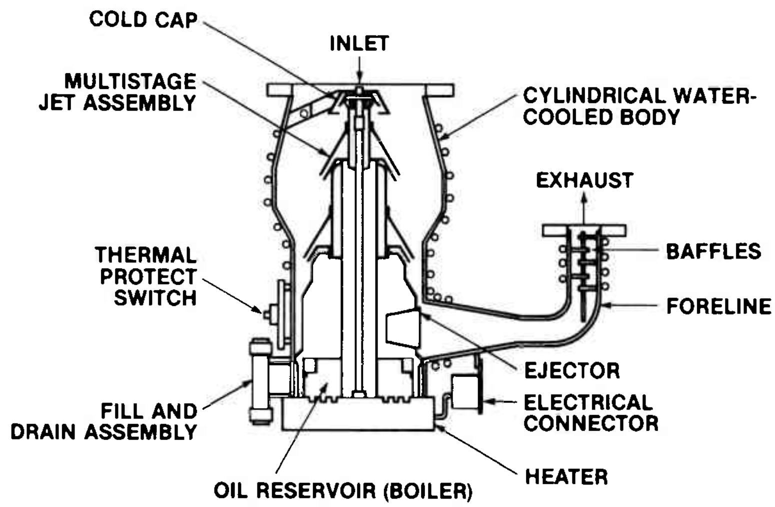
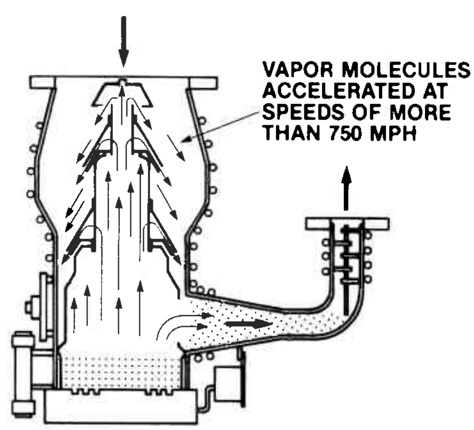
There are no moving parts in this pump.



How the Pump Works

Pump Operation

The diffusion pump works by heating the pump fluid to its boiling point. The vapors travel upward inside the jet assembly and exit through the jet nozzles. In fact, they are accelerated downward through the jet nozzles. The vapor molecules travel very fast and can actually reach supersonic speeds!



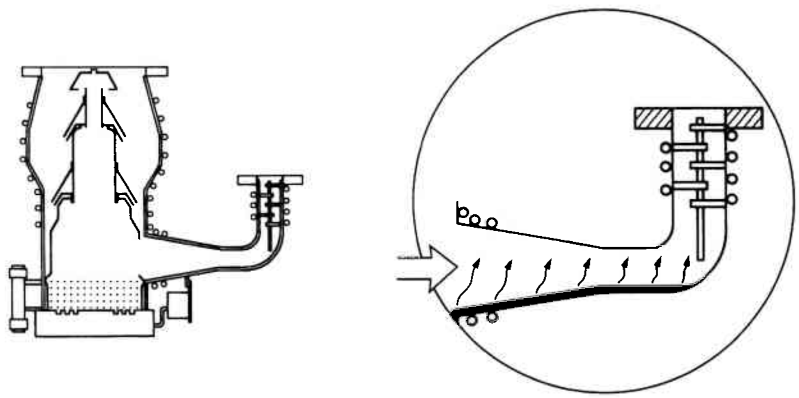
These vapor streams are directed toward the outer walls of the pump. The walls are typically cooled by water. When the vapor hits the cooled walls, it condenses back into a fluid. This fluid then flows downward into the pump boiler for reboiling.

The actual pumping of gases happens when the large, heavy, high-speed oil vapor molecules hit gas molecules. The gas molecules are knocked downward and compressed by the movement of the vapor jet stream.

The gas molecules are thereby compressed in several stages to higher pressures. They are finally pumped away through the foreline by the mechanical pump.

In the pumping process, some of the gas is trapped, or entrained, in the fluid. This trapped gas could be re-released above the pump by the top vapor jet and re-enter the chamber. To minimize this effect, the lower portion of the pump body and foreline are kept hot in order to help drive the gas out of the contaminated fluid. The released vapors are then removed by the mechanical forepump.

