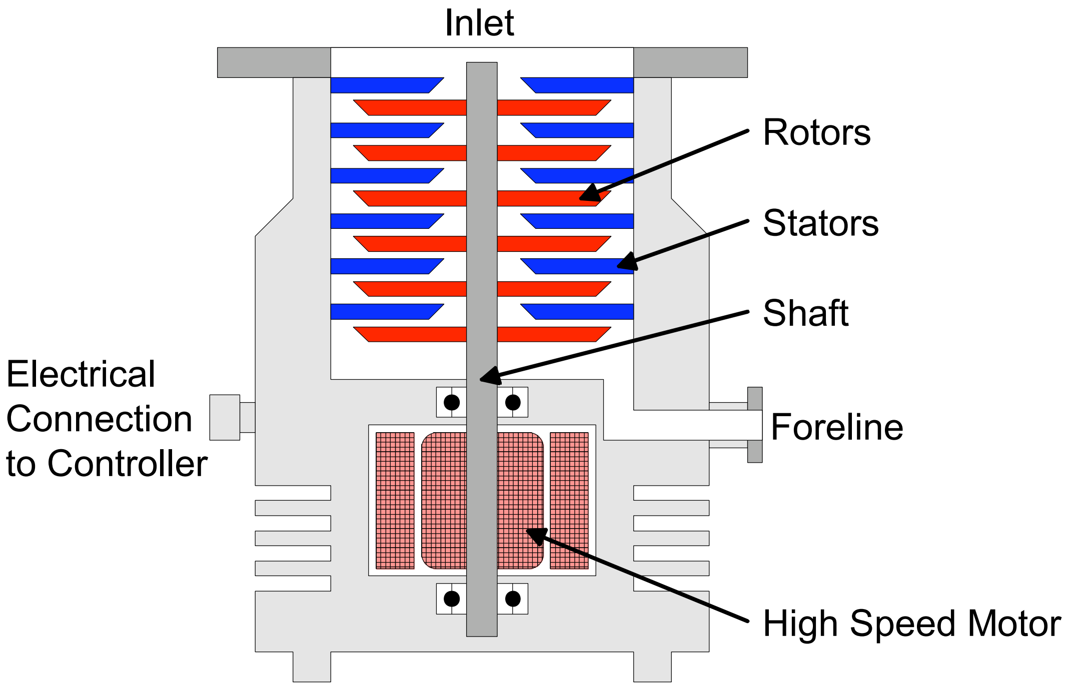
Liquid Nitrogen Traps / Baffles - 2

- 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.
- LN_2 cryotraps 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 N_2 before filling with LN_2.
- LN_2 cryotraps 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

