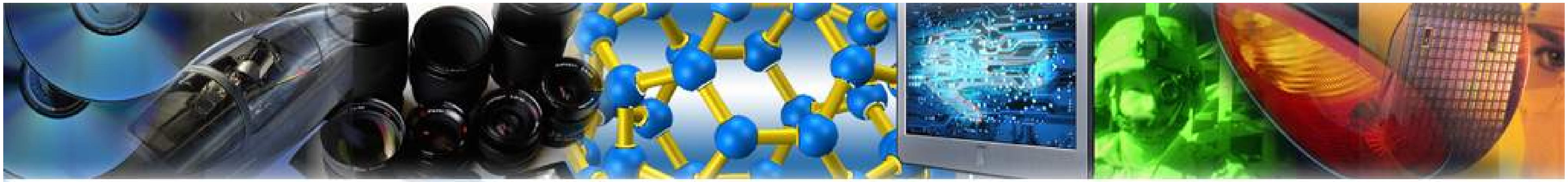
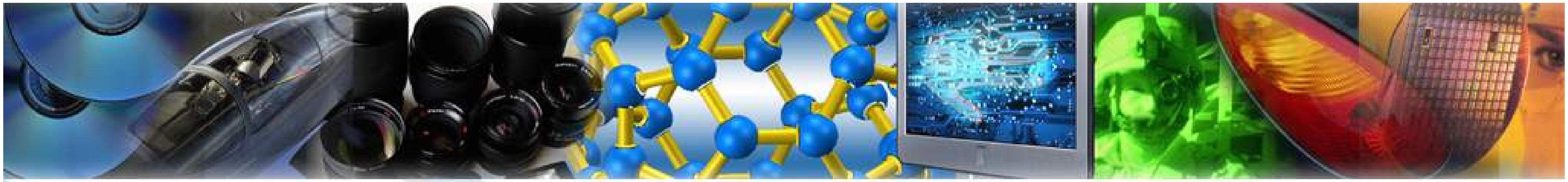


Vacuum Technology

Introduction to concepts that should be understood before designing, constructing, modifying, 'assessing' or, perhaps even using a vacuum system

Michael McKeown

Kurt J. Lesker Company

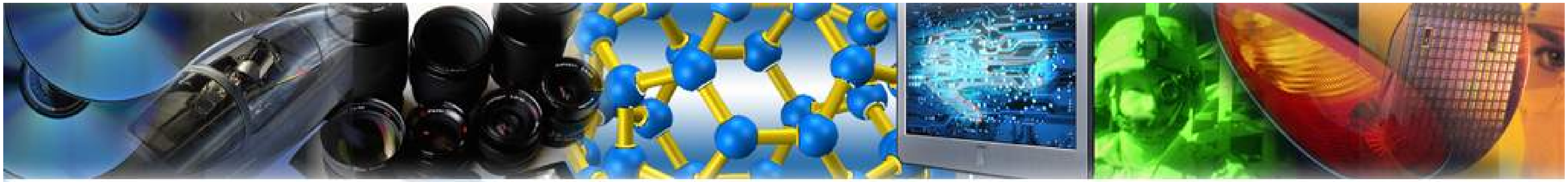


Outline

- *Gas–solid surface interactions**
- *Basics of conductance & pumping*
- *Gas load and its many sources*
- *Outgassing & ways to reduce it*
- *Pump throughput & keeping it high*
- *Equating gas load & throughput*
- *Modeling performance with VacTran*

With KTG defines VT
Gas Load = total
Outgassing – major source

Kurt J. Lesker Company



Gas-Surface Interactions

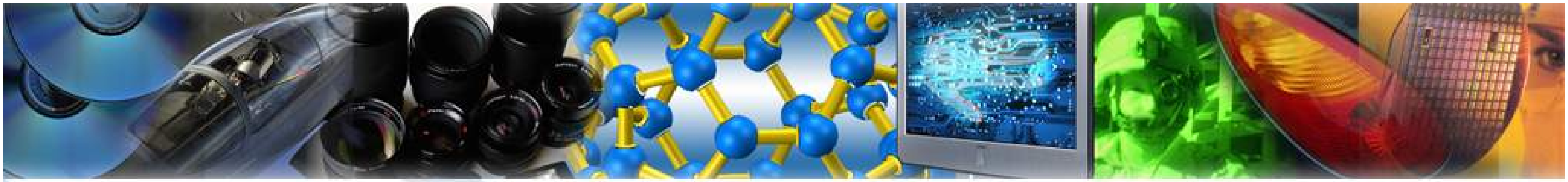
- *References*

- *Overview*
  - Adsorption-Desorption,
    Diffusion & Permeation

- *Arrival at Surface*
  - Reflection & Sticking

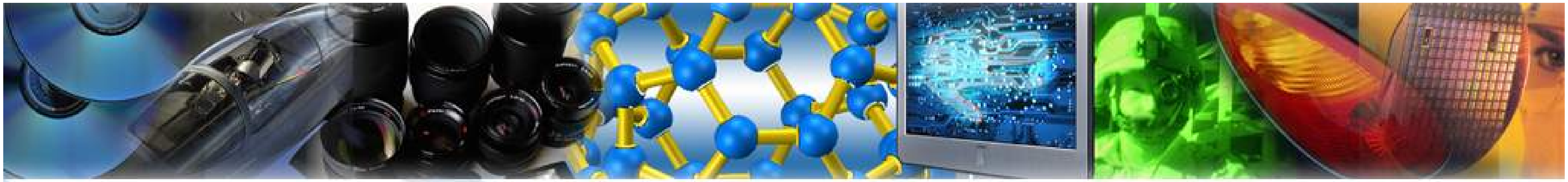
- *Departure from Surface*
  - Cosine Distribution

Kurt J. Lesker Company



References

1.	*Modern Vacuum Practice*	**Harris**
2.	*Vacuum Technology*	**Roth**
3.	*Foundations of Vacuum Science and Technology*	**Lafferty**
4.	*The Physical Basis of Ultrahigh Vacuum*	**Redhead**
5.	*A User's Guide to Vacuum Technology*	**O'Hanlon**
6.	*Vacuum Sealing Techniques*	**Roth**
7.	*Handbook of Electron Tube and Vacuum Techniques*	**Rosebury**

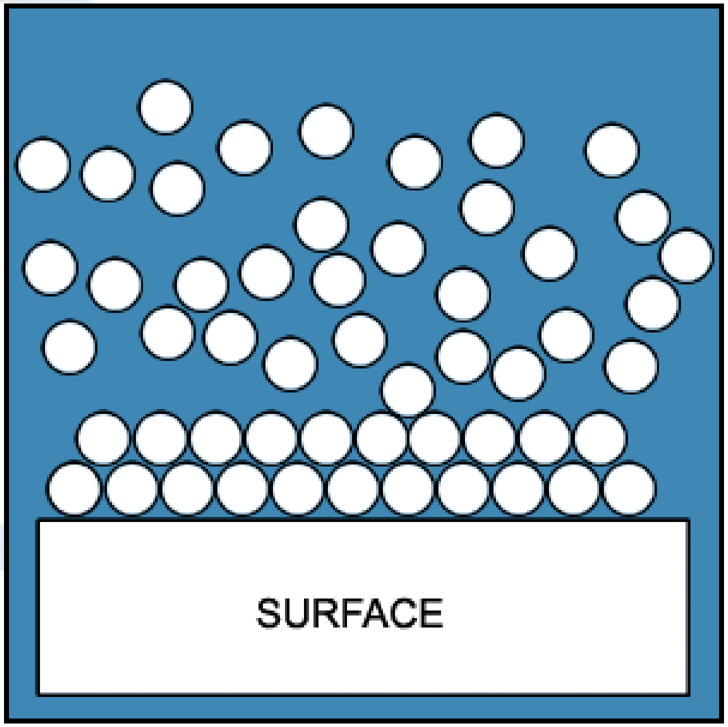


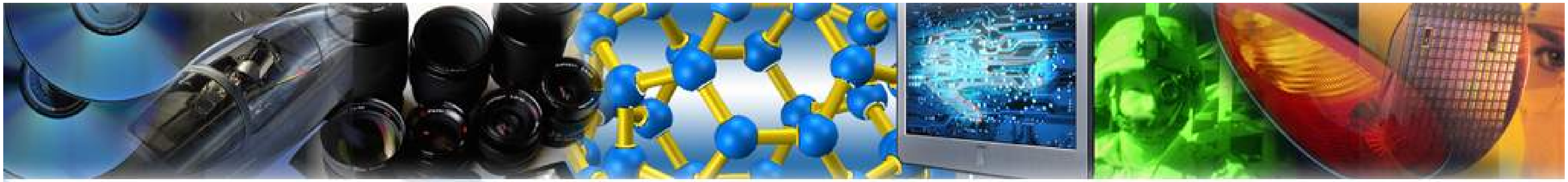
Gas-Surface Interactions 1

Adsorption

‘Satisfying’ surface’s residual forces
Initially molecules of any type adsorbed
More polar molecules preferred

Reduced by higher temperature
Increased by lower temperature *





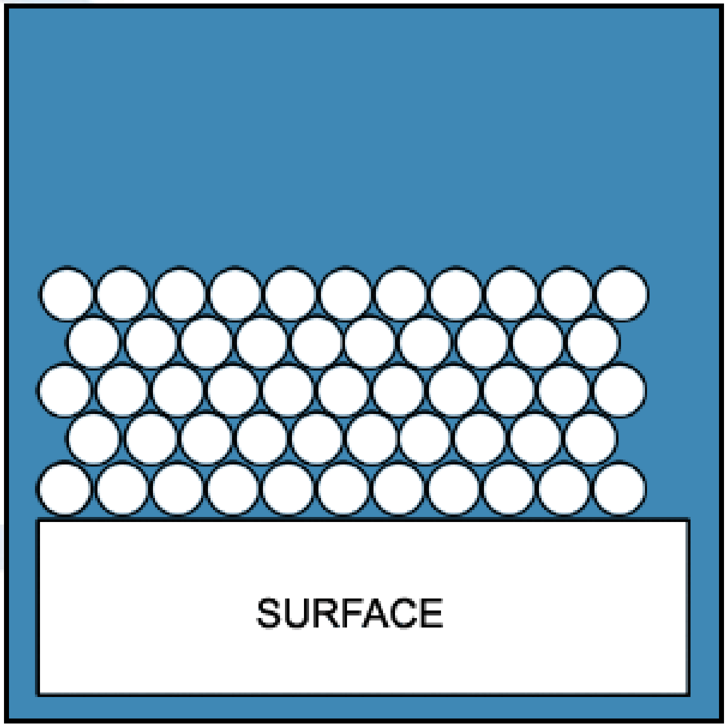
Desorption – *(outgassing)*

Opposite of adsorption

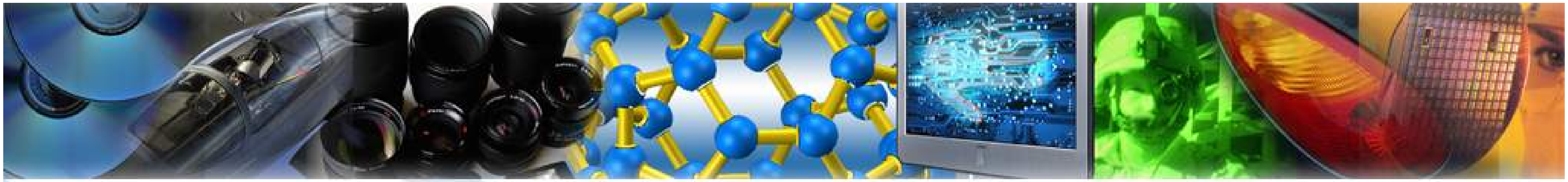
Molecule gains sufficient energy to overcome binding energy to peers or surface

Increased by higher temperature

Reduced by lower temperature



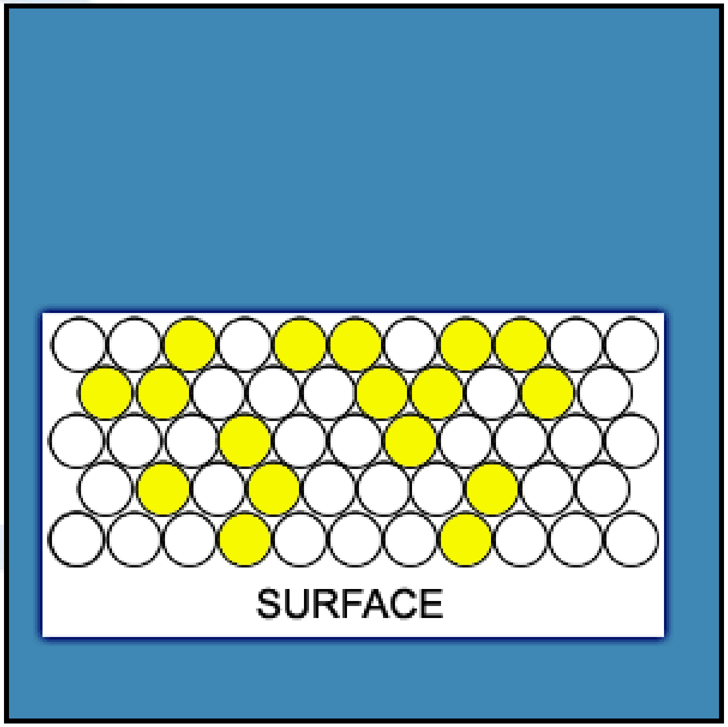
main problem



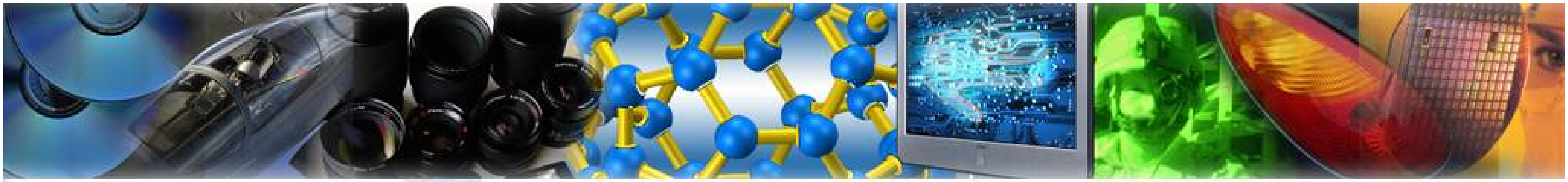
Diffusion

Gas trapped in bulk interstices
Concentration gradient near surface
Stainless steel: atomic H and CO

Increased by higher temperature *
Reduced by lower temperature



1000C 3hr



Gas-Surface Interactions 4

Permeation

Gases permeate through all materials

Gas/Solid usually immeasurably slow*

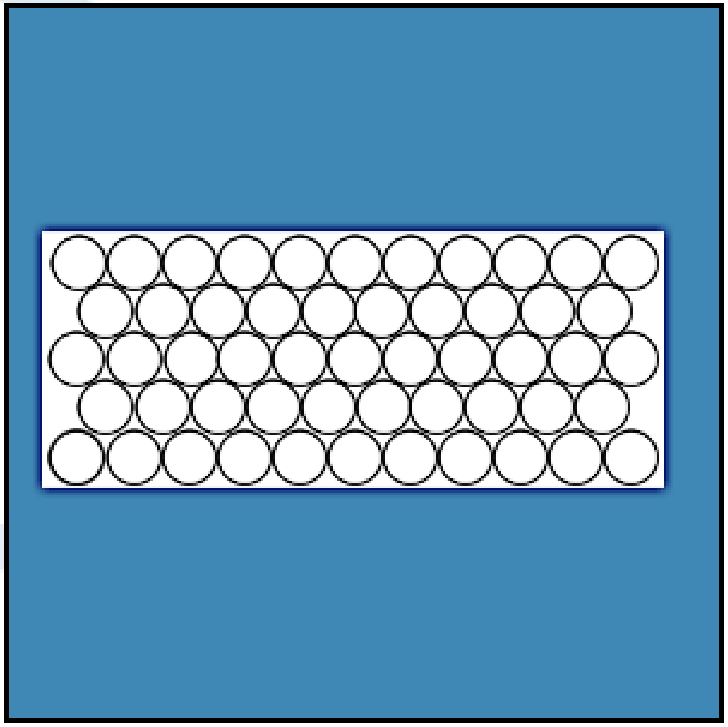
Gas/Elastomer are measurable*

Permeation rate

f (partial pressure)

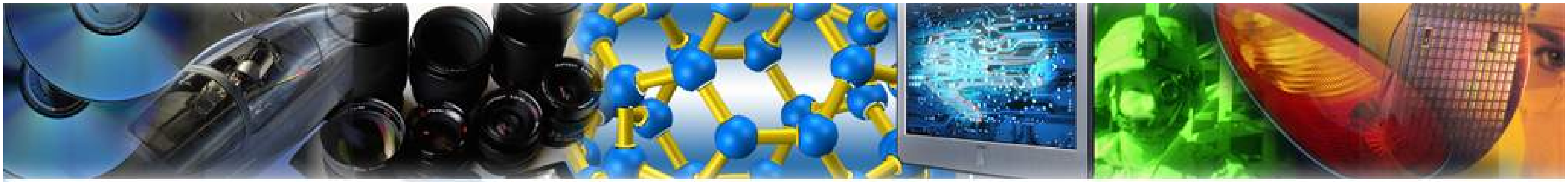
f (specific for gas & elastomer)

f (temperature)^{q}



H2 > Pd & He > quartz
H20,N2,O2 Viton, Buna

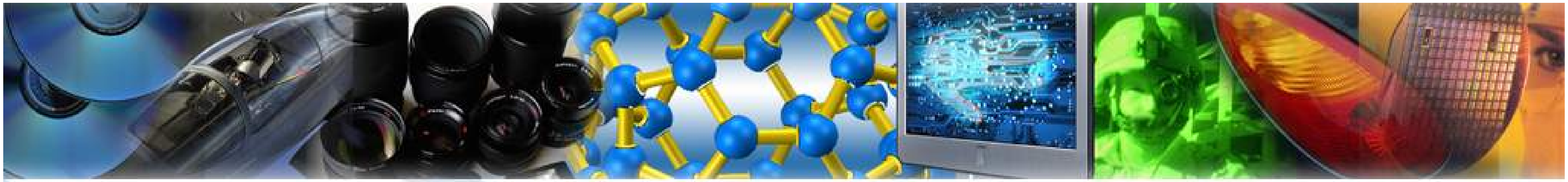
Kurt J. Lesker Company



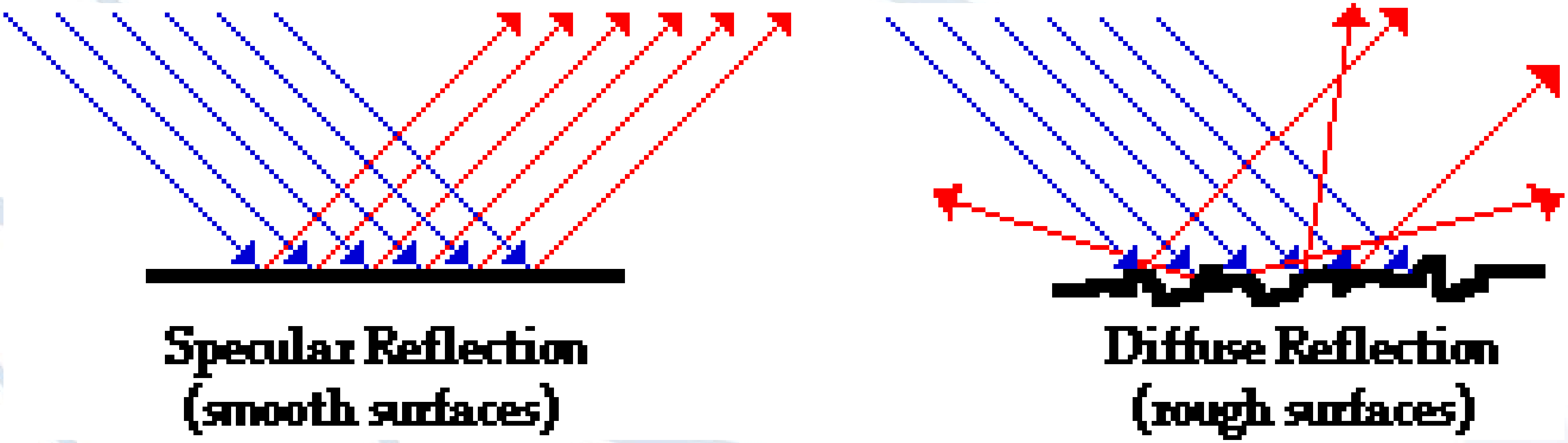
Molecules Arriving at Surface

1. Reflect back into gas phase with no energy exchange *
2. Reflect back into gas phase with energy exchange *
3. Trapped shallow minimum energy state:*
   Physisorption 0 – 10 kcals/mole
4. Trapped in deep minimum energy state:
   Chemisorption 20 – 100 kcals/mole
5. Chemically react:
   Heat of formation ~100 – 500 kcals/mole