HOT SECTION OF FORELINE
DEGASSES CONTAMINATED OIL



In addition to the vertical jet assembly, modern pump designs incorporate an ejector stage. This stage helps to move gas molecules out of the pump body and into the foreline. This action allows higher pressures in the foreline, which in turn allow the mechanical forepump to efficiently remove the compressed gas molecules. Pumps with ejector stages usually have a baffle in the foreline to prevent oil vapor loss to the forepump.

Fractionation

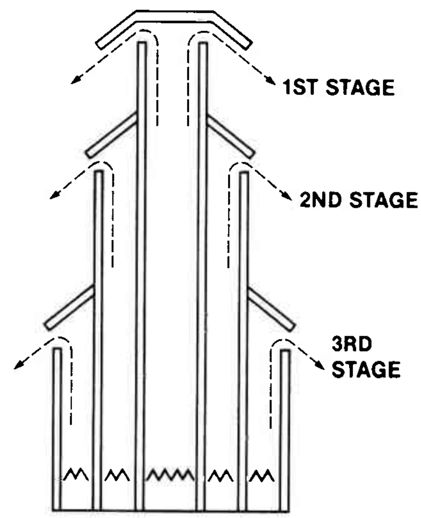
fractionation

Some diffusion pumps are designed to use a simple fractional distillation process that helps to purify the condensed fluid. This process is called *fractionation.*

What happens is this:

Condensed pump fluid vapor returns to the boiler from the cooled walls. In its course from the outer edges to the center of the boiler, its temperature rises rapidly and new vapor is continuously formed. Diffusion pump fluid slowly decomposes and produces contaminants, or lighter fractions. Over long periods of time, enough of these fractions may build up to reduce the effective pumping speed and require draining and refilling the pump with new fluid. Here is where the special construction of the boiler and jet assembly is put to use. If the boiler and jet assembly are designed to separate fractions as they are formed, these fractions will be pumped away with the other gases. The purity of the original fluid is thus maintained. The large surface area of a grooved boiler plate distributes heat to the oil more uniformly to minimize the forming of the bad, lighter oil fractions.

So, in this design, the vertical tubes of the jet assembly will separate the first-stage vapors from the others. This design ensures that only the purest fluid reaches the center of the boiler and is forced out of the top jet. This in turn ensures the best vacuum conditions above the first stage, which is the part of the pump closest to the chamber. Less pure fluid vapor is forced out of the lower jets.

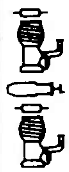


Backstreaming

backstreaming

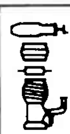
Backstreaming occurs with all diffusion pumps. By definition, it is that small amount of pump fluid vapor that goes in the wrong direction toward the chamber. Various methods are used to reduce the amount of backstreaming fluid reaching the chamber. The table on the next page shows how cryotraps and other components added to the diffusion pump can affect the backstreaming rate. You might also note the decrease in pump speed as a more effective device for controlling backstreaming is used.

This data sheet for a 2,400 ℓ/sec diffusion pump illustrates some of the characteristics of the diffusion pump. Note that efforts to decrease the backstreaming rate slow the pump speed significantly.

Combinations		Typical Applications	Pumping Speed (ℓ/sec) (air)		Backstreaming Rate* (mg/cm²/min) (DC-705)		Ultimate Pressure** (torr)	
			With Cold Cap	With Mexican Hat	With Cold Cap	With Mexican Hat	Using DC-704	Using DC-705 or S-5
Pump only • highest speed • lowest cost		General purpose Vacuum furnaces	2,400	1,600	5×10^{-4}	$<1 \times 10^{-4}$***	$<5 \times 10^{-8}$	$<5 \times 10^{-9}$
Pump and Low-Profile Baffle • high speed • clean • fast cycles (valved)		Metallizing Protective coatings Vacuum furnaces	900	Water-Cooled Baffle normally not necessary when Mexican Hat is used.	$<1 \times 10^{-4}$***	$<1 \times 10^{-4}$***	$<5 \times 10^{-8}$	$<5 \times 10^{-9}$
		10^{-4} to 10^{-7} torr range	800		$<1 \times 10^{-4}$***	$<1 \times 10^{-4}$***	5×10^{-8}	5×10^{-8}
Pump and Cryotrap • high speed • very clean • fast cycles (valved) • long LN_2 duration		Thin-film deposition Optical coatings Electronic coatings Solid-state research Molecular beams	1,050	870	1×10^{-7}	1×10^{-7}	5×10^{-9}	2×10^{-9}
		10^{-6} to low 10^{-8} torr range	900	750	1×10^{-7}	1×10^{-7}	2×10^{-8}	2×10^{-8}

*Backstreaming rates (near ambient temperatures) vary directly with vapor pressure of fluid.
**Approximate values at inlet of pumping combination. System ultimate depends on chamber design, type of seals, and process outgassing. Mild bakeout is usually required to reach 10^{-9} torr levels.
***Too small to be measured by standard collection method of American Vacuum Society.

