The US Particle Accelerator School
Cryosorption Pumps

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Lawrence Livermore National Laboratory
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Cryopumping Basics . . . Cryocondensation

Cooling gases to the extent that gas molecules lose sufficient energy to form condensation layers.

- A cryogenic surface will trap any molecule that contacts the surface if it is cold enough.
Cryopumping Basics . . .
Equilibrium Vapor Pressure

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></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Cryopumping Basics . . . Cryocondensation

4.2 K is impractical as Helium still boils

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.

![Cryosorbing Plate Diagram](image)
Cryopumping Basics . . . Cryosorption

- Sieve material, such as 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.
Cryopumping Basics . . . Surface Equilibrium

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

Equilibrium Vapor Pressure:
- CONDENSATION
- VAPORIZATION

Surface Equilibrium:
- ADSORPTION
- DESORPTION
Cryopumping Basics . . . Cryosorption and Cryocondensation

Air gases and water vapor are condensed, noncondensible gases are captured.

10-20 K

2nd Stage

60-80 K

1st Stage

H₂O
N₂
Ar
H₂
Ne
He
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**

\[
\sigma = 0.20 \quad \text{surface 20\% covered}
\]

\[
\sigma = 1 \quad \text{One monolayer (}\sigma_m\text{)}
\]

\[
\sigma = 2 \quad \text{Two monolayers (}2\sigma_m\text{)}
\]

**Molecules/cm^2**

\[
\sigma = 10^{15} \text{ molecules/cm}^2
\]
Cryopumping Basics . . . Adsorption Isotherm

- Usually an adsorption isotherm represents pressure vs. coverage data for 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 . . . 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.
- As the surface coverage increases, the equilibrium pressure increases.

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

- \( S_{\text{max}} \) is set by the surface conductance limitations of the cryopump.

In cryosorption pumping, speed is dependent on the quantity of gas already adsorbed and the pressure.
### Cryopumping Basics . . . Sticking Coefficients

<table>
<thead>
<tr>
<th>CryoSurface Temperature (K)</th>
<th><strong>Gas and Gas Temperature</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>N₂</strong></td>
<td><strong>CO</strong></td>
</tr>
<tr>
<td></td>
<td>77 K</td>
<td>300 K</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>0.65</td>
</tr>
<tr>
<td>12.5</td>
<td>0.99</td>
<td>0.63</td>
</tr>
<tr>
<td>15</td>
<td>0.96</td>
<td>0.62</td>
</tr>
<tr>
<td>17.5</td>
<td>0.90</td>
<td>0.61</td>
</tr>
<tr>
<td>20</td>
<td>0.84</td>
<td>0.60</td>
</tr>
<tr>
<td>22.5</td>
<td>0.80</td>
<td>0.60</td>
</tr>
<tr>
<td>25</td>
<td>0.79</td>
<td>0.60</td>
</tr>
<tr>
<td>77</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Cryopump**

**Characteristics:**
- No fluids, lubricants, or moving parts
- High crossover capability minimizes backstreaming
- High water pumping speed
- Tailorable pumping speeds
- Operate in all orientations
- Continuous backing not required

![Capture Type Pump Diagram](image-url)
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 $H_2$, $He$, $Ne$
Primary Displacer
- Stainless housing
- Brass screen for thermal mass
- Phenolic casing
- Helium inlet and exhaust
Secondary Displacer
- Second stage attached to top of primary displacer allows even lower temperatures.
- Lead shot for thermal mass.
- Phenolic casing.
Cyopump System . . . The Refrigerator

- Cycle begins with both displacers at TDC.
Cryopump System . . . Refrigeration Cycle

- Cycle begins with both displacers at TDC.
- Inlet valve opens.
- Displacers move downward.
Cryopump System . . . Refrigeration Cycle

- Cycle begins with both displacers at TDC.
- Inlet valve opens.
- Displacers move downward.
- Helium fills void above primary displacer and passes through secondary displacer to fill second void.
At BDC, inlet valve closes.

Exhaust valve opens.

Gas has expanded in both voids and cools.

Displacers move upward.
Cooled gas flows down through both displacer matrices removing heat from thermal masses.

Gas exits through exhaust valve.
Displacers again at TDC.
• **Displacers again at TDC.**

• **Remaining gas exits.**

• **Exhaust valve closes.**

• **Cycle repeats at 72 rpm.**
After each cycle both displacer matrices (thermal masses) are colder, with the secondary mass colder than the primary ...

... incoming helium is pre-cooled accordingly BEFORE expansion.
Cryopump System Overview

- Helium Compressor Unit
- Control Module
- Cold Head
- Mounting Flange (Interface to Vacuum Chamber)
- Supply Line
- Return Line
- Input Power Cable
- Cold-Head Power Cable
- Cryopump
- To Roughing System
Water molecules collide with the cooled surfaces of the 65 K first stage array.

Condensation layers form as more of these molecules collect.
Cryopump Operation - Cryocondensation

- 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 $H_2$, 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 \( \text{H}_2 \), \( \text{He} \), and \( \text{Ne} \) 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

<table>
<thead>
<tr>
<th>EQUILIBRIUM VAPOR PRESSURE</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.
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 Design . . . Capacities

**Typical Capacity - 8” Cryopump**

\[
\text{Gas Collected} = \text{Pressure} \times \text{Speed} \times \text{Time}
\]

<table>
<thead>
<tr>
<th>Gas</th>
<th>Capacity (at STP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Vapor</td>
<td>1000 liters (gas)</td>
</tr>
<tr>
<td></td>
<td>1 liter (ice)</td>
</tr>
<tr>
<td>Nitrogen &amp; Argon</td>
<td>1000 liters (gas)</td>
</tr>
<tr>
<td></td>
<td>1 liter (ice)</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>17 liters (gas)</td>
</tr>
</tbody>
</table>
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.
Cryopump Operation . . . Crossover

Example: Crossover Pressure Calculation

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

Crossover formula:  \[
\text{Crossover value} = \frac{P \text{ in Torr}}{\text{Chamber volume}}
\]

\[
\frac{150 \text{ Torr-liters}}{300 \text{ liters}} = 0.5 \text{ Torr or 500 milliTorr}
\]

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

![Diagram showing cryopump regeneration process]

<table>
<thead>
<tr>
<th>TIME (hrs)</th>
<th>TEMP (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Warm-Up and Purge</strong></td>
</tr>
</tbody>
</table>

High Vacuum Valve Closed
Pump Off Purge Tube

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Cryopump Operation . . . Regeneration

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

![Diagram showing Cryopump Operation and Regeneration process]

TEMP (K)

TIME (hrs)

Extended Purge, Rough, & Rate-of-Rise Test

Warm-Up and Purge
Cryopump Operation . . . Regeneration

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

![Diagram of Cryopump Regeneration Process]

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

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Cryopump Operation . . . Regeneration

- Regeneration

Typically 5-6 hours cold-to-cold.

![Cryopump Diagram]

<table>
<thead>
<tr>
<th>TIME (hrs)</th>
<th>TEMP (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Warm-Up and Purge
- Extended Purge, Rough, & Rate-of-Rise Test
- Cool Down
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/LED facility.