

# Vacuum Science and Technology for Accelerator Vacuum Systems

*Yulin Li and Xianghong Liu  
Cornell University, Ithaca, NY*

Duke  
UNIVERSITY

USPAS - Vacuum Fundamentals



Cornell Laboratory  
for Accelerator-based Sciences  
and Education (CLASSE)



# About Your Instructors



- Yulin Li & Xianghong Liu
  - Vacuum Scientists ([yulin.li@cornell.edu](mailto:yulin.li@cornell.edu), [XL66@cornell.edu](mailto:XL66@cornell.edu) )
  - Cornell Laboratory for Accelerator-based Sciences and Educations (CLASSE)
  - Self-taught vacuum practitioners, starting as surface scientists
  - As research staff members at CLASSE over 17 & 8 years overseeing all aspect of vacuum operations, designs and R&D
- CLASSE – A Research Center on Cornell’ s Ithaca Campus
  - Primary funding – NSF, with additional funding from DOE
  - Cornell Electron Storage Ring (CESR): 780-m, 500-mA, 5-GeV
  - Cornell High Energy Synchrotron Sources (CHESS) – A SR-user facility w/ 12 experimental stations
  - CEsrTA – CESR as a Test Accelerator for International Linear Collider Damping Ring R&D, with focus on Electron Cloud studies
  - Cornell Energy Recover LINAC – DC Photo-cathode injector
  - Superconducting RF researches
  - High-energy physics – CLEO, LHC, etc.



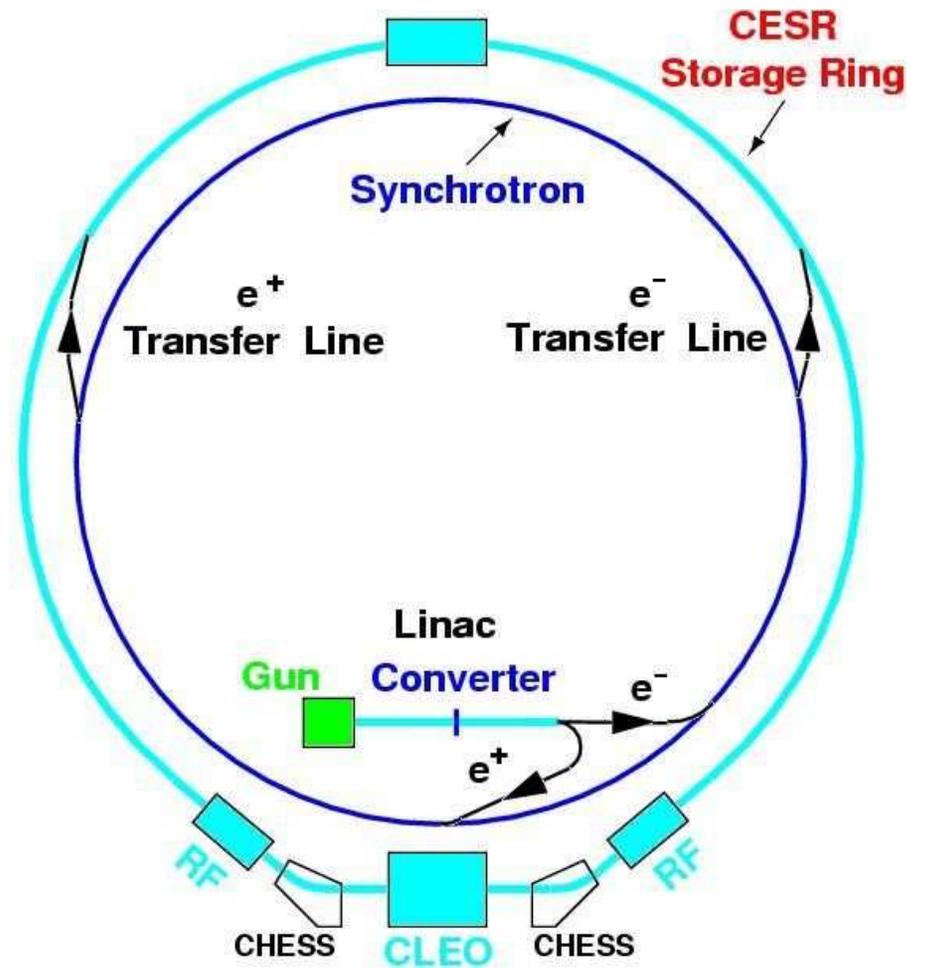
# Acknowledgements

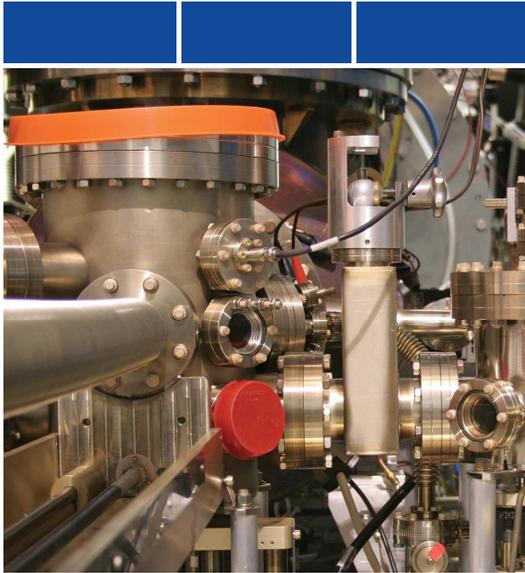
---



- ❑ *Special thanks go to Mr. Lou Bertolini of LLNL, who shared ~1000 slides with me from his previous USPAS Vacuum lectures.*
- ❑ *Thanks also go to many of my colleagues from other accelerator facilities, who provided valuable information.*
- ❑ *Many vacuum product companies graciously supported with their presentations, detail technical information and demo products.*
- ❑ *Most importantly, I am grateful for CLASSE-Cornell's supports, and for NSF's continuous support in our researches.*







# Table of Contents

- **Vacuum Fundamentals**
  - Vacuum Instrumentation
  - Vacuum Pumps
  - Vacuum Components/Hardware
  - Vacuum Systems Engineering
  - Accelerator Vacuum Considerations, etc.

# SESSION 1: VACUUM FUNDAMENTALS

- Vacuum definition and scales
- Gas properties and laws
- Gas flow and conductance
- Sources of gasses



---

# ***The Basics***



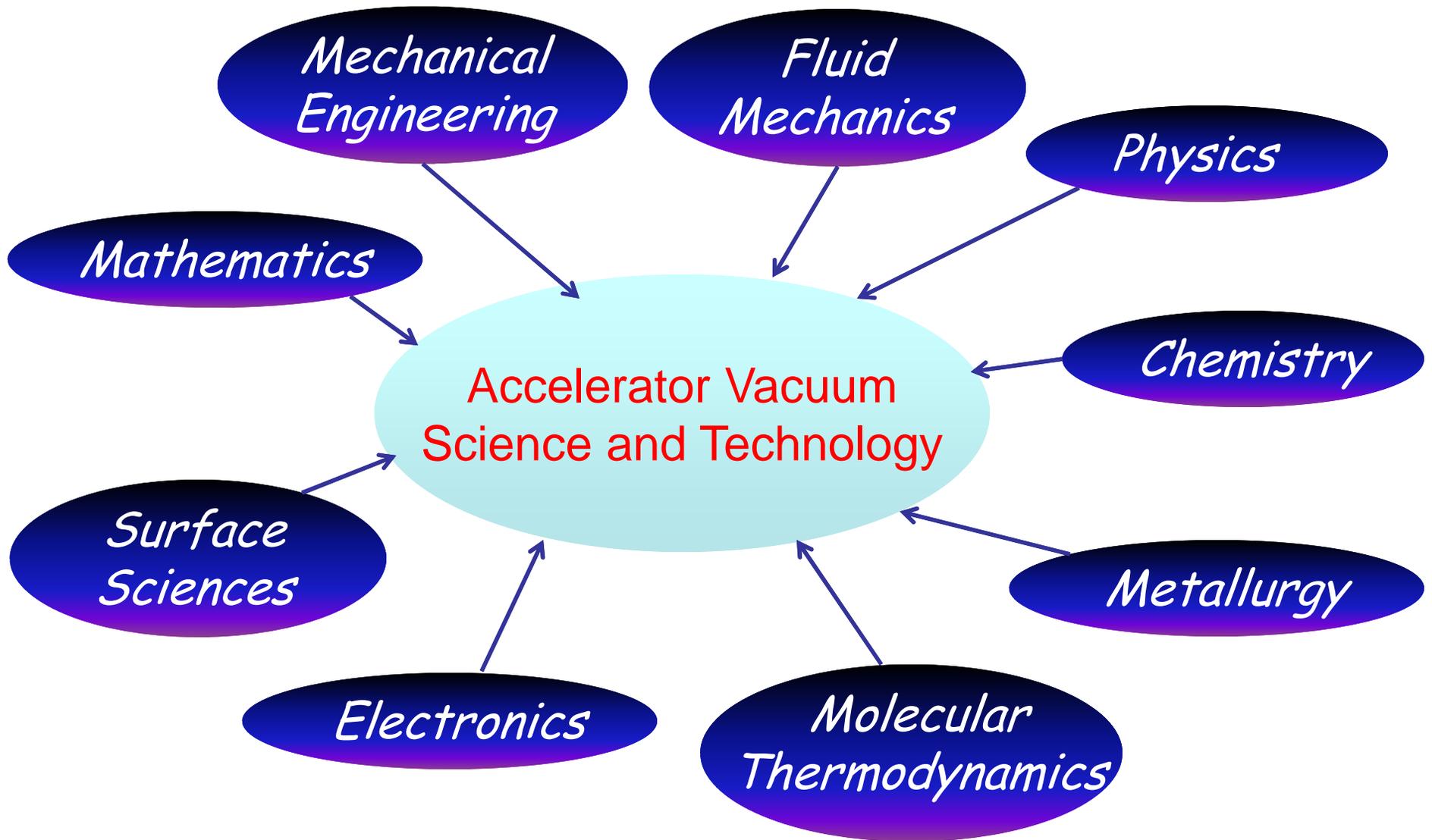
# What is a Vacuum ?



- *A vacuum is the state of a gas where the density of the particles is lower than atmospheric pressure at the earth's surface*
- *Vacuum science studies behavior of rarefied gases, interactions between gas and solid surfaces (adsorption and desorption), etc.*
- *Vacuum technology covers wide range of vacuum pumping, instrumentations, material engineering, and surface engineering*



# Accelerator Vacuum – highly interdisciplinary



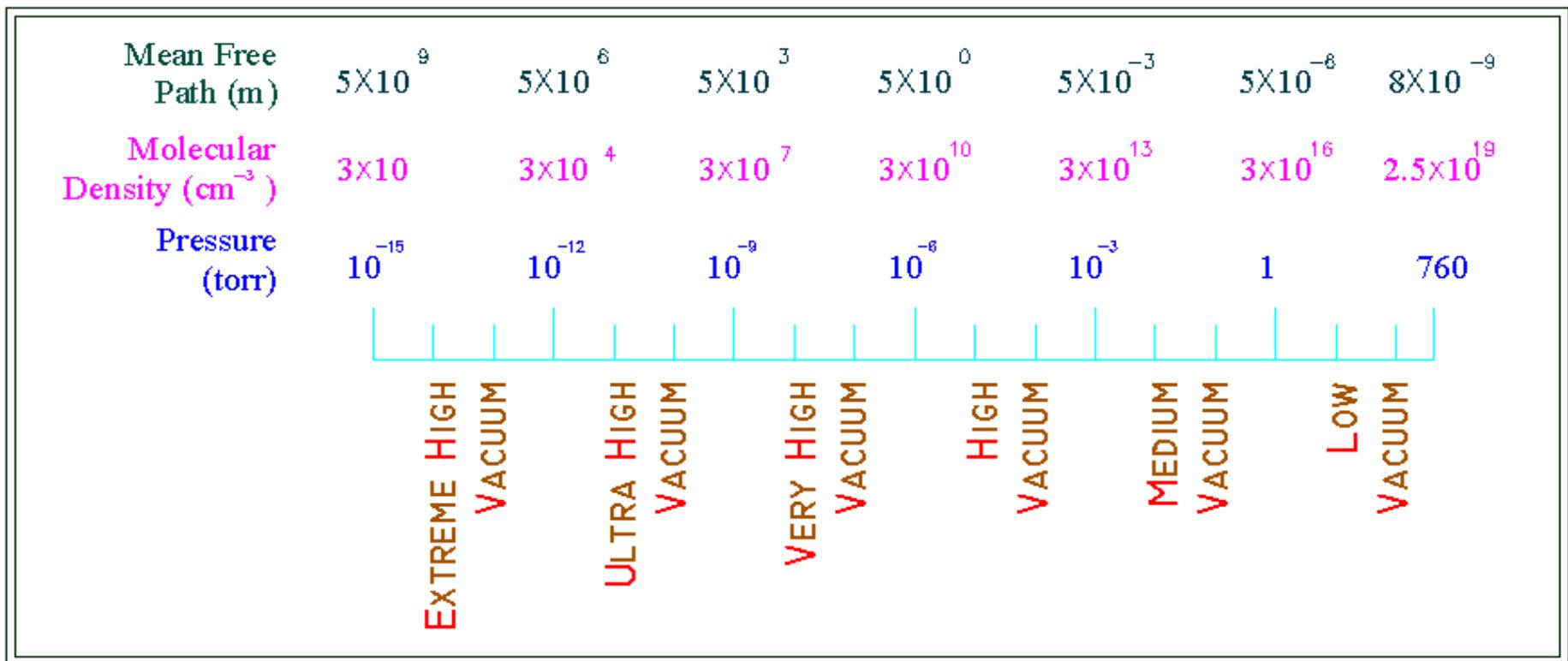
# Units, Scales & Molecular Densities



SI Pressure Unit: Pascal (Pa) = N/m<sup>2</sup>

Other commonly used units: Torr (mmHg) = 133.3 Pa

mbar = 100 Pa = 0.75 Torr



# Example Vacuum Applications



<i>Extreme High Vacuum (<math>P &lt; 10^{-11}</math> torr)</i>	<i>Photo-cathode electron sources (Cornell, JLab, etc.)</i>
<i>Ultra-High Vacuum (<math>10^{-9}</math> to <math>10^{-11}</math> torr)</i>	<i>Storage rings, surface sciences, etc.</i>
<i>High Vacuum (<math>10^{-3}</math> to <math>10^{-9}</math> torr)</i>	<i>Device fabrications, medical accelerators, mass spectrometry, SEM, etc.</i>
<i>Medium &amp; Low Vacuum</i>	<i>Cryo system insulation, coating, vacuum furnaces, beam welders, etc.</i>



# Dry Air Composition and Molecular Mass



Constituent	Volume Content		Molecular Mass	Molecular Mass in Air
	Percent	ppm		
N <sub>2</sub>	78.08		28.02	21.88
O <sub>2</sub>	20.95		32.00	6.704
Ar	0.934		39.94	0.373
CO <sub>2</sub>	0.037		44.01	0.013
H <sub>2</sub>		0.5	2.02	---
Ne		18.2	20.18	---
He		5.24	4.00	---
Kr		1.14	83.8	---
Xe		0.087	131.3	---
CH <sub>4</sub>		2.0	16.04	---
N <sub>2</sub> O		0.5	44.01	---
Total				28.97

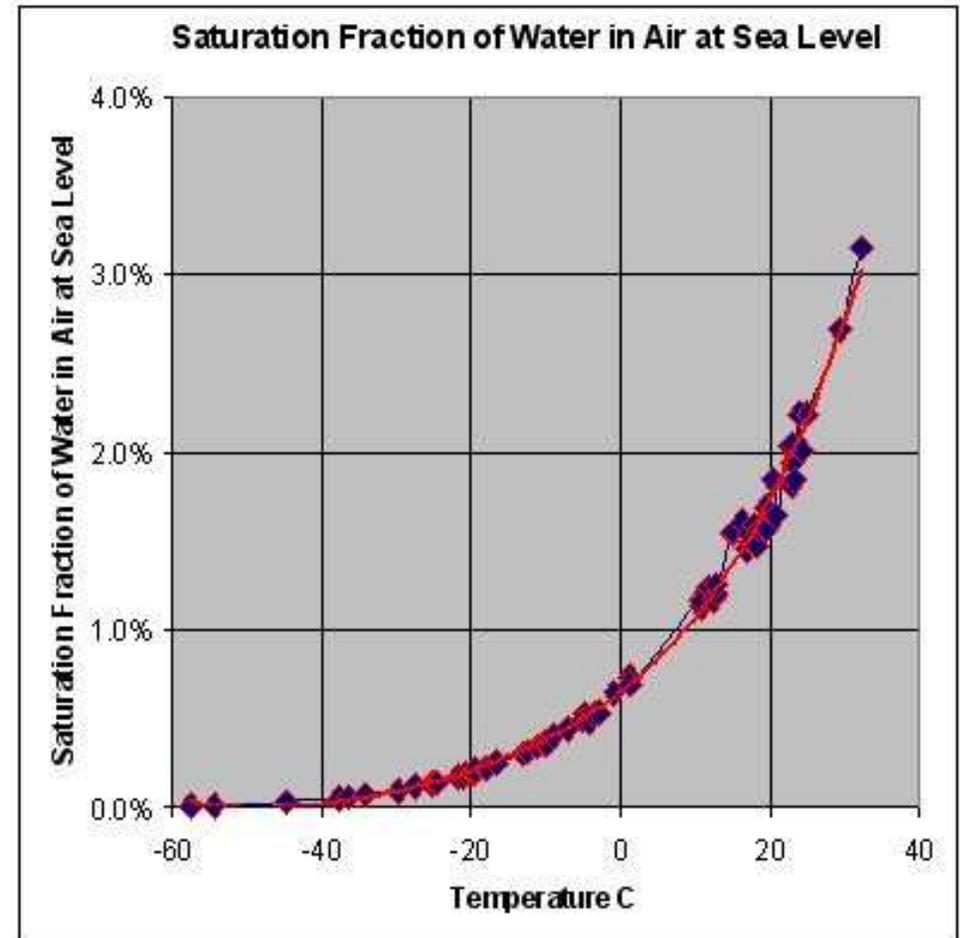




# Water Vapor in Air

- Water has most detrimental effects in a clean vacuum system
- Water molecular mass:  
18.08 kg/mole  
(‘humid’-air is less dense!)
- Water content in air is usually expressed in relative humidity ( $\phi$ ):

$$\phi = \frac{PP_w}{PP_{w\_sat}} \times 100\%$$





---

# *Gas Properties & Laws*



# Kinetic Picture of a Gas



- 1. The volume of gas under consideration contains a large number of molecules and atoms – Statistic distribution applies*
- 2. Molecules are far apart in space, comparing to their individual diameters.*
- 3. Molecules exert no force on one another, except when they collide. All collisions are elastic (i.e. no internal excitation).*
- 4. Molecules are in a constant state of motion, in all direction equally. They will travel in straight lines until they collide with a wall, or with one another*



# Maxwell-Boltzmann Velocity Distribution



$$\frac{dn}{dv} = \frac{2N}{\pi^{1/2}} \left( \frac{m}{2kT} \right)^{3/2} v^2 e^{-\left( \frac{m}{2kT} \right) v^2}$$

***v*** – velocity of molecules (m/s)

***n*** – number of molecules with *v* between *v* and *v* + *dv*

***N*** – the total number of molecules

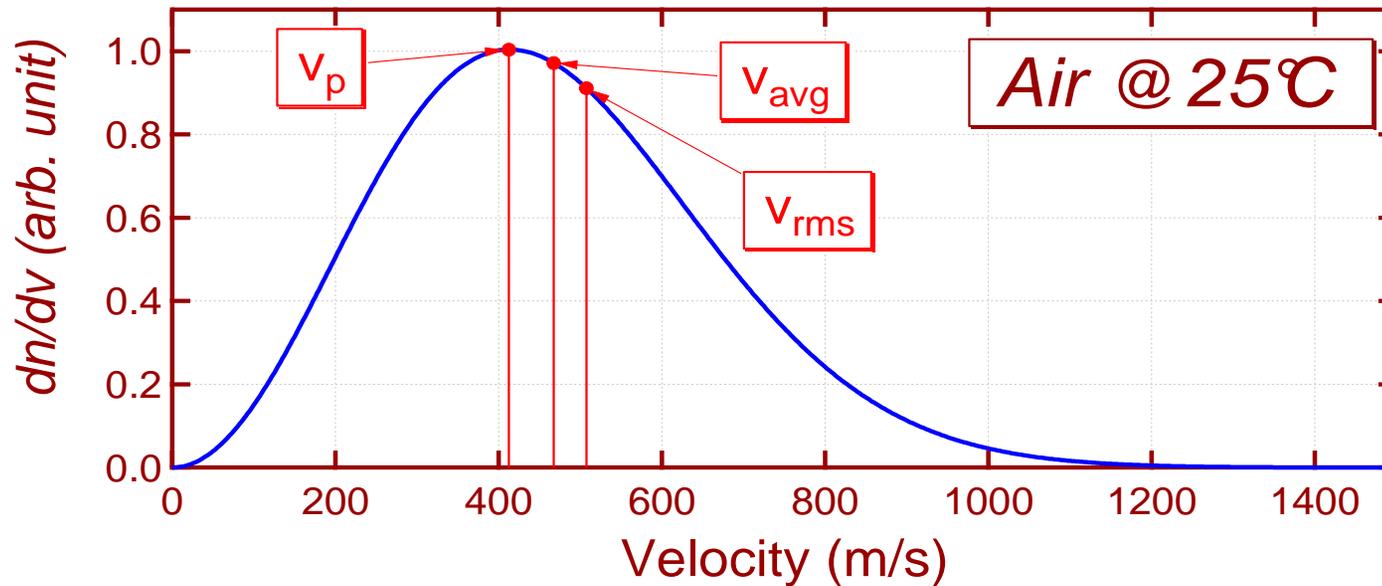
***m*** – mass of molecules (kg)

***k*** – Boltzmann constant,  $1.3806503 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$

***T*** – temperature (kelvin)



# A Close Look at Velocity Distribution



- Most probable velocity (m/s):  $v_p = \sqrt{2kT/m} = 128.44 \sqrt{T/M_{mole}}$
- Arithmetic mean velocity:  $v_{avg} = \sqrt{8kT/\pi m} = 1.128 v_p$
- Root Mean Squared velocity:  $v_{rms} = \sqrt{3kT/m} = 1.225 v_p$

