The US Particle Accelerator School
Cryosorption Pumps

Lou Bertolini

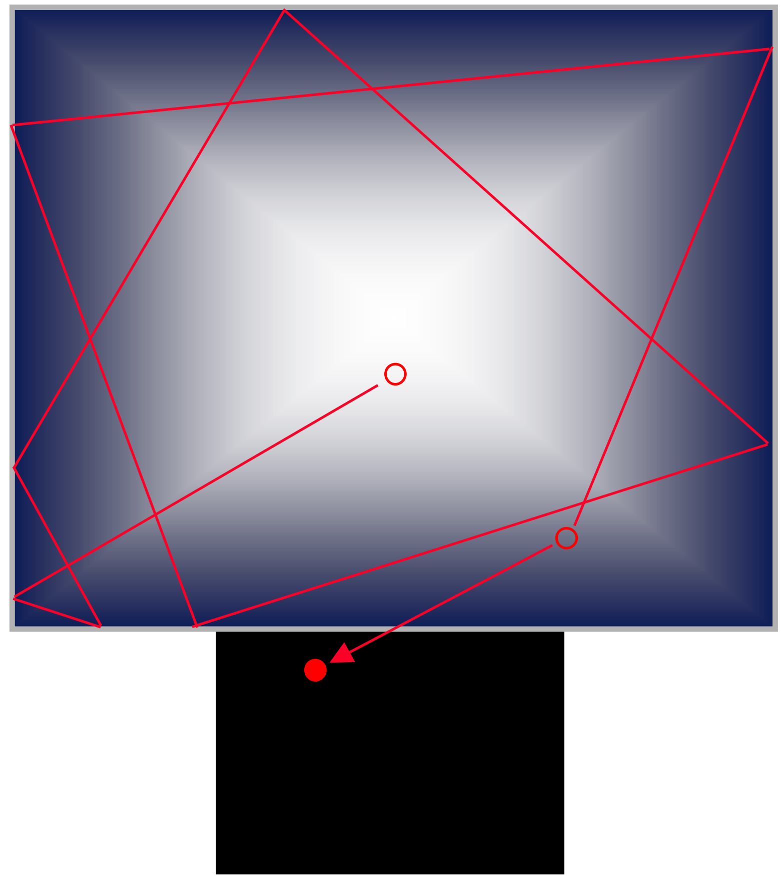
Lawrence Livermore National Laboratory

June 10-14, 2002

Cryopumping Basics . . . Cryocondensation

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

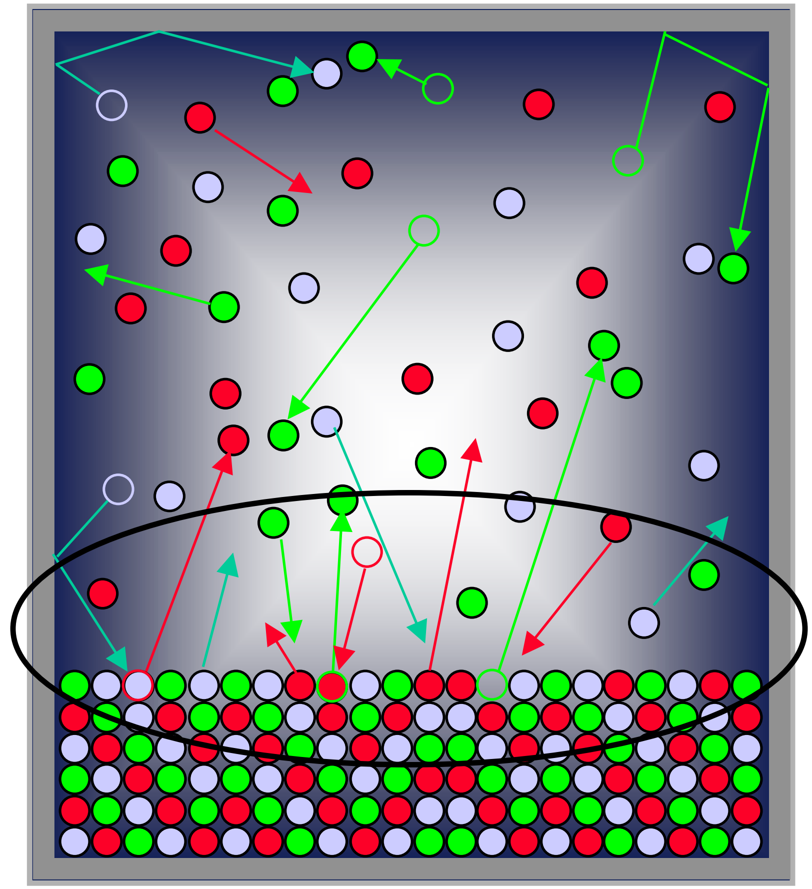
- A cryogenic surface will trap any molecule that contacts the surface if it is cold enough.



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).



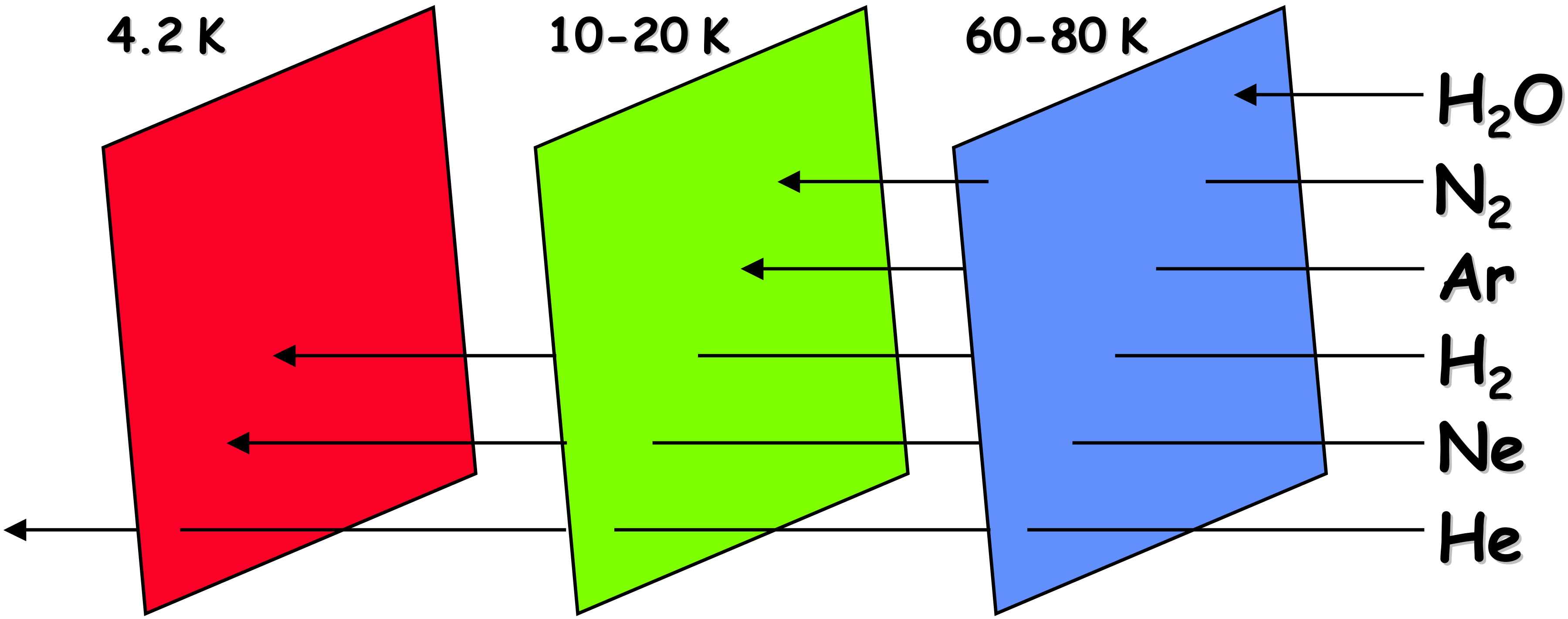
Cryopumping Basics . . .
Pressure within a Cryopump

What determines the Pressure inside a Cryopump?

Surface Temp.	at 16K	at 25K	at 31K
•Nitrogen	> 10^{-12} Torr	> 10^{-7} Torr	> 10^{-4} Torr
•Argon	> 10^{-12} Torr	> 10^{-9} Torr	> 10^{-4} Torr
•Oxygen	> 10^{-12} Torr	> 10^{-10}Torr	> 10^{-4} Torr
•Hydrogen	> 10^{+2} Torr		
•Helium	> Atm.		

Cryopumping Basics . . . Cryocondensation

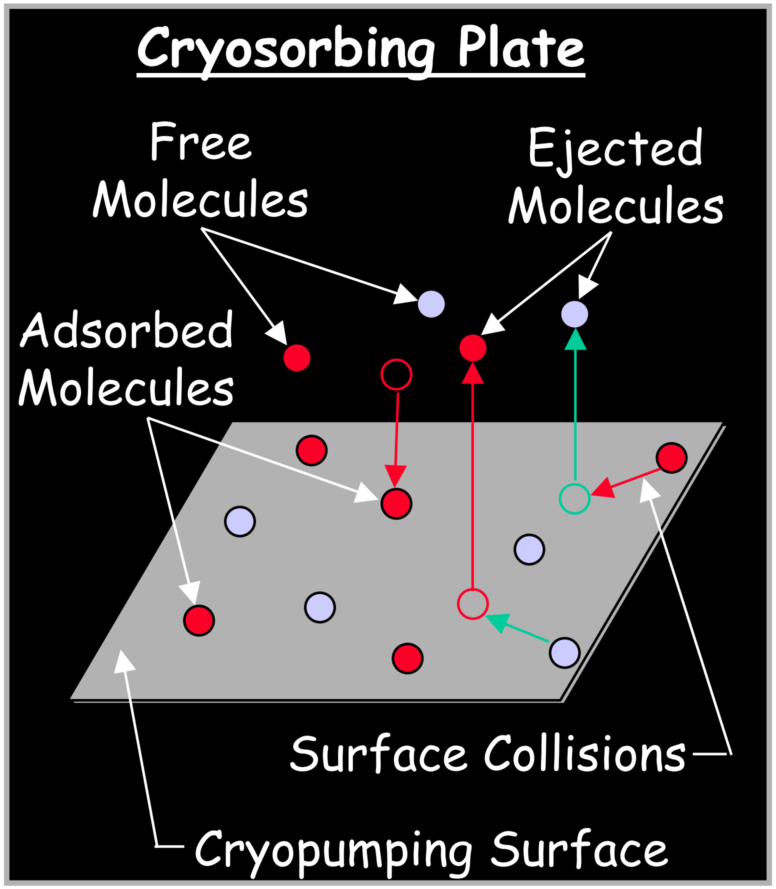
4.2 K is impractical as Helium still boils



Cryopumping Basics . . . Cryosorption

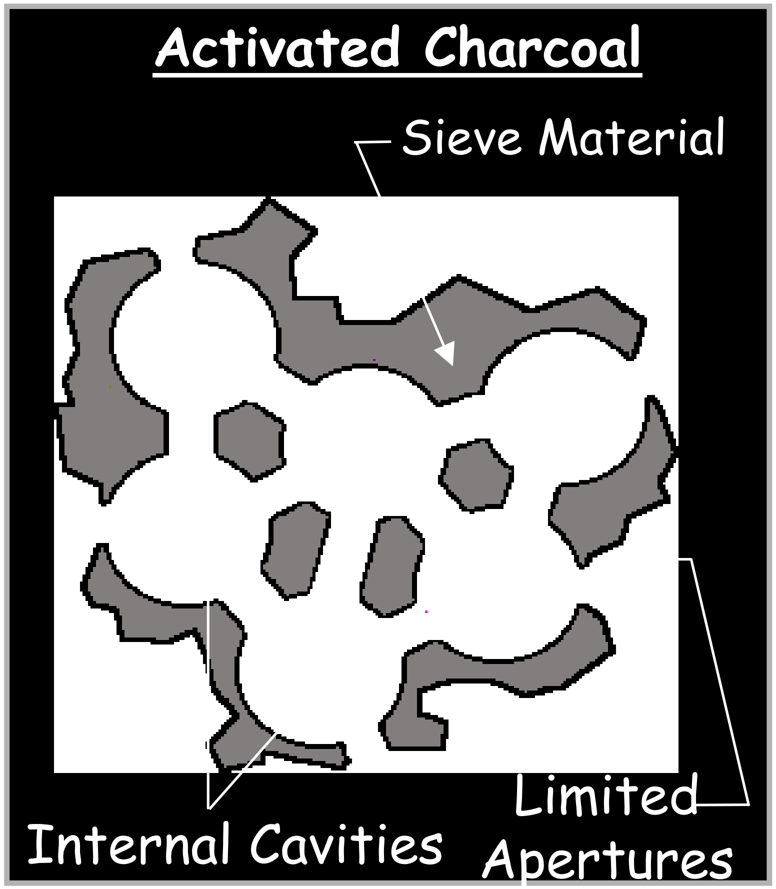
Cooling gas molecules to the extent that gas molecules, upon contacting a sufficiently cooled surface, lose enough energy to accumulate on the surface.