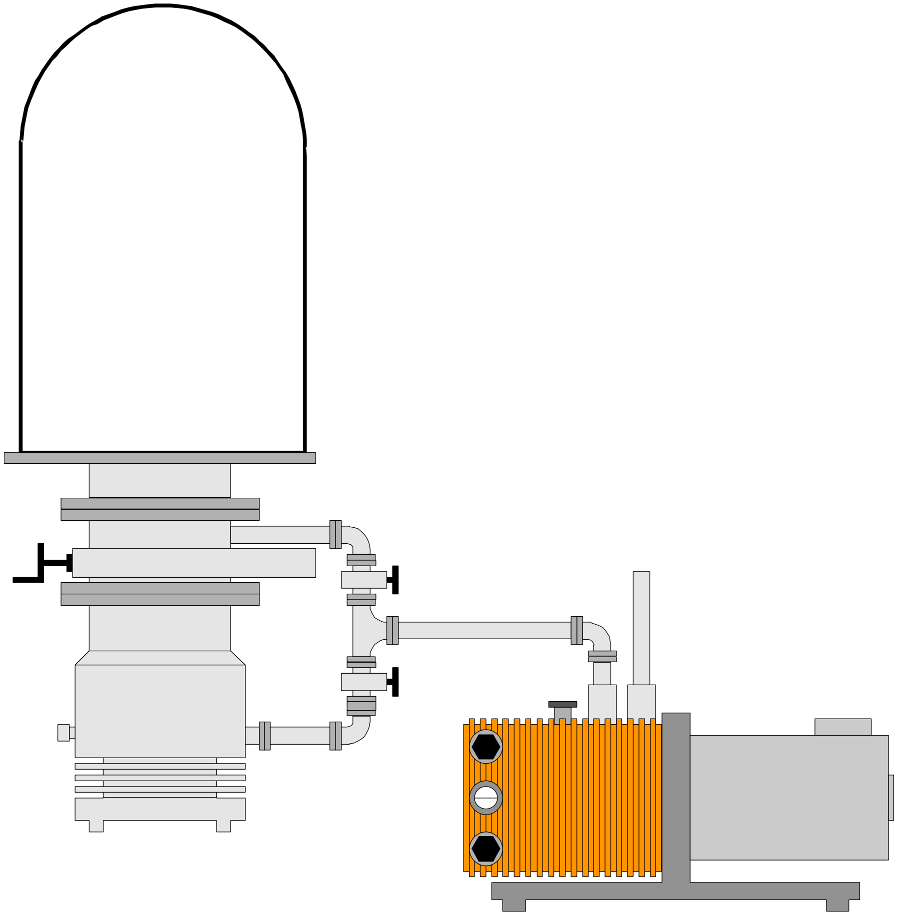
Turbomolecular Pumps - 3

- 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



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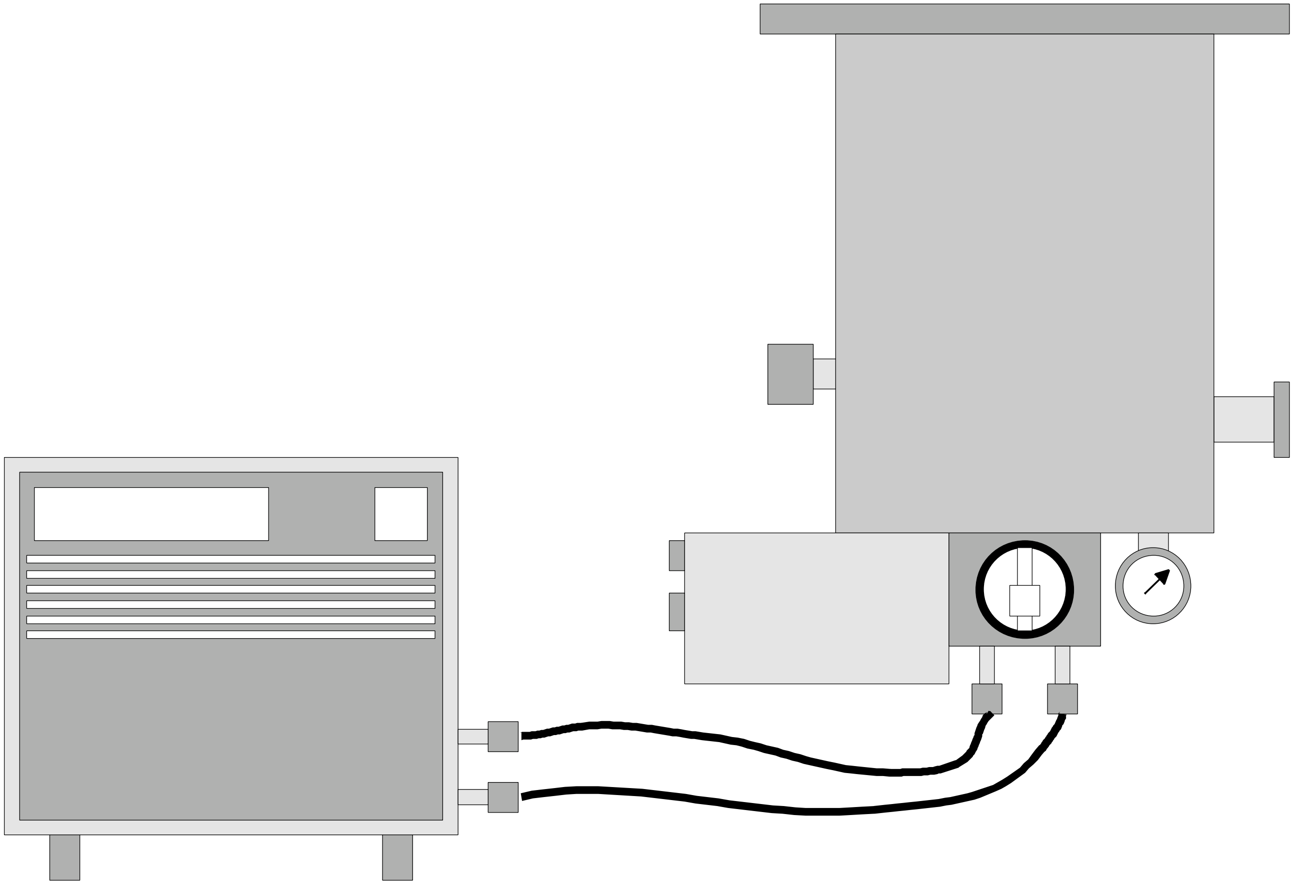
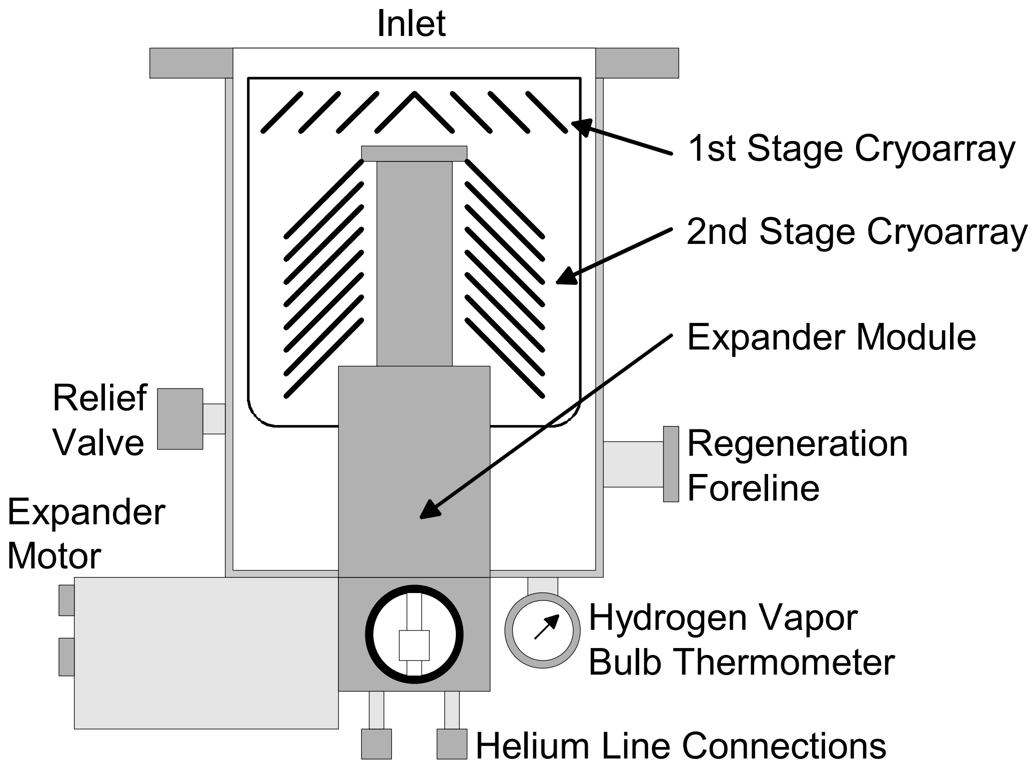
Cryopumps - 1



Cryopumps - 2


Inlet
1st Stage Cryoarray
2nd Stage Cryoarray
Expander Module
Relief Valve
Regeneration Foreline
Expander Motor
Hydrogen Vapor Bulb Thermometer
Helium Line Connections

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.