*Velocity depends on mass and temperature,  
but independent of pressure*





# Speed of Sound in Ideal Gases

$$v_{\text{sound}} = \sqrt{\gamma \frac{P}{\rho}} = \sqrt{\frac{\gamma kT}{m}} \quad \text{where} \quad \gamma = C_p / C_v \quad \text{is the isentropic expansion factor}$$

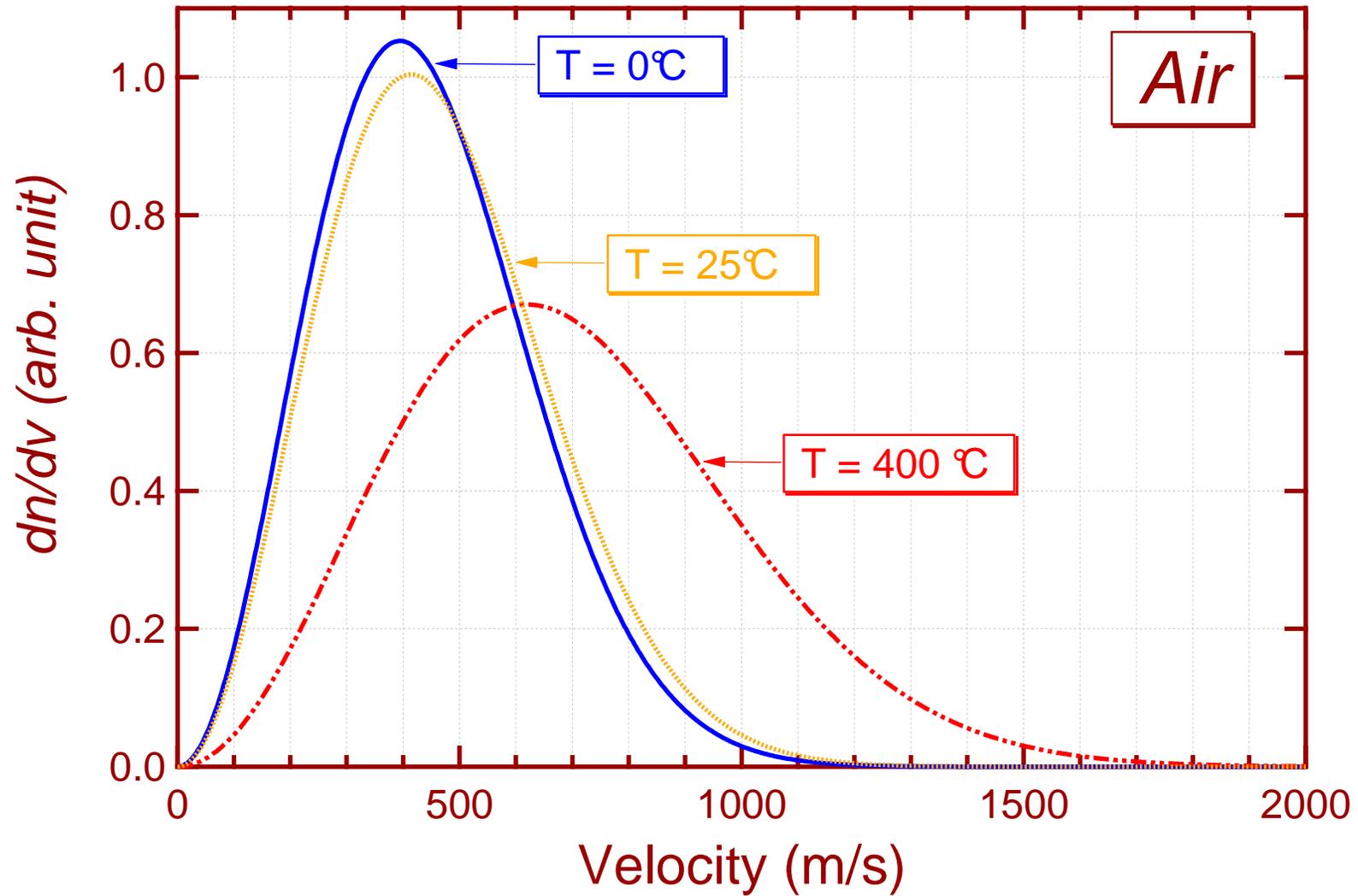
$\gamma=1.667$  (atoms);  $\gamma \approx 1.40$  (diatomic);  $\gamma \approx 1.31$  (triatomic)

	Mono-atomic	Di-atomic	Tri-atomic
$v_p / v_{\text{sound}}$	1.10	1.19	1.24
$v_{\text{avg}} / v_{\text{sound}}$	1.24	1.34	1.39
$v_{\text{rms}} / v_{\text{sound}}$	1.34	1.46	1.51

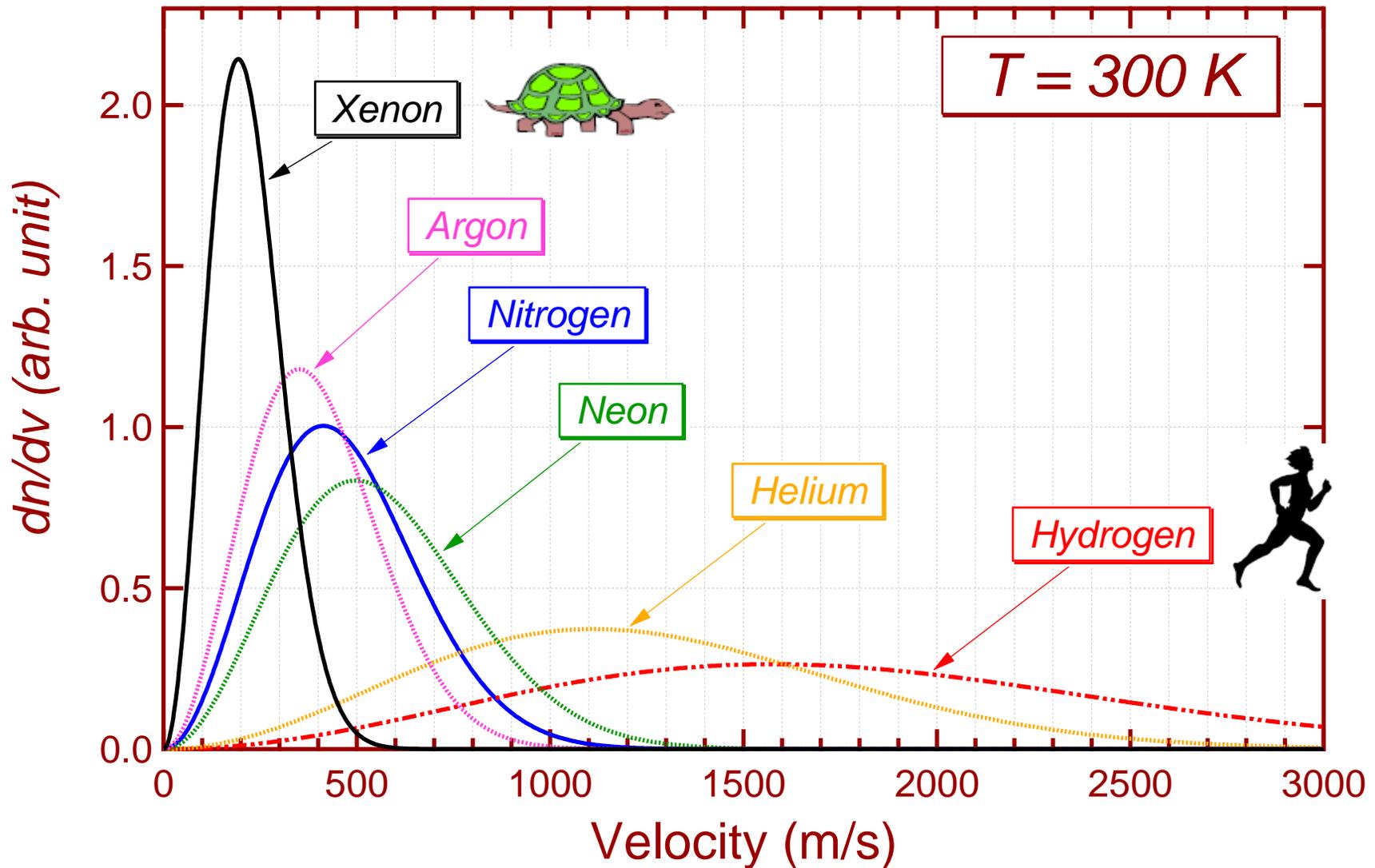
*Though not directly related, the characteristic gas speeds are close to the speed of sound in ideal gases.*



# Molecules Moves Fast at Higher Temperatures



# Light Molecules Moves Faster



# Maxwell-Boltzmann Energy Distribution



$$\frac{dn}{dE} = \frac{2 N}{\pi^{1/2}} \frac{E^{1/2}}{(kT)^{3/2}} e^{-\left(\frac{E}{2kT}\right)}$$

- Average Energy:  $E_{avg} = 3kT/2$
- Most probable Energy:  $E_p = kT/2$

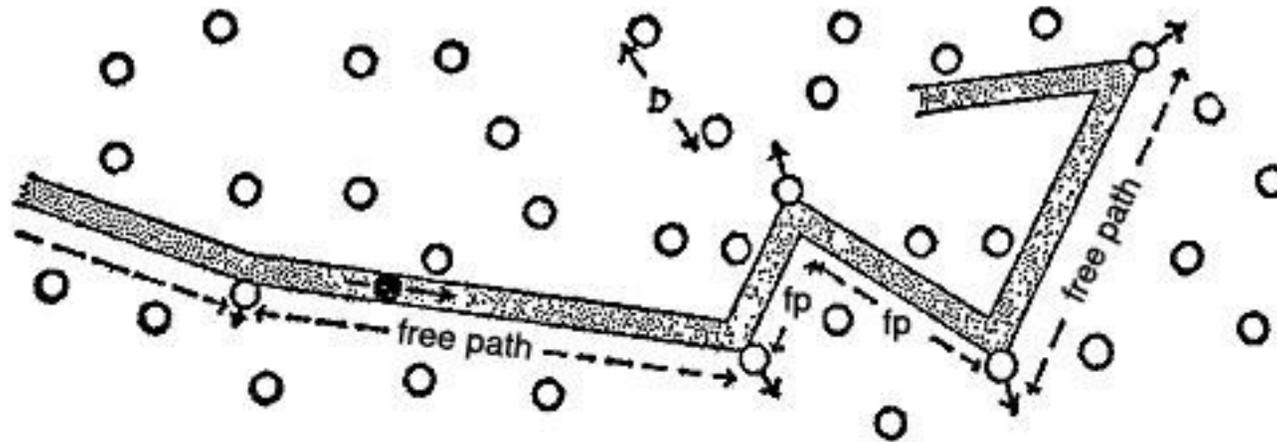
*Neither the energy distribution nor the average energy of the gas is a function of the molecular mass. They ONLY depend on temperature !*



# Mean Free Path



**The mean free path is the average distance that a gas molecule can travel before colliding with another gas molecule.**



Mean free path of a gas molecule

*Mean Free Path is determined by:  
size of molecules, density (thus pressure and temperature)*

# Mean Free Path Equation



$$\lambda = \frac{1}{\sqrt{2}\pi d_0^2 n} = \frac{kT}{\sqrt{2}\pi d_0^2 P}$$

$\lambda$  - mean free path (m)

$d_0$  - diameter of molecule (m)

$n$  - Molecular density ( $m^{-3}$ )

$T$  - Temperature (Kelvin)

$P$  - Pressure (Pascal)

$k$  - Boltzmann constant,  $1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$



# Mean Free Path – Air @ 22°C



$$\lambda(\text{cm}) = \frac{0.67}{P(\text{Pa})} = \frac{0.005}{P(\text{Torr})}$$

P (torr)	760	1	10 <sup>-3</sup>	10 <sup>-6</sup>	10 <sup>-9</sup>
$\lambda$ (cm)	6.6x10 <sup>-6</sup>	5.1x10 <sup>-3</sup>	5.1	5100	5.1x10 <sup>6</sup>

For air, average molecular diameter = 3.74 x10<sup>-8</sup> cm



# Properties of Some Gases at R.T.



Properties	H <sub>2</sub>	He	CH <sub>4</sub>	Air	O <sub>2</sub>	Ar	CO <sub>2</sub>
$v_{avg}$ (m/s)	1776	1256	628	467	444	397	379
$d_0$ (10 <sup>-10</sup> m)	2.75	2.18	4.19	3.74	3.64	3.67	4.65
$\lambda_{atm}$ (10 <sup>-8</sup> m)	12.2	19.4	5.24	6.58	6.94	6.83	4.25
$\omega_{atm}$ (10 <sup>10</sup> s <sup>-1</sup> )	1.46	0.65	1.20	0.71	0.64	0.58	0.89

→  $v_{avg}$  : mean velocity

→  $d_0$  : molecular/atomic diameter

→  $\lambda_{atm}$  : mean free length at atmosphere pressure

→  $\omega_{atm}$  : mean collision rate,  $\omega_{atm} = v_{avg} / \lambda_{atm}$

# Particle Flux

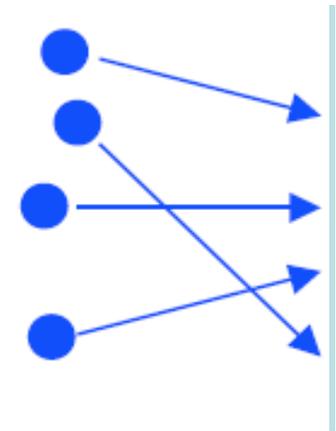


*Particle Flux - rate of gas striking a surface or an imaginary plane of unit area*

*Kinetic theory shows the flux as:*

$$\Gamma(m^{-2} \cdot s^{-1}) = \frac{1}{4} n v_{avg} = n \sqrt{\frac{kT}{2\pi m}}$$

*where  $n$  is the gas density*



*Particle flux is helpful in understanding gas flow, pumping, adsorption and desorption processes.*

# Particle Flux - Examples



P	n	Particle Flux ( $\text{m}^{-2}\cdot\text{s}^{-1}$ )				
(torr)	$\text{m}^{-3}$	$\text{H}_2$	$\text{H}_2\text{O}$	$\text{CO}/\text{N}_2$	$\text{CO}_2$	Kr
760	$2.5 \times 10^{25}$	$1.1 \times 10^{28}$	$3.6 \times 10^{27}$	$2.9 \times 10^{27}$	$2.3 \times 10^{27}$	$1.7 \times 10^{27}$
$10^{-6}$	$3.2 \times 10^{16}$	$1.4 \times 10^{19}$	$4.8 \times 10^{18}$	$3.8 \times 10^{18}$	$3.1 \times 10^{18}$	$2.2 \times 10^{18}$
$10^{-9}$	$3.2 \times 10^{13}$	$1.4 \times 10^{16}$	$4.8 \times 10^{15}$	$3.8 \times 10^{15}$	$3.1 \times 10^{15}$	$2.2 \times 10^{15}$

*Typical atomic density on a solid surface:  $5.0 \sim 12.0 \times 10^{18} \text{ m}^{-2}$   
 Thus monolayer formation time at  $10^{-6}$  torr:  $\sim 1\text{-sec}$ !*

*A commonly used exposure unit: 1 Langmuir =  $10^6$  torr·sec*

# The Ideal Gas Law



→  $\nu$  molecules striking a unit area, with projected velocity of  $v_z$  exert an impulse, or pressure, of:

$$P = 2m \sum v_z \cdot \nu$$

→ Integrate over all velocity, based on kinetics,

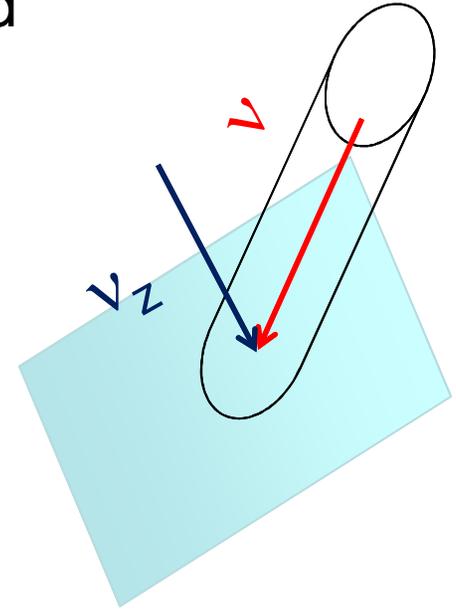
$$P = \frac{1}{3} nm v_{rms}^2 \quad (A)$$

→ The average kinetic energy of a gas is:

$$E = \frac{1}{2} m v_{rms}^2 = \frac{3}{2} kT \quad (B)$$

→ Equations (A) and (B) results in ***the Ideal Gas Law***:

$$P = nkT$$



# Gas Laws



## *Charles' Law*

*Volume vs. temperature*

## *Boyle's Law*

*Pressure vs. Volume*

## *Avogadro's Law*

*Volume vs. Number of molecules*

*All these laws derivable from the Ideal Gas Law  
They apply to all molecules and atoms, regardless of their sizes*



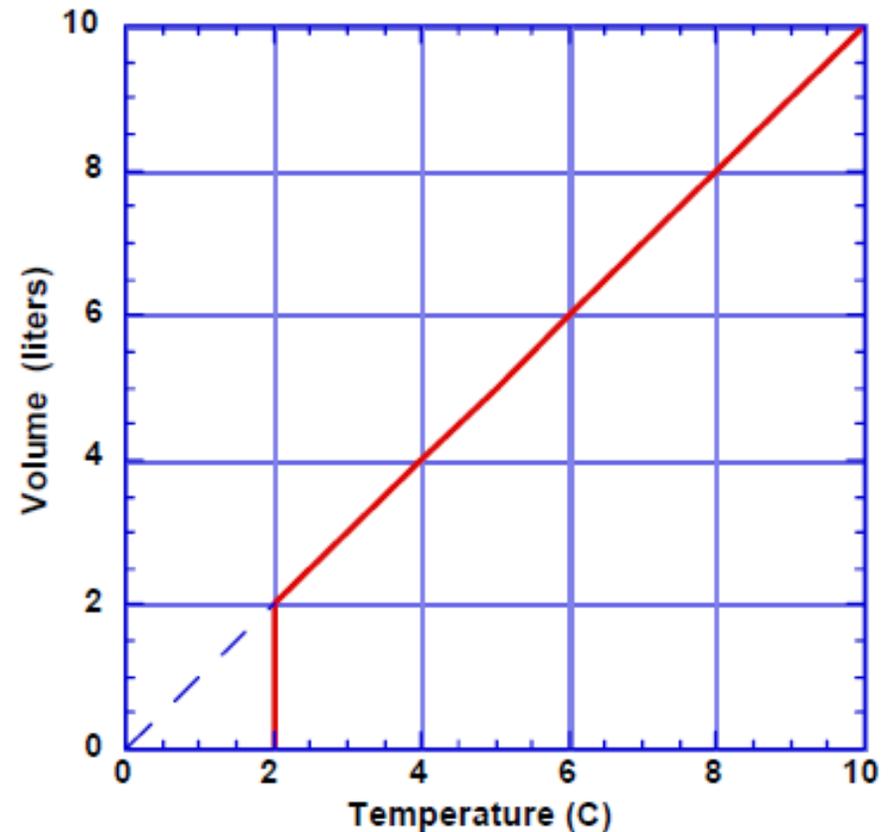
# Charles' Law



The volume of a fixed amount of gas at a fixed pressure will vary proportionally with absolute temperature.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

*(N, P Constant)*



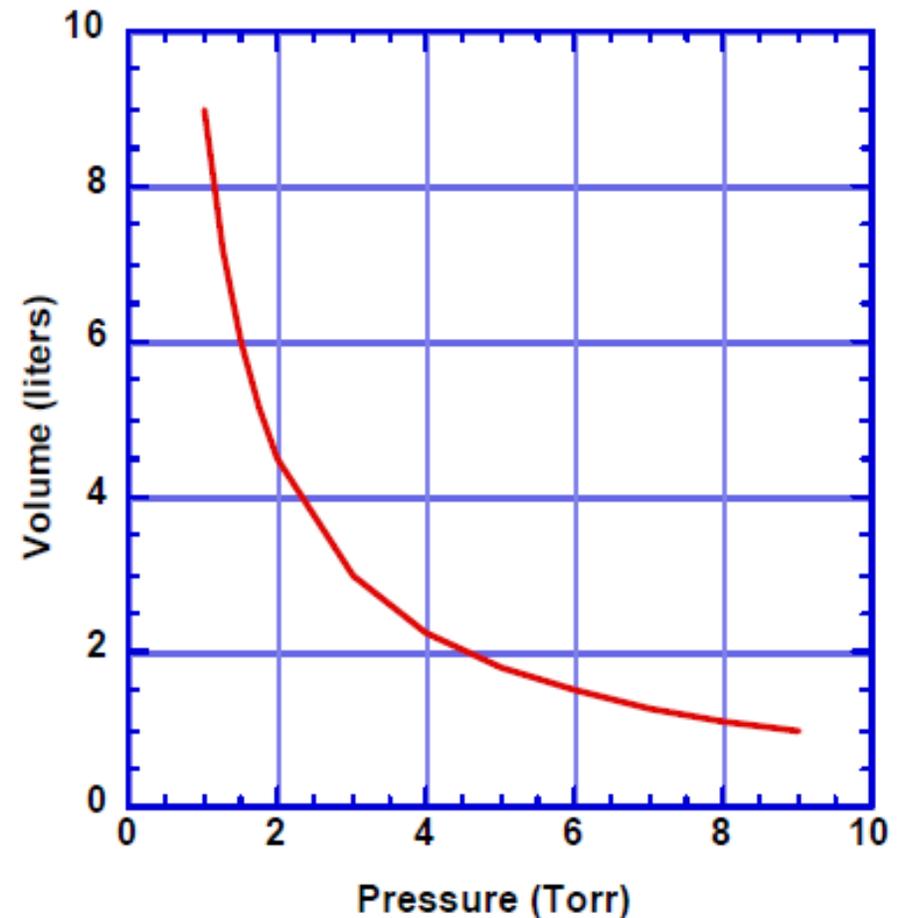
# Boyle's Law



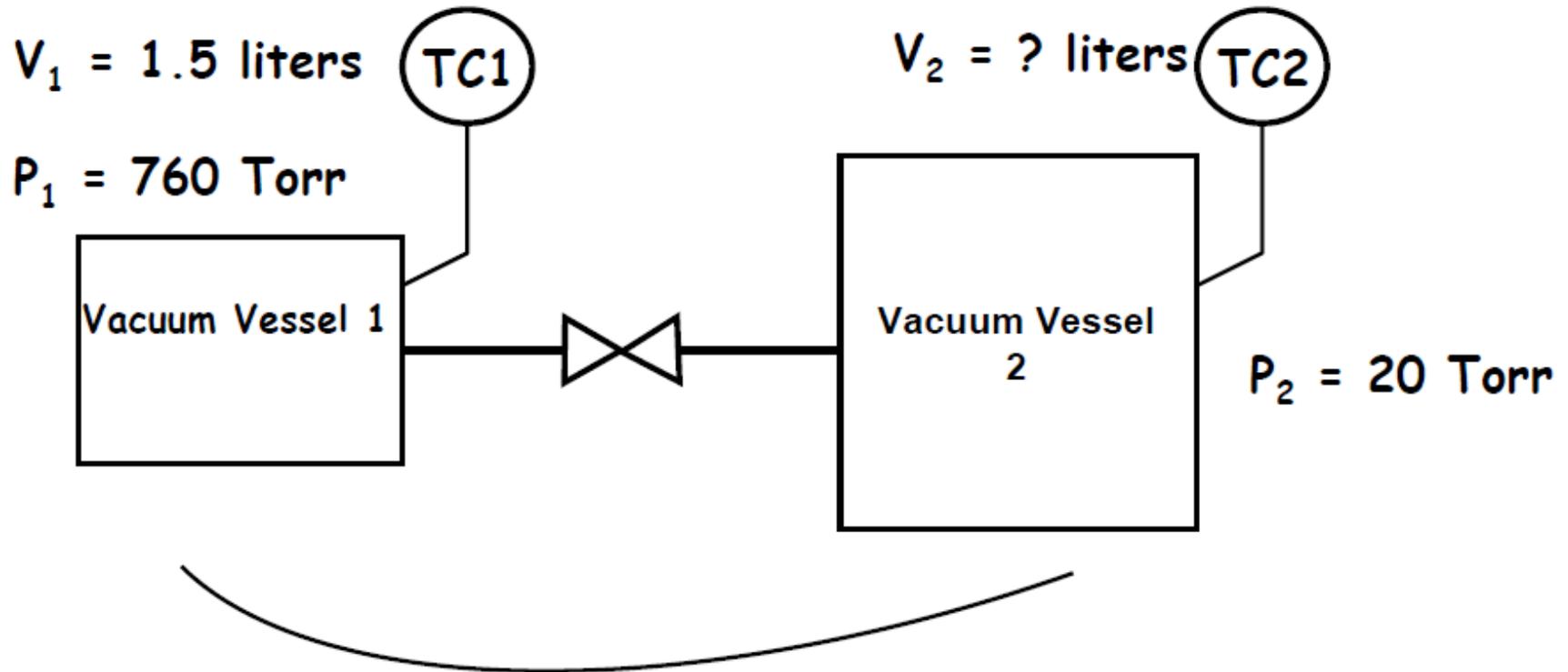
For a fixed amount of gas at a fixed temperature, its pressure is inversely proportional to its volume.