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



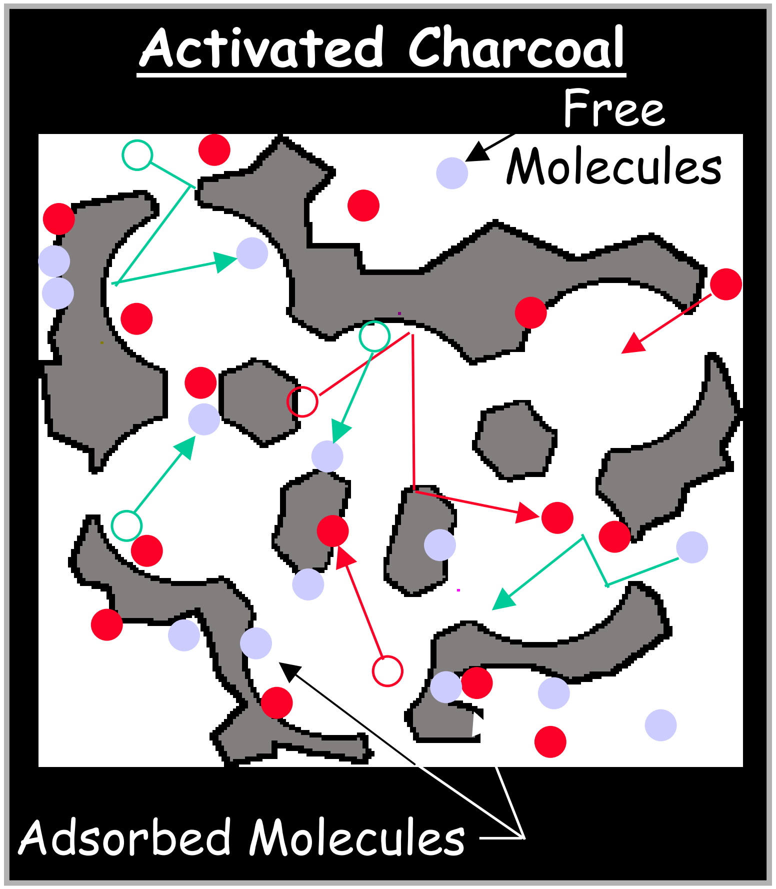
Cryopumping Basics . . . Cryosorption

- Sieve material, such as charcoal, provides greater surface area and limited apertures.
- Large surface area capacity:
  1150-1250 m^2/gm



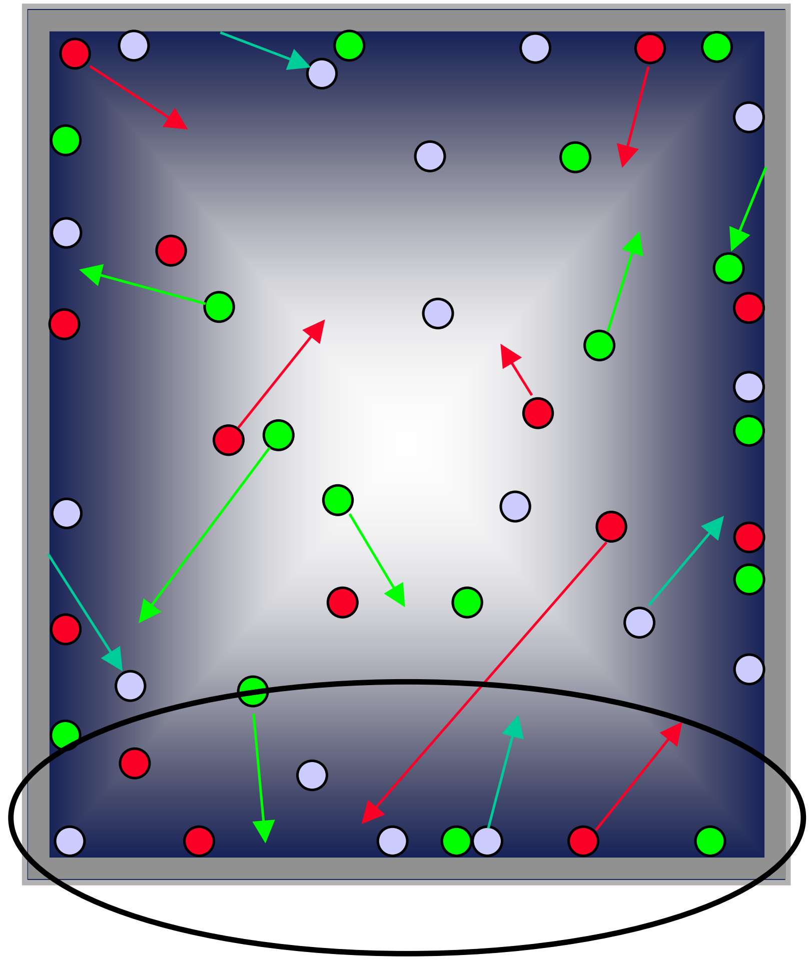
Cryopumping Basics . . . Cryosorption

- 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:

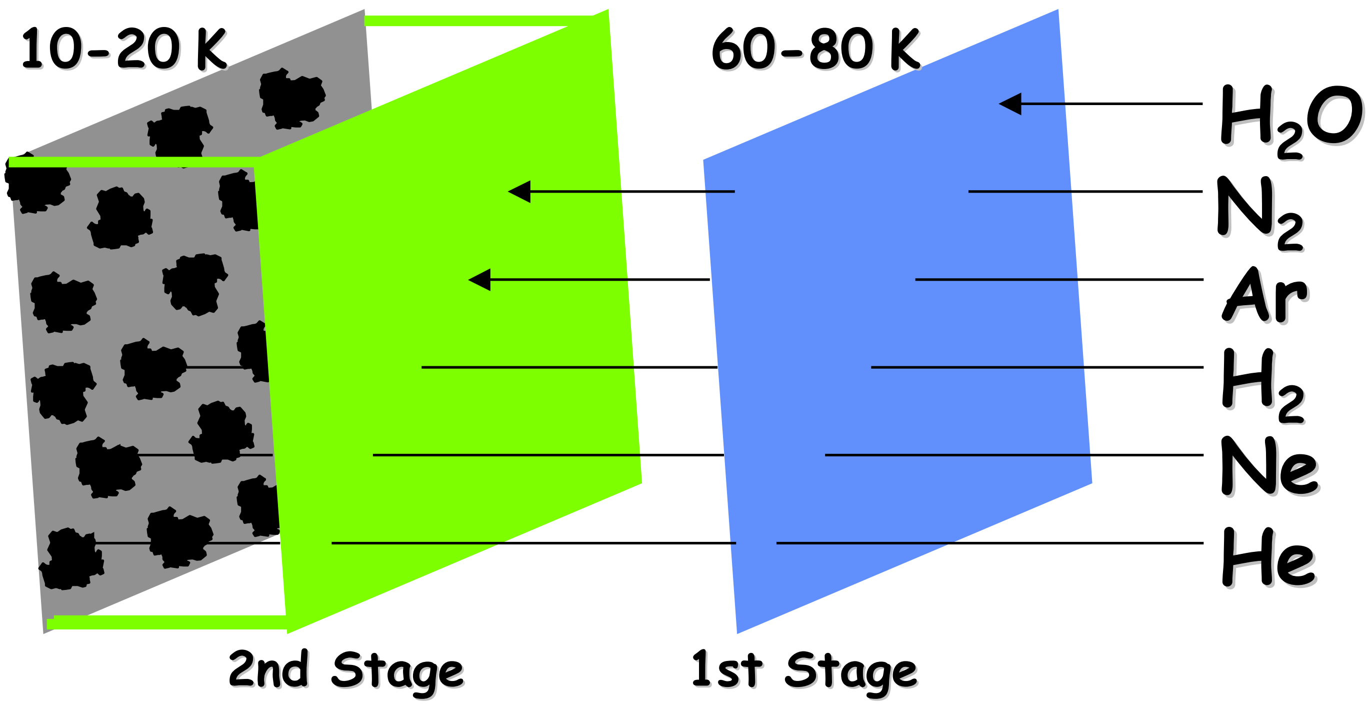
- CONDENSATION
- VAPORIZATION

Surface Equilibrium:

- ADSORPTION
- DESORPTION

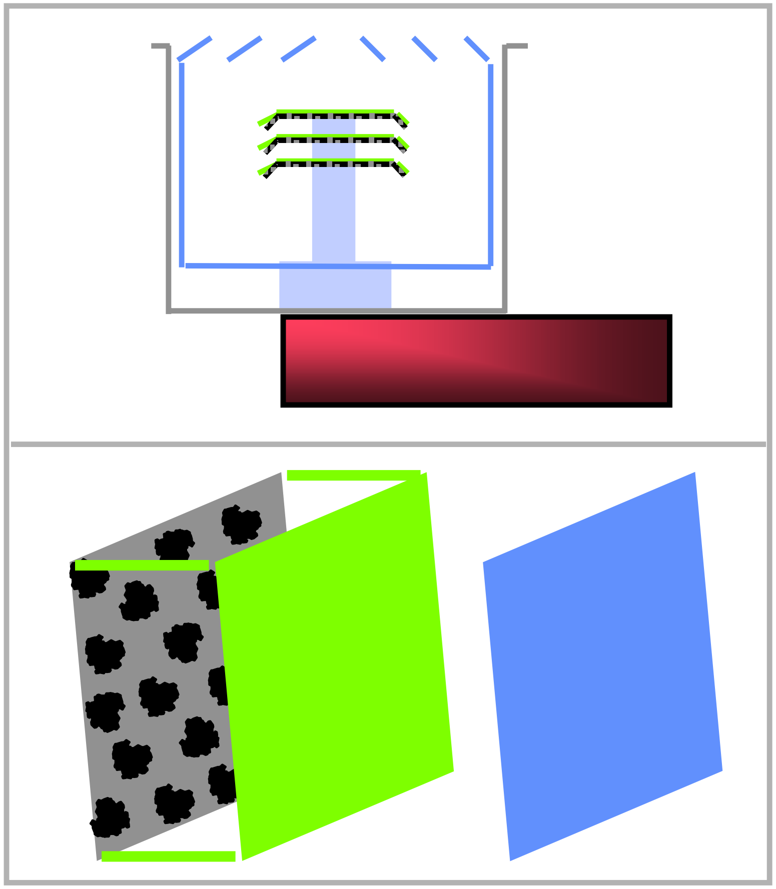
Cryopumping Basics . . . Cryosorption and Cryocondensation

Air gases and water vapor still condensed - noncondensible gases captured.



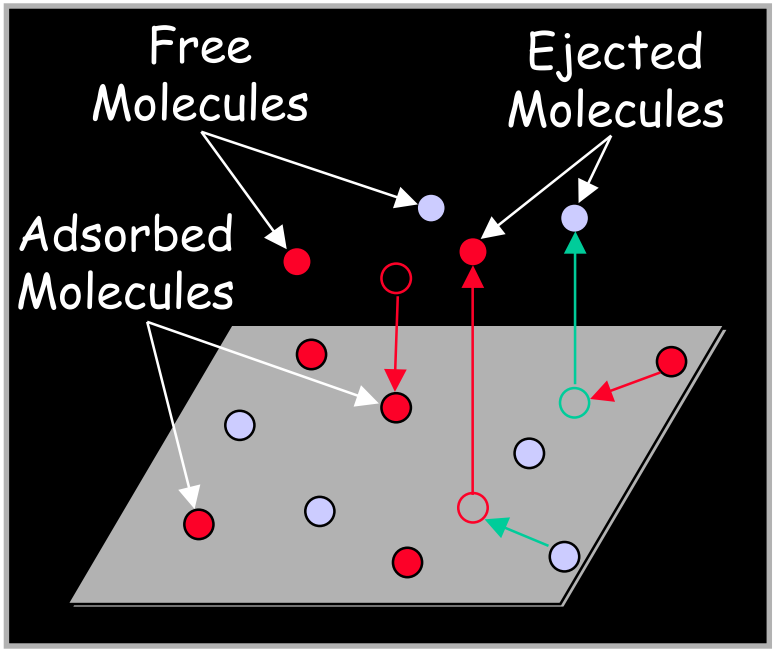
Cryopump Concept

- Cryopumps are designed to create these condensing and adsorbing surfaces.



Cryopumping Basics . . . Adsorption Isotherm

An adsorption isotherm is a measure of the surface population density of a gas at a constant temperature.

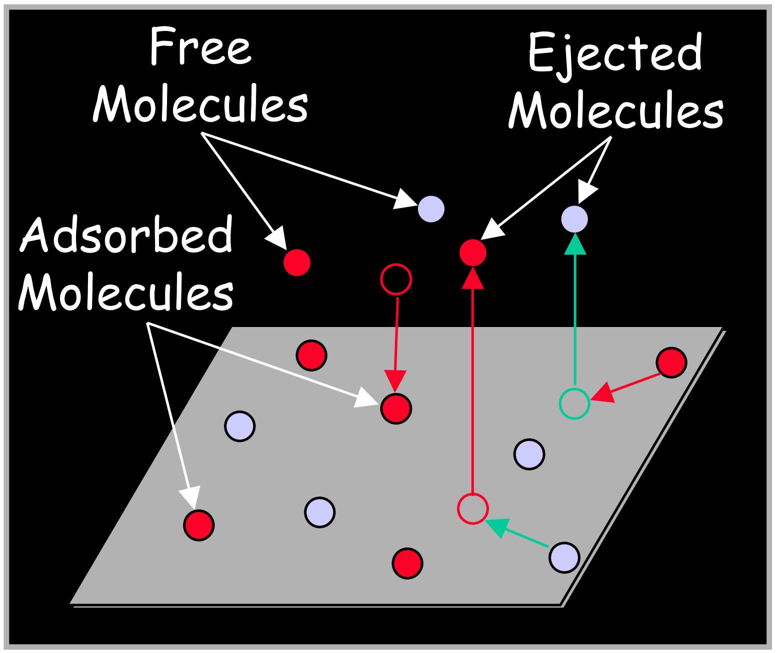


$$\sigma = f(P, T)$$

where σ = density of molecules of gas on a surface per cm^2
P = equilibrium pressure of system
T = system temperature

Cryopumping Basics . . . Adsorption Isotherm

Adsorption isotherms can be expressed several ways:



% Coverage

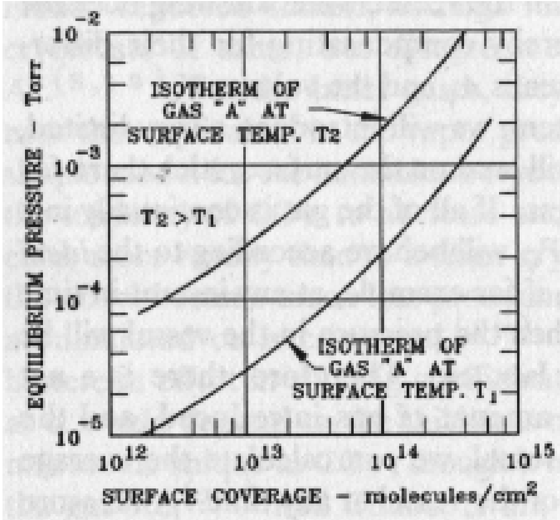
σ = 0.20 surface 20% covered
σ = 1 One monolayer (σ_m)
σ = 2 Two monolayers ($2\sigma_m$)

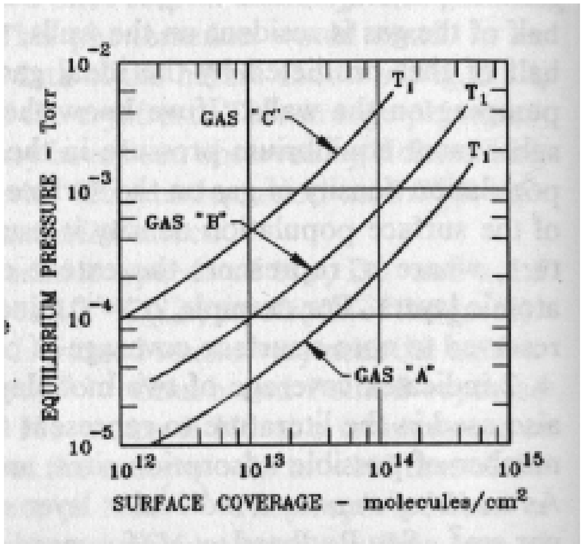
Molecules/cm²

$\sigma = 10^{15}$ 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.