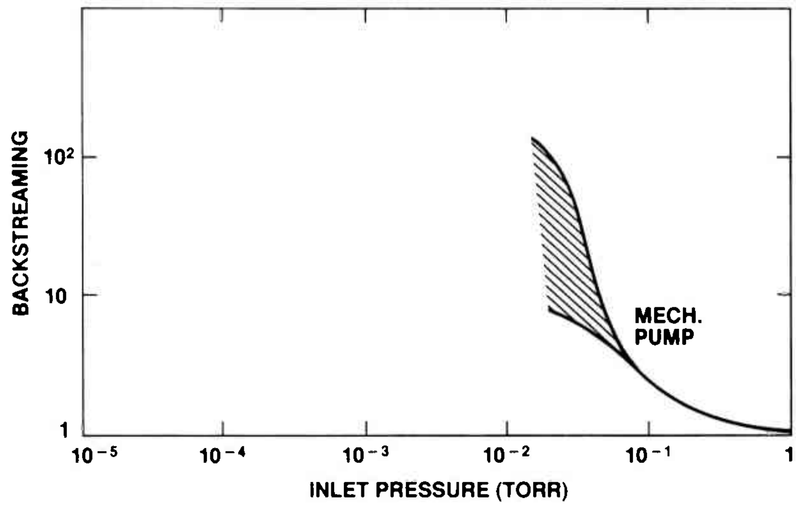
The combination given below reduces pumping speed by approximately 40% (550 ℓ/sec vs. 900 ℓ/sec for valved combinations.) This system may provide added protection against accidental exposure of the diffusion pump to pressures exceeding the normal operating range.

Pump, Low-Profile Baffle, Cryotrap and Slide Valve • extremely clean • extra protection		Thin-film deposition Optical coatings Electronic coatings Solid-state research Molecular beams 10^{-6} to low 10^{-8} torr range	800	Water-Cooled Baffle normally not necessary when Mexican Hat is used.	$<1 \times 10^{-7}$	$<1 \times 10^{-7}$	$<2 \times 10^{-8}$	$<5 \times 10^{-9}$

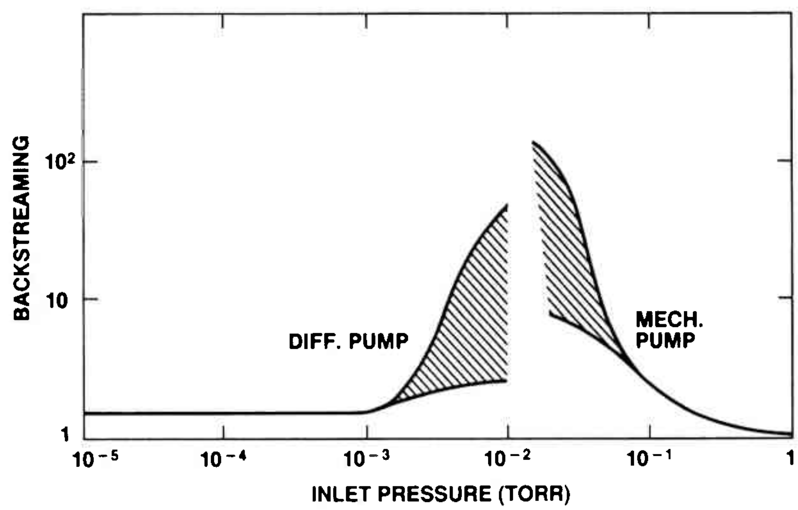
If excessive backstreaming occurs, a major system cleanup may be necessary. Large amounts of oil vapor may end up in the chamber. This results from various causes– sudden pressure bursts in the chamber; opening the high vacuum valve at high pressures; loss of the mechanical forepump as a result of perhaps a broken drive belt; loss of power; and, in some cases, improper valving sequence which overpressures the foreline. This is not backstreaming but is dumping– caused by improper operation or malfunction of the system.