$$P_1V_1 = P_2V_2$$

*(N, T Constant)*



# Finding volume of a vessel with Boyle's Law



*Boyle's Law can also be used to expand gauge calibration range via expansion*

# Avogadro's Law



*Equal volumes of gases at the same temperature and pressure contain the same number of molecules regardless of their chemical nature and physical properties*

$$\frac{V_1}{N_1} = \frac{V_2}{N_2} \quad (P, T \text{ Constant})$$

At **S**tandard **T**emperature and **P**ressure (STP, 0°C at 1 atmosphere), a mole has a volume of  $V_o$ , and contains  $N_o$  molecules and atoms:

$$N_o = 6.02214 \times 10^{23} \text{ mol}^{-1}$$

$$V_o = 6.02214129(27) \times 10^{23} \text{ mol}^{-1}$$



# Avogadro's Number



At **S**tandard **T**emperature and **P**ressure (**STP**, 0°C at 1 atmosphere), a mole of ideal gas has a volume of  $V_0$ , and contains  $N_0$  molecules and atoms:

$$N_0 = 6.02214 \times 10^{23} \text{ mol}^{-1}$$

$$V_0 = 22.414 \text{ L/mol}$$

*Definition of mole:*

*the number of atoms of exact 12-gram of Carbon-12*

# Partial Pressure - The Dalton's Law



*The total pressure exerted by the mixture of non-reactive gases equals to the sum of the partial pressures of individual gases*

$$P_{total} = p_1 + p_2 + \dots + p_n$$

*where  $p_1, p_2, \dots, p_n$  represent the partial pressure of each component.*

*Applying the Ideal Gas Law:*

$$P_{total} = (n_1 + n_2 + \dots + n_n)kT$$



# Elementary Gas Transport Phenomena



→ *Viscosity - molecular momentum transfer, depending on density, velocity, mass and mean free path*

$$\eta = 0.499nmv\lambda \quad (\text{Pa-s in SI})$$

→ *Thermal Conductivity - molecular energy transfer*

$$K = \frac{1}{4}(9\gamma - 5)\eta c_v \quad (\text{W/m-K in SI})$$

where  $\gamma = c_p/c_v$ ,  $c_p$ , and  $c_v$  are specific heat in a **constant pressure** and a **constant volume** process, respectively.

$$\gamma = 1.667 \text{ (atoms)}; \quad \gamma \approx 1.40 \text{ (diatomic)}; \quad \gamma \approx 1.31 \text{ (triatomic)}$$





---

# *Gas Flows*



# Gas Flow Regimes - Knudsen Number



The flow of gases in a vacuum system is divided into three regimes. These regimes are defined by specific value ranges of a dimensionless parameter, known as the **Knudsen Number,  $K_n$**

$$K_n = \frac{\lambda}{a}$$

← Mean free path

← Characteristic dimension of flow channel (for example, a pipe diameter)



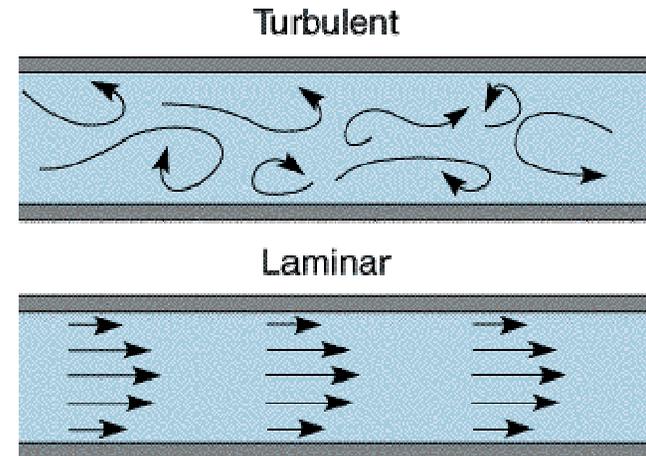
# Three Gas Flow Regimes



→ *Viscous Flow:*

Characterized by  
molecule-molecule  
collisions

$$K_n = \frac{\lambda}{a} < 0.01$$

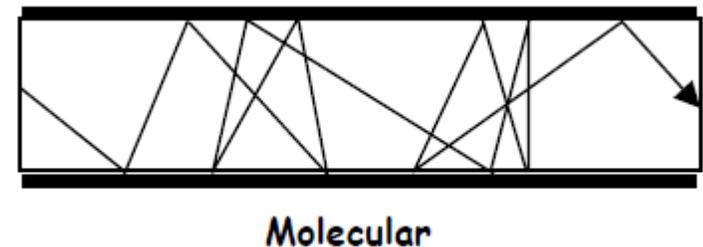


→ *Transition Flow:*  $0.01 < K_n < 1.0$

→ *Molecular Flow:*

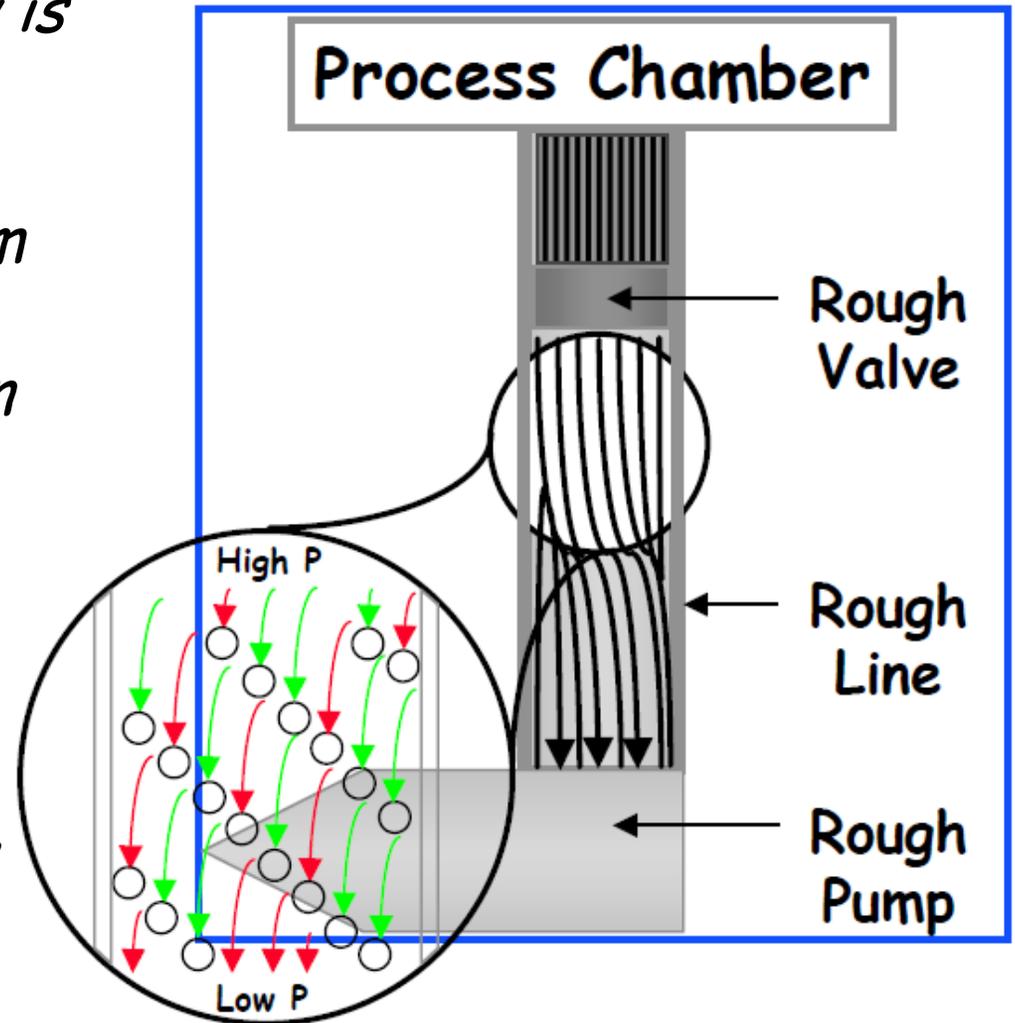
Characterized by  
molecule-wall  
collisions

$$K_n > 1.0$$



# Viscous (or Continuum) Flow

- The character of the flow is determined by gas-gas collisions
- Molecules travel in uniform motion toward lower pressure, molecular motion 'against' flow direction unlikely
- The flow can be either *turbulent* or *laminar*, characterized by another dimensionless number, the *Reynolds' number,  $R$*



# Viscous Flow - Reynolds' Number



$$R = \frac{U \rho d}{\eta}$$

*U* - stream velocity

$\rho$  - gas density

*d* - pipe diameter

$\eta$  - viscosity

→ *Laminar Flow: zero flow velocity at wall*

$$R < 1200$$

→ *Turbulent Flow: eddies at wall and strong mixing*

$$R > 2200$$

# Throughput



*Throughput is defined as the quantity of gas flow rate, that is, the volume of gas at a known pressure passing a plane in a known time*

$$Q = \frac{d(PV)}{dt}$$

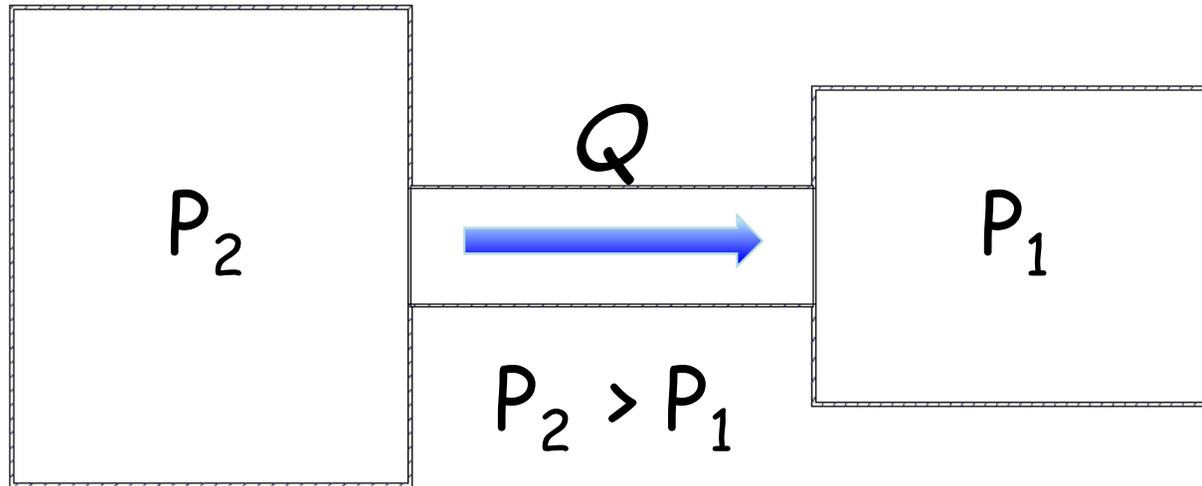
*In SI unit,  $[Q] = \text{Pa}\cdot\text{m}^3/\text{s}$  ( $= 7.5 \text{ torr}\cdot\text{liter}/\text{s}$ )*

*Interesting Point:*

$$\text{Pa}\cdot\text{m}^3/\text{s} = \text{N}\cdot\text{m}/\text{s} = \text{J}/\text{s} = \text{Watt}!$$



# Gas Conductance - Definition



- The flow of gas in a duct or pipe depends on the pressure differential, as well on the connection geometry
- The gas conductance of the connection is defined:

$$C = \frac{Q}{P_2 - P_1}$$

In SI unit:  $m^3/s$

Commonly used:  $liter/s$

$1-m^3/s = 1000-liter/s$



# Vacuum Pump - Pumping Speed



- *Defined as a measure of volumetric displacement rate, ( $m^3/sec$ , cu-ft/min, liter/sec, etc.)*

$$S = \frac{dV}{dt}$$

- *The throughput of a vacuum pump is related the pressure at the pump inlet as:*

$$Q = P \cdot \frac{dV}{dt} = P \cdot S$$

# Gas Conductance - Continuum Flow



- *Viscous flow is usually encountered during vacuum system roughing down processes.*
- *Gas flow in the viscous flow regime is very complicated. A great amount of theoretic works can be found in the literatures on the subject.*
- *Depending the value of Reynolds' number, the flow can be either laminar or turbulent.*
- *Turbulent flow is usually to be avoided (by 'throttling'), to reduce contamination (to the upstream system), and to reduce vibration.*

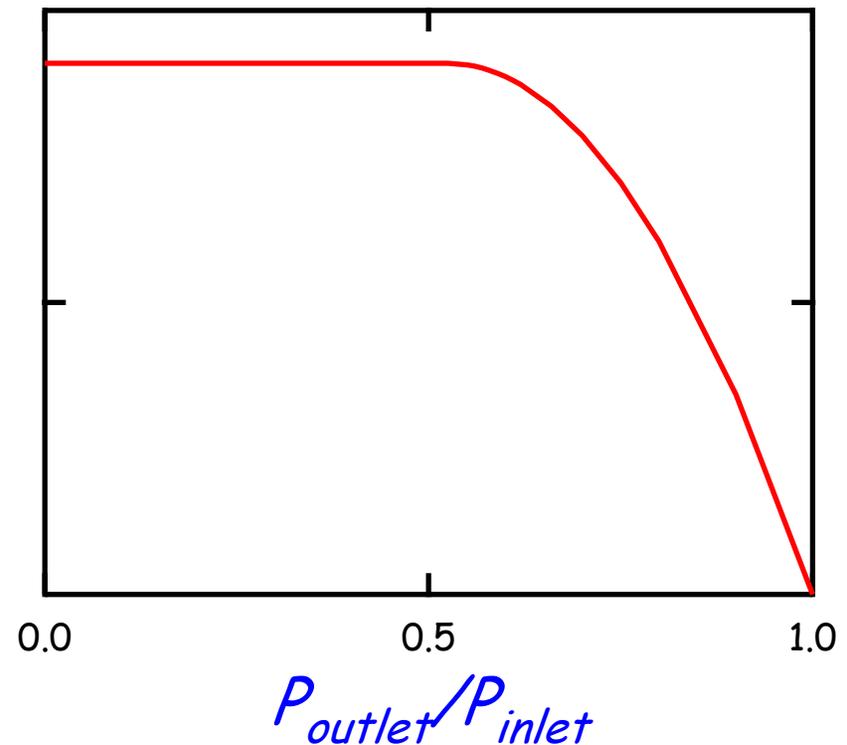
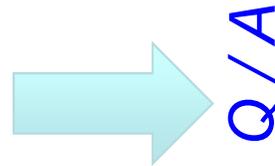


# Gas Conductance - Continuum Flow (2)



- The gas throughput (and conductance) is dependent on both the 'inlet' pressure and the 'outlet' pressure in most situations, and (of course) on the piping geometry.
- The flow usually increases with reduced outlet pressure, but will be "choked" when the gas stream speed exceeds the speed of sound.

Flow  
through  
an thin  
orifice



# Molecular Flow - Orifices

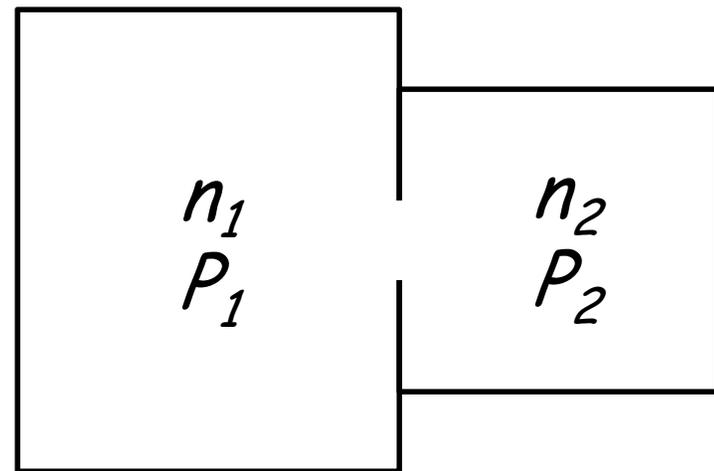


*If two large vessels are connected by an thin orifice of opening area  $A$ , then gas flow from vessel 1 to vessel 2 is given by the particle flux exchange:*

$$Q = \frac{kT}{4} v A (n_1 - n_2) = \frac{v}{4} A (P_1 - P_2)$$

*From definition of the conductance:*

$$C = \frac{Q}{P_1 - P_2} = \frac{v}{4} A$$



# Molecular Flow - Orifices (2)



With:  $v = \sqrt{8kT/\pi m}$

We have:

$$C_{\text{Orifice}} (m^3 / s) = 36.24 \sqrt{\frac{T}{M_{\text{amu}}}} A (m^2)$$

where:  $T$  is temperature in Kelvin;  $M_{\text{amu}}$  is molecular mass in atomic mass unit

For air ( $M_{\text{amu}}=28.97$ ) at  $22^\circ\text{C}$ :

$$C (m^3/s) = 116 A (m^2)$$

Or:

$$C (L/s) = 11.6 A (cm^2)$$



# Molecular Flow - Long Round Tube



$$C = \frac{\pi}{12} v \frac{d^3}{l} = 37.94 \sqrt{\frac{T}{M_{amu}}} \frac{d^3}{l}$$

where  $T$  is the temperature in Kelvin,  $M$  the molecular mass in AMU,  $d$  and  $l$  are diameter and length of the tube in meter, with  $l \gg d$

For air ( $M_{amu}=28.97$ ) at 22°C:

$$C(m^3 / s) = 121 \frac{d^3}{l}$$



# Molecular Flow - Short Tube



No analytical formula for the short pipe conductance. But for a pipe of constant cross section, it is common to introduce a parameter called *transmission probability,  $a$* , so that:

$$C = aC_{\text{Orifice}} = a \frac{v}{4} A$$

where  $A$  is the area of the pipe cross section.

