The US Particle Accelerator School
Cryosorption Pumps

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Lawrence Livermore National Laboratory
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Updated: 12/1/2014 (Yulin Li)
Cryopumping Basics . . . Cryocondensation

- A cryogenic surface will trap any molecule that contacts the surface if it is cold enough.

Cooling gases to the extent that gas molecules lose sufficient energy to form condensation layers.
Equilibrium vapor pressure is the state where as many molecules are condensing as are vaporizing.

Equilibrium occurs when the rate of gas molecules returning to the liquid/solid (condensing) is equal to the rate of energetic molecules becoming gaseous (vaporizing).
## What determines the Pressure inside a Cryopump?

<table>
<thead>
<tr>
<th>Surface Temp.</th>
<th>at 16K</th>
<th>at 25K</th>
<th>at 31K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>$&gt; 10^{-12}$ Torr</td>
<td>$&gt; 10^{-7}$ Torr</td>
<td>$&gt; 10^{-4}$ Torr</td>
</tr>
<tr>
<td>Argon</td>
<td>$&gt; 10^{-12}$ Torr</td>
<td>$&gt; 10^{-9}$ Torr</td>
<td>$&gt; 10^{-4}$ Torr</td>
</tr>
<tr>
<td>Oxygen</td>
<td>$&gt; 10^{-12}$ Torr</td>
<td>$&gt; 10^{-10}$ Torr</td>
<td>$&gt; 10^{-4}$ Torr</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>$&gt; 10^2$ Torr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium</td>
<td>$&gt; \text{Atm.}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cryopumping Basics . . . Cryocondensation

4.2 K

10-20 K

60-80 K

H₂O

N₂

Ar

H₂

Ne

He
Cryopumping Basics . . . Cryosorption

Cooling gas molecules to the extent that gas molecules, upon contacting a sufficiently cooled surface, lose enough energy to accumulate on the surface.

- A flat cryoadsorbing plate retains some molecules.
- Flat surface allows molecules to continue moving.

Diagram:
- Cryosorbing Plate
  - Free Molecules
  - Ejected Molecules
  - Adsorbed Molecules
  - Surface Collisions
  - Cryopumping Surface
Cryopumping Basics . . . Cryosorption

- Sieve material, such as Zeolite, charcoal, provides greater surface area and limited apertures.

- Large surface area capacity; 1150-1250 m²/gm
Cryopumping Basics... Cryosorption

- Increased surface area provides greater capacity.
- Released molecules remain confined.
- Irregular surface constricts motion.
- Cryosorption of hydrogen, neon, and helium accomplished.
When the number of molecules arriving on the chamber surface (adsorbing) equals the number leaving the surface (desorbing), then the system is in "Surface Equilibrium".
Equilibrium Vapor Pressure:
- CONDENSATION
- VAPORIZATION

Surface Equilibrium:
- ADSORPTION
- DESORPTION
Air gases and water vapor are condensed, noncondensible gases are captured.

1st Stage
- H$_2$O
- N$_2$
- Ar
- H$_2$
- Ne
- He

2nd Stage
- 10-20 K

60-80 K
Saturation curves of common gases
Cryopump Concept

- Cryopumps are designed to create these condensing and adsorbing surfaces.
An adsorption isotherm is a measure of the surface population density of a gas at a constant temperature.

$$\sigma = f(P, T)$$

where $\sigma =$ density of molecules of gas on a surface per cm$^2$

$P =$ equilibrium pressure of system

$T =$ system temperature
Adsorption isotherms can be expressed several ways:

### % Coverage

- $\sigma = 0.20$  surface 20% covered
- $\sigma = 1$  One monolayer ($\sigma_m$)
- $\sigma = 2$  Two monolayers ($2\sigma_m$)

### Molecules/cm$^2$

- $\sigma = 10^{15}$ molecules/cm$^2$
Cryopumping Basics . . . Adsorption Isotherm

- Usually an adsorption isotherm represents pressure vs. coverage data at a specific temperature.
- As the temperature increases, the equilibrium pressure increases for a specific surface coverage.
- Each gas has its own unique adsorption isotherm for the same temperature.
- For all gases, the equilibrium pressure of an adsorption isotherm is less than the vapor pressure at that temperature.
- As surface coverage goes up (to several monolayers), the equilibrium pressure will approach the vapor pressure.
Cryopumping Basics . . . Example Isotherms

E. Wallen: "Adsorption Isotherms of He and H₂ at Liquid Helium Temperature", JVST A15, p.265
Cryopumping Basics . . . Pumping Speed

- A cold surface has a finite pumping speed for a gas as long as the pressure of the adsorption isotherm is less than the pressure of the gas ($P_e$).
- As the surface coverage increases, the equilibrium pressure increases.
- $S_{\text{max}}$ is set by the surface conductance limitations of the cryopump.