Another source of oil is the mechanical pump or forepump. When the mechanical pump operates in the molecular flow range, the oil is free to migrate out of the pump into the lines and from there into the chamber. The figures on the next page indicate the likely pressure range where the problem is greatest.

BACKSTREAMING VS. PRESSURE CURVES



RELATIVE AMOUNT OF BACKSTREAMING OIL FROM A MECHANICAL PUMP

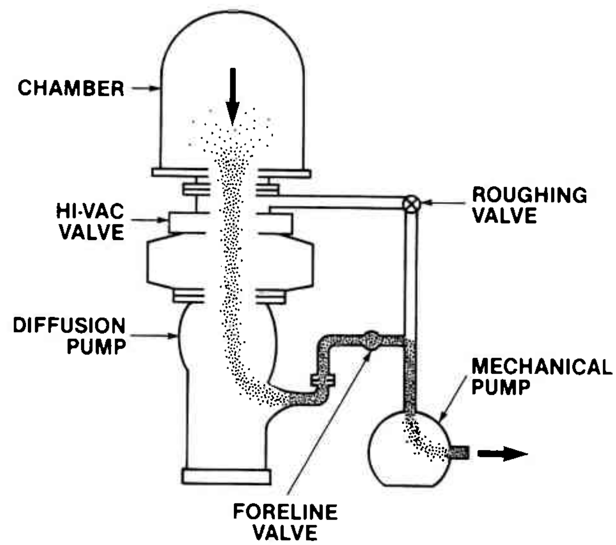


PUMPING AND LUBRICATION FLUID BACKSTREAMING IN THE TRANSITION ZONE BETWEEN DIFFUSION AND MECHANICAL PUMPS

Notice that the mechanical pump backstreams oil more at lower inlet pressures. It reaches its lowest practical limit below 10^{-2} torr (10 mtorr).

By comparison, the diffusion pump backstreams more at its upper limit and typically fails completely above 10^{-2} torr.

A diffusion pump can't exhaust directly to atmosphere. Instead, it compresses the incoming gases to the millitorr range and exhausts them into another pump. The mechanical pump then compresses the gases further, and expels them to atmosphere.



If an operating diffusion pump is exposed to atmosphere for any length of time, severe oxidation or breakdown of the fluid can occur. Sometimes, in extreme cases, a fire or explosion in the pump may result. The contaminants created in these cases will severely hinder pumping speed and operation due to the gas loads they will contribute to the system. A diffusion pump at atmospheric pressure acts just like a pan of hot oil on a stove. Leave it too long– it will thicken, harden or burn!

Pressure in the foreline *must* be kept below the maximum tolerable foreline pressure, or critical forepressure.

Maximum Tolerable Foreline Pressure

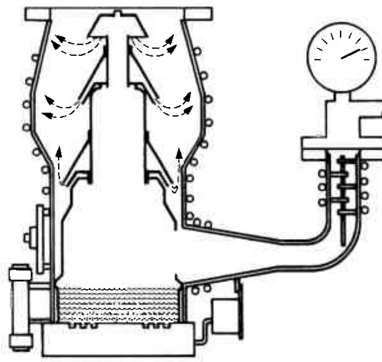
maximum tolerable foreline pressure

Maximum tolerable foreline pressure is a measure of the ability of the diffusion pump to pump gases against an external pressure. If this pressure in the foreline is exceeded, pump vapors will be forced into the chamber or high vacuum valve in great amounts. Naturally, the presence of these "contaminants" above the pump will increase pumpdown times and raise the system base pressure.

critical forepressure

Critical forepressure is another term used to describe maximum tolerable foreline pressure.

If the foreline pressure becomes too high, the fluid vapors blow backward or upward. Now, instead of pumping, the diffusion pump contributes to the contamination in the chamber from the diffusion pump fluid being forced to go in the wrong direction. A common expression for this is "dumping" the pump. For this reason, a proper-size mechanical pump is needed to help the diffusion pump hold the foreline pressure at an acceptable level.



A reduction of the normal pumping speed (actually throughput)—caused, for example, by a reduction in heater power to the boiler—will cause a corresponding reduction of the maximum tolerable forepressure.