Rare even for He
T/C, Pirani
Residence time defined by energy
Contimuum



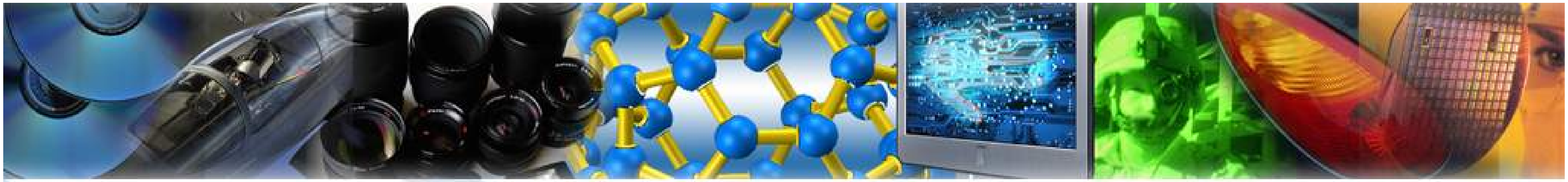
Reflection of Light



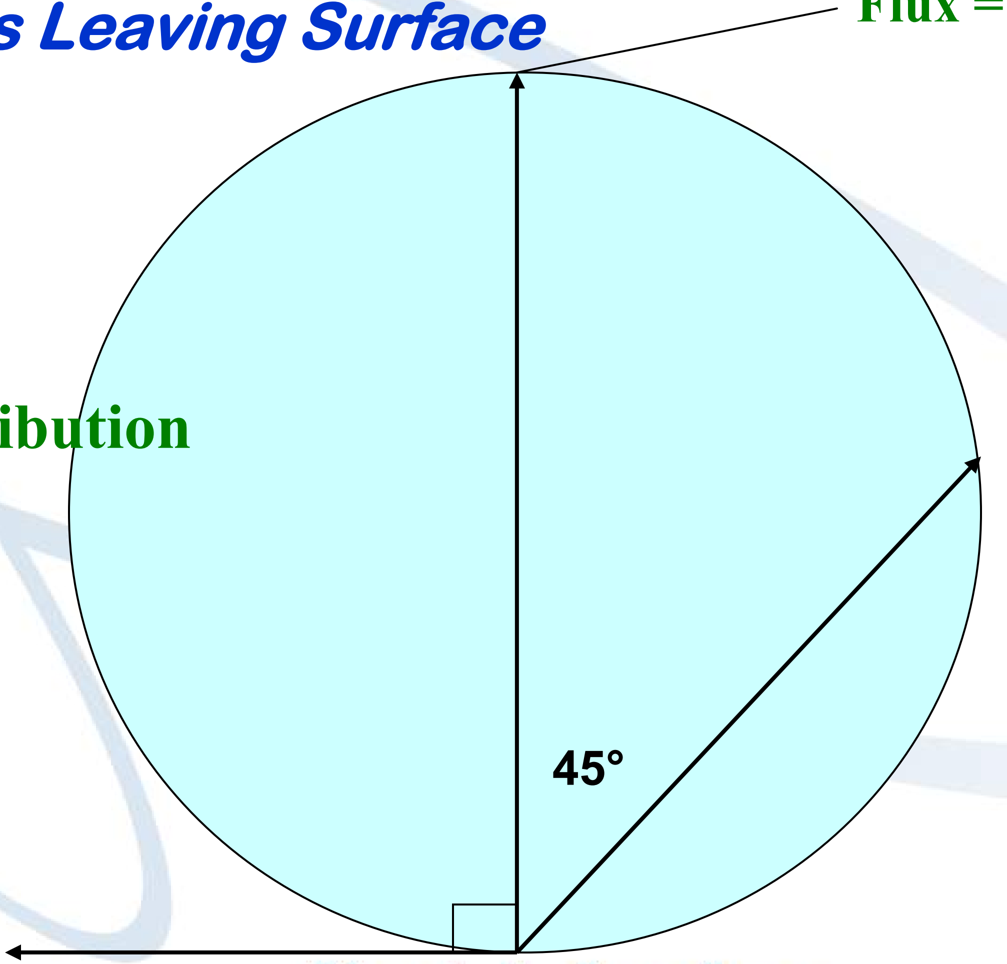
Specular Reflection
(smooth surfaces)

Diffuse Reflection
(rough surfaces)

QED Feynman
Moelcules?



Molecules Leaving Surface



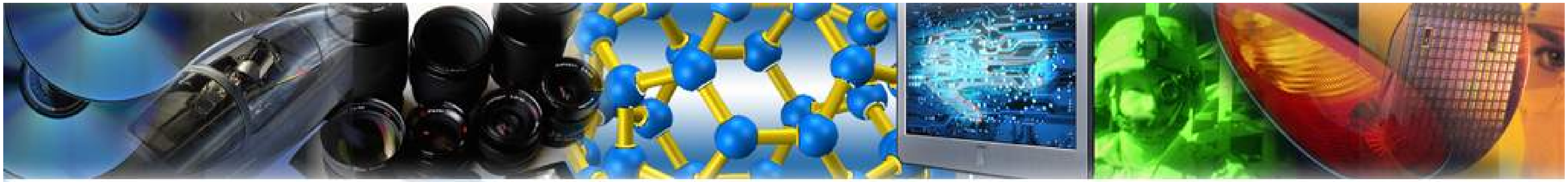
Flux = 1

Cosine Distribution

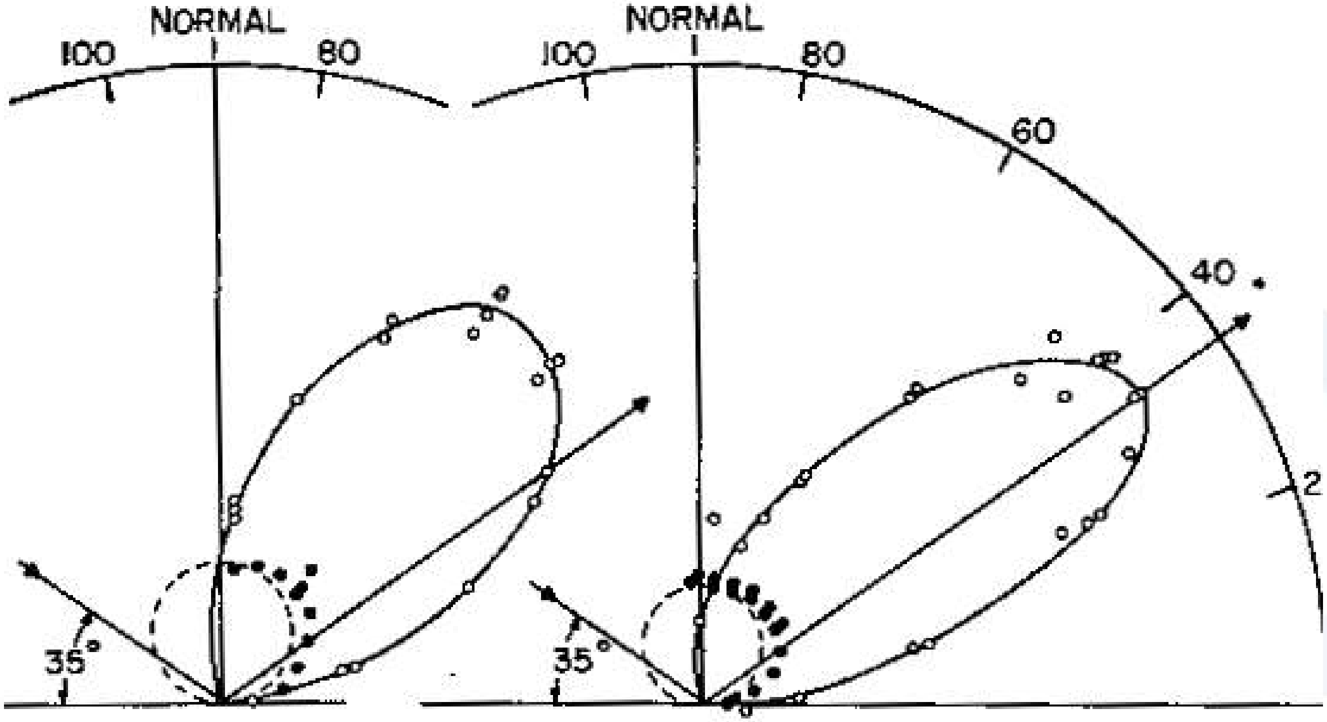
Flux = 0.707

45°

Flux = 0



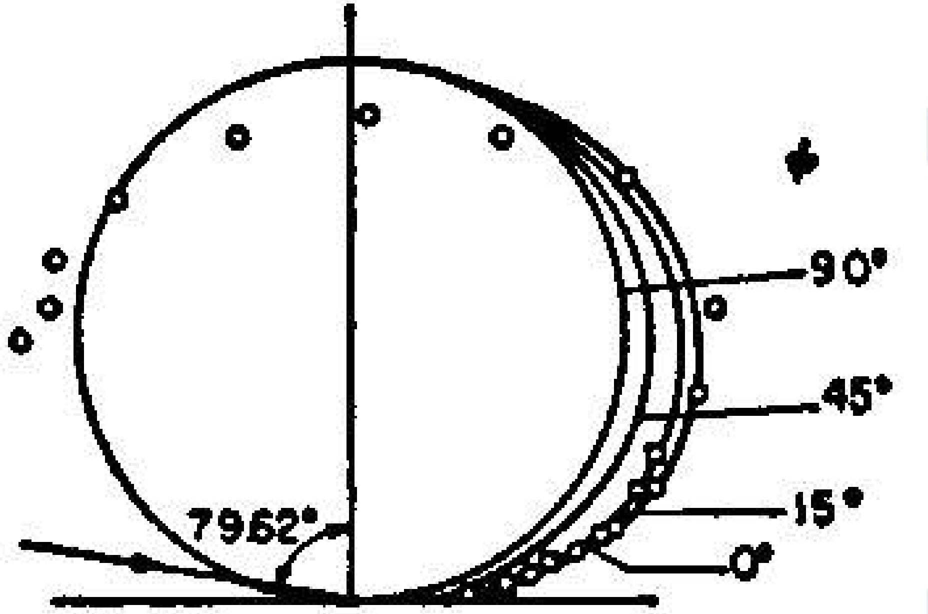
Reflection of Atoms/Molecules

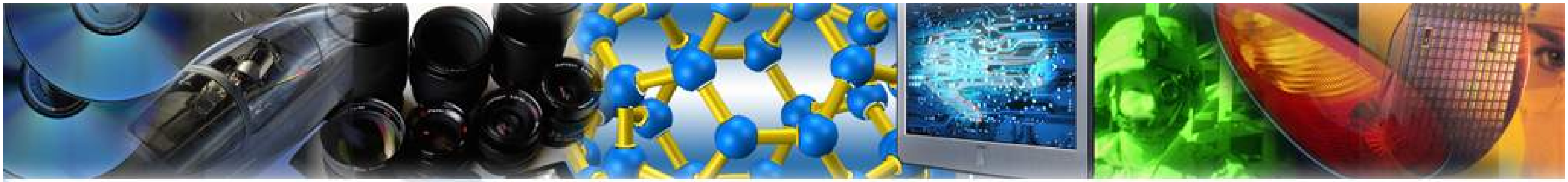


L – dot RT Pt/RT He, circle hot Pt/RT He   Pt 1300°C He 1800°C
R – dot RT Pt/hot He, circle hot Pt/hot He

Reflection of Atoms/Molecules at Large Angles

N2 - Glass



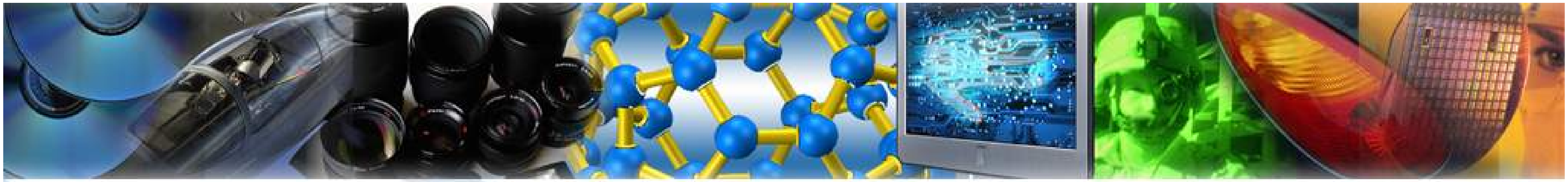


Adsorption of Atoms/Molecules

Accommodation coeff — reflection with energy exchange

Condensation coeff — adsorption into shallow minimum

Sticking probability — adsorption into deep minimum

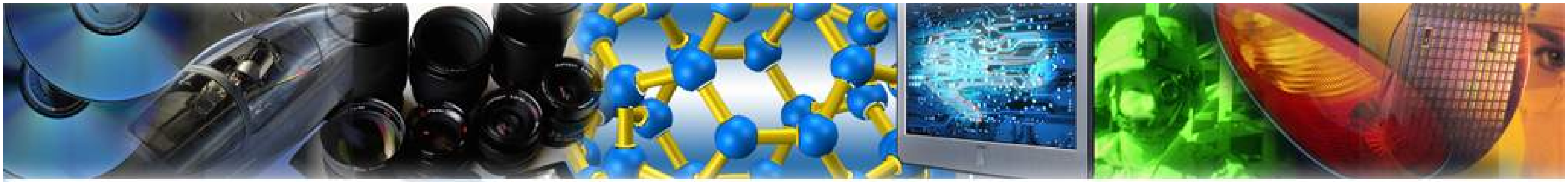


Accommodation Coefficients of Atoms/Molecules

Gas	Substrate	Coefficient
He	Ni (298K)	0.385
H_2	Ni (298K)	0.249
Ar	Ni (298K)	0.935
N_2	Pt (?)	0.816

Condensation Coefficients of Atoms/Molecules

Gas	Substrate	Coefficient
He	glass at 50°C	0.17
H_2		0.57
N_2		0.76
O_2		0.82
Ar		0.86



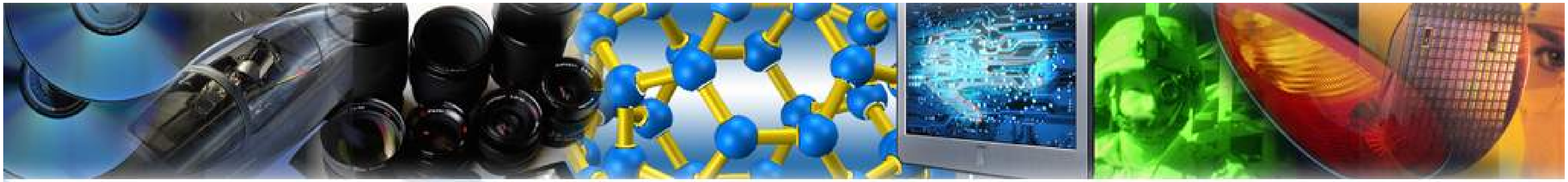
Gas-Surface Conclusions

Molecules hitting a surface:

- Do NOT reflect like light
- Stick (momentarily ► permanently)
- Desorb with cosine distribution

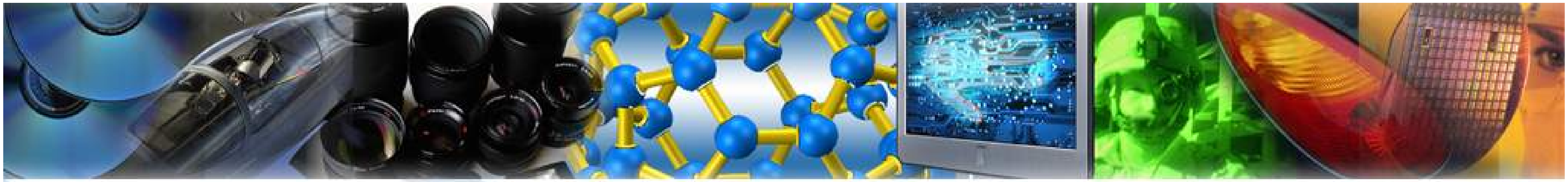
(Under vacuum: every solid surface desorbs gas)

Kurt J. Lesker Company



Basic Pumping Concepts

- Flow Regimes
- Conductance
- Pumping Speed
- Conductance plus Pumping Speed
- ‘Effective’ Pumping Speeds (EPS)
- Measuring EPS



Flow Regimes

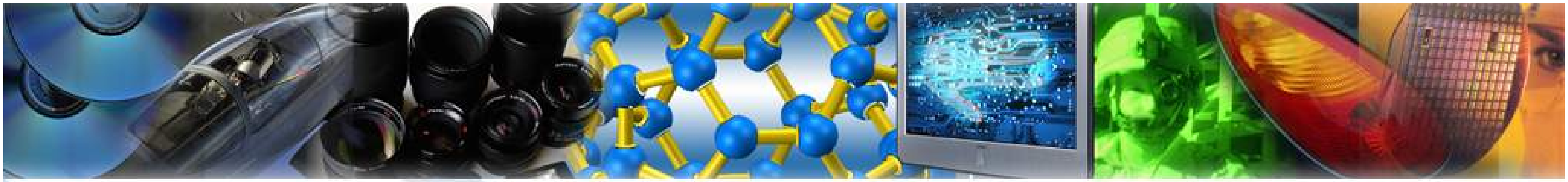
mfp -- mean free path

***Continuum Flow*: molecules' mfp is small compared to characteristic dimensions of vacuum volume**

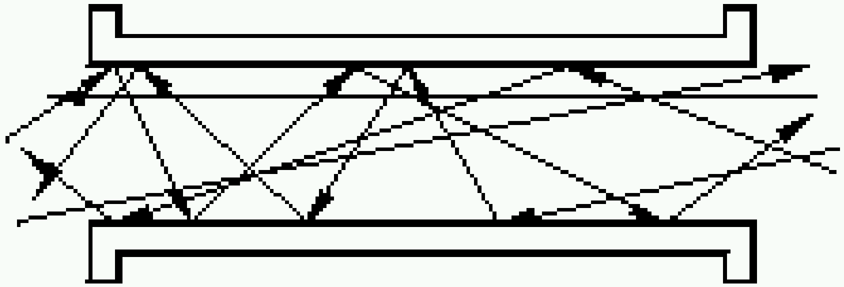
***Transitional Flow*: molecules' mfp roughly equal to characteristic dimensions of vacuum volume**

***Molecular Flow*: molecules' mfp is large compared to characteristic dimensions of vacuum volume**

Flow regime (ie pressure) affects conductance



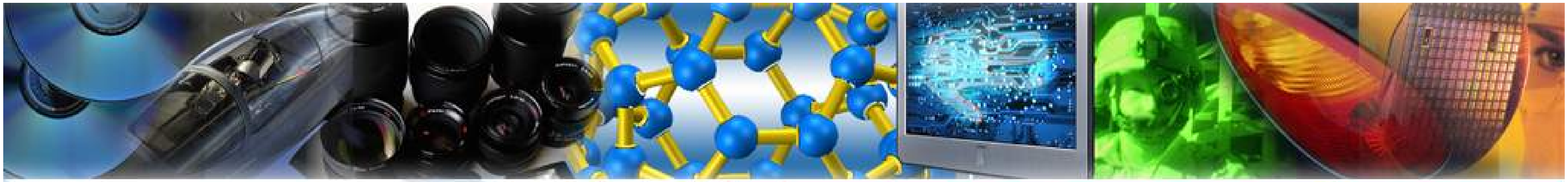
Conductance



Passive Components

Ability to transfer gas *volume* in unit *time*

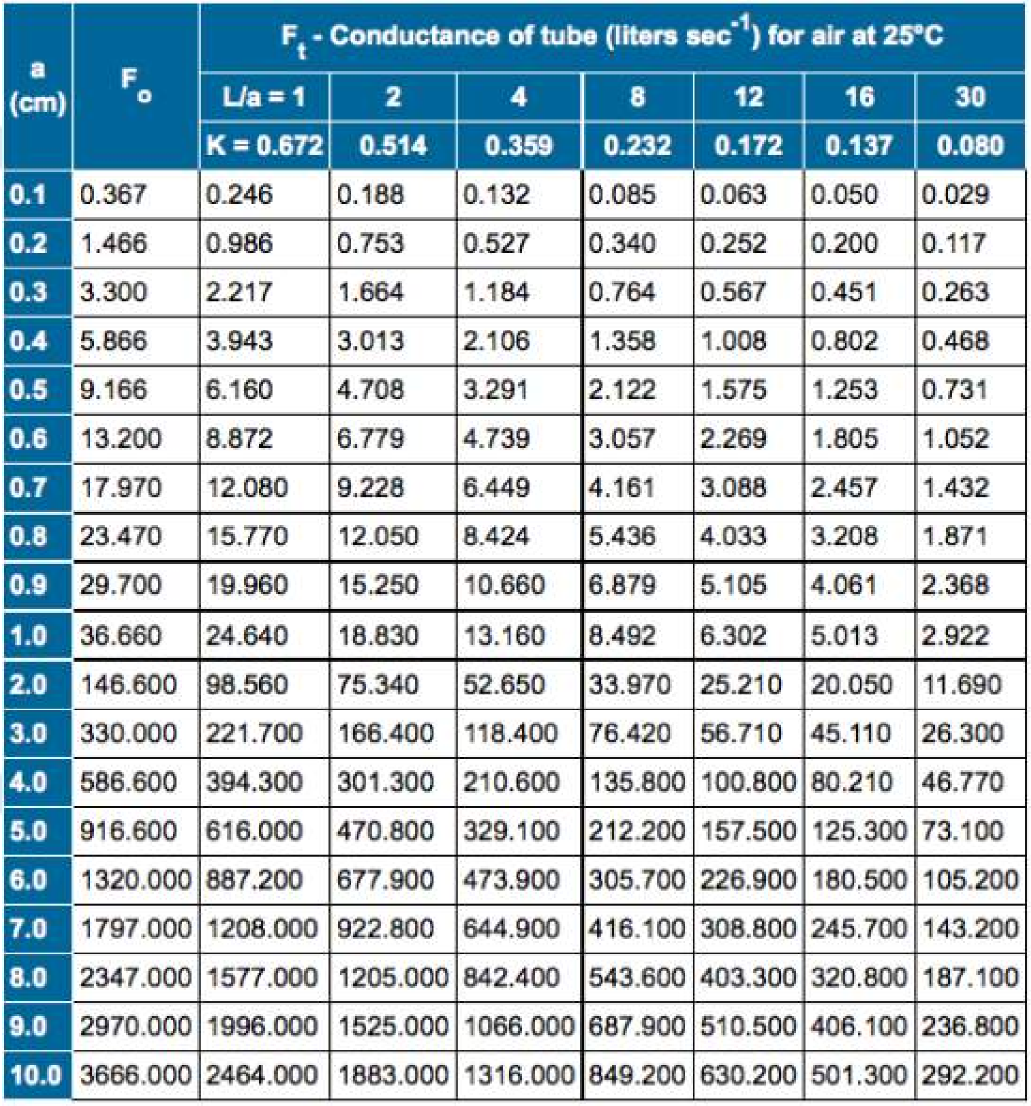
Determined by shape, open area, length, gas, & pressure
(Volumetric flow measured in: L/s, cfm, m^3/hr, L/m)



