NanoCourses 2004, Part 2

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Practical Vacuum Technology

Why is there air?

by

Lynn Rathbun, Ph.D

Presented by the
***CNF* Technical Staff**
for the education of CNF Users,
Potential Users, and Industrial Sponsors

Outline

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- **Introduction**
- **Kinetics, Thermodynamics and Gas Flow**
- **Primary Hardware**
- **Vacuum Materials and System Performance**

Introduction

Why is there Air ?

- **Appropriate vacuum is critical to most semiconductor fabrication processes**
- **Understand the hardware.**
- **Understand how it works as a system**
- **If you don't know how it works you can't use it intelligently**
- **In many real cases, what you do with or to a vacuum systems has just as much effect on performance as the hardware you have**

What is Vacuum

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- What is a vacuum?
  - Any gas at sub-atmospheric pressure
  - Vacuum is really the absence of gas
  - Vacuum is not absolute, but a continuous range of conditions
    - 15 orders of magnitude in common usage
      - Wide variety of phenomena
- Vacuum Technology
  - Moving and removing gases

How / Why do we use Vacuum?

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- Force *(P) (Suction)*
- Transport Medium *(Q) Throughput*
  - Chemical Vapor Deposition
  - To “outgas” solids and liquids
- Low Density Molecular Space *(MFP, n)*
  - Thermal Insulation
  - Plasmas
  - Molecular Transport
  - Extend Mean Free Path
  - Reduce Chemical Reactions
- Create/Maintain a clean surface *(Flux)*

Macroscopic Descriptions

How to Characterize Vacuum

- Just like we characterize a gas
  - Pressure: (force/area)
    - Force exerted is not really a useful concept
  - Volume:
    - Volume of container
  - Temperature:
    - Temperature of the walls (almost always)
  - Number Density: (number of molecules per unit volume)
    - Related to Pressure
    - A more useful quantity than actual "pressure"

Units of Pressure

- **Pressure is Force per Unit Area**
  - **Pounds/sq. in**
  - **Newtons / sq.meter**
  - **Tons/ sq. angstrom**
  - **Atmospheric Pressure**
    - **14.7 pounds/sq. in.**
    - **10^5 Newtons/sq. meter**
      - **approx. ton/sq ft**
      - **approx. kg(force) / sq.cm.**
- **SI UNITS:**
  - **Pascal = 1 Newton/ sq. meter**
  - **1 atm = 10^5 pascals**
  - **Non-Si Units: (common units)**
  - **Torr, millitorr**
  - **Bar, millibar**
- **Torr is an archaic unit but widely used and widely understood**
  - **Avoiding it is difficult**

Pressure Conversions

- **1 torr = 133.2 Pascals (Pa)**
- **1 Pa= 7.5 millitorr (mt) = 7.5 x 10^{-3} Torr**
- **1 Bar = 10^5 Pascals**

- **1 Std Atmosphere = 760 Torr = 1000 millibar**
- **1 Std Atmosphere = 1.013 x 10^5 Pascal**

Torr

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- ~1 / 760 of atmospheric pressure.
- Pressure exerted by 1mm tall column of Hg.
  - Pretty useless as a real measurement of real vacuum.
- Sloppy unit.
  - Torr aka "mm-Hg" aka "mm."

Pressure Sub-Units

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- Correct use:
  - Torr.
    - 10^{-n} Torr.
  - Note: Factors of 10.
    - 10^{-6} is 10x 10^{-7}
    - high 10^{-7} is almost 10x higher than low 10^{-7}
- Sloppy use:
  - 10^{-3} torr = 1 millitorr= 10^{-3} "mm-hg"= 10^{-3} "mm" = 10^{-6} "meters Hg" = 1 "micron Hg"= 1 "micron"
    - a "micron" is not 10^{-6} torr, just 10^{-3} torr

Relationship of Pressure Units

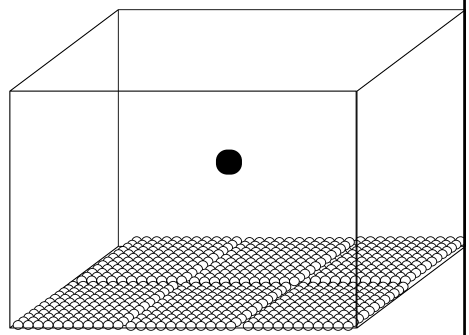
		Loose Usage
10^{3} Torr		
10^{2} Torr		
10^{1} Torr		
1 Torr		
10^{-1} Torr	100 millitorr	100 microns
10^{-2} Torr	10 millitorr	10 microns
10^{-3} Torr	1 millitorr	1 micron
10^{-4} Torr		
10^{-5} Torr		
10^{-6} Torr		
10^{-8} Torr		
10^{-9} Torr		
10^{-10} Torr		

Ideal Gas Law

- Most of vacuum technology flows directly from this simple statement
- PV=NkT
  - P= Pressure
  - V= Volume
  - T= Absolute Temp (Kelvin)
  - $k=1.38 \times 10^{-23}$ Joules/molecule/Kelvin (Boltzmann’s Constant)
    - In engineering units $kT=3.1 \times 10^{-20}$ torr-liters
  - N=Number of molecules
  - n=N/V=number density
- At constant T ----- P is proportional to n !!

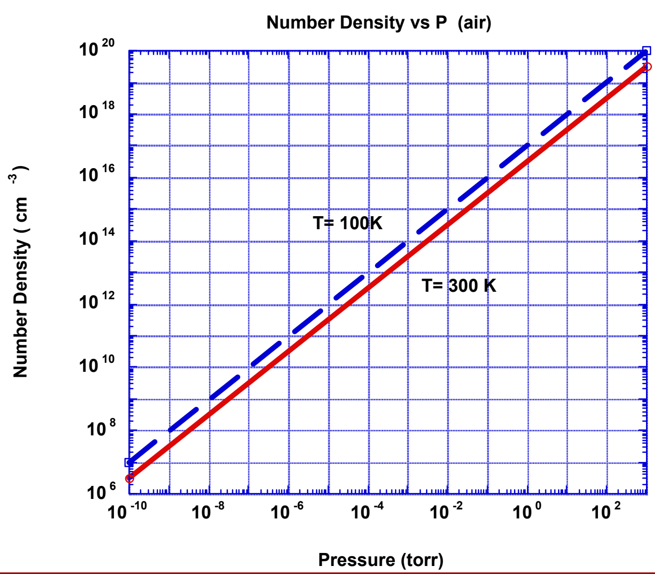
Number Density

- "Pressure" is actually pretty irrelevant
  - Infinitesimal forces
- Number density (n) is a more useful concept.
  - Proportional to P
  - Number density is more easily measured
  - Number density is more relevant to actual phenomena
  - Number density in a gas is also very small compared to solid densities



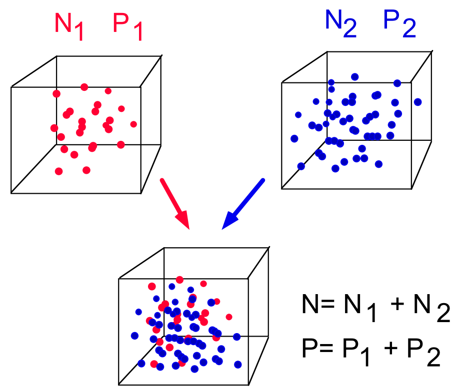
Solid surface vs gas at STP

Number Density (air)



Dalton's Law of Partial Pressure

- In a mixture of ideal gases in a common vessel, each exerts its pressure independent of the others
- i.e. If……
  - $N_t=N_1+N_2+N_3$…
  - $P_t=P_1+P_2+P_3$….
- Then….
  - $P_1V=N_1kT$
  - $P_2V=N_2kT$
- Total Pressure = Sum of "Partial Pressures"
- Ideal gas....Non-interacting



Microscopic Description

Microscopic vs. Macroscopic

- Gas Laws are Empirical
- Gas Laws are Macroscopic
- What can we do with Thermodynamics / Kinetics?
  - What is going on at the atomic scale that manifests itself as PV=NKT?

Kinetic Theory of the Ideal Gas

- Assumptions:
  - Molecules are small
  - Molecules are fast and chaotic
  - Molecules are sparse
  - Molecules are independent
  - Energy is partitioned according to thermodynamics
    - Maxwell Boltzmann speed distribution

$$dn \approx \exp\left(-[\mathrm{v}/\mathrm{v}_o]^2\right) d^3\mathrm{v}$$

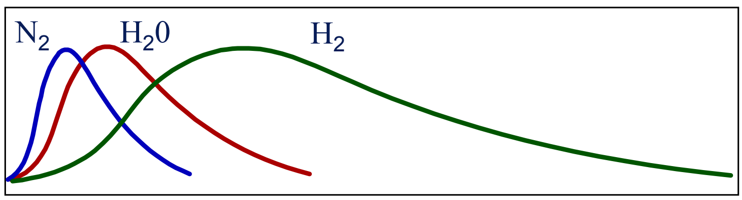
$$dn \approx \mathrm{v}^2 \exp\left(-[\mathrm{v}/\mathrm{v}_o]^2\right) d\mathrm{v}$$

Velocity Distributions

- Boltzmann distribution of velocities
- Most probable velocity:
  - For H_2 = 1572 m/sec
  - For N_2 = 421 m/sec
  - for H_2O = 525 m/sec

$$v_o = \sqrt{\frac{2kT}{m}}$$

- Significant differences in velocity:
  - Between molecules of different kinds
  - Between different molecules of the same kind



Molecular Transport

- We can calculate 2 important quantities:
  - ------Details omitted
- Mean free path (lambda)
  - How far does a molecule go before it strikes another?
- Impingement rate --- Surface Flux
  - How many molecules strike the surface in a given period of time?

At atmosphere, MFP is very short and Surface Flux is very high

At high vacuum, MFP is very long and Surface Flux is very low

Mean Free Path

- **Mean free path:**
  - **d = molecular diameter**

$$\lambda = \frac{1}{\sqrt{2}\pi n d^2}$$

$$\lambda_{cm} = \frac{5*10^{-3}}{P_{torr}}$$

  - **For Air:**

$$\lambda_{cm} = \frac{5}{P_{millitorr}}$$

Mean Free Path (air)

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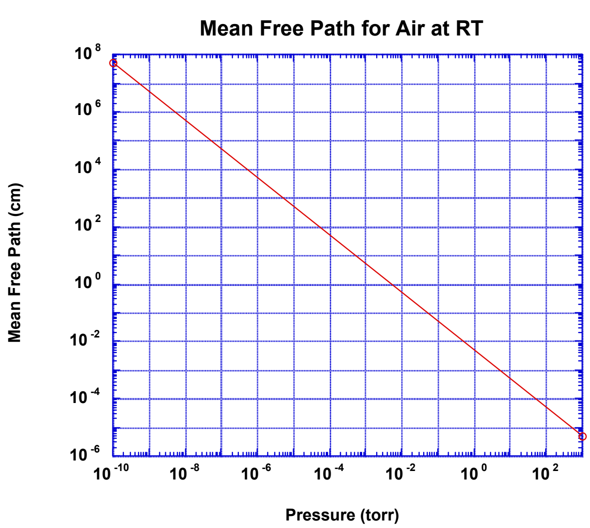


50 meters @ 10^{-6} torr

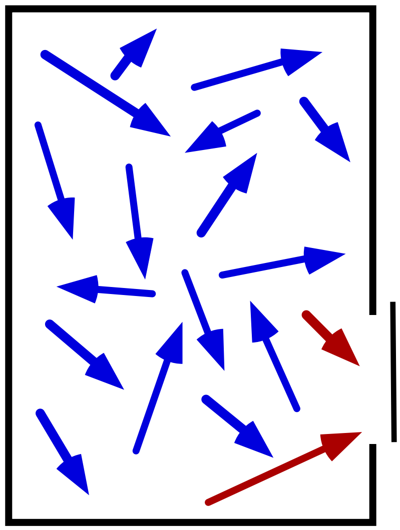
$5*10^{-5}$ m@1 torr

50 micrometers

$5*10^{-8}$ m @ 1000 torr

50 nanometers

Impingement Rate



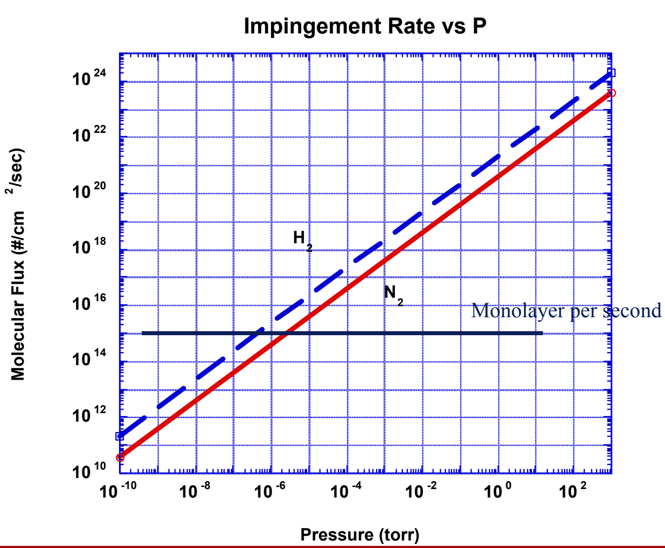
- Rate at which molecules strike the surface:

$$\phi = n\bar{v}/4$$

$$\bar{v} = \sqrt{\frac{8kT}{\pi m}}$$

$$\phi \propto \frac{P}{\sqrt{mT}}$$

Number Hitting Surface



Flow Regimes

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- Simplify!
- Qualitatively, 2 main different regions of flow.
  - Viscous Flow
  - Free Molecular flow
- Ratio of MFP λ to the "typical dimension"
  - Importance of wall collisions *vs* intermolecular collisions
  - Relative Size on mfp scale

Flow Regimes

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Fluid like

- MFP << "a"

  "crowded"
  - Molecules interact with each other more than walls
  - Act as a "fluid"
  - Flow
  - Diffusion
  - Viscosity
- Familiar region
- Molecules act on each other
- We can act on the gas " as a whole"
- Essentially most of "rough" vacuum range

Viscous Flow

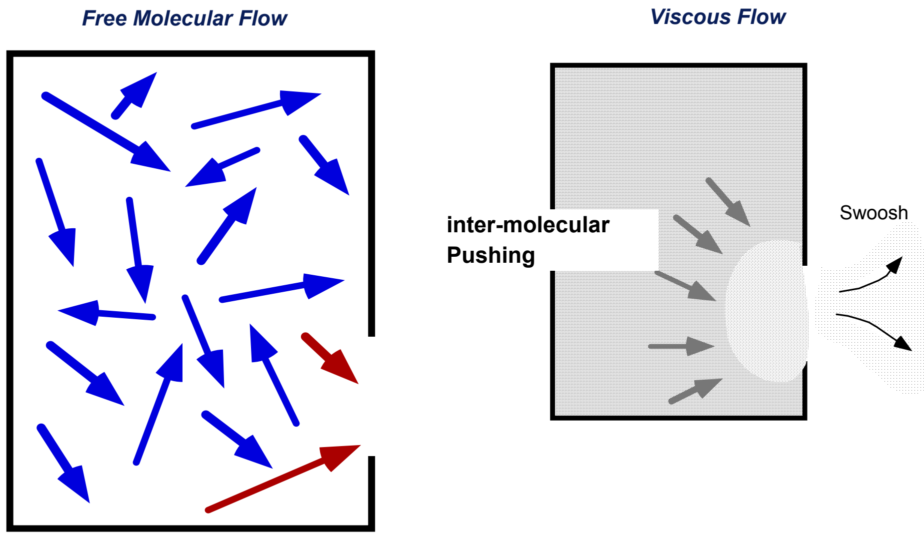
Molecule like

- MFP >> "a"

  "sparse"/ "vacant"
  - A "sparse" gas on the scale of the tube dimension
  - Molecules interact only with the walls
  - Every molecule to itself
  - No intermolecular forces or energy transfer
- We can only act on ONE MOLECULE AT A TIME
- A VERY UNFAMILIAR REGIME.
- Most of mid, high and ultra high vacuum

Free Molecular Flow

Free Molecular vs. Viscous Flow



Quantity Throughput (number throughput)

- **Q**
- **Quantity of gas in PV units flowing past some location in unit time.**
  - **PV/t**
  - **Torr liters/sec**
- **From ideal gas law, essentially # flow**

Analogous to a "current" in electronics

Pumping Speed or Volume Throughput

- **Ratio of Q (number throughput) to Pressure for a given gas.**
- **or**
- **Volume of gas (at given P) that is moved in given period of time**
- **Q=PS**
- **When talking of a vacuum pump, S is called the pumping speed.**
- **S is basically a physical characteristic of a Pump**
  - **The ability to sink gas**

Analogous to a "power" in electronics—
in fact it actually has the dimensionality of watts

Conductance

- **C**
- **Flow between two places, i.e. through a tube.**
- **Q/ΔP.**
- **A property of the tube and a function of gas type and pressure, etc.**

Directly analogous to electrical conductivity, or inverse resistance

Pumping Speed or Capacity

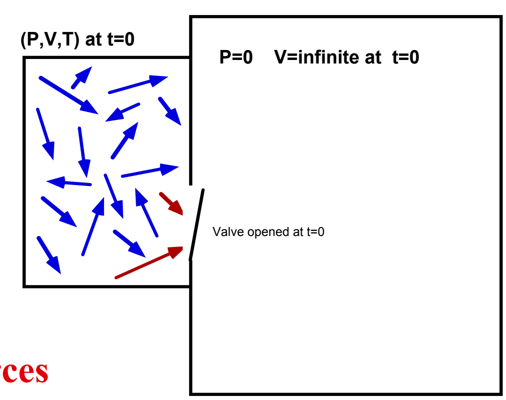
- Pumps likewise have a “capacity”, an ability to “sink” gas, known as S or Pumping Speed

For you electrical guys, this is like the output impedance of a power supply

Molecular Transport at Free Molecular Flow

- Low P
- Free Molecular Flow
- Rate of escape = rate at which they hit the “hole”
- Impingement rate

$$\phi = \frac{n\bar{v}}{4}$$



- No intermolecular forces
- No such thing as suction !

Free Molecular Transport

- **Number Flux:**

$$\phi = n\bar{v}/4$$

- **Volume Flux:**

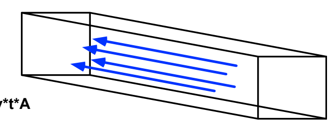
$$\text{Volume Flux} = \frac{\bar{v}}{4}$$

Units = distance / sec

Units = (volume / sec) / area

For air at Room temperature:

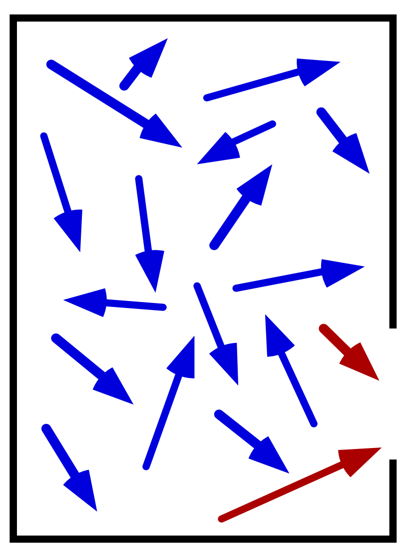
- **11.6 liters/sec/cm^2**
- **Independent of PRESSURE.**
- **Depends on Mass (velocity) but mostly we just talk about "air."**



#=v*t*A

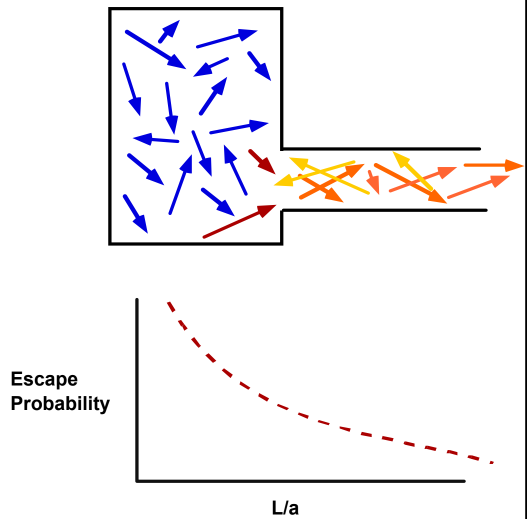
Removing Gas

- **11.6 liters per second**
- **Can't remove it any faster than it arrives**



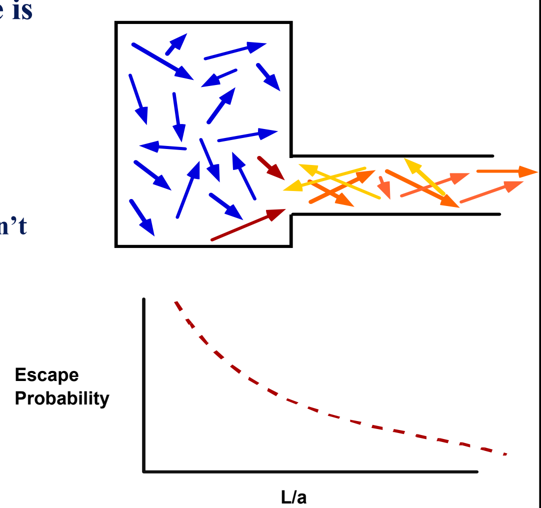
Transport through a Tube

- Not everything that enters the hole (tube) gets to the other end
- Longer the tube the higher the probability of 'reflection'

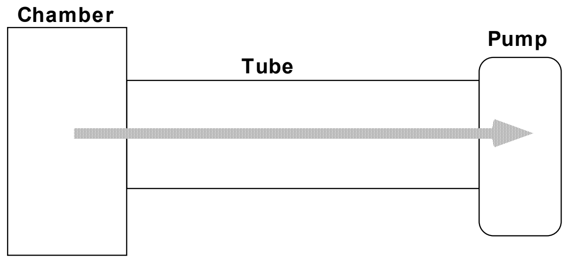


Conductance

- Transport through a tube is less than through a hole
  - Transport = speed
- Conductance.
  - Property of a tube
  - What goes in one end doesn't necessarily make it to the other



Conductance in Series



$$P_0 = \frac{Q}{S_0} \qquad C = \frac{Q}{P_0 - P_1} \qquad P_1 = \frac{Q}{S_1}$$

$$C = \frac{Q}{\frac{Q}{S_1} - \frac{Q}{S_0}} \longrightarrow \frac{1}{S_1} = \frac{1}{S_0} + \frac{1}{C}$$

