Vacuum Systems

- System Pressure
- Total Gas Load
- Materials Selection & Outgassing
- System Pumping Speed
- Gauges
- System Operation
- Discussion on Accelerator Vacuum
Basic UHV System

UHV CHAMBER

TURBO PUMP

ION GAUGE

SCROLL PUMP

ION & TSP PUMP
Degrees Of Vacuum

ROUGH
ATM to 10^{-3} TORR

HIGH
10^{-3} to 10^{-9} TORR
>30M mole./cc

ULTRAHIGH
10^{-9} to 10^{-12} TORR
## Vacuum Characteristics

<table>
<thead>
<tr>
<th>Pressure (Torr)</th>
<th>Major Gas Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atm.</td>
<td>Air (N&lt;sub&gt;2&lt;/sub&gt;, O&lt;sub&gt;2&lt;/sub&gt;, H&lt;sub&gt;2&lt;/sub&gt;O, Ar, CO&lt;sub&gt;2&lt;/sub&gt;)</td>
</tr>
<tr>
<td>10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>Water Vapor (75% - 95%)</td>
</tr>
<tr>
<td>10&lt;sup&gt;-6&lt;/sup&gt;</td>
<td>H&lt;sub&gt;2&lt;/sub&gt;O, CO</td>
</tr>
<tr>
<td>10&lt;sup&gt;-9&lt;/sup&gt;</td>
<td>CO, N&lt;sub&gt;2&lt;/sub&gt;, H&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>10&lt;sup&gt;-10&lt;/sup&gt;</td>
<td>CO, H&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>10&lt;sup&gt;-11&lt;/sup&gt;</td>
<td>H&lt;sub&gt;2&lt;/sub&gt; (3x10&lt;sup&gt;5&lt;/sup&gt; molecules/cm&lt;sup&gt;3&lt;/sup&gt;)</td>
</tr>
</tbody>
</table>
Vacuum System Performance

• Vacuum system performance is determined by
  – System Design (volume, conductance, surface, materials)
  – Gas Load (rate gas evolves within or enters the volume)
  – Pump Performance (pump speed, compression)

• Equilibrium Pressure \( P \) in a vacuum system is determined by the total Gas Load \( Q \) and the System Pumping Speed \( S \)

\[
P = \frac{Q}{S}
\]
Vacuum System Gas Load

- Vacuum system gas load results from
  - Leaks (real and internal leaks)
  - Surface Condition (outgassing and virtual leaks)
  - System Materials (diffusion and permeation)
System Pressure - Rough Vacuum

This relation provides approximate pumpdown times in rough vacuum. Outgassing becomes significant at lower pressures and accuracy fails.

\[ t = c \cdot \frac{V}{S} \ln \left( \frac{P_i}{P_l} \right) \]

The pressure evolution in a vacuum system of volume \( V \) and effective pumping speed \( S \) is given by:

\[ P(t) = P_i \exp \left( -S \cdot t / V \right) \]
System Pressure - Leaks or Permeability

If $Q_\infty$ represents a constant gas load due to leaks or permeability of the vessel walls then the ultimate pressure is determined by the gas load and system pumping speed rather than a physical limitation of the pump.

$$P_\infty = \frac{Q_\infty}{S}$$

Thus a term for the constant gas load is added

$$-V \frac{dP}{dt} + Q_\infty = S \cdot P$$
System Pressure - Outgassing

For qualitative purposes, the outgassing rate of a surface in high vacuum can be represented as:

\[ Q = Q_0 e^{-\frac{t}{\tau}} \]

where \( Q_0 \) is the initial outgassing rate, \( t \) is the time, and \( \tau \) is rate outgassing decays with time (assumed to be constant over a reasonable time).

\[ Q = Ae^{-at} + Be^{-bt} \]
System Pressure - Pumpdown

The solution for pressure decay relative to time that includes the volume gas (1st term), outgassing (2nd term), leaks and permeation (3rd term) is given by:

\[-V \frac{dP}{dt} + Q_0 e^{-\frac{t}{\tau}} + Q_\infty = S \cdot P\]
Gas Load Limiting Pumpdown