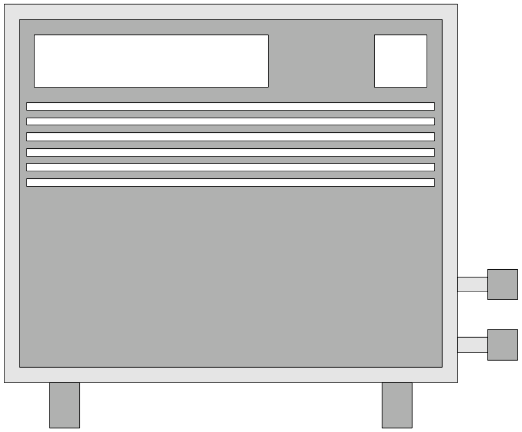
Cryopumps - 4

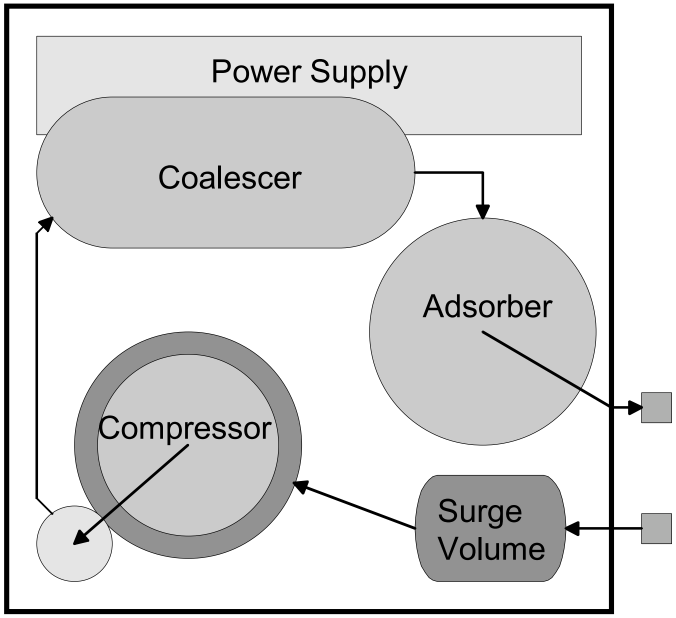
- First stage array operates at 50 to 80 K
  - Primarily used for pumping water vapor and carbon dioxide.
- Second stage array operates at 10 to 20 K
  - Primarily used for pumping other condensable gases.
- Activated charcoal in the second stage provides cryosorption.
  - Primarily used for pumping other non-condensable gases.
  - Charcoal and zeolites have about 8000 ft^2/cm^3 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

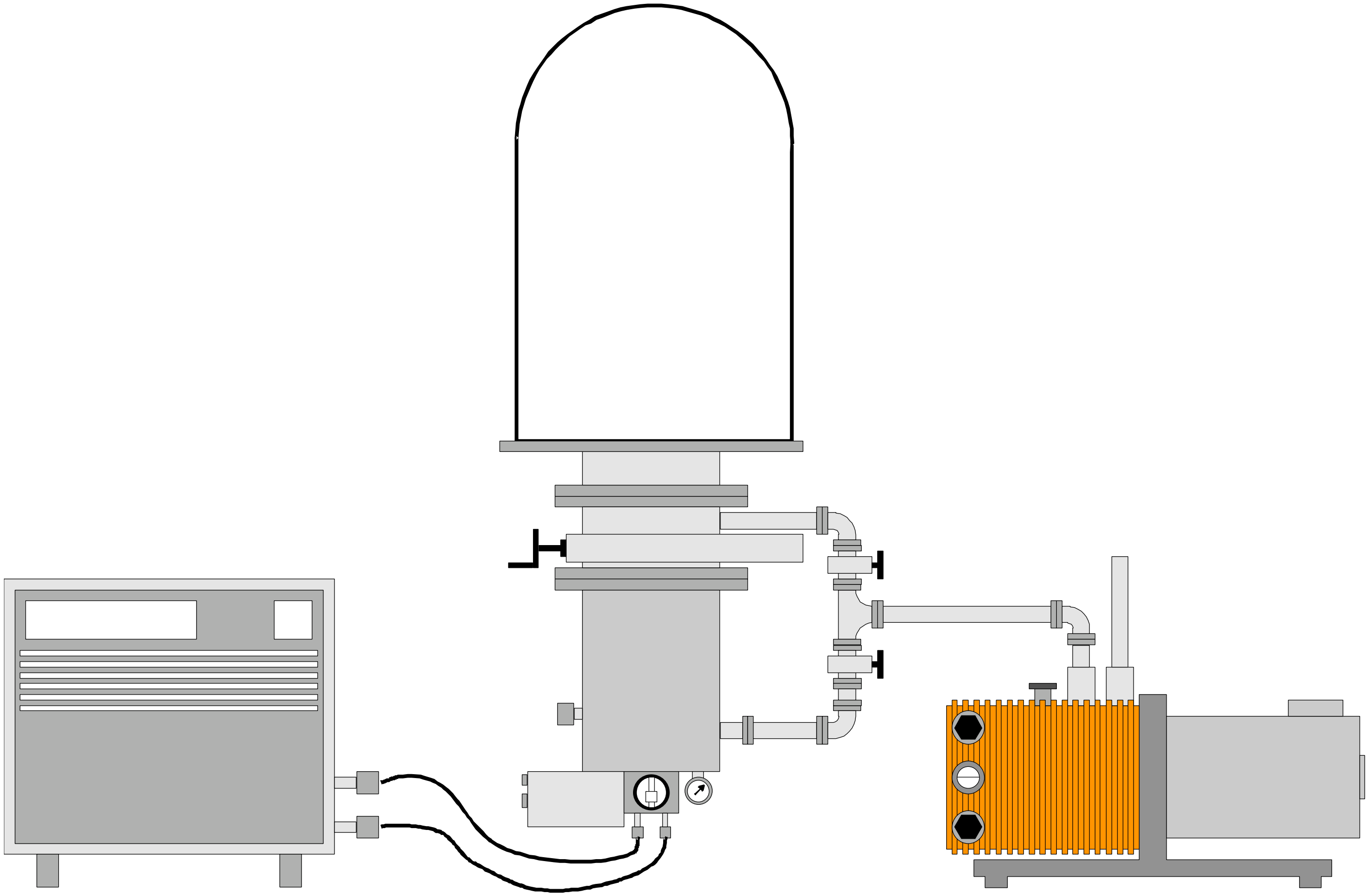
- Potential Problems:
  - Must be regenerated to extract the trapped gases
    - Allow to warm to room temperature (slow), or
    - Use a built-in heater to warm to 250 C and outgas (fast).
    - Regeneration takes the pump off-line for several hours.
  - Regeneration process can produce considerable 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