Conductance

- **Components in Series:**

$$\frac{1}{C_{net}} = \frac{1}{C_1} + \frac{1}{C_2}$$

- **Components in Parallel:**

$$C_{net} = C_1 + C_2$$

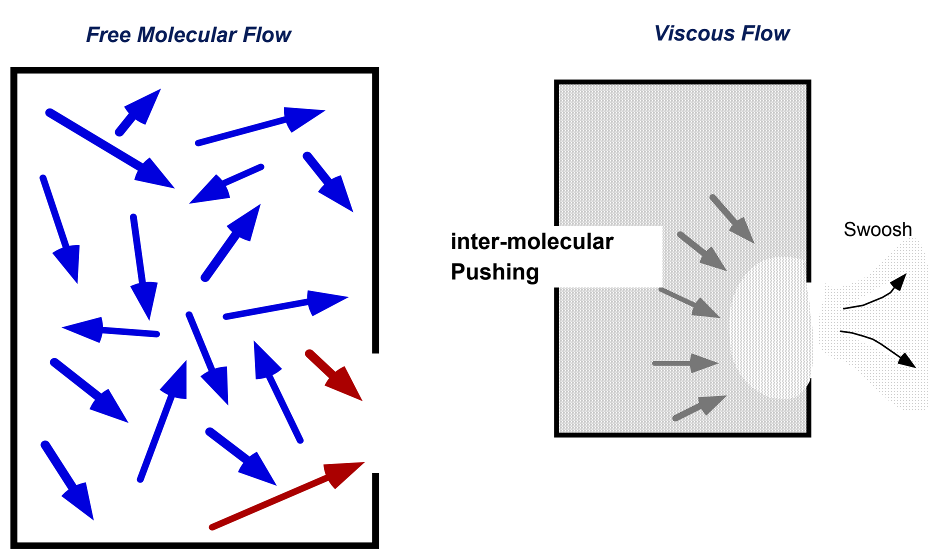
Calculating Conductances

- Ugly

- Deal only with the end regimes.
  - Free Molecular Flow
  - Viscous Flow

  - Geometry effects

Free Molecular vs. Viscous Flow



Conductance of a tube

Calculating is ugly….just look at end result and dependence

Molecular flow

$$C_{air(longtube)} = 100\frac{a^3}{L}$$

Viscous flow

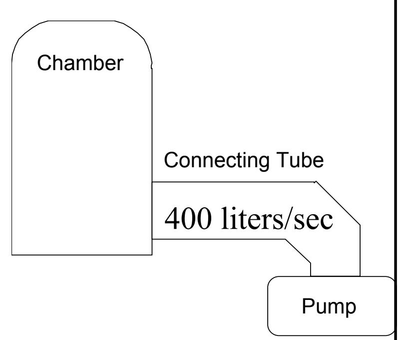
Units---liters/sec and cm

$$C_{viscous} = \frac{\pi a^4}{8\eta L} P_a$$

Look up the equations and units and limitations if you need them

Typical Conductance Limitation

- **Typical System:**
  - **1000 liter/sec**
  - **Air**
  - **10 cm diameter tube**
  - **30 cm long**
  - **Short tube**
  - **Free Molecular flow**
- **C=Conductance=400 L/sec**



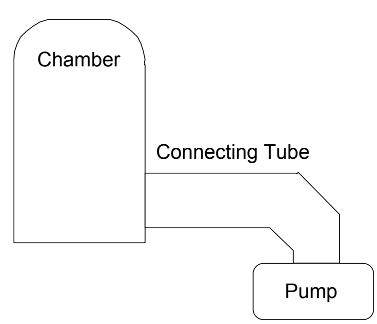
1000 liters/sec

Pumping Speed and Conductance

- **Gross Speed-Conductance:**
  - **1000 L/sec pump**
  - **400 L/sec tube conductance**
- **Net Speed:**
  - S_{net} **= 285 L/sec**
- **A long tube is even worse.**
- **2000 L/sec pump----> 333 L/sec.**

Conductance Limitation

- **Big Pumps (expensive) don't buy you anything is you are conductance limited**
- **Common case**
- **If you have a pump inlet bigger than the connecting tube (short) then you either have too big a pump or too small a tube**
- **Short fat tubes!!!**



Vacuum Pumps

So what is a Vacuum Pump?

- **This is not a trivial question!**
  - **A pump removes gas from the volume of interest**
    - **Transport through compression (Bulk action)**
      - **Mechanical "compressor"**
    - **Momentum transfer directly to molecules (molecular action)**
      - **Collisions with Macroscopic Items**
      - **Entrainment: Collisions with other molecules.**
    - **Immobilization: Store at surfaces for a time >>> time of experiment**
    - **Most vacuum pumps only work over a:**
      - **Limited range of conditions**
      - **Limited types of gases**

Pumping Concepts

- Storage Pumps
- Compression Pumps and Transport Pumps
  - Compression losses its familiar meaning when we have very low density molecular space
  - More easily understandable is the concept of "diode"
    - A pump is a diode for gas flow!
    - Difference between "forward" and "reverse" transition probability will sustain a pressure difference
      - "rectification"

A pump is something that can sustain a pressure differential

Engineering Vacuum Ranges

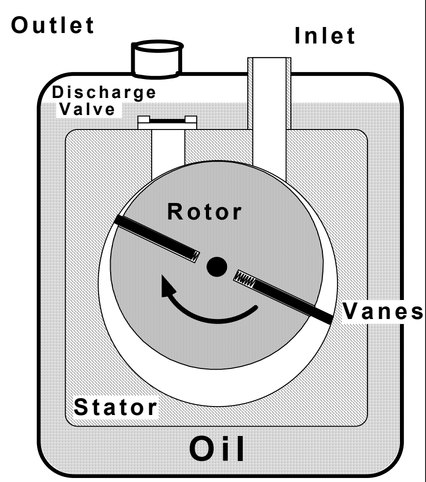
- Rough Vacuum
  - Down to 1 millitorr
  - Part viscous flow
  - Part free molecular flow
  - Gas flow and chemical reaction application
- High Vacuum
  - 10^{-6} torr to 10^{-9} torr
  - Completely free molecular flow
  - Long mfp applications (evaporation and electron beams)
- Ultrahigh vacuum
  - $<10^{-9}$ torr
  - Keep surfaces clean

Common Ranges of Pumps

- **Rough Vacuum Pump:**
  - Atmosphere to 10^{-3} torr
  - Rotary Vane Pumps
  - Rotary Piston Pumps
  - Venturi Pumps
  - Cryosorption Pumps
  - Roots Blowers
  - "Dry" Pumps
- **High Vacuum Pumps:**
  - From 10^{-3} to 10^{-n} torr
  - Diffusion Pumps
  - Cryopumps
  - Turbomolecular Pumps
  - Ion Pumps (UHV)
- **You will find most of these types in our laboratories.**

Rotary Vane Pump

- **Most common type of rough vacuum pump:**
  - Belt drive or Direct drive.
  - One Stage or two state.
  - Actually a small rotary compressor.



Rotary Vane Pumping Cycle

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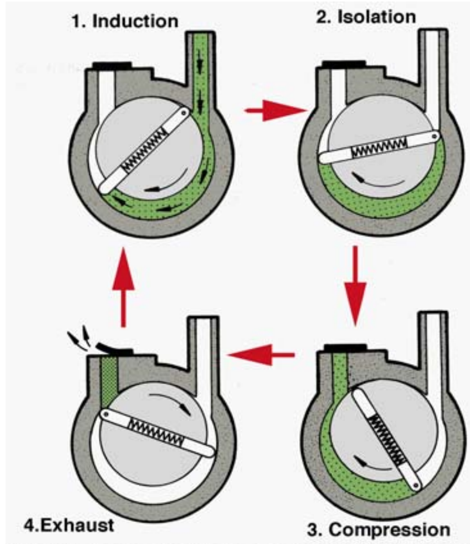

Four Stages in the Cycle of a Rotary-Vane Pump

Typical Direct Drive Vane Pump

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Pump Housing

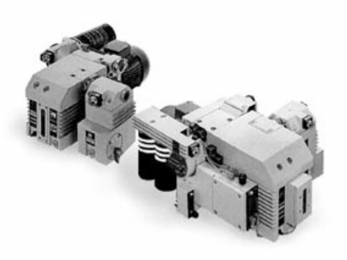
1 cfm - 60 cfm

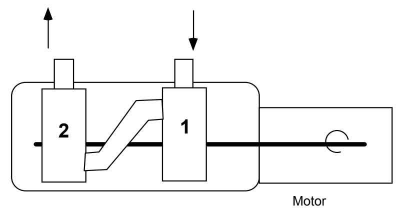
Electric Motor

- **7 cfm cubic ft per minute = shoe box size**
- **60 cfm = size of a medium sized dog**
- **Essentially all rotary vane pumps in research laboratories are now Direct Drive**

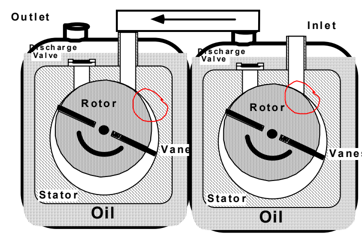
Component photos from Stokes

Rotary Vane Pumps





Schematic of 2 stage pump



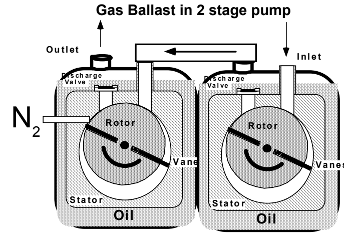
- Typically 2 stages
- Better Vacuum
- Less outgassing of oil
- Gas saturation in output stages

Component photos from Leybold and Lesker

Pumping Condensables / Gas Ballast

- As you compress gas from vacuum, “stuff” can condense out:
  - Water
  - Chlorine
  - Etc.
- Bad for pump, Bad for vacuum
- Gas Ballast
  - Nitrogen bleed
    - Flushes out condensates.
    - Lowers compression ratio in output stage.

Gas Ballast in 2 stage pump



Mechanical Pump Oils

- Most "mechanical pumps" require a Pump Fluid
  - Functions:
    - Lubricant
    - Sealant
    - Heat Transfer/coolant
    - Corrosion Protection
  - Requisite Properties:
    - Chemically stable
    - Thermally stable
    - Appropriate lubricating ability
    - Appropriate viscosity
    - Low vapor pressure

Pump Oils

- Normal Mineral Oils:
  - Various distillations
  - The brown stuff- $ 5/ liter
  - The white stuff - $20/ liter
  - Reactions with chemicals and particularly oxygen
- Artificial Oils:
  - Fully halogenated Fluorocarbon
    - Fomblin and Krytox (brand names)
    - PFPE Perfluorinated polypheyl ether
    - "Almost" totally inert
    - $500 per liter !!!!!

Component photos from Lesker

Oil Filtration

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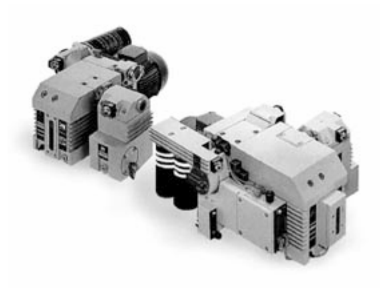
- **Vacuum Pump Oil is not "wonder fluid"**
  - **Oil Degrades**
  - **Oil collects reaction products**
  - **Need to remove "impurities"**
- **Oil Filtration System:**
  - **Small fluid pump**
  - **Filter**
    - **Particulate (SiO_2)**
    - **Acid neutralization (HCl)**
  - **Stand alone or built-in**
  - **Continuous filtration**
- **Essential on all processing pumps**
  - **Lifetime = zip without them**



Component photos from Leybold

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Costs of "Wet" Pumps

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- **Standard pump for non-corrosive:**
  - **Plain vanilla small pump. (8 cfm) $1500**
  - **Plain vanilla BIG pump. (30 -60 cfm) $3000**
  - **"Low maintenance", lasts forever.**
  - **Great for pumping on air.**
- **BUT, for heavy duty chemical processing (RIE, CVD, ...):**
  - **Pump**
  - **Chemically resistant/oxygen service**
  - **Oil filter, inlet particle filter**
  - **Exhaust oil mist filter filter**
  - **Prepare for inert fluid.**
  - **Inert fluid**
  - **High maintenance, short life**
- **Full blown system for corrosive chemistry > $15,000**
- **Then there are maintenance /expendables, oil changes, filters, etc.**

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Rotary Vane Pump Summary

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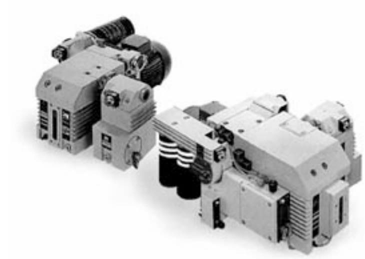
- Advantages:
  - Reliable
  - Cheap
  - Removes gases permanently
- Disadvantages:
  - Noisy
  - Dirty
  - Oily
  - Big
  - Heavy



Component photos from Leybold, Stokes, and Lesker

Roots Blower

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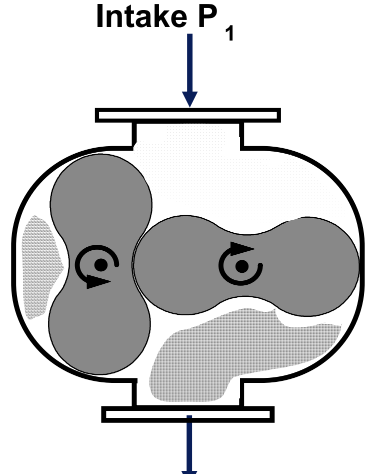
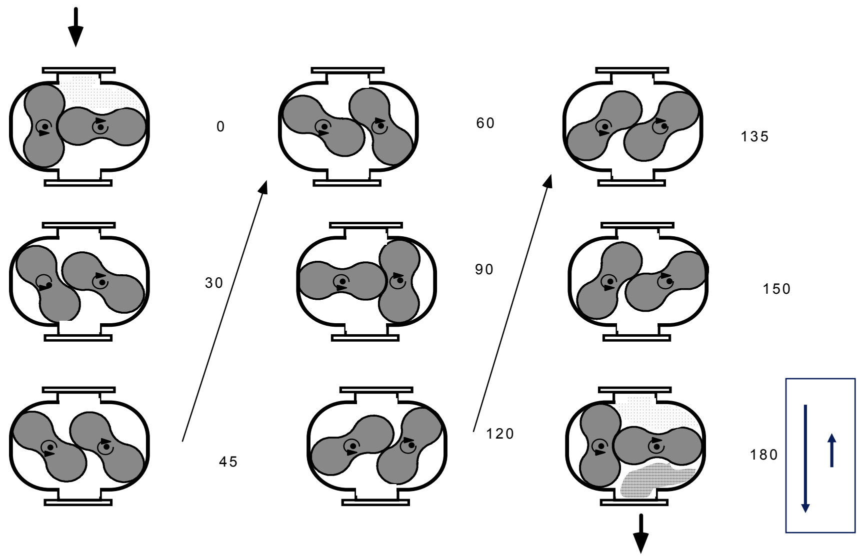
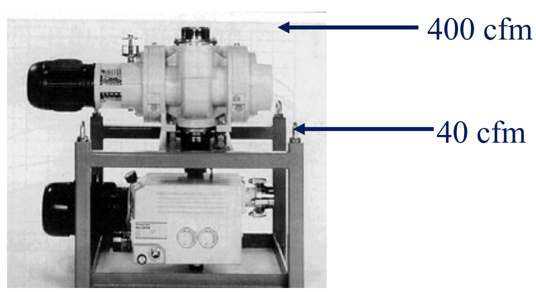
- Can we extend the range/capacity of a rotary Vane pump:
  - A pre-compressor
  - High throughput but low pressure difference
  - It compresses the gas before the main pump to give you higher throughput at the same inlet pressure (Q= PS)
  - Actual Compression Ratio about 10 X
- A "diode" for gas
- A booster --- Can't pump by itself



Roots Blower Cycle



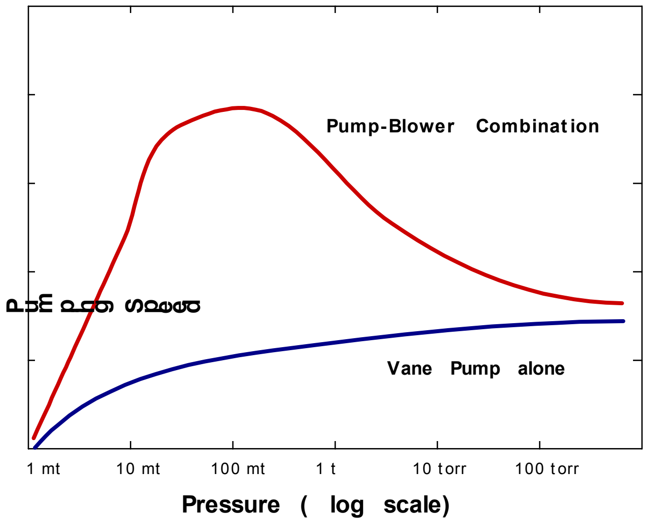
Roots Blower Package



- **Closely coupled pump package**
  - **Roots blower on top**
  - **Direct Drive Rotary Vane pump on bottom**
- **Much more “throughput” than vane pump alone**

Component photos from Leybold

Speed Comparison



"Dry" Pumps

- **Wet pumps are a pain- lots of maintenance**
  - **If only we didn't have all the oil problems**
- **A dry roughing vacuum pump is the answer !**
  - **Roots Blowers prove we can have compression without fluid**
  - **What's wrong with a roots blower??**
    - **Won't exhaust to atmosphere**
    - **Small compression ratio**
- **Various kinds of other dry mechanical "compressors"**
  - **Put together to make a "dry" pump**

"Dry" Pumps

- A dry mechanical pumping element will not have much "compression" as there is no sealing fluid
- But:
  - If you can get 10x compression in one stage, it is only 6 orders of magnitude from rough vacuum to atmosphere
  - 6 "bad" pumps in series = 1 good pump

Component photos from Leybold

"Dry" Pumps

- General Characteristics:
  - Close mechanical tolerances
  - High Rotational Speed
  - Hot to reduce condensation
- Types of Stages:
  - Lobe pumps (Roots)
  - Claw pumps
  - Scroll pumps
  - Molecular drag pumps
  - Diaphragm pumps

Component photos from Leybold

"Claw" Pumping Principal

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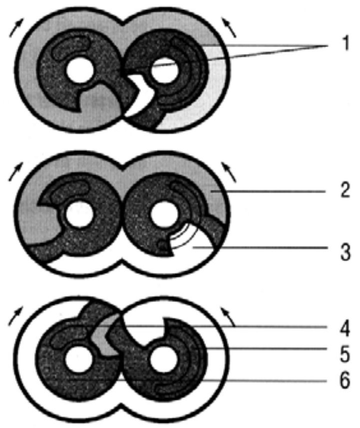
- One of several types of dry pump stages (Leybold)
- Close tolerances
- Poor performance as a single stage



Schematic diagram of the pumping principle

Dry Pump

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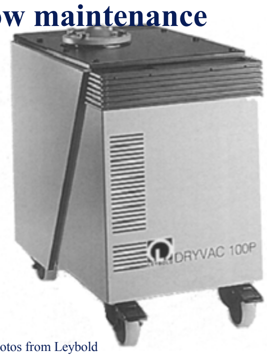
- To "make" a Dry Pump:
  - Stick 6 of them in a box, in series
  - Optimize the configuration and interconnection
  - Common motor and control
- The "in" thing for semiconductor processing

Component photos from Leybold

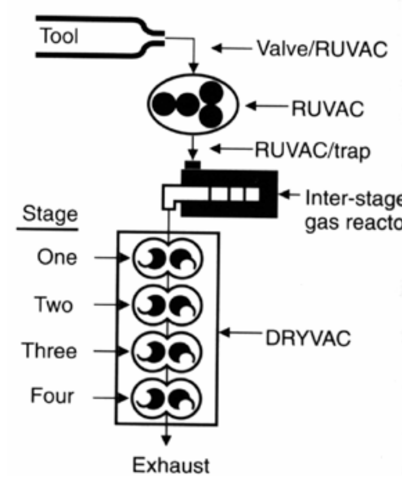
Dry Pumps

- Quite Expensive
  - $40,000 each vs $5-10K for wet pump
  - Complex
- Reliable
- Low maintenance



Component photos from Leybold

LPCVD Dry Pump stack



Capture Pumps

- So far we have talked only of "compressors"
  - Moving viscous gas, as a fluid
- Mechanics is very limited, however, in manipulating molecules. To do better we have to use some science
- We are going to "pump" not by removal but by capture
- Various types of "capture" pumps at both rough and high vacuum
- Not as universal as mechanical pumps: Capture pumps are more dependent on gas (vacuum) composition
  - Chemistry
  - Physics

Capture Mechanisms

- Capture pumps rely on "Surface processes" to trap and bond gases for a "long" time
  - Temperature
  - Molecular Surface "chemical" bonding
- Surface Process:
  - Area sensitive process--- Capacity !!
    - Exposed "surface" molecules
    - Large areas required
  - Chemically selective ------- selective pumping
- Almost any material will bond or trap some gas
- Most effective: Special sorbent materials with large effective surface areas

Types of Sorbent Materials

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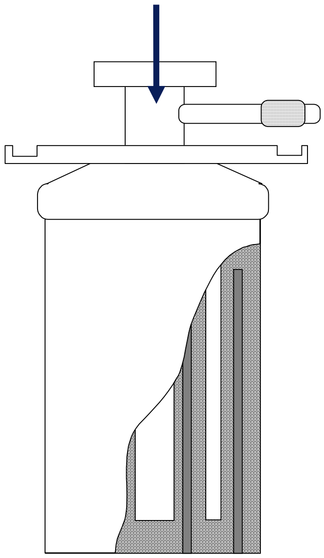
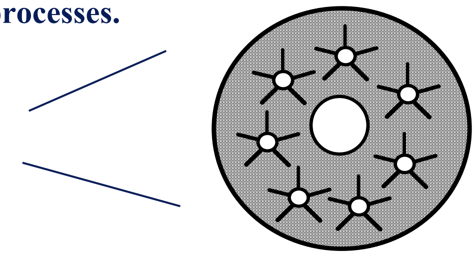
- We need something with lots of surface area per gram or per cc.
  - Activated charcoal
  - Zeolite (aluminosilicate material)
    - (Linde 5A , Linde 13X)
  - "Pores" down to "atomic" dimensions
    - Narrow pore size distribution
      - Molecular sieve
      - Selective adsorbent
- Typically 800 square meters "effective area" per cc.

