2 Roughing Pumps

Here is a list of things we think you should be able to do after reading this chapter:

You should be able to—

1. Give the three major pressure ranges of vacuum pumps.

2. List the types of pumps in each of the pressure ranges.

3. Describe the major components of each roughing pump type.

4. Explain how the major types of roughing pumps work.

5. Describe the place of these pumps in vacuum system use.

6. Describe in general how these pumps are maintained.

Introduction

It is important to choose the right pump for your vacuum system. A number of pumps are used in vacuum work. Some remove the gases from the chamber; others trap gases or change their form. Their ranges of operation differ, and usually no single pump develops the degree of vacuum needed. Therefore, the pumps are used in various combinations.

While some pumps seem quite ordinary, others pump in strange ways, using chemical or electrical methods. Some vacuum pumps merely capture and store the gases.

In this chapter, we will explain how one of the three general categories of vacuum pumps— roughing pumps— works and the general ways they are used. We will also discuss the major roughing pump components and how the pumps are maintained. And we will give an overview of how they fit into vacuum systems. System operation is explained in more detail in chapter 7.

First, however, we will describe vacuum pumps in general and their pressure ranges, and how pumps are teamed up.

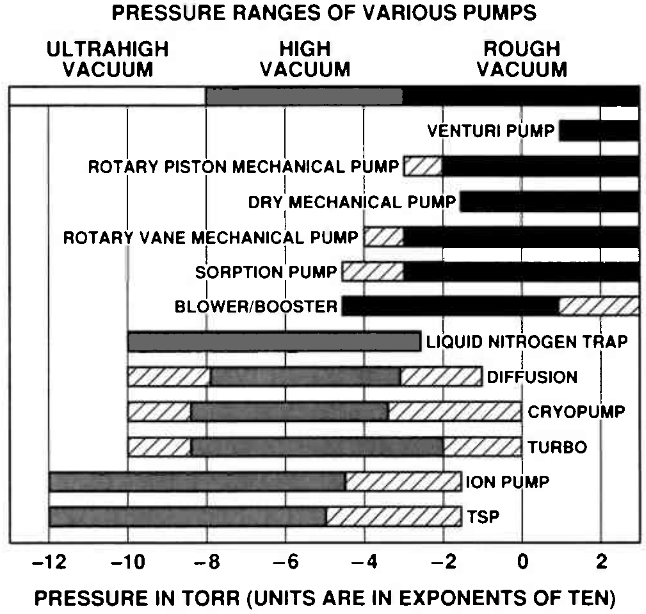
Pressure Ranges of Pumps

We cannot expect one pump to take a system from atmosphere to the high or ultrahigh vacuum range. Two or more pumps must be used to reach and sustain a particular pressure.

As you can see in the chart on the next page, each type or kind of pump has a useful operating range. At higher pressures, some might not operate or might even contaminate a system. Some pumps can cause contamination if they are exposed to pressures below their operating range. Usually, a pump will perform well if it is used within its operating pressure range. If the process pressure and system base pressure requirements are both in the rough vacuum range, a single roughing pump may be enough. Often, however, this is not the case.

useful operating range

A pump usually has a higher pressure limit where it will begin pumping, and a base pressure (or ultimate pressure), which is its lower limit. The pressure range between these two extremes is the pump's *useful operating range.*



This chart shows typical operating ranges for a variety of vacuum pumps. The full range is broad, going from atmospheric pressure down to 10^{-12} torr. The range is divided into rough vacuum, high vacuum, and ultrahigh vacuum operation. Baking the system is usually required to reach UHV range.

The solid bars indicate the normal *steady-state* operating range. The diagonally cross-hatched part of the bars indicate extensions of the normal operating range under *transient and special* conditions or may require the use of a specially-designed pump.

To summarize:

- *Roughing Pumps:* 760 torr to 1×10^{-3} torr

  Rotary Piston Oil-Sealed Mechanical Pump
  Rotary Vane, Oil-Sealed Mechanical Pump
  Dry Vacuum Pump (oil-free)
  Sorption Pump
  Venturi Pump
  Booster/Blower Pump

- *High Vacuum Pumps:* 1×10^{-3} torr to 1×10^{-8} torr

  Oil Diffusion Pump
  Cryotraps and Baffles
  Mechanical Cryopump
  Turbomolecular Pump

- *Ultrahigh Vacuum Pumps:* 1×10^{-8} torr and lower

  Titanium Sublimation Pump (TSP)
  Ion Pump
  Non-Evaporable Getter Pump (NEG)

How Pumps Are Teamed Up

Vacuum pumps are teamed up. Usually no single pump develops the needed degree of vacuum. Therefore, pumps are used in various combinations. Typical combinations are shown in the following chart.