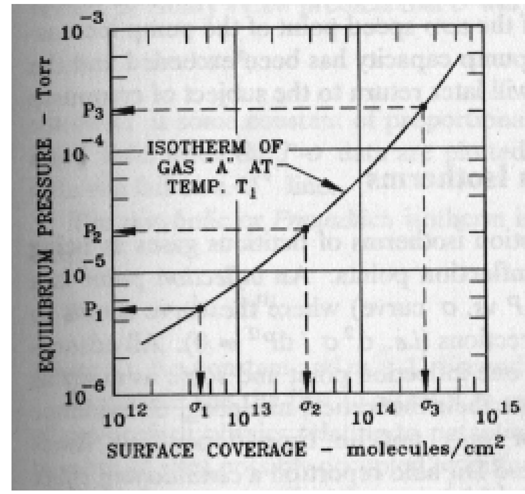
Cryopumping Basics . . . Pumping Speed

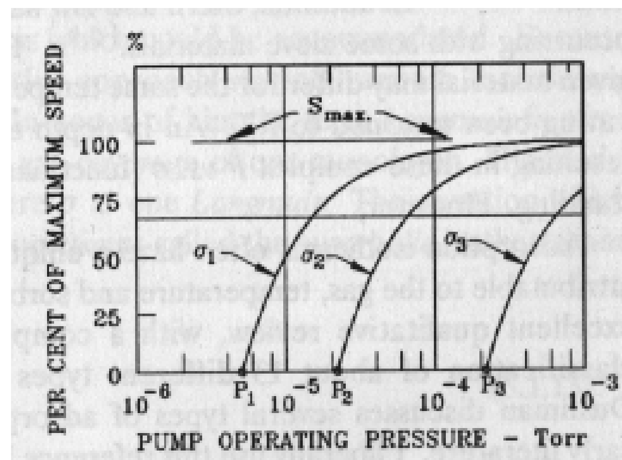
- A cold surface has a finite pumping speed for a gas as long as the pressure of the adsorption isotherm is less than the pressure of the gas.
- As the surface coverage increases, the equilibrium pressure increases.

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

- S_{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.



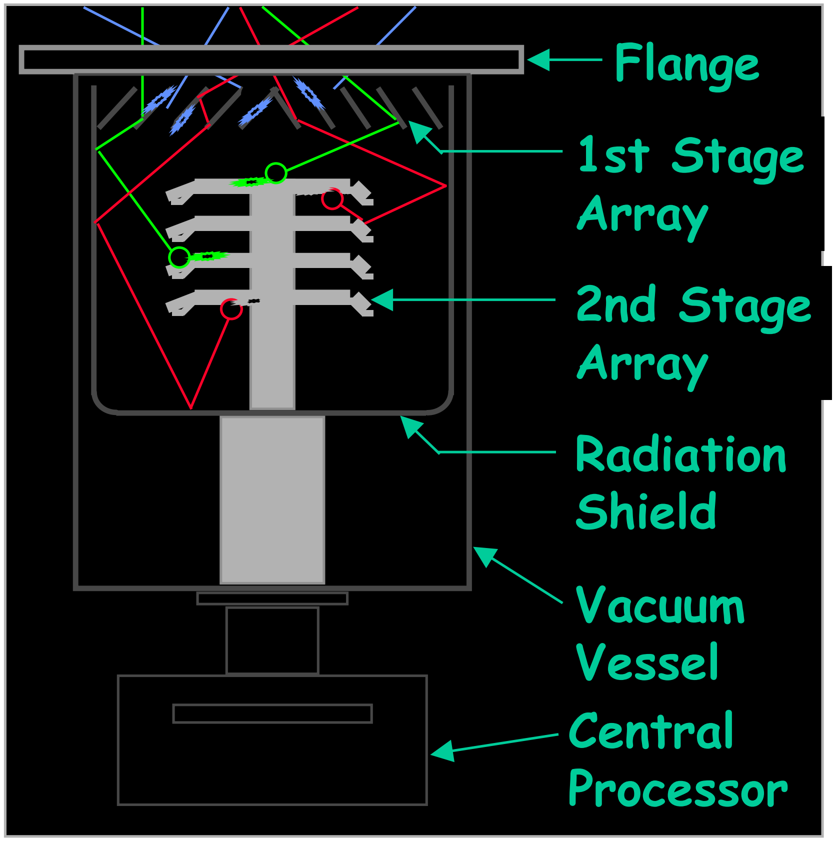


Cryopumping Basics . . . Sticking Coefficients

CryoSurface Temperature (K)	Gas and Gas Temperature									
	N_2		CO		O_2		Ar		CO_2	
	77 K	300 K	77 K	300 K	77 K	300 K	77 K	300 K	77 K	300 K
10	1.0	0.65	1.0	0.90			1.0	0.68	1.0	0.75
12.5	0.99	0.63	1.0	0.85			1.0	0.68	0.98	0.70
15	0.96	0.62	1.0	0.85			0.90	0.67	0.96	0.67
17.5	0.90	0.61	1.0	0.85	1.0	0.86	0.81	0.66	0.92	0.65
20	0.84	0.60	1.0	0.85			0.80	0.66	0.90	0.63
22.5	0.80	0.60	1.0	0.85			0.79	0.66	0.87	0.63
25	0.79	0.60	1.0	0.85			0.79	0.66	0.85	0.63
77									0.85	0.63

Ref. "Cryopumping", Dawson and Haygood, Cryogenics 5 (2), 57, (1965)

Cryopump



Capture Type Pump

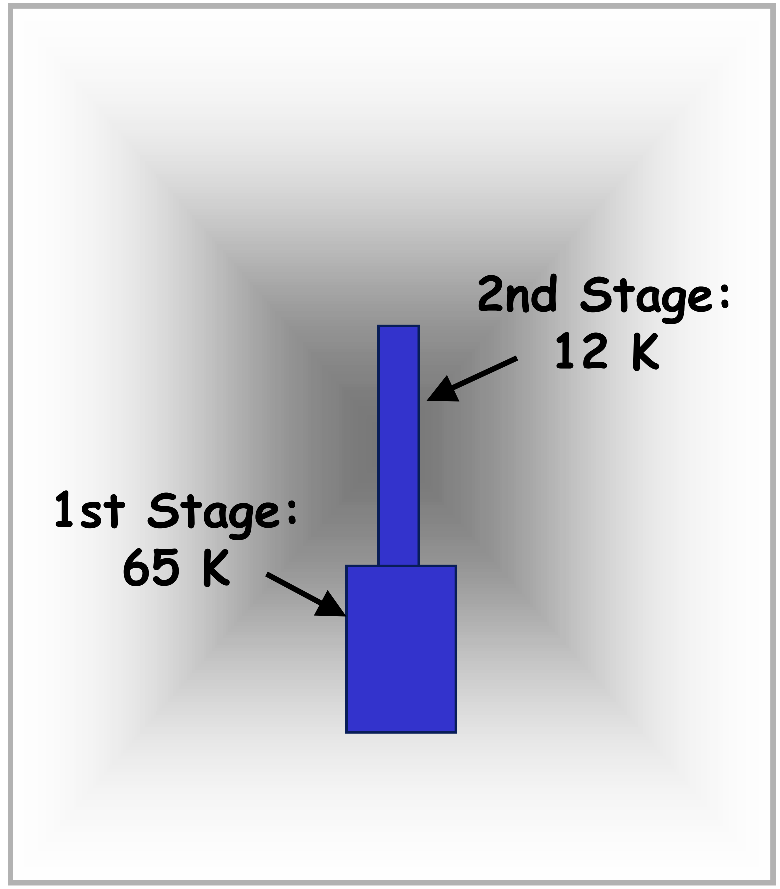
Characteristics:

- 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*

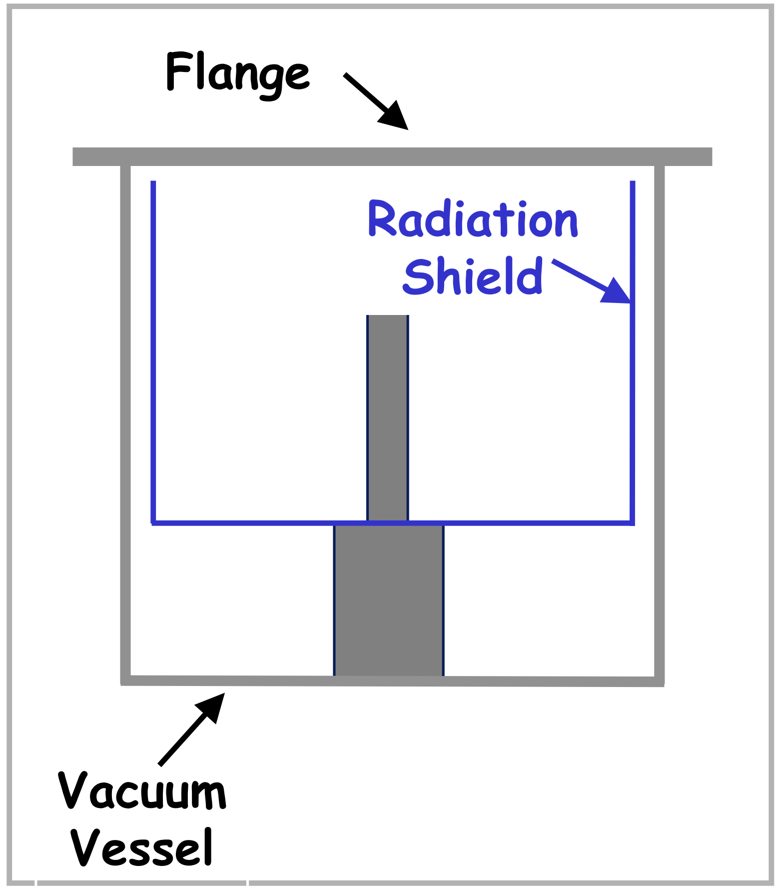
- A cryopump is built around the cold-head.
  - Creates the cold temperatures needed to condense and adsorb gases
  - Two stages, each at a different temperature

- Achieves these temperatures by the expansion of helium.



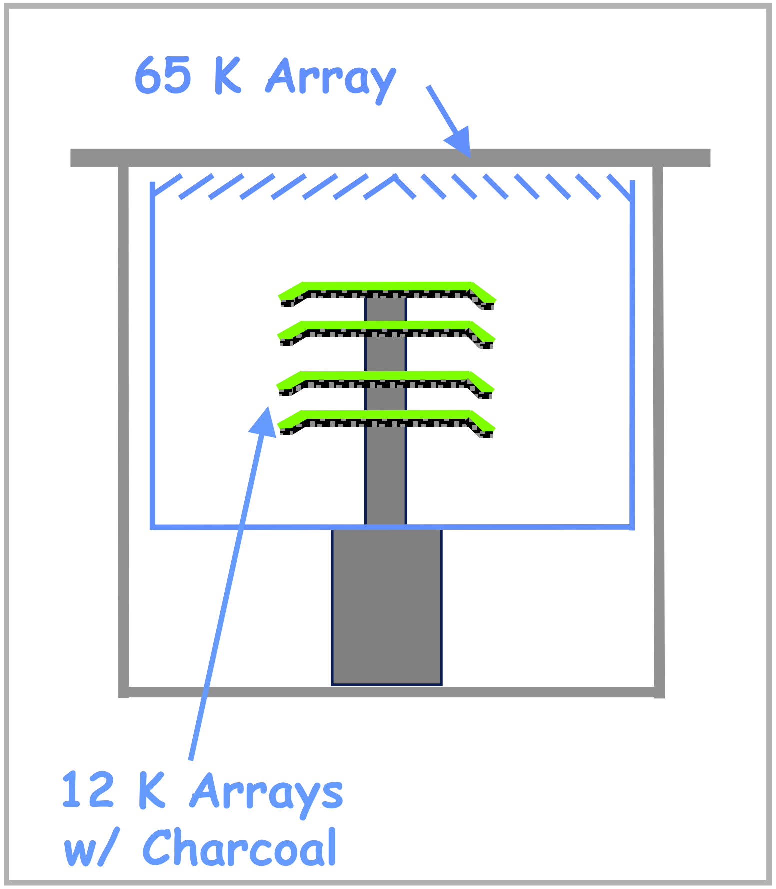
Cryopump Components . . .
shield, vacuum vessel, and flange

- 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.