For long round tube, the transmission probability is:

$$a_{\text{long\_tube}} = \frac{4d}{3l}$$

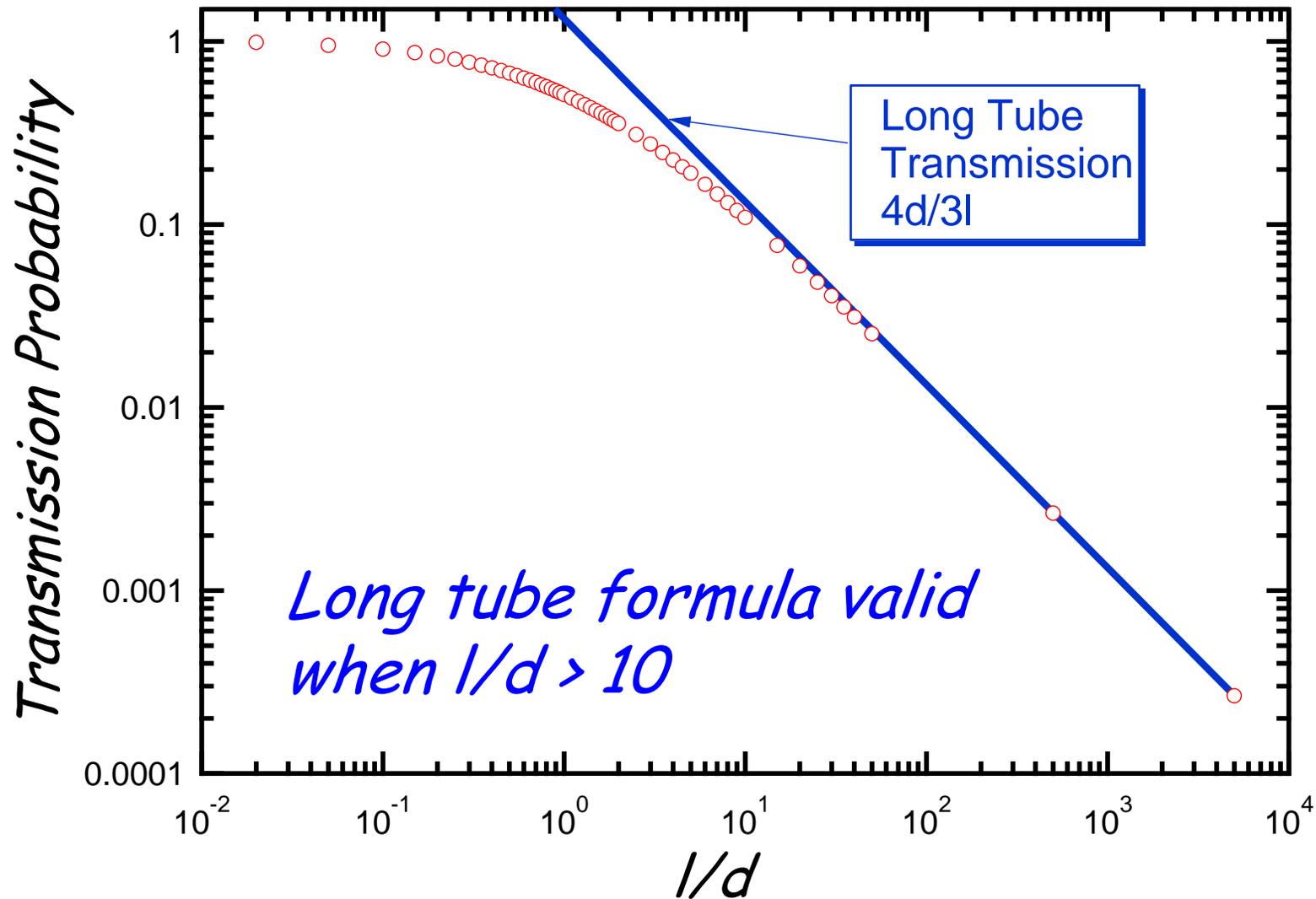
# Molecular Flow - Transmission of Round Tube



$l/d$	$a$	$l/d$	$a$	$l/d$	$a$
0.00	1.00000	0.9	0.53898	5.0	0.19099
0.05	0.95240	1.0	0.51423	6.0	0.16596
0.10	0.90922	1.1	0.49185	7.0	0.14684
0.15	0.86993	1.2	0.47149	8.0	0.13175
0.20	0.83408	1.3	0.45289	9.0	0.11951
0.25	0.80127	1.4	0.43581	10	0.10938
0.30	0.77115	1.5	0.42006	15	0.07699
0.35	0.74341	1.6	0.40548	20	0.05949
0.40	0.71779	1.8	0.37935	25	0.04851
0.45	0.69404	2.0	0.35658	30	0.04097
0.50	0.69178	2.5	0.31054	35	0.03546
0.55	0.65143	3.0	0.27546	40	0.03127
0.60	0.63223	3.5	0.24776	50	0.02529
0.70	0.59737	4.0	0.22530	500	$2.65 \times 10^{-2}$
0.80	0.56655	4.5	0.20669	5000	$2.66 \times 10^{-3}$



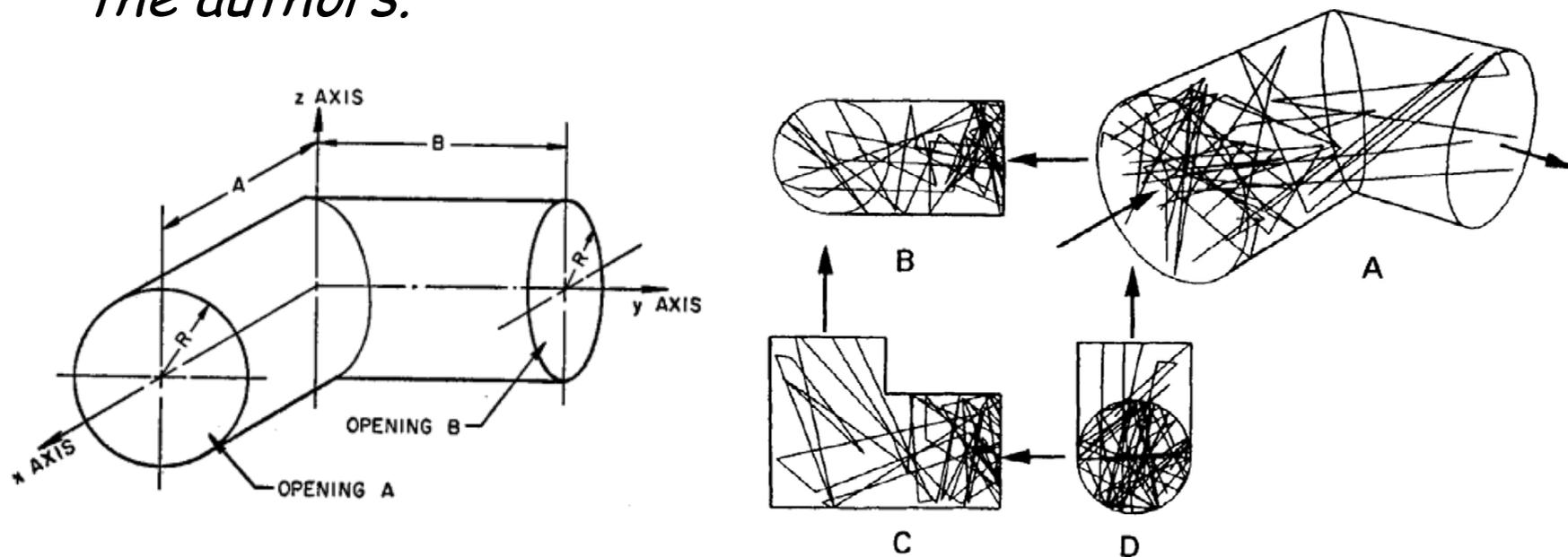
# Molecular Flow - Transmission of Round Tube



# Monte Carlo Test Particle Calculations



- Monte Carlo (MC) statistic method is often used to calculate complex, but practical vacuum components, such as elbows, baffles, traps, etc.
- In MC calculations, large number of test particles 'injected' at entrance, and tracked through the geometry.
- One of such MC packages, MOLFLOW is available through the authors.



# Combining Molecular Conductances

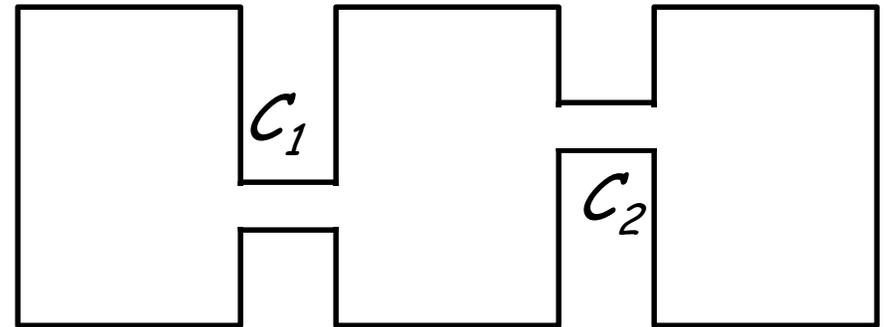


- The conductance of tubes connected in parallel can be obtained from simple sum, and is independent of any end effects.

$$C_T = C_1 + C_2 + C_3 + \dots + C_n$$

- Series conductances of *truly independent* elements can be calculated:

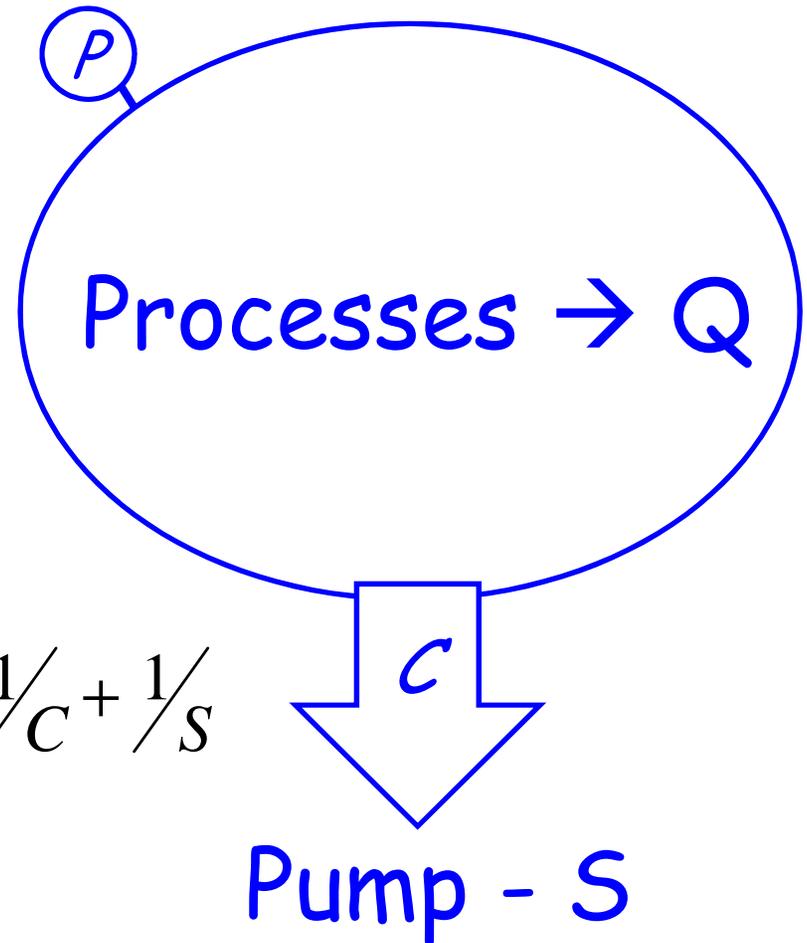
$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_N}$$



*The series elements must be separated by large volumes, so that the molecular flow is re-randomized before entering next element*

# A Generic Vacuum System

- A vacuum system consists of chamber(s), pipes and ducts, to enable desired process.
- A certain vacuum level (working pressure,  $P$ ) is specified.
- Both the chamber materials and the process produces gases,  $Q$ .
- Vacuum pump with pumping speed  $S$  is installed via a conductance ( $C$ ) to achieve the required vacuum level.



$$P = \frac{Q}{S_{eff}}$$

$$\frac{1}{S_{eff}} = \frac{1}{C} + \frac{1}{S}$$

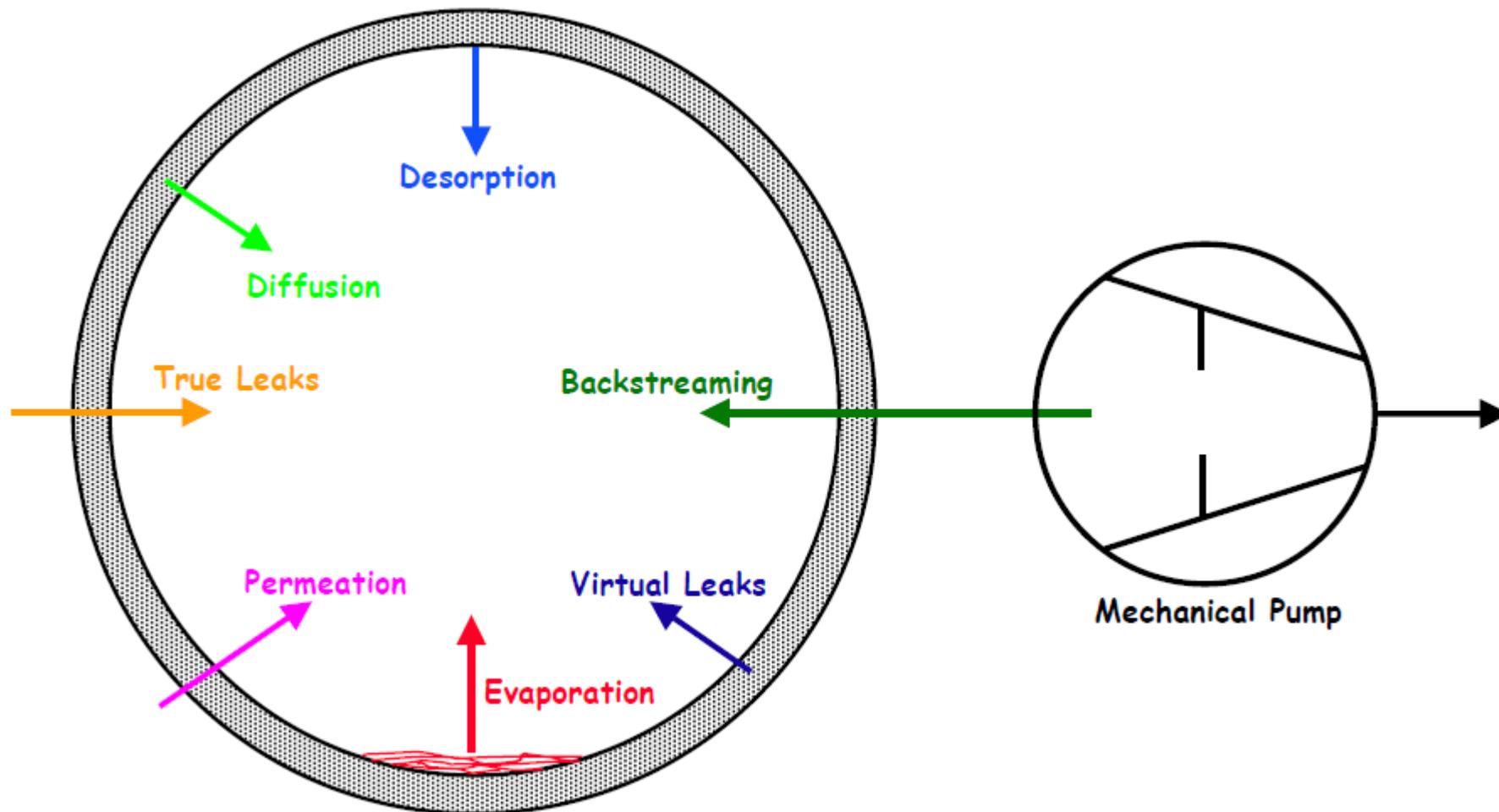


---

# *Sources of Gases in Vacuum Systems*



# "Static" Gas Loads



# "Static" Gas Loads - Leaks



True Leaks are steady-state gas loads, which limit the ultimate pressure of a vacuum system.

There are two categories of leaks in a vacuum system:

1. **External Leaks or True Leaks** ( $Q_{Lt}$ )

$Q_{Lt} > 10^{-5}$  Torr-liter/sec      laminar flow leak

$Q_{Lt} < 10^{-8}$  Torr-liter/sec      molecular flow leak

Ref. "Vacuum Technology and Space Simulation",  
Santeler et al, NASA SP-105, 1966



# "Static" Gas Loads - Leaks



## 2. Internal Leaks or Virtual Leaks ( $Q_{LV}$ )

$$Q_{LV} = \frac{P_a V}{et}$$

where  $Q_{LV}$  = gasload due to virtual leak (Torr-liters/sec)

$P_a$  = pressure of trapped gas (Torr)

$V$  = volume of trapped gas (liters)

$e$  = 2.7183 base to natural logarithm

$t$  = time (sec)

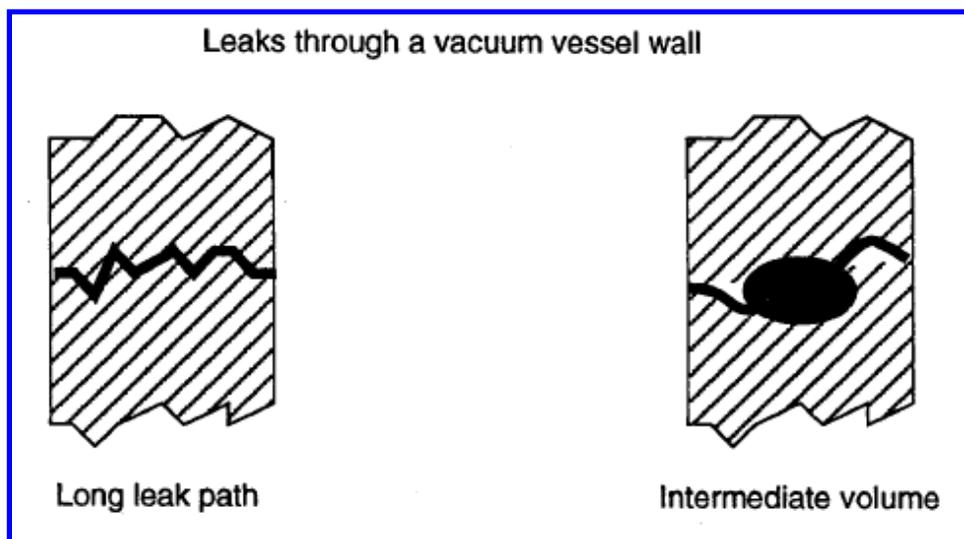
Ref. "Vacuum Technology and Space Simulation", Santeler et al, NASA SP-105, 1966



# Examples of True Leaks

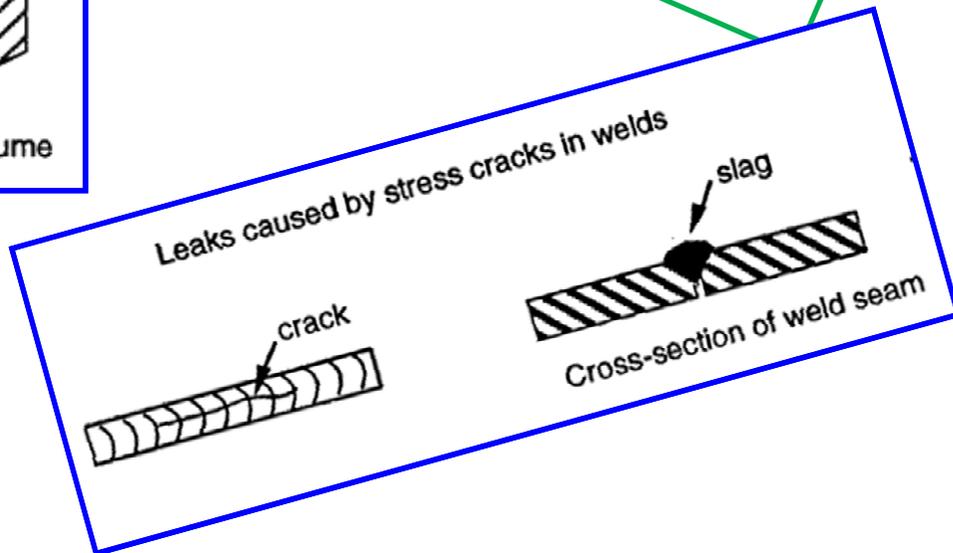


**Real leak** → physical hole or crack in vessel wall, and/or faulty joint allowing gas to enter the vessel



Improper seating of gaskets, etc.

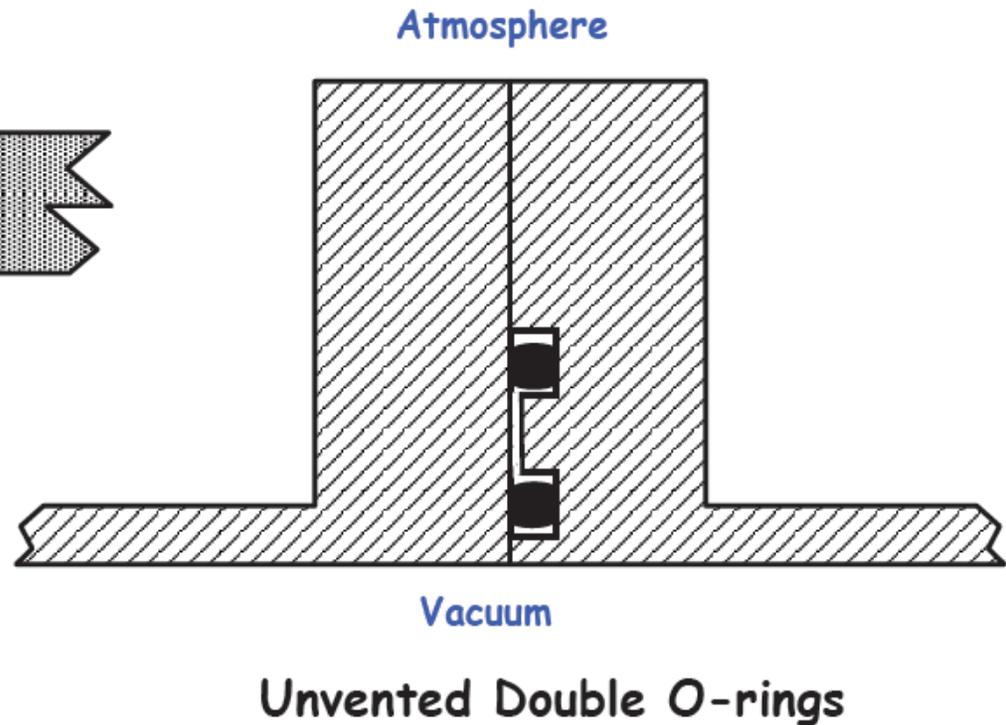
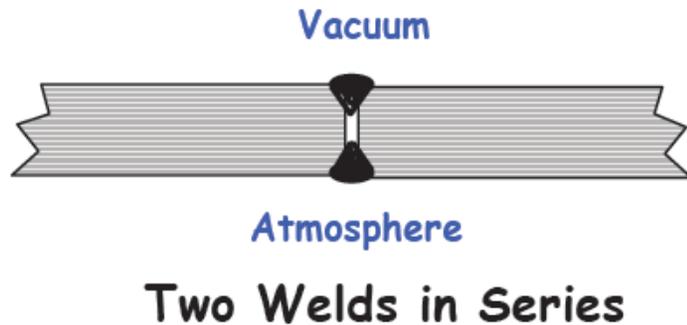
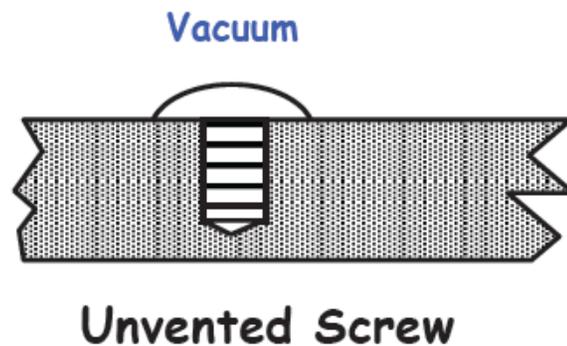
Scratch sealing surfaces, or rolled/nicked knife-edge, etc.