Pumping Concepts 3

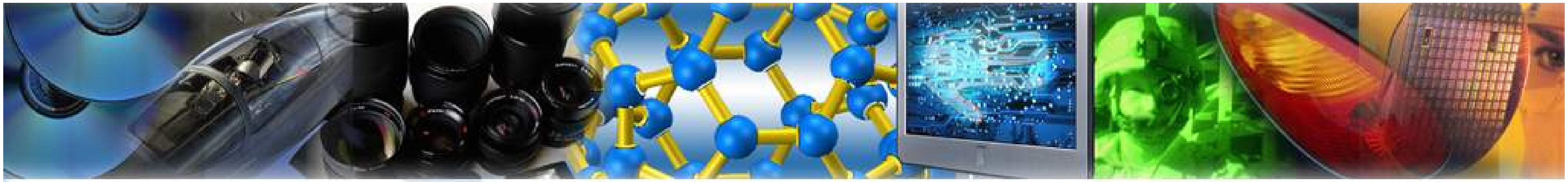
Calculating Conductance

- **Dushman’s Table**
- **Transmission Probability**
- **VacTran®**



a (cm)	F_o	F_t - Conductance of tube (liters sec^{-1}) for air at 25°C						
		L/a = 1	2	4	8	12	16	30
		K = 0.672	0.514	0.359	0.232	0.172	0.137	0.080
0.1	0.367	0.246	0.188	0.132	0.085	0.063	0.050	0.029
0.2	1.466	0.986	0.753	0.527	0.340	0.252	0.200	0.117
0.3	3.300	2.217	1.664	1.184	0.764	0.567	0.451	0.263
0.4	5.866	3.943	3.013	2.106	1.358	1.008	0.802	0.468
0.5	9.166	6.160	4.708	3.291	2.122	1.575	1.253	0.731
0.6	13.200	8.872	6.779	4.739	3.057	2.269	1.805	1.052
0.7	17.970	12.080	9.228	6.449	4.161	3.088	2.457	1.432
0.8	23.470	15.770	12.050	8.424	5.436	4.033	3.208	1.871
0.9	29.700	19.960	15.250	10.660	6.879	5.105	4.061	2.368
1.0	36.660	24.640	18.830	13.160	8.492	6.302	5.013	2.922
2.0	146.600	98.560	75.340	52.650	33.970	25.210	20.050	11.690
3.0	330.000	221.700	166.400	118.400	76.420	56.710	45.110	26.300
4.0	586.600	394.300	301.300	210.600	135.800	100.800	80.210	46.770
5.0	916.600	616.000	470.800	329.100	212.200	157.500	125.300	73.100
6.0	1320.000	887.200	677.900	473.900	305.700	226.900	180.500	105.200
7.0	1797.000	1208.000	922.800	644.900	416.100	308.800	245.700	143.200
8.0	2347.000	1577.000	1205.000	842.400	543.600	403.300	320.800	187.100
9.0	2970.000	1996.000	1525.000	1066.000	687.900	510.500	406.100	236.800
10.0	3666.000	2464.000	1883.000	1316.000	849.200	630.200	501.300	292.200

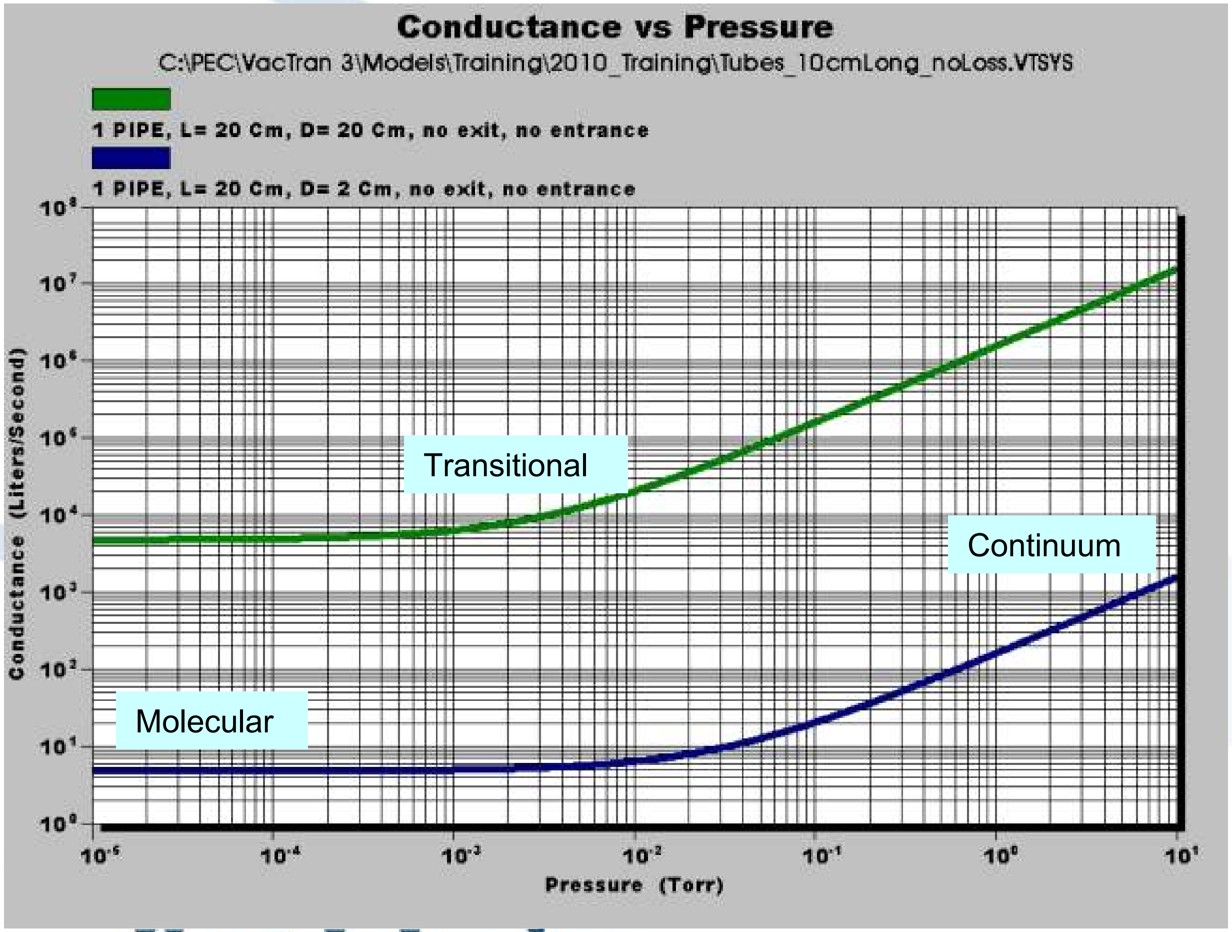
Aperture, long ducts (1/L), short ducts



Pumping Concepts 4

Conductance vs Pressure

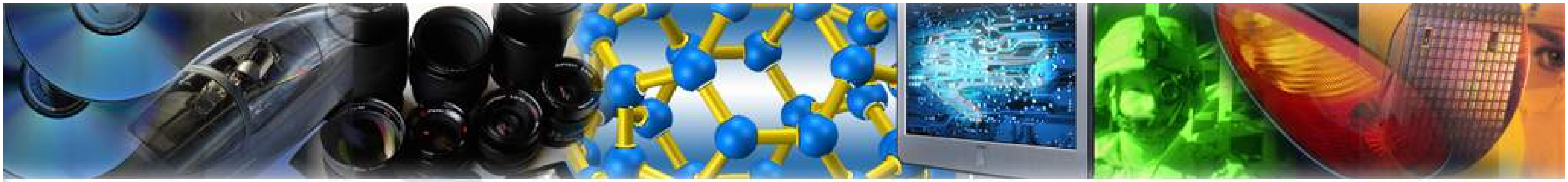
Tubes
(with no losses)



Transitional

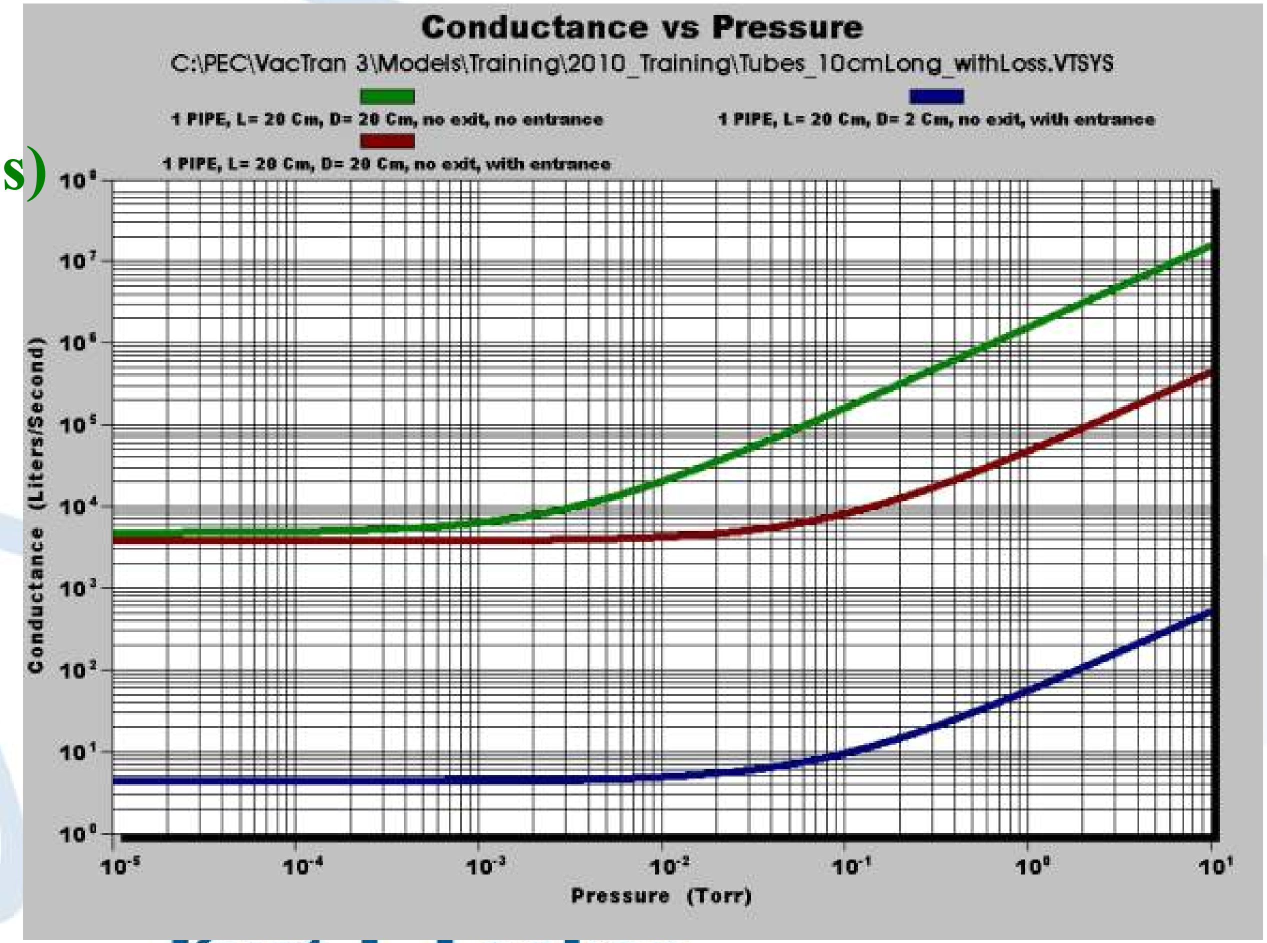
Continuum

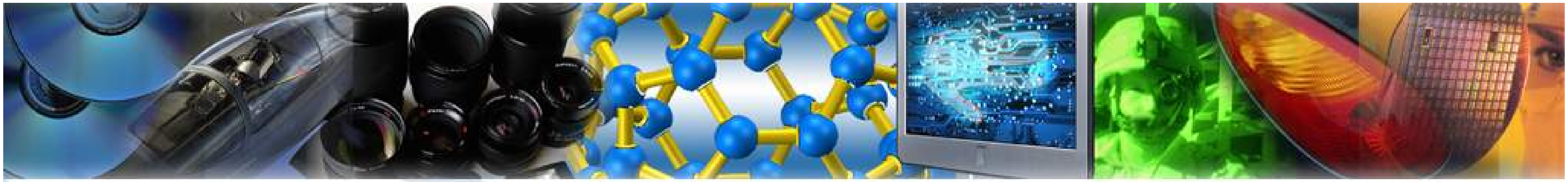
Molecular



Conductance vs Pressure

Tubes
(with entrance loss)

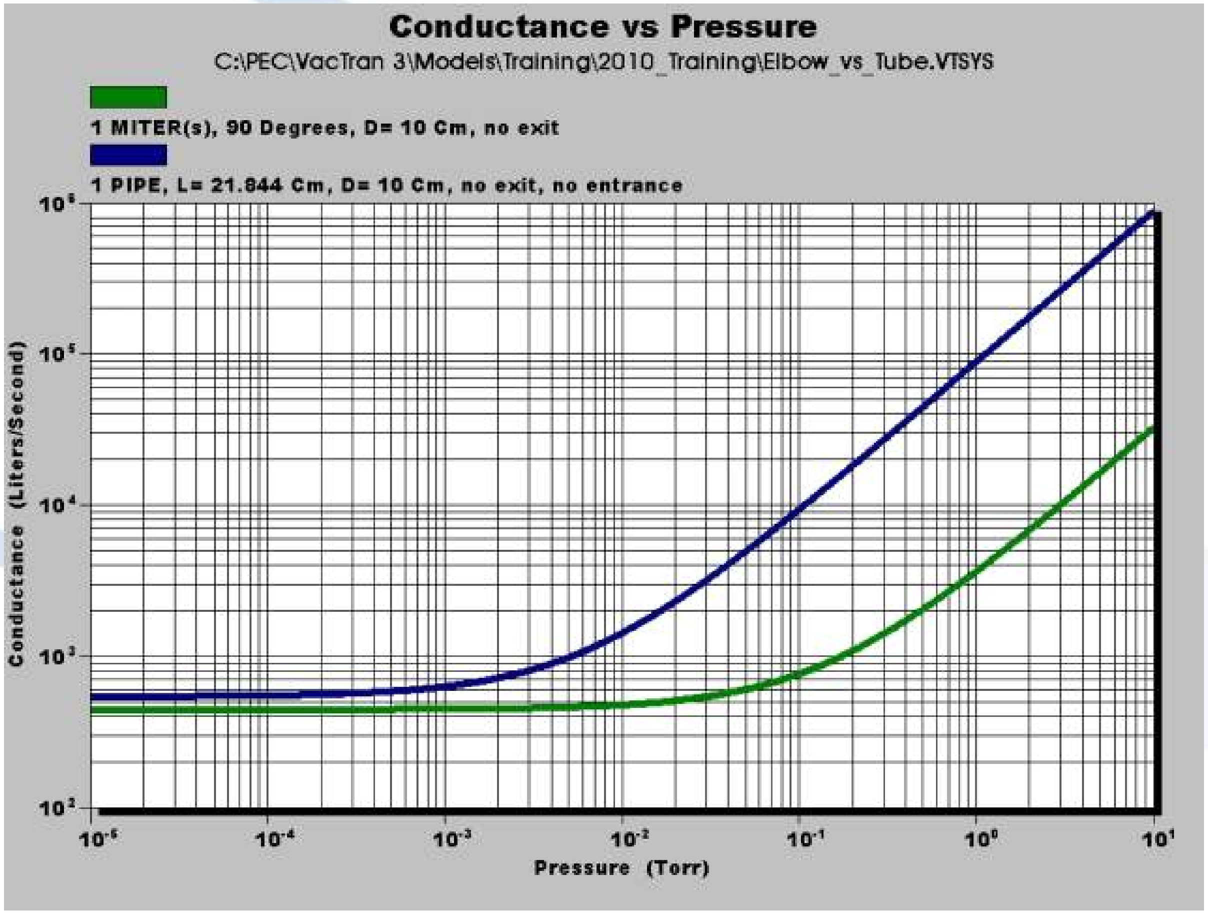


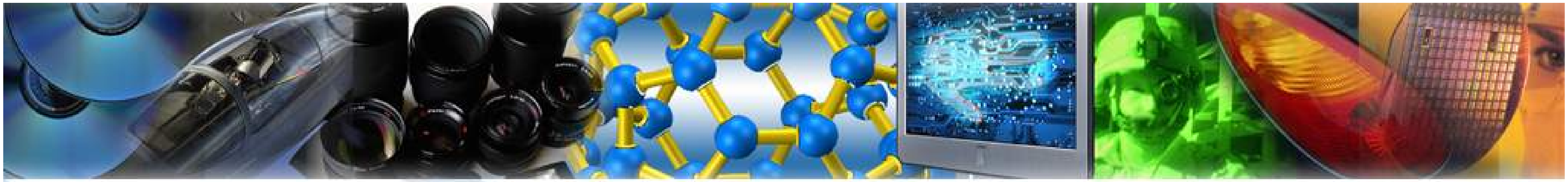


Pumping Concepts 6

Conductance vs Pressure

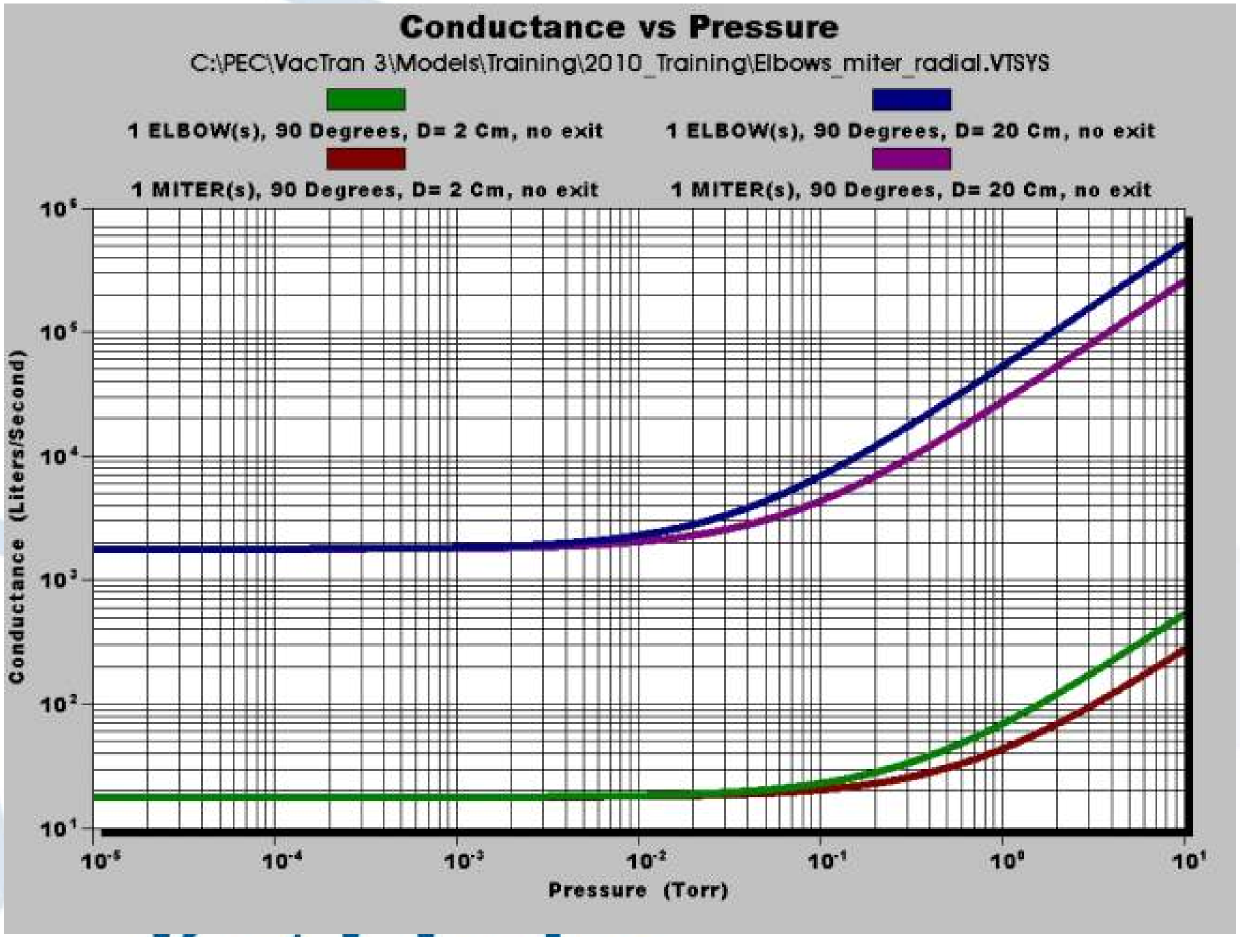
Tube vs Elbow
(of equal 'length')