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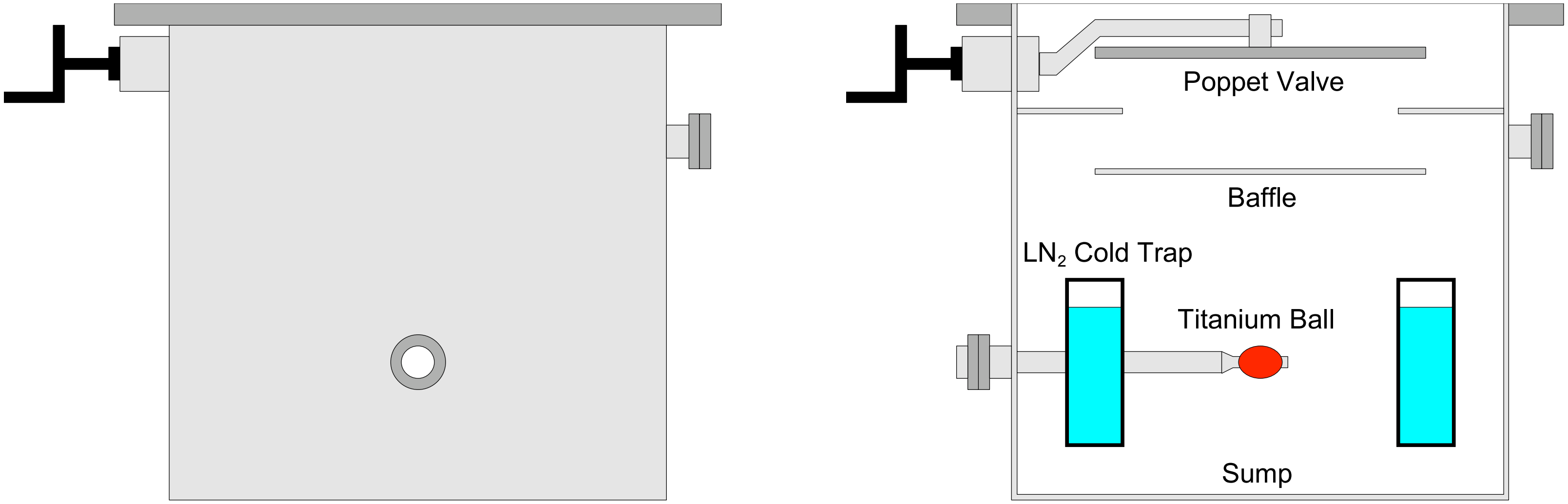
Titanium Sublimation Pumps - 1



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

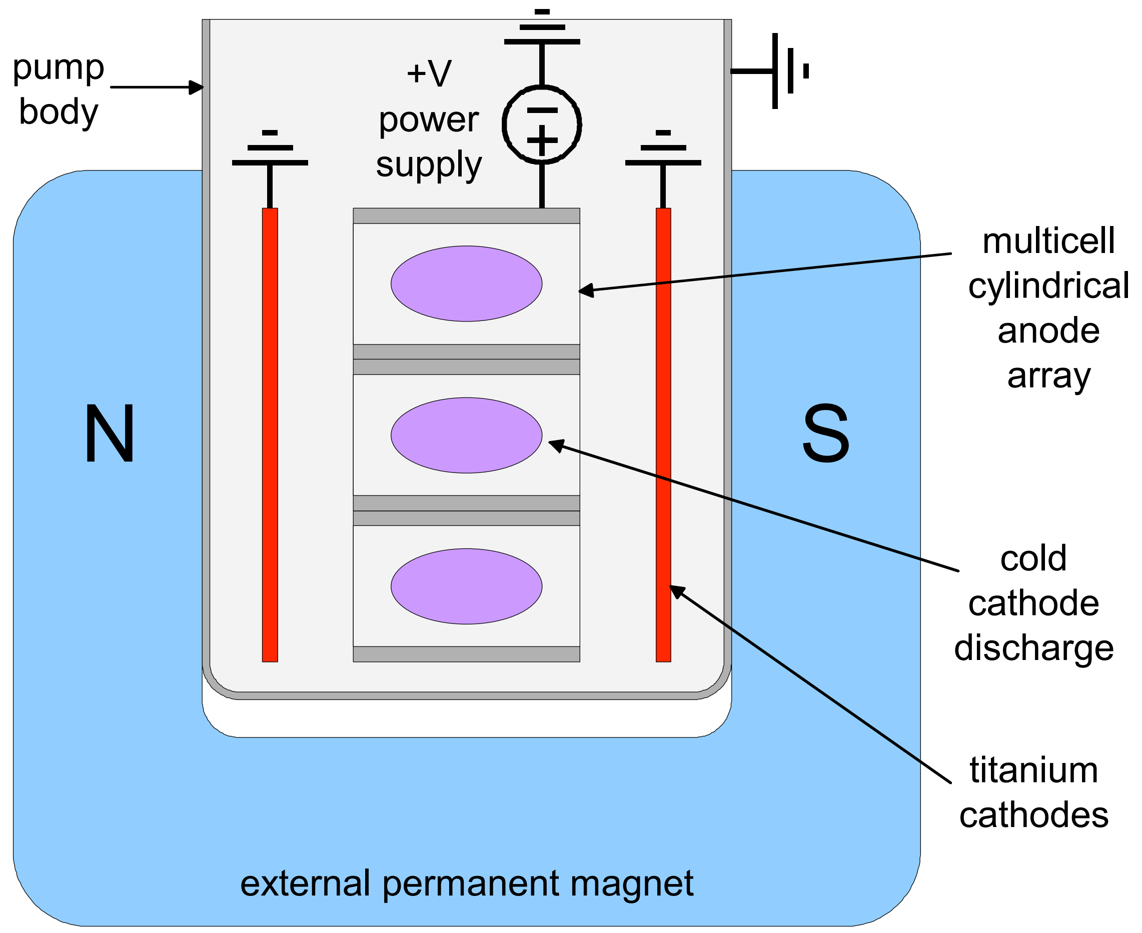
Typical pumping speeds for freshly coated Ti surfaces (L/sec-in^2):