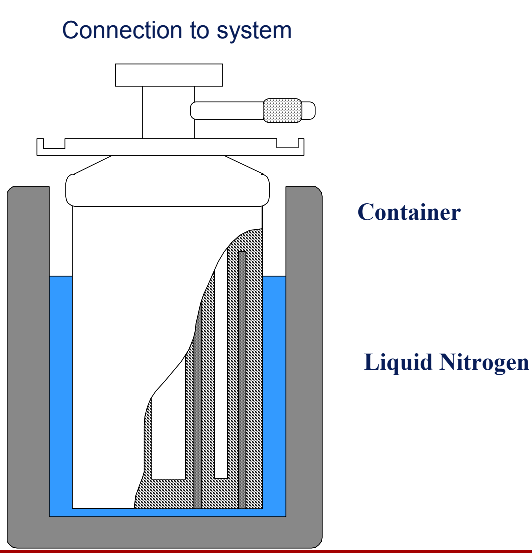
Sorption Pump



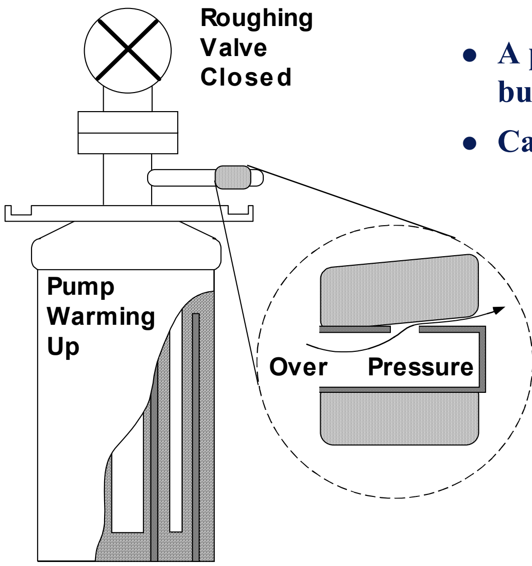
- "Zeolite in a can."
  - Square miles of surface area
- Cooled to Liquid Nitrogen temperature.
- Combination of temperature bonding and pore bonding processes.



Sorption Pump



Regeneration of Sorption Pump



- A pump can store a lot of gas, but where does it all go later??
- Capacity ~ 10 cubic meters

Composition of Air

Partial Pressure in Air -- in torr

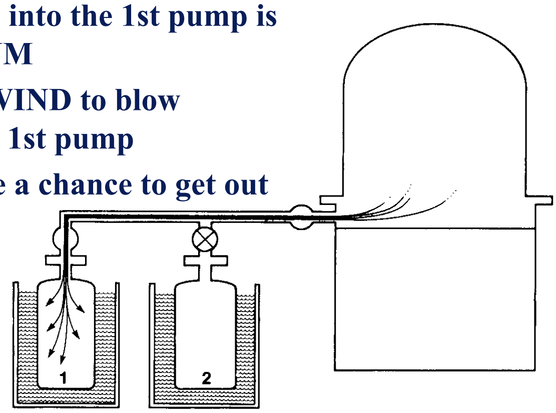
	Dry Air	20 Ȼ 100% RH
Nitrogen	593.00	579.35
Oxygen	159.00	155.34
Water vapor		17.50
Argon	7.10	6.94
Carbon Monoxide	0.25	0.24
Neon	0.01	0.01
Helium	4.0E-03	3.9E-03
Methane	1.5E-03	1.5E-03
Krypton	8.6E-04	8.4E-04
Hydrogen	3.8E-04	3.7E-04
Nitrous Oxide	3.8E-04	3.7E-04
Xenon	6.6E-05	6.4E-05

Using Sorption Pumps

- Sorption pumps are generally used in pairs
  - One for coarse pumping from atmosphere, switching to:
  - One for fine pumping to achieve low vacuum
- Vapor pressure of Argon could limit if used improperly
  - Equilibrium
  - Non-equilibrium
    - Swoosh effect

Swoosh !!

- Thermodynamics would limit us to 7 mt at EQUILIBRIUM
- Don’t go to Equilibrium !!!
  - Stop at ~100 mtorr
- The initial “rush” of gas into the 1st pump is
  NOT EQUILIBRIUM
- Take advantage of the WIND to blow “unpumpables” into the 1st pump
- Close it before they have a chance to get out



Sorption Pump Operation

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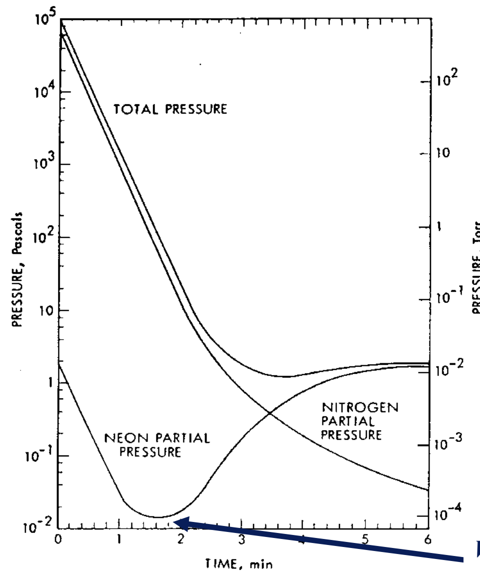
Single Sorption Pump



Valve it off HERE !!

Sorption Pump Summary

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- **Advantages:**
  - **Clean**
  - **Quiet**
  - **No backstreaming**
  - **No electricity**
- **Disadvantages:**
  - **Needs Liquid Nitrogen**
  - **Selective**
  - **Limited Capacity**
    - **5-10 pump downs before regenerations.**
- **Often used on ion pumped UHV systems**

High Vacuum Pumps

High Vacuum Pumps

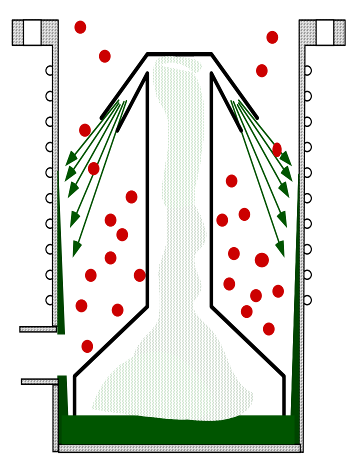
- So far we have talked about ROUGH pumps, pumps down to 10^{-3} torr
- Need fundamentally different pumps, different mechanisms to go the High Vacuum (< 10^{-5} torr)
- Note there is not much interesting in the Mid Vacuum range (10^{-3} - - 10^{-5} torr)
- High Vacuum is entirely Free Molecular Flow

High Vacuum Pumps: General Concepts

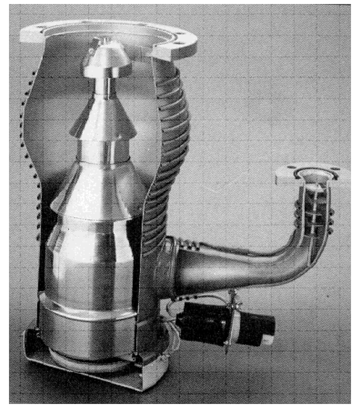
- Most HV pumps can not exhaust to atmosphere.
  - Rough pump in series, called a backing pump.
- Most HV pumps can not start at atmosphere, i.e. they have an upper limit. You must get to Rough vacuum some other way
  - Backing Pump or Fore Pump
- Pumping System:
  - Pumps in Parallel
  - Pumping in Series

Diffusion Pump

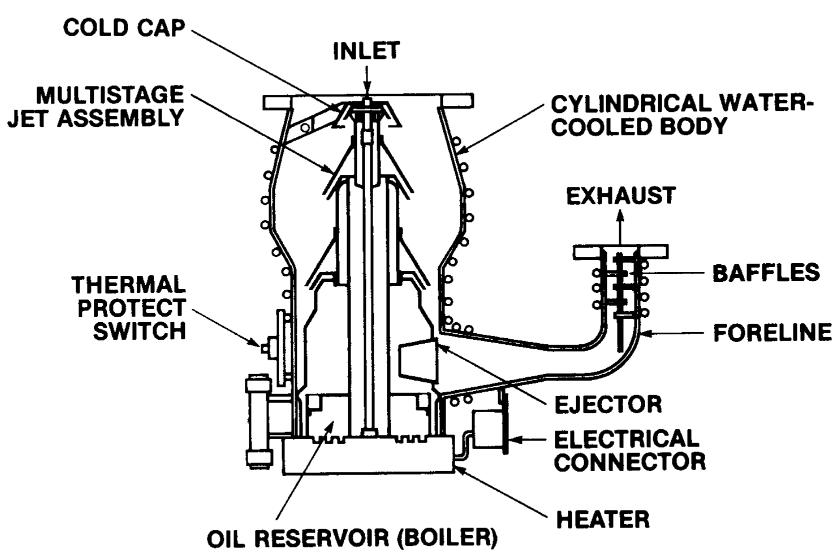
- The Diffusion Pump is (was) most common type of HV pump.
  - The principle seems almost silly.
  - Knock gas molecules (the bad molecules) by bonking them with the Good Molecules (the well trained ones).
  - Intermolecular Momentum Transfer.



Diffusion Pump Cutaway

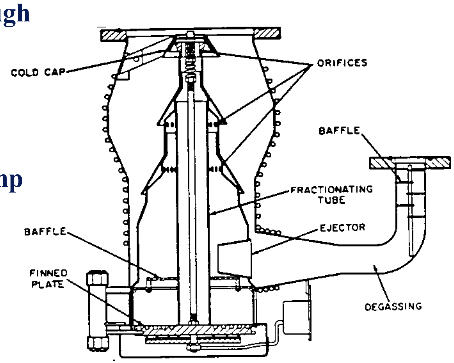


Diffusion Pump Cutaway



Diffusion Pumps Don't Work Alone

- Roughing Pump
  - To get the chamber down to Rough vacuum so DP can take over
  - Typically Big -- 30 cfm
- Backing Pump or Fore Pump
  - Pump on output of diffusion pump
  - Keep below ~ 1 torr
  - Typically smaller
- Generally not the same pump



Multistage diffusion pump.

Diffusion Pump Fluids

- Working Fluid:
  - Heavy molecule
  - Liquid
  - Low Vapor Pressure
- Examples:
  - Hg - historic but rarely used anymore
  - Oil (Diffusion Pump Oil)
      - Like good Mech pump oil but better.
    - Natural Oils (mineral oils)
    - Synthetic oils
      - Silicones (siloxanes) (DC-704)(Common)
      - polyphenyl ether (hydrocarbon) (Sanovac 5) (HV)
      - Perfluorinated poly ether (Fluorocarbon) (reactives)
        - Fomblin, Krytox

Diffusion Pumps

- Advantages:
  - Cheap (to acquire)
  - High throughput per $
  - Only way to get GIGANTIC pumping speeds
  - Gas is removed
  - Reliable
  - No moving parts or vibration
  - Not particularly selective
- Disadvantages:
  - Expensive to run
  - Needs trap, etc
  - Misuse, backstreaming, and contamination
  - Gas reactions with hot oil
  - Requires backing pump full time

Photo from Varian

Where Do You Find Diffusion Pumps ?

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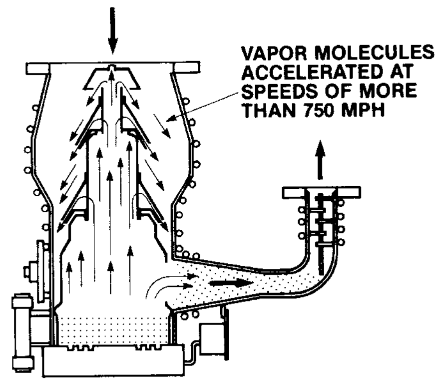
- Lots of places!
  - Electron Microscopes (typ. lower end)
  - Leak Detectors
  - Space Chambers
  - Low end thin-film equipment
- Not very common in semiconductor laboratory
- Generally cheap, low tech solution to High Vacuum

Baffles and Traps

- Pump is full of hot oil vapor flying around.
- We don't want our chamber full of hot oil vapor.
- Pump oil can get to chamber by:
  - Backstreaming.
    - Improper operation.
    - Fractionation.
  - Creep.



Cold Trap

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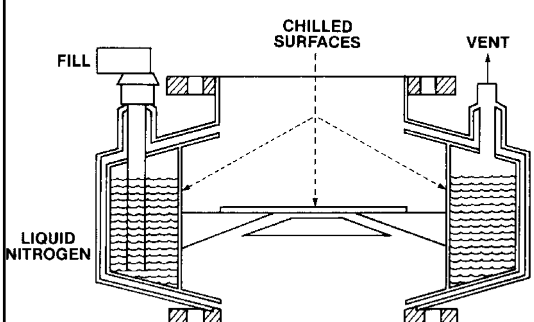

- Liquid Nitrogen cooled.
- Trap oil vapors going up.
  - Last resort.
- "Pump" water vapor.

Photo from Varian

Diffusion Pump Performance

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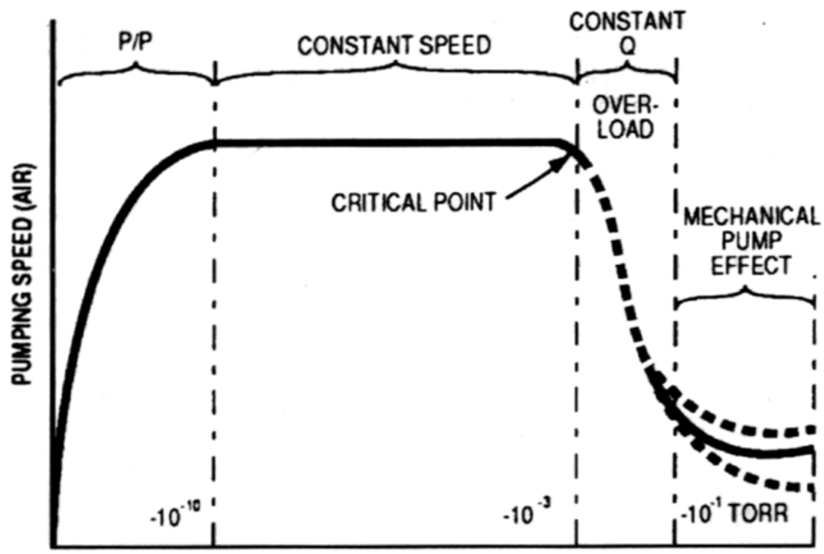

Diffusion Pump Abuse

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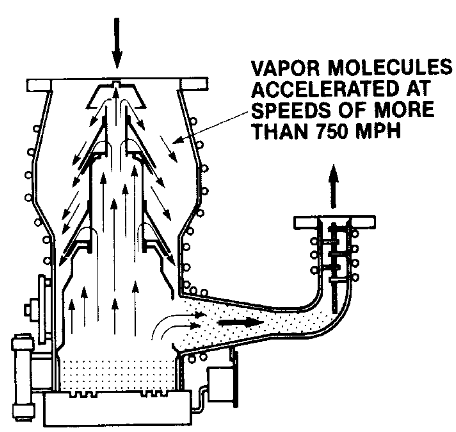
- What happens if you run it at too high pressure
  - Stops pumping
  - Turns into an oil sprayer



Diffusion Pump Stack

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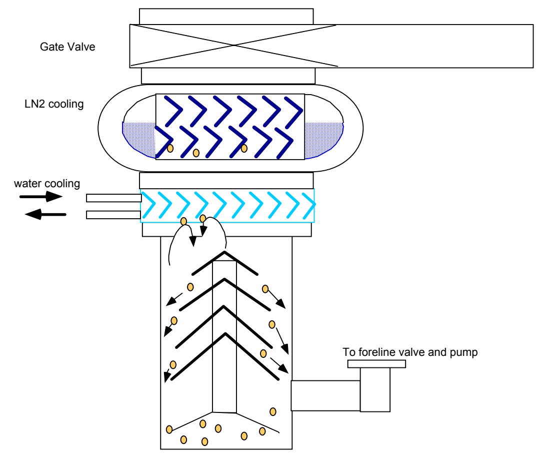
- Many components working together.
- Cost goes up.
- Complexity goes up.
- Net speed goes down.



Diffusion Pump System

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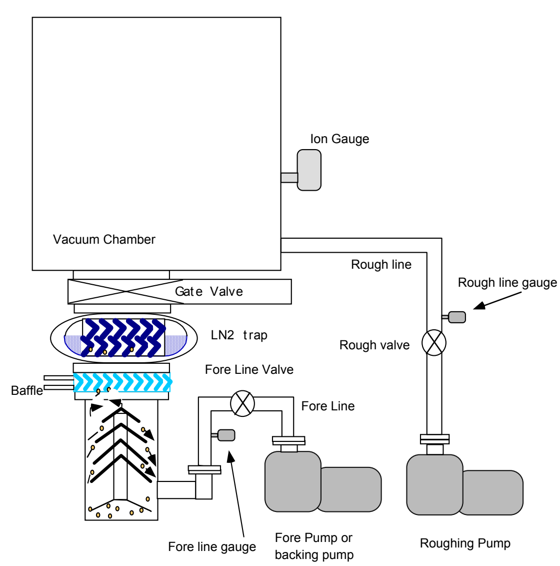

Turbomolecular Pump

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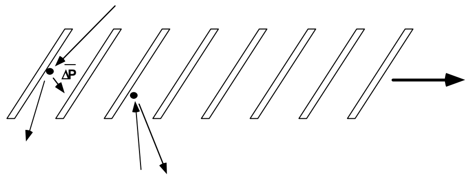

- A Precision High Speed Rotating Instrument
- Multiple Stages
- Each stage only provides small "compression"
- Combine many sections close together in series
- Each section optimized for pressure
- High Speed, Multistage Turbine (40,000-60,000 rpm)
- Impart Momentum (ΔP) to individual gas molecules by collision with high speed turbine blades
- Blade speed must be order of molecular speed

Multiple Stages

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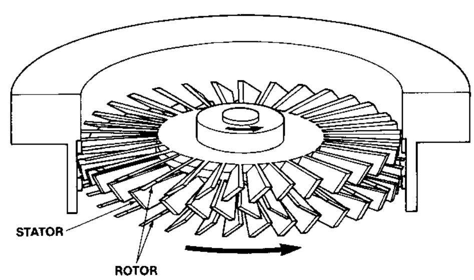
- In reality, only every other "stage" needs to rotate
  - Rotor and Stators
- Approximately 10 pairs
- Effectiveness depends on ratio of blade speed to molecular speed



- Tip Speed vs Center Speed
- Pumps heavy gases better than light ones because the light ones are going too fast
- At ultimate pressure, for a turbopumped system, the residual gas is 99% H_2

Stators and Rotors

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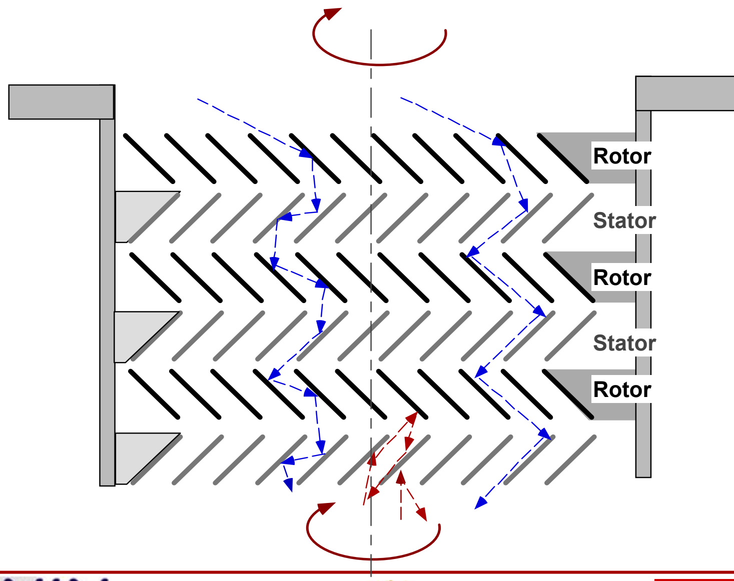

Turbo Pump Cutaway

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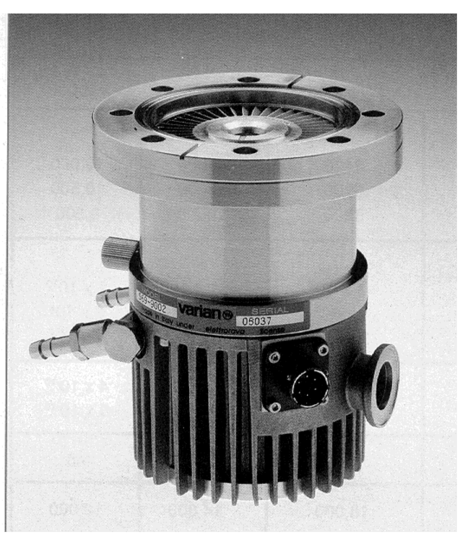

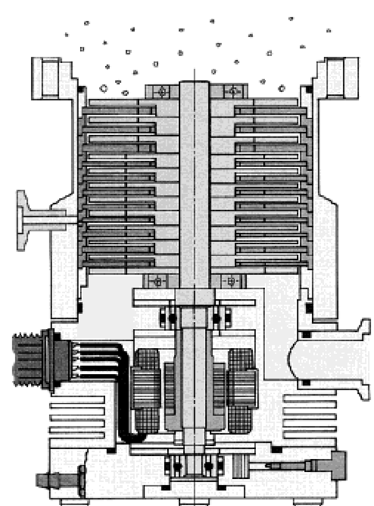

Turbo Pumps

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- High speed rotating instrument
  - 40,000 rpm
- Catastrophic failure
- Lots of little pieces of shrapnel

Bam !!!

Turbo Pumps

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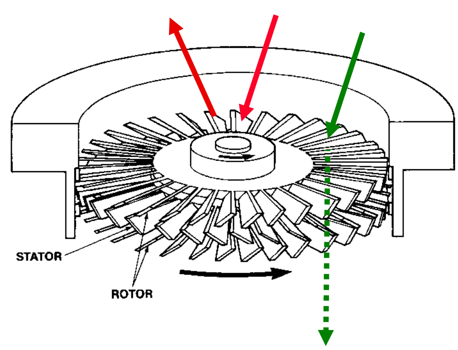
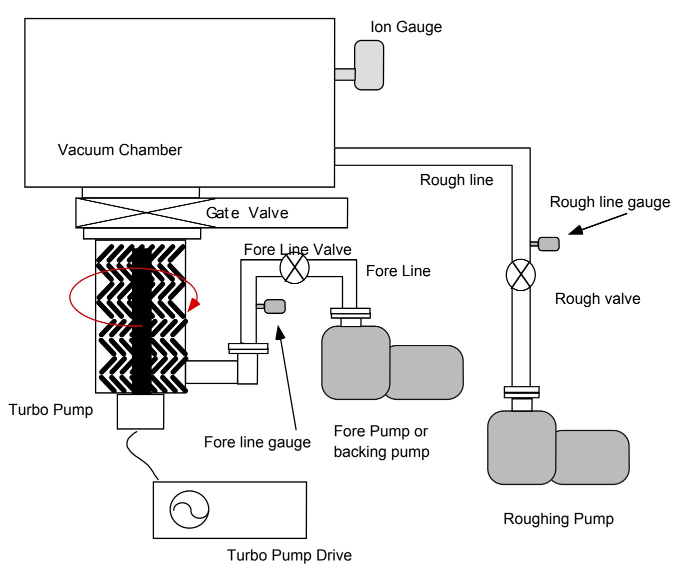
- Pumping speed proportional to blade speed
- Only the tips pump well
- Pumps very badly when not up to full speed
- Can take 15 minutes to get up to speed (big ones)
- Variety of sizes:
  - 100 l/sec small and compact
  - 2500 l/sec BIG and EXPENSIVE



Turbo Molecular Pump

- Turbo pump can't act alone
  - Needs a Roughing Pump
    - Something to get the chamber to low pressure
  - Needs a Backing Pump
    - Can't exhaust to atmosphere

Turbo Pumped System



Turbomolecular Pumps

- **Where Used:**
  - **Good SEMS**
  - **Etching Systems and other thin film tools**

Turbo Pump Summary

- **Advantages:**
  - **Clean, No backstreaming**
  - **Good for inerts**
  - **Good for reactives**
    - **Removes gas**
- **Disadvantages:**
  - **Vibration**
  - **Relatively expensive (\$/liter/sec)**
  - **Relatively inefficient (speed/diameter)**
  - **Pump He, H_2 slowly**
  - **CATASTROPHIC FAILURE!**

High Vacuum Cryopumps

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- Cryosorption pump is a "Capture Pump."
- Analogous to rough vacuum sorption pump but more sophisticated.
- Most gases have negligible vapor pressure at 20K and below.
  - Helium.
  - Hydrogen.
- "Freeze them out."
- A very cold refrigerator.
  - 20K.
  - Helium as the working fluid.