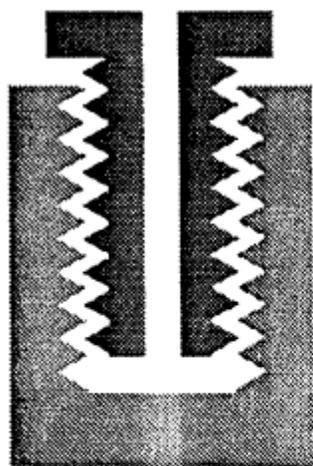
# Examples of Virtue Leaks



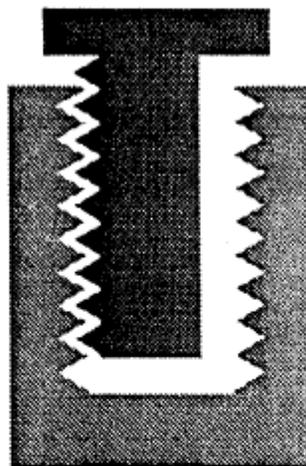
**Virtue leak** → A virtual leak is a volume of trapped atmospheric gas that leaks into the vacuum vessel through holes or cracks that do not go all the way through the vessel wall



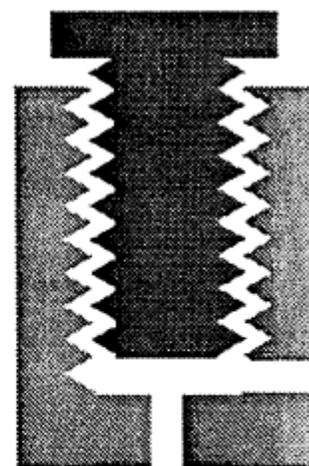
# Venting the blind holes



Drill Thru-Hole  
In Screw



Grind Flat Side  
On Screw



Drill Vent Holes  
In Piece

*Center-vented and edge slot-vented UHV ready fasteners are readily available for most commonly sizes*



# Evaporation



$$Q_E = 3.639 \sqrt{\frac{T}{M}} (P_E - P) A$$

where  $Q_E$  = gas-load due to evaporation (Torr-liter/sec)  
 $T$  = Temperature (K)  
 $M$  = molecular weight (grams/mole)  
 $P_E$  = vapor pressure of material at the temperature  
 $P$  = Partial pressure of evaporating molecules  
 $A$  = surface area of evaporating material (cm<sup>2</sup>)

*Material vapor pressure ( $P_E$ ) is a strongly dependent on temperature  $T$*

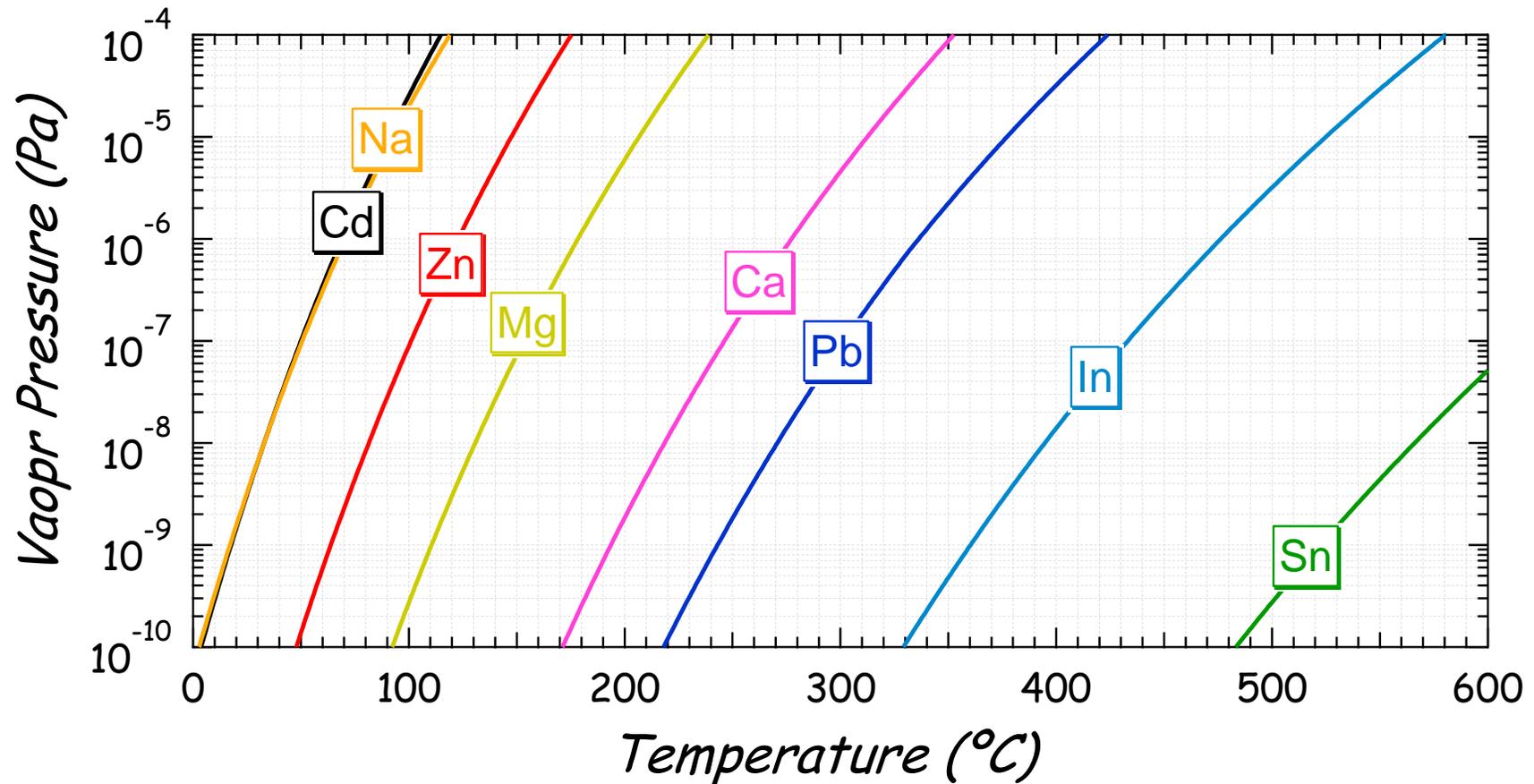


# Vapor Pressure - Antoine Equation



$$\log_{10} P_E = A - \frac{B}{C + T}$$

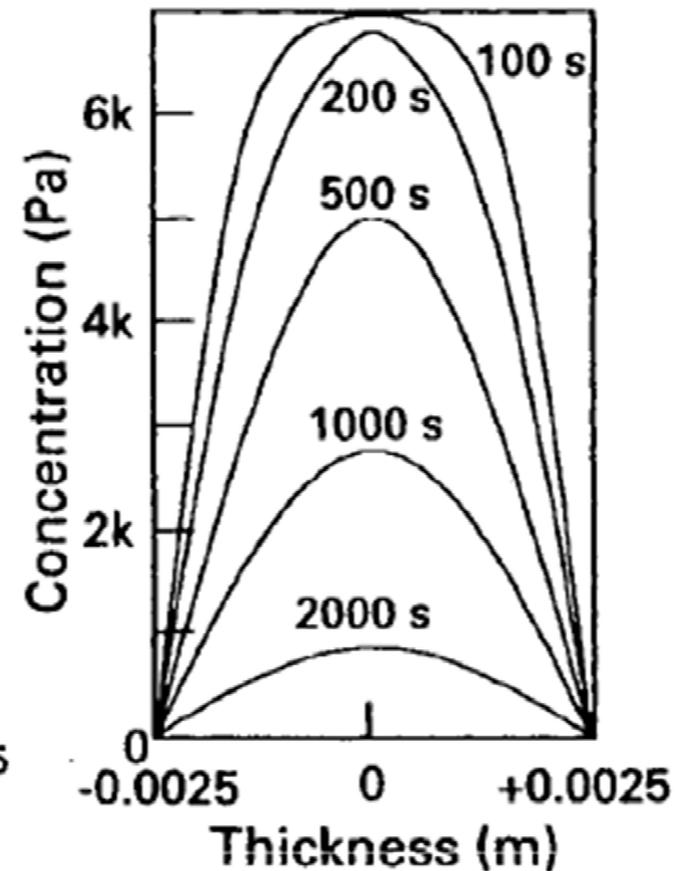
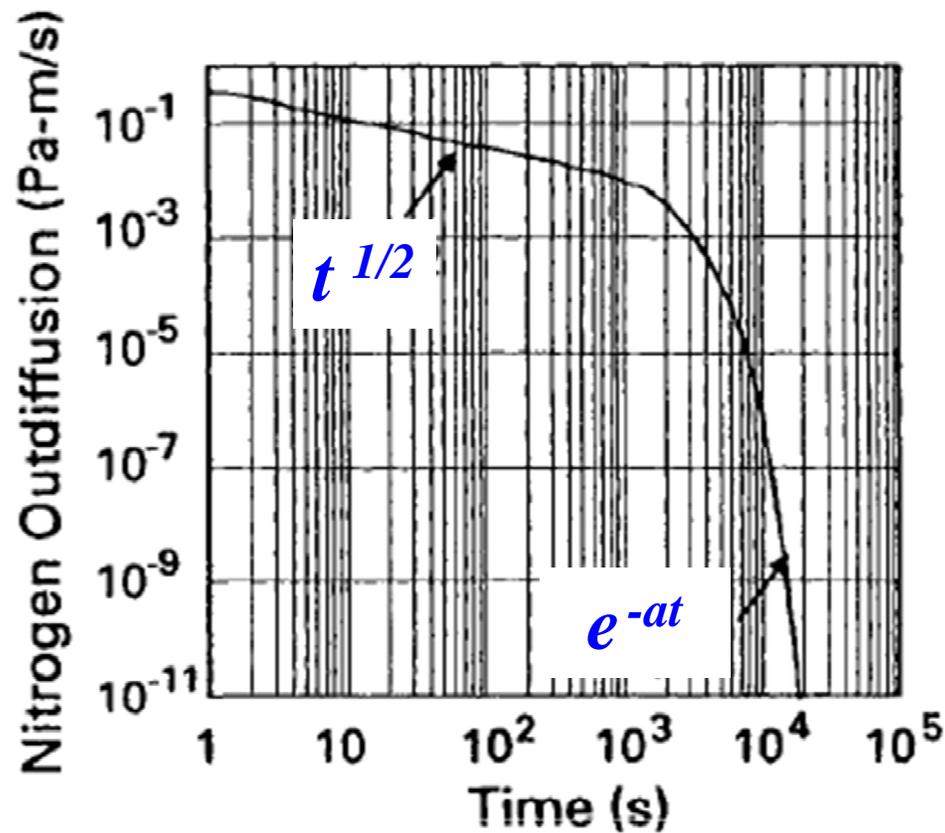
*Coefficients A, B, C are measured for finite temperature ranges*



# Diffusion from Solid



*Diffusion: Transport of gas dissolved in the solid to the interior wall of a vacuum system and followed by desorption.*



# Thermal Desorption (Outgassing)



*Heat-stimulated release of gases or vapors adsorbed on chamber walls (from exposure to environment, or reached inner surfaces by diffusion within.*

- **Physisorption** - molecules bonded weakly to the surfaces by van der Waals forces, with typical bonding energy  $< 50$  kJ/mole (0.5 eV). Most condensed gases (such as top layers of water molecules) are physisorption in nature.
- **Chemisorption** - molecules bonded to surfaces at much higher energies are chemisorbed.



# Thermal Desorption Dynamics (Science)



- *Zero-order desorption - from multi-layer of molecules. This is equivalent to evaporation, with a constant rate:*

$$\frac{dn}{dt} = K_0 e^{-\frac{E_v}{kT}}$$

- *First-order desorption - when less than a monolayer, non-dissociative desorption. An exponential dependence rate of desorption is predicted:*

$$\frac{dn}{dt} = n_0 K_1 e^{-\frac{t}{\tau}}$$

- *Second-order desorption - diatomic molecules desorption, such as hydrogen on metal surfaces with recombination prior to the desorption:*

$$\frac{dn}{dt} = \frac{-K_2 n_0^2}{(1 + n_0 K_2 t)^2}$$

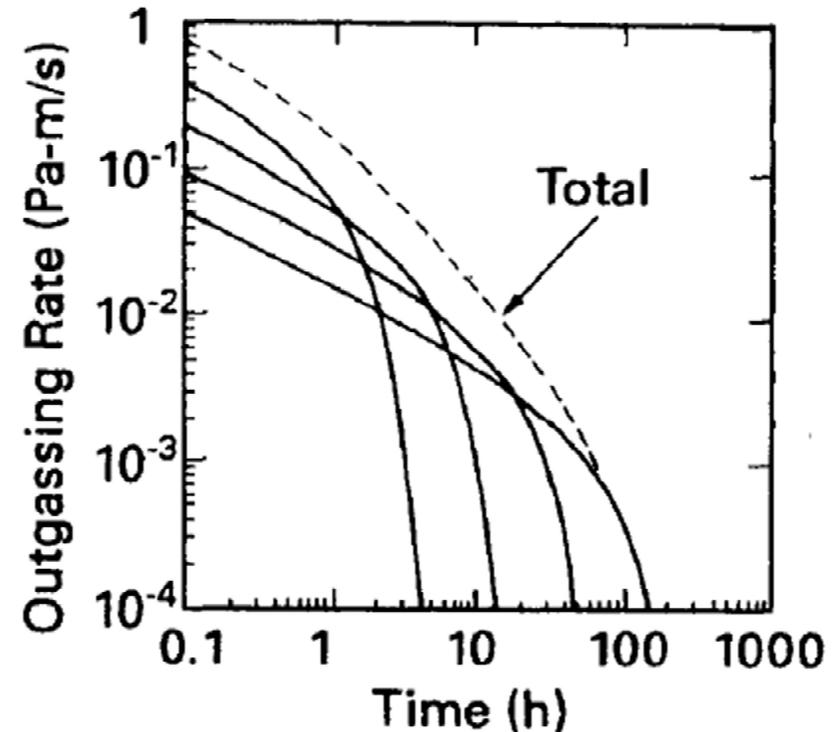
# Thermal Desorption - Real Surfaces



→ In most real vacuum systems, the observed thermal outgassing rate usually varies as:

$$q_n = \frac{q_o}{t^{\alpha_n}}$$

with  $\alpha_n = 0.5 \sim 2.0$ , while  $\alpha_n \sim 1$  commonly measured.



→ The  $t^{-\alpha_n}$  trend has been explained as a result of averaging over desorptions from multiple surface bonding states



# Reduction of Outgassing by Bakeout



- *It is well known that bakeout of a vacuum system can significantly reduce the thermal outgassing.*
- *The baking temperature should be sufficiently high to overcome the binding energy of adsorbed molecules on surfaces. For example,  $>120^{\circ}\text{C}$  is needed for removing adsorbed  $\text{H}_2\text{O}$  on most metal surfaces.*
- *When baking vacuum system, it is imperative that all surfaces be baked. Any cold surfaces (even a small portion of) will contribute exceedingly large gas flux.*
- *For many UHV system, high-temperature firing of material (especially stainless steels) is proven to reduce dissolved gas in bulk, thus significantly reduce out-diffusion time and thermal outgassing*



# Measuring Outgassing Rate - Why

---



- *Though there are massive amount published outgassing rate data for most commonly used metallic and dielectric materials, these data should be taken with caution.*
- *In most accelerators, specialty materials (insulators, RF absorbing tiles, etc.) are used at unusual conditions.*



# Measuring Outgassing Rate

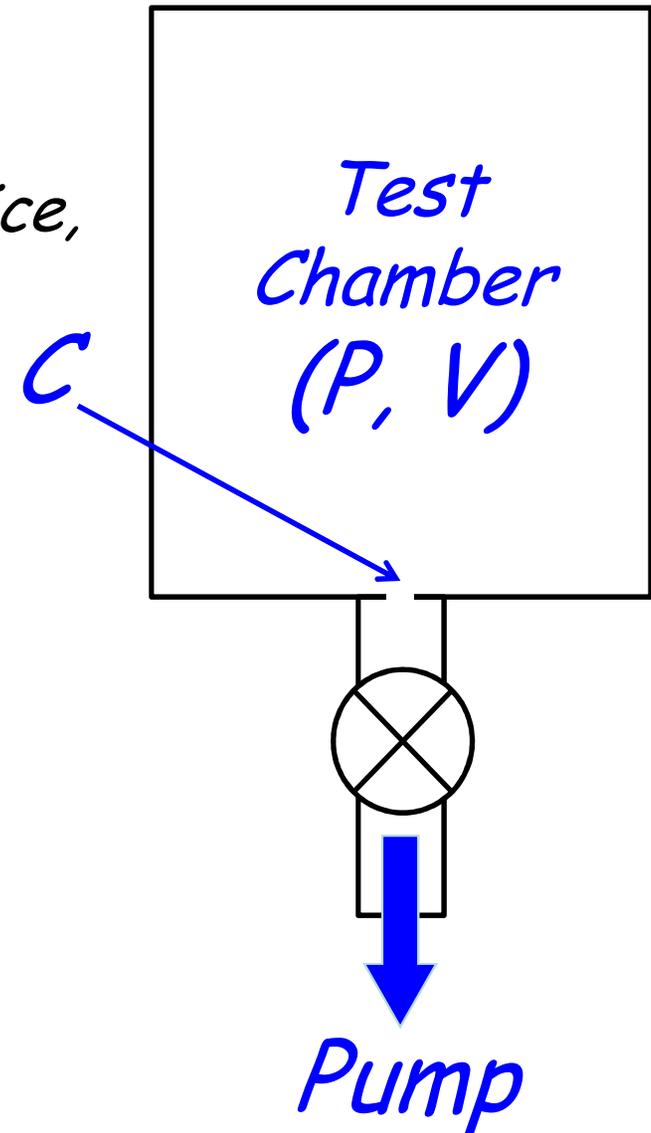


- *Throughput method - Gas from test samples or chamber flow through a defined conductance, usually an orifice, to a vacuum pump*

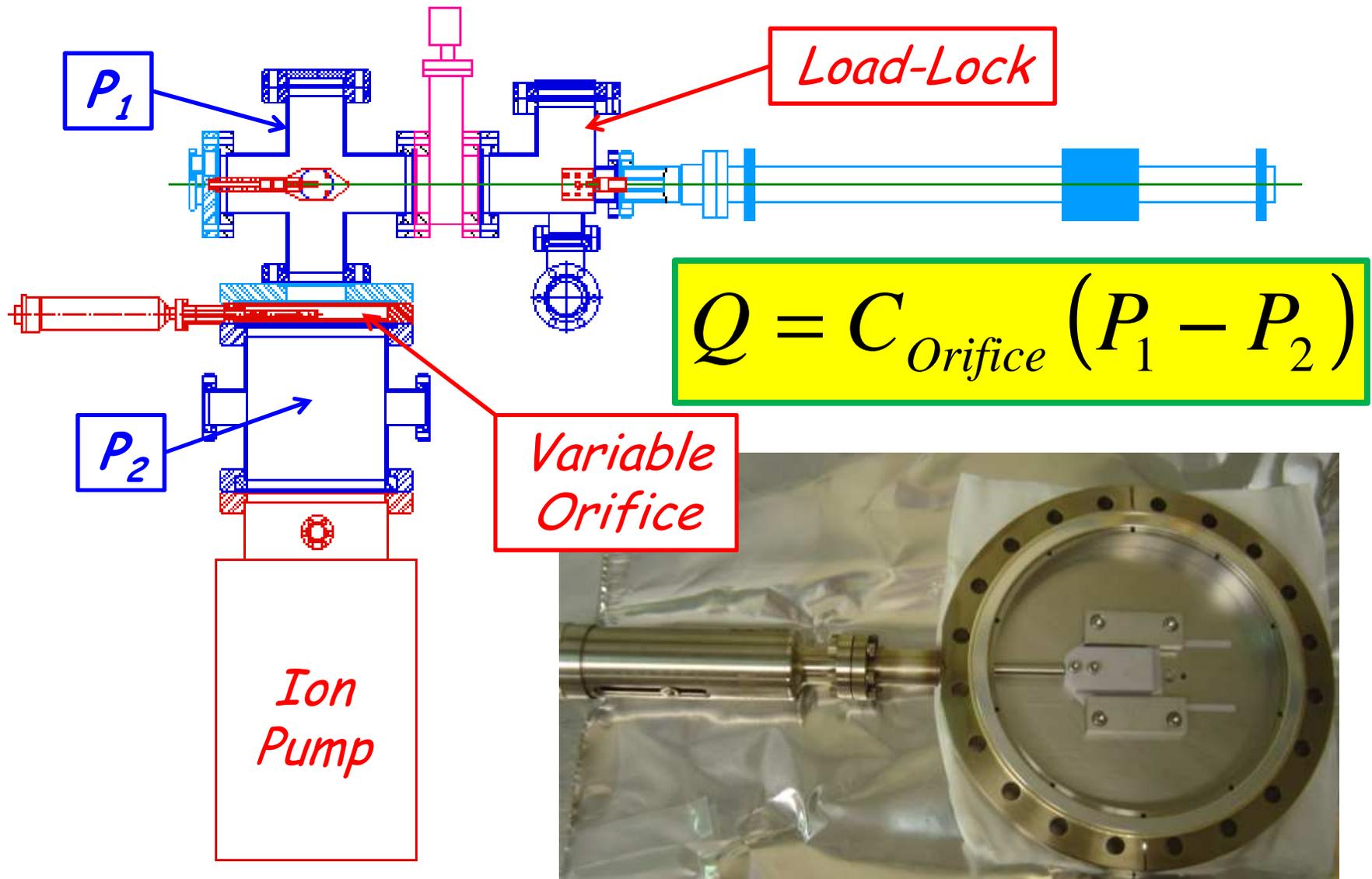
$$q = \frac{C \cdot P(t)}{A}$$

- *Rate-of-rise method - Seal off test chamber to allow pressure build-up*

$$q = \frac{V}{A} \left( \frac{\Delta P}{\Delta t} \right)$$



# Load-Locked Outgas Setup @ CLASSE



# Some Unbaked Metal Outgassing Rates



<i>Material</i>	$q_1$ ( $10^{-7}$ Pa-m/s)	$\alpha_1$	$q_{10}$ ( $10^{-7}$ Pa-m/s)	$\alpha_{10}$
<i>Aluminum (Fresh)</i>	83	1.0	4.3	0.9
<i>Aluminum (anodized)</i>	3679	0.9	429	0.9
<i>Copper OFHC (fresh)</i>	251	1.3	4.8	1.0
<i>Copper OFHC (polished)</i>	25	1.1	2.2	1.0
<i>Stainless Steel</i>	192	1.3	18	1.9
<i>Titanium</i>	53	1.0	4.9	1.0