	H_2	N_2	O_2	CO	CO_2	H_2O
20°C:	20	30	60	60	50	20
-190°C:	65	65	70	70	60	90

Non-Evaporable Getter Pumps

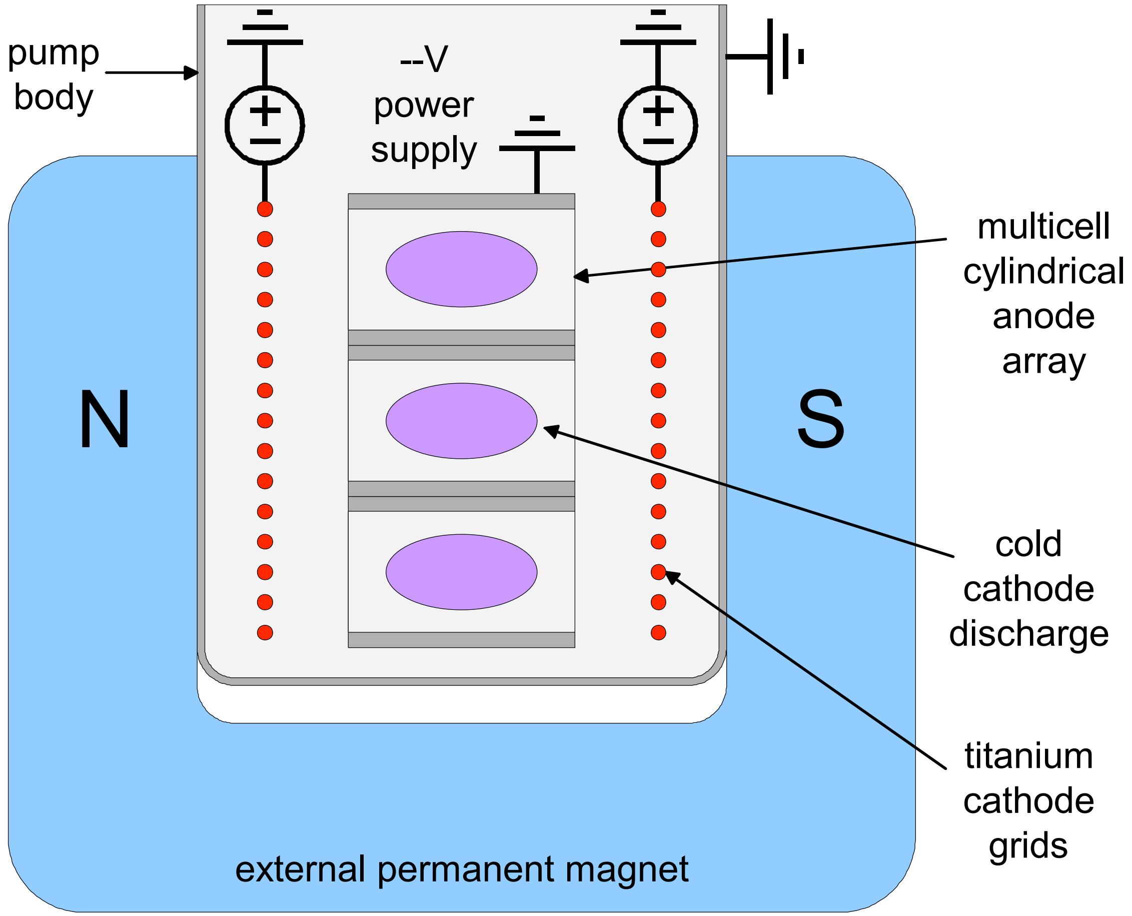
- "NEG" pumps.
- Zr-V-Fe alloy that is formed into a cartridge over a constantan strip heater.
- Pumps all of the time, until loaded with gas molecules.
- Regenerated by heating to ~350°C for 30 mins. to degas the alloy.
- Very simple in construction and operation.

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 <u>cold cathode discharge</u>.
  - Gas ions accelerated into the cathode can stick and therefore be pumped.