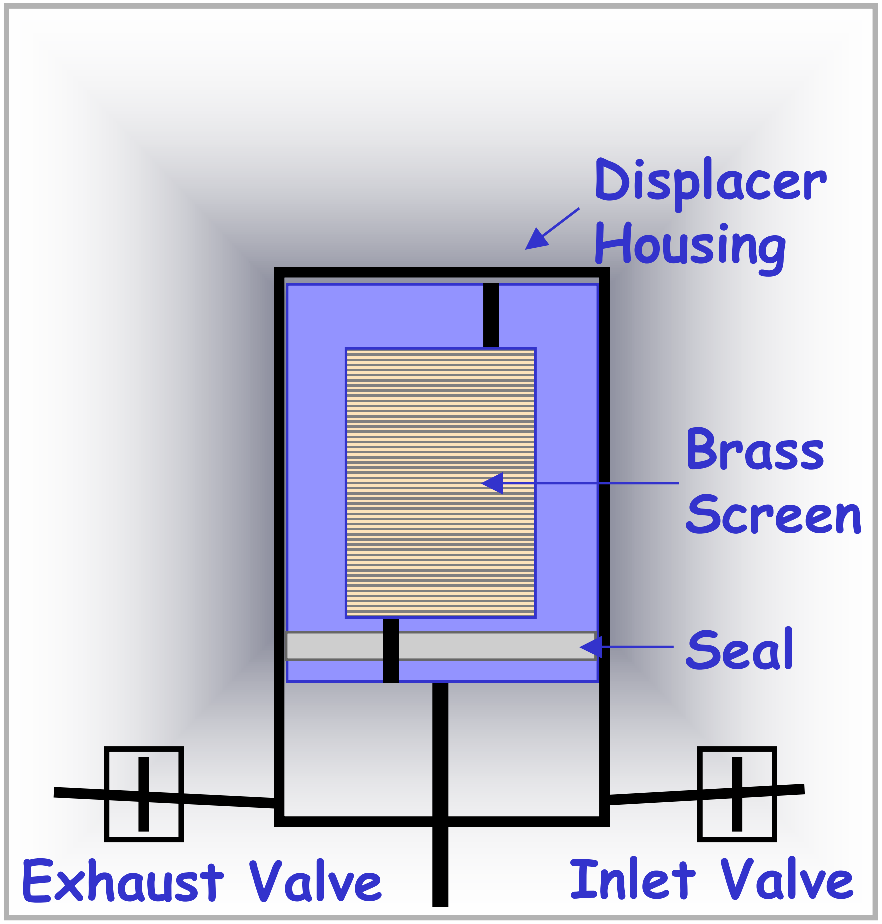
Cryopump Components . . .
1st and 2nd Stage Arrays

- 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



Ref ©2000 Helix Technology Corporation

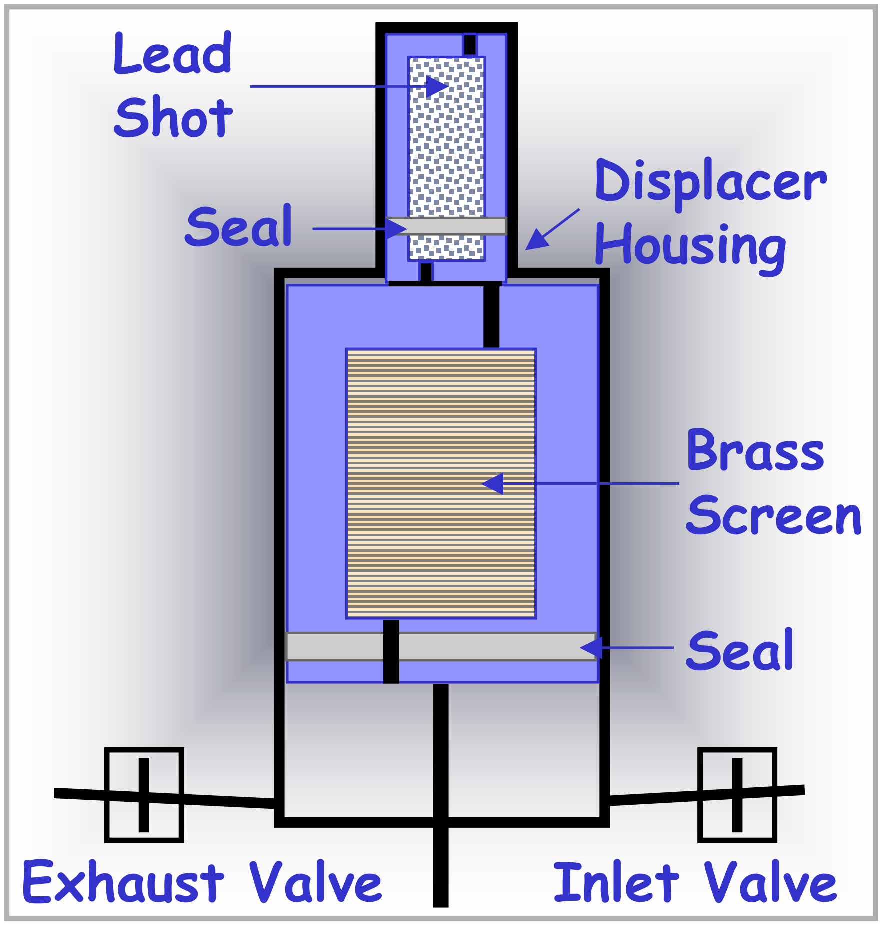
Cryopump System . . . *The Refrigerator*



Primary Displacer

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

Cyropump System . . . *The Refrigerator*

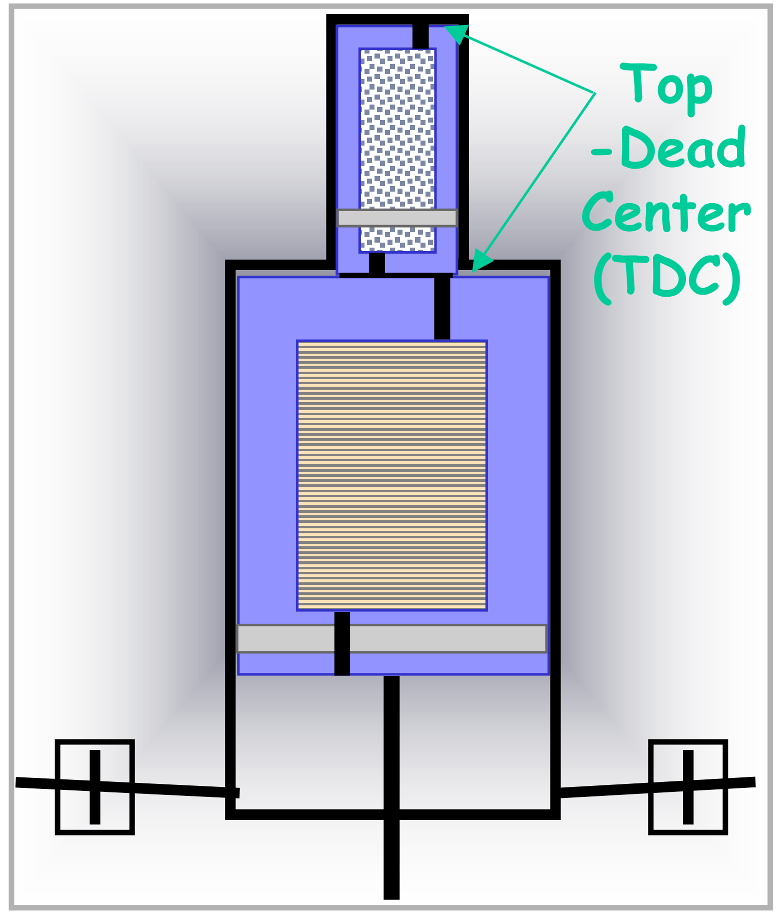


Secondary Displacer

- Second stage attached to top of primary displacer allows even lower temperatures.
- Lead shot for thermal mass.
- Phenolic casing.

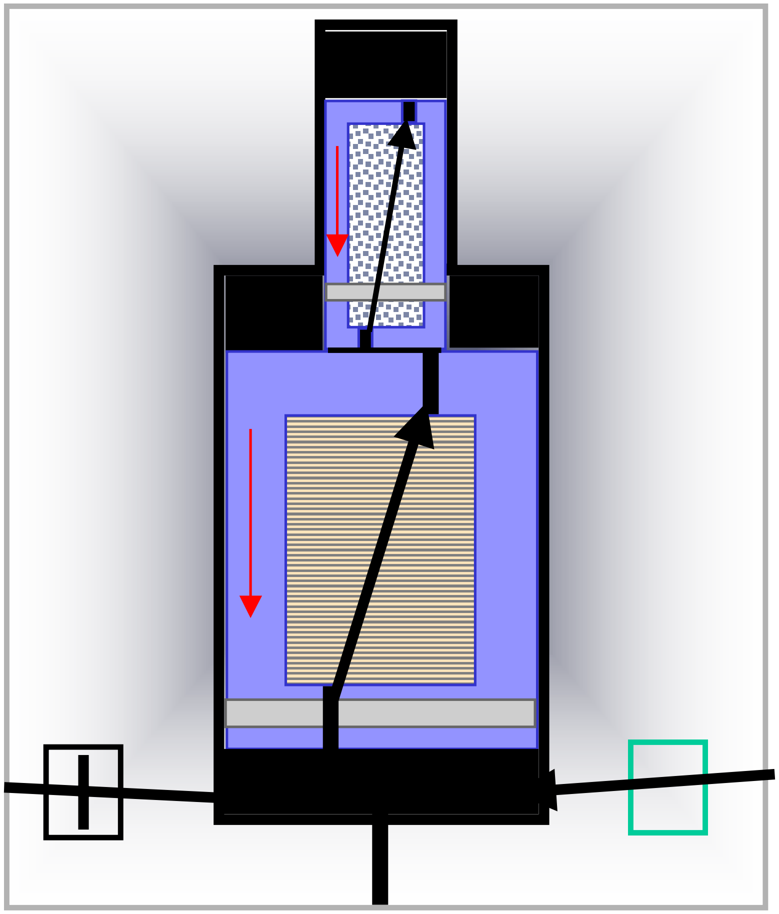
Cyopump System . . . *The Refrigerator*

- Cycle begins with both displacers at TDC.



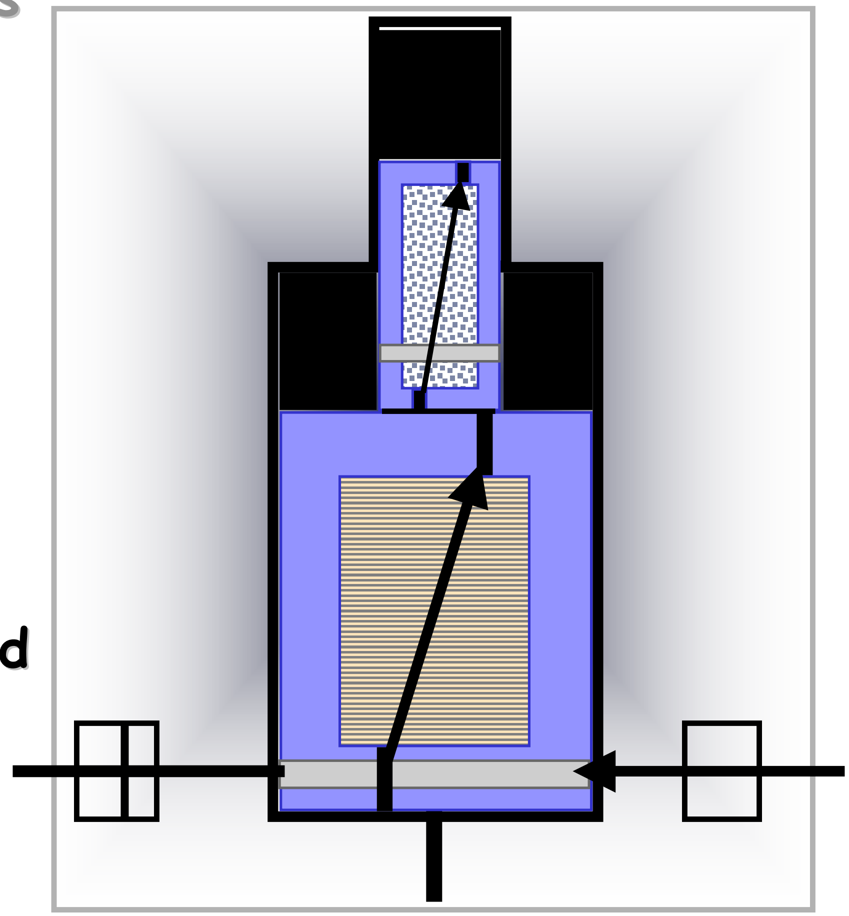
Cryopump System . . . *Refrigeration Cycle*

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



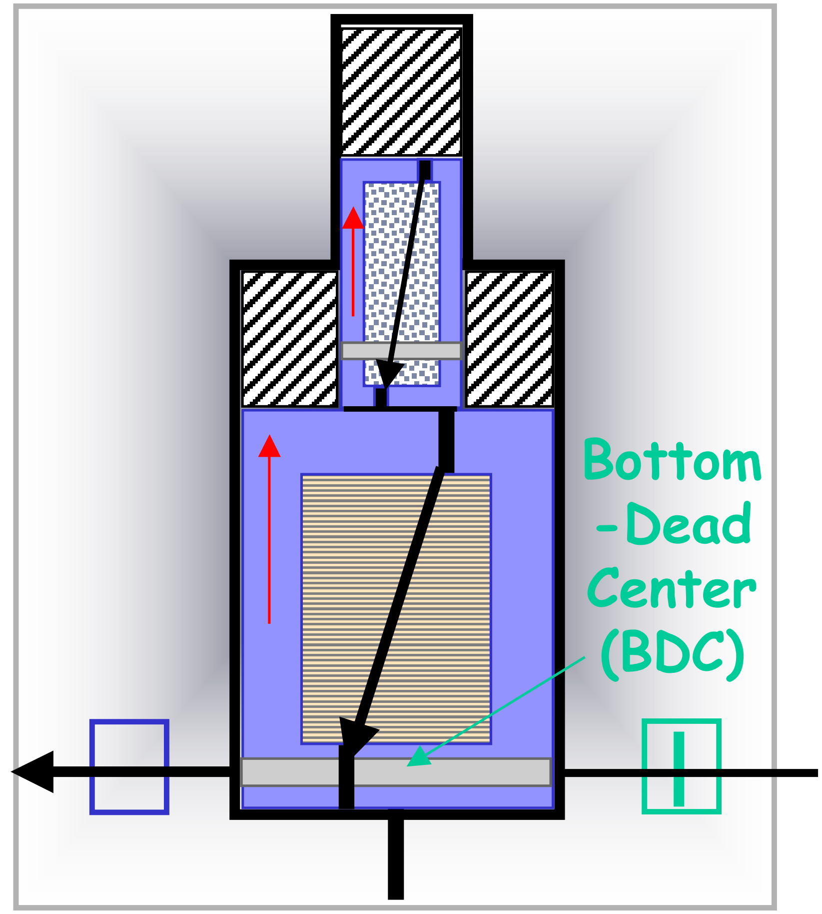
Cryopump System . . . *Refrigeration Cycle*

- 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.**



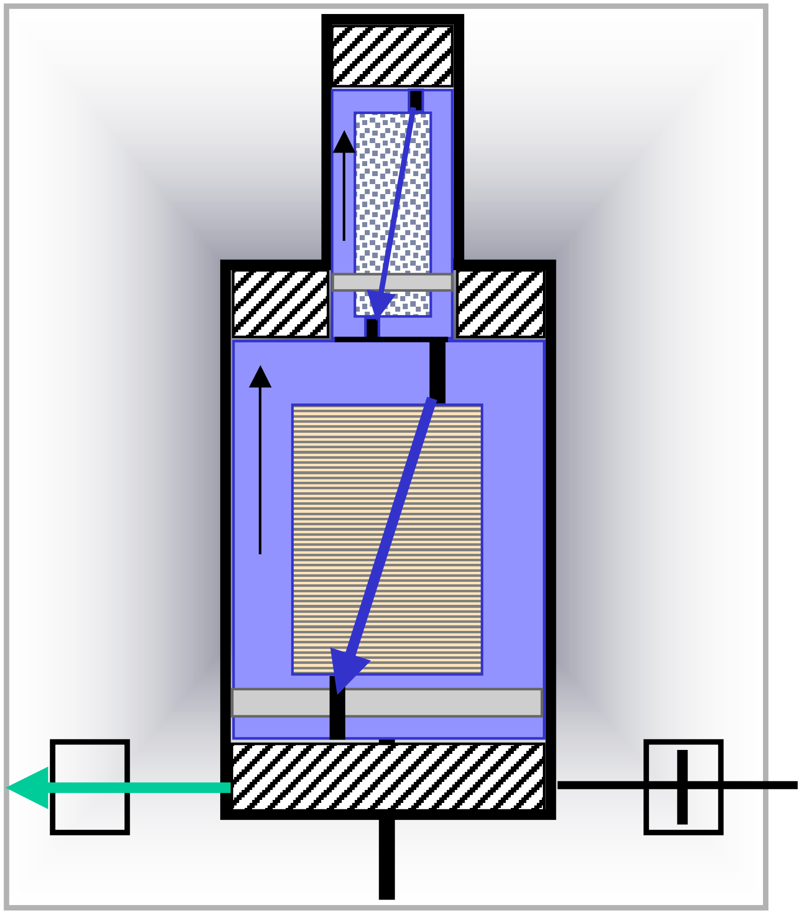
Cryopump System . . . *Refrigeration Cycle*

- At BDC, inlet valve closes.
- Exhaust valve opens.
- Gas has expanded in both voids and cools.
- Displacers move upward.