Roughing Systems	High Vacuum Systems	Ultrahigh Vacuum Systems
Mechanical Pump	Mechanical Pump Cryotrap or Baffle Diffusion Pump	Sorption Pump Cryotrap Ion Pump Titanium Sublimation Pump
Dry Vacuum Pump	Trapped Mechanical Pump Mechanical Cryopump	Venturi Pump Sorption Pump Cryotrap Ion Pump Titanium Sublimation Pump
Mechanical Pump Booster/Blower Pump	Mechanical Pump Turbomolecular Pump	

Now, let's move on to roughing pumps. We will discuss only roughing pumps in this chapter; other pumps are described in later chapters.

Roughing Pumps

Rotary Piston Oil-Sealed Mechanical Pump
Rotary Vane, Oil-Sealed Mechanical Pump
Dry Mechanical Vacuum Pump (oil-free)
Sorption Pump
Venturi Pump
Booster/Blower Pump

The roughing pumps we'll consider in this chapter are the rotary piston mechanical pump, rotary vane, oil-sealed mechanical pump, the dry mechanical pump, the sorption pump, the Venturi pump, and the blower/booster pump.

Rotary Piston Mechanical Pump

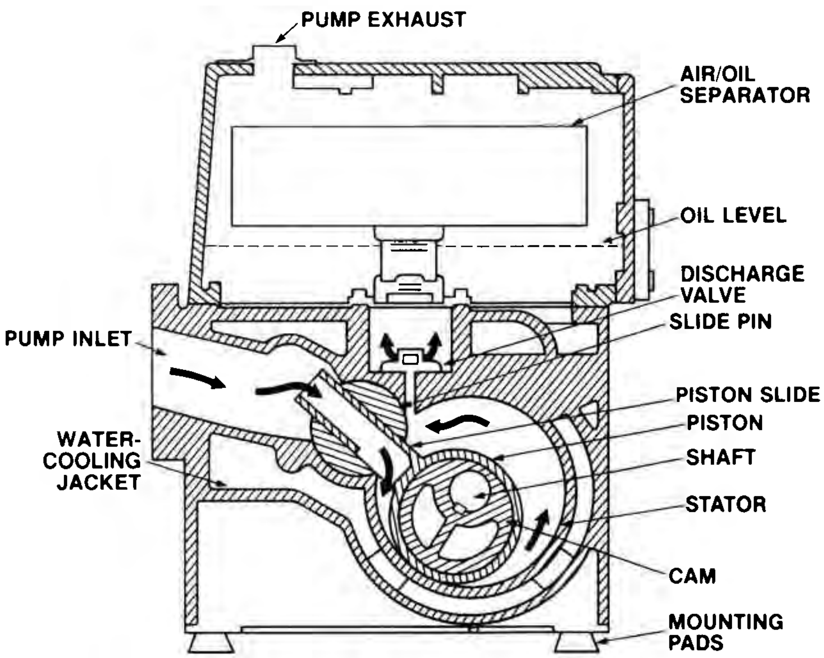
The rotary piston oil-sealed mechanical pump pumps gases by compressing them mechanically and expelling them to the atmosphere.

It is used when roughing pressures are needed, there is a fairly high incidence of particulates at the pump inlet, and large volumes of gas must be pumped quickly. It is available in pumping speeds as large as 1,000 cubic feet per minute (cfm) or more.

Components

The rotary piston pump has a hollow cylindrical piston with an eccentric cam driving it. It is contained in a cylindrical stator chamber. The piston has a sliding valve on it. The cylindrical chamber has an exhaust valve submerged in low vapor pressure oil. This oil also lubricates the pump and seals the space between the rotor and stator.