Pressure (Torr)

Volume
Desorption
Diffusion
Permeation

Time

10^3
10^0
10^-3
10^-6
10^-9
0

Volume
Desorption
Diffusion
Permeation
Pressure Decay
Total Gas Load

The gas load is the rate gas enters the system volume.
The total gas load on a vacuum system is comprised of:

\[ Q_{TOTAL} = Q_{VOLUME} + Q_{LEAK} + Q_{OUTGAS} + Q_{DIFFUSION} + Q_{PERMEATION} \]

- \( Q \) (gas load, throughput, leak rate) is expressed in units of pressure \( \cdot \) volume/time
  - Torr\( \cdot \)liters/sec, atm\( \cdot \)cc/sec, sccm, mBar\( \cdot \)liters/sec, Pa\( \cdot \)m\(^3\)/hr

Example: To reach \( 10^{-12} \) Torr in a system with 1000 l/s pumping speed, the gas load must be less than \( 10^{-9} \) Torr l/s.

\[ S \cdot P = Q \quad \text{1000 l/s} \cdot 10^{-12} T = 10^{-9} T \cdot \text{l/s} \]
Significance of Adsorbed Gas

<table>
<thead>
<tr>
<th>$P$ (mbar)</th>
<th>Molecules on Surface</th>
<th>Time to Form Monolayer (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-3}$</td>
<td>0.5</td>
<td>$2.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>500</td>
<td>2.2</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>500,000</td>
<td>$2.2 \times 10^3$</td>
</tr>
</tbody>
</table>
\[ Q_{\text{outgas}} = q_{\text{outgas}} \cdot A \]

where \( q_{\text{outgas}} \) is the rate of outgassing per unit area and A is the surface area exposed to the vacuum.

Rate of outgassing is dependent upon the base material, temperature, time and treatment.

- Untreated (as received)
- Machined (cutting oil used, etc...)
- Degreased (method and solvents)
- Post fabrication treatment (baking, degassing)
Degassing By Baking

Pressure (Torr)

Time (Arbitrary Units)

Heating

Without Baking

With Baking
**Common UHV Materials**

**Stainless Steel:** use as vacuum chambers, flanges…

Low outgassing rate, Weldability, Corrosion resistance

**Copper:** Used as conductors and seals

Low outgassing rate if properly cleaned

**Aluminum:** use as chambers due to thermal property and cost

Higher outgassing, harder to weld

*♦Ceramics* (Alumina (Al₂O₃)) : insulators

*♦Other metals and inorganic compound:* Inconel, Kovar….
## Average outgassing rates*

*Data taken from several sources, averaged for air. For info on specific material or gas specie refer to original documentation.