\[ S = S_{\text{max}} \left(1 - \frac{P_c}{P}\right) \]

In cryosorption pumping, speed is dependent on the quantity of gas already adsorbed and the pressure. That is, a cryopump has a finite capacity.

\[ \sigma_1 < \sigma_2 < \sigma_3 \]
## Cryopumping Basics . . . Sticking Coefficients

<table>
<thead>
<tr>
<th>CryoSurface Temperature (K)</th>
<th>( N_2 )</th>
<th>( CO )</th>
<th>( O_2 )</th>
<th>( Ar )</th>
<th>( CO_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>77 K</td>
<td>300 K</td>
<td>77 K</td>
<td>300 K</td>
<td>77 K</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>0.65</td>
<td>1.0</td>
<td>0.90</td>
<td>1.0</td>
</tr>
<tr>
<td>12.5</td>
<td>0.99</td>
<td>0.63</td>
<td>1.0</td>
<td>0.85</td>
<td>1.0</td>
</tr>
<tr>
<td>15</td>
<td>0.96</td>
<td>0.62</td>
<td>1.0</td>
<td>0.85</td>
<td>0.90</td>
</tr>
<tr>
<td>17.5</td>
<td>0.90</td>
<td>0.61</td>
<td>1.0</td>
<td>0.85</td>
<td>1.0</td>
</tr>
<tr>
<td>20</td>
<td>0.84</td>
<td>0.60</td>
<td>1.0</td>
<td>0.85</td>
<td>0.80</td>
</tr>
<tr>
<td>22.5</td>
<td>0.80</td>
<td>0.60</td>
<td>1.0</td>
<td>0.85</td>
<td>0.79</td>
</tr>
<tr>
<td>25</td>
<td>0.79</td>
<td>0.60</td>
<td>1.0</td>
<td>0.85</td>
<td>0.79</td>
</tr>
<tr>
<td>77</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ref. “Cryopumping”, Dawson and Haygood, Cryogenics 5 (2), 57, (1965)
Cryopump

Characteristics:

- No fluids, lubricants, or (in-vacuum) moving parts
- High crossover capability minimizes back-streaming
- High water pumping speed
- Tailorable pumping speeds
- Operate in all orientations
- Continuous backing not required
A cryopump is built around the cold-head.

- Creates the cold temperatures needed to condense and adsorb gases
- Two stages, each at a different temperature

Achieves these temperatures by the expansion of helium.
Cryopump Components . . .
shield, vacuum vessel, and flange

- A **radiation shield** is attached to the 1st stage of the cold-head.
  - Copper for conductivity
  - Nickel plating for protection

- The **vacuum vessel** isolates the cryopump.

- The inlet **flange** attaches to the chamber.
Cryopump Components . . .

*1st and 2nd Stage Arrays*

• The **1st stage** (65 K) array is attached to the radiation shield.
  - Condenses water vapor

• A series of arrays with charcoal are attached to the **2nd stage** (12 K) of the cold-head.
  - Condenses $O_2$, $N_2$, $Ar$
  - Adsorbs $H_2$, $He$, $Ne$
Cryopump System Overview

- Input Power Cable
- Supply Line
- Return Line
- Cold-Head Power Cable
- Helium Compressor Unit
- Control Module
- Cold Head
- Mounting Flange
  (Interface to Vacuum Chamber)
- Cryopump
- To Roughing System
Cryopump Operation - *Cryocondensation*

- **Water molecules collide with the cooled surfaces of the 65 K first stage array.**
- **Condensation layers form as more of these molecules collect.**
Other molecules such as oxygen, nitrogen, and argon pass between the first stage arrays.

By colliding with the 12 K second stage arrays, these molecules also form condensation layers.
Cryopump Operation - Cryoadsorption

- The noncondensible H₂, He, and Ne molecules pass between the first stage arrays.
- Collide with walls and second stage arrays.
- Become adsorbed upon contacting the charcoal surfaces.
• Affixing activated charcoal sieve material to the underside of the 12 K second stage arrays, allows H₂, He, and Ne to be cryoadsorbed.
During normal operation, water vapor is condensed on the 65 K first stage array while oxygen, nitrogen, and argon are condensed on the 12 K second stage array.
Cryopump Operation – Argon Hang-Up

- Argon Hang-Up can occur if the first stage gets too cold.

- Results in argon being condensed (pumped) on the first stage.