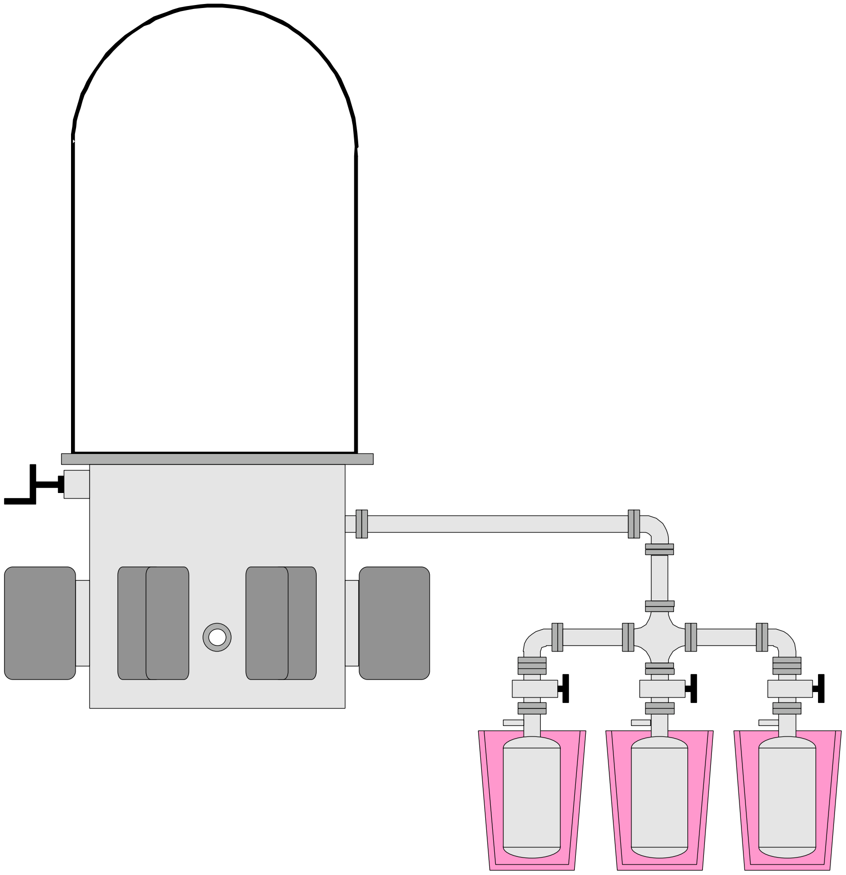
Ion Pumps - 4

- 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.
  - H_2 is directly absorbed by the fresh Ti surfaces.
  - Gas molecules may be trapped and burried 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.