### Outgassing rates in Torr liter/sec cm²

<table>
<thead>
<tr>
<th>Material / (Surface Condition)</th>
<th>1 hour</th>
<th>10 hours</th>
<th>&gt;24 hrs</th>
<th>untreated</th>
<th>degreased</th>
<th>polished</th>
<th>baked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (anodized)</td>
<td>$3 \times 10^{-5}$</td>
<td>$3 \times 10^{-7}$</td>
<td>$8 \times 10^{-8}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$3 \times 10^{-5}$</td>
<td>N/A</td>
<td>$5 \times 10^{-10}$</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$8 \times 10^{-7}$</td>
<td>$5 \times 10^{-8}$</td>
<td>$1 \times 10^{-10}$</td>
<td>$8 \times 10^{-7}$</td>
<td>$1 \times 10^{-8}$</td>
<td>$1 \times 10^{-8}$</td>
<td>$5 \times 10^{-13}$</td>
</tr>
<tr>
<td>Brass</td>
<td>$2 \times 10^{-6}$</td>
<td>$6 \times 10^{-7}$</td>
<td>$1 \times 10^{-7}$</td>
<td>$1 \times 10^{-6}$</td>
<td>$1 \times 10^{-6}$</td>
<td>$8 \times 10^{-6}$</td>
<td>N/A</td>
</tr>
<tr>
<td>Beryllium</td>
<td>$1 \times 10^{-6}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$1 \times 10^{-9}$</td>
<td>$1 \times 10^{-6}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$1 \times 10^{-6}$</td>
<td>N/A</td>
</tr>
<tr>
<td>Copper</td>
<td>$1 \times 10^{-7}$</td>
<td>$5 \times 10^{-9}$</td>
<td>$1 \times 10^{-10}$</td>
<td>$1 \times 10^{-7}$</td>
<td>$1 \times 10^{-8}$</td>
<td>$1 \times 10^{-9}$</td>
<td>$1 \times 10^{-12}$</td>
</tr>
<tr>
<td>Copper (OFHC)</td>
<td>$8 \times 10^{-9}$</td>
<td>$2 \times 10^{-9}$</td>
<td>$3 \times 10^{-11}$</td>
<td>$8 \times 10^{-9}$</td>
<td>$8 \times 10^{-9}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$1 \times 10^{-12}$</td>
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<tr>
<td>Delrin</td>
<td>$6 \times 10^{-6}$</td>
<td>$1 \times 10^{-7}$</td>
<td>$7 \times 10^{-7}$</td>
<td>$6 \times 10^{-6}$</td>
<td>not available</td>
<td>not available</td>
<td>$8 \times 10^{-7}$</td>
</tr>
<tr>
<td>Lead</td>
<td>$1 \times 10^{-7}$</td>
<td>$2 \times 10^{-8}$</td>
<td>$4 \times 10^{-9}$</td>
<td>$1 \times 10^{-8}$</td>
<td>$5 \times 10^{-8}$</td>
<td>$1 \times 10^{-8}$</td>
<td>N/A</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>$2 \times 10^{-6}$</td>
<td>$2 \times 10^{-7}$</td>
<td>$3 \times 10^{-8}$</td>
<td>$2 \times 10^{-6}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$5 \times 10^{-8}$</td>
<td>$5 \times 10^{-10}$</td>
</tr>
<tr>
<td>1018 Steel (Ni plated)</td>
<td>$2 \times 10^{-6}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$1 \times 10^{-8}$</td>
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<td>not available</td>
<td>not available</td>
<td>not available</td>
</tr>
<tr>
<td>Gold Sheet</td>
<td>$8 \times 10^{-8}$</td>
<td>not available</td>
<td>$5 \times 10^{-9}$</td>
<td>$8 \times 10^{-8}$</td>
<td>$1 \times 10^{-8}$</td>
<td>not available</td>
<td>not available</td>
</tr>
<tr>
<td>Titanium</td>
<td>$1 \times 10^{-9}$</td>
<td>not available</td>
<td>$5 \times 10^{-10}$</td>
<td>$1 \times 10^{-9}$</td>
<td>not available</td>
<td>not available</td>
<td>$2 \times 10^{-12}$</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>$5 \times 10^{-8}$</td>
<td>$1 \times 10^{-8}$</td>
<td>$1 \times 10^{-10}$</td>
<td>$7 \times 10^{-8}$</td>
<td>$1 \times 10^{-9}$</td>
<td>$5 \times 10^{-9}$</td>
<td>$3 \times 10^{-13}$</td>
</tr>
</tbody>
</table>
### Average outgassing rates (cont'd)