Pumping speed of diffusion pumps is usually rated in liters per second. This speed is constant below 1 mtorr. Of course, at lower pressures, a liter of gas contains fewer molecules. Thus the pumping process slows down. Finally, the lowest (ultimate) pressure is reached when the number of gas molecules removed per second is matched by the number of molecules released into the chamber which were not previously there in the gas phase—from tiny leaks and desorption from interior surfaces.

Selection of Forepump

The mechanical forepump must be able to handle the gas load the diffusion pump is compressing into its foreline. That is, the Q of the mechanical pump must match the Q of the diffusion pump.

The equations below show how to calculate the proper mechanical pump size that will keep the pressure below the critical forepressure.

$$Q_{(MP)} = Q_{(DP)}$$

But $Q = SP$ (Substituting SP for Q)

$$SP_{(MP)} = SP_{(DP)}$$ (Then divide both sides by $P_{(MP)}$)

$$S_{(MP)} = \frac{SP_{(DP)}}{P_{(MP)}}$$ (Solving for $S_{(MP)}$)

Consider a 2,000 ℓ/sec diffusion pump speed at 1 mtorr (inlet pressure). According to the manufacturer's specification sheet, the maximum tolerable forepressure is 400 mtorr. Then,

$$S_{(MP)} = \frac{(2{,}000\ \ell/\text{sec})\ (1\ \text{mtorr})}{400\ \text{mtorr}} = 5\ \ell/\text{sec}$$

Mechanical pumps are not generally specified in liters per second (ℓ/sec) but, rather, in cubic feet per minute (cfm). To convert cfm into ℓ/sec, remember that there are 60 seconds in 1 minute. And also remember that there are 28.4 liters in 1 cubic foot (ft^3). Then,

$$S_{(MP)} = \frac{5\ \ell/\text{sec} \times 60\ \text{sec}}{28.4\ \ell/\ \text{ft}^3} = 10.6\ \text{cfm}$$

This design, of course, would prevent us from valving off the foreline for any reason while the diffusion pump is operating. We would also be extremely vulnerable to dumping the diffusion pump due to improper valving. It would certainly serve us to operate the diffusion pump with the foreline pressure far below the critical value in order to assure proper operation. In practice, we specify a maximum foreline pressure well below the maximum permitted. So let's reduce the forepressure we will allow to a maximum of 150 mtorr and recalculate:

$$S_{(MP)} = \frac{(2{,}000\ \ell/\text{sec})\ (1\ \text{mtorr})}{150\ \text{mtorr}} = 13.3\ \ell/\text{sec}$$

$$S_{(MP)} = \frac{13.3\ \ell/\text{sec} \times 60\ \text{sec}}{28.4\ \ell/\ \text{ft}^3} = 28\ \text{cfm}$$

So, let's go buy a pump that is between 28 and 35 cfm.

Diffusion Pump Fluids

The fluid vapor pressure largely determines the ultimate pressure attainable by a diffusion pump at its inlet. Therefore, diffusion pump fluid is formulated to possess very low vapor pressure at operating temperatures.

Currently, the commonly used fluids for producing clean high vacuums are DC-704™, DC-705™ (silicone-based) and Santovac 5™ or Convalex 10™ (polyphenyl ethers). These tables show the properties of several diffusion pump fluids.

SOME DIFFUSION PUMP FLUIDS

Trade Name	Chemical Name	MW (ave)	P_v at 25°C (Pa)	Viscosity at 25°C (mm^2/s)	Boiler Temp. at 100 Pa (°C)
Convoil®-20	Hydrocarbon	400	5×10^{-5}	80	210
Octoil-S®	Bis (2-ethyl-hexyl) sebacate	427	3×10^{-6}	18.2	220
Invoil®	Dioctylphthalate	390	3×10^{-5}	51	200
Dow Corning®-704	Tetraphenyl-tetra methyl trisiloxane	484	3×10^{-6}	38	220
Dow Corning®-705	Pentaphenyl-tri methyl trisiloxane	546	4×10^{-8}	175	250
Santovac 5®	Mixed 5-ring polyphenylether	447	6×10^{-8}	2400	275
Fomblin® Y VAC 25/9	Perfluoropoly-ether	3400	9×10^{-7}	190	230

Characteristics of Diffusion Pump Fluids

(1) Hydrocarbon Oils
- (a) low cost
- (b) decompose on air exposure
- (c) o.k. for gauges and ion sources