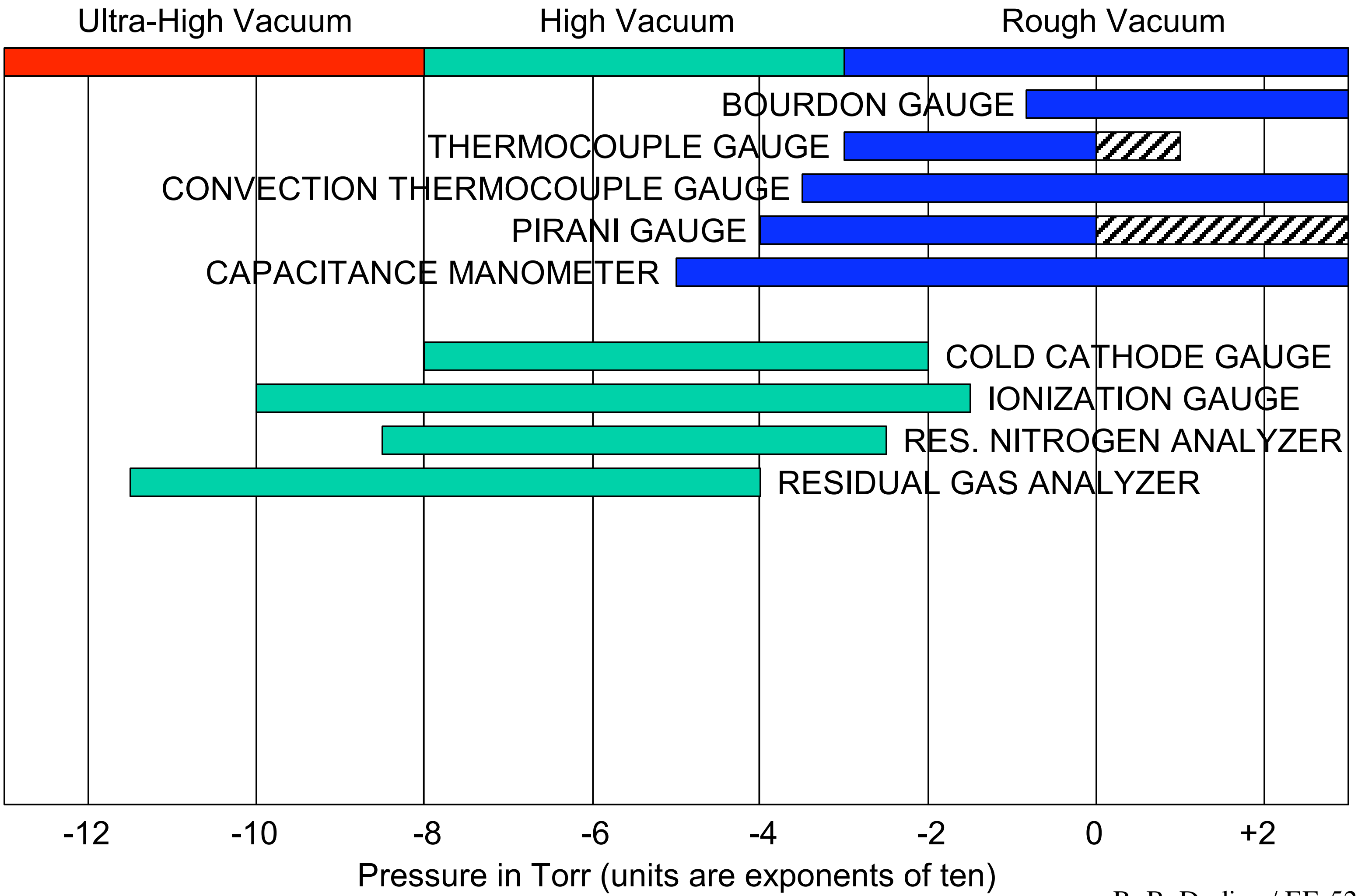
Ion Pumps - 5

- 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

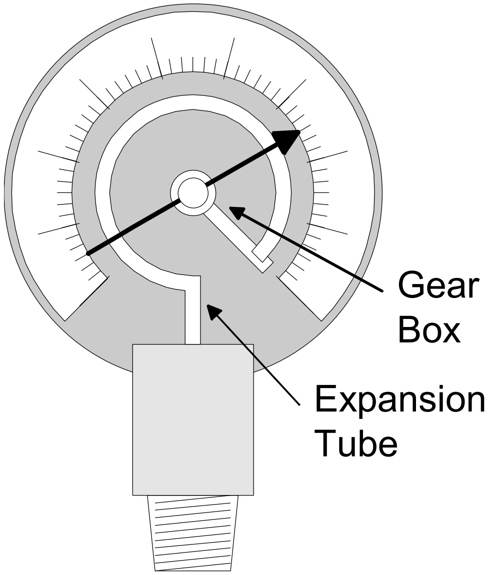


Vacuum Gauge Pressure Ranges



R. B. Darling / EE-527

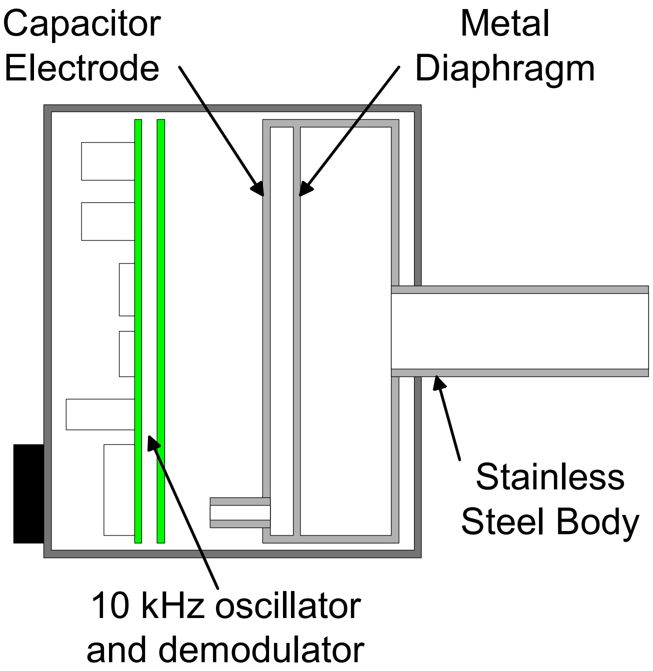
Bourdon Gauges - 1



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



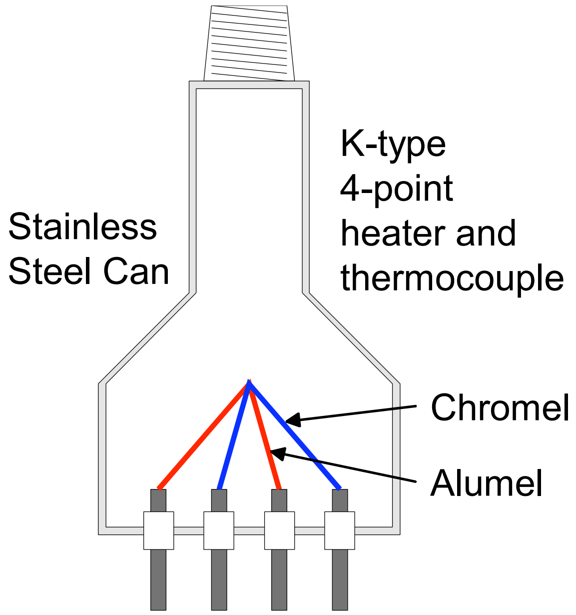
Capacitance Manometers - 2

- 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 ~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.

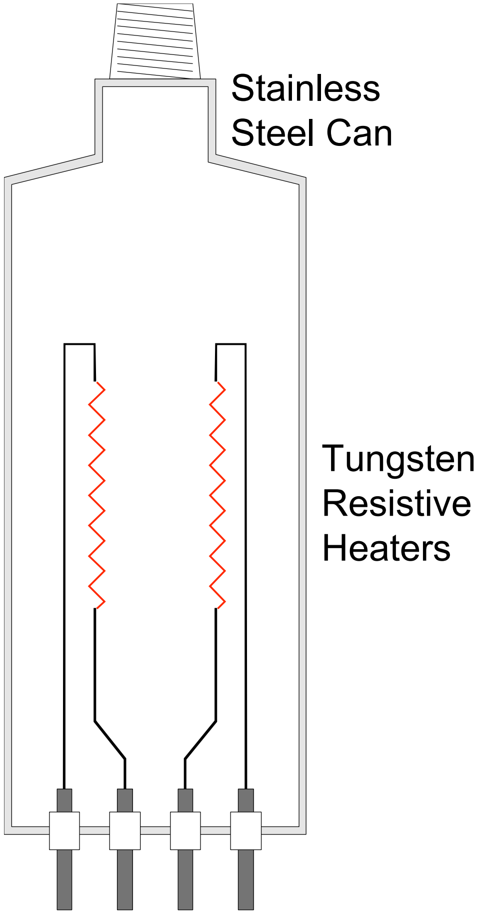
Thermocouple Gauges - 1



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.