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Gas Pressures at Cryogenic Temperatures

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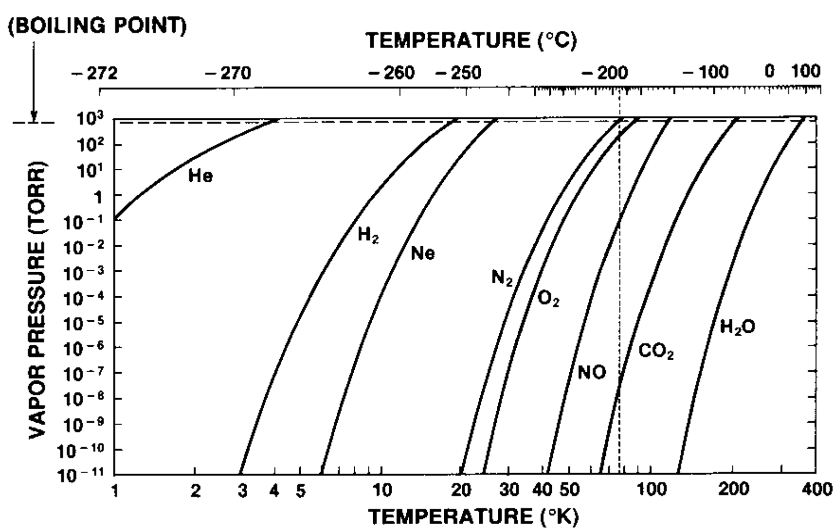


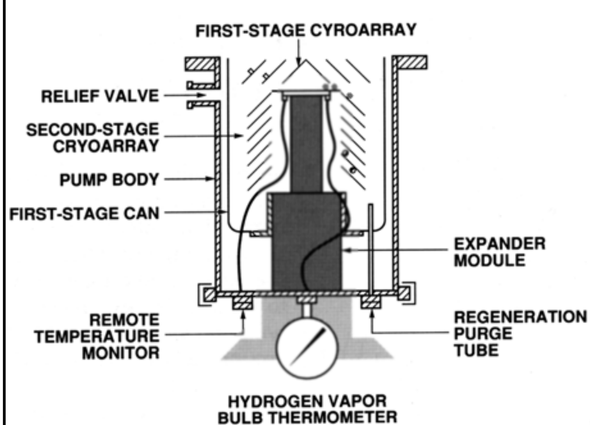
VAPOR PRESSURES OF COMMON GASES

NNIN CNF NanoCourses Vacuum Technology, page 110 CORNELL UNIVERSITY

Cryopump

- “Condensation” by itself is not quite good enough.
- Need SORPTION not just CONDENSATION to pump He and H_2.
  - Bond directly to surface.
  - Large surface area.
  - Use a very large surface area material (virtual surface) on a very cold surface.
    - Porous , e.g. activated charcoal.

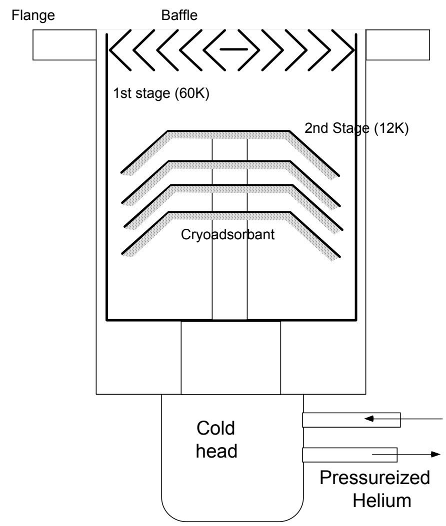
Cryopump Cutaway



THE PUMP MODULE

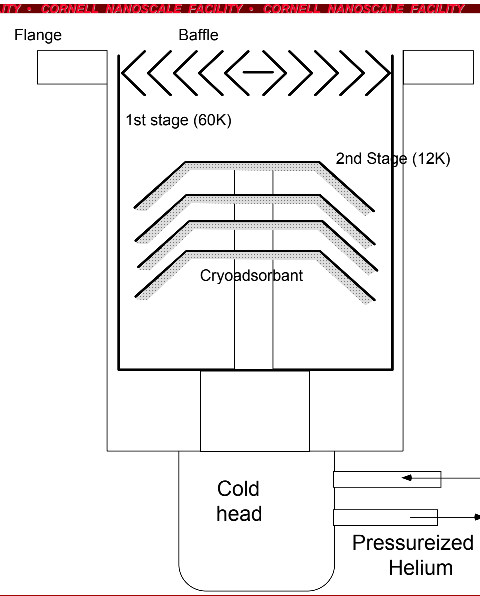
Refrigerated Cryopump

- Generally 2 stages.
- Lots of H_2O vapor to pump.
  - Pumps easily at 60K.
- Helium and Hydrogen very difficult.
  - 10 K is difficult.
  - Limited He/H_2 capacity.
- Protect the 2nd stage.
  - From being saturated by "easy" gases.
  - From heat load.



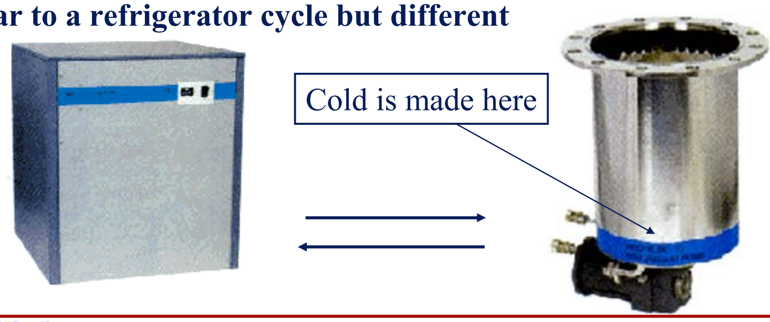
2 Stage Cryopump

- Stage 1--60 K.
  - 8 watts of cooling
- Stage 2 -10K
  - 2 watts of cooling
  - Porosity important
    - Don't poison with oil



Cryopump Refrigeration

- Helium as the working fluid
  - Ultra pure
- External Compressor.
  - 150 psi
- Expansion head at the cryopump
- Similar to a refrigerator cycle but different



Cryopumps Metrics

- Capacity:
  - How much can a pump adsorb?
  - Depends on gas and pumping mechanism
    - 9000 torr-liters of H_2 ----a lot but not infinite
      - 12 standard liters ---12000 std cc
    - 10^6 torr-liters of Argon
      - 1.2 million std-cc
        - 100 sccm for 12000 minutes or 200 hours
    - Air/water-- similar amounts
- Speed:
  - Depends on flux hitting top hole
  - Depends on probability it will “stick” and not come back out

Cryopump Diagram

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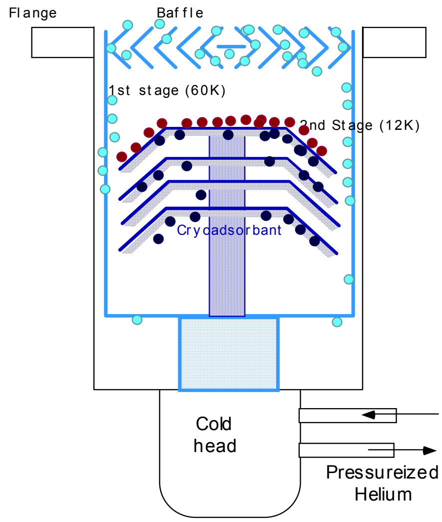

Pumping Speeds

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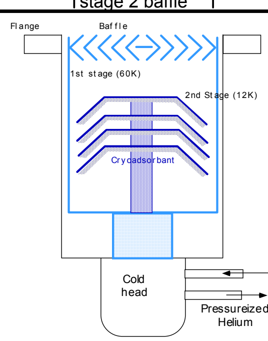
Gross and Net pumping Speeds in Cryopump

Gas	Pumping Surface	Arrival rate	Escape Rate	Net Speed	Units
Water	Top cold cap-Stage 1	**15**	**0**	**15**	liters/sec/sq.cm
Nitrogen	Top of State 2 baffle	**11.9**	**8.9**	**3**	liters/sec/sq.cm
Hydrogen	Underside of stage 2 baffle	**45**	**39**	**6**	liters/sec/sq.cm



A black hole for water vapor

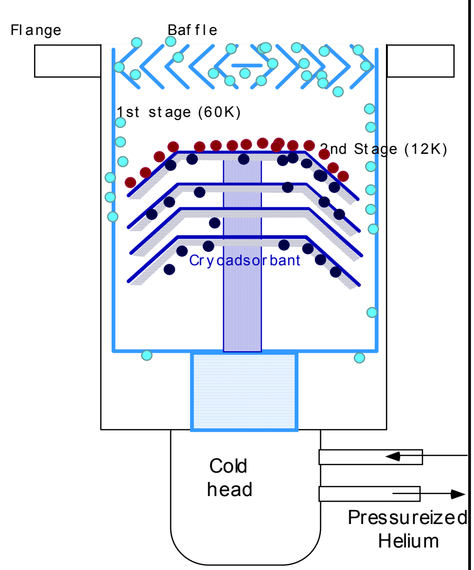
Cryopump Statistics

- Vital Statistics of a real cryopump
- A Varian 10” cryopump out of the catalog
  - ASA 10” flange (12” I.D. hole)
  - Rated Pumping speed
  - 10,000 liter/second H_2O
  - 1700 liters /second Ar
  - 4700 liters per second H_2
  - 2000 liters per second N_2
    - Note the large variation in speed due to differences in impingement rate and differences in vapor pressure

Cryopump Speed

- Max. theoretical speed = impingement rate
- 12” dia= 80 cm^2
- 11/liters/sec (air)
- --> 9000 liters/sec air max theoretical

- 2000 l/sec actual
  - Not so efficient for air
  - Very efficient for water vapor



Cryopump Regeneration

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- **Periodically saturates with adsorbed gases**
  - Saturate the pores so it wont pump He/H_2
  - Physically obscure the entry way with "ice"
    - the frosty refrigerator problem
- **Capacity.**
  - Almost infinite for H_20, N_2, O_2
  - Limited for H_2 , He
  - Moderate for Ar
- **Months between regenerations**
  - More commonly due to power failure or misuse than to over capacity

Regeneration Procedure

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- **Turn off refrigeration power**
- **Bleed dry N_2 through pump**
  - Heat transfer
  - Flushing
- **Gases bleed out over pressure relief valve**
- **Periodically cycle roughing pump (optional)**
- **Typically:**
  - Several hours to warm up
  - Several hours to flush
  - Several hours to cool back down again
- **Often done automatically overnight**

Cryopump Safety

Caution

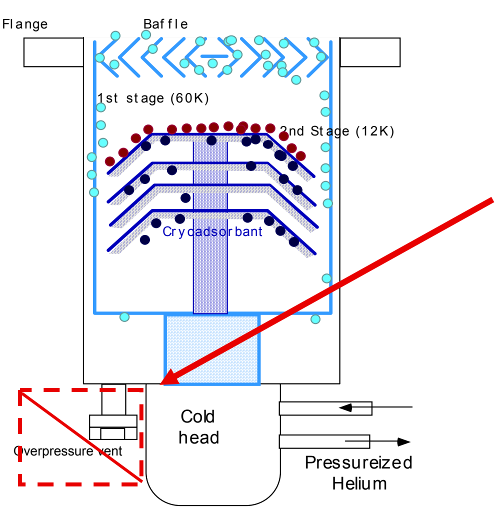
Cryopumps are capture pumps.

Gases pumped are retained only while the pump is cold.

Gases stored may be toxic, flammable, or result in high pressures when the pump is warmed up.

- **Do not block pressure relief valve**
- **Vent toxic and flammable gases safely**
- **Do not attach ignition source to pump body (ion gauge)**

The Most Important Part



- **Overpressure vent valve.**
- **Simple pressure sealed check valve.**
- **NEVER EVER MESS WITH IT !!**

Cryopump Summary

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- Advantages:
  - Clean
  - Fast at moderate cost
  - Can be BIG
  - HV and UHV compatible to 10^{-9} torr
  - Almost Infinite Capacity (except He, H_2)
- Disadvantages:
  - Store Large quantity of gas
  - Toxics
  - Reactives
  - Vibration
  - Heat Sensitivity
- Used in good evaporators and sputterers

Cyropumped Vacuum System

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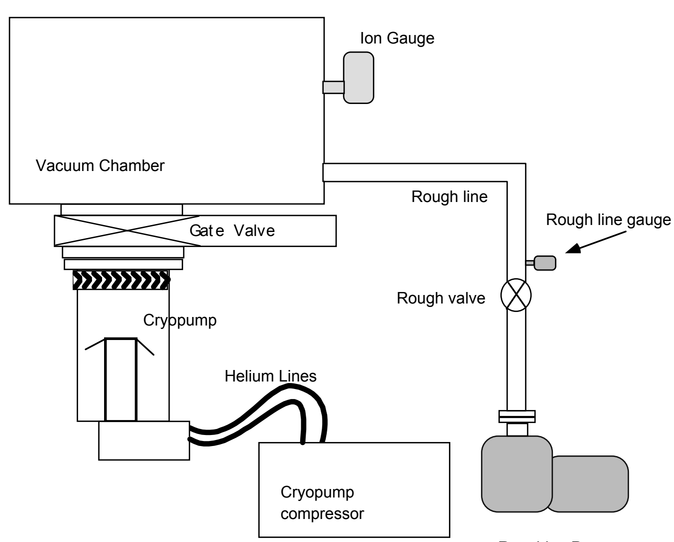


Turbos vs. Cryos

- **Turbos:**
  - **Small to medium sizes**
  - **Reactive gases**
  - **Removes gas**

Typically in etch applications

- **Cryos:**
  - **Medium to large sizes**
  - **Not reactive gases**
  - **Stores gas**

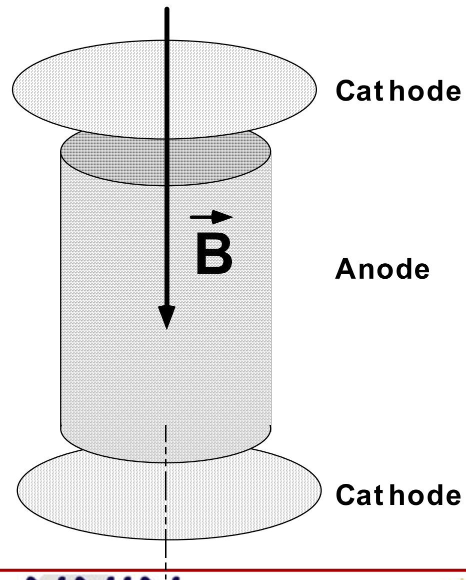
Typically in film depostion applications

Both are "clean", modern vacuum pumps used extensively in semiconductor processes

Ion Pump

- **Standard Ultra High Vacuum Pump**
  - **An electromagnetic pump**
  - **We can only move ions but not atoms, but we can make atoms into ions**
- **"Cold" "penning" discharge**
  - **Use Magnetic Field to confine electrons and sustain "discharge"**
- **Use Electric Field to accelerate ions away and "stick" them someplace**
- **A capture pump**
  - **Works by ionizing gas and implanting it or burying it in the electrodes**

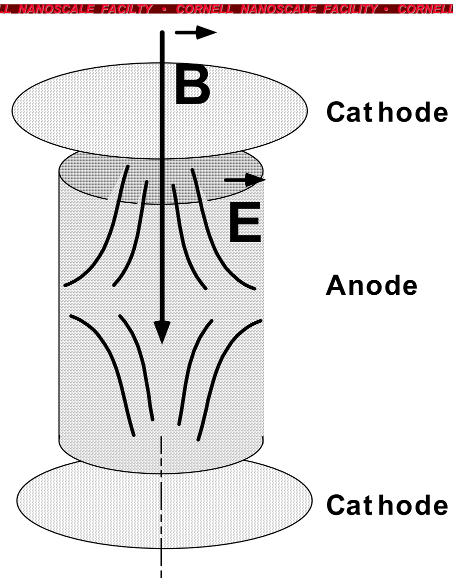
Ion Pump "Cell"



Ion Pump
Single Pump Cell

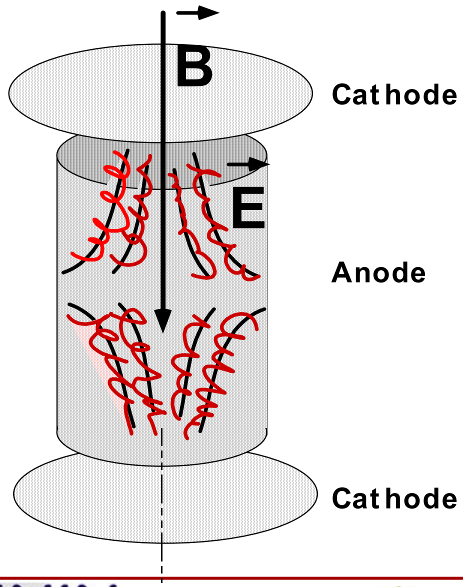
cm scale dimensions
~ 0.5 l/sec pumping speed

E x B fields in Ion Pump Cell



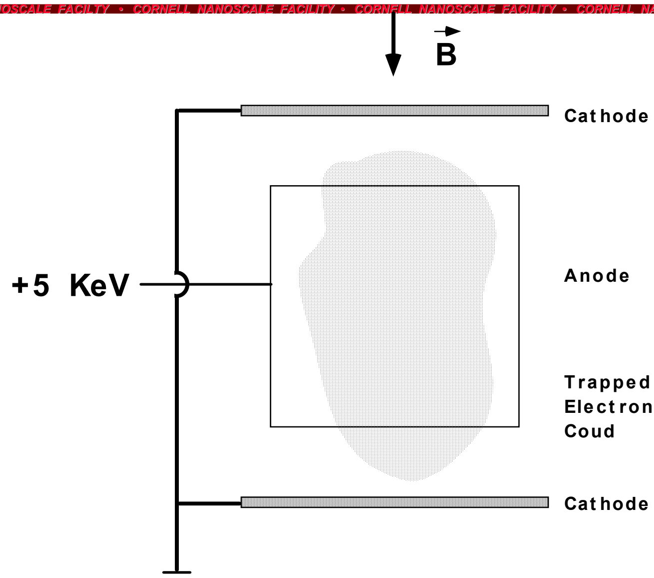
Ion Pump
Single Pump Cell

Spiraling Electrons and Ions



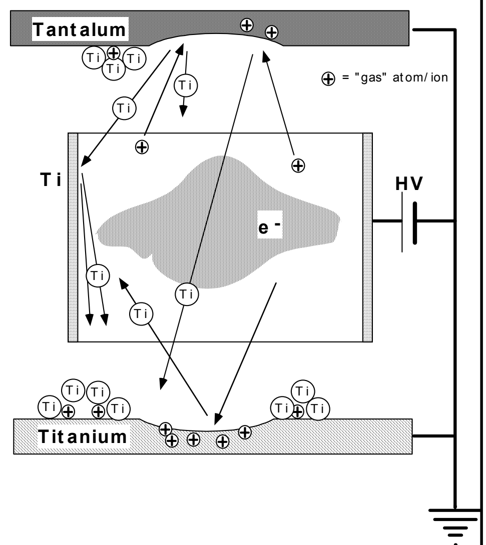
Ion Pump
Single Pump Cell

Ion Pump Cell Biasing



Ion Pump Mechanisms

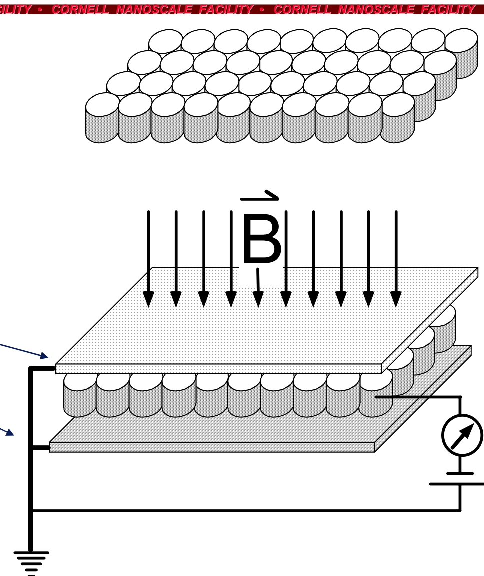
- Gas pumped by:
  - Reaction with Ti/Ta atoms (chemical)
  - Implantation into Ti/Ta Plates (electrical)
  - Burial under falling Ti/Pt atoms (physical)
- What goes in might come back out!
  - Memory



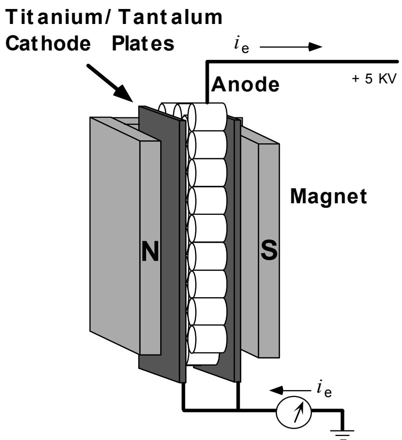
Ion Pump Element

- Cells clustered into a basic ion pump element
- ~50 cells in parallel

All the gas ends up implanted or otherwise burried in these metal plates



Multicell Ion Pump Assembly



Total Current (i_e) =Discharge Current plus Leakage Current

- Real discharge current is proportional to pressure
- Apparent discharge current = real discharge current PLUS leakage current
- Current meter typically calibrated in "pressure" units
- Indicated "pressure" can be artificially high

Ion pumps

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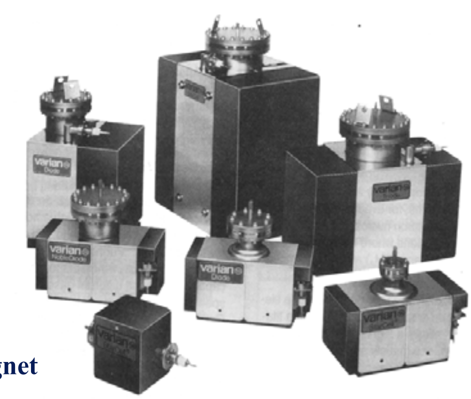
- One cell array assembly
  ~ 25 liters/sec
- Many together in one canister and one big magnet to make bigger pumps
  - 25 l/sec
  - 200 l/sec
  - 1000 l/sec
  - VERY HEAVY due to BIG Magnet
  - Tiny