(2) Silicone Compounds
- (a) moderate cost
- (b) good on air exposure
- (c) bad for gauges and ion sources

(3) Polyphenyl Ether
- (a) high cost
- (b) good on air exposure
- (c) o.k. for gauges and ion sources

(4) Fatty Esters
- (a) low cost
- (b) poor on air exposure
- (c) o.k. for gauges and ion sources

(5) Halogenated Compounds
- (a) high cost
- (b) oxygen compatible
- (c) may be decomposed by Lewis acids

Brands of Diffusion Pump Fluid

(1) Hydrocarbon Oils
- (a) Apiezon A, B, C
- (b) Litton oil
- (c) Convoil-20

(2) Silicone Compounds
- (a) DC-704
- (b) DC-705
- (c) Invoil 940

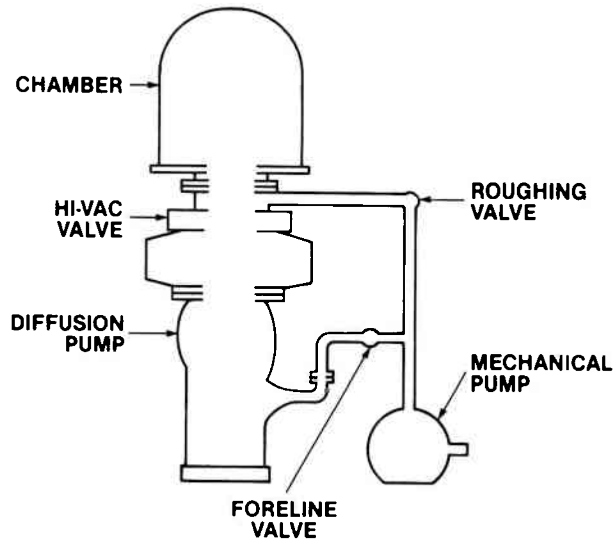
(3) Polyphenyl Ether
- (a) Santovac 5
- (b) Convalex 10

(4) Fatty Esters
- (a) Octoil and Octoil-S
- (b) Butyl Phthalate
- (c) Amoil and Amoil-S
- (d) Invoils

(5) Fluoroether Polymers
- (a) Krytox
- (b) Fomblin

Vacuum System Use

Diffusion pumps are quite widely used for high vacuum systems. In fact, they are the most common type of pump used. We will discuss the actual operation and valving of a diffusion pump system in the chapter on vacuum systems.



Maintenance

If a diffusion pump is properly operated, maintenance is simple.

Whenever the pump is taken apart, used O-ring seals should be replaced. Old or contaminated fluid should be drained from the pump. Many companies now recycle their diffusion pump oil. Special precautions must be taken when the pump has been used to pump toxic or caustic gases because these materials will be present in the pump and its fluid in perhaps dangerous concentrations.

All components should be disassembled. Internal pump surfaces and components must be cleaned as directed by the manufacturer. Any oxidized fluid deposits should be removed as directed. The components should then be rinsed (also as directed) to remove solvent films and minimize condensed water vapor.

New O-rings should be lubricated and installed. The pump should be reassembled, filled with new, clean fluid and reinstalled in the system.

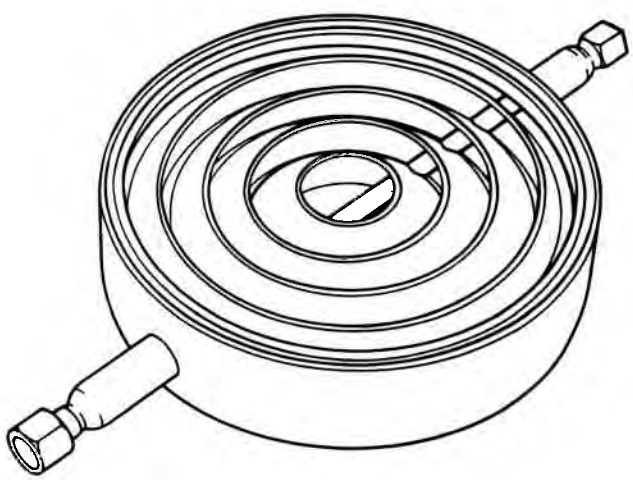
Baffles and Traps

Earlier, we saw how the cryotrap can be used to reduce backstreaming. The baffle can also be used for the same purpose. Let's go on now to discuss baffles and traps in more detail.