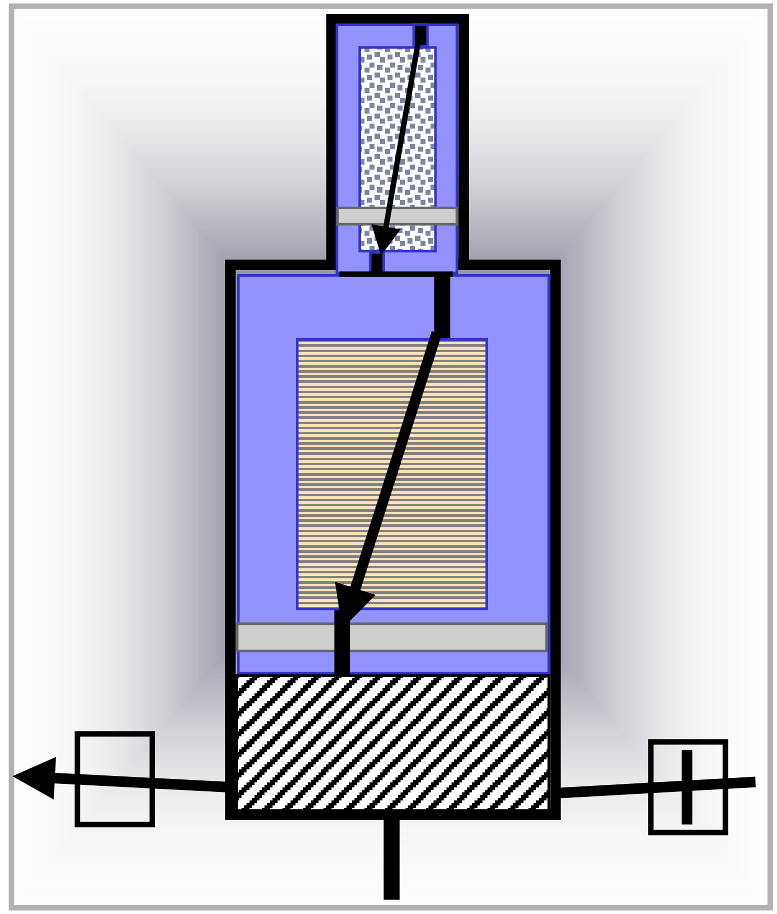
Cryopump System . . . *Refrigeration Cycle*

- Cooled gas flows down through both displacer matrices removing heat from thermal masses.
- Gas exits through exhaust valve.



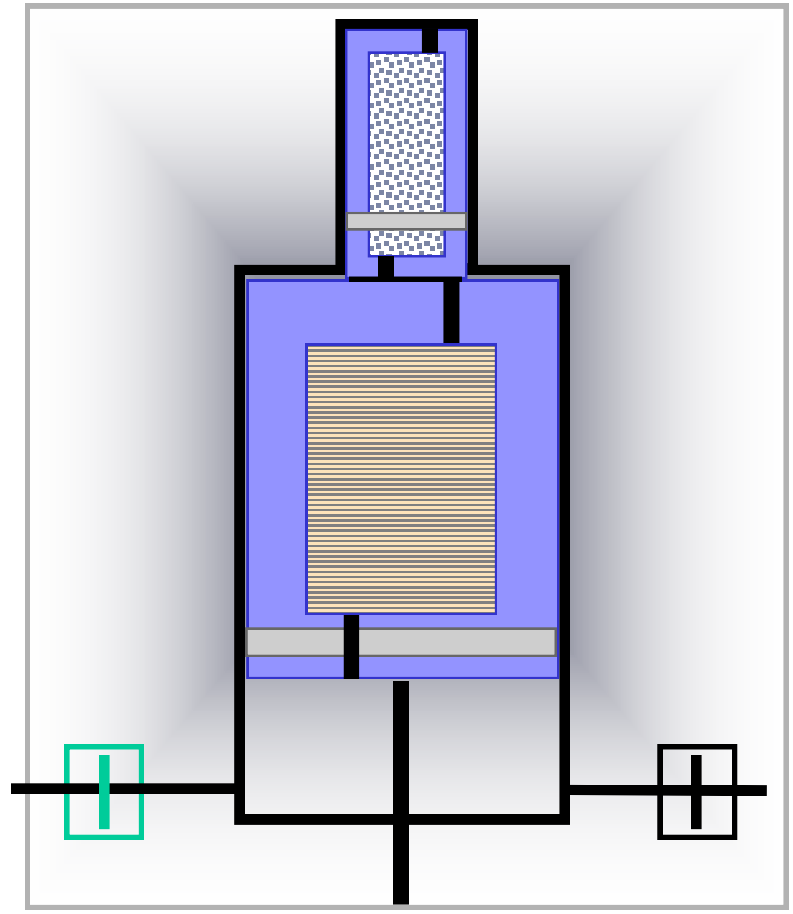
Cryopump System . . . *Refrigeration Cycle*

- **Displacers again at TDC.**



Cryopump System . . . *Refrigeration Cycle*

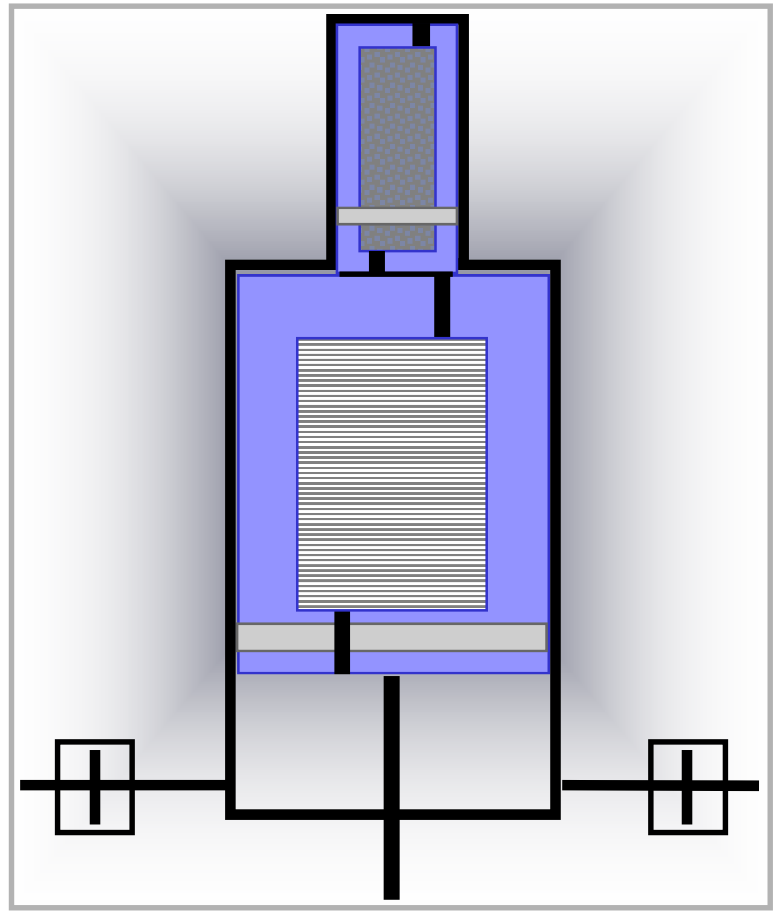
- Displacers again at TDC.
- Remaining gas exits.
- Exhaust valve closes.
- Cycle repeats at 72 rpm.



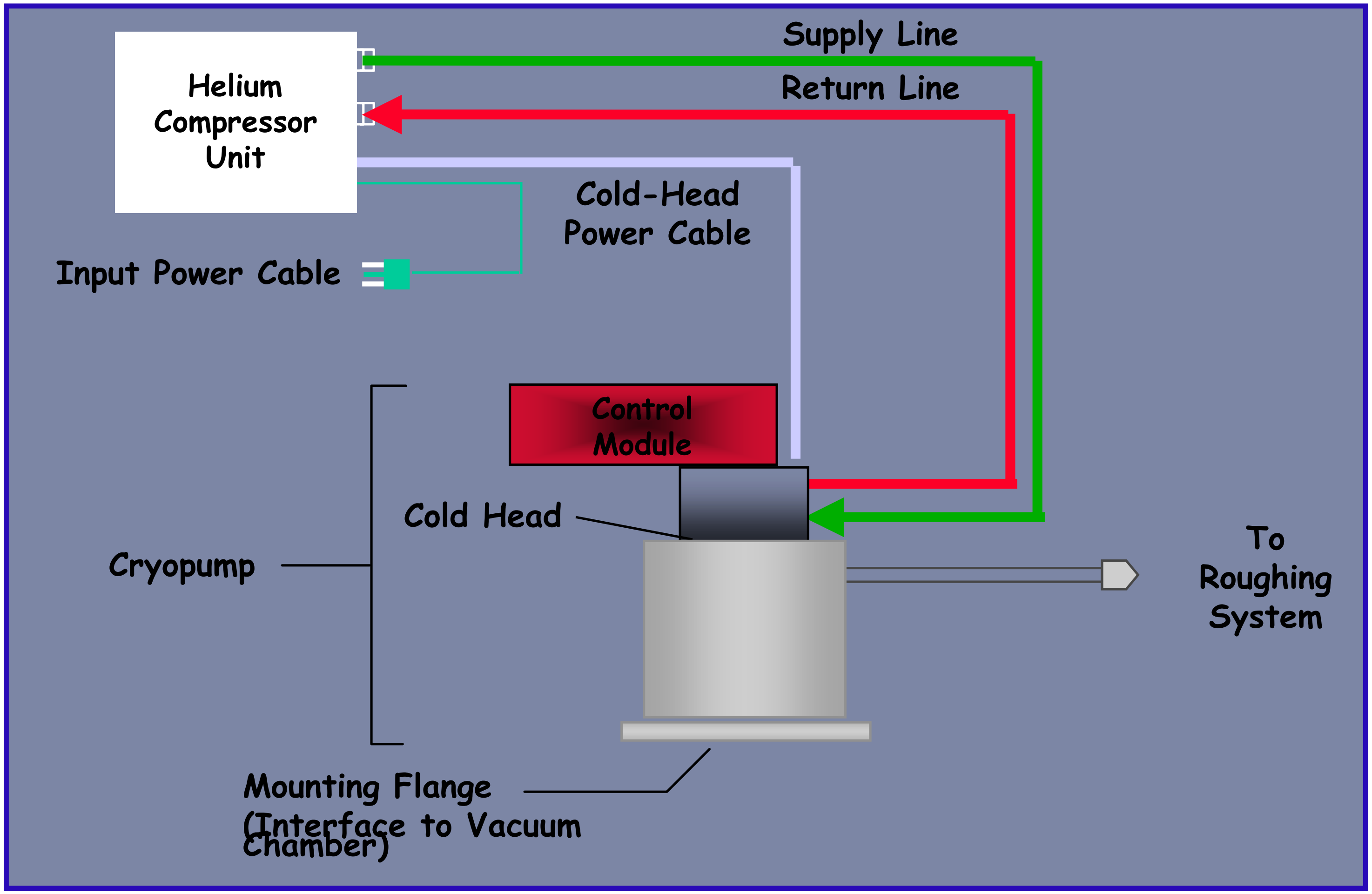
Cryopump System . . . *Refrigeration Cycle*

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.