- Where it stays until lower partial pressures are reached.
Cryopump Operation – Argon Hang-Up

- When the equilibrium pressure is reached.
  - Argon liberates
  - Pumpdown slows
  - Causes “False Full” condition

### Equilibrium Vapor Pressure

<table>
<thead>
<tr>
<th></th>
<th>10^{-10}</th>
<th>10^{-7}</th>
<th>10^{-4}</th>
<th>10^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>130K</td>
<td>153K</td>
<td>185K</td>
<td>198.5K</td>
</tr>
<tr>
<td>Argon</td>
<td>23.7K</td>
<td>28.6K</td>
<td>35.9K</td>
<td>39.2K</td>
</tr>
</tbody>
</table>
Cryopump Operation – Argon Hang-Up

- Argon liberates until it is repumped onto the second stage where it should have been pumped.

65 K
Cryopump Operation – Argon Hang-Up

- Argon Hang-Up can be avoided with modern controllers interfaced to the first stage sensor and heater.
  - Monitors and controls temperature
  - Prevents a “Too Cold” condition
### Cryopump Example Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping speed (l/s) water</td>
<td>9000–10500</td>
</tr>
<tr>
<td>Air</td>
<td>3000–3250</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4500–5200</td>
</tr>
<tr>
<td>Argon</td>
<td>2500–2700</td>
</tr>
<tr>
<td>Helium</td>
<td>1500–2300</td>
</tr>
<tr>
<td>Maximum throughput (Pa·m³/s) argon</td>
<td>1.0–2.5</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1.2</td>
</tr>
<tr>
<td>Pumping capacity (Pa·m³) argon</td>
<td>$1.5 \times 10^5–3 \times 10^5$</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1500–5000</td>
</tr>
<tr>
<td>Helium</td>
<td>10–100</td>
</tr>
<tr>
<td>Ultimate pressure (N₂ equivalent) (Pa)</td>
<td>$10^{-9} – 10^{-10}$</td>
</tr>
<tr>
<td>Cool-down time (h)</td>
<td>1.5–2.5</td>
</tr>
<tr>
<td>Crossover (Pa·m³)</td>
<td>35–50</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>30–50</td>
</tr>
</tbody>
</table>

Listed performance data (averaging from the catalogue of different manufacturers) for a typical 3000 l/s class two-stage cryopump.
During chamber evacuation, when should the high-vacuum valve be opened?

For cryopumps, the maximum crossover capability is specified as the impulsive mass input that causes the second stage to rise no higher than 20 K.
Example: Crossover Pressure Calculation

Crossover value for a CTI On-Board 8 = 150 Torr-liters

Crossover formula: \( \frac{\text{Crossover value}}{\text{Chamber volume}} = P \text{ in Torr} \)

\( \frac{150 \text{ Torr-liters}}{300 \text{ liters}} = .5 \text{ Torr or 500 milliTorr} \)

Understanding crossover can produce faster pumpdown times and cleaner vacuum too.
The objective of regenerating a cryopump is to remove the captured gases from the pump and restore its pumping capacity.

So ... when should cryopumps be regenerated?
 Whenever your system is down is a good opportunity to regenerate your cryopump without affecting your up-time.
Cryopump Operation . . . Regeneration

- Regeneration
  - Warm-Up and Purge

<table>
<thead>
<tr>
<th>TIME (hrs)</th>
<th>TEMP (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

High Vacuum Valve Closed

Pump Off Purge Tube

Regeneration
Cryopump Operation . . . Regeneration

- **Regeneration**
  - Warm-Up and Purge
  - Extended Purge
  - Rough Out
  - Rate-of-Rise (ROR) Test
Regeneration

- Warm-Up and Purge
- Extended Purge
- Rough Out
- Rate-of-Rise (ROR) Test
- Cool Down

Regeneration

<table>
<thead>
<tr>
<th>TIME (hrs)</th>
<th>TEMP (K)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Extended Purge, Rough, & Rate-of-Rise Test
- Warm-Up and Purge
- Cool Down
Cryopump Operation . . .

- **Regeneration**

Typically 5-6 hours cold-to-cold.

<table>
<thead>
<tr>
<th>TIME (hrs)</th>
<th>TEMP (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm-Up and Purge</td>
<td>5</td>
</tr>
<tr>
<td>Extended Purge, Rough, &amp; Rate-of-Rise Test</td>
<td></td>
</tr>
<tr>
<td>Cool Down</td>
<td></td>
</tr>
</tbody>
</table>

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Example of Cryo-pumped Accelerator - DARHT II
(the Dual Axis Radiographic Hydro-Test)
Example of Cryopumped Accelerator – APT RFQ

- Cryogenic Pumping System for Cavity system, with $\text{H}_2$ Pumping Speed of 12,000 L/s

- This assembly was completed and successfully tested at LLNL Vacuum Lab. The whole system was then delivered and installed at the APT/LEDA facility.