Water-Cooled Baffle

Water-cooled baffles aren't designed to be pumps. However, baffles are used above the diffusion pump inlet to condense backstreaming pump vapors before they reach the chamber. In some applications, water-cooled baffles serve to remove (or reduce) excessive heat loads generated in a process which might adversely affect pump performance.

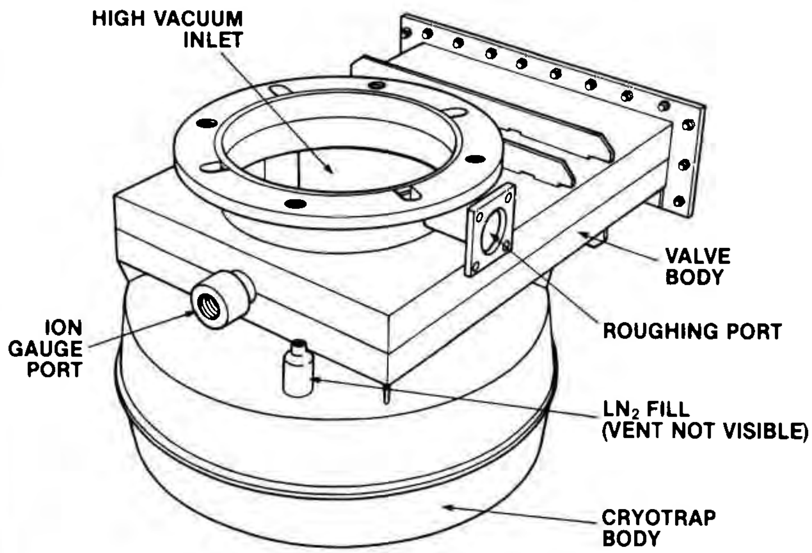
Baffles are composed of arrays of fins that are optically dense. That is, you cannot see through them. These arrays are cooled by continuous water flow through or about their internal components.



Baffles, however, make a useful contribution to the effectiveness of diffusion pumps. (Refer to the chart titled "Backstreaming" in the Diffusion Pump section to see how baffles can reduce diffusion pump backstreaming.)

Cryotrap

Cryotraps also aren't designed to be pumps. They do act as a selective pump for certain gases—namely, water vapor, carbon dioxide and most solvents. Cryotraps also restrict pump fluid backstreaming while giving reasonable conductance figures. A cryotrap is often combined with a high vacuum valve in a single high conductance unit. (See table.)



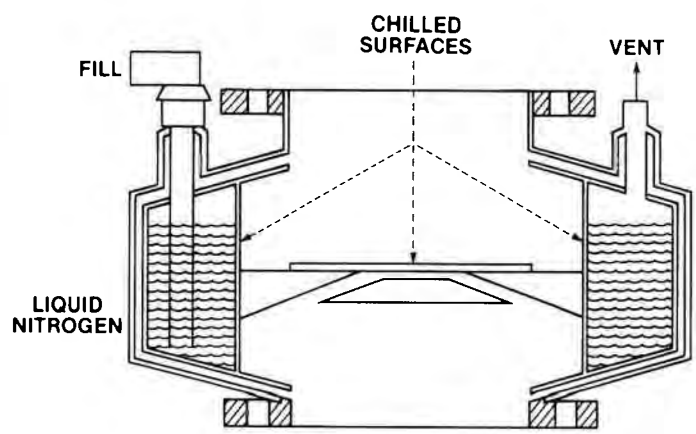
Components

liquid nitrogen cold trap

A cryotrap, or *liquid nitrogen cold trap,* has a liquid nitrogen reservoir and various baffling surfaces. The reservoir is insulated from the environment by an evacuated space. The LN_2 boils off to atmosphere through a vent port. Since LN_2 boils at −196°C, the trap's internal surfaces are extremely cold.

open-loop refrigeration system

The cryotrap can be called an *open-loop refrigeration system,* since the coolant vents to atmosphere. An example of a closed-loop refrigeration system is the mechanical cryopump.