*Ref - A Schram, Le Vide, No. 103, 55 (1963)*

*Note - There are wide spread of outgassing data for similar materials*

$$q_n = \frac{q_o}{t^{\alpha_n}} \quad n - \text{hours of pumping}$$



# Outgassing Rates of Baked Metals



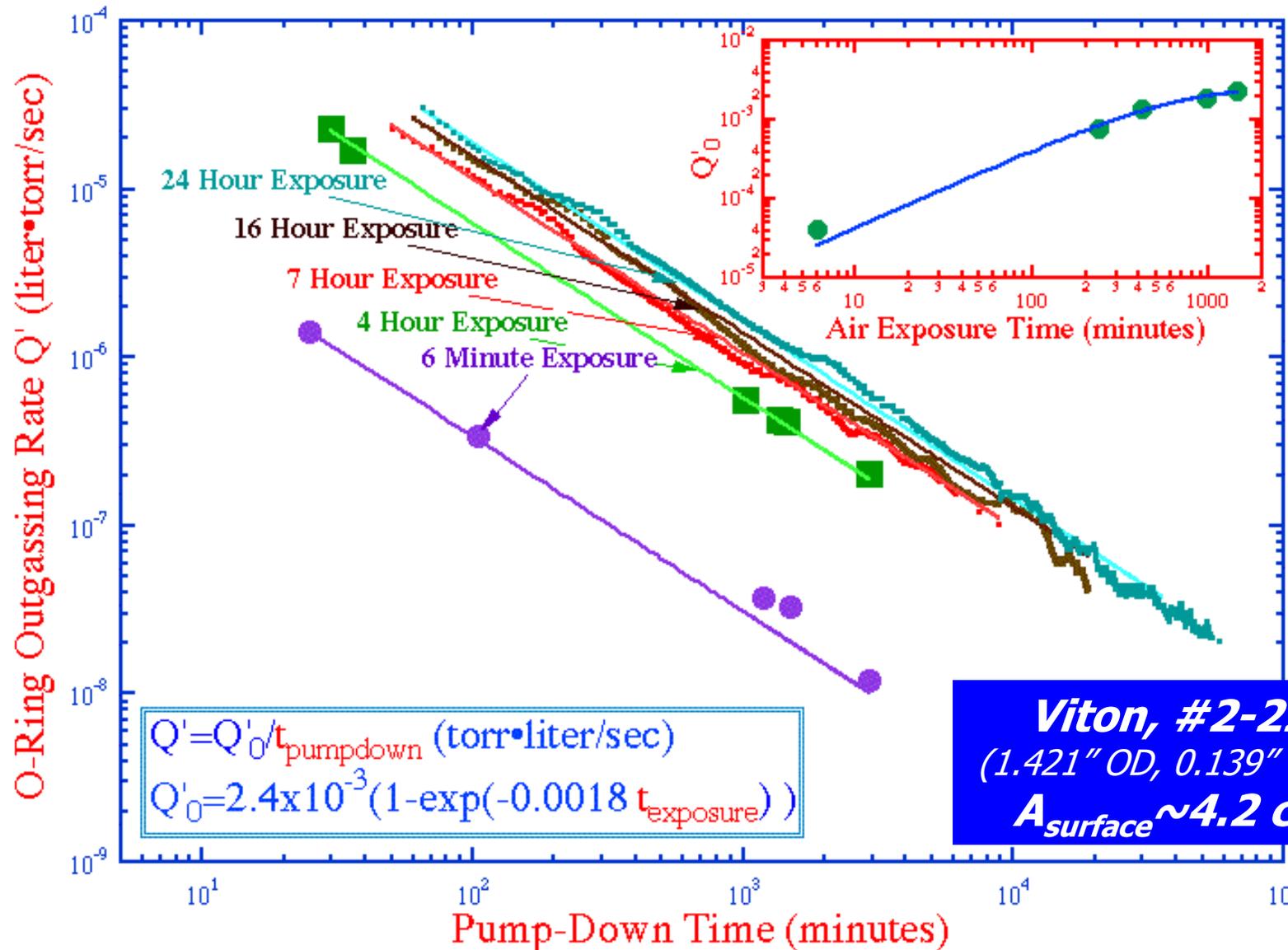
<i>Material</i>	<i>Treatment</i>	<i>q</i> <i>(10<sup>-11</sup> Pa-m/s)</i>
<i>Aluminum</i>	<i>15-h bake at 250°C</i>	<i>53</i>
<i>Aluminum</i>	<i>20-h at 100°C</i>	<i>5.3</i>
<i>6061 Aluminum</i>	<i>Glow discharge + 200°C bake</i>	<i>1.3</i>
<i>Copper (OFHC)</i>	<i>24-h bake at 100°C</i>	<i>2.9</i>
	<i>24-h bake at 250°C</i>	<i>0.18</i>
<i>304 Stn. Stl</i>	<i>20-h bake at 250°C</i>	<i>400</i>
	<i>2-h 850/900°C vacuum firing</i>	<i>27</i>

*From: J. O'Hanlon, "A User's Guide to Vacuum Technology", 3<sup>rd</sup> Ed.,  
Appendix C.1*

# Example - Measured O-Ring Outgassing



## Viton O-Ring Outgassing vs. Air Exposure Time



LNSLY\_SCSID/VAC R&D:O-RingOutgassing:O-Ring\_Outgassing\_0803:Graph(O\_Ring\_Outgas\_data)

# Permeation

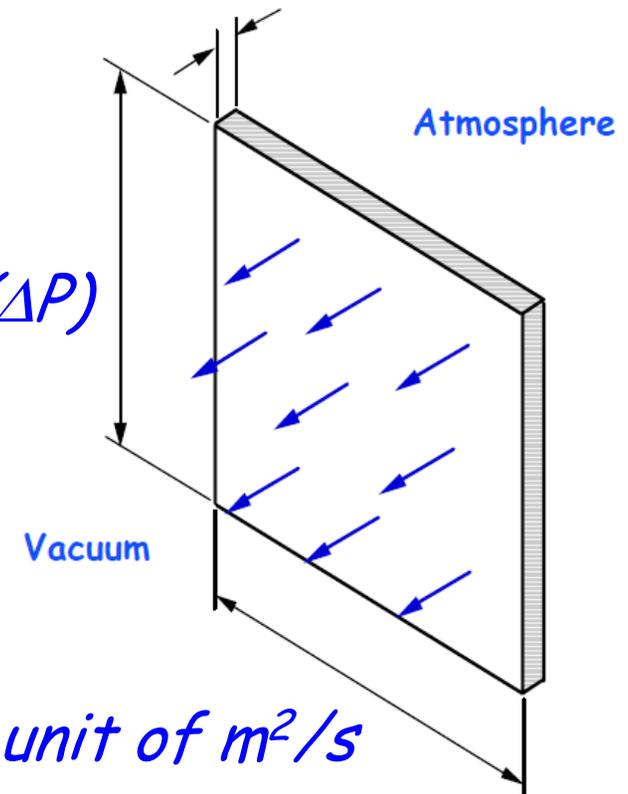


Permeation is a three step process. Gas first adsorbs on the outer wall of a vacuum vessel, diffuses through the bulk, and lastly desorbs from the interior wall.

## Factors influence permeation rate:

- ❖ Material combination
- ❖ Temperature
- ❖ Permeation thickness ( $d$ )
- ❖ Gas type and pressure differential ( $\Delta P$ )

$$Q_p = q_p A = \frac{K_p \Delta P}{d} A$$



In SI, the permeation constant  $K_p$  has a unit of  $m^2/s$

# Permeation - O-Rings



$$Q_p = 0.7FD(\Delta P) K(1 - S)^2$$

- where
- Q = leak rate (std cc/sec)
  - F = permeability rate for a specific gas through a specific elastomer at a specific temperature (std cc-cm/cm<sup>2</sup> sec bar)
  - D = o-ring dia. (in)
  - ΔP = pressure differential across o-ring (psi)
  - K = factor depending on % squeeze and lubrication (see next slide)
  - S = % squeeze

Ref. Parker O-ring Handbook

*Permeability rates of various gases for many commercial polymers are tabulated in Parker O-Ring Handbook.*



# Example Calculation of O-ring Permeability



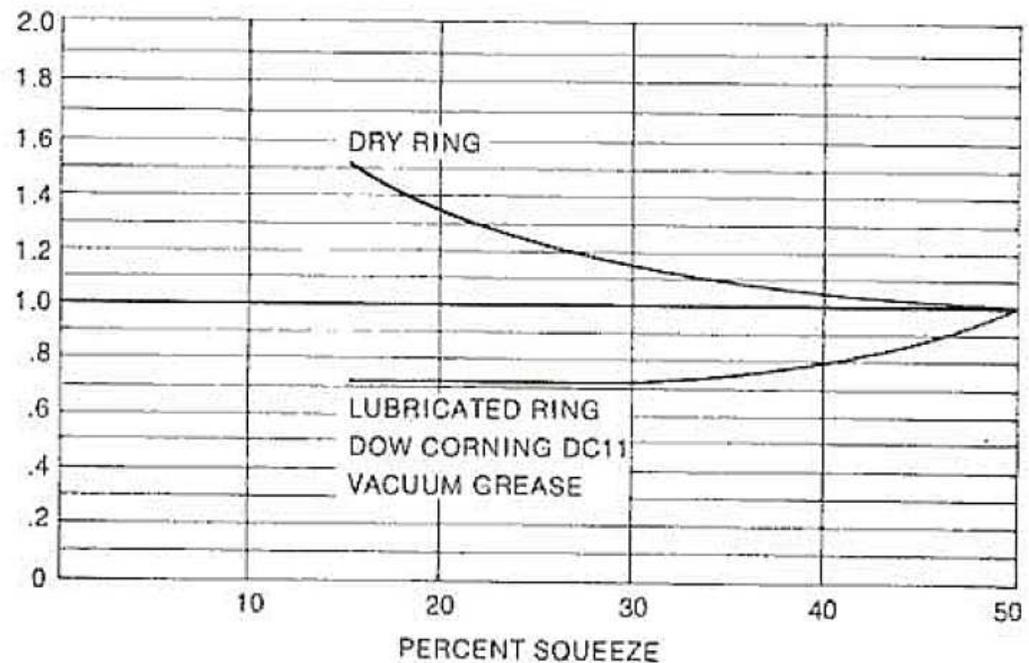
What is the approximate He and N<sub>2</sub> permeability rates through a 10" diameter Viton O-ring (no lubrication, with a 20% squeeze) at a  $\Delta p = 14.7$  psi?

$D=10''$ ,  $K=1.35$  (see insert),  $S=0.20$

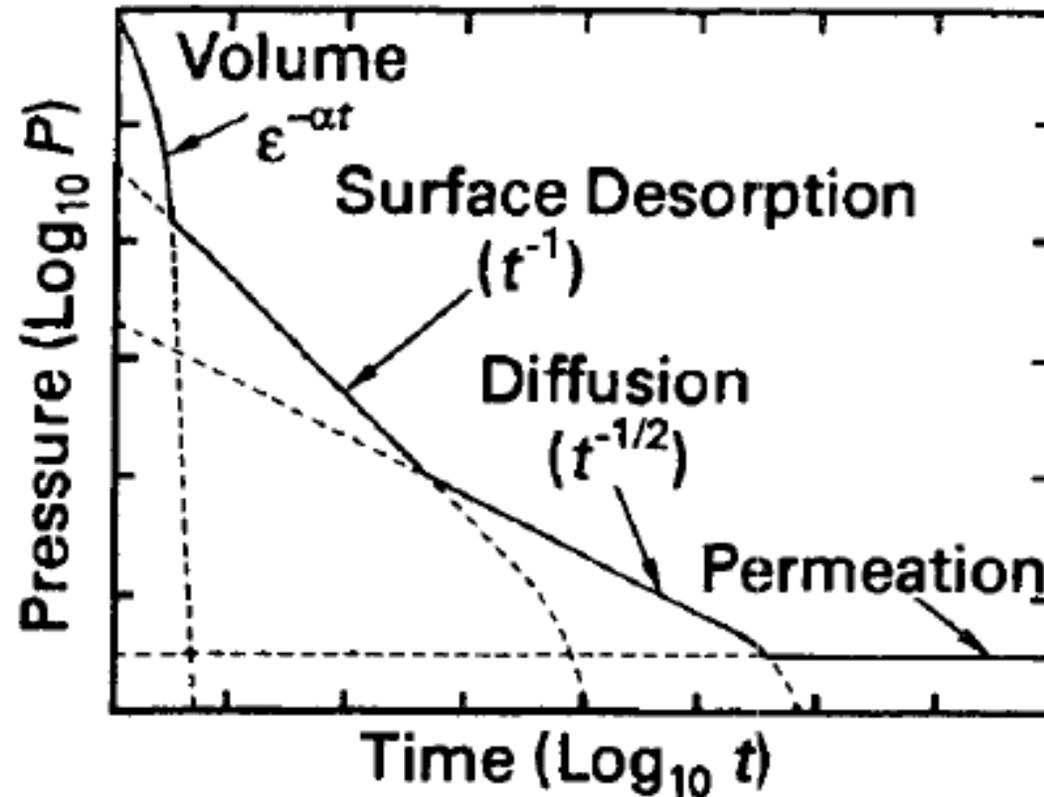
$F_{He}=13.0 \times 10^{-8}$ ;  $F_{N_2}=3.0 \times 10^{-8}$  (std.cc/cm<sup>2</sup>-sec-bar)

$$Q_{He} = 1.2 \times 10^{-5} \text{ std.cc/s} \\ = 8.8 \times 10^{-6} \text{ torr-l/s}_K$$

$$Q_{N_2} = 1.6 \times 10^{-7} \text{ torr-l/s}$$



# Ultimate Pressure (Static)



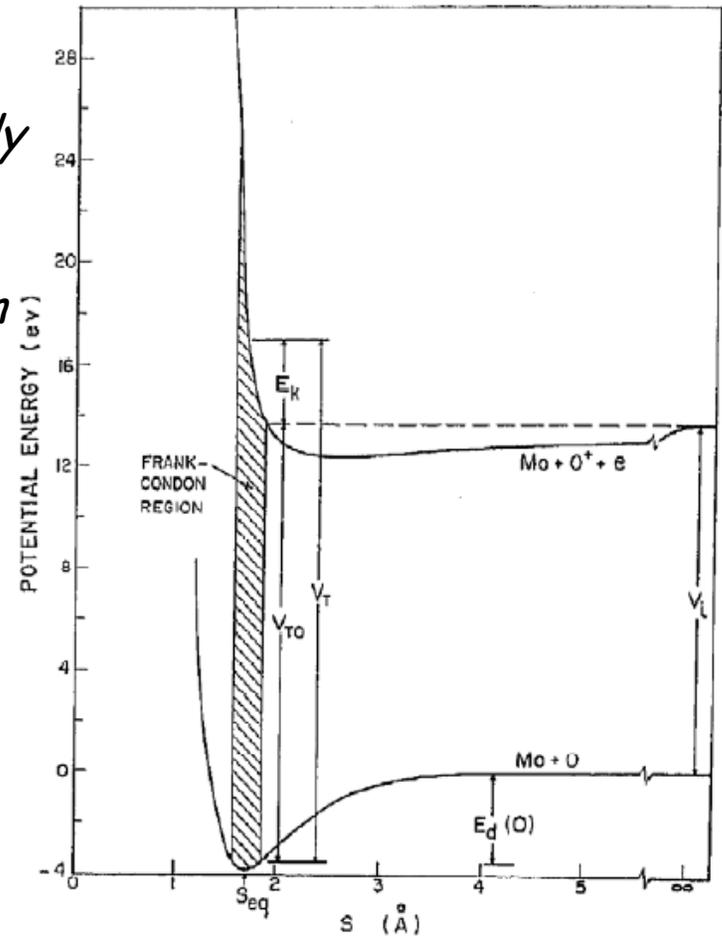
$$P = P_o e^{-S \cdot t / V} + \frac{Q_{thermal}}{S} + \frac{Q_{Diffusion}}{S} + \frac{Q_{Permeation}}{S}$$



# Induced Desorptions - Dynamic Gas Load



- In particle accelerators, energized particles (ions, electrons and photons) may impinge on vacuum vessel interior walls, and induce desorption of adsorbed molecules. In most cases, these dynamic gas loads are dominate.
- Two possible mechanisms:
  - Direct 'knock-out' via impact. This is usually for physisorbed multilayer molecules and atoms
  - Desorption induced by electronic transition (DIET), where a binding electron of the chemisorbed molecule is excited in an anti-bonding state.
- There is a desorption energy threshold of  $\sim 10$  eV
- Desorbed species are dominated by neutral atoms and molecules, with only a fraction ( $10^{-2} \sim 10^{-4}$ ) of ions.



# Induced Desorptions - Parameters



- *Desorption Yield - number of desorbed molecules ( $N_m$ ) of a given gas species per incident particle ( $N_i$ ):*

$$\eta = \frac{N_m}{N_i}$$

- *The yield measurement often requires dedicated setup, in order to quantify both the desorbed molecules and the incident particle flux.*

- *"Conditioning"- the yield of induced desorption usually decreases with accumulated dose ( $D_i$ ) of the particles as:*

$$\eta = \eta_0 D_i^{-\alpha}$$



# *Ion Induced Desorption (IID)*

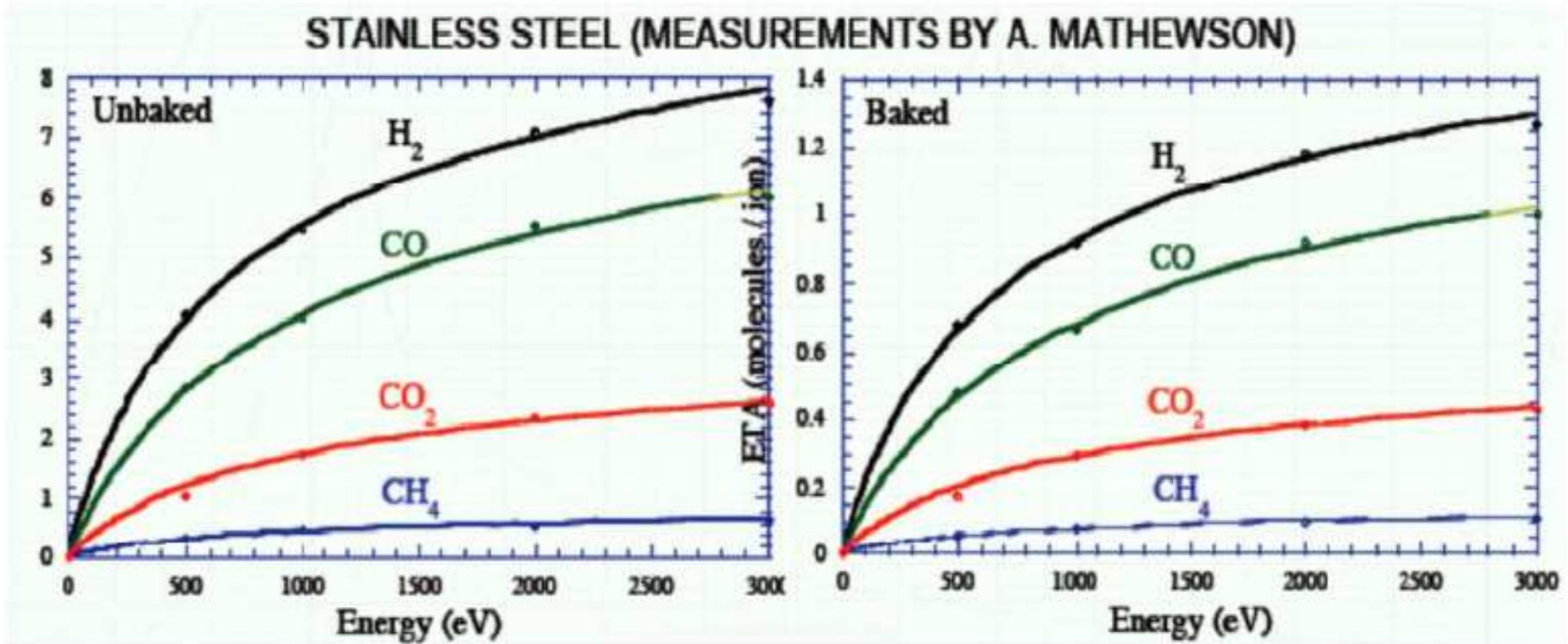
---



- *Relatively low energy ( $\sim$  keV) ions are routinely used to clean surfaces via IID.*
- *IID can have significant detrimental impacts on the performance of ion beam accelerators, such as RHIC at BNL, ISR & SPS at CERN.*
- *IID usually is associated with very high yield.*