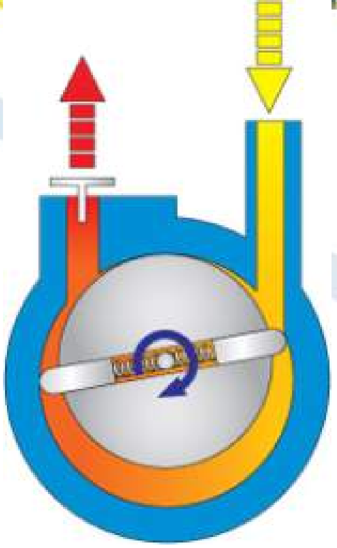
Conductance vs Pressure

Elbow vs Elbow (radius vs miter)



Pumping Concepts 8

*Pumping Speed **



Active Components (Pump/Trap)

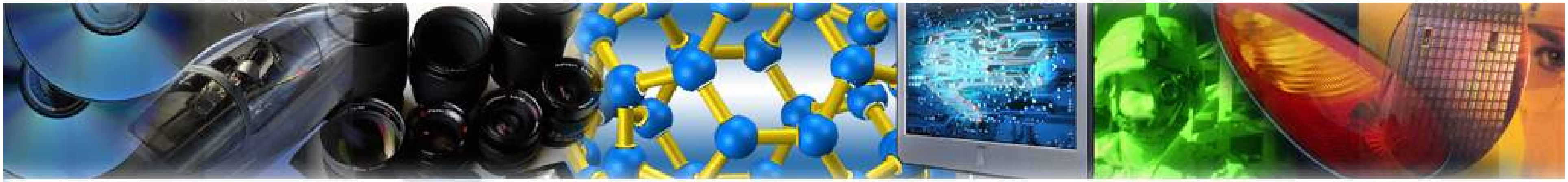
Ability to transfer (remove) gas volume in unit time

Determined by gas, pump's mechanism, and *pressure*)
(Volumetric flow measured in: L/s, cfm, m^3/hr, L/m)

