The US Particle Accelerator School
Cryosorption Pumps

Lou Bertolini
Lawrence Livermore National Laboratory
June 10-14, 2002
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.
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>Gas</th>
<th>Pressure (Torr) at 16K</th>
<th>Pressure (Torr) at 25K</th>
<th>Pressure (Torr) at 31K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>&gt; 10^{-12}</td>
<td>&gt; 10^{-7}</td>
<td>&gt; 10^{-4}</td>
</tr>
<tr>
<td>Argon</td>
<td>&gt; 10^{-12}</td>
<td>&gt; 10^{-9}</td>
<td>&gt; 10^{-4}</td>
</tr>
<tr>
<td>Oxygen</td>
<td>&gt; 10^{-12}</td>
<td>&gt; 10^{-10}</td>
<td>&gt; 10^{-4}</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>&gt; 10^{-2}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium</td>
<td>&gt; Atm.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cryopumping Basics . . . Cryocondensation

4.2 K is impractical as Helium still boils

4.2 K

10-20 K

60-80 K

H$_2$O

N$_2$

Ar

H$_2$

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.
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.
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 still condensed - noncondensible gases captured.

10-20 K
2nd Stage

60-80 K
1st Stage

H₂O
H₂
Ne
Ar
N₂
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**

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

**Molecules/cm²**

- $\sigma = 10^{15}$ molecules/cm²
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.

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

- \( S_{\text{max}} \) 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>Gas and Gas Temperature</th>
<th>N₂</th>
<th>CO</th>
<th>O₂</th>
<th>Ar</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<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 0.65</td>
<td>1.0</td>
<td>0.90</td>
<td></td>
<td></td>
<td>1.0  0.68</td>
</tr>
<tr>
<td>12.5</td>
<td>0.99 0.63</td>
<td>1.0</td>
<td>0.85</td>
<td></td>
<td></td>
<td>1.0  0.68</td>
</tr>
<tr>
<td>15</td>
<td>0.96 0.62</td>
<td>1.0</td>
<td>0.85</td>
<td></td>
<td></td>
<td>0.90 0.67</td>
</tr>
<tr>
<td>17.5</td>
<td>0.90 0.61</td>
<td>1.0</td>
<td>0.85</td>
<td>1.0</td>
<td>0.86</td>
<td>0.81 0.66</td>
</tr>
<tr>
<td>20</td>
<td>0.84 0.60</td>
<td>1.0</td>
<td>0.85</td>
<td></td>
<td></td>
<td>0.80 0.66</td>
</tr>
<tr>
<td>22.5</td>
<td>0.80 0.60</td>
<td>1.0</td>
<td>0.85</td>
<td></td>
<td></td>
<td>0.79 0.66</td>
</tr>
<tr>
<td>25</td>
<td>0.79 0.60</td>
<td>1.0</td>
<td>0.85</td>
<td></td>
<td></td>
<td>0.79 0.66</td>
</tr>
<tr>
<td>77</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.85 0.63</td>
</tr>
</tbody>
</table>

Ref. “Cryopumping”, Dawson and Haygood, Cryogenics 5 (2), 57, (1965)
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
Cryopump Components . . . The Cold-Head

- 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 . . .

1\textsuperscript{st} and 2\textsuperscript{nd} Stage Arrays

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

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

![Diagram of cryopump components with 65 K Array and 12 K Arrays with Charcoal]
Cryopump System . . . The Refrigerator

**Primary Displacer**
- Stainless housing
- Brass screen for thermal mass
- Phenolic casing
- Helium inlet and exhaust

Exhaust Valve

Inlet Valve

Displacer Housing

Brass Screen

Seal
Cyropump System . . . The Refrigerator

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.
Cryopump System . . . Refrigeration Cycle

- Displacers again at TDC.
Cryopump System . . . Refrigeration Cycle

- 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

Input Power Cable

Cold-Head Power Cable

Cryopump

Control Module

Cold Head

Mounting Flange (Interface to Vacuum Chamber)

Supply Line
Return Line

To Roughing System
**Cyropump 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.**
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.
Cyropump 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.
Cyropump 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.