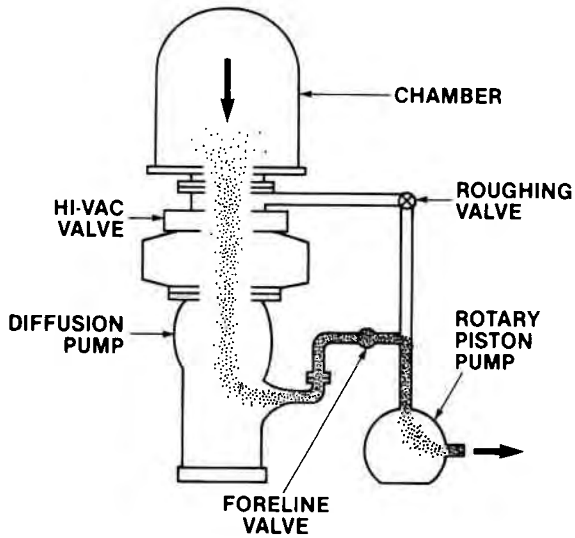
How the Pump Works



As the eccentric cam turns, it rotates the piston inside the stator. Thus, gases that come in through the sliding valve are compressed by the piston and forced out through the discharge valve and exhaust port. At first, this may seem to be a complicated way of doing things. In fact, however, this is one of the most rugged of the industrial vacuum pumps. Properly maintained and used, pumps of this type have been in operation for twenty years or more. Because of the mechanisms involved, these pumps are usually belt-driven. The heat of compression as well as the heat of mechanical friction may be removed by a water cooling jacket. Friction between the rotor and stator is not a problem in this pump, because two or three thousandths of an inch clearance exists between the rotor and stator. This limits its ultimate pressure to about 10 mtorr.

Vacuum System Use

These pumps are made in one-stage or two-stage models. They can be used as a roughing pump or as a forepump to exhaust high vacuum pumps.



Maintenance

The best indicator of proper performance, in most pumps, is to see if it can reach its normal ultimate or base pressure. This is done by isolating the pump inlet from any significant gas loads while measuring the inlet pressure with a reliable gauge. This, in effect, checks the oil condition (vapor pressure), physical damage or wear as well as air leakage. Doing this on a regular basis will aid in troubleshooting.

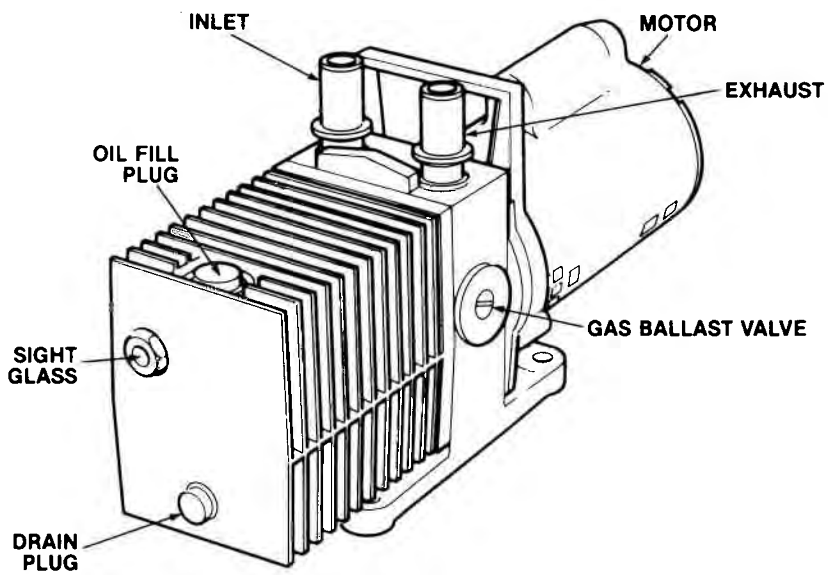
A progressive rise in ultimate pressure, each time the pump is checked, usually indicates a low oil level, a breakdown of pump oil or a buildup of condensable vapors such as water vapor in the oil. If adding oil to the correct level does not help, one or more changes of oil should be done, but only if the pump is at normal operating temperature. If frothy, white (milky) oil appears in the oil-level sight glass, opening the gas ballast valve for an extended period of time (half an hour or more) may slowly purge the oil of condensable vapors.

The drive belts on belt-driven pumps should be regularly checked for proper tension and wear. On multiple belt pumps, if one belt is worn, replace all drive belts in matched sets.

Follow the manufacturer's instructions to change oil and to gas ballast properly.

Rotary Vane, Oil-Sealed Mechanical Pump

The rotary vane, oil-sealed mechanical pump removes gases by compressing them to a point slightly above atmospheric pressure. It then expels the gases to the outside world. It is used to produce roughing or forepressures lower than the rotary piston pump. Due to the friction caused by the sliding vanes in this type of pump, the largest size available is about 150 cfm, the smallest is less than 1 cfm.