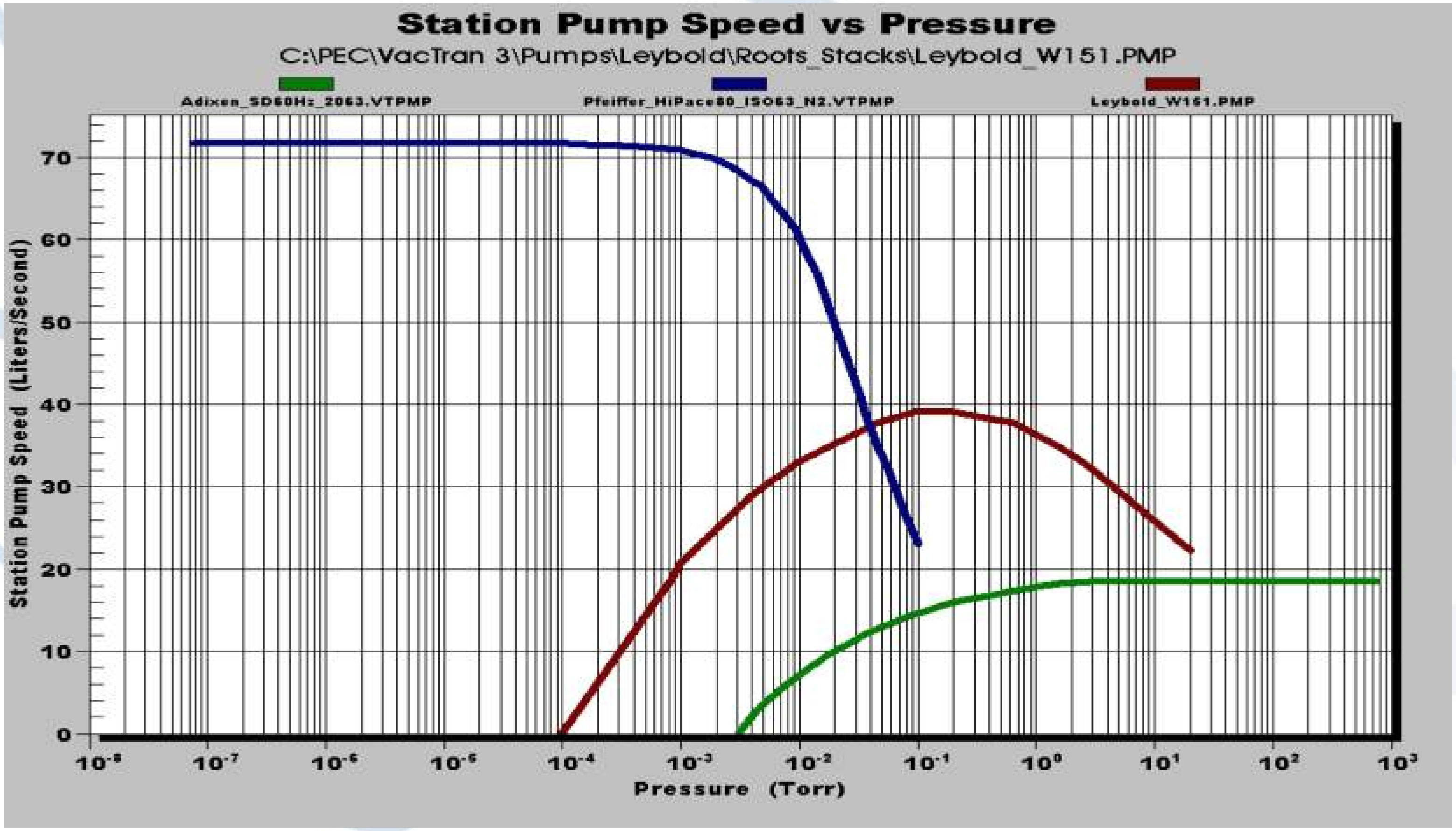
Manuf quotes max value

Ult press

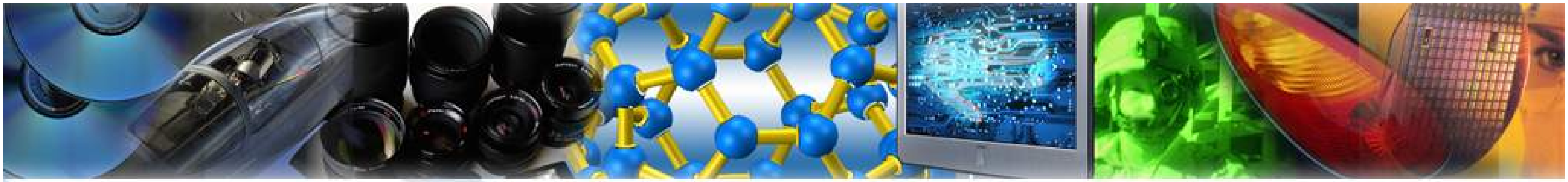
Kurt J. Lesker Company



Pumping Speed vs Pressure



max values



Combining Conductance with Pumping Speed

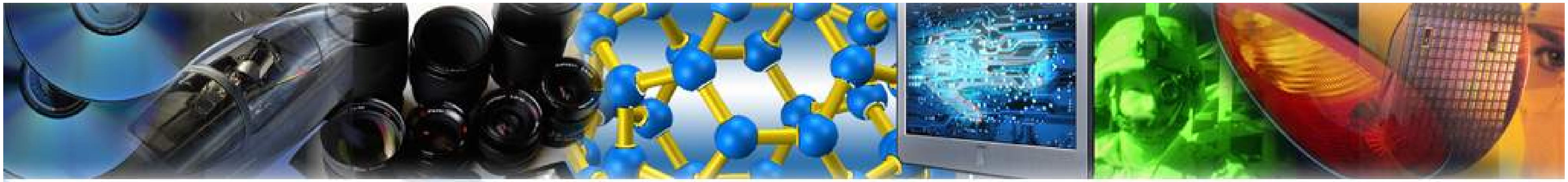
Units for both: *volume / unit time*

Combined as reciprocals

1/Conductance + 1/Pump Speed = 1/Effective Pump Speed

1/EPS = 1/PS + 1/C1 + 1/C2 + 1/C3

Kurt J. Lesker Company



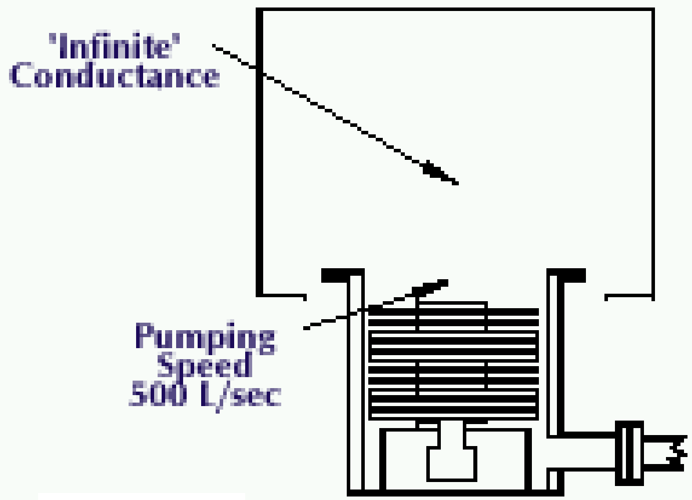
Effective Pumping Speed

500 L/s pump & infinite conductance

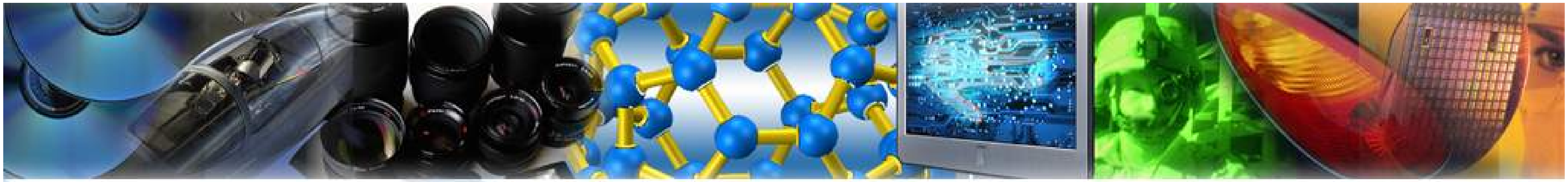
$$1/EPS = 1/500 + 1/\infty$$

$$1/EPS = 1/500$$

$$EPS = 500\ L/s$$



Kurt J. Lesker Company



Pumping Concepts 12

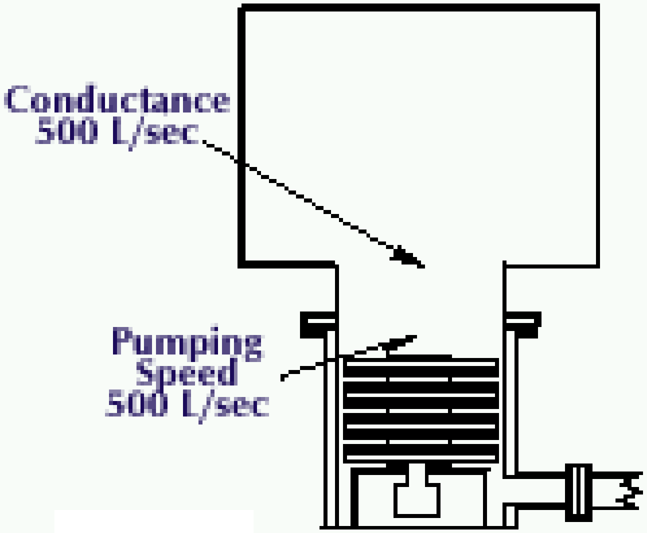
Effective Pumping Speed

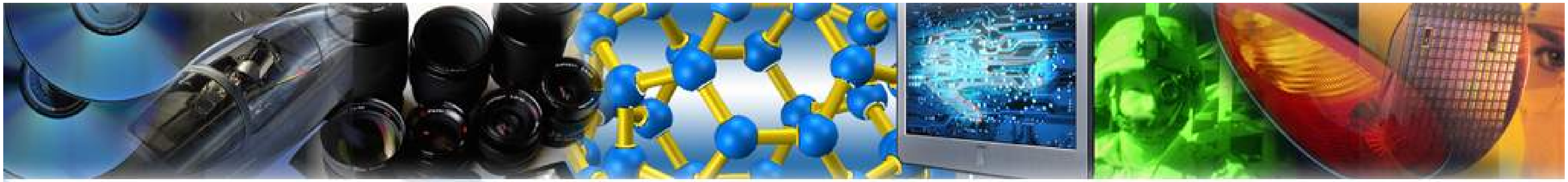
500 L/s pump & 500 L/s conductance

$$1/EPS = 1/500 + 1/500$$

$$1/EPS = 2/500$$

$$EPS = 250\ L/s$$





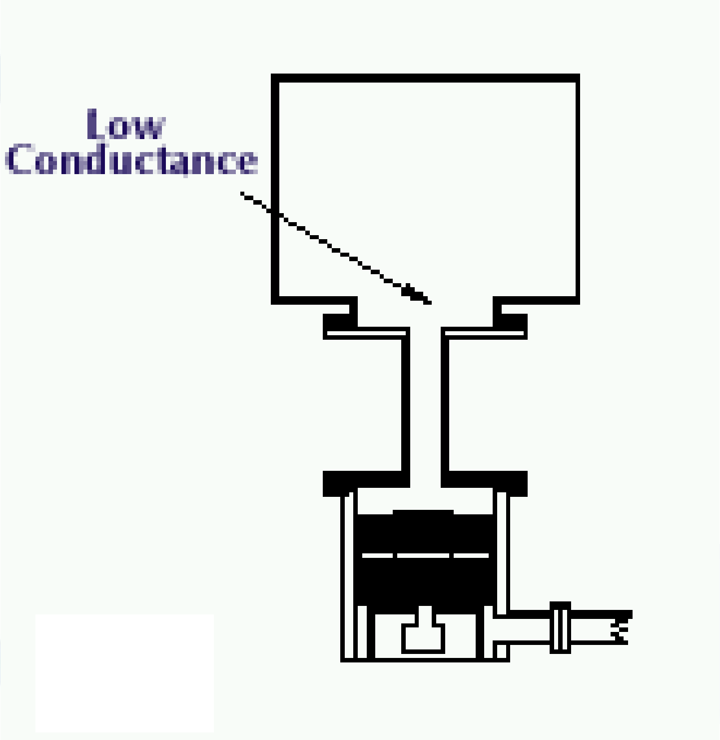
Effective Pumping Speed

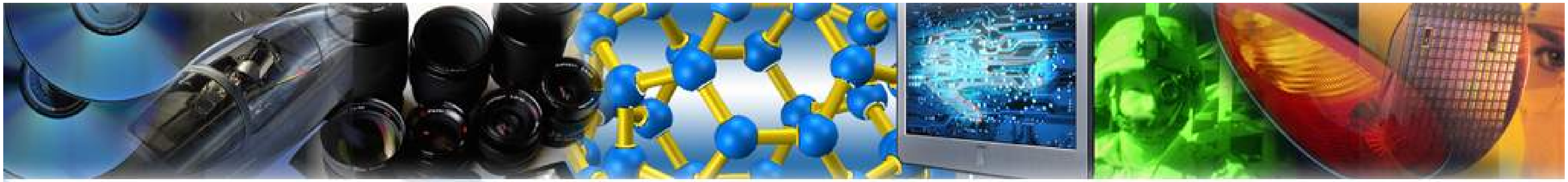
500 L/s pump & 50 L/s conductance

1/EPS = 1/500 + 1/50

1/EPS = 11/500

EPS = 45 L/s

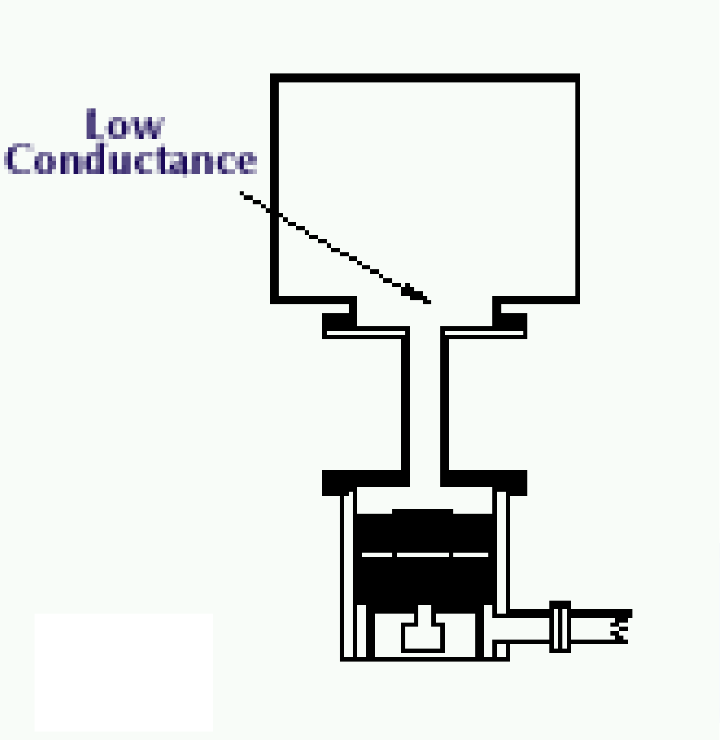




Pumping Concepts 14

Effective Pumping Speed

5000 L/s pump & 50 L/s conductance

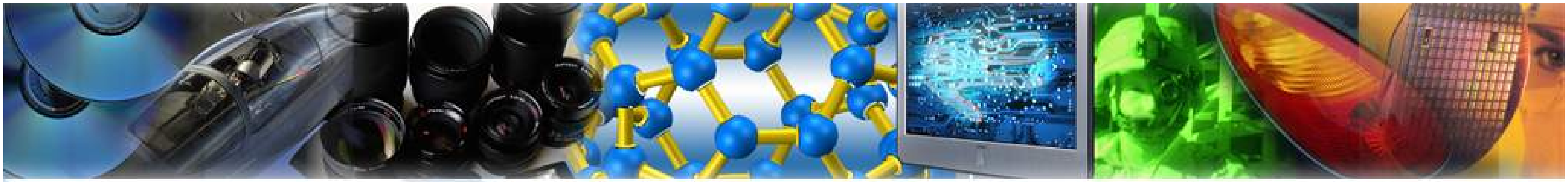


1/EPS = 1/5000 + 1/50

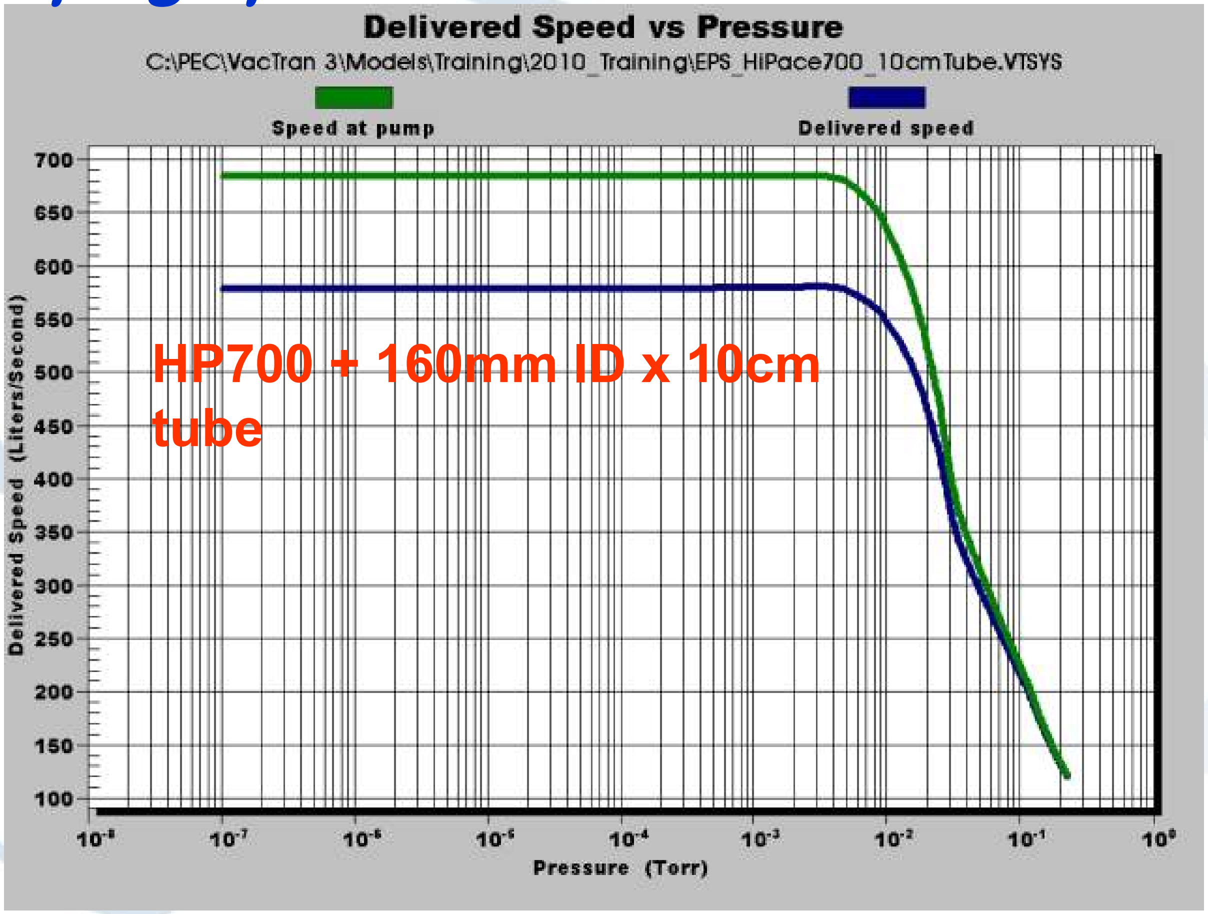
1/EPS = 101/5000

EPS = 49.5 L/s *

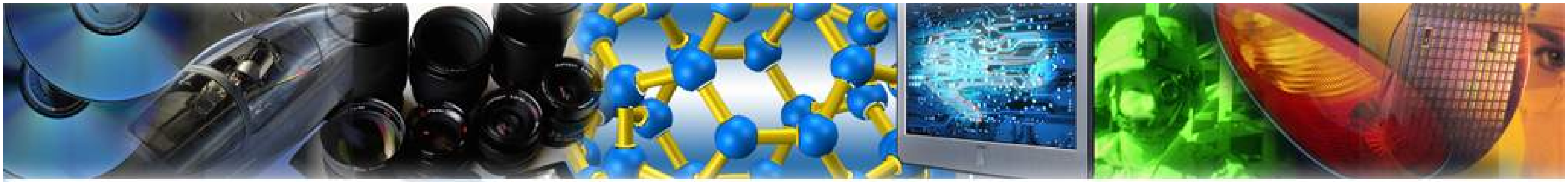
5E6 L/s/



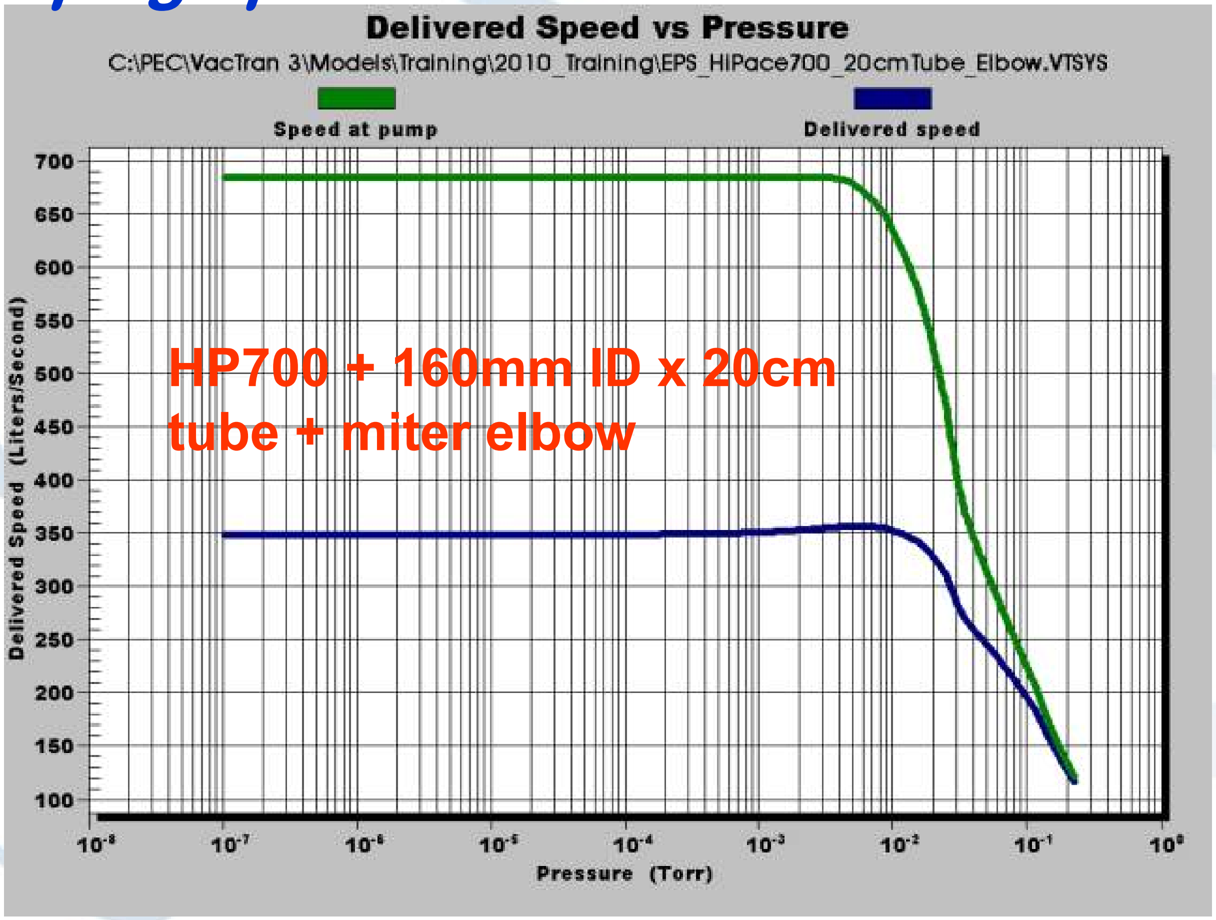
Effective Pumping Speed



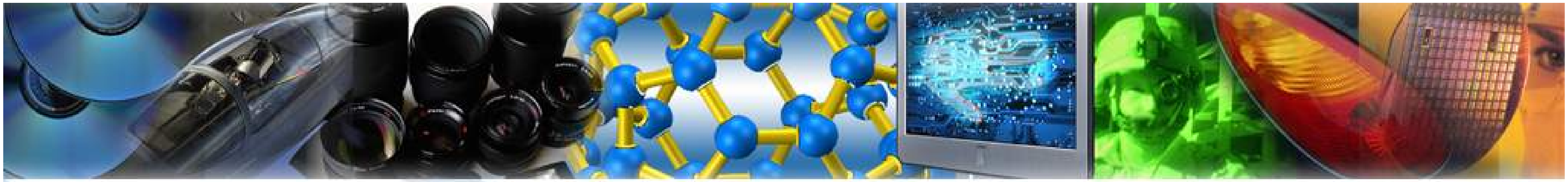
HP700 + 160mm ID x 10cm tube



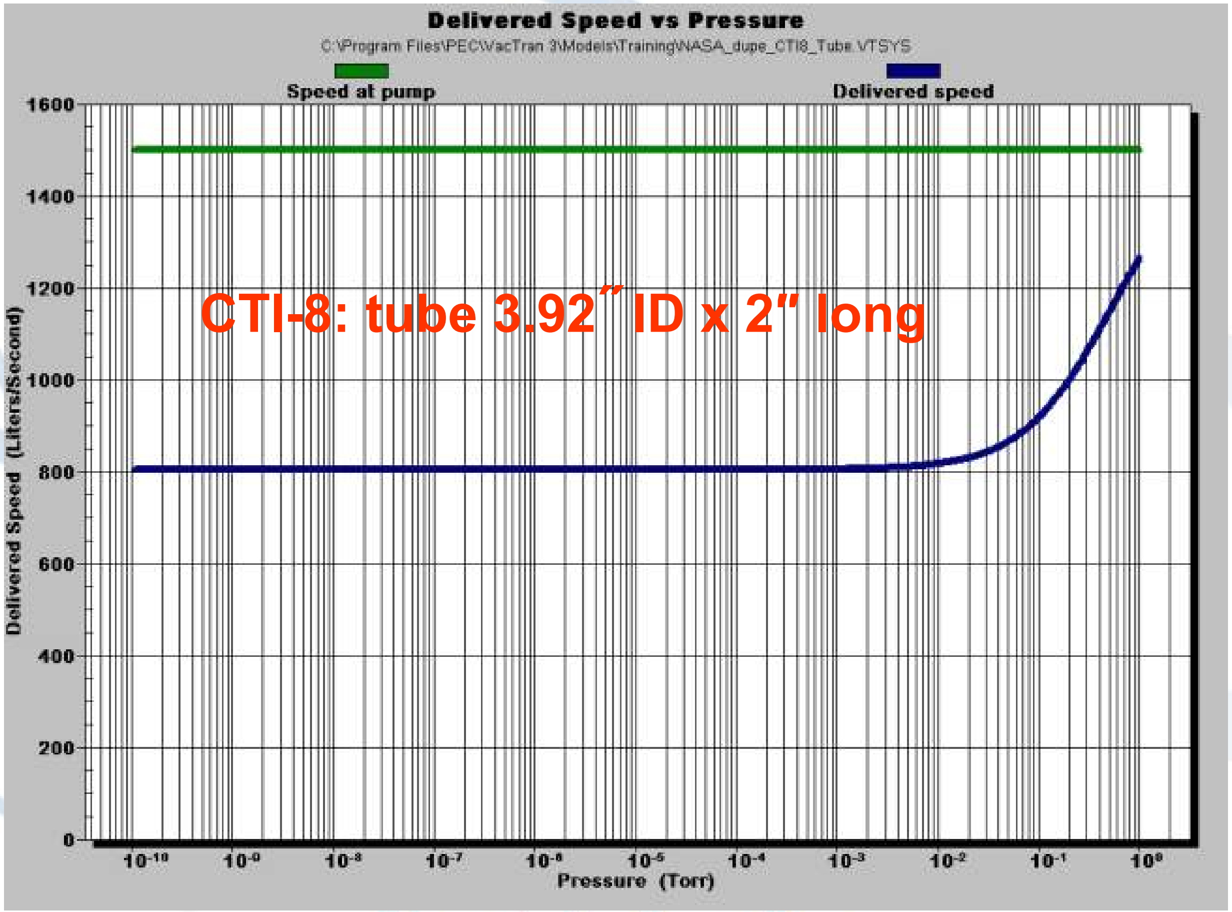
Effective Pumping Speed



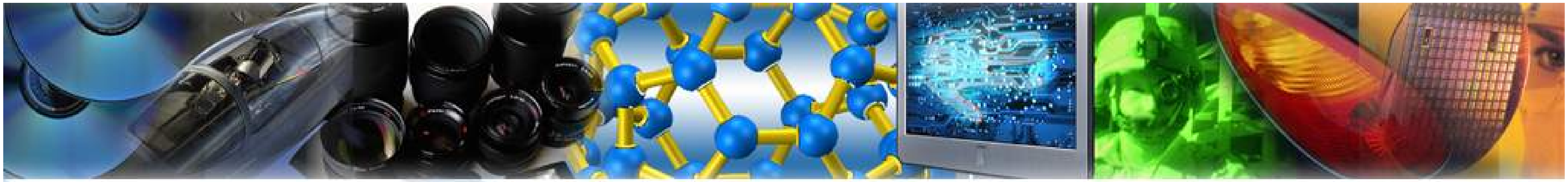
HP700 + 160mm ID x 20cm tube + miter elbow



Effective Pumping Speed



CTI-8: tube 3.92˝ ID x 2" long

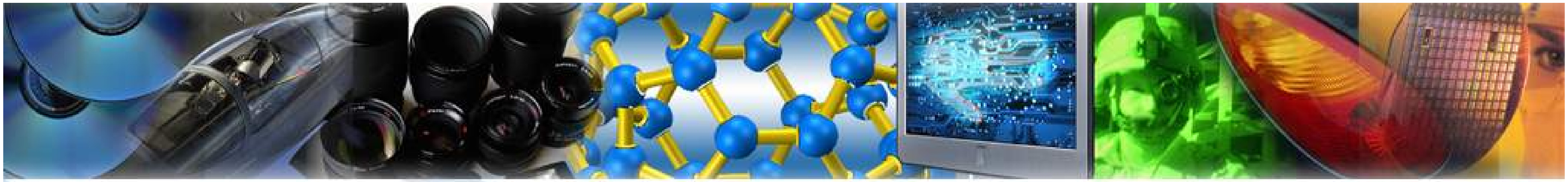


Measuring EPS 1 (i)

1. **Measure chamber (base) pressure** **P1**
2. **Inject known mass flow rate of gas**
3. **Measure new (working) pressure** **P2**
4. **Calculate pressure difference** **P2 – P1**

(Convert mass flow units as needed)

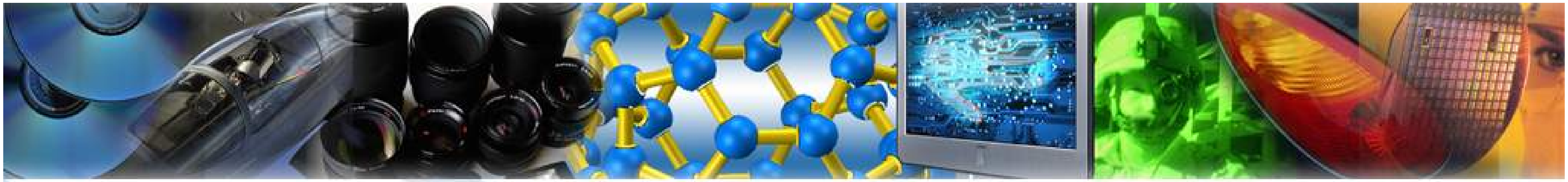
Mass flow / Pressure Difference = EPS



Measuring EPS 1 (ii)

1. Base pressure P1	5×10^{-7} Torr
2. Mass flow (N_2)	10 sccm
3. Working pressure P2	5×10^{-5} Torr
4. P2 – P1	4.95×10^{-5} Torr
10 sccm (10/60) x (760/1000)	1.27×10^{-1} T.L/s
EPS	1.27×10^{-1} T.L/s / 4.95×10^{-5} T
EPS (N_2)	1600 L/s

Kurt J. Lesker Company



Measuring EPS 2 (i)

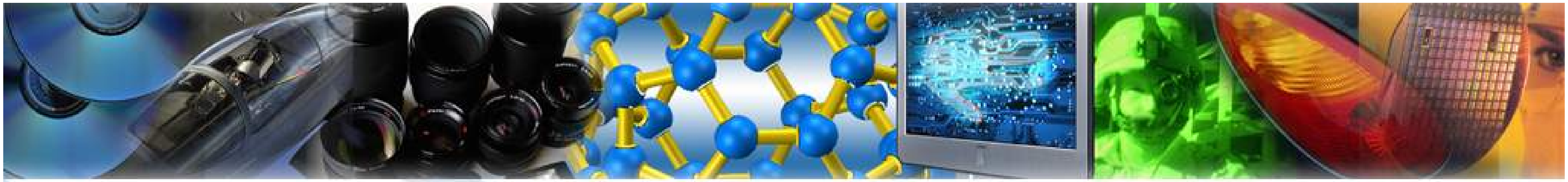
1. Estimate chamber volume V
2. Inject unknown flow of gas
3. Measure (working) pressure P1
4. Time pressure decay

At time = 0 shut off gas flow

At time = t sec measure pressure P2

$$EPS = V/t \times \log_e (P1/P2)$$

Kurt J. Lesker Company



Measuring EPS 2 (ii)

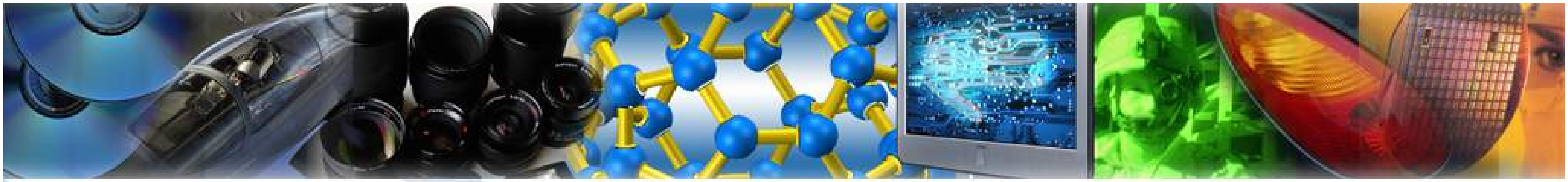
1. **Chamber volume** **150 L**
2. **Inject unknown flow of gas**
3. **Working pressure** **4×10^{-4} Torr**
4. **Time** **15 sec**
5. **Pressure (t = 15 s)** **6×10^{-6} Torr**

EPS $V/t \times \log_e (P1/P2)$

EPS $150/15 \times \ln(4 \times 10^{-4}/6 \times 10^{-6})$

EPS **42 L/sec**

Molecular flow only

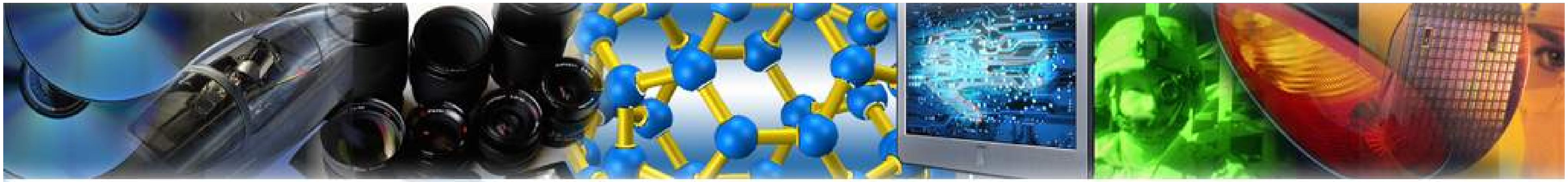


Conductance & Pumping Speed Conclusions

High conductance	shorter/fatter is better
Conductance is too high	(I wish!)
Conductance is too low	serious (and expensive!)
The lowest conductance	wins
Pump's `quoted´ PS	means very little

Think: Effective Pumping Speed

Kurt J. Lesker Company

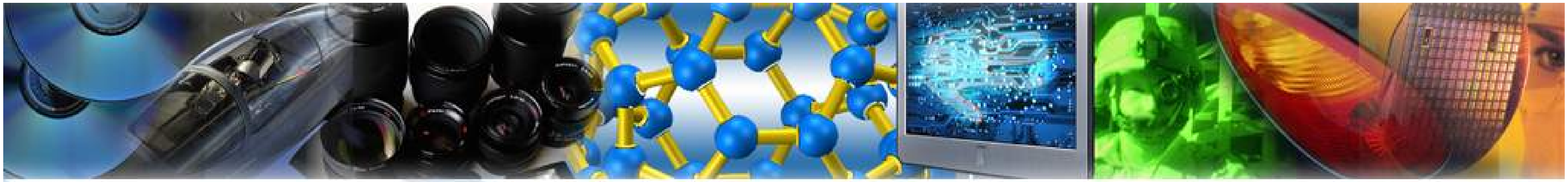


Gas Load

Meaning & Units

Sources of Gas Load

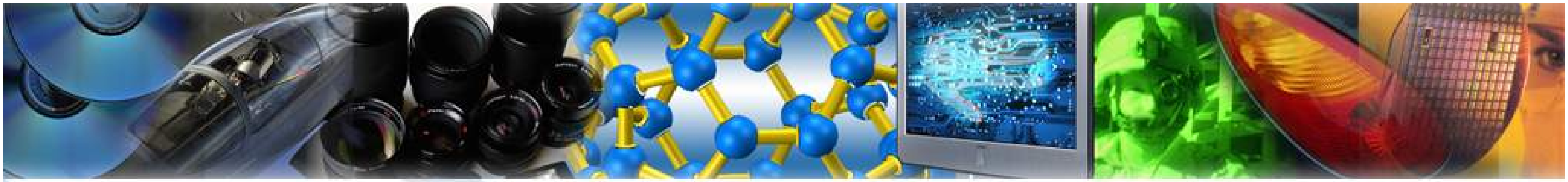
Kurt J. Lesker Company



Gas Load

The total *mass* (quantity/amount) of gas entering the vacuum volume in a given time period

Mass flow measured in: T.L/s, Pa.m^3/s, mbar.cc/s, atm.cc/s, sccm (pressure x volume / time)



Gas Load *- Sources*

Permeation

Real leaks: from air / not from air

Virtual leaks

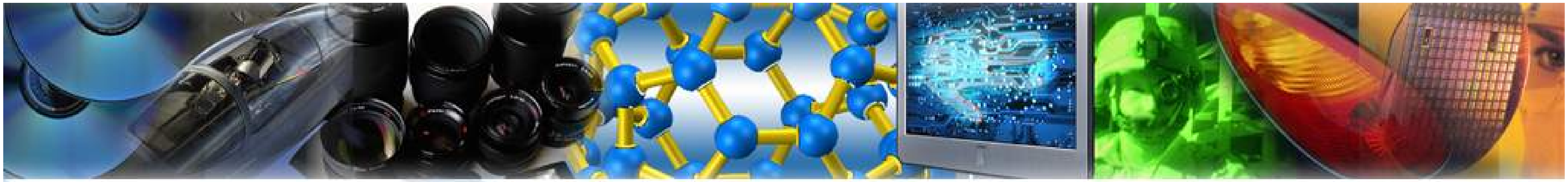
Backstreaming

Diffusion

Sublimation/Evaporation

Injected gas*

Outgassing



Gas Load 3

Gas Load — Permeation

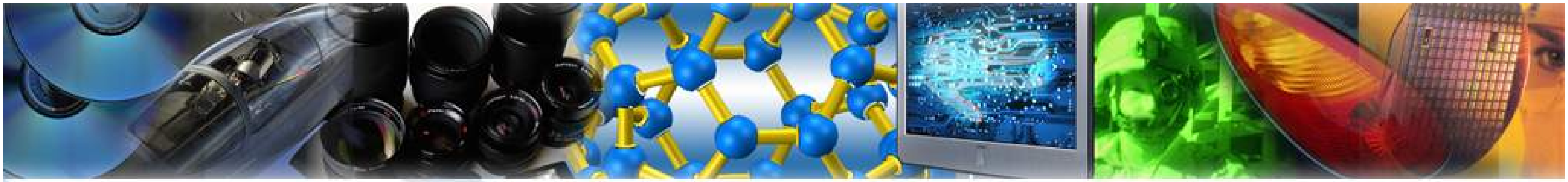
Air / H_2O and o-rings
Air / H_2O and plastic gas line tubing *
H_2O and Teflon insulators *
H_2O and plastic cooling lines (in chamber) *
H_2 / He and glass/silica tubing
H_2 / CO and high temp. metal tubes *

Permeation rates through o-rings depend on:
gas, elastomer, elastomer compounding,
partial pressure, temperature.