<table>
<thead>
<tr>
<th>Material</th>
<th>1 hour</th>
<th>10 hours</th>
<th>&gt;24 hrs</th>
<th>untreated</th>
<th>degreased</th>
<th>polished</th>
<th>baked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy (Shell Epon)</td>
<td>$2\times10^{-5}$</td>
<td>$1\times10^{-6}$</td>
<td>not available</td>
<td>not available</td>
<td>not available</td>
<td>N/A</td>
<td>$8\times10^{-8}$</td>
</tr>
<tr>
<td>Buna N</td>
<td>$8\times10^{-6}$</td>
<td>$2\times10^{-6}$</td>
<td>$8\times10^{-7}$</td>
<td>$8\times10^{-6}$</td>
<td>$8\times10^{-7}$</td>
<td>N/A</td>
<td>$4\times10^{-8}$</td>
</tr>
<tr>
<td>Neoprene</td>
<td>$3\times10^{-6}$</td>
<td>$8\times10^{-7}$</td>
<td>$4\times10^{-8}$</td>
<td>$3\times10^{-6}$</td>
<td>$6\times10^{-7}$</td>
<td>N/A</td>
<td>$2\times10^{-9}$</td>
</tr>
<tr>
<td>Mylar</td>
<td>$8\times10^{-7}$</td>
<td>$1\times10^{-7}$</td>
<td>$7\times10^{-9}$</td>
<td>$8\times10^{-7}$</td>
<td>N/A</td>
<td>N/A</td>
<td>$2\times10^{-9}$</td>
</tr>
<tr>
<td>Acrylic</td>
<td>$2\times10^{-6}$</td>
<td>$1\times10^{-6}$</td>
<td>$5\times10^{-7}$</td>
<td>$2\times10^{-6}$</td>
<td>$8\times10^{-7}$</td>
<td>N/A</td>
<td>$1\times10^{-8}$</td>
</tr>
<tr>
<td>Teflon (polyfluoro‘lene)</td>
<td>$2\times10^{-7}$</td>
<td>$8\times10^{-8}$</td>
<td>$2\times10^{-8}$</td>
<td>$2\times10^{-7}$</td>
<td>N/A</td>
<td>N/A</td>
<td>$8\times10^{-9}$</td>
</tr>
<tr>
<td>Nylon (polyamide)</td>
<td>$5\times10^{-6}$</td>
<td>$3\times10^{-7}$</td>
<td>$4\times10^{-8}$</td>
<td>$5\times10^{-6}$</td>
<td>N/A</td>
<td>N/A</td>
<td>$6\times10^{-9}$</td>
</tr>
<tr>
<td>Lexan (polycarbonate)</td>
<td>$7\times10^{-7}$</td>
<td>$2\times10^{-7}$</td>
<td>$6\times10^{-8}$</td>
<td>$1\times10^{-7}$</td>
<td>N/A</td>
<td>N/A</td>
<td>$8\times10^{-9}$</td>
</tr>
<tr>
<td>PVC</td>
<td>$5\times10^{-7}$</td>
<td>$3\times10^{-7}$</td>
<td>$1\times10^{-7}$</td>
<td>$5\times10^{-7}$</td>
<td>N/A</td>
<td>N/A</td>
<td>$8\times10^{-8}$</td>
</tr>
<tr>
<td>Silicon rubber</td>
<td>$7\times10^{-6}$</td>
<td>$8\times10^{-7}$</td>
<td>$6\times10^{-8}$</td>
<td>$7\times10^{-7}$</td>
<td>$2\times10^{-7}$</td>
<td>N/A</td>
<td>$6\times10^{-10}$</td>
</tr>
<tr>
<td>Silastic (sealant)</td>
<td>$5\times10^{-5}$</td>
<td>$3\times10^{-6}$</td>
<td>$6\times10^{-7}$</td>
<td>$8\times10^{-5}$</td>
<td>N/A</td>
<td>N/A</td>
<td>$5\times10^{-8}$</td>
</tr>
<tr>
<td>Viton</td>
<td>$8\times10^{-7}$</td>
<td>$5\times10^{-8}$</td>
<td>$2\times10^{-8}$</td>
<td>$8\times10^{-7}$</td>
<td>$1\times10^{-7}$</td>
<td>N/A</td>
<td>$5\times10^{-10}$</td>
</tr>
<tr>
<td>Steatite (ceramic)</td>
<td>$5\times10^{-8}$</td>
<td>$1\times10^{-8}$</td>
<td>$7\times10^{-9}$</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Pyrex (7740)</td>
<td>$1\times10^{-7}$</td>
<td>$2\times10^{-8}$</td>
<td>$5\times10^{-9}$</td>
<td>not available</td>
<td>not available</td>
<td>N/A</td>
<td>$2\times10^{-9}$</td>
</tr>
</tbody>
</table>
System Pumping Speed