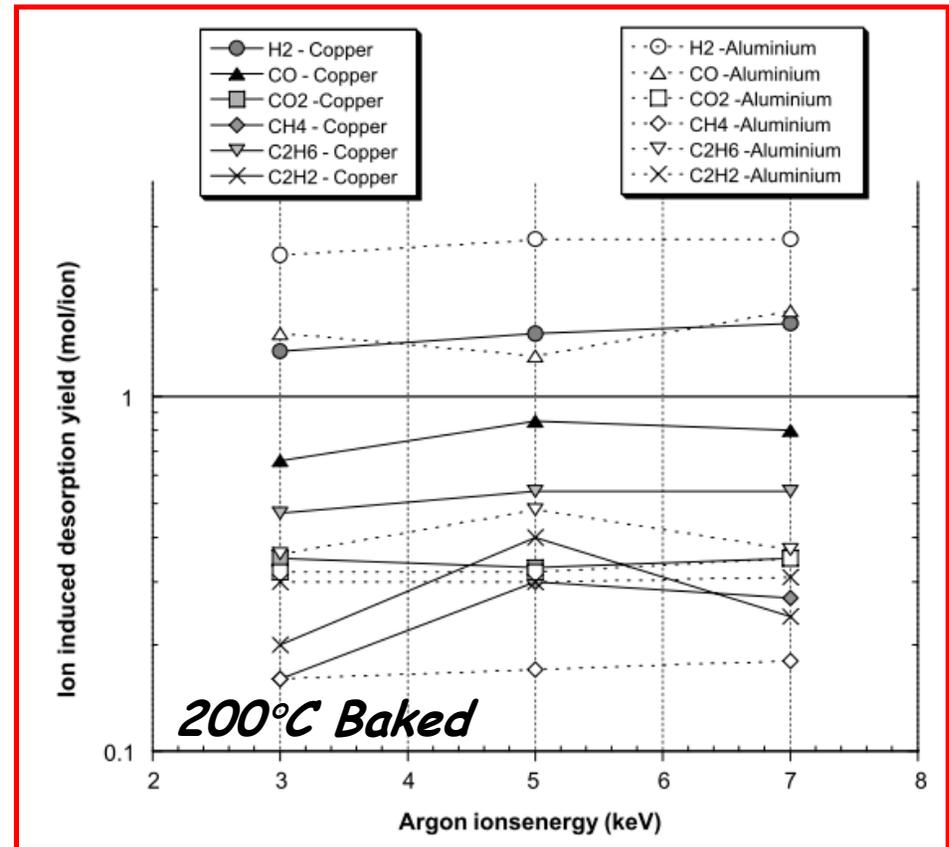
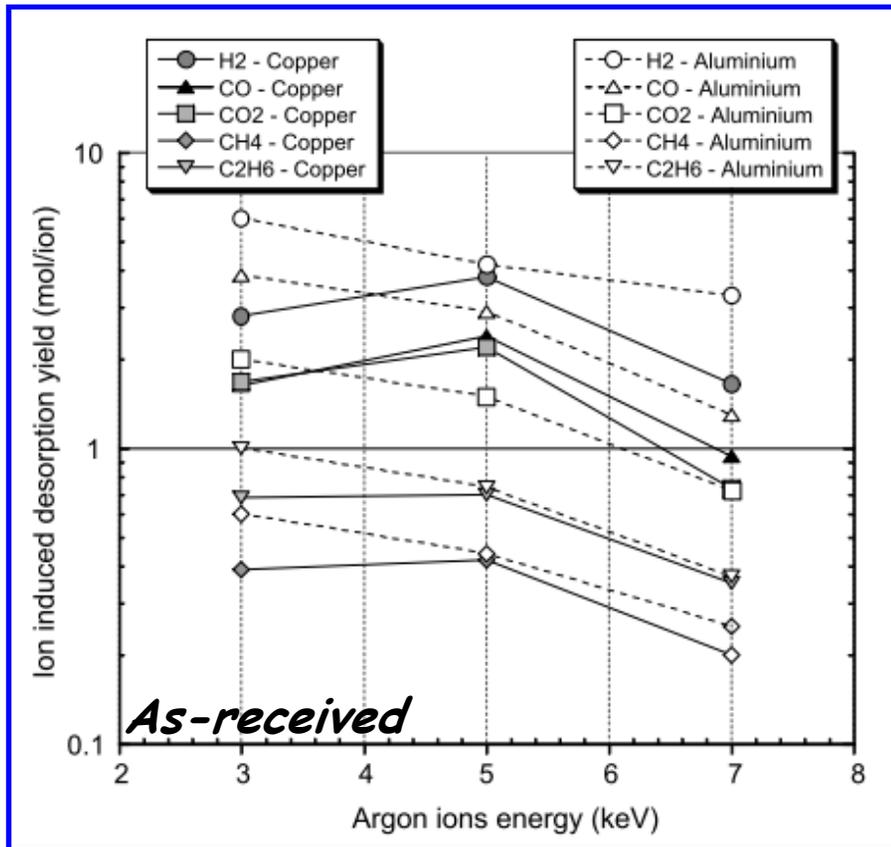
# IID - Dependence on Ion Energy (1)



*IID by  $^{15}\text{N}^+$  beam (low ion energy)*

*From: V.V. Mathewson, CERN-ISR-VA/76-5 (CERN, Geneva, 1976)*

# IID - Dependence on Ion Energy (2)



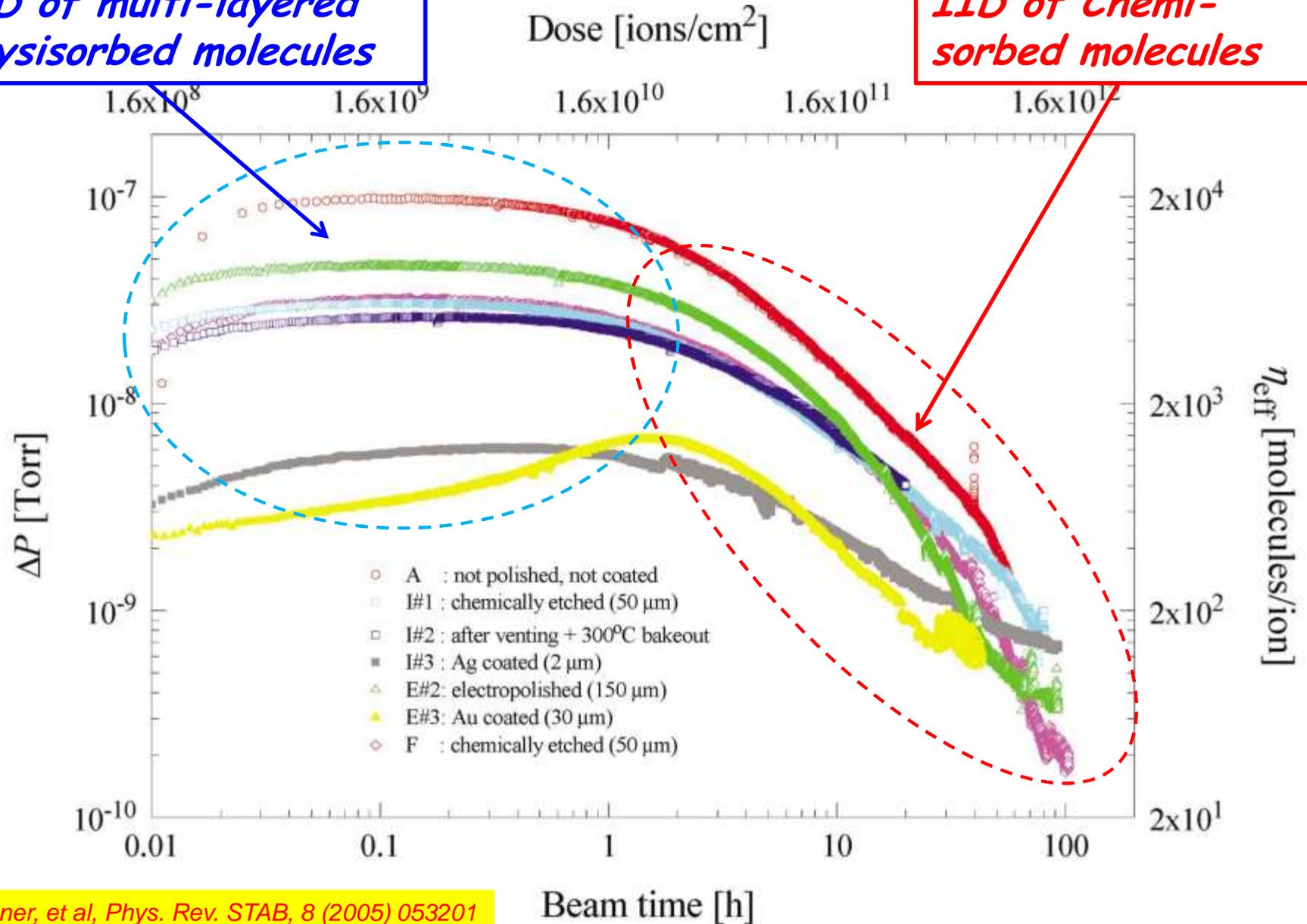
*IID by Ar<sup>+</sup> beam (high ion energy)  
From: M. P. Lozano, Vacuum 67 (2002) 339*

# IID - Heavy Ion Beams ( $52 \text{ MeV/u Pb}^{53+}$ )



*IID of multi-layered physisorbed molecules*

*IID of Chemisorbed molecules*



# *Electron Induced Desorption (EID)*

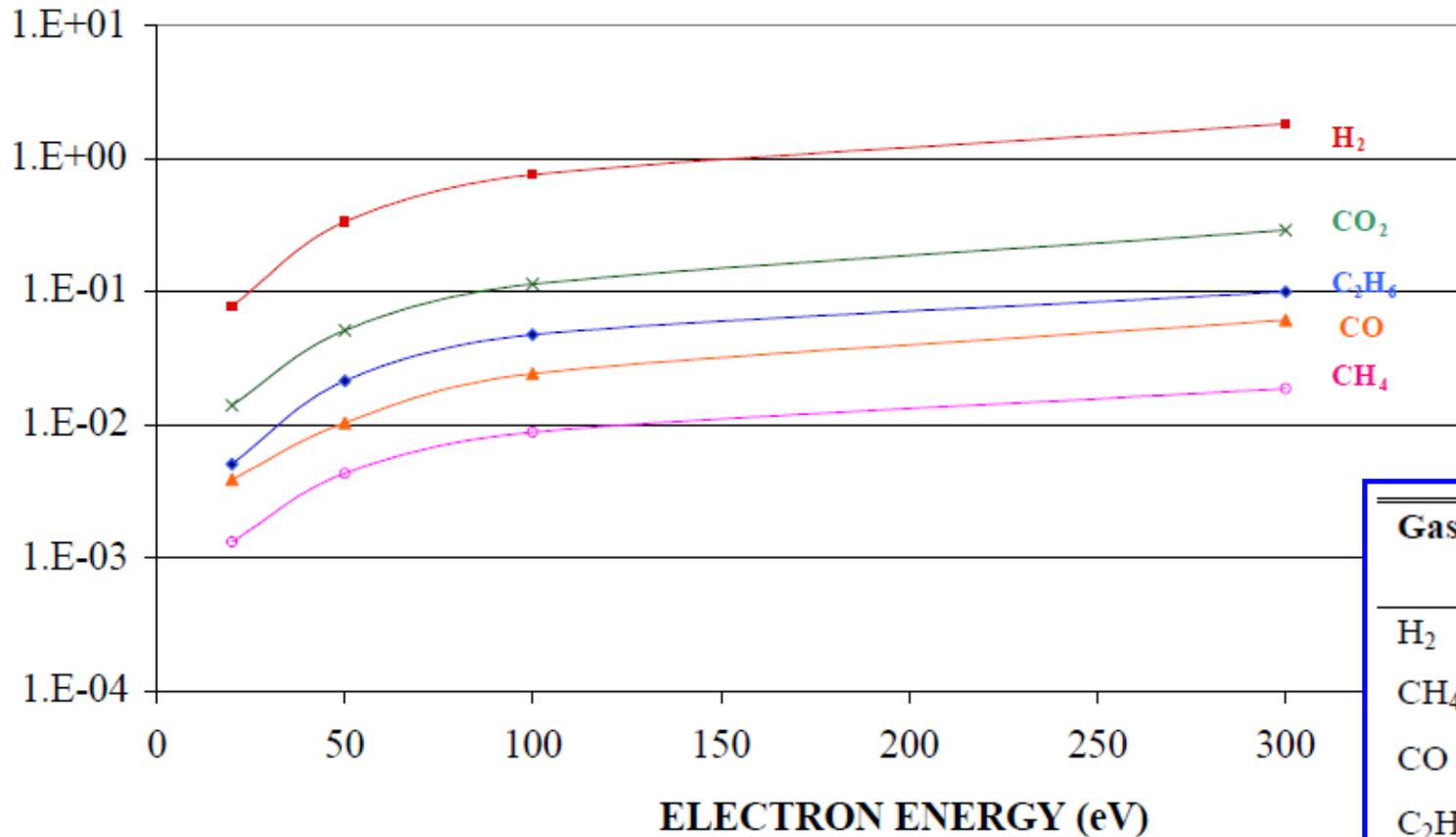
---



- *Most studied in accelerator community, related to the study of desorption mechanisms*
- *Direct EID process becomes significant in the regions of accelerators where electron multiplications can occur, such as in RF cavities and couplers, 'electron cloud' build-up in positive charges beams (positrons, protons and ions, etc.)*
- *Much lower yield as compared to IID*



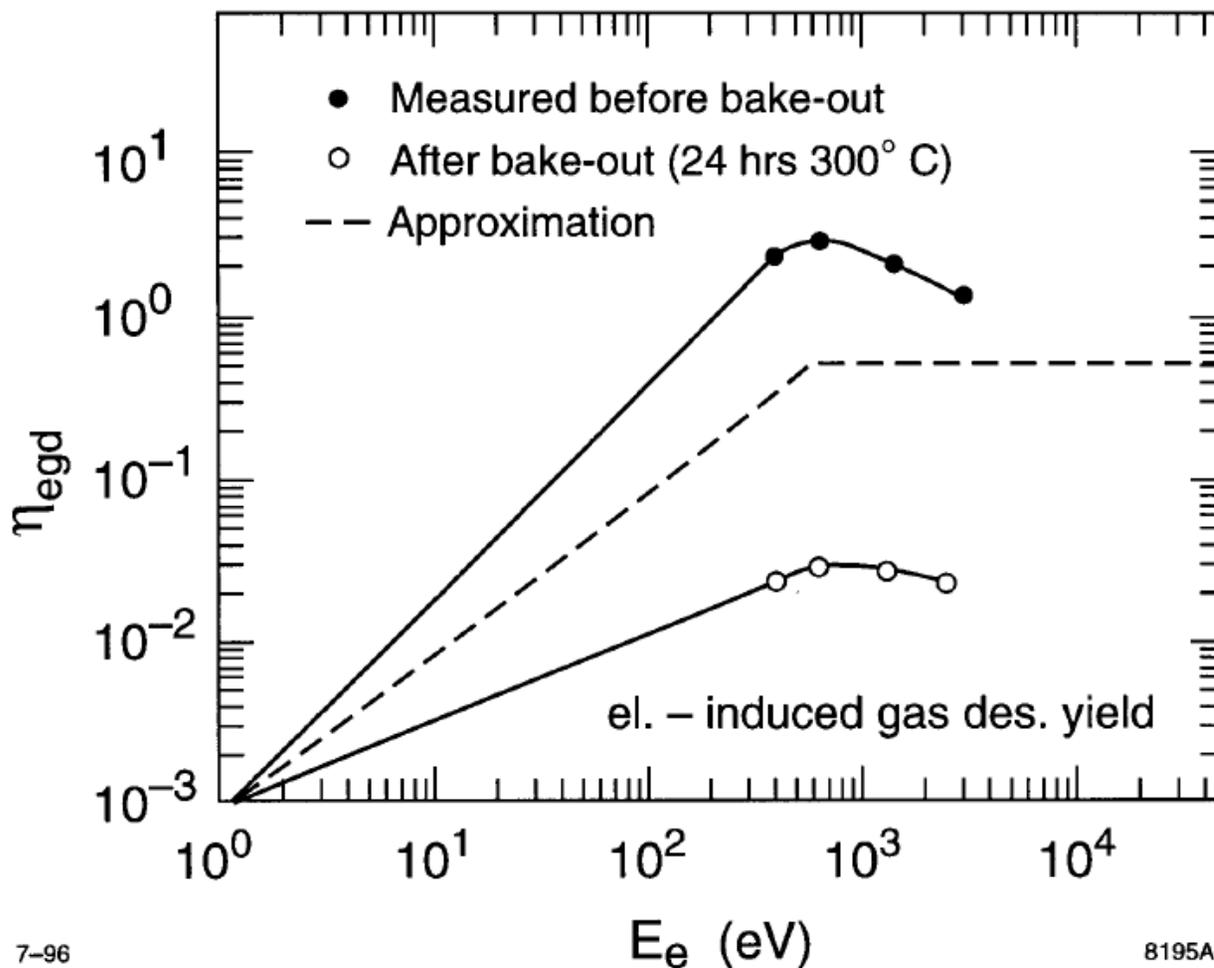
# EID - Dependence on Electron Energy (Copper)



Gas	Threshold energy (eV)
H <sub>2</sub>	12.7
CH <sub>4</sub>	7.5
CO	7.2
C <sub>2</sub> H <sub>6</sub>	11.4
CO <sub>2</sub>	9.1

*Variation of EID yield with electron energy on copper surfaces*  
(from: F. Billard, et al, Vac. Tech. Note 00-32 (CERN, Geneva, 2000))

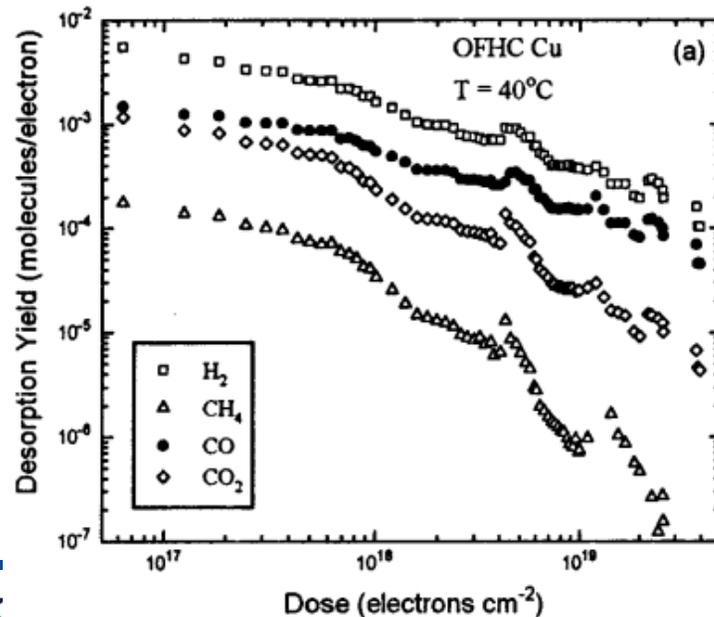
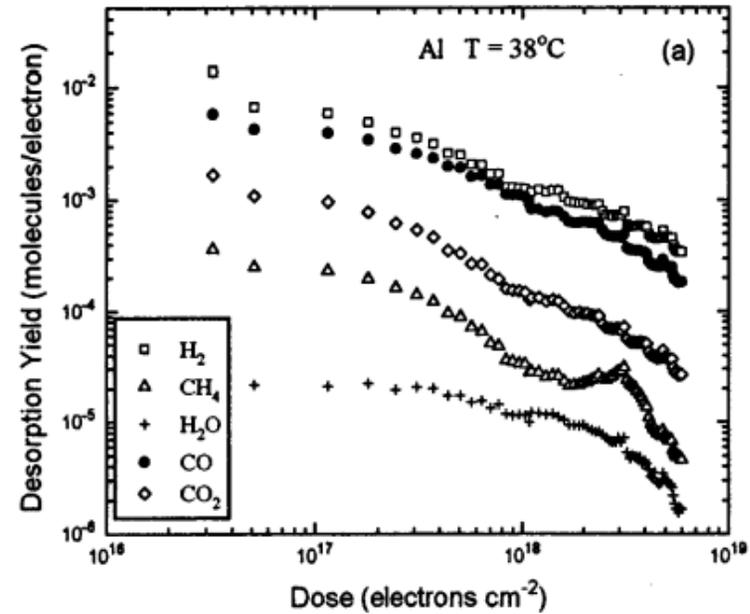
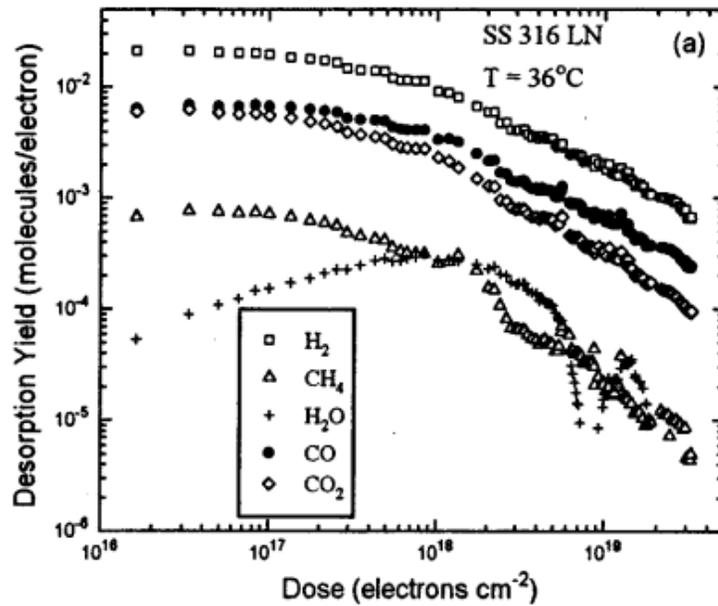
# EID - Dependence on Electron Energy (Aluminum)



*EID yield vs. electron energy on pure aluminum  
(from: Frank Zimmerman, SLAC-PUB-7238, August 1996)*



# EID - Dependence on Electron Dose



*EID yield vs. electron dose*

*(from: J. Gomez-Goni, A. G. Mathewson  
J. Vac. Sci. Technol. A 15 (1997) 3093)*

# Photon Induced Desorption (PID)

---



- *Considerations of PID process is important to the design and operations of synchrotron light sources and electron/positron storage rings, due to the presence of very high intensity of synchrotron radiation.*
- *The PID has many features similar to the EID.*