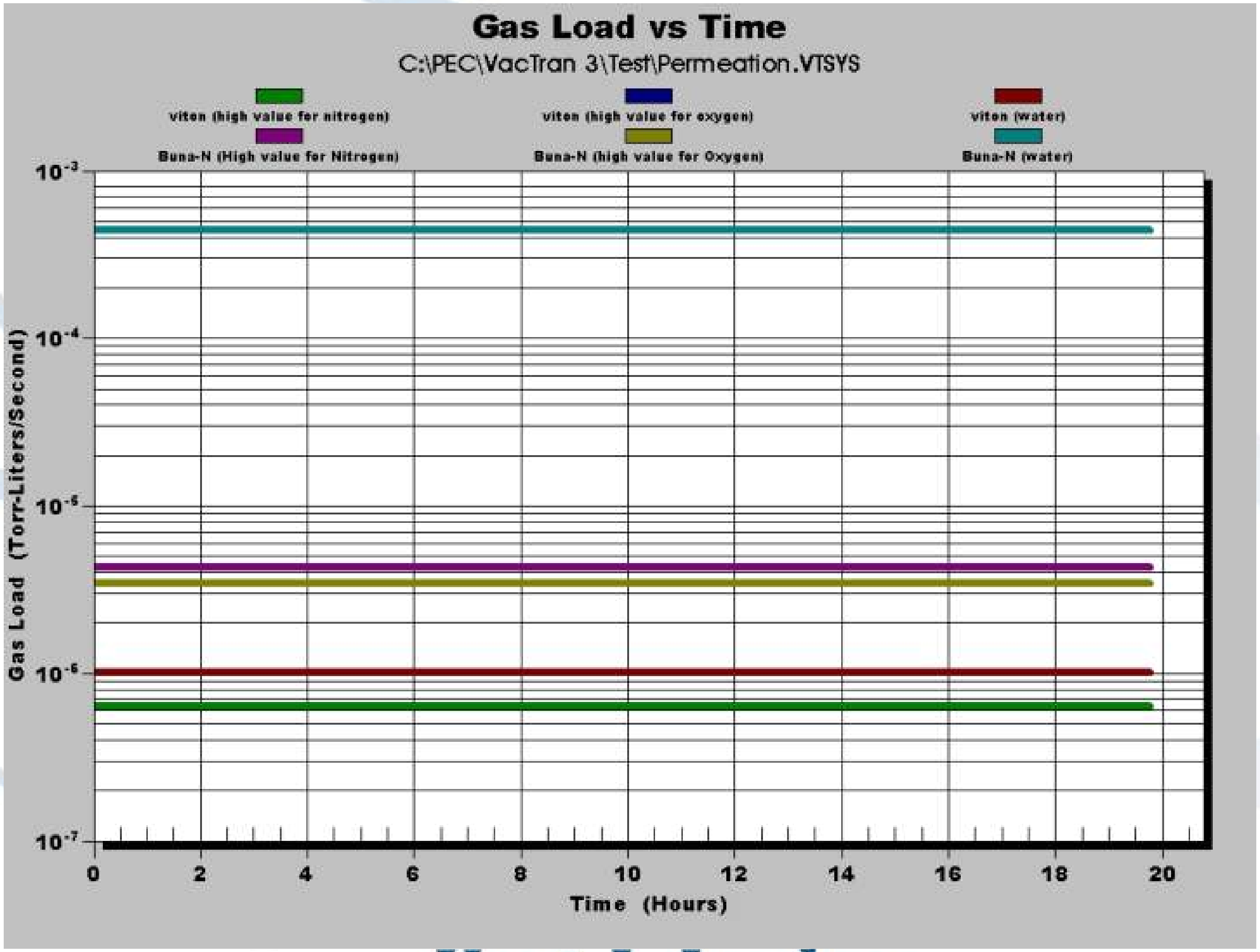
*Reducing permeation? **

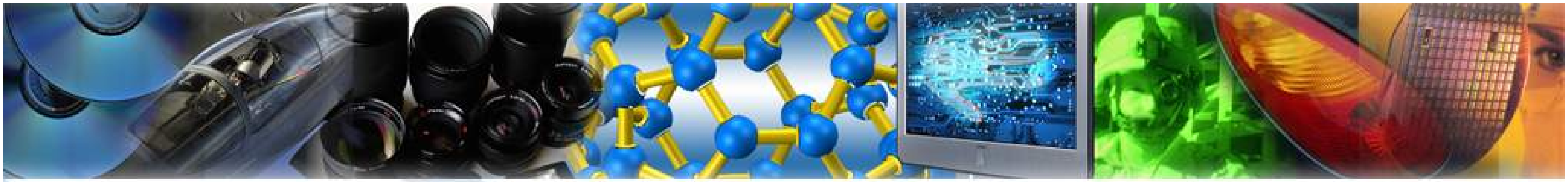
Ar from cyl to cham^x
Terawatt facility
Flex lines
Tritium thru SS
Double with evac

Kurt J. Lesker
Company



Gas Load 4


Gas Load vs Time
C:\PEC\VacTran 3\Test\Permeation.VTSYS
🟩 viton (high value for nitrogen)
🟦 viton (high value for oxygen)
🟥 viton (water)
🟪 Buna-N (High value for Nitrogen)
🟨 Buna-N (high value for Oxygen)
🟦 Buna-N (water)
Gas Load (Torr-Liters/Second)
10-3
10-4
10-5
10-6
10-7
0
2
4
6
8
10
12
14
16
18
20
Time (Hours)



Gas Load 5

Gas Load *— Real Leaks (air)*

Gaskets at flanges/joints

Re-welds (in high carbon SS)

At welds after baking/cleaning

At welds in cryo conditions

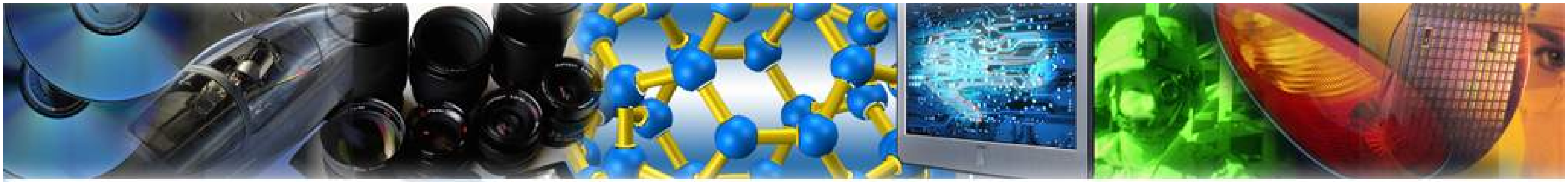
Blank flanges cut from bar

Feedthroughs:

- **braze faults/cracked ceramics**
- **porous deep drawn weld lips**

Detecting leaks?

Kurt J. Lesker Company



Gas Load 6

Gas Load — Real Leaks (not air)

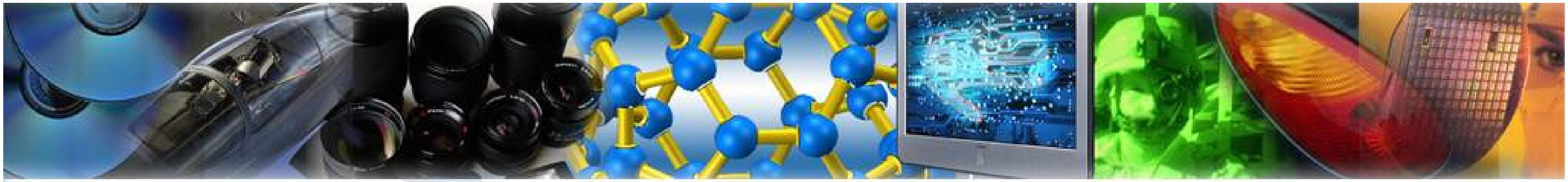
Needle valves connected to gas source

Leaking shut-off valves connected to gas source

Leaking valve on shut-off mass flow controller

Gas/water circulation lines inside chamber with cracked tube or leaking joint

Detecting (not air) leaks?



Gas Load *— Virtual Leaks*

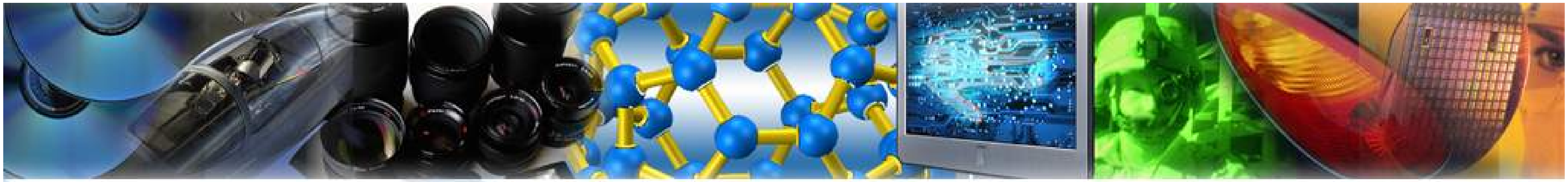
Blind tapped holes / non-vented hardware

Multi-strand wire with plastic insulation

Flat surfaces clamped together

Welds on air-side surfaces

Test for virtual leaks?



Gas Load — *Backstreaming*

Oil vapor: ***rotary vane & piston, diffusion, oil ejector***

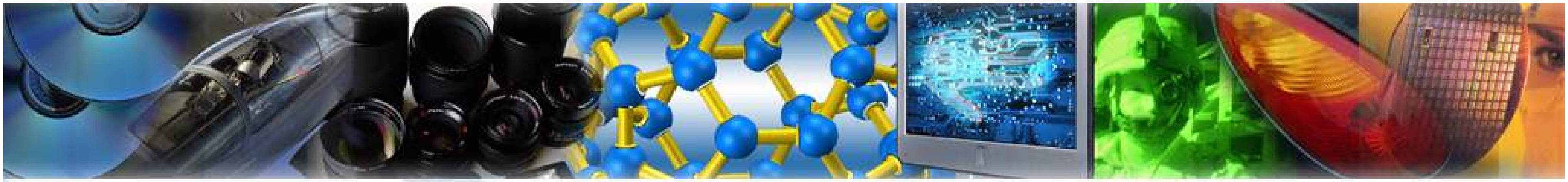
Methane, argon: ***ion (and getter?)***

Hydrogen, helium, neon: ***turbo, cryo, molecular drag***

Water vapor: ***liquid ring, stream ejector***

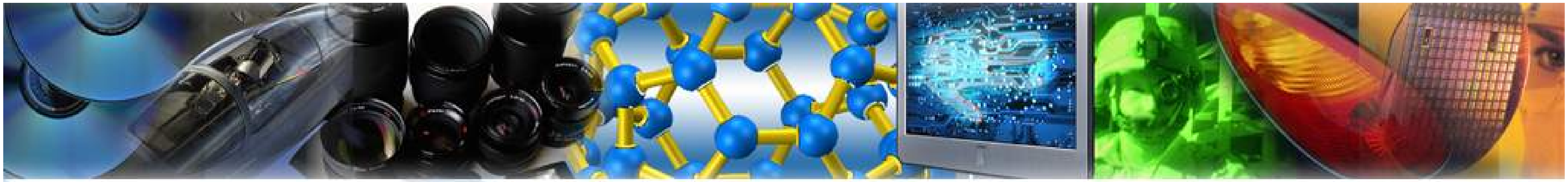
Check for backstreaming?

Kurt J. Lesker Company



Gas Load *— Diffusion*

H_2 & CO	**stainless**
H_2	**titanium* / palladium**
H_2O	**glass**
VOMs	**plastics**



Gas Load *— Sublimation/Evaporation*

Metals to avoid

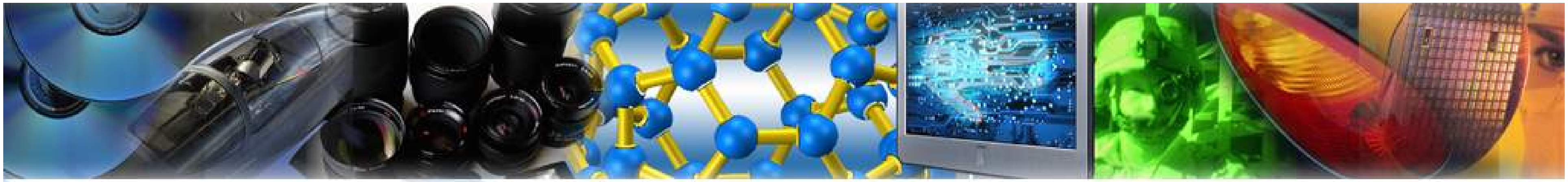
- **Mercury, cadmium, zinc**
- **Cesium, rubidium, potassium, sodium**
- **Stainless steels (containing non-metals)**

Non-Metals to avoid

- **Phosphorus, arsenic**
- **Sulfur, selenium**

Refer to VP charts

Kurt J. Lesker Company



Outgassing

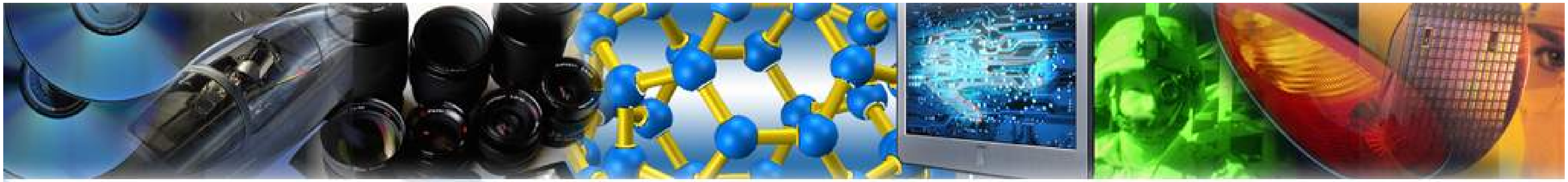
What is it? Units of measure

What are the worst sources?

Main components

Reducing outgassing

Kurt J. Lesker Company



Outgassing 1

Outgassing

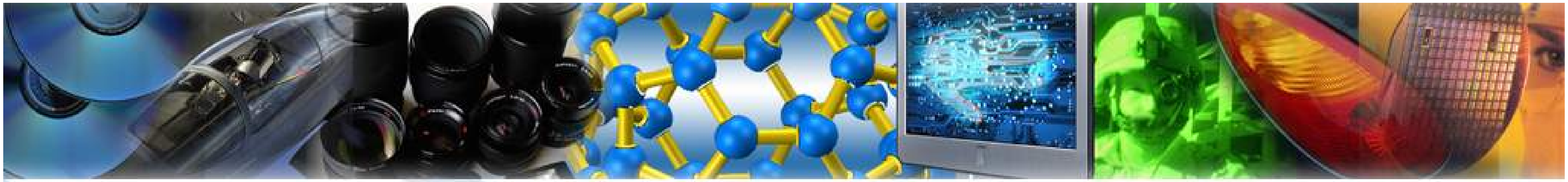
Consider all gas phase and absorbed vapor molecules inside a vacuum chamber

Outgassing Rate is difference between number of molecules:

- **desorbing from the surface (in time ‘t’)**
- **absorbing on the surface (in time ‘t’)**

Outgassing follows exponential decay

Kurt J. Lesker Company



Outgassing Rate

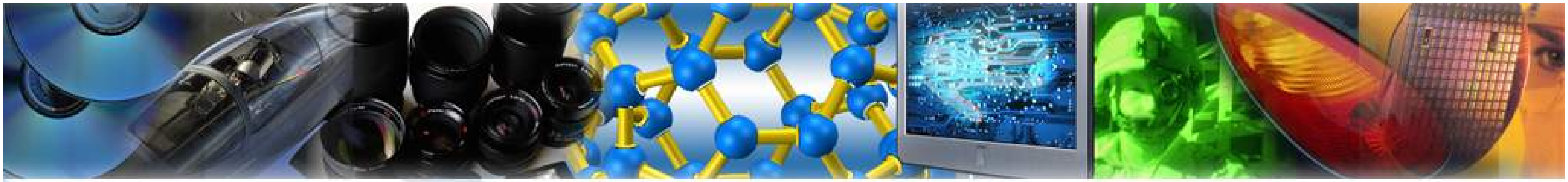
Effective desorption rate from a given surface measured by rate-of-rise test (from a significantly large area)

- **After preparation & cleaning in a repeatable way**
- **At a particular temperature**
- **After a specified time under vacuum (1 & 10 hours)**
- **From a specified area**

Mass flow/unit area measured in:

$T.L.cm^{-2}.s^{-1}$; $mbar.L/cm^{2}.s$; $Pa.m^{3}/m^{2}.s$; ($W.m^{-2}$)

(Pressure x volume / area x time)



Outgassing 3

Main Components

Water vapor

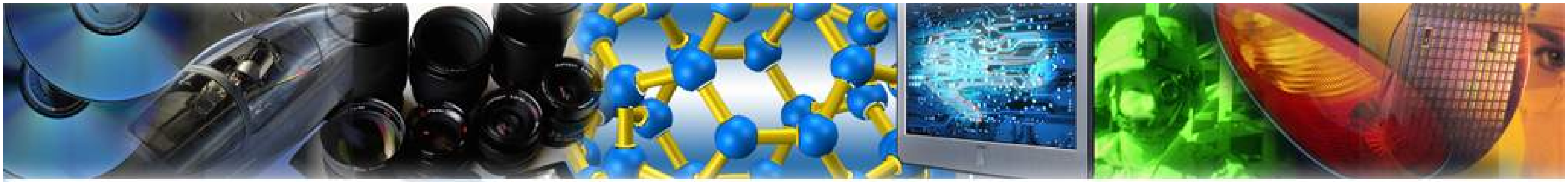
Oil/grease (‘hydrocarbons’)