Ion Pump Power Supply

- Ion pump needs a power supply
  - A big mostly unregulated HV power supply (5 keV)
  - A current meter, typically log scale and multiple decade scales
  - A pressure scale with is really just discharge current
    - Not very accurate
  - A volt meter
  - Pressure too high=low voltage
  - Enough current to fry you!
- Simple or fancy

Ion Pump Operation

- Ion pumps work very well at High vacuum but how do you get there
  - Pump down to 10^{-4} torr
    - Sorption pump
  - Ion pump is typically “valved off” ,”isolated”, pumping on itself at high vacuum
  - Slowly open valve to let pump gradually take on gas load
- Much more difficult to start “cold”
  - Almost impossible to start if inert gas

Ion Pump Lifetime

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- Life depends on gas load pumped
- Life time at HV is very long
  - ~ 5 years.
- Life time at low vacuum can be short
- Holes through the electrode plates

Ion Pump Summary

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- Advantages:
  - Clean
  - Quiet
  - Maintenance free
  - Electric only
  - UHV -- 10^{-11} torr
- Disadvantages:
  - Strong magnetic fields
  - Gas memory
  - Poor inert gas performance
  - Relatively expensive for speed
  - Not good for reactive gases

Ion Pumped System

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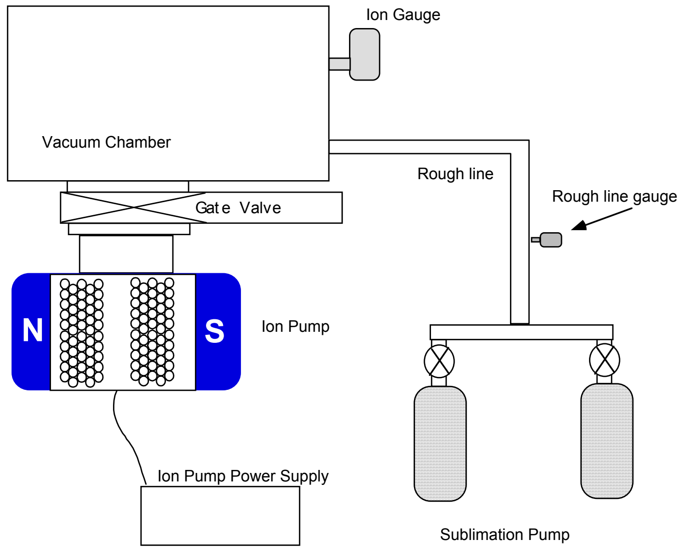

Where do you find Ion Pumps

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- Standard UHV pump:
  - SEM columns
  - Surface analysis equipment
  - MBEs
  - Portable Systems
- Low gas load, UHV applications

Meissner Trap

- A cold trap used as a pump RIGHT IN THE VACUUM SYSTEM
  - Commonly a large LN_2 cooled coil or surface
- Massive pumping speeds for condensables.
  - 1 sq. meter=10,000 sq cm
  - 11 liter/sec/cm^2
  - 105 liters per second pumping speed!!!
- Very cheap
- No conductance loss
- Not real practical
  - Heat load

Getter Pump

- Pump by chemical reaction
  - Selective?
  - Ti Sublimation pump is type of Getter Pump
- Typically small
- Barium compounds

Vacuum Gauges

Measuring Vacuum

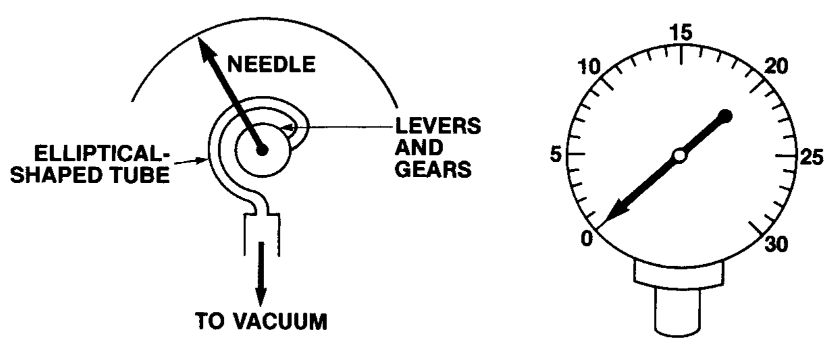
Why Vacuum Gauges

- System Operation
  - Order of magnitude
- Understand Phenomena
  - Calculations of mfp, collisions, adsorption, etc
  - Approximate
- Reproduce Conditions
  - Process Control
  - Reproducibility but not necessarily accuracy
- Scientifically characterize a vacuum/gas process
  - Accuracy and reproducibility
- Accuracy is hard to come by, particularly over a range of conditions

Types of Measurement

- Direct (typically "rough" vacuum range)
  - Actually measure FORCE exerted by the gas
    - Manometer
    - Bourdon Tube
    - Diaphragm gauge
      - Capacitance manometer
- Indirect ("rough" and "high vacuum")
  - Measure some gas property which is RELATED to pressure or number density
    - Thermal Conductivity
    - Ionization
    - Optical emission
  - Generally the "relation" is a function of gas and need not be linear
  - Should be monotonic

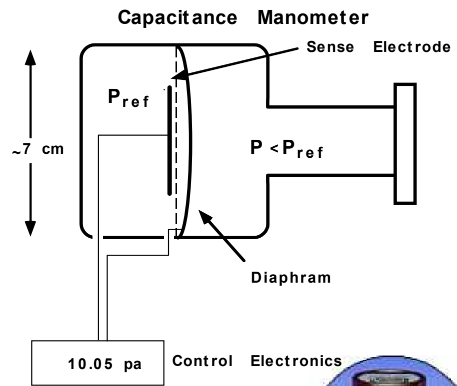
Bourdon Tube Gauge



- Purely Mechanical
- Mostly > 1 atm
- Compressed Gases

Capacitance Manometer

- A very sensitive diaphragm gauge
- Diaphragm displacement is measure by capacitance changes
  - Trade name “Baratron” (MKS) but other brands.
- Absolute pressure gauge
  - Actually measures a force
  - Independent of gas type
- Very popular for Reactive Ion Etching Systems
- Basically the is the ONLY true pressure gauge we have



Capacitance Manometers

- Lower practical limit .
  - 1 mt   1 x 10^{-3} torr
- Absolute lower limit State of the art.
  - 1 x 10^{-4} torr
    - Temperature controlled electronics, etc.
- Typically 10^4 dynamic range
  - Gauge with lsb 1 mtorr, has max range of 10 torr.
- Very sensitive electronics
  - Warm up
- Gauge of choice for RIE and Sputtering
- $1500 gauge, $1500 control readout

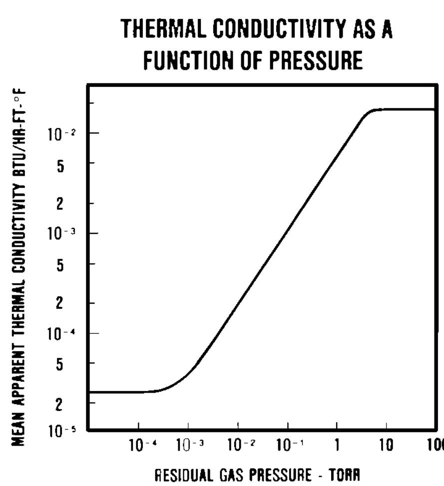
Thermal Conductivity Gauges

- Most common
- Relatively inexpensive
- Relatively inaccurate
- Several Types

- Measure changes in "pressure" by measuring changes in heat conductivity of the gas, i.e. thermal transfer through the vacuum

Thermal Conductivity Gauges

- Not very linear
- Limited "accurate" range
- Strongly dependent on gas type



Heat Loss in Vacuum

- Convection (air flow)
  - Not very important at "low" pressure
- Conduction
  - Through gas
    - Function of P and gas type and Temperature
  - Through mounting.
    - Function of construction
- Radiation
  - Stefan-Boltzmann law
  - Very temperature sensitive

$$\approx \sigma\left(T^4 - T_0^{\ 4}\right)$$

Heat Loss

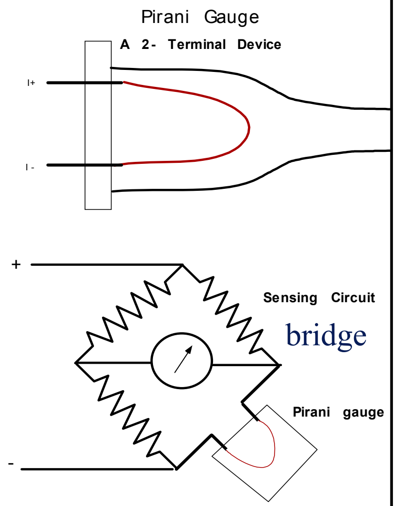
$$\text{heat loss} \approx a\Delta T + b\sigma(T^4 - T_0^{\ 4}) + f(P)\Delta T$$

leads radiation gas

- Very sensitive to T
- Very sensitive to gas type

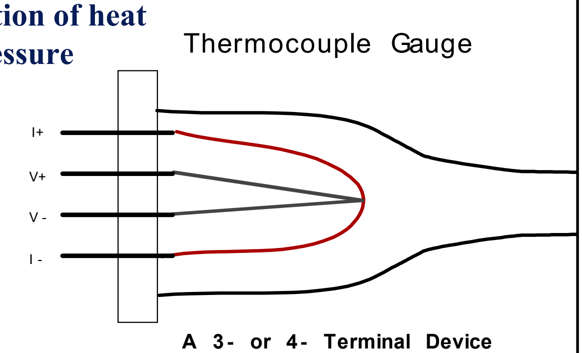
Pirani Gauge

- Simple and not very accurate
- 2 terminal device
- Essentially measuring resistance change with temperature of a hot wire
- Temperature is a function of heat loss is a function of pressure
- Thermistor gauge uses an semiconductor element instead of a resistor-same principle



Thermocouple Gauge

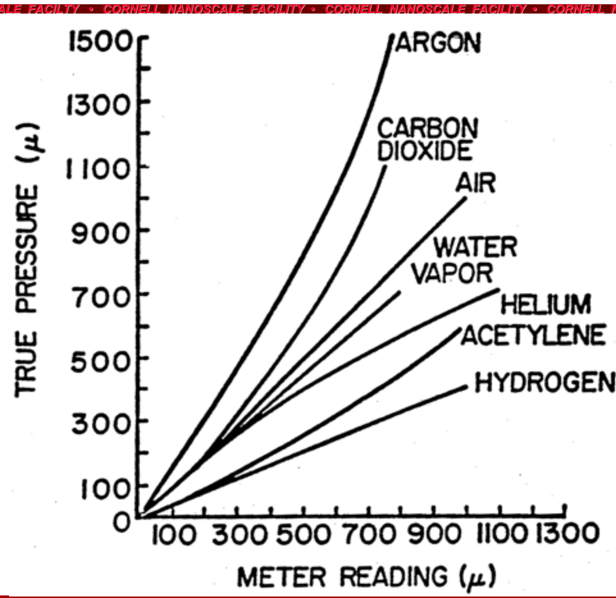
- A thermocouple vacuum gauge not a thermocouple temperature gauge
- Measure temperature of hot wire with a thermocouple
- Calibrated scale
- Temperature is a function of heat loss is a function of pressure
- Cheap and rugged but not accurate



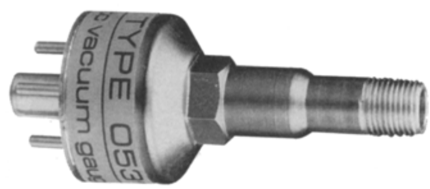
A Thermocouple is Not a Thermocouple Gauge

- A thermocouple is a thing to measure temperature
- A thermocouple gauge is a vacuum gauge that uses a thermocouple
- Actually a thermocouple vacuum gauge but we get sloppy

Sensitivity Variations



TC Gauge Family



"Convectron Family"

Which is more accurate??

Rough Vacuum Gauges: Summary

- Thermal gauges:
  - Cheap and not accurate
  - System control
- Capacitance gauges:
  - Accurate and sensitive but expensive
  - Process control

High Vacuum Gauges

Ion Gauges

- **High Vacuum Gauges, below 10^{-4} torr**
- **Measure "pressure" by measuring ion current created by specific electron bombardment**
  - **Current proportional to n , therefore proportional to P**
- **High P limit imposed by mfp**
- **Low P limit imposed by cosmic ray photoemission**

Ion Gauges

- **Electron impact causes ionization of gas**
- **Ionization thresholds ~ 3 - 20 eV**
- **"Beam" of electrons in gas at pressure P will create ions**

$$i_+ = \sigma \cdot i_e \cdot L \cdot P$$

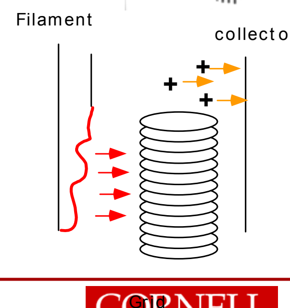
where σ is effective

x − section and L is pathlength

- **How to make the electrons and collect the ions**

Hot Filament Ion Gauge

- Essentially a triode
  - Filament (cathode)
  - Ion Collector
  - Grid (electron collector)
- Electrons create ions
  - Proportional to pressure
  - Collect and measure ions
- Assumption:
  - Ion current is directly proportional (linearly) to the pressure (number density) and the emission current
- Constraint
  - mfp_e > size of gauge



Hot Filament Ion Gauges

- Tubulated or nude
- Not particularly accurate but who cares
- 1×10^{-4} to 1×10^{-11} torr

Ion Gauge Circuit

- **Filament Current (e^-)**
  - **2-4 Amps**
  - **Heat filament**
- **Emission Current (e^-)**
  - **4-25 ma**
  - **Filament to grid**
  - **Causes ionization**
- **Collector Current (ion)**
  - **10^{-5} to 10^{-11} amps**
  - **Pressure measurement**

$$i_+ = S \cdot i_e \cdot P$$

$$S \equiv \text{Sensitivity Factor}$$

Function of Geometry and gas

Pressure Measurement

- **Ion Current (measured) is proportional to:**
  - **Pressure (what we want to know)**
  - **Electron current (controlled)**
  - **Geometry**
  - **Gas type**
- **Geometry and gas type are lumped together as “sensitivity factor” S**
  - **Typically 10/torr or 25/torr depending on gauge (for Nitrogen)**
    - **4 ma emission and S=25/torr**
    - **Ptorr=10 i^+ (amps)**
    - **Nanoamp at 10^{-8} torr ------> Sensitive electrometer**

Gas Calibrations

- Sensitivity varies by gas type
- Ratio to Nitrogen sensitivity:
  - Nitrogen 1.00
  - Oxygen 0.84
  - He .15
  - Ar 1.19
  - Xe 2.73
  - H_2 0.46
- You divide apparent pressure by factor to get actual pressure
- Ion gauge measurements can be "off" if you don't correct or don't know gas composition
- Typically just use N_2 equivalent pressure

Accuracy and Precision

- Actual gas is a mixture
- Each gas has one S
- Ion gauge thus measures some effective ionization which is somewhat related to P but not accurately unless you know and can control the gas composition

Ion Gauge Filaments

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- Hot source of electrons
- Typically a pair
  - Use one then the other
- Low work function, high temperature material
  - Tungsten
  - Thoriated Tungsten
  - Iridia (oxide)

Outgassing

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- Hot ion gauge
- Gases can be desorbed by heat and electron bombardment
- Remove by "degassing"
  - Heat it very hot
  - Metal parts pink hot
- Pressure goes way up temporarily but gets better

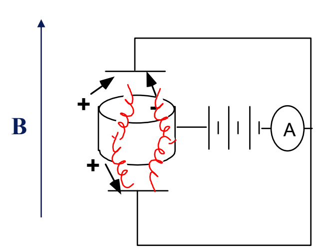
Penning "Cold Cathode" Gauge

- **Hot filaments in ion gauges can "burn out"**
  - **No filaments ==> more rugged simpler gauge**
  - **But where will ionization come from?**

- **Cold discharge:**
  - **Initial electrons come from cosmic rays or field emission**
  - **e x b fields cause long spiral paths, so that we make maximum use of each initial electron.**
  - **Self sustaining "cold" discharge**
  - **High Voltage and strong magnetic field**
  - **Discharge current proportional to pressure**

Penning Gauge

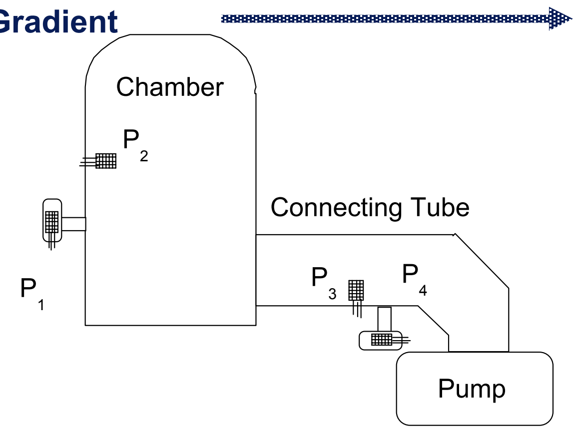
- **Simple cheap rugged**
- **Not very accurate, precise, limited range**
- **Mostly 1×10^{-5} torr range device, but 10^{-7} on some instruments**



If you make a big one, you call it an ion pump

Vacuum Gauge Placement

Pressure Gradient



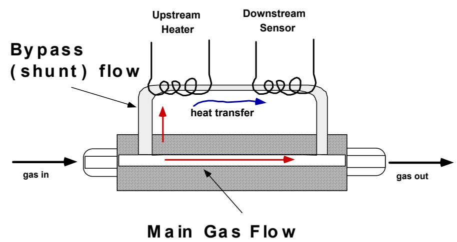
- **Readings:**
  - $P_1 > P_4$
  - $P_2 > P_3$
- **P_2 may be < or > P_1 depending on pressure and if the gauge is outgassing or is acting as a small pump.**

Flow Measurement

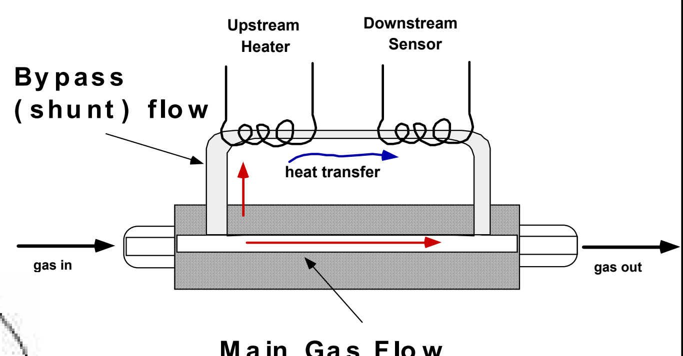
- **Often want to measure flow in, i.e. process gas flow introduced**
  - **Standard cubic centimeters per minute**
    - **sccm**
    - **cc per minute at STP**
- **Mass flow meter**

Mass Flow Meter

- Based on thermal transport by flowing gas.
  - Upstream heater
  - Downstream sensor
- Each molecule carries energy from upstream to down stream
- Measure heat transfer
  - Proportional to flow (# of molecules) and type of molecule
  - Each gas has a "sensitivity" factor
    - Essentially heat capacity per molecule.



Mass Flow Meter -- Cut Away



Vacuum Materials and Processes

Materials and Performance

- **Physical processes determine vacuum system performance**
  - **Pump down rate**
  - **Ultimate pressure**
  - **Gas composition**
- **Most of these processes involve materials.**
  - **Construction materials**
  - **Things you put in on purpose**
  - **Things you put in by accident**

Materials and Performance

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- How do we choose materials wisely?
- How do we operate a system wisely?
- What really controls vacuum system performance?