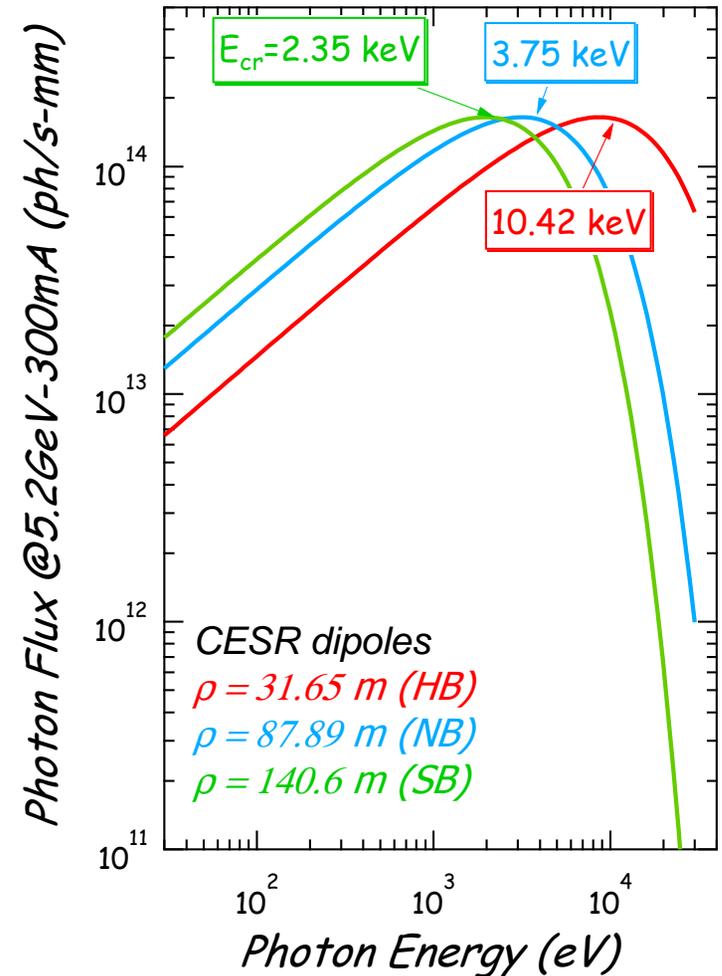


# Synchrotron Radiation



- When the trajectory of an electron or a positron is bended (by a magnetic field), the electron or positron will radiate photon, with broad spectrum.
- The SR spectrum may be characterized the critical energy,  $E_{cr}$ :

$$E_{cr} (keV) = 2.218 \times \frac{E_{electron}^3 (GeV)}{\rho (m)}$$



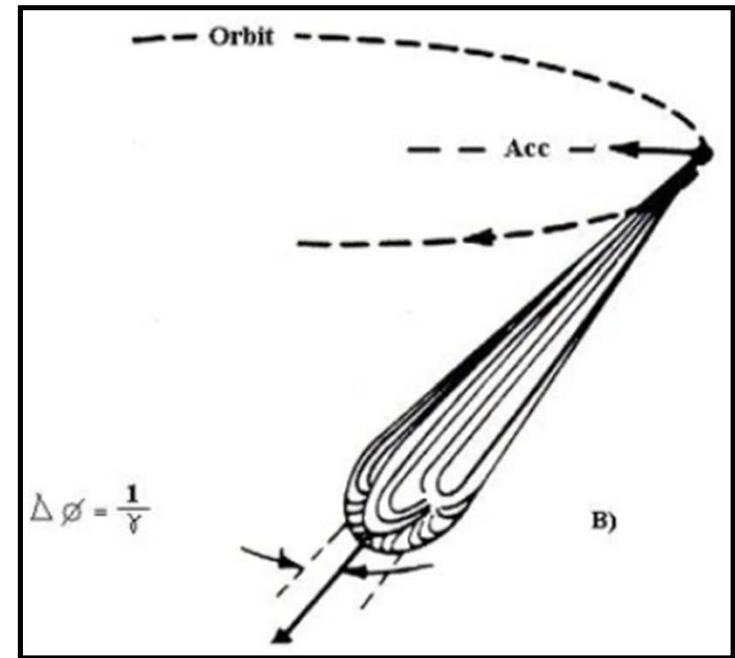
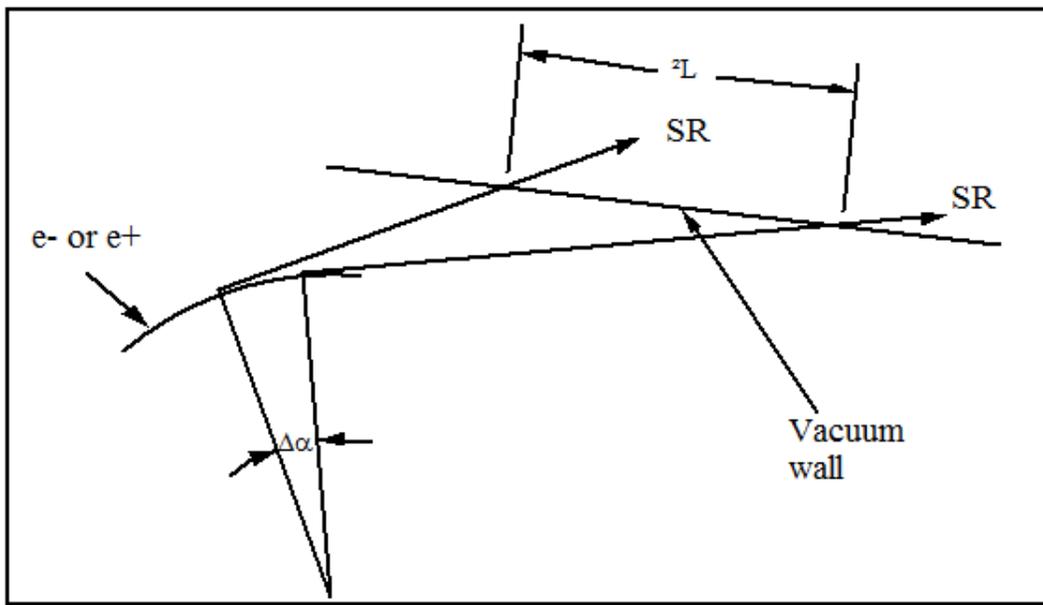
# Synchrotron Radiation Flux



- Total SR flux may be calculated as the following:

$$\Gamma(\text{ph} / \text{sec} \cdot \text{mA}) = 8.08 \times 10^{17} E_{\text{beam}}(\text{GeV}) \frac{\Delta\alpha}{2\pi}$$

- The SR is highly collimated, with angular spread  $\sim 1/\gamma$  ( $\gamma = E_{\text{beam}}/E_{\text{rest}}$ )



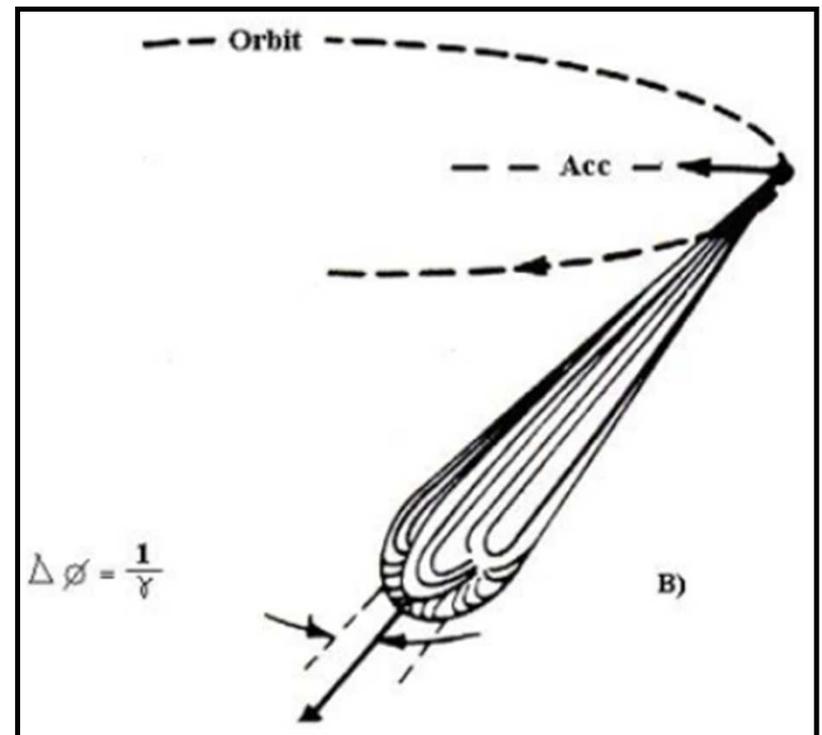
# Synchrotron Radiation Power



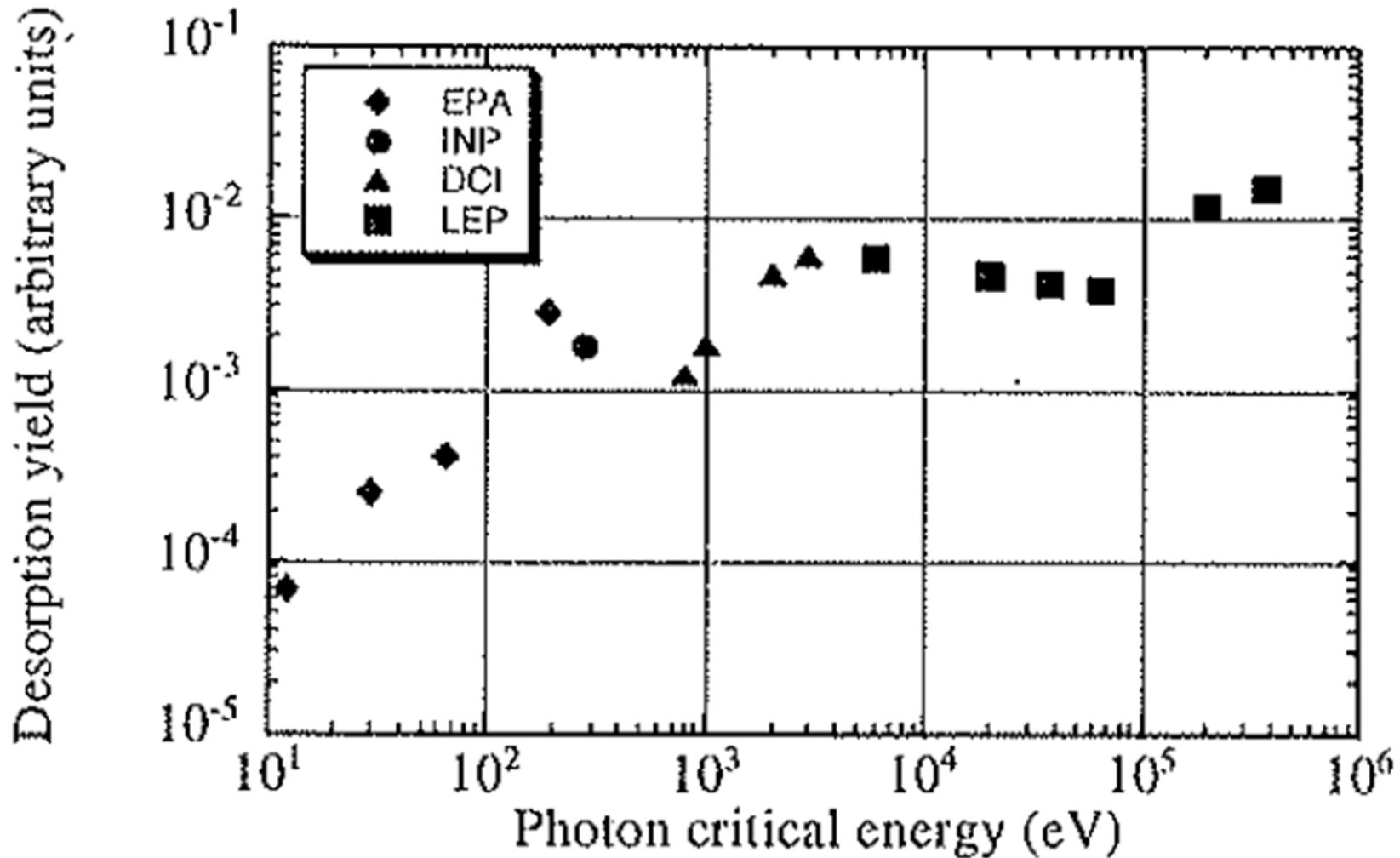
- Total SR power may be calculated as the following:

$$P(W / mA) = 88.5 \frac{E^4 (GeV)}{R(m)} \frac{\Delta\alpha}{2\pi}$$

- The SR is highly collimated, with angular spread  $\sim 1/\gamma$  ( $\gamma = E_{beam}/E_{rest}$ ;  $\gamma = 10^4$  for 5 GeV electron beam)
- SR power density impinging on a vacuum wall can be very high.

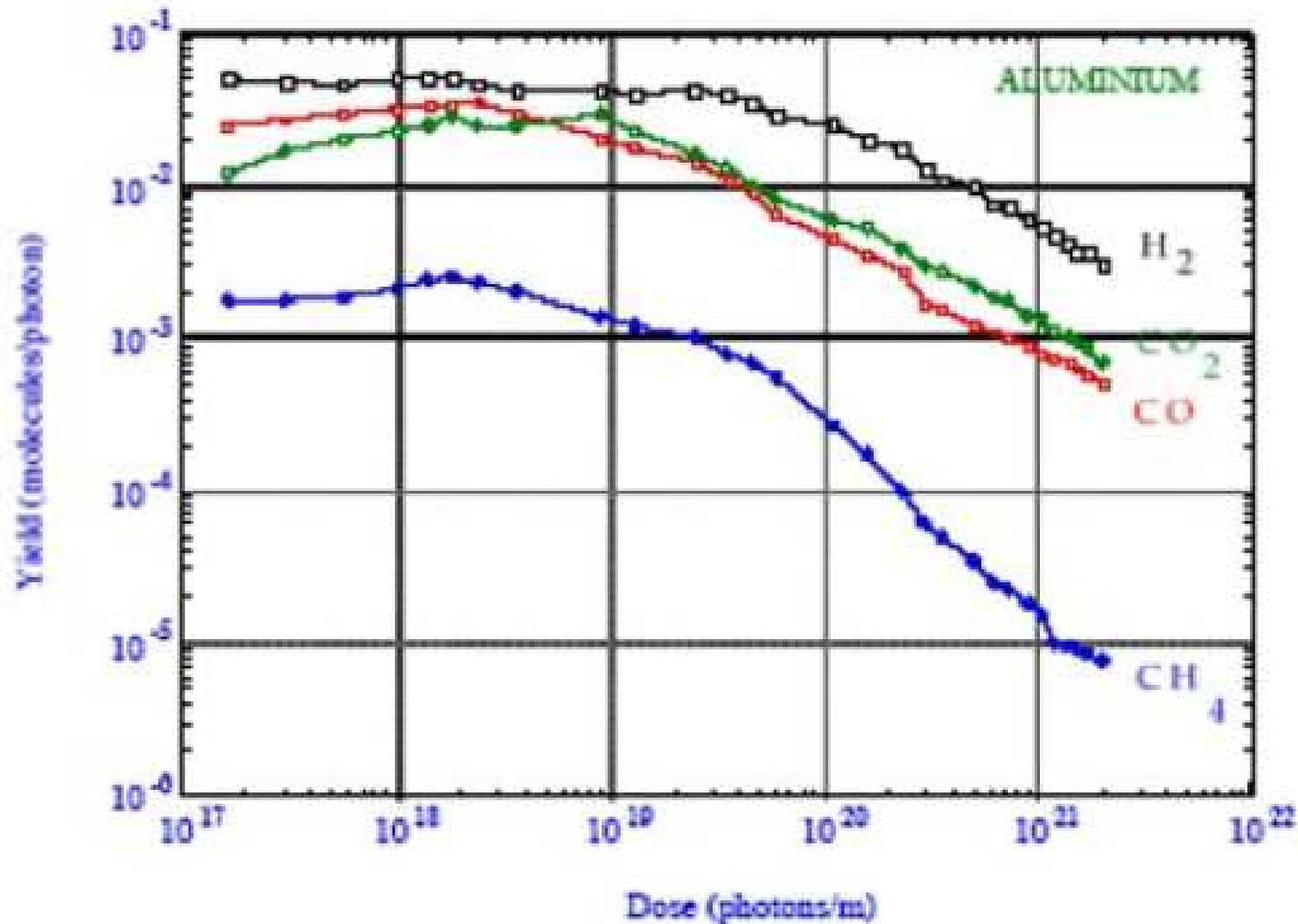


# PID Yield vs. SR Energy



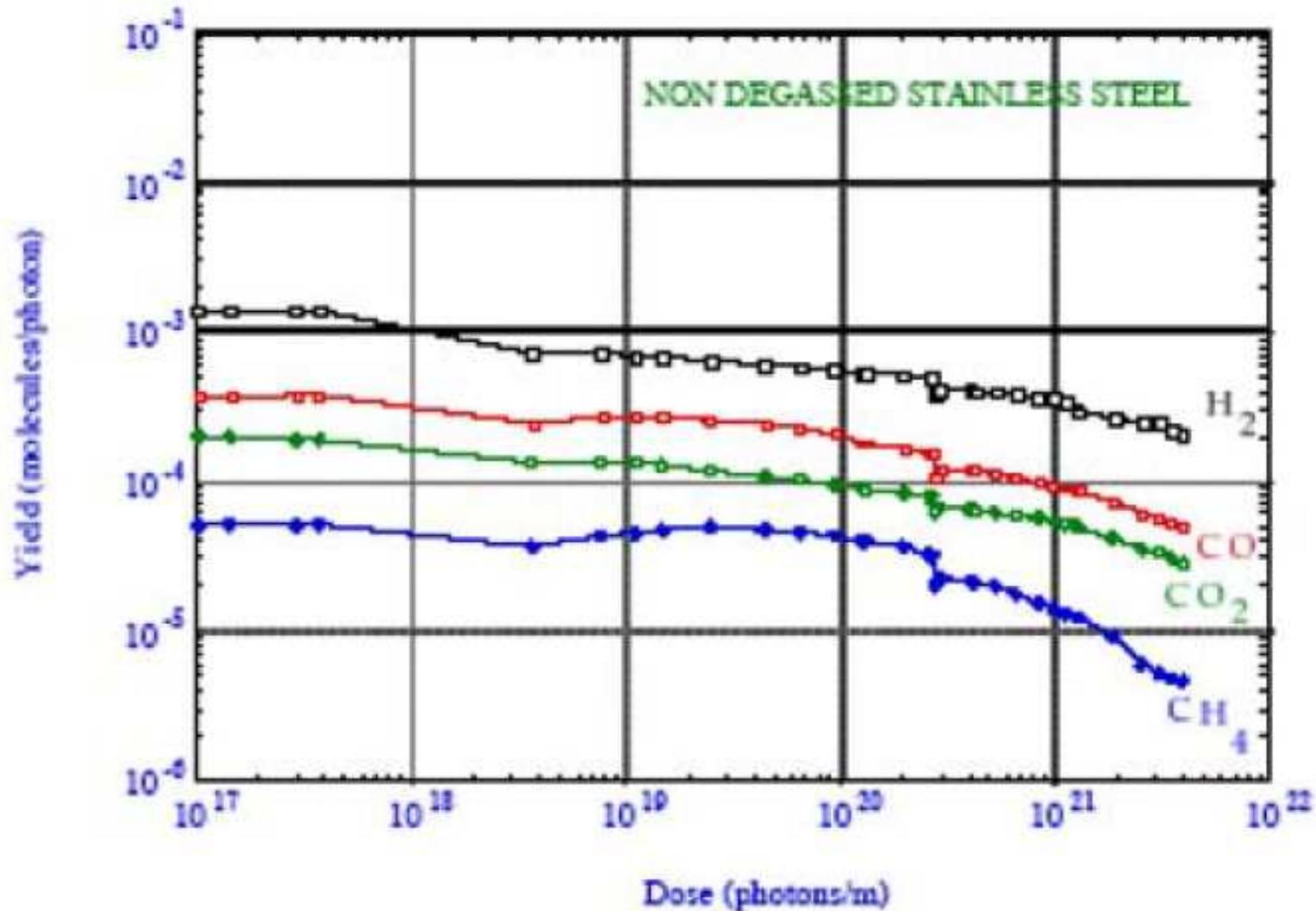
From: O. Grobner, CERN Accelerator School: Vacuum Technology, 1999

# PID Yield vs. SR Dose - 6063 Aluminum



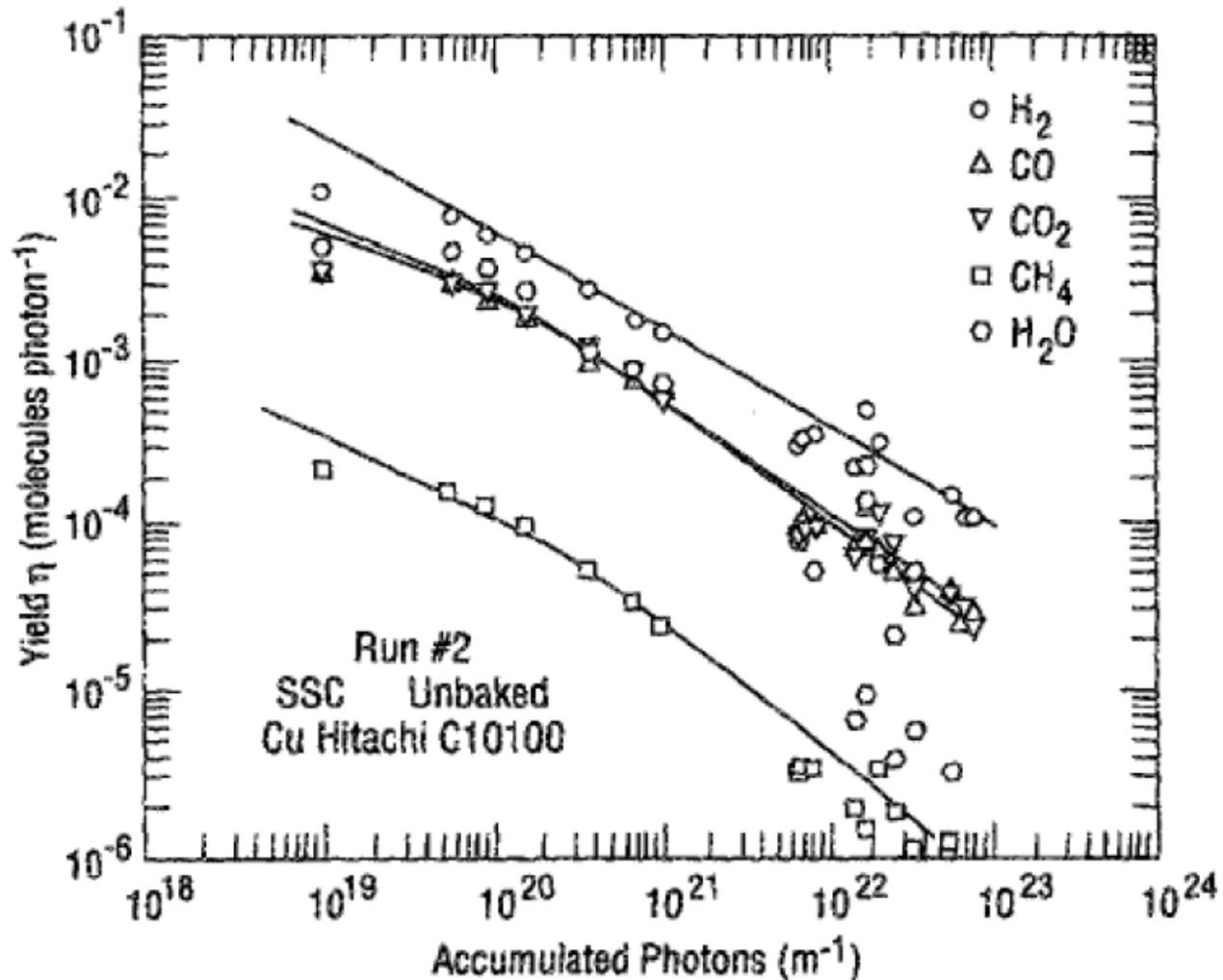
From: O. Grobner, CERN Accelerator School: Vacuum Technology, 1999

# PID Yield vs. SR Dose - 304L Stn. Stl.



From: O. Grobner, CERN Accelerator School: Vacuum Technology, 1999

# PID Yield vs. SR Dose - Copper



From: C.L.Foester, *J. Vac. Sci. Technol.*, A 12 (1994), p.1673

# PID Yield vs. SR Dose - CESR Aluminum