Solvents

VOMs

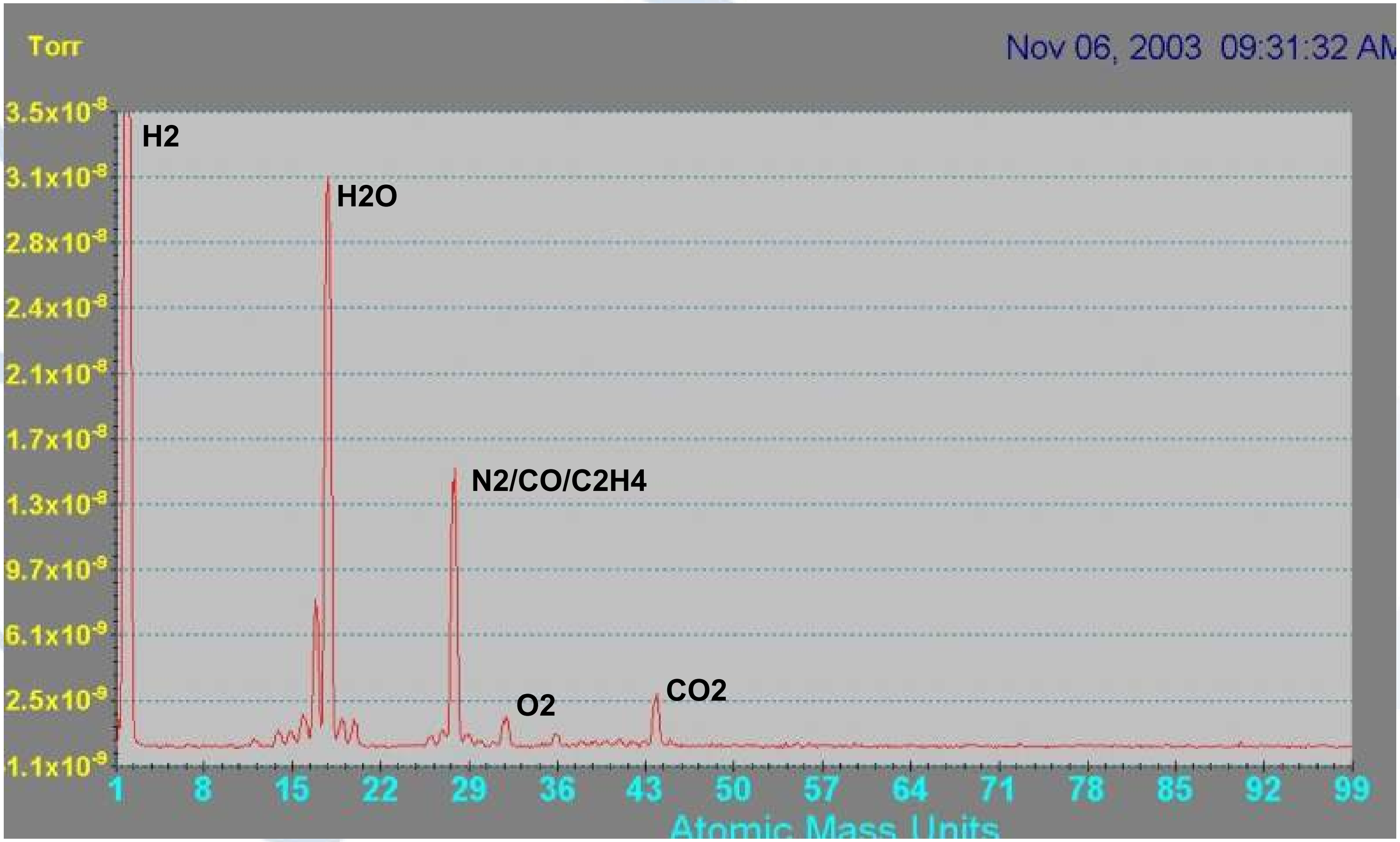
H_2 and CO

'Other stuff'

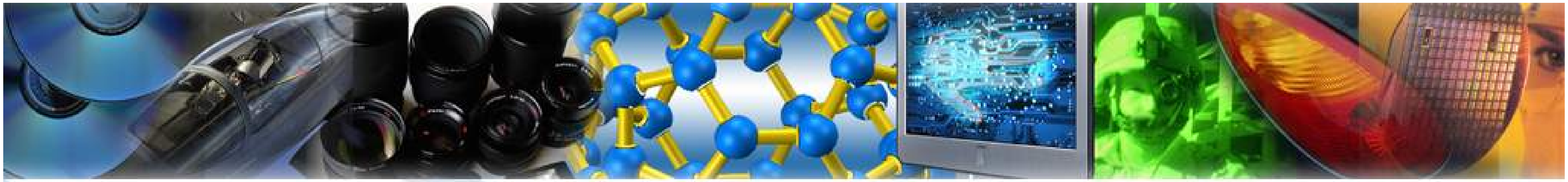


Outgassing 4

Main Components



Kurt J. Lesker Company



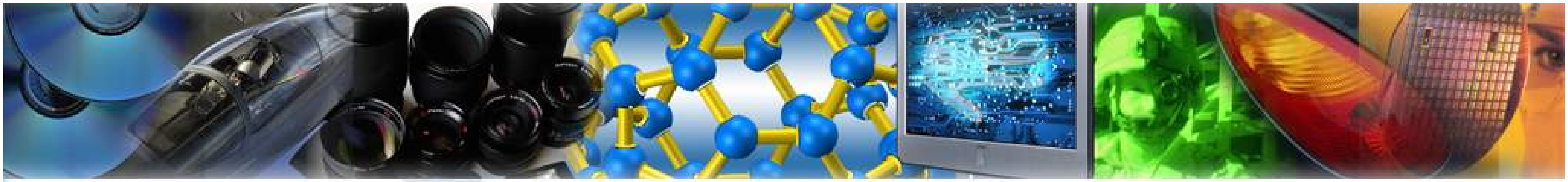
Worst Sources

Porous surfaces (ceramics or metals)
Plastics, elastomers, polymers
Previously backstreamed oil
Epoxy glues
Lubricating/sealing/heat transfer greases

and

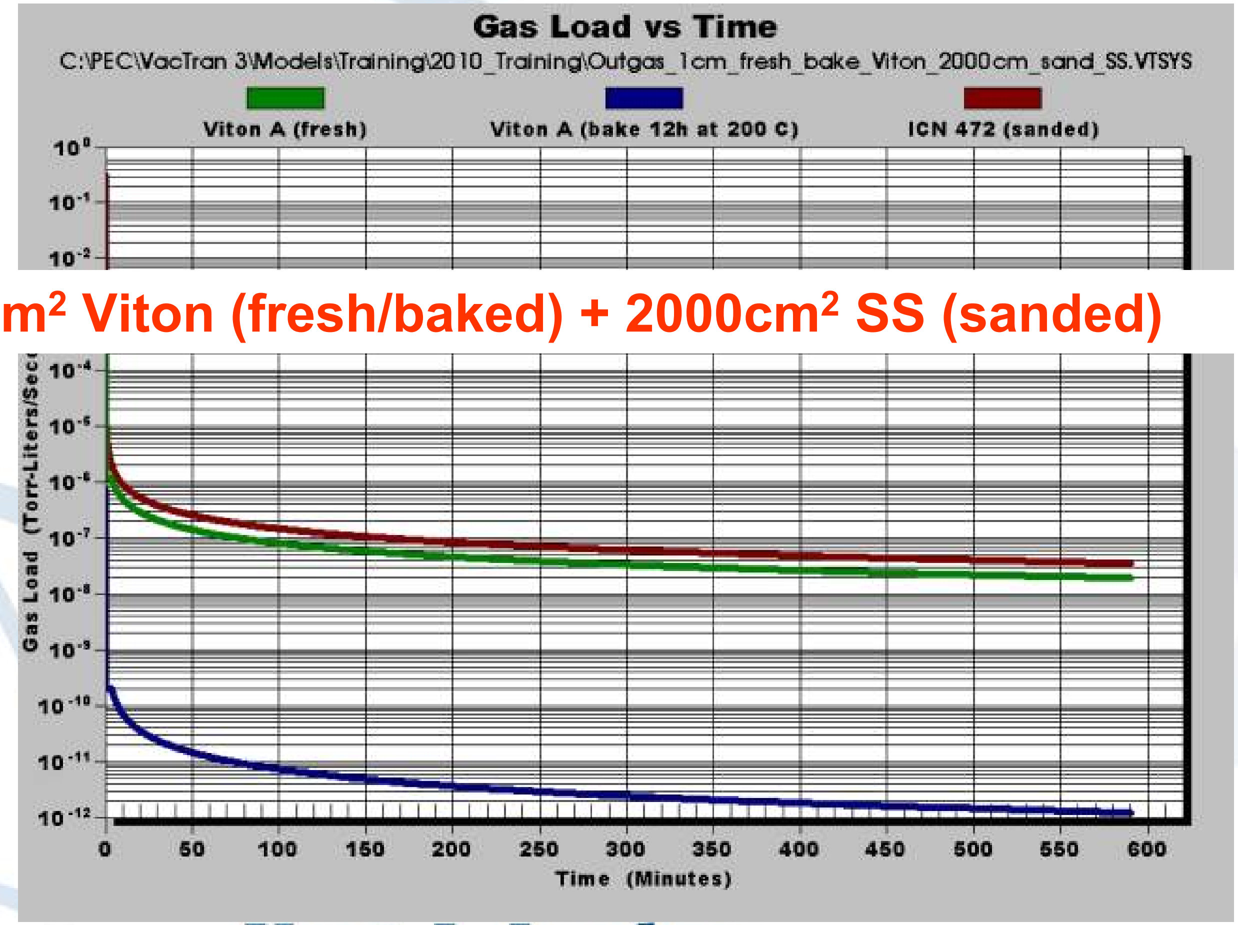
Us!

(*hair, skin cells, dust mites, spit, fingerprints, food*)

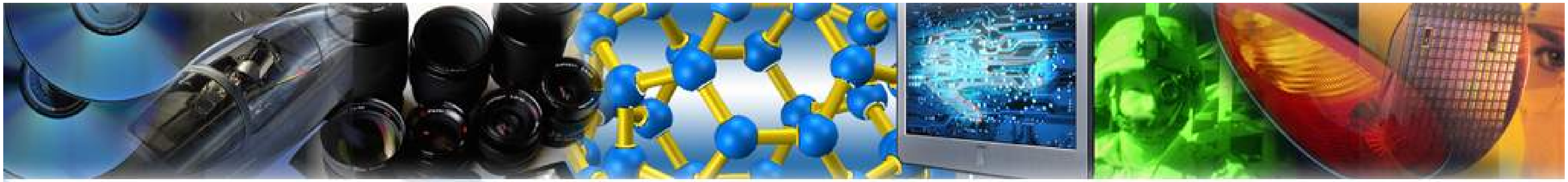


Outgassing 6

Outgassing vs Time

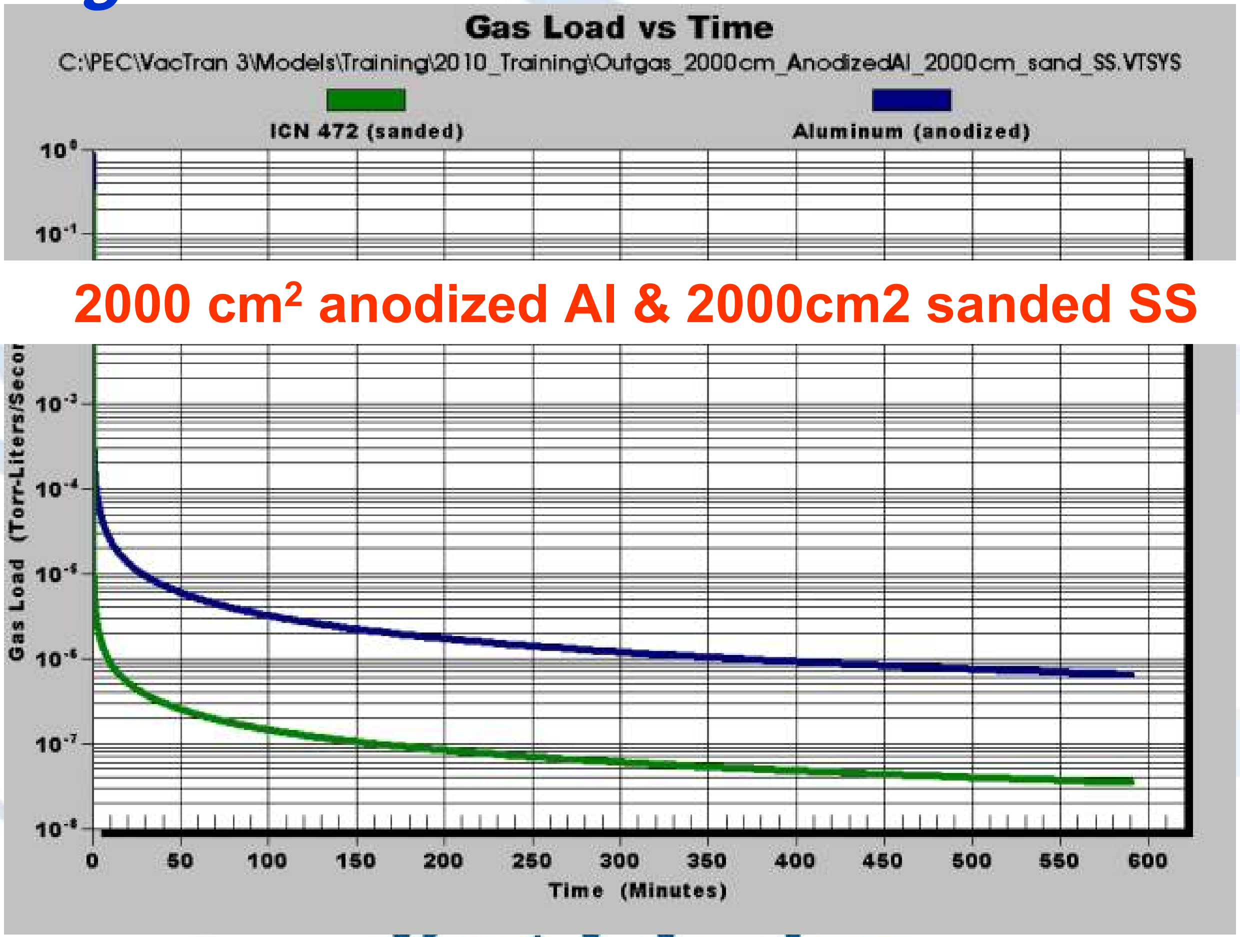


1cm^2 Viton (fresh/baked) + 2000cm^2 SS (sanded)



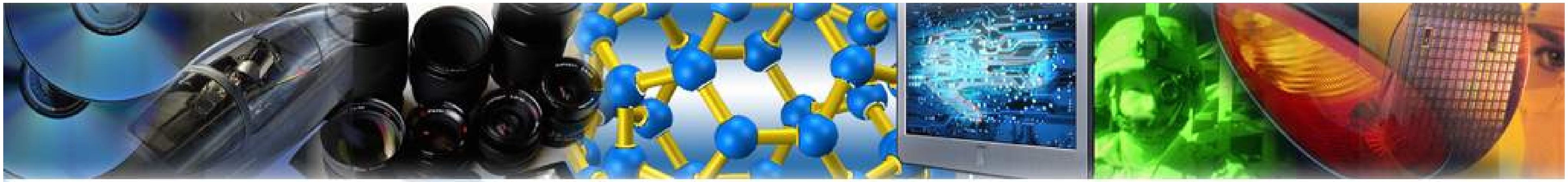
Outgassing 7

Outgassing vs Time



2000 cm^2 anodized Al & 2000cm2 sanded SS

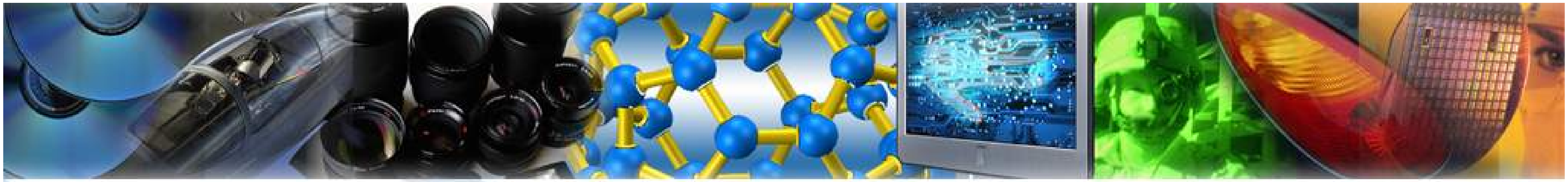
Kurt J. Lesker
Company



Reducing Outgassing – 1st Steps

1. **Make a *log book* and document everything!**
2. **Don’t put weird stuff in the chamber**
3. **Solvent clean everything (no plastic squash bottles) ***
4. **Vacuum bake before assembly (if possible)**
5. **Wrap it (in what?) until ready to mount**
6. **Never touch anything with bare hands!**

Vapor degrease



Reducing Outgassing – 2nd Steps

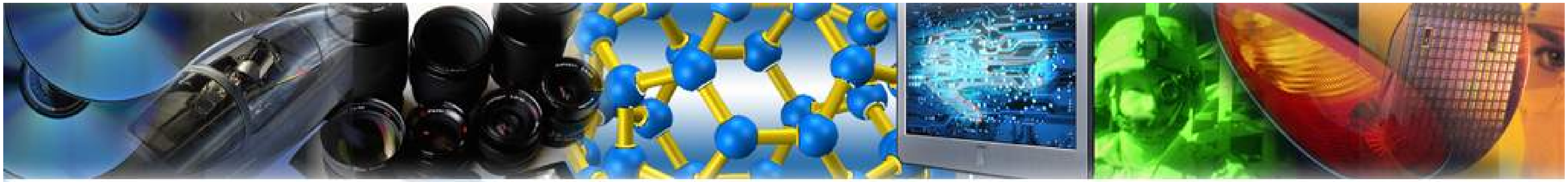
Vacuum History

Heat

Light

Plasma

(Chemistry)

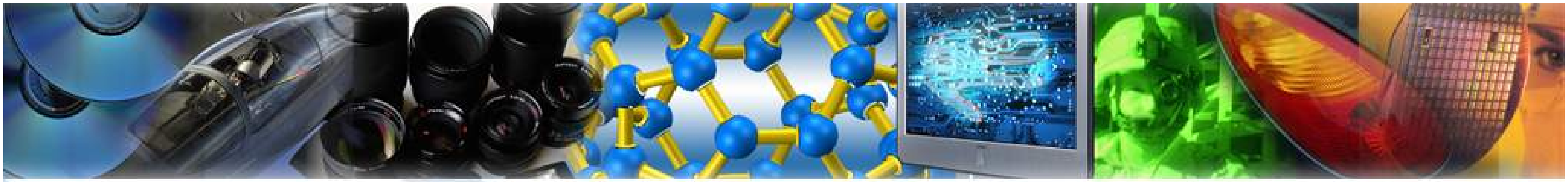


Reducing Outgassing *– Vacuum History*

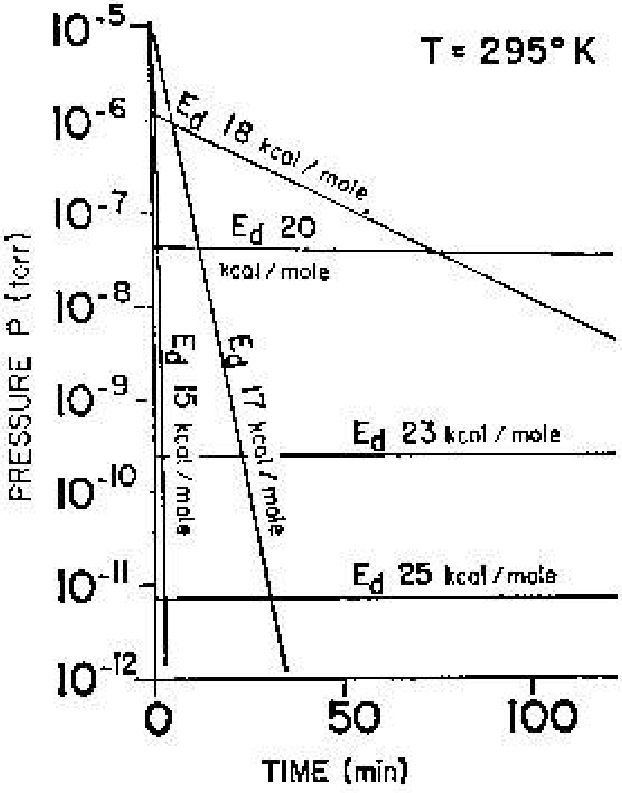
Following initial pump-down, subsequent pump-down times depends on:

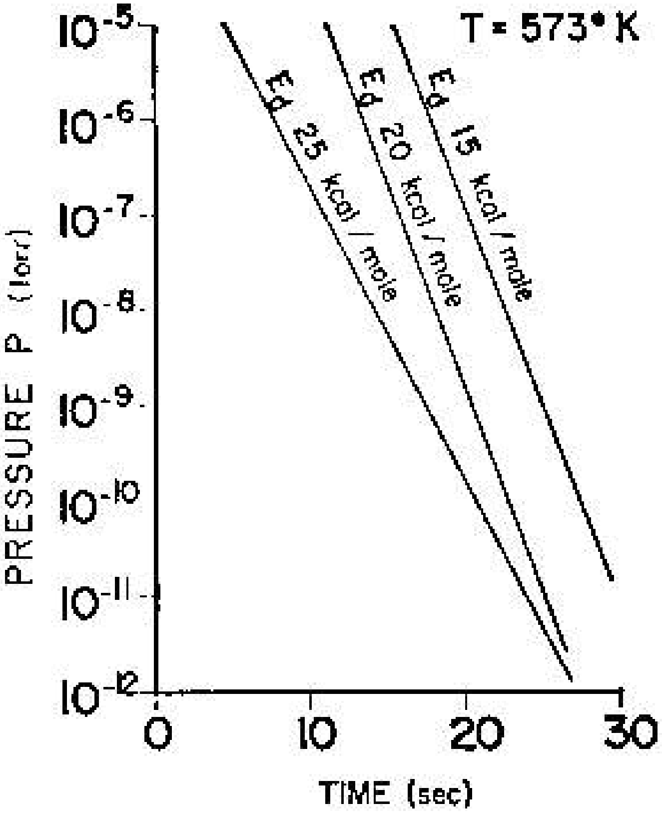
- **Time at atmosphere when vented**
- **Venting gas & dryness of vent gas ***
- **Dry gas flowing while chamber vented ***
- **Application or process in chamber ***