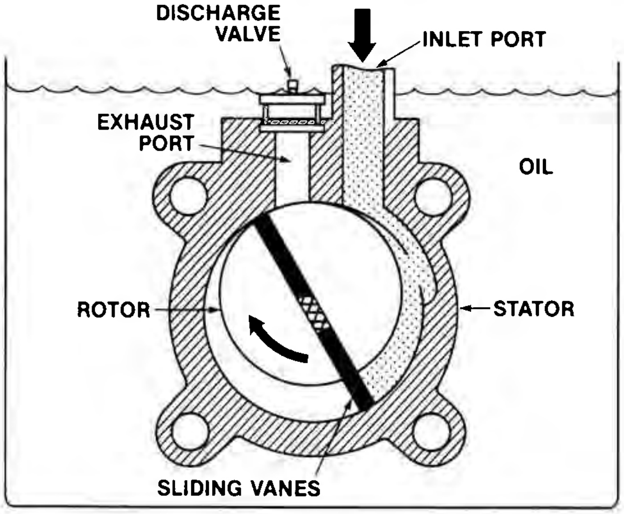


The pump module is immersed in an oil bath. This oil is purified to remove high vapor pressure contaminants. The oil serves the following purposes:

1. Cools the pump.
2. Lubricates.
3. Seals against atmospheric pressure.
4. Opens second-stage exhaust valve at low inlet pressures.

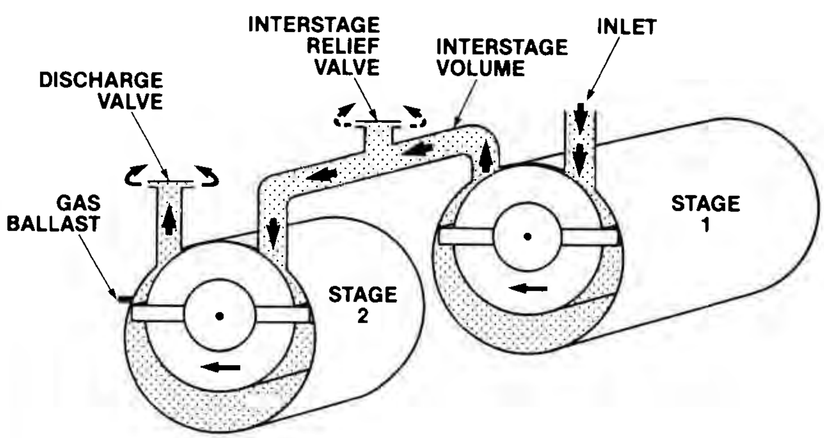
Components

An oil-sealed mechanical pump includes a housing, or stator, an offset rotor with spring-loaded vanes, an intake port and an exhaust port equipped with a discharge valve. It may also have a ballast valve. The pump rotor may be driven by a belt-drive mechanism or it may be directly coupled to the drive motor. Belt-driven pump speeds range from 250 to 400 rpm. Direct drive pumps usually run at 1,725 rpm. Most pumps have two stages to produce better vacuum. This view of a mechanical pump shows the inlet and exhaust ports of one stage.

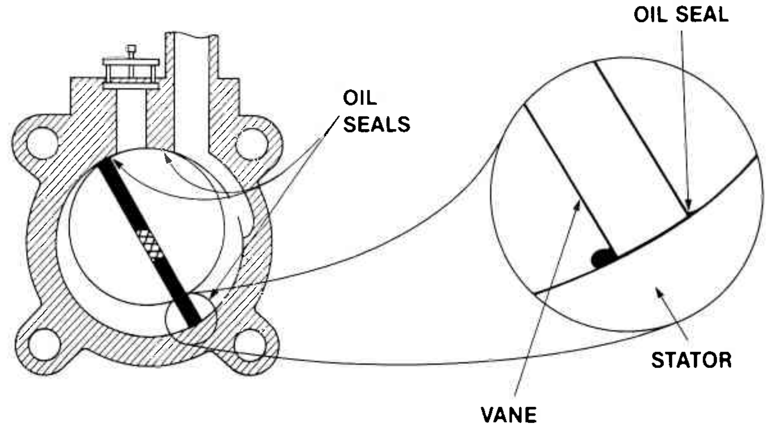


ROTARY OIL-SEALED MECHANICAL PUMP MODULE

How the Pump Works



Gases from the chamber enter the inlet port. They are swept around by vanes, and compressed. Compression builds up pressure to overcome atmospheric pressure. The spring-loaded discharge valve is opened. The air is then expelled to atmosphere. These pumps can remove over 99.