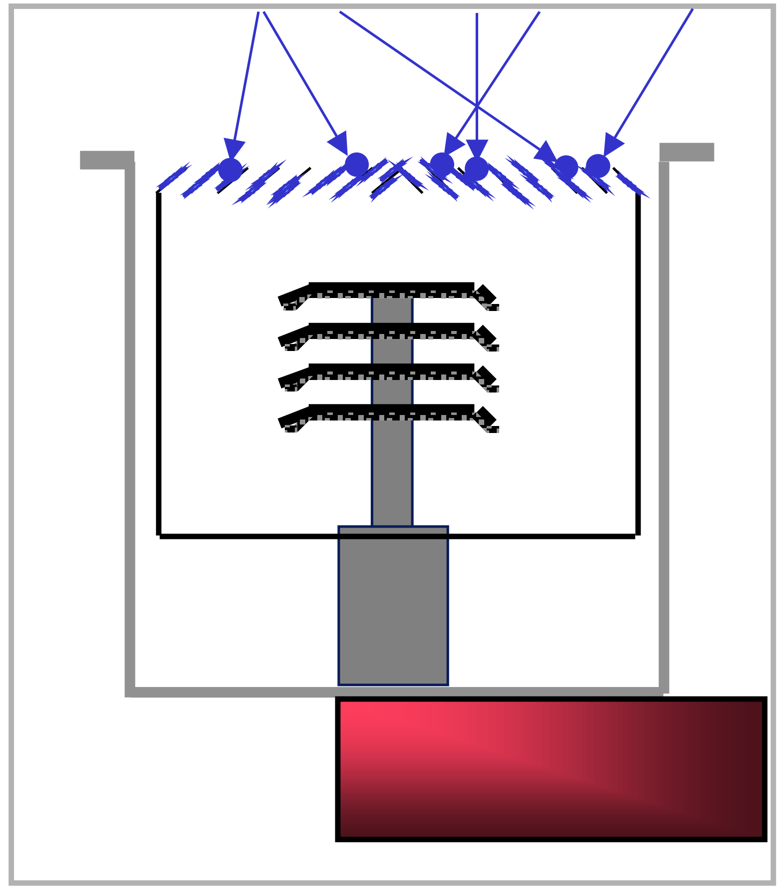


Cryopump System Overview



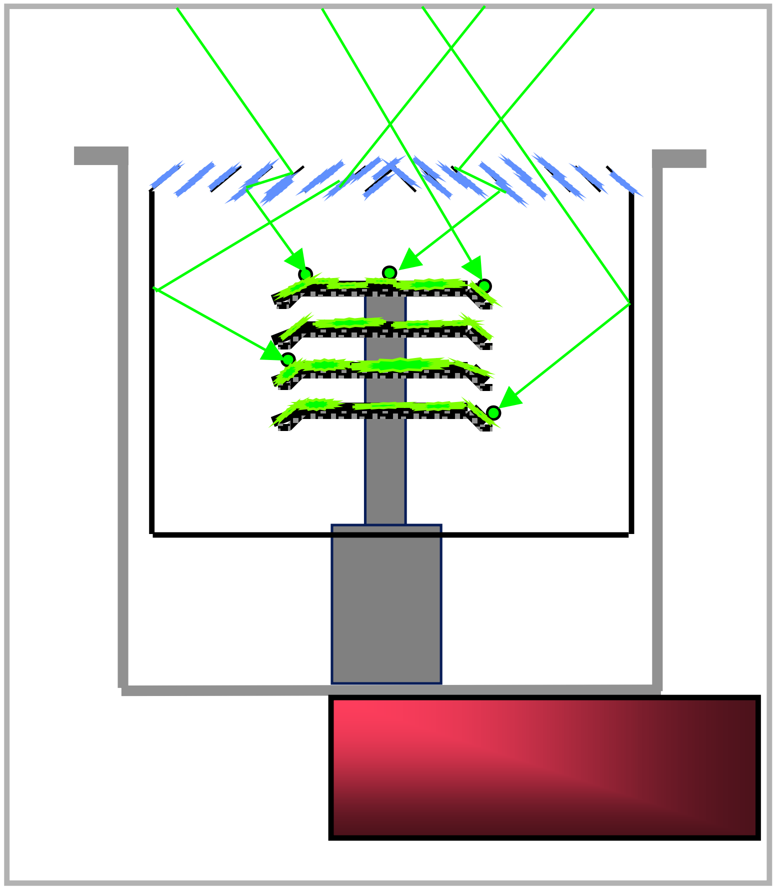
Cyropump Operation - *Cryocondensation*

- Water molecules collide with the cooled surfaces of the 65 K first stage array.
- Condensation layers form as more of these molecules collect.



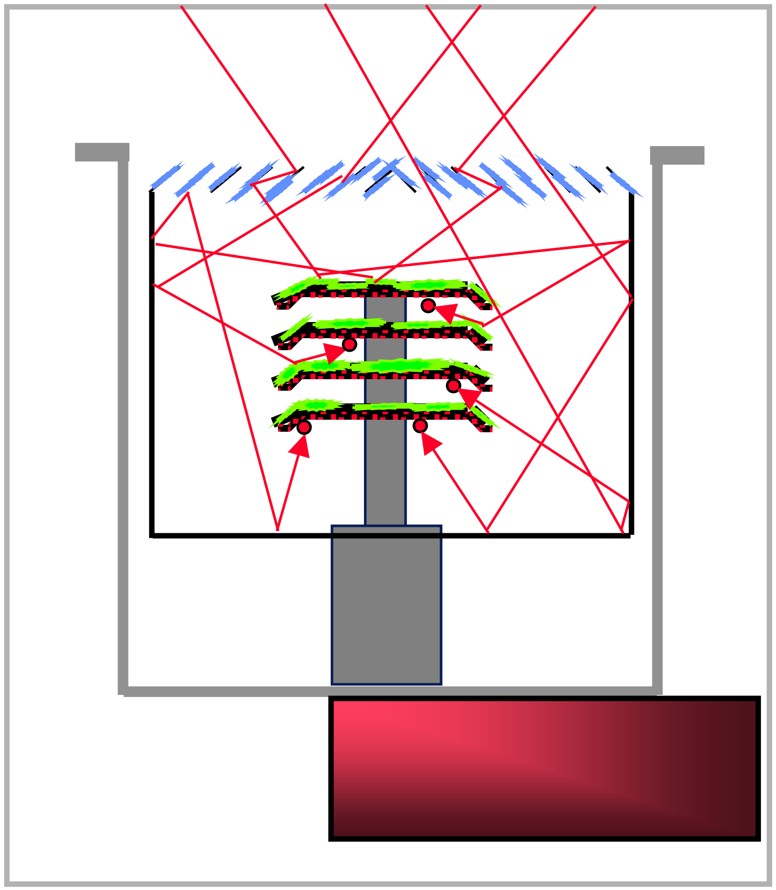
Cyropump Operation - *Cryocondensation*

- 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.



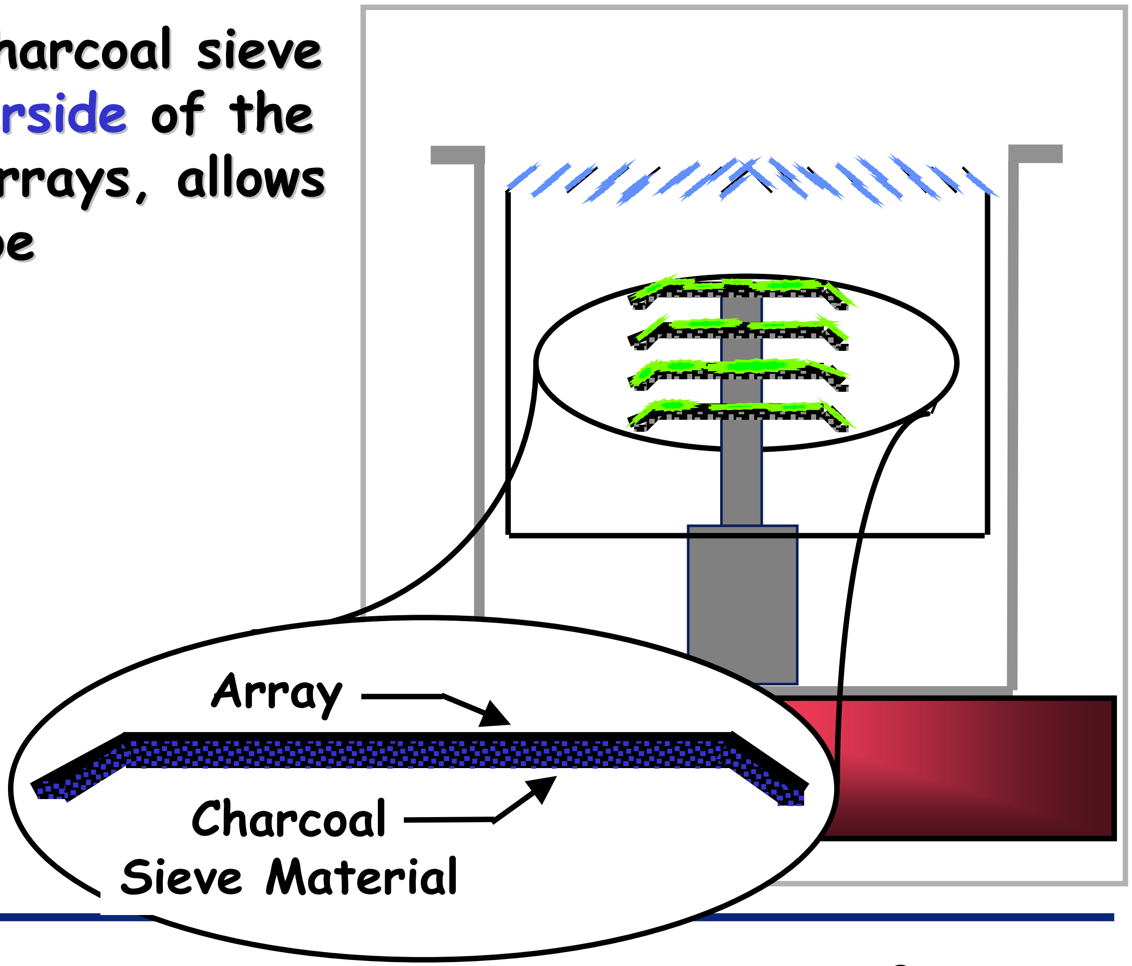
Cyropump Operation - *Cryoadsorption*

- The noncondensible 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.



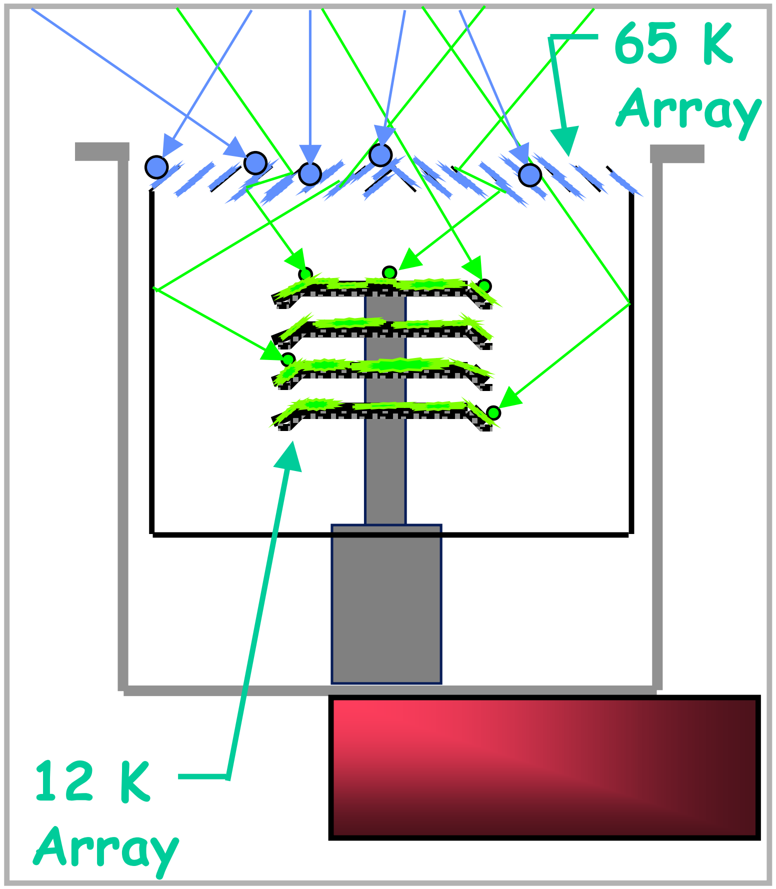
Cyropump Operation - *Cryoadsorption*

- Affixing activated charcoal sieve material to the underside of the 12 K second stage arrays, allows H_2, He, and Ne to be cryoadsorbed.



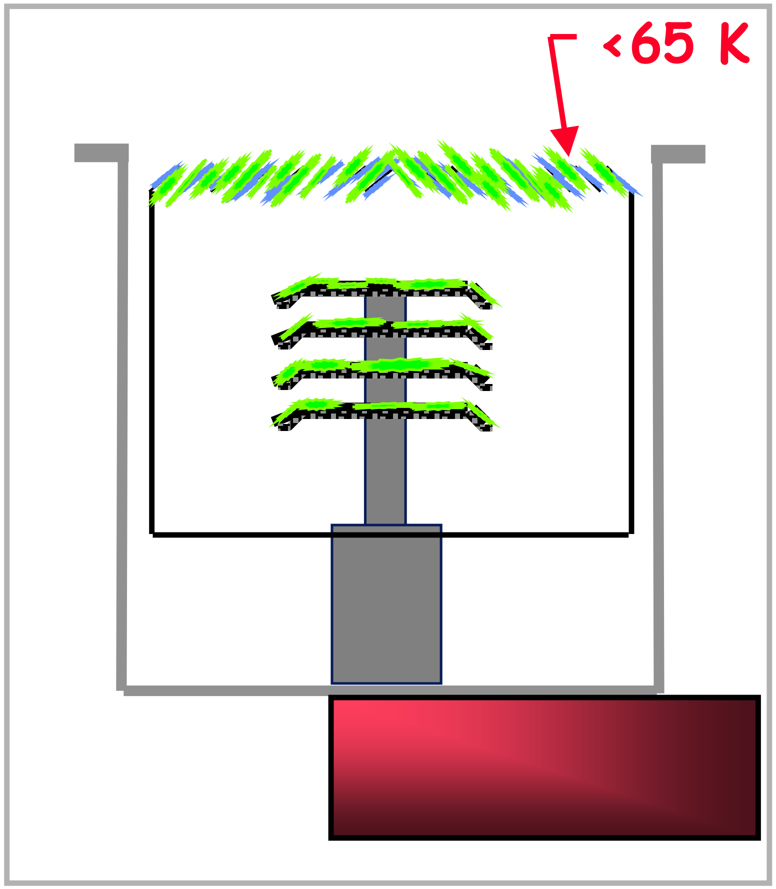
Cyropump Operation – *Argon Hang-Up*

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.