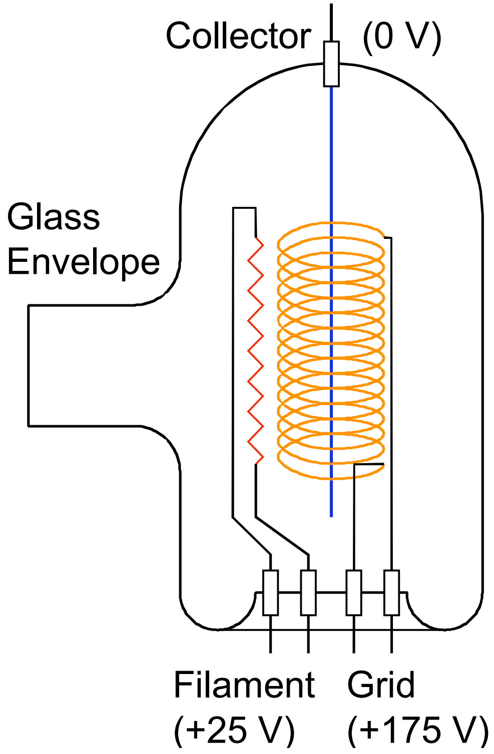
Pirani Gauges - 1



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



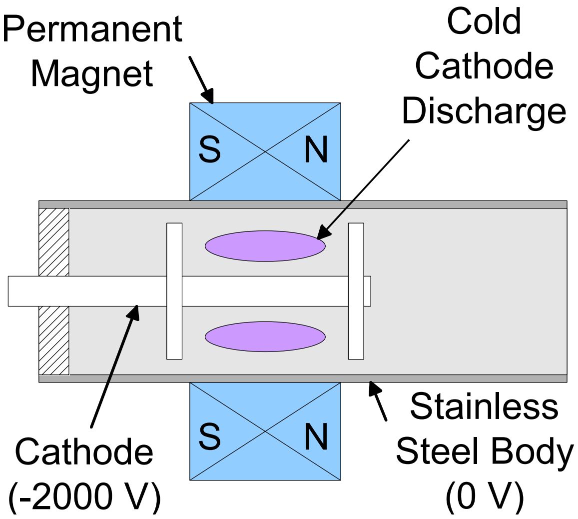
Hot Filament Ionization Gauges - 2

- Also know as “Bayerd-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/cm^3
  - the mean free path is about 5×10^3 cm
  - the impingement rate is about 10^{15} molecules/cm^2/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 μm), when vaporized, will produce a pressure of 10^{-4} torr inside a 10 ft^3 vacuum chamber!
- Thus: ALWAYS WEAR GLOVES!!!

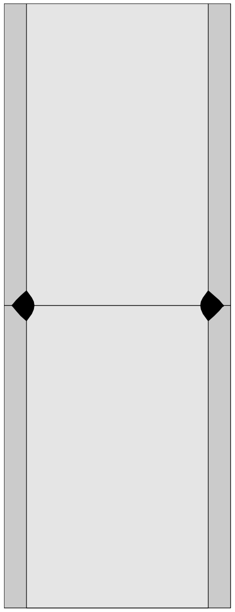
Vacuum Materials - 1

- 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 H_2O vapor.
  - Silicones
    - Can handle higher temperatures, but very permeable to H_2O and He.
  - Teflon
    - Very inert, but exhibits cold flow plasticity, making it a poor seal.
    - Very permeable to He, good to 150°C.

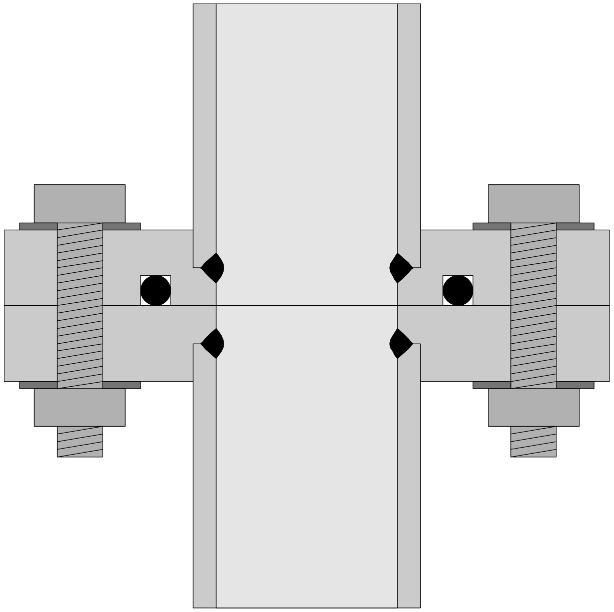
Vacuum Joining Techniques - 1



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

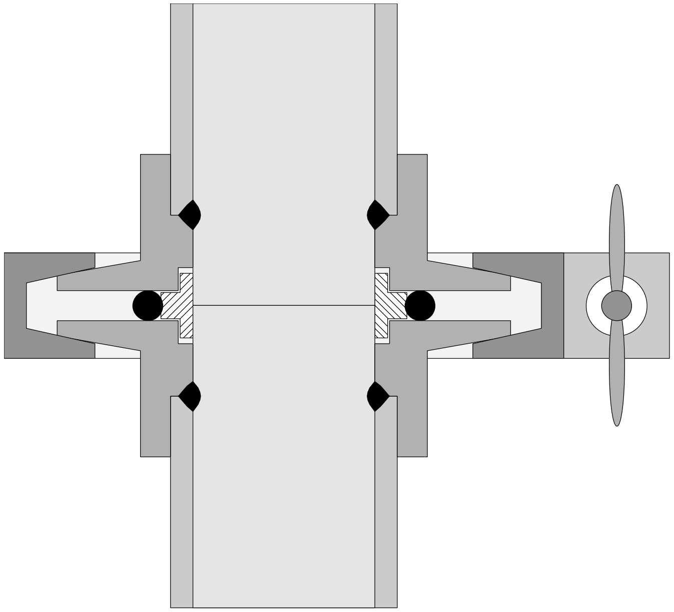
For small bore tubing, external orbital welding must produce complete penetration welds.

Vacuum Joining Techniques - 2



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

Vacuum Joining Techniques - 3

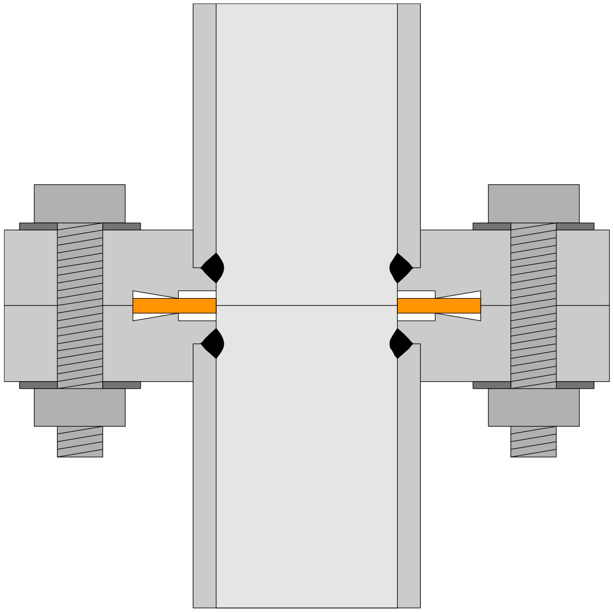


KF or “Quick-Flanges” are a common standard for rough or high vacuum plumbing.

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