- At any given time:
  - $Q_{in} = Q_{out}$
  - Q= quantity of gas/ time (essentially N/t)

Gas Balance

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- Q_{in} (gas load)
  - Gas flow (process)
  - Desorption (materials)
  - Decomposition (materials)
  - Diffusion (materials)
  - Permeation (materials)
  - Leaks (materials)
  - Backstreaming (operation and materials)
- Q_{out}
  - Pumping (hardware)
  - Adsorption (materials)
  - Absorption (materials)
  - Reaction (materials)

Of all these things, only one depends on how big your pump is; only one depends on how well you assemble it

Rest depends on MATERIALS

System Performance and Materials

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- Rate out (pumped)= Rate In (gas load)
- Source rate can be very nonlinear in P and t and T
- Small things can make a big difference in Pressure

- "Acceptable material" and "acceptable practice" depends on vacuum region
  - Rough
  - High vacuum
  - Ultra high vacuum

Gas Sources

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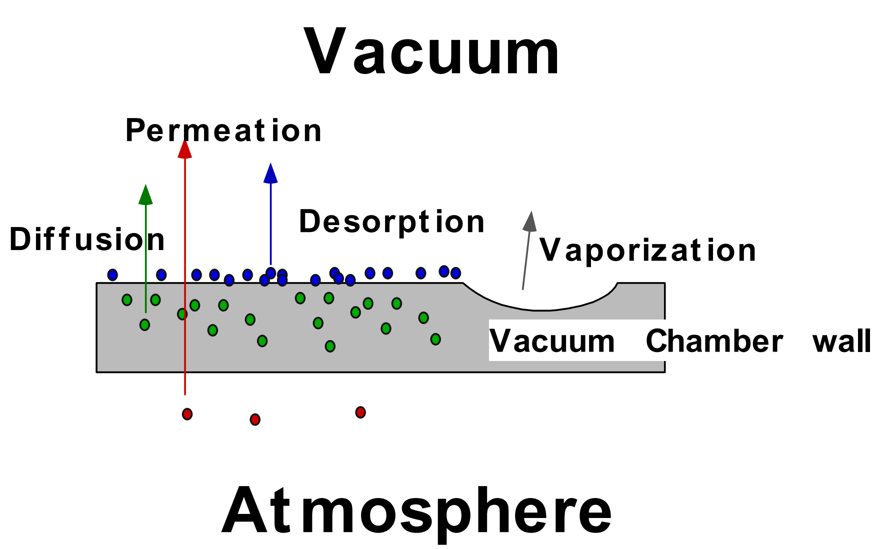


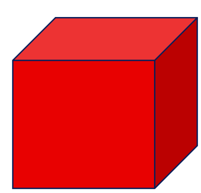
A Short Language Lesson on the Sorbs

- **Sorb (verb):**
  - **To take up and hold**
  - **Absorb (into...as a sponge)**
  - **Adsorb (onto...as on a surface)**
  - **Desorb (the reverse of both)**
- **Sorption (irr) (noun):**
  - **The act of sorbing**
  - **Adsorption ⇒ (Adsorbtion is not a word)**
  - **Absorption (Absorbtion is not a word)**
  - **Desorption (Desorbtion is not a word)**
- **Sorbent (adj):**
  - **Sorbant (adj) (acceptable variation)**

Evacuation

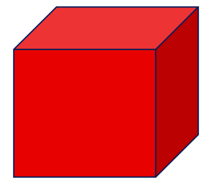
- **"Sucking out the air" from a container**
- **PV=NkT yield two relations:**
  - **(dP/dt) V = (dN/dt) kT**
  - **PS= - (dN/dt) kT**
- **(dP/dt)= - PS/V**

$$P(t) = P_0 \cdot e^{-\frac{S \cdot t}{V}}$$



Evacuation: Example

- Official Hypothetical Vacuum System
  - 1000 l/sec pump
  - Stainless Steel cube, 1 meter on a side, 1 cu meter
  - Filled with air, and “practically perfect in every way”
- How long should it take to evacuate, i.e. to remove the 1 cu meter of air molecules?



$$P(t) = P_0 \cdot e^{-\frac{S \cdot t}{V}} \qquad P(t) = P_0 \cdot e^{-t}$$

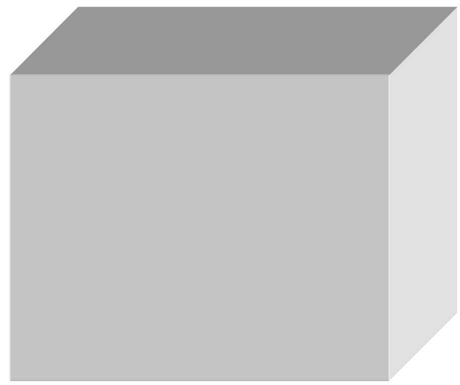
Evacuation

- Plug in numbers.
  - t=0 P= P_o
  - t= 10 sec. P= 4 x 10^{-5} *P_o
  - t=60 sec. P= 10^{-27}*P_o
- In reality, it takes a lot longer!!
- Why?
  - Evacuation is easy
  - Other processes control system performance
- Materials Processes

Vacuum technology is NOT about Evacuation !!—at least very little

More on the Hypothetical System

- Air, at STP, 1 cubic meter= 3 x 10^{25} molecules
- Therefore, at 10^{-6} torr, volume contains:
  - N= 3 x 10^{16} molecules
- Surface:
  - 6 sq meters
  - 10^{15} sites/sq cm
  - 6 x 10^{19} surface sites



Surface Layers

Gas Phase

- N_{gas} = 3 x 10^{16} @10^{-6} torr

Surface

- 1-100 layers of adsorbed "gas," "dirt," "grease," "fingerprints," "solvent residue," etc, on surface
- i.e. 1-100 molecules for each surface site
- $N_{surface}$ = 6 x 10^{21}

Pores and Scratches

Gas Phase

- $N_{gas} = 3 \times 10^{16}$
- **ONE MILLION times as many molecules on surface as in volume**
- **For every one you take out, there are a million more waiting to take its place !!!!**

Surface

- **Surface is actually quite rough**
- **Pores, scratches, crevices**
  - **Atomic scale**
  - **Macroscopic scale**
- **Assume actual area= 10 x geometrical area**

- $N_{surface} = 6 \times 10^{22}$

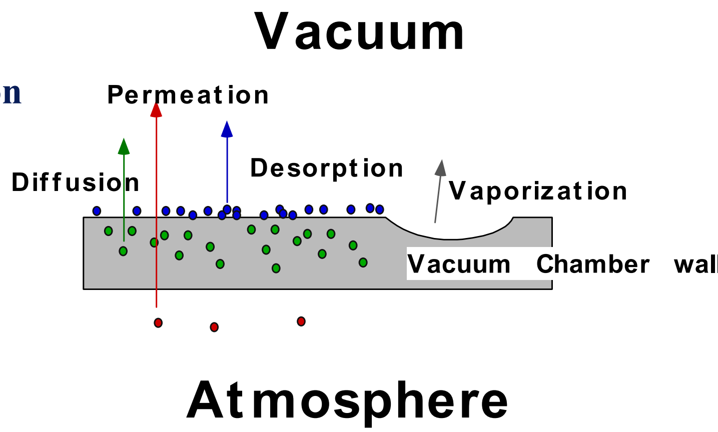
The Prime Directive

Areas issues >>> volume issues ===> Materials !!!!!

- **Fact**
  - **Vacuum System Performance is Determined by Materials Properties**
- **Corollaries:**
  - **Materials Effects (surface effects) overwhelm any Volume Effects**
  - **Materials Effects can overwhelm an hardware issues**
    - **Big pumps, etc**
  - **Even Small Surface Effects can have a Large Effect on System Performance**
    - **Pump down time**
    - **Base pressure**
    - **Operating pressure**
    - **Background gas**

Materials Processes

- **Decomposition (Vaporization)**
- **Desorption**
- **Diffusion**
- **Permeation**



Vaporization

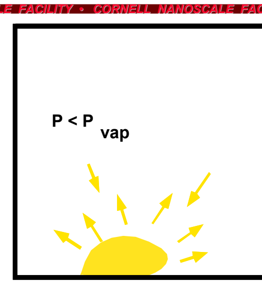
- What is a vapor?
  - A vapor is the gas phase of a substance which coexists with its solid/liquid at that particular temperature
  - At room temperature
    - Nitrogen is a gas
    - Water (vapor) is a vapor

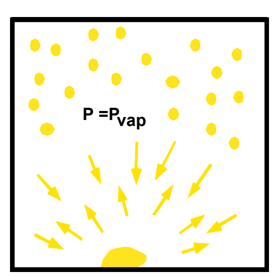
Vapor Pressure

- Normally we are talking about equilibrium vapor pressure
- Saturation (equilibrium) vapor pressure is when the solid and vapor are in equilibrium
  - Thermodynamic quantity
  - Conceptually, a function of binding energy.
    - Escape = Impingement
- Everything has a vapor pressure
- Intrinsic material property
  - Independent of other materials

Saturation Vapor Pressure

- Empirically:
  - $\text{Log } P_{vapor} = A/T + B_{log}T$
- If $P < P_{vapor}$, the material will spontaneously evaporate to restore equilibrium
- Can take "forever"
- High vapor pressure can thus put a "clamp" on your vacuum until it is all gone





Vaporization

- Rapidly increases with T
- Material dependent
  - Many orders of magnitude difference
- Each material is in equilibrium with its own vapor, independent of other components
- P= sum of partial pressures

- Graphs of Vapor Pressure.
  - RCA Review 30 (1969).

Vapor Pressure Curves

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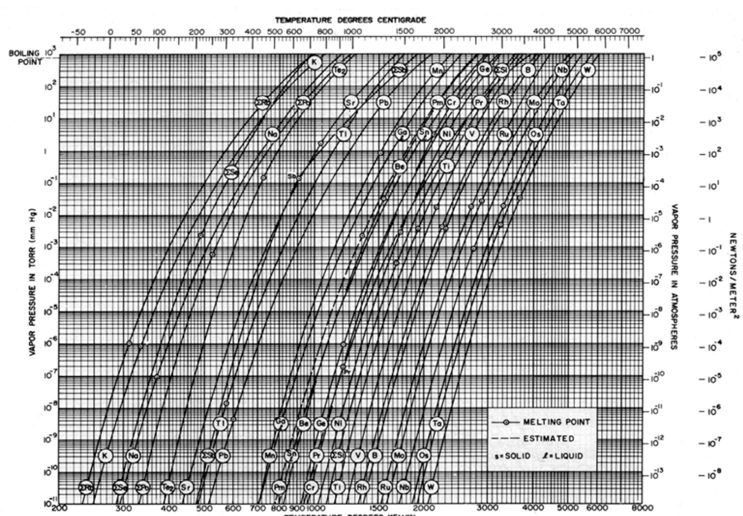

FIG. 2. Vapor pressure of elements as a function of temperature. Melting points are indicated by the small circles. These data were compiled by R. E. Honig and D. E. Kramer, *RCA Rev.* **30**, 285 (1969).

Materials Rules of Thumb

- Avoid high vapor pressure materials
  - Organics, oils, greases (fingerprints)
  - Zn,Cd,Sn (Brass, plated screws)
  - S (in some alloys)
  - Solder, Flux
  - Most Polymers
- Even traces are important
- When in doubt, don't use it
- The good news is you can avoid decomposition and vaporization problems by careful materials selection

Desorption

- Adsorbed gases coming off walls.
  - 100s of layers.
- Not all molecules are bonded to the surface the same.
  - Different adsorption (binding) states.
  - Before we can talk about Desorption we have to talk about Adsorption.

Surface Bonding

- How are things "attached" to surfaces?
  - A variety of forces and bonding mechanisms.
    - Condensation
    - Physisorption
    - Chemisorption

Condensation

- Atoms bound weakly to their own kind, as multiple layers.

- Binding energy is characteristic of bulk adsorbing material.
  - Vapor pressure of the adsorbate is the relevant quantity.

- Typical of outermost layers.

Physisorption

- Weak binding of adsorbed layer to the substrate
- Typically only a few layers
- Van der Walls forces (electrostatic)
- Binding Energy ~ tenths of eV
- Desorbable and reversible
- Typically not dissociative
- Typically stronger bonds than condensation

Chemisorption

- Strong Chemical bonds directly to substrate
- Binding energies measured in eVs
- Definite energy states unique to adsorbate / adsorbant combination
- Typically dissociative
  - Atoms not molecules

Types of Surface Bonding

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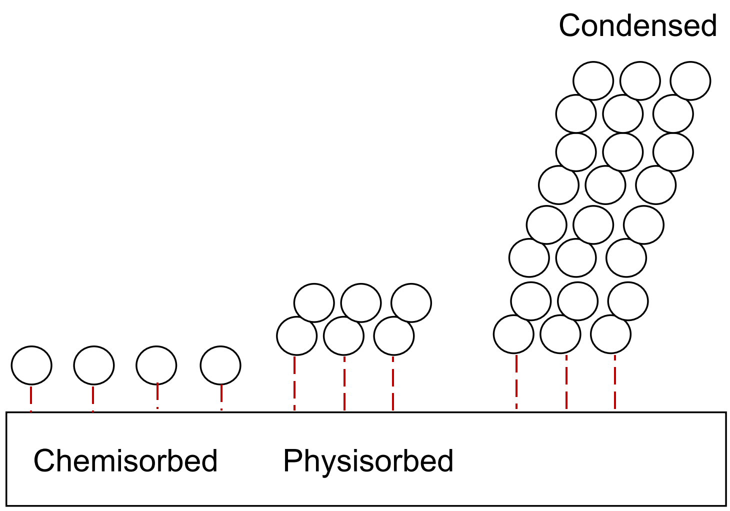

Reaction Coordinate

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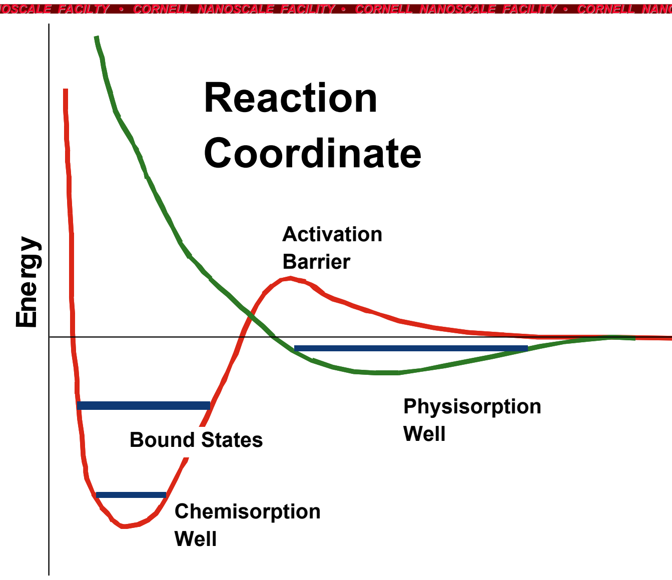

Desorption

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- To “desorb,” an atom/molecule has to gain enough energy to escape from the well and over the barrier (if any)
  - Boltzmann distribution of energy
  - Escape is very sensitive to temperature , E_b
    - Exponential in binding energy (E_b) divided by T

I kcal/more= 0.043 eV

- At room temperature
    - E_b < 10 kcal/mole (i.e < .5 ev)
      - Gone instantly (argon, helium)
    - E_b < 20 kcal/mole
      - Hours
    - E_b > 30 kcal/mole (i.e. > 1.5 eV)
      - Negligible, forever (metals, glass, etc)

Desorption

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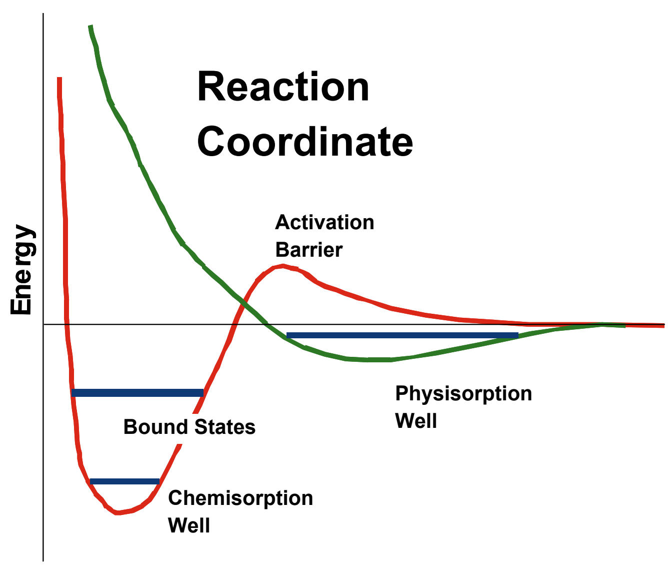

Desorption

- Bad range is 15-25 kcal/mole (order .5 eV- 1 eV).
  - Not instantly
  - Not hours
  - But Not forever either

Desorption of Water Vapor

- Water vapor is bad news....22-24 kcal /mole on most surfaces
- H_20 is 3d most common ‘gas’
- Nitrogen and oxygen are gone rapidly or bound forever, but water stays a long time but not long enough
- Worse in the summer
- Rate generally goes as to t^{-1}

Pumping Water Vapor

- "Vacuum" as we know it is basically water vapor
- Everything else is pumped out rapidly
  - From volume
  - From surfaces
- We are left dealing with desorbing water vapor for many many hours
- Most prominent down to 10^{-8} torr
- Control of water vapor and water adsorption is thus the most significant and easiest thing you can do
- The most critical thing

Control of Water Vapor

- Don't vent to air
  - Vent with dry nitrogen
  - Saturate surfaces with N_2 rather than H_20
- Don't put wet things in the vacuum system
- Don't rinse things with water or let air dry
  - Rinse in alcohol and blow dry or bake dry
- Don't expose to atmosphere long
  - Open and shut
- Low Humidity

Pumping Down

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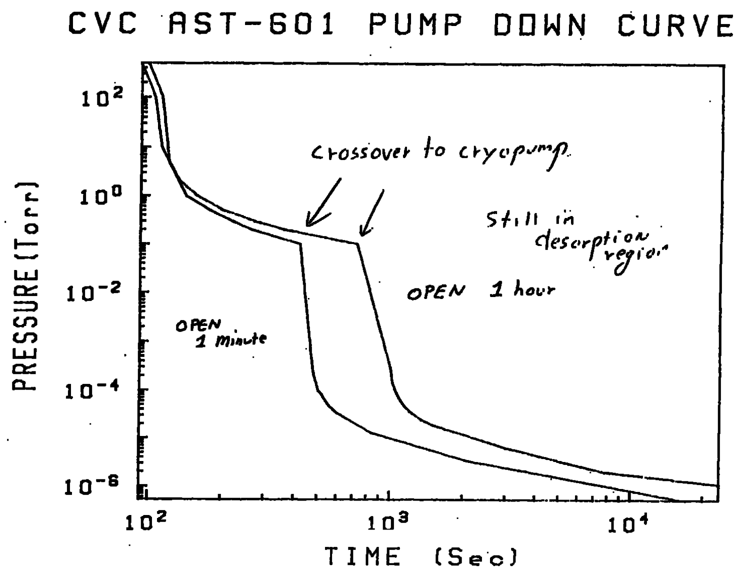

Baking

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- Desorption is temperature sensitive
- Heat everything to 200°C - 300°C for a few hours while pumping
  - 8-24 hour process
- Glass or Stainless Steel vessels
- Standard part of UHV technology
- Drive off water vapor
- Bake EVERYTHING!

- Desorption is a surface process
- "Eventually" we will deplete all the adsorbed species and have a "clean surface"
  - Or will we?

Diffusion

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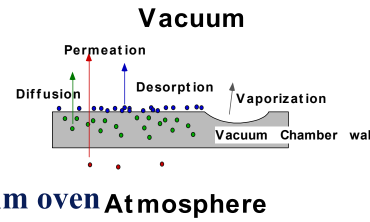
- Gas from the bulk (inside the metal) replenishes the surface
- 1-10% absorbed gas
  - Often hydrogen, oxygen
- Diffusion is slower than desorption
  - Not a negligible process at high vacuum
- Drive out by pre-firing parts in vacuum oven
- Generally irreversible...Drive it out and it stays out
- Diffusion ~ 1/ sqrt(t)



Diffusion Rates

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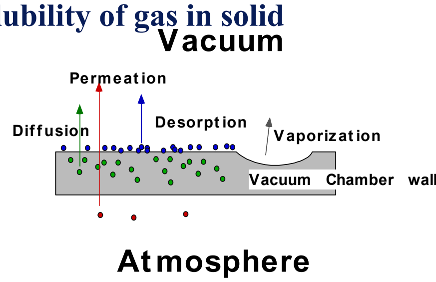
- Typical Rates:
  - 10^{-7} -- 10^{-8} torr-liters/sec/sq.cm. Elastomers
  - 10^{-8} torr-liters/sec/sq.cm. Rusty mild steel
  - 10^{-9} torr-liters/sec/sq.cm. Clean mild steel
  - 10^{-10} torr-liters/sec/sq.cm. Clean Stainless
  - 10^{-14} torr-liters/sec/sq.cm. Baked Stainless
- Well, “eventually” we manage to drive all the gas out of the metal and off the surface, surely then we can get on with things
  - Or can we?

Permeation

- Atomic transport through a material, in our case the vacuum chamber wall
- Three steps:
  - Adsorption on outer surface
  - Absorption and diffusion through the wall
  - Desorption from the inner surface
- Depends strongly on solubility of gas in solid



Permeation

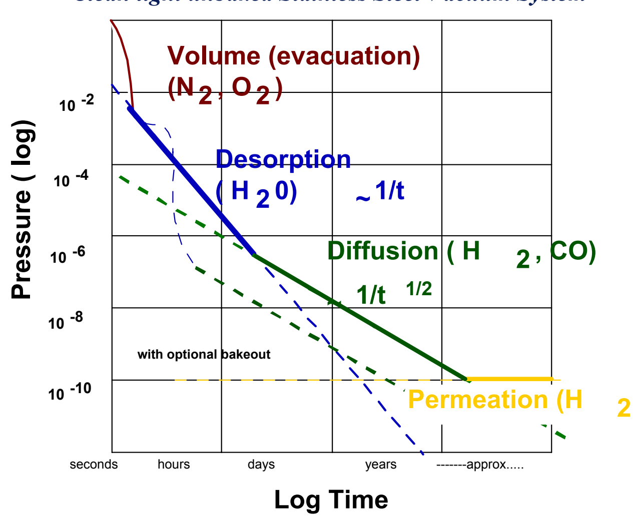
- Certain combinations are quite permeable, particularly at high temperature
  - H_2-Pd
  - H_2-Fe
  - O_2-Ag
  - He-quartz
- Can be used as a selective filter for gas

Permeation

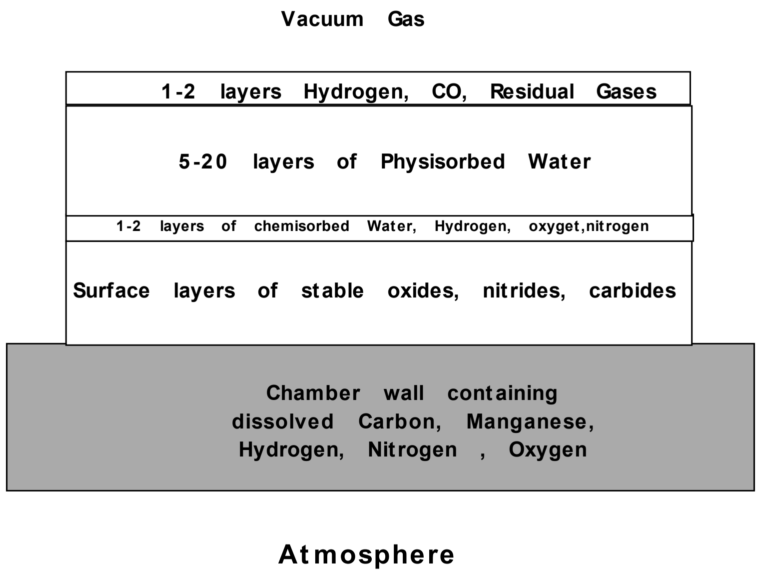
- Typical 5 x 10^{-3} Pa-M^3/sec
- 1 sq meter area, 2 mm thick wall
- 500 liter/sec pump
- 10^{-10} Pascal STEADY STATE PRESSURE forever, i.e. 10^{-12} torr
- Polymers are particularly bad for both diffusion and permeability

Combined Materials Processes

Clean tight unbaked Stainless Steel Vacuum System



Summary of Surface Problems



Backstreaming

- One of the few non-materials processes
- Improper operation
- Simple traps may or may not help

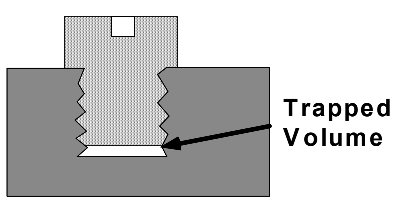
- Also Leaks

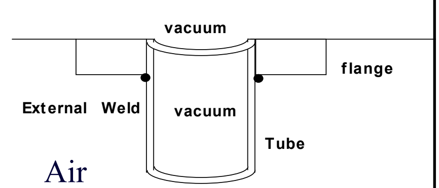
Virtual Leaks

- An inadvertent (uncontrolled) source of gas **inside** the vacuum system which limits the ultimate pressure
  - Outgassing.
    - Things Hot
    - Things Dirty
    - Porous Things
  - Trapped Gas
    - Pockets of gas (atmosphere) in welds, holes, threads, behind screws, etc.
    - Long term source of 'air'
    - Impossible to find, so work to make sure you don't introduce them

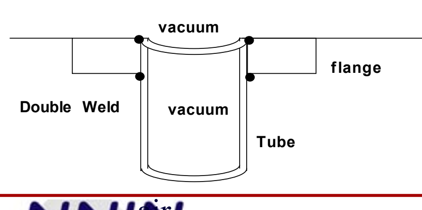
Bad Assembly Techniques

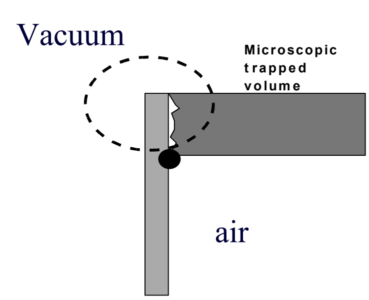
An un-vented screw





Vented screws??