<65 K
Cyropump Operation - Argon Hang-Up

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

<table>
<thead>
<tr>
<th></th>
<th>EQUILIBRIUM VAPOR PRESSURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10^-10</td>
</tr>
<tr>
<td>Water</td>
<td>130K</td>
</tr>
<tr>
<td>Argon</td>
<td>23.7K</td>
</tr>
</tbody>
</table>

When the equilibrium pressure is reached, Argon liberates, pumpdown slows, and causes “False Full” condition.
Argon liberates until it is repumped onto the second stage where it should have been pumped.
Cyropump 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
# Cyropump 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.
Cyropump Operation . . . Crossover

Example: Crossover Pressure Calculation

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

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

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

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.
Cyropump Operation...Regeneration

- Regeneration
  - Warm-Up and Purge

Regeneration

TEMP (K)

Warm-Up and Purge

TIME (hrs)

High Vacuum Valve Closed

Pump Off Purge Tube
**Cyropump Operation . . . Regeneration**

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

![Graph showing Regeneration process with TIME (hrs) and TEMP (K)]


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

![Diagram](image_url)

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

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

- Regeneration

Typically 5-6 hours cold-to-cold.

Regeneration

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

- Warm-Up and Purge
- Cool Down
- Extended Purge, Rough, & Rate-of-Rise Test
Helium Compressors

- Helium Compressors provide a continuous source of clean high pressure helium to the cryopump cold head.

- Helium Compressors also provide conditioned electrical power to the cold head.

- A compressor consists of four main systems:
  - Pump
  - Cooling
  - Oil injection / separation
  - Cold head power
The pump is the “Heart” of the compressor. Compressors utilize two different types of positive displacement pumps:

- Rotary Pumps
- Piston Pumps
Compressors use either water or air to cool the helium and the oil within the compressor. Cooling is critical to insure proper compressor operation. Without proper cooling:

- The compressor will overheat and shut off.
- The oil separation system will not operate and oil-contamination can reach the cold head.
- The helium will become overheated and the cold head will warm up.

Cooling is typically achieved by the use of counterflow heat exchangers.
A typical Helium Compressor Schematic
Helium Compressor Oil System

- The compression of helium generates heat within the compressor pump.
- Oil must be injected during compression to cool the pump and helium.
- The helium-oil mixture is cooled at the heat exchanger.
- The oil must be separated from the helium before the gas is pumped back to the cryopump(s). The oil will then be recirculated within the compressor.
Helium Compressor Oil System

The oil system consists of **FOUR** main elements:

- The Oil Heat Exchanger
- The Bulk Oil Separator
- The Oil Mist Separator
- The Adsorber

*(See Compressor Schematic)*
In compressors with **rotary pumps**, the pump acts as a bulk (oil stream) separator by slowing down the velocity of the helium and oil mixture. The oil stream then “rains” directly into the oil sump.

In compressors with **piston pumps**, a separate bulk separator is used and the oil is then returned to the pump.
The oil mist (aerosol) separator utilizes very fine fibers to coalesce oil vapor into droplets and thus “clean” the helium gas. Oil from this separator is re-injected into the pump.
The adsorber contains activated charcoal to filter out the remaining oil in the helium by adsorption. As the adsorber gets filled up with oil and other contaminants it needs to be replaced (typically once a year).
Most Compressors can operate in ambient temperatures from 50-100 °F.

Note: Starting a compressor that is colder than 50 °F can cause start up problems.
## Typical Operating Parameters for CTI-CRYOGENICS Compressor Chart

<table>
<thead>
<tr>
<th>Compressor Type</th>
<th>Static Charge</th>
<th>Operating Pressure</th>
<th>Running Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>250 psig</td>
<td>275 psig</td>
<td>8 amps @ 208 V</td>
</tr>
<tr>
<td>8200</td>
<td>250 psig</td>
<td>275 psig</td>
<td>8 amps @ 208 V</td>
</tr>
<tr>
<td>1020R</td>
<td>185 psig</td>
<td>275/80 psig*</td>
<td>14.5 amps @ 208 V</td>
</tr>
</tbody>
</table>

The thermal switch on these compressors trips the main circuit breaker.

<table>
<thead>
<tr>
<th>Compressor Type</th>
<th>Static Charge</th>
<th>Operating Pressure</th>
<th>Running Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>8300</td>
<td>250 psig</td>
<td>95 psig</td>
<td>8 amps @ 208 V</td>
</tr>
<tr>
<td>8500/8510</td>
<td>200 psig</td>
<td>60-90 psig*</td>
<td>14.5 amps @ 208 V</td>
</tr>
<tr>
<td>9600</td>
<td>250 psig</td>
<td>110 psig</td>
<td>15 amps @ 208 V</td>
</tr>
</tbody>
</table>

When running multiple cryopumps with these compressor, the return pressure will be about 110 psig.