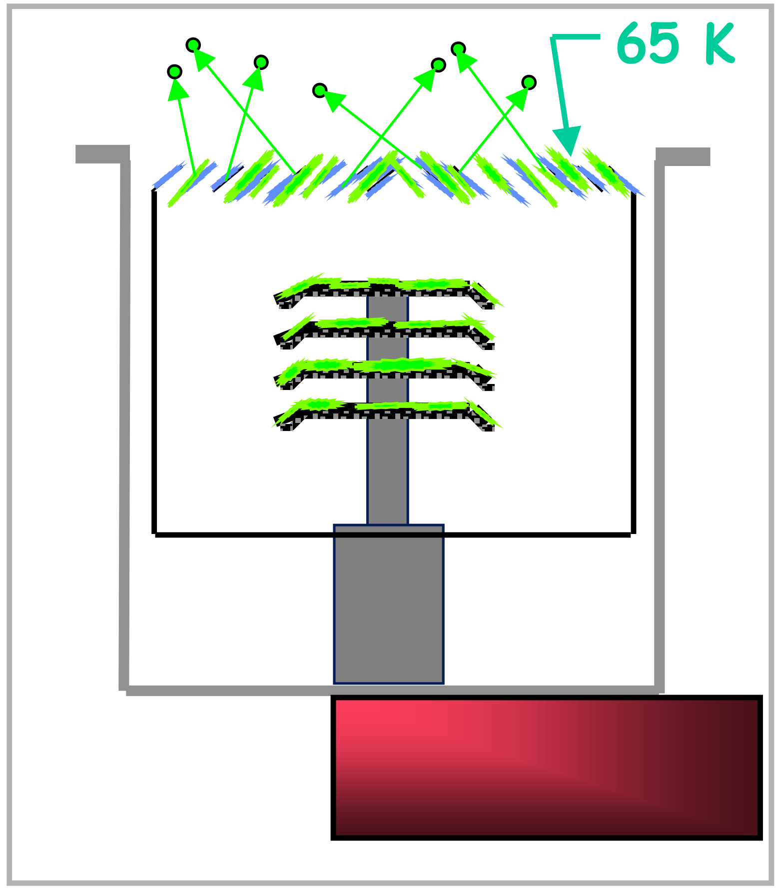
Cyropump Operation – *Argon Hang-Up*

- 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.



Cyropump Operation – *Argon Hang-Up*

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

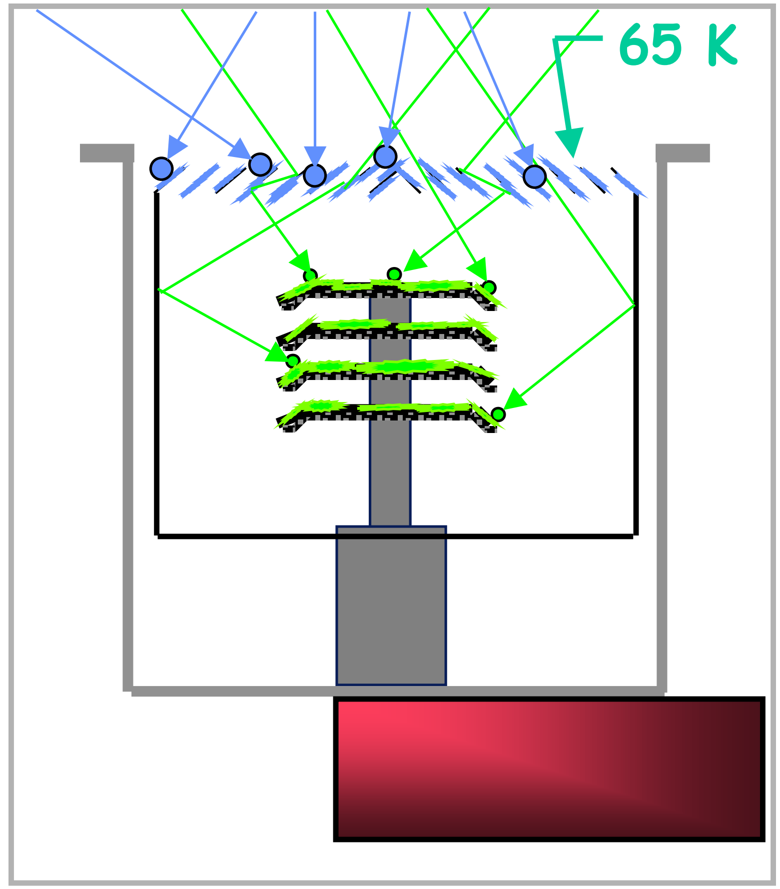


EQUILIBRIUM VAPOR PRESSURE

	10^{-10}	10^{-7}	10^{-4}	10^{-3}
Water	130K	153K	185K	198.5K
Argon	23.7K	28.6K	35.9K	39.2K

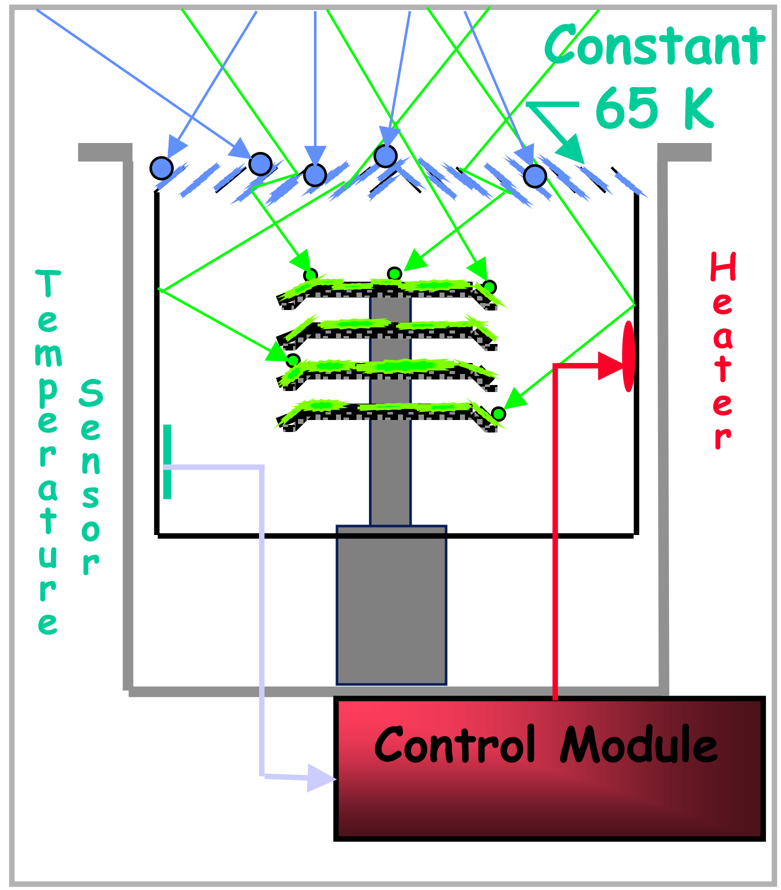
Cyropump Operation – *Argon Hang-Up*

- 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*

Gas Collected = Pressure x Speed x Time

Gas	Capacity (at STP)
Water Vapor	1000 liters (gas)
	1 liter (ice)
Nitrogen & Argon	1000 liters (gas)
	1 liter (ice)
Hydrogen	17 liters (gas)

Cyropump Operation . . . *Crossover*

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: $\frac{\text{Crossover value}}{\text{Chamber volume}}$ = P in Torr

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

Understanding crossover can produce faster pumpdown times and cleaner vacuum too.

Cyropump Operation . . . *Regeneration*

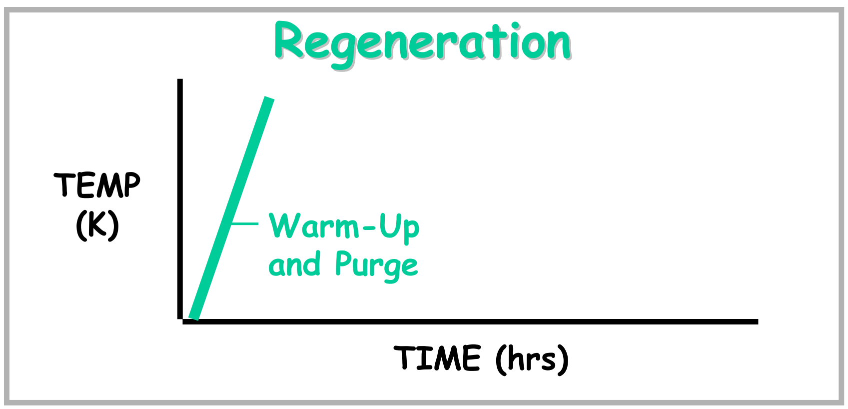
The objective of regenerating a cryopump is to remove the captured gases from the pump and restore its pumping capacity.

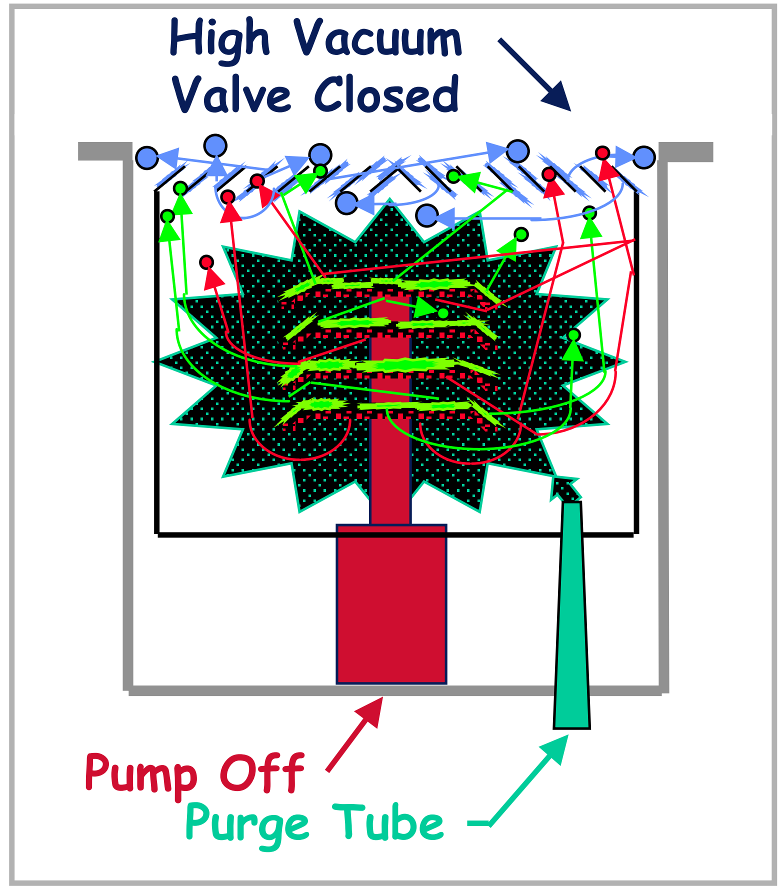
So . .. when should cryopumps be regenerated?

Whenever your system is down is a good opportunity to regenerate your cryopump without affecting your up-time.

Cyropump Operation . . . *Regeneration*

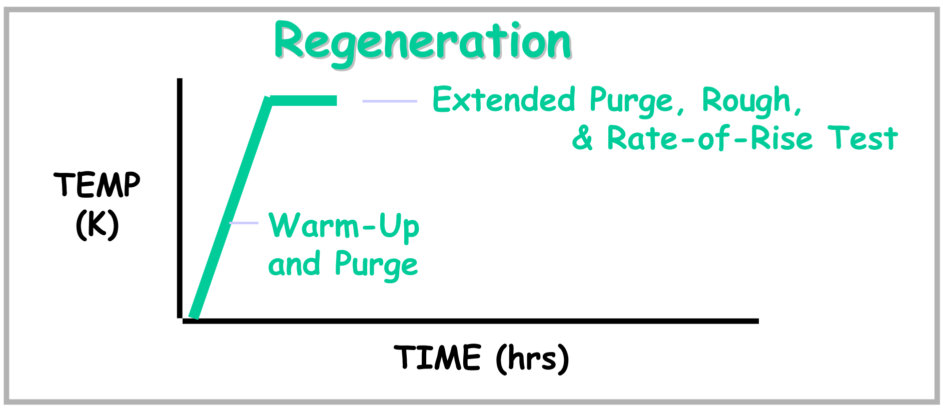
- **Regeneration**
  - Warm-Up and Purge

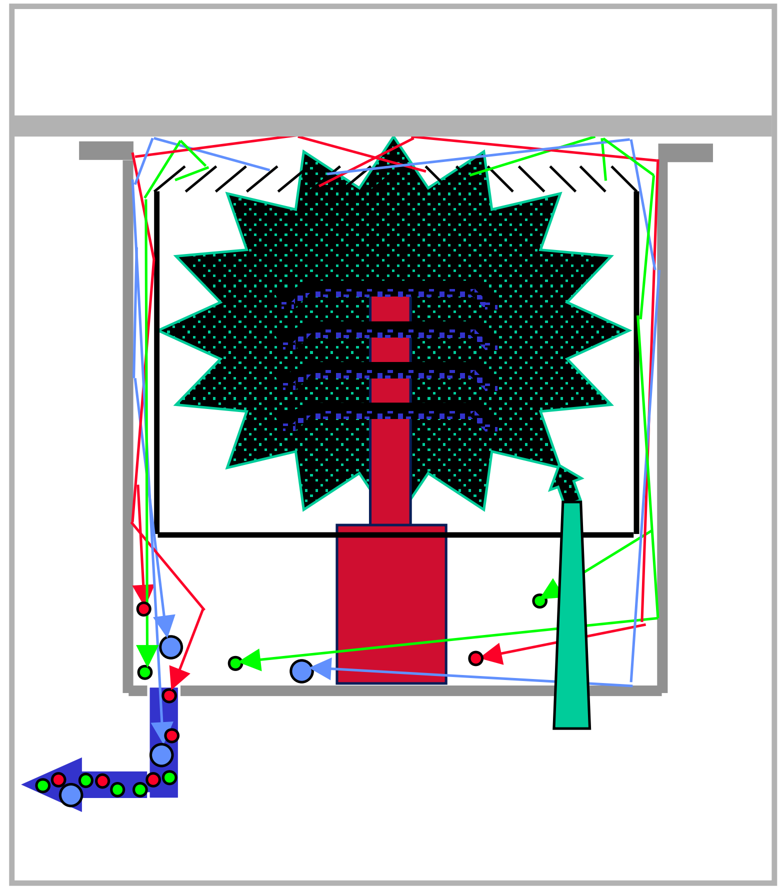




Cyropump Operation . . . *Regeneration*

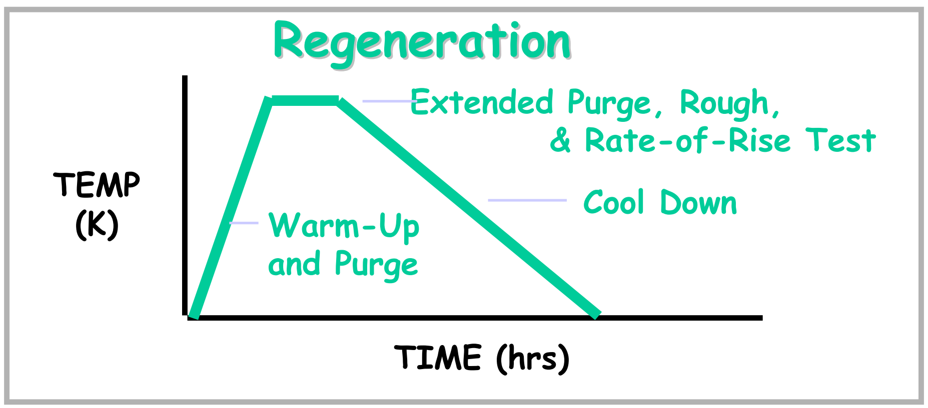
- Regeneration
  - Warm-Up and Purge
  - Extended Purge
  - Rough Out
  - Rate-of-Rise (ROR) Test