How the Cryotrap Works

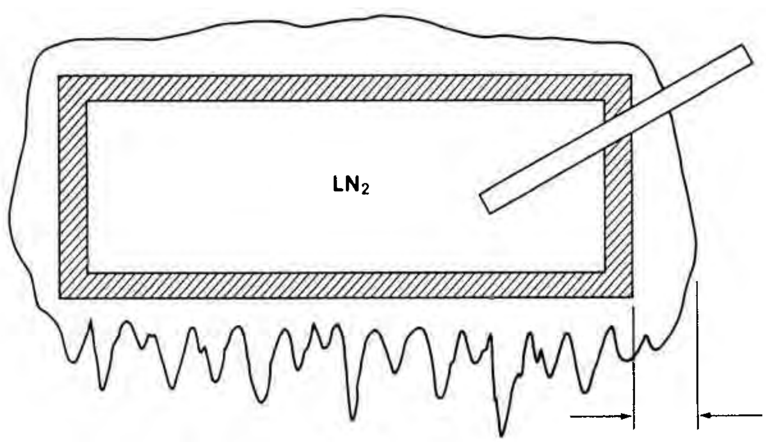
Cryotraps pump gases or vapors by freezing, or condensing, them on their chilled surfaces. This cryocondensation effectively removes them from the work chamber. However, some gases don't condense at liquid nitrogen temperature, or –196°C.

The table shows that water vapor is trapped very effectively at –190°C. However, other gases are not trapped at all, since their vapor pressures are quite high at this temperature. Therefore, other means must be used to pump noncondensable gases.

VAPOR PRESSURES OF SOME GASES AT –190°C

Gas	Approximate Vapor Pressure (Torr)
Water (H_2O)	10^{-22}
Argon (A)	500
Carbon Dioxide (CO_2)	10^{-7}
Carbon Monoxide (CO)	760
Helium (He)	760
Hydrogen (H_2)	760
Oxygen (O_2)	350
Neon (Ne)	760
Nitrogen (N_2)	760
Solvents	Very Low

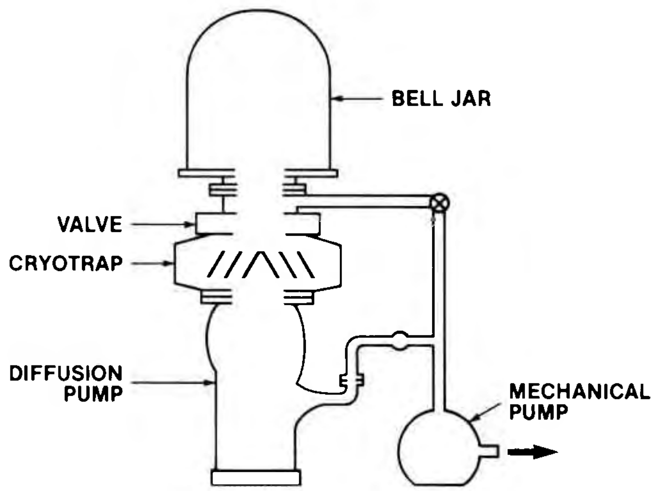
LN_2 traps should be filled after roughing pressures near 50 mtorr have been reached in the area where they are being used. At this pressure, much of the water vapor in the chamber volume has been removed. The mean free path of the remaining gases is long enough to create an insulating vacuum. If exposed to pressure above 100 mtorr, heavy frost builds up on the cryotrap. This frost insulates the chilled surfaces and thus reduces the pumping action.



FROST BUILDUP ON CRYOGENIC SURFACES CAN ACT AS AN INSULATING LAYER, MINIMIZING OR DEFEATING TRAPPING EFFICIENCY.

Instead, the chamber must be rough pumped to remove the bulk of the condensable gases. Then, the cryotrap provides continuous trapping of small but significant amounts of the remaining condensable gases.

Vacuum System Use



Typically, cryotraps are teamed with diffusion pumps (or other high and ultrahigh vacuum pump systems). Cryotraps have also been used in roughing lines to minimize mechanical pump oil migration toward the chamber. In addition, they have been used with helium leak detectors for the same purpose. For these applications, however, a molecular sieve trap is usually better.

It is important to remember that if a cryotrap is not kept properly filled, the baffle surfaces will warm up. This rise in temperature will release condensed gases. The result will be a rise in system pressure, further rise in temperature, and potential contamination of the area or component we are trying to protect. To prevent this contamination, the valve between the work chamber and the cryotrap must be closed if warmup possibility exists.

Maintenance

The cryotrap needs to be replenished with LN_2 frequently, before warmup starts.

The cryotrap requires little maintenance other than periodic cleaning of internal surfaces according to manufacturer's directions.