LN2 offgas
Partial close openings
Live with it



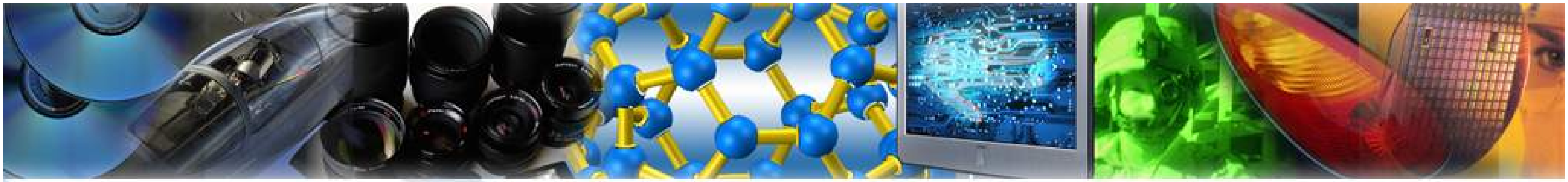
Reducing Outgassing* — *Heat





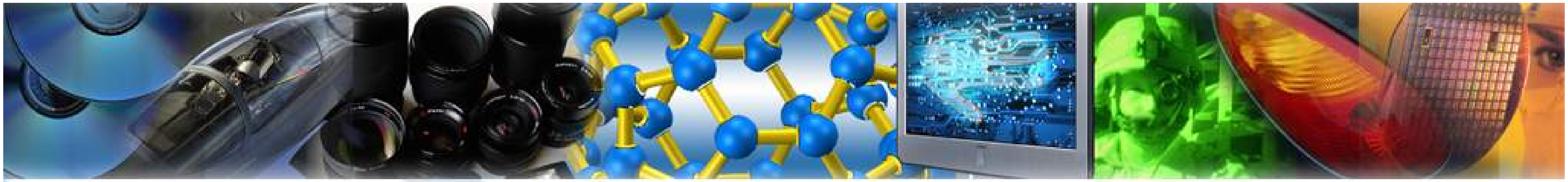
1L, 1L.s, 100cm2

Kurt J. Lesker Company

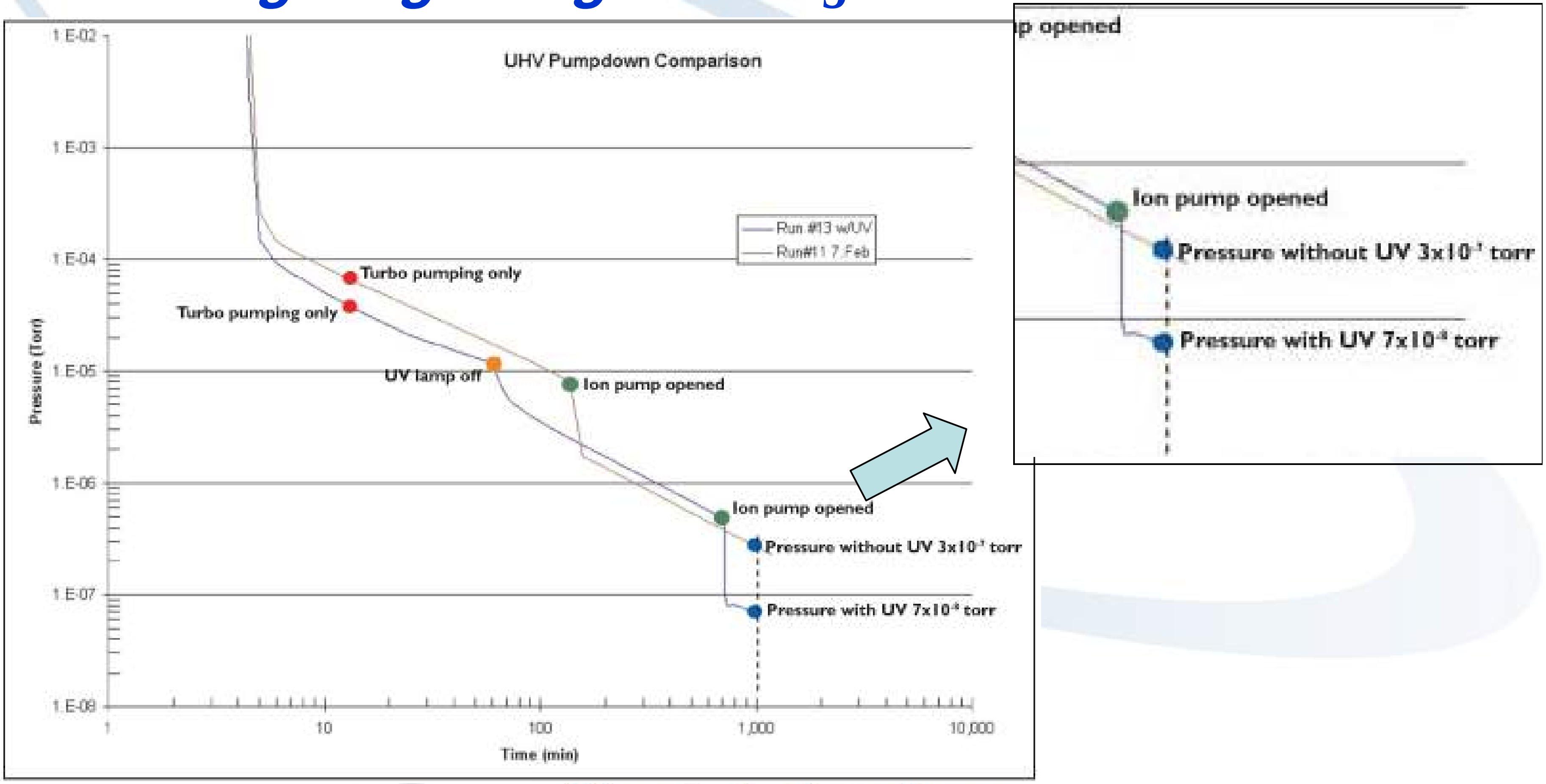


Reducing Outgassing – Heat

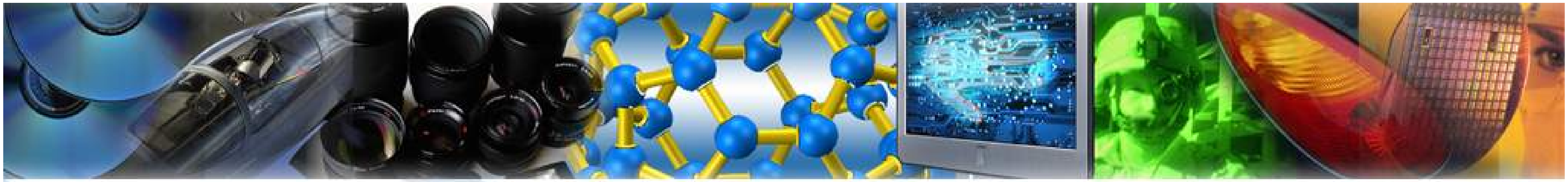
	Unbaked (W/m²)	Baked (W/m²)	Time/Temperature
Stainless	6×10^{-7}	4×10^{-9}	30hr / 250ºC
		3×10^{-10}	2hr / 900ºC
		2×10^{-11}	3hr / 1000ºC +
Aluminum	6×10^{-7}	5×10^{-10}	15hr / 250ºC
		1×10^{-11}	GD & 200ºC
Copper	5×10^{-6}	2×10^{-9}	20hr / 100ºC



Reducing Outgassing – *UV Light*



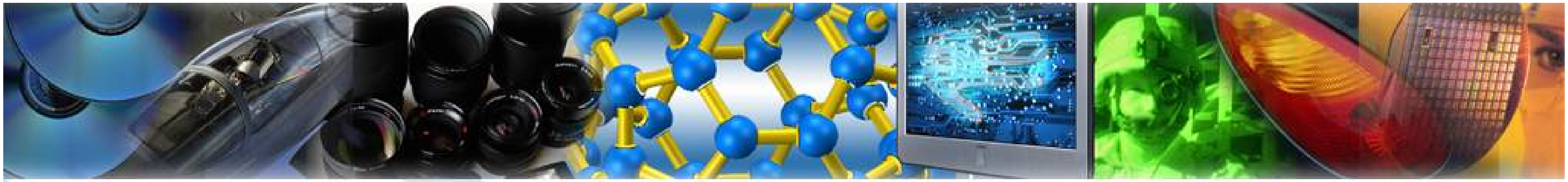
Kurt J. Lesker Company



Reducing Outgassing *– Plasma / Glow Discharge*

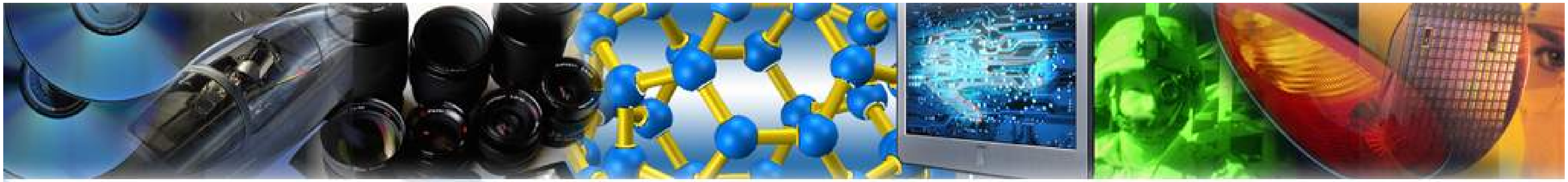
Outgassing Mechanisms Include:

- **UV stimulated desorption**
- **Electron stimulated desorption**
- **Ion bombardment**
- **Hot atom energy transfer**
- **Free radical ‘oxidation’**



Pump Throughput

- *Pump Throughput*
- *Equating Throughput & Gas Load*
- *Flow Conversions & Calculations**



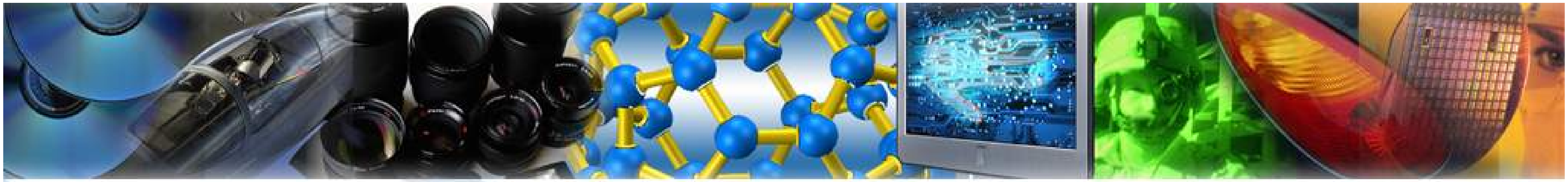
Pump Throughput 1

***Gas Load** — reminder*

Total *mass* (quantity/amount) of gas *entering* the vacuum volume in a given *time* period

Mass flow measured in: T.L/s, Pa.m^3/s, mbar.cc/s, atm.cc/s, sccm (pressure x volume / time)

Kurt J. Lesker Company



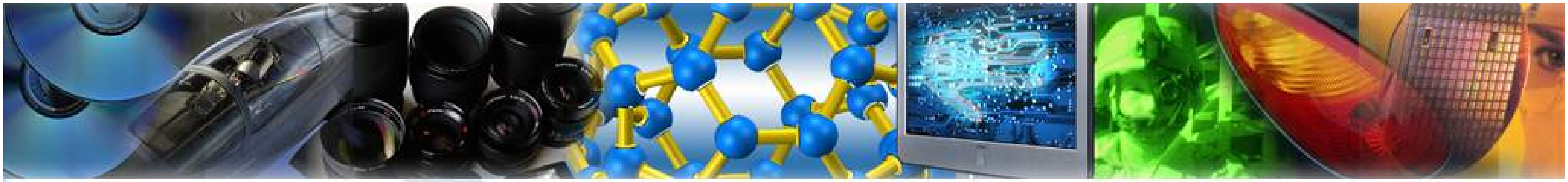
Pump Throughput 2

Pump Throughput

Total *mass* (quantity/amount) of gas *leaving* the vacuum volume (via the pumps) in a given *time* period

Mass flow measured in: T.L/s, Pa.m^3/s, mbar.cc/s, atm.cc/s, sccm (pressure x volume / time)

Kurt J. Lesker Company



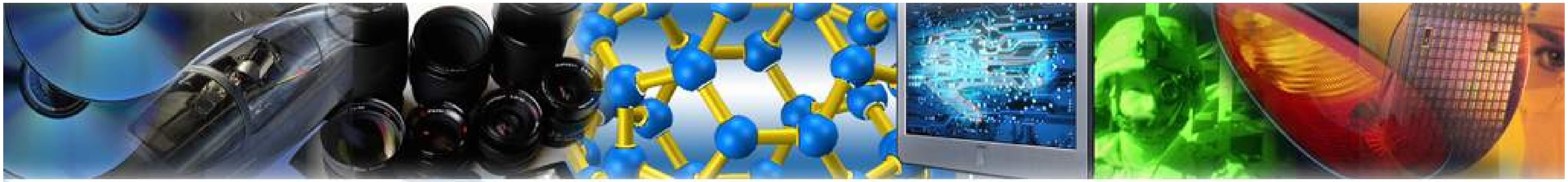
Equating Gas Load & Pump Throughput

Gas Load	**Torr.Liter/sec**
Pump Throughput	**Torr.Liter/sec**

When Gas Load = Pump Throughput *

(Gas In = Gas Out)

Chamber pressure is stable!



Throughput Calculations — 1

Injecting 800 sccm, chamber pressure 2 mbar.
What is the effective pumping speed needed in L/min?

= 800/1000 sL/min

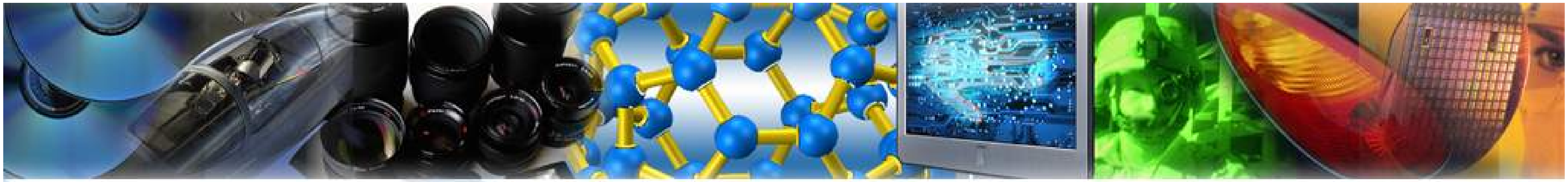
= (800/1000) x 1013 mbar.L/min

= 810 mbar.L/min

= 810/2 L/min @ 2 mbar

EPS = 405 L/min

Kurt J. Lesker Company



Throughput Calculations — 2

Injecting 100 sccm, chamber pressure 3×10^{-3} Torr. What is the effective pumping speed needed in L/s?

$= 100/60$ scc/s

$= (100/60) \times (1/1000)$ sL/s

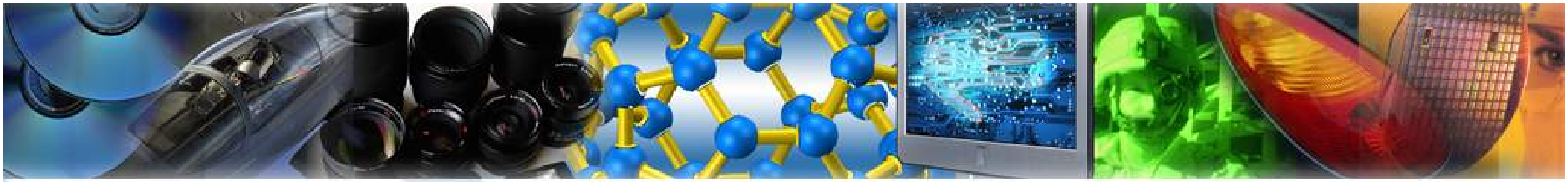
$= (100/60) \times (1/1000) \times 760$ Torr.L/s

$= 1.27$ Torr.L/s

$= 1.27/(3 \times 10^{-3})$ L/s @ 3×10^{-3} Torr

EPS = 422 L/s

Kurt J. Lesker Company



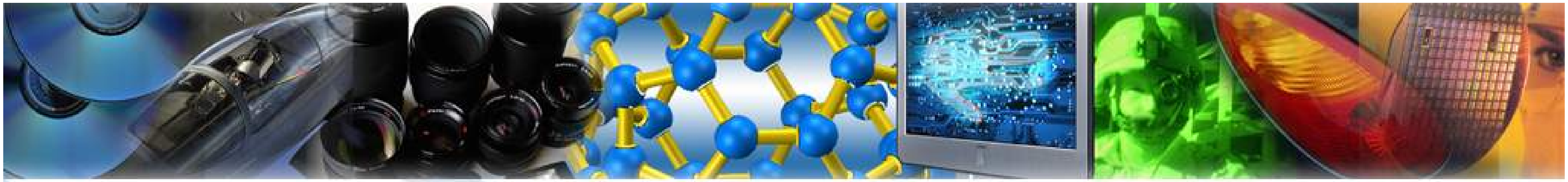
Throughput Calculations — 3

Injecting 1 sLm, chamber pressure 0.5 mbar.
What is the effective pumping speed needed in m^3/h?

$= 1 \times 60$ sL/h
$= (1 \times 60) \times (1/1000)$ sm^3/h
$= (1 \times 60) \times (1/1000) \times 1013$ $mbar.m^3/h$
$= 60.8$ $mbar.m^3/h$
$= 60.8/(0.5)$ m^3/h @ 0.5 mbar

EPS = 122 m^3/h

Kurt J. Lesker Company



Throughput Calculations — 4

Injecting 300 sccm, have 500 L/s pump.
What is base pressure in mbar?

= 300/60 scc/s

= (300/60) x (1/1000) sL/s

= (300/60) x (1/1000) x 1013 mbar.L/s

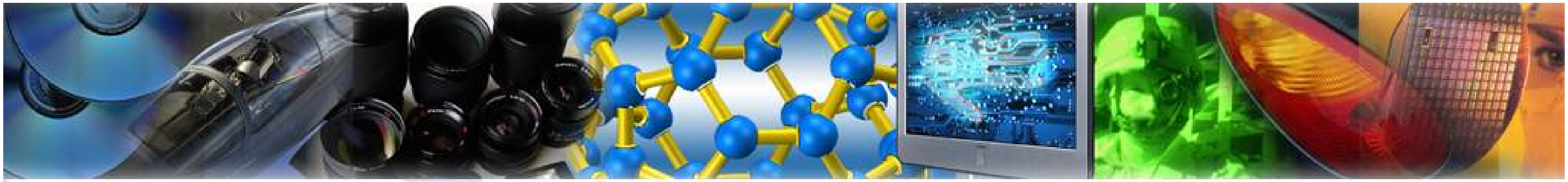
= 5.06 mbar.L/s

(assume EPS is ½ quoted pumping speed)

= 5.06/(250) mbar

Base Pressure = 0.02 mbar

Kurt J. Lesker Company



Throughput Calculations — 5

Injecting 200 sccm, 400 L/s turbo backed by 3.8 m^3/h vane pump. Turbo's max foreline pressure 2 mbar.

Will this work?

= 200 x 60 scc/h

= (200 x 60) x (1/1000) sL/h

= (200 x 60) x (1/1000) x (1/1000) sm^3/h

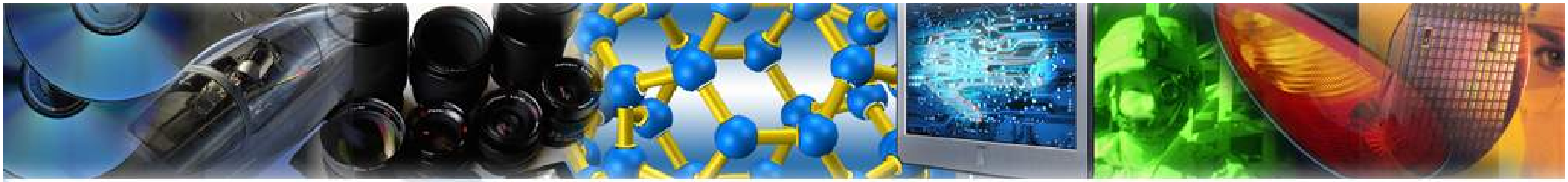
= (200 x 60) x (1/1000) x (1/1000) x 1013 mbar.m^3/h

= 12.2 mbar.m^3/h

(assume EPS equals quoted pumping speed)

= 12.2/(3.8) mbar = 3.2 mbar

It will not work!



Gas Load & Pump Throughput Conclusions

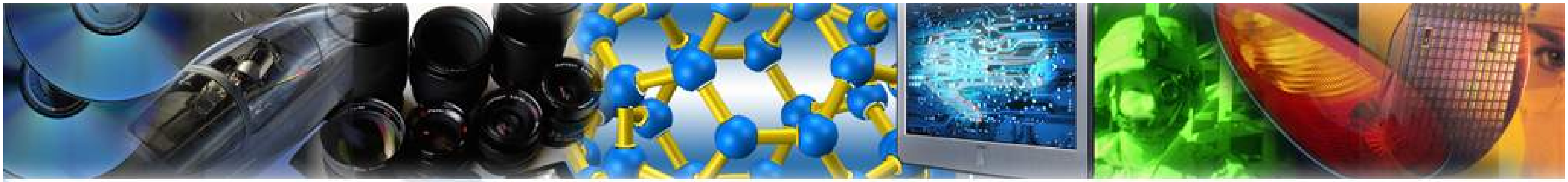
When Gas Load = Effective Pump Throughput

Chamber pressure is stable

If you don't like that pressure your options are:

1. **Reduce gas load**
2. **Increase pump throughput**

Kurt J. Lesker Company



Modeling with VacTran®

Kurt J. Lesker Company