To achieve the best possible vacuum or lowest system pressure with a given pump, it is necessary to maximize effective pumping speed at the chamber while minimizing gas load.

\[ S_{\text{EFF}} = \frac{SC}{S + C} = \frac{S}{1 + S/C} \]

- \( C \gg S \) \quad \Rightarrow \quad S_{\text{EFF}} = S
- \( C \sim S \) \quad \Rightarrow \quad S_{\text{EFF}} = S/2
- \( C \ll S \) \quad \Rightarrow \quad S_{\text{EFF}} = C

Maximum theoretical pumping speed \( S_{\text{EFF}} \) into a 12” diam chamber is about 8000 liter / sec
Conductance in molecular flow (Long round tube)

\[ C = 3.81 \times \frac{d^3}{l} \times \sqrt{\frac{T}{M}} \] \text{ (l/sec)}

- \( d \) = diameter of tube in cm
- \( l \) = length of tube in cm
- \( T \) = temperature (K)
- \( M \) = A.M.U.

Example: 4 cm diameter, 100 cm tube, \( \text{N}_2 \), 295 K

\[ C = \sim 8 \text{ l/s} \]
Series Conductance

Tube \((C_1)\): 200 l/s  
Baffle \((C_2)\): 200 l/s

\[
C_T = \frac{200 \times 200}{200 + 200} \text{ (l/s)}
\]

\[
C_T = 100 \text{ (l/s)}
\]
Series Conductance

Tube + Baffle ($C_{1+2}$): 100 l/s
Pump ($C_3$): 200 l/s

$$C_T = \frac{200 \times 100}{200 + 100} \text{ (l/s)}$$
$$C_T = 67 \text{ (l/s)}$$
Turbomolecular Pump

- INLET FLANGE
- STATOR BLADES
- BEARING
- BEARING
- ROTOR BODY
- HIGH PUMPING SPEED
- HIGH COMPRESSION
- EXHAUST
- HIGH FREQ. MOTOR
TURBOMOLECULAR PUMP (TMP)
PRINCIPLE OF OPERATION

Molecule

Moving Wall with Speed V
COMPRESSION RATIO FOR VARIOUS GASES AS A FUNCTION OF THE FORELINE PRESSURE

- Nitrogen
- Helium
- Hydrogen

FORELINE PRESSURE (MBAR)
ION PUMP
PRINCIPLE OF OPERATION

- Electric discharge in crossed electric and magnetic field (Penning cell)
- Ion bombardment of the cathode
- Deposition of a chemically reactive film (Ti) (Sputtering)
- Gas sticks on the Ti film (chemisorption)
Ion pump

Ion Pumps
Diode and triode schematically

PUMPING MECHANISMS

(A) DIODE ION PUMP

(B) TRIODE ION PUMP
Ion Pump Pumping Speed
Ionization current is the measure of pressure
Ion gauge
Cross-section
System Operation

1. Use turbo and scroll pumps to rough chamber and sump to approx. $10^{-5}$ torr.
2. Bake at highest allowable temperature for several (overnite) hours.
3. Turn on TSP/ion pump towards end of bake period.
4. Valve out rough pump system.
Pumpdown Curves

DISTINGUISH NORMAL PUMPDOWN FROM REAL LEAK

CURVE DUE TO REAL LEAK

"NORMAL" PUMPDOWN