Gas Balance

$$Q_T = PS = Q_{Decomposition} + Q_{Desorption} + Q_{Diffusion} + Q_{Permeation} + Q_{leaks} + Q_{Virtual\ Leaks} + Q_{\text{backstreaming}}$$

We can eliminate or minimize most of these by proper materials selection

Materials for Vacuum Use

General Materials

- If you are not sure, don't use it.
  - Many common materials are not good for vacuum systems

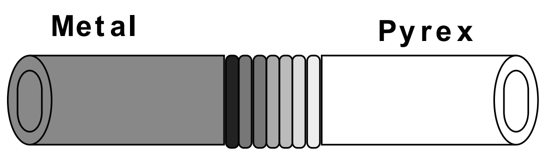
Construction Materials: Chambers and structural members

- Stainless Steel is good
- Iron is bad
- Al is OK, but generally not HV
- For HV, Brass is out due to Zn
- For Rough, Brass is OK
- Ni, Cu, are OK for small things
  - May need to be fired to drive out gas
  - Cu(OFHC) the good stuff

Glass

- **A good vacuum material**
  - **Brittle but good in compression**
- **UHV Systems to 10^{-12} torr**
- **Bake to 400°C.**
- **O-ring connections or glass blown or glass to metal seals**

Graded glass to metal seal



Graded region of 5-6 different glasses, each with a small change in thermal expansion from the prior

Insulators

- **Alumina (99.9%)**
  - **Ivory colored**
  - **The good stuff**
  - **Diamond grind**
  - **Good to very high T**
- **Mullite.**
  - **The cheap stuff**
  - **Not as pure**
  - **White**
- **Macor$_{tm}$ (Corning Product) Machinable Glass Ceramic**
  - **Easily machinable**
  - **Good to 1000°C**

Polymers and Fluids

- Much bigger gas sources than metals and solid stuff
- Use sparingly

O rings

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- Viton:
  - A hard synthetic rubber
  - Lower outgassing
  - Higher Temperatures (>100°C)
  - Glossy Black or Brown
- Buna N:
  - Plain old rubber
  - Softer
  - Generally a chalkier black (grey)
- Silicone (red)
- Generally limited to 10^{-7} torr
  - Can't bake

Greases and Fluids

- Even "low vapor pressure" greases have high vapor pressure relative to everything else
  - Decompose if heated
  - Use sparingly if at all
- Common Vacuum grease (Dow Corning, etc)
  - Really yuk
  - Mostly for hoses and ground glass fittings and other archaic stuff
- Apiazon (brand) (various grades)
  - Better

Greases and Fluids

- The right way to grease an o-ring
- Heat transfer medium
- Leak sealants = Yuk

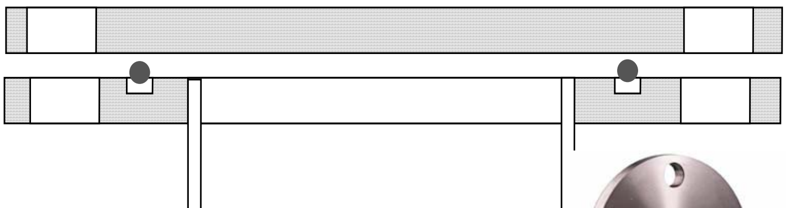
Other Vacuum Hardware

Vacuum Flanges

- **How do we connect pumps and gauges, etc?**
- **Demountable couplings**
- **Different types for different purposes**

ASA Flange "System"

ASA Flanges

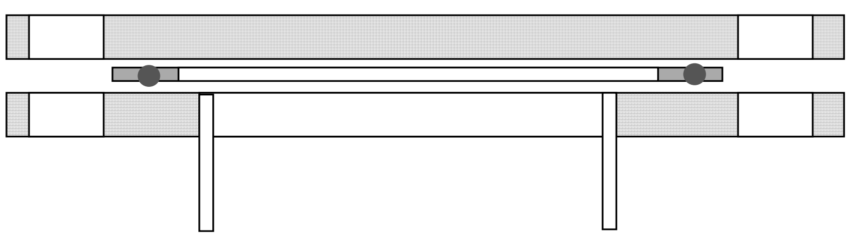


- Pipe fitters flanges
- Nothing is standard
- Typically thin, few large bolt holes
- O-ring
  - Which side
  - What diameter
- Confusing name convention
- Typically found on some HV pumps

Component photos from www.lesker.com

ASA

ASA Flanges with Sealing Ring

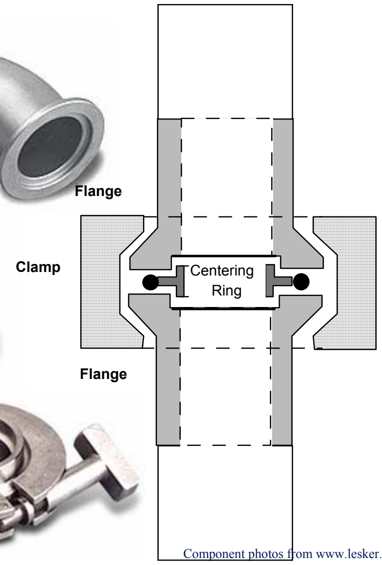


- Solve the O-ring confusion by not putting it in either one
- Separate "sealing ring," a captured o-ring
- Sexless system but still has other problems

Component photos from www.lesker.com

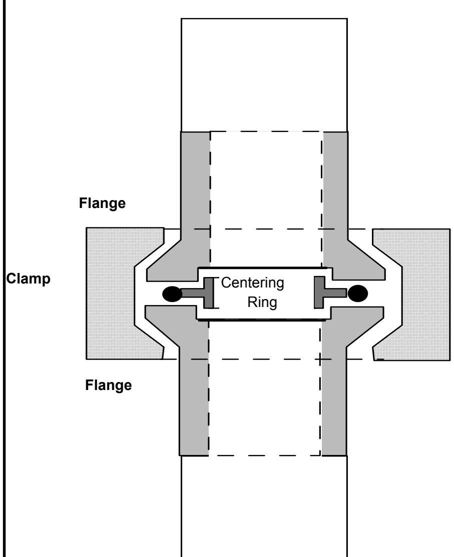
KF Flange Assembly

- KF, QF, various brands
- ISO Standard
- Universal and Modular
- Cheap
- Sexless
- Up to 2” dia tube
- Pieces
  - Flanges
  - Clamp
  - Sealing/centering ring



Component photos from www.lesker.com

KF Flange Assembly

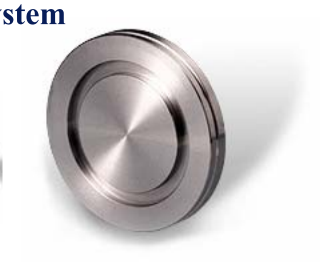


- Easy to seal
- Easy to design system
- Various Sizes:
  - KF 16
  - KF 25
  - KF 40
  - KF 50
- Brass, Stainless, Aluminum, Plastic
- Generally “rough” vacuum range, but good to 10^{-6} torr

Component photos from www.lesker.com

LF ISO

- Large Flange equivalent of the KF system
  - Similar in concept but high vacuum
  - Different clamps
- ISO
- Modular
- Sexless
- Different type of clamps and flange configuration
- 100mm-200 mm diameter range
- Common on modern pumps



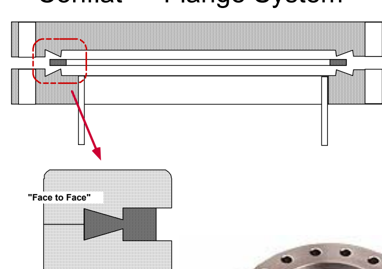
Component photos from www.lesker.com

Component photos from www.lesker.com

"Conflat^{tm} " "Del-Seal" Flanges

- A well defined standard.
  - Various brands
- Sexless
- Copper Gasket.
  - Use gasket once
  - Sheered and cold formed
  - Very stable to UHV & high temp
  - Bakable
- Various diameters
  - 1.33", 2.75", 4.5", 6", 8", 10", OD
- Reliable, inexpensive and ubiquitous
- Time consuming and muscle building

Conflat ^{tm} Flange System

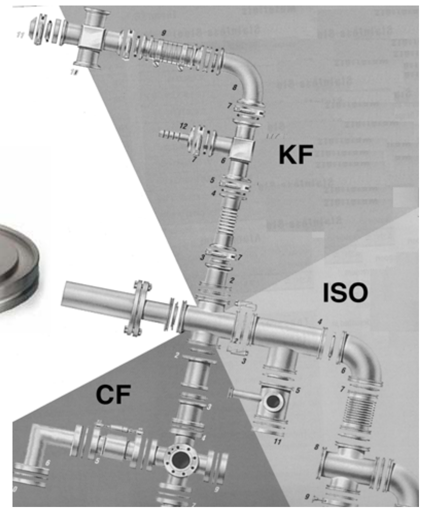


Component photos from www.lesker.com

Modularity

- Valves, and elbows and tees all the same size
- Standard adapters
- Choose and assemble

Component photos from www.lesker.com

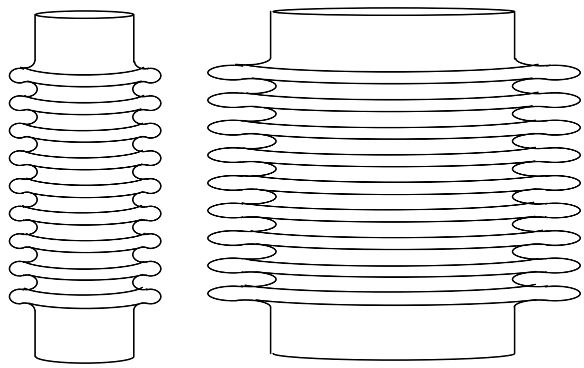


Odd Flanges

- Strange Shapes
- Gold or silver or indium wire
- On SEMS and cheap equipment

Formed Bellows (Rolled Bellows)

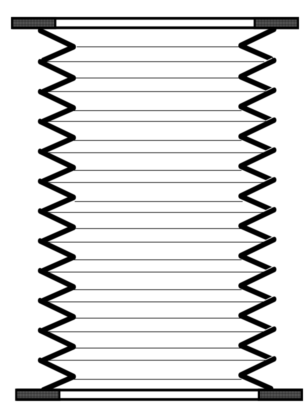
- Relatively inexpensive
- Not Particularly Flexible
- Stiff
- Small motion
- Vibration isolation



Component photos from www.lesker.com

Welded Bellows

- Expensive
- Delicate
- Very Flexible
- “Soft”
- Precise motion or alignment or “soft” movement



Stem Sealed Valve

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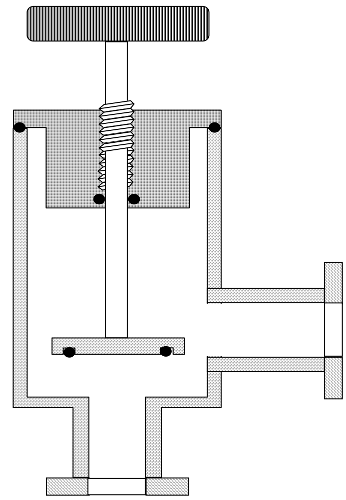
- Rotating seal (stem) is hard
- Stem leak
- Typ. size 0.25”-2” dia.
- Brass or stainless
- ~ $100



Component photos from www.lesker.com

Bellows Sealed Valve

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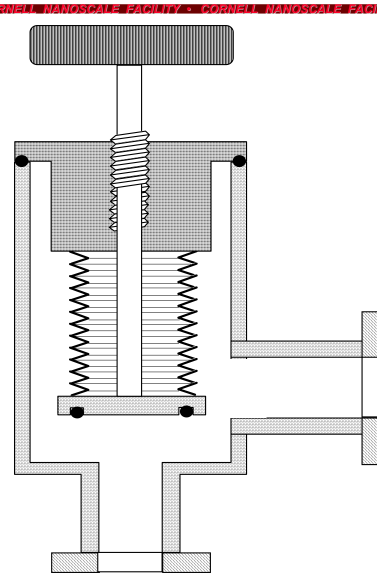
- No rotating seal.
- No stem leakage.
- Typ. 1-2” dia.
- ~ $1000.

Component photos from www.lesker.com



Gate Valve

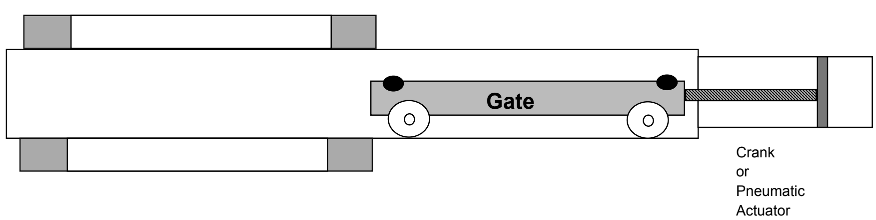
- Clear through path.
  - Pumping.
  - Stick things through.

- 2-16" diameter.

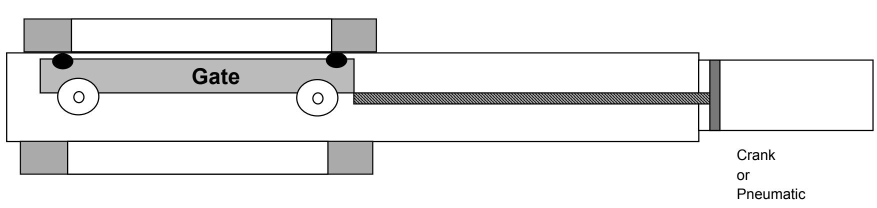
Component photos from www.lesker.com

Gate Valves

Gate Valve Open



Gate Valve Closed



Component Summary

- Pump
- Gauges
- Valves
- Flanges

- Control System
- Container

- Vacuum System!

Vacuum Systems

Vacuum Systems

- Many components to make a vacuum systems
  - Pumps
  - Chambers
  - Valves
  - Gauges
  - Flanges
  - Controls
- From Huge to .....
- From Complex to ....

The Common Light Bulb

Water Cycle

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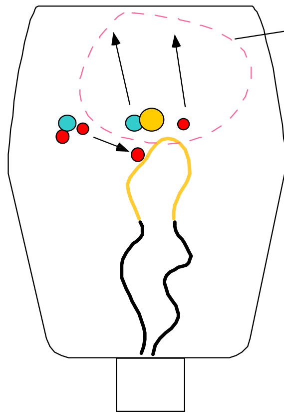

- Interesting Cyclical Reaction.
- Transport from hot filament to cold walls.
- Effect on lifetime of gauges and bulbs.

A Bright Light

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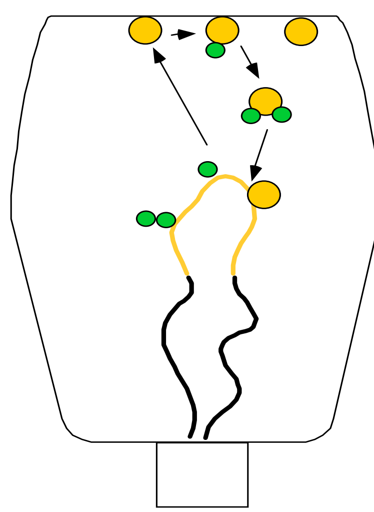
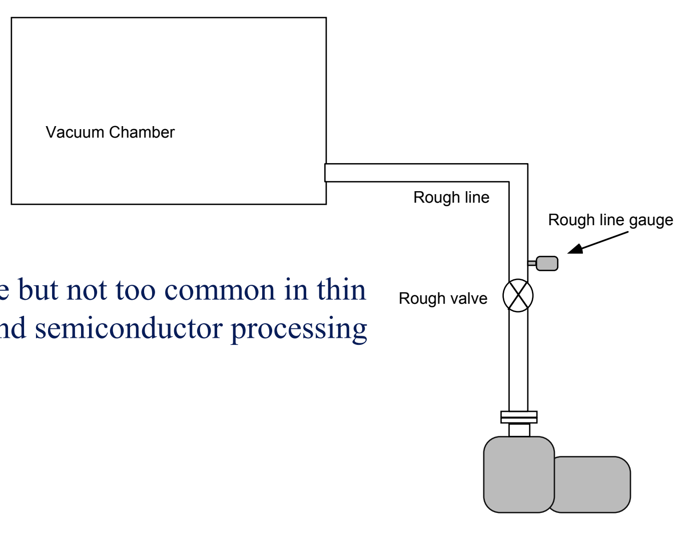
- Brighter-->hotter-->more evaporation--> shorter life.
- Hotter-->melt the glass.
- What do we do ???

- Make it out of Quartz.
- Cure or reverse the evaporation.
  - Halogen cycle.



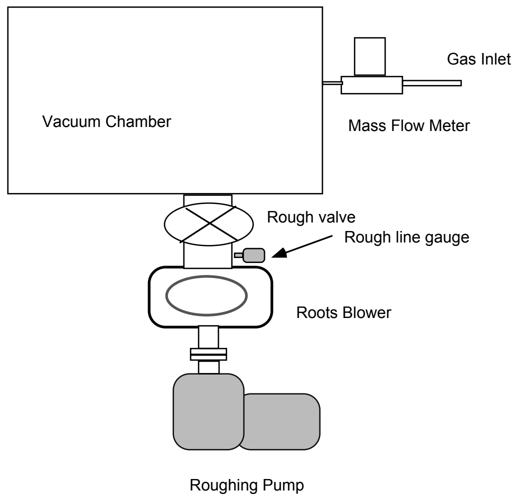
Rough Vacuum Systems

Mechanical Pump Only



Simple but not too common in thin film and semiconductor processing

High Gas Load System-Rough Vacuum



High Vacuum Systems

Diffusion Pump System

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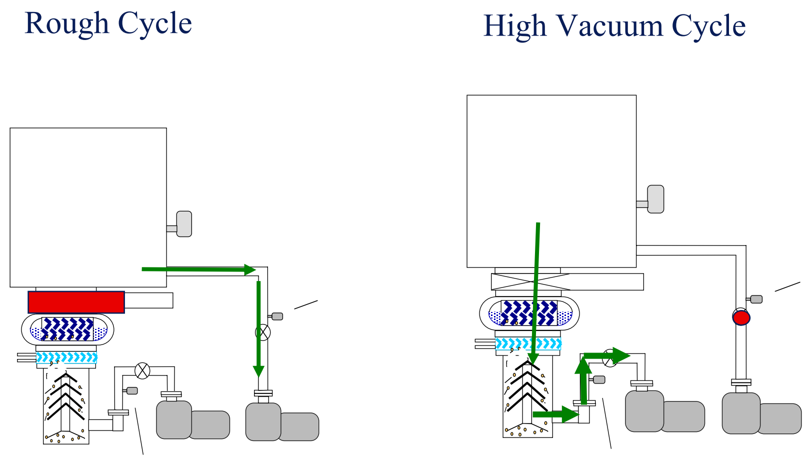

Roughing Traps

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- **Mechanical Pumps are full of oil ----ick**
- **We don't want our vacuum system full of oil vapors**
- **Traps:**
  - **Cold-LN_2**
  - **Adsorbant**
    - **Copper wool**
    - **Zeolite**
      - **Large surface area, etc.**
  - **Goes in the rough line between pump and chamber**
  - **Generally not particularly effective**

The Alternative

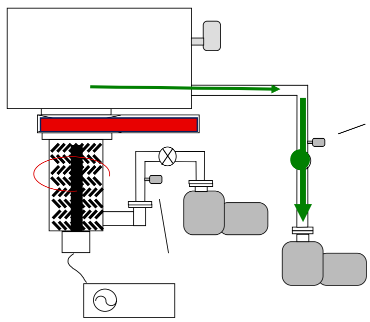
- **Backstreaming (oil contamination) occurs primarily at molecular flow**
  - **Few bounces**
- **Very hard for an oil molecule to swim upstream in viscous flow**
- **Really only need to rough far enough to cross-over**
  - **Less is better**

Proper Roughing Procedure

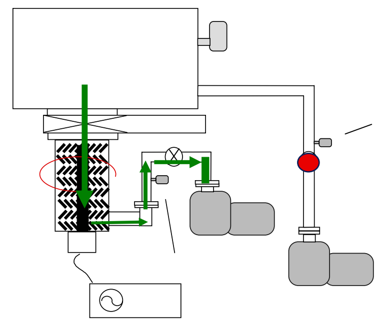
- **Keep the rough line in viscous flow**
  - **Nitrogen purge**
  - **100-200 mtorr in a 3 cm diameter line**
  - **MFP_{cm}=5/P_{mtorr} =.05 cm**

Turbo Pump System

Rough Cycle



High Vacuum Cycle



Cryopumped System

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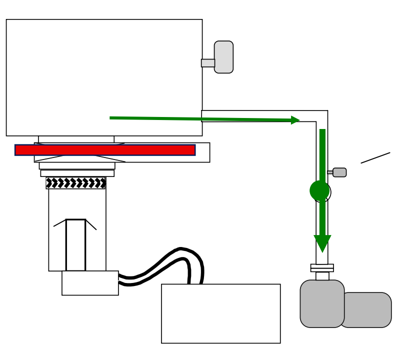
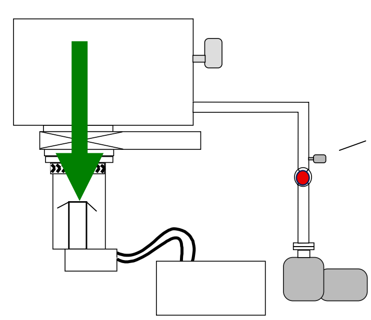
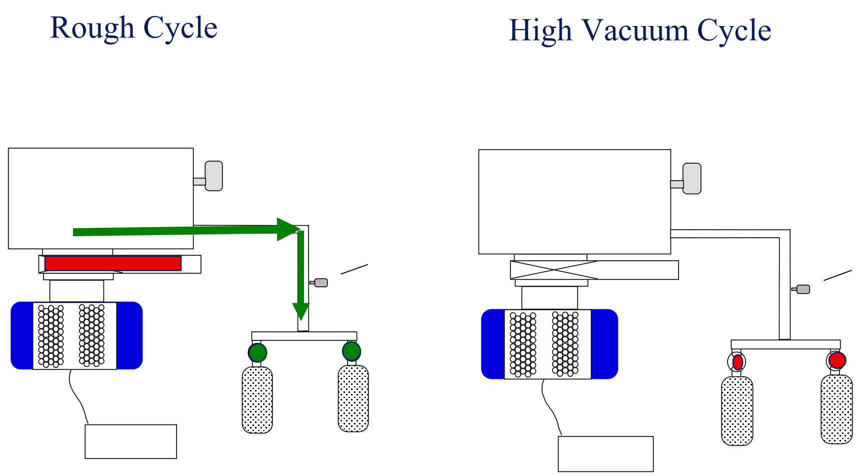
Rough Cycle



High Vacuum Cycle



Typical Ion Pumped Vacuum System



Residual Gas Analysis

How do you tell what is in the vacuum?