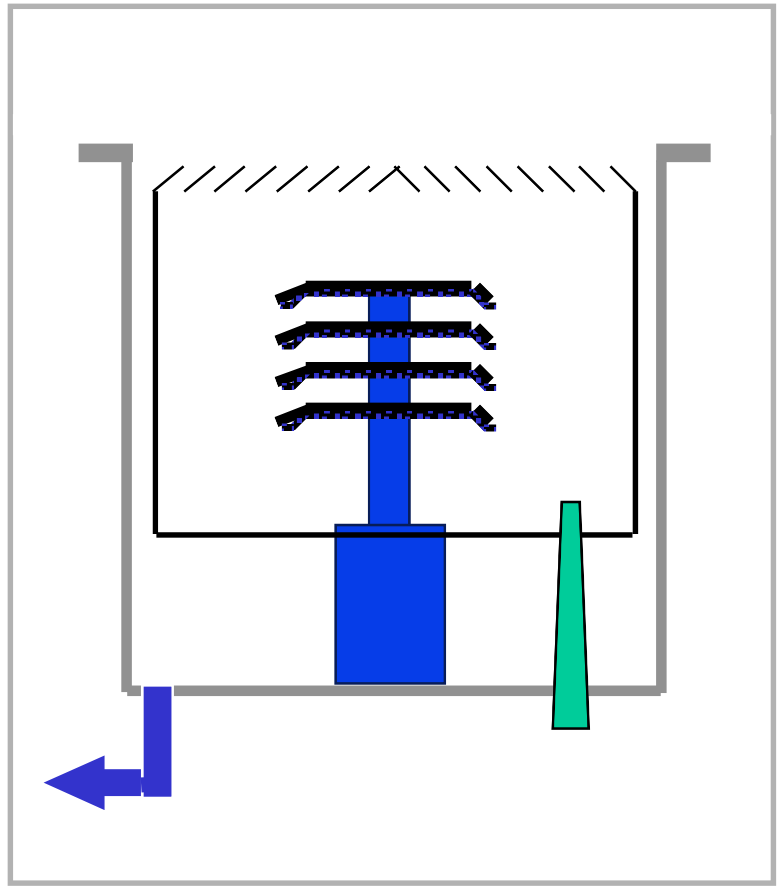




Cyropump Operation . . . *Regeneration*

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

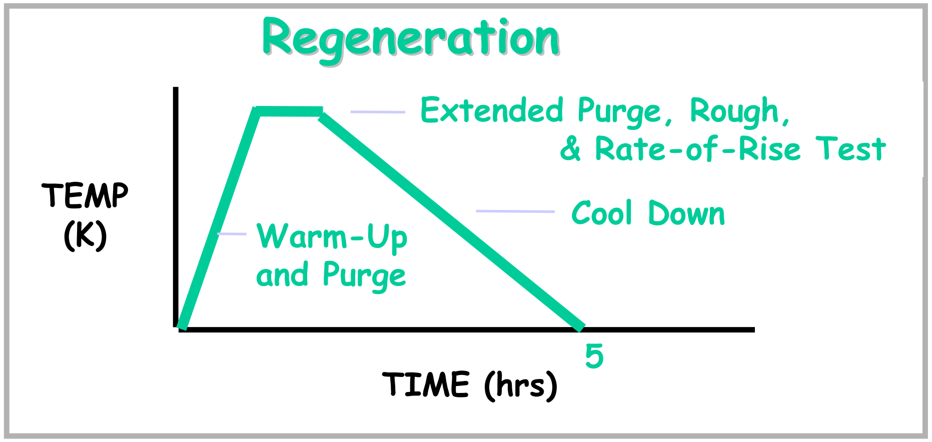


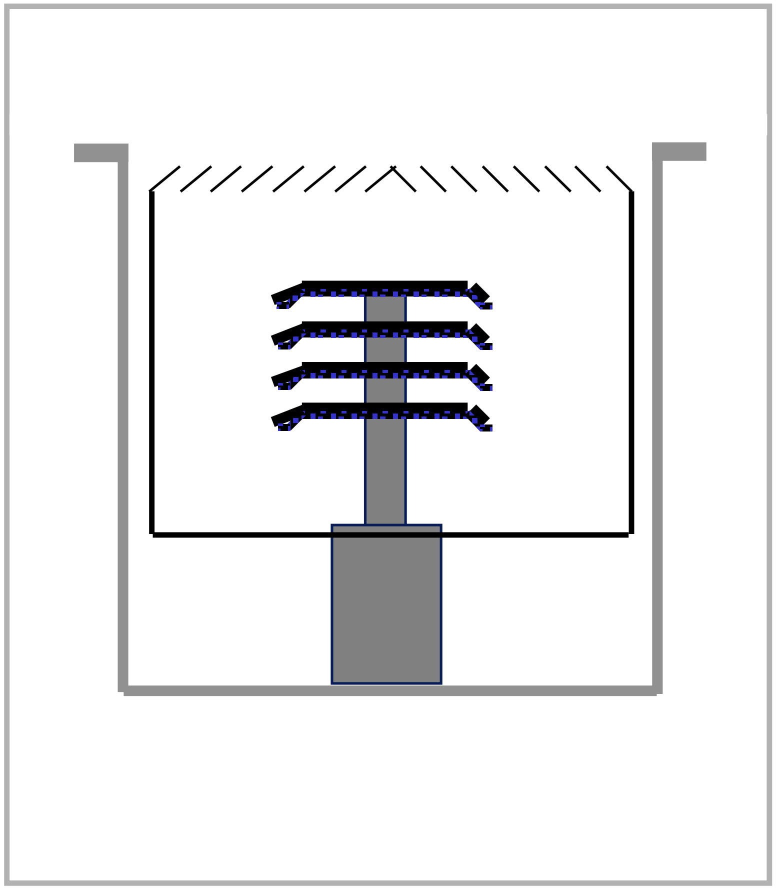


Cyropump Operation . . . *Regeneration*

- **Regeneration**

Typically 5-6 hours cold-to-cold.





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

Helium Compressor Pumps

The pump is the "Heart" of the compressor. Compressors utilize two different types of positive displacement pumps:

- **Rotary Pumps**
- **Piston Pumps**

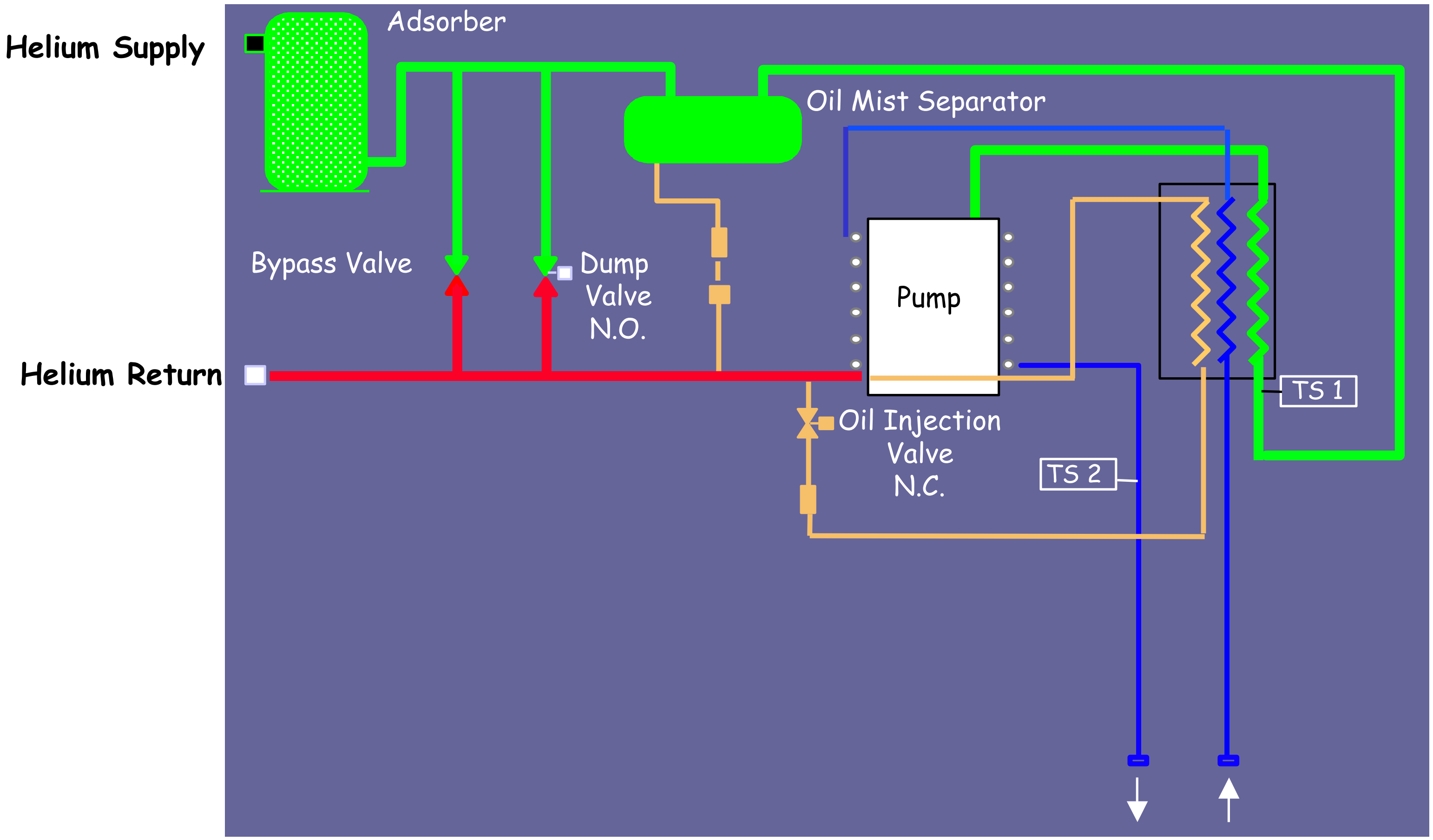
Helium Compressor Cooling System

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



Ref ©2000 Helix Technology Corporation

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)

Helium Compressor Oil System:
Bulk Oil Separation

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.

Helium Compressor Oil System:
Oil Mist Separator

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.

Helium Compressor Oil System: Adsorber

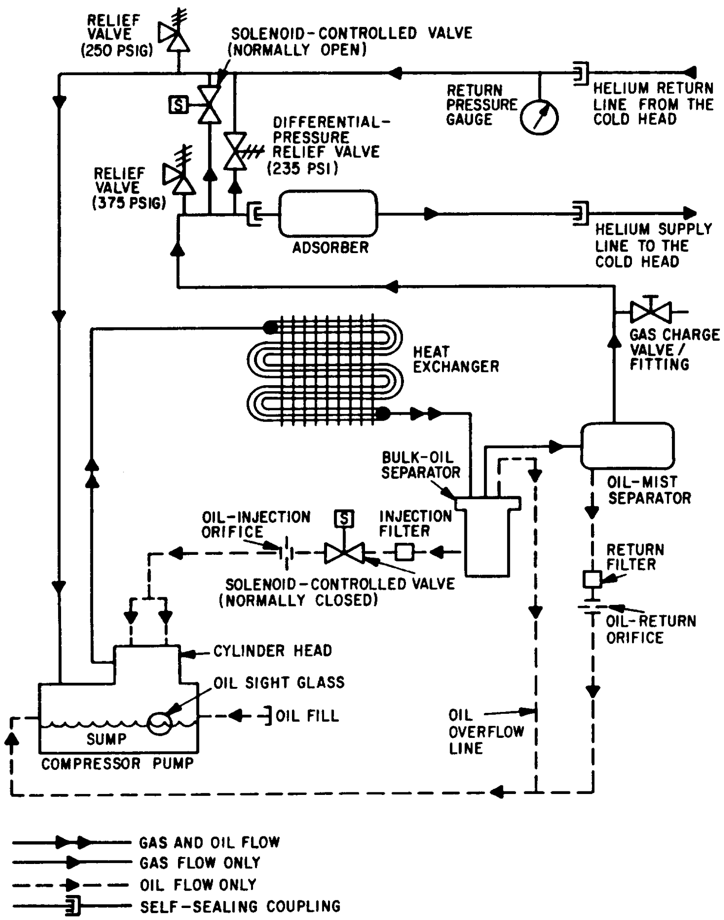
The adsorber contains activated charcoal to filter out the remaining oil in the helium by adsorption. As the adsorber gets filled up with oil and other contaminants it needs to be replaced (typically once a year).

Helium Compressor Operating Temperature

Most Compressors can operate in ambient temperatures from 50-100 ^{o}F.

Note: Starting a compressor that is colder than 50 ^{o}F can cause start up problems.

CTI-CRYOGENICS
Helium Compressor Schematic



Ref ©2000 Helix Technology Corporation

Typical Operating Parameters for CTI-CRYOGENICS Compressor Chart

Compressor	Static	Operating	Running
Type	Charge	Pressure	Current
SC	250 psig	275 psig	8 amps @ 208 V
8200	250 psig	275 psig	8 amps @ 208 V
1020R	185 psig	275/80 psig*	14.5 amps @ 208 V

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

Compressor	Static	Operating	Running
Type	Charge	Pressure	Current
8300	250 psig	95 psig	8 amps @ 208 V
8500/8510	200 psig	60-90 psig*	14.5 amps @ 208 V
9600	250 psig	110 psig	15 amps @ 208 V

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