Residual Gas Analyzers

- Sometimes it is important WHAT KIND OF GAS is in the vacuum
  - Leak checking
  - Process control
  - Process documentation
- "Residual Gas Analyzer" measures the gas composition of the "vacuum"
- Basically a small mass spectrometer

Residual Gas Analyzer

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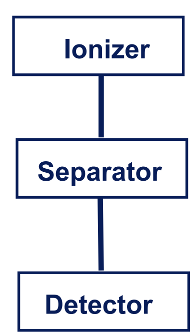
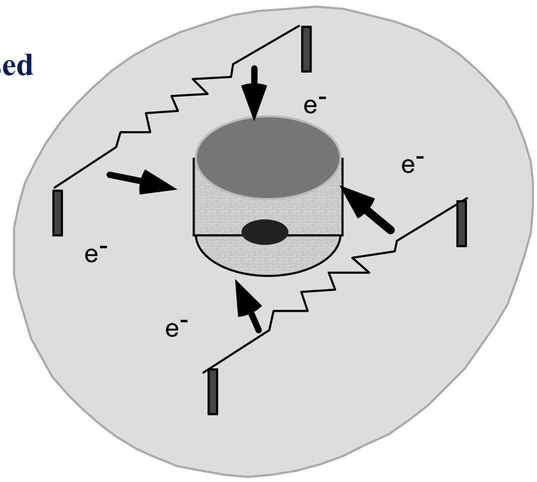
- Really an analyzer of gas ions, not neutral atoms or molecules.
- Ionizer
  - Electron impact
  - An ion gauge like device
- Separator.
  - Magnetic field
  - Time of flight
  - Electric field
  - Quadrupole Mass Spectrometer
- Detector
  - Faraday cup
  - Electron multiplier



Electron Impact Ionizer

- Ion gauge like device
- Hot filament
- Ions extracted and focused



Mass Filters

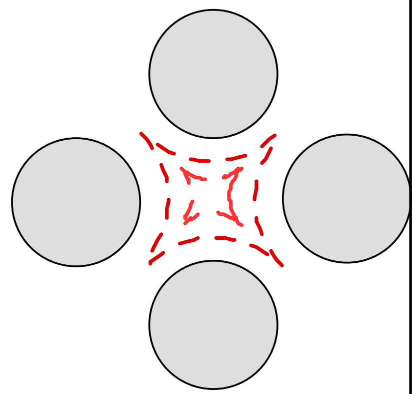
- Charge to mass ratio
  - Time of Flight
  - Magnetic sector
  - Electrostatic sector
  - RF electric resonant filter, aka
    - Quadrupole mass filter
    - Quadrupole
    - Quad
    - RGA

Quadrupole RGA

- Hyperbolic fields.
- Paired opposite electrodes
- Excitation

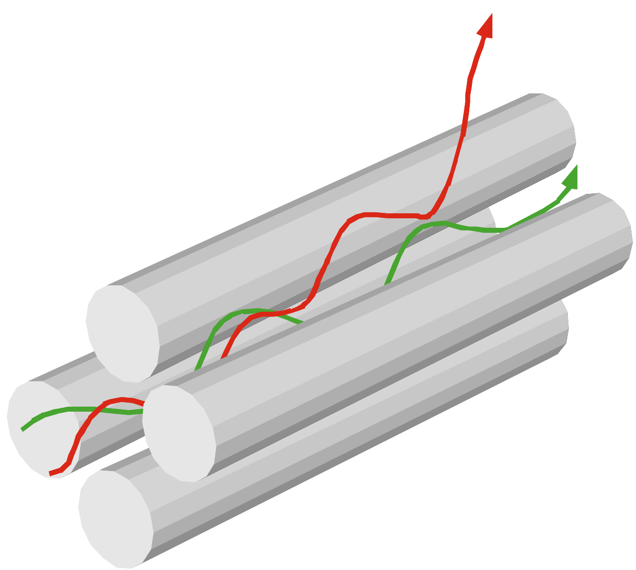
$$X = -U - V\cos\omega t$$

$$Y = +U + V\cos\omega t$$



- Bandpass filter.
- Voltage is scanned.
  - Pass band is scanned.
- Signal vs time= mass spectrum.

Quadrupole Mass Filter



Quadrupole Based Mass Filter Assembly

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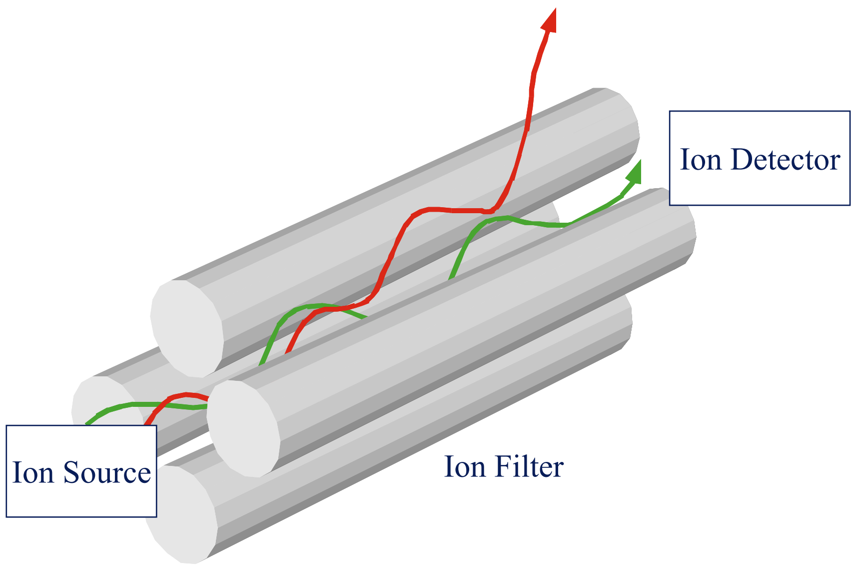

Ion Detectors

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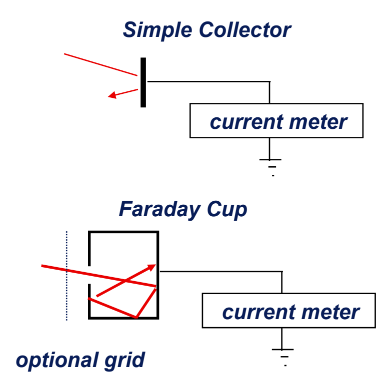
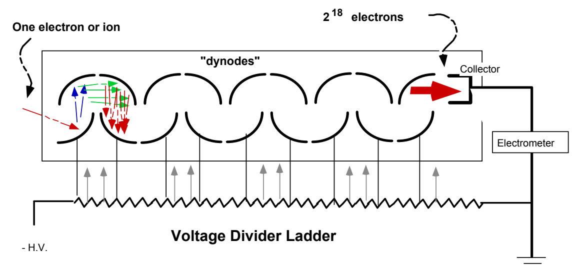
- Faraday Cup.
  - Simple current collector.
  - Suppress secondary electrons.
  - Used when lots of signal.

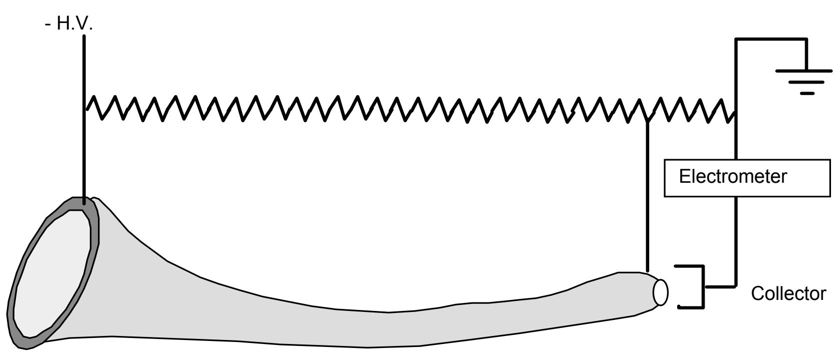


Electron Multiplier

- An electron amplifier.
  - Physical process.
  - Less noise.
  - Discrete series of "dynodes."
- Secondary electron coefficient = α >1.
- Gain ~ α^n.
- Electron in.
- Output.
  - Current.
  - Pulse of electrons.
- Also:
  - Photo multiplier.
  - Ion multiplier.



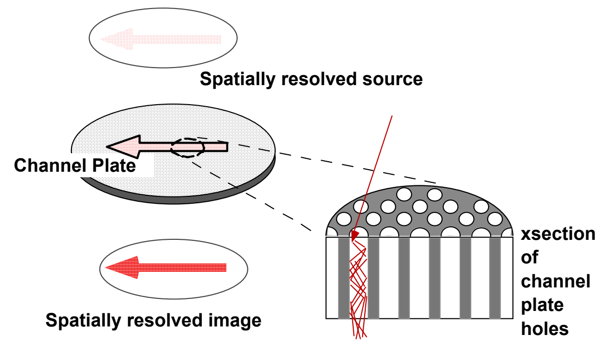
Electron Multiplier



Glass "funnel" coated with high resistive film INSIDE

- Continuous Dynode.

Channel Plate as Imaging Detector

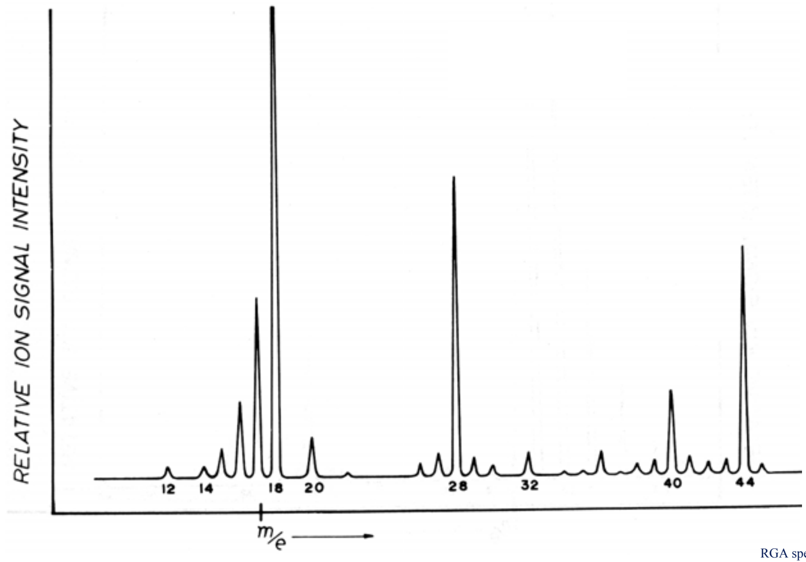


- Spatially resolved detector
- Array of mini tube shaped electron multipliers
- Imaging
- Gain 10^5-10^6

Electron Multiplier as a Detector

- Electron detector.
- Ion detector.
- Photon detector.
  - Photomultiplier.
  - Generally in a glass vacuum tube.
- A ‘noiseless’ signal multiplier.
  - Pulse mode.
    - Counting technology.
  - Current mode.
    - Current gain of 10^6 to 10^8.

Typical RGA Spectrum



RGA spectra from AVS

Cracking Patterns

- **What you see is not always what you have.**
- **Ionizer knocks electrons off molecules, sometimes it knocks off fragments.**
  - **Loosely bound groups most susceptible.**
  - **H_20 Mass 18 18, 17, 16.**
  - **CH_4 Mass 16 16, 15, 14, 13, 12.**
  - **Can knock off large groups.**
    - **Methyl groups off organic molecules.**

Cracking Patterns

- Cracking patterns (ratios) are function of gas, electron energy, and ionizer conditions.
- Helps identification.
- Makes quantification difficult.

Common Peaks

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Mass	Species	Explanation
0		Zero Blast , unfiltered fragments
1	H	Cracking of hydrogen
2	H_2	Dominant Species at UHV
4	He	Permeation through polymers or leak detection residue
16	O	Crcking of O2 or H20. Electron Desorption from Surfaces
16	CH_4	Methane produced in system by ion pumps
18	Water	Dominant Species except at UHV
19	F	ionic ghost, see below
20	Ne, Ar^{++}	Inert Gases not pumped well by ion pumps
28	N_2	Air leak if accomanied by 14
28	CO	A major constituent at UHV. Desorption
35	Cl	Process gas or residue or ionic ghosts (see below)
37	Cl isotope	
40	Ar	Inert Gases not pumped well by ion pumps
>40		Generally hydrocarbon contamination
intervals of 14		CH_2 groups cracked off long hydrocarbon chain
16,19,35,37		Residue of O,F,Cl desorbed from surfaces in RGA by electron bombardment. Artifacts.

Cracking Patterns and Spectra

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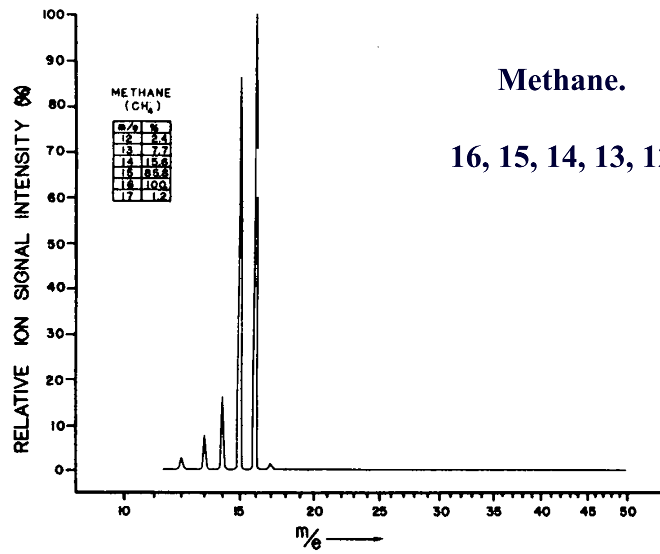

Methane.

16, 15, 14, 13, 12

RGA spectra from AVS

NNIN *CNF* NanoCourses Vacuum Technology, page 285 CORNELL UNIVERSITY

Cracking Pattern

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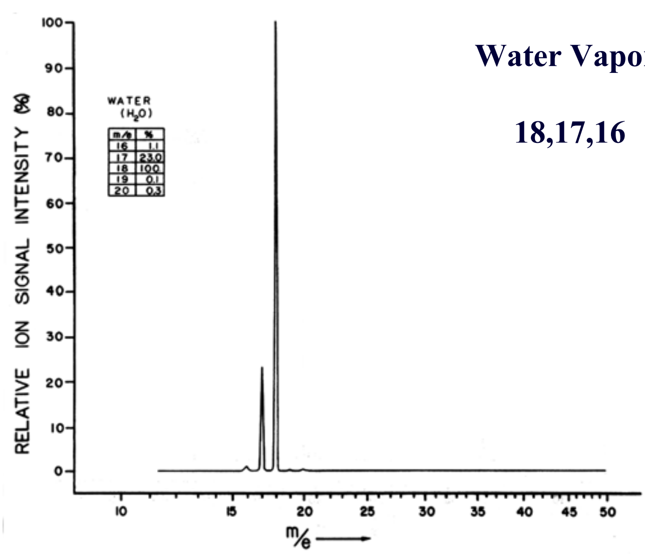


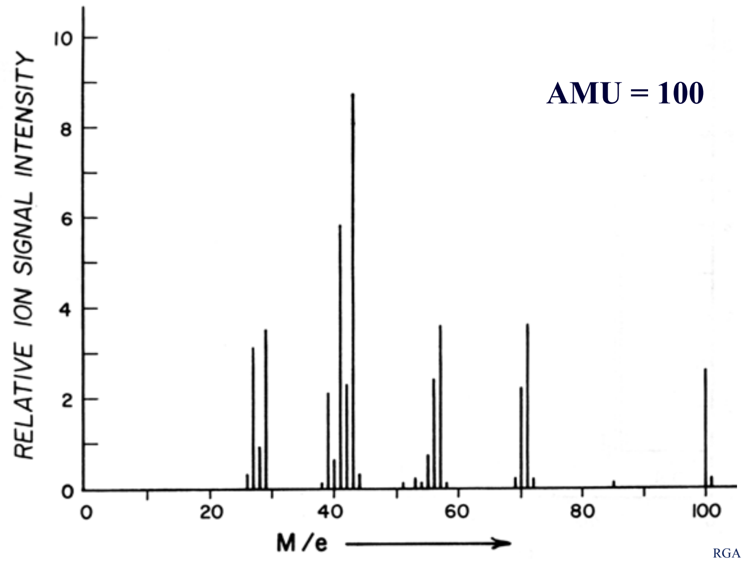
Water Vapor.

18,17,16

RGA spectra from AVS

NNIN *CNF* NanoCourses Vacuum Technology, page 286 CORNELL UNIVERSITY

Heptane Spectrum

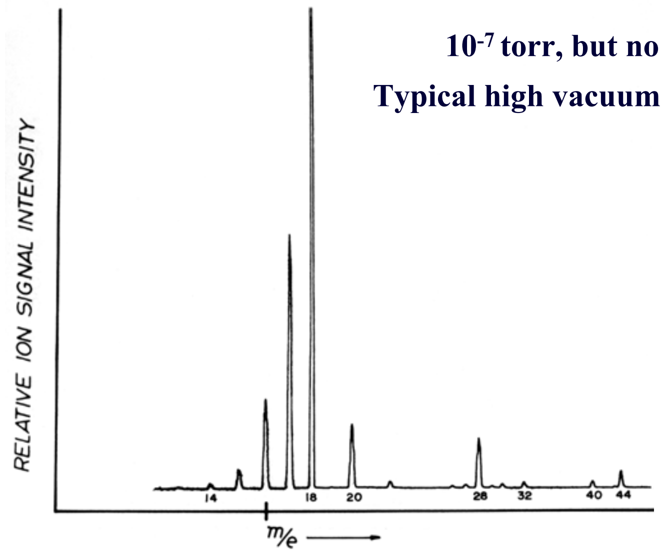


RGA spectra from AVS

What Can You Tell from an RGA ?

- System Status
- System Recent History
- Leaks
- Contamination
- Type of Pumping System
- Vacuum level

System Spectrum

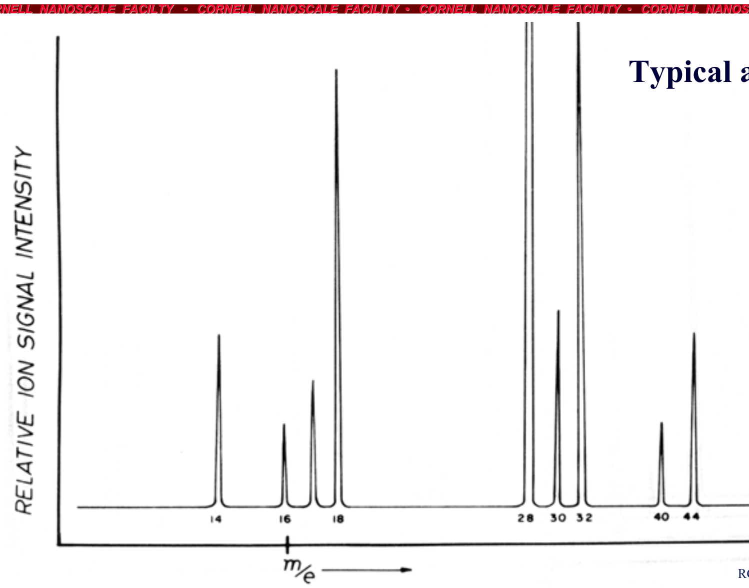


10^{-7} torr, but no leak.

Typical high vacuum spectrum.

RGA spectra from AVS

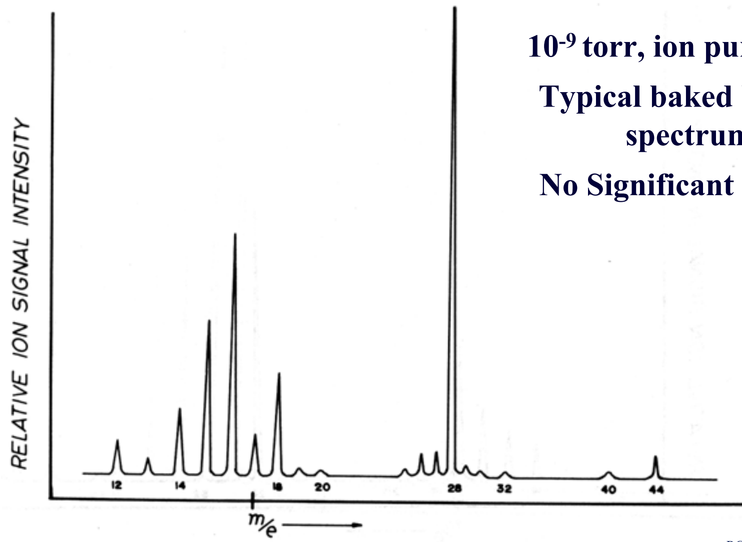
RGA Spectrum



Typical air leak.

RGA spectra from AVS

System Spectrum



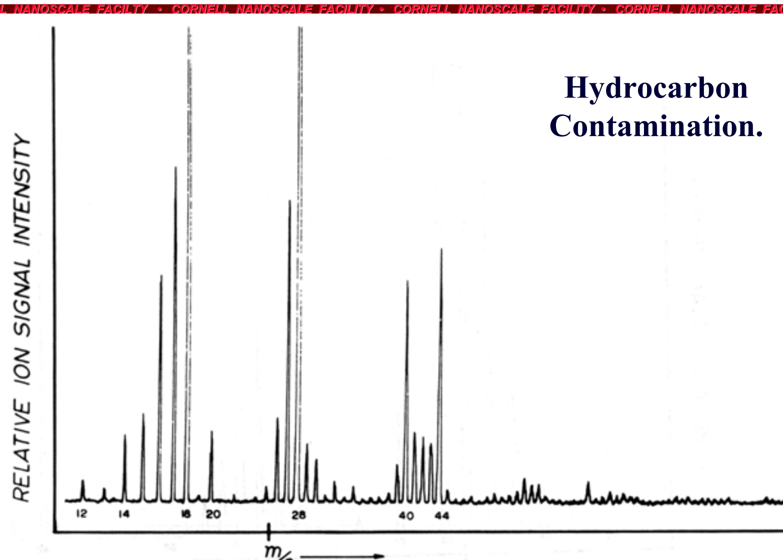
10^{-9} torr, ion pumped.

Typical baked UHV spectrum.

No Significant Leak

RGA spectra from AVS

RGA Spectrum



Hydrocarbon Contamination.

RGA spectra from AVS

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  - **Partial Pressure Analyzers.**
  - **Handbook of Vacuum Leak Detection.**
  - **Introduction to Fundamentals of Vacuum Technology.**
- **Scientific Foundations of Vacuum Technique, Dushman and Lafferty, Wiley and Sons, (the old bible, somewhat dated but lots of useful info).**
- **Handbook of Vacuum Tube Techniques, Roth (re-issued) (A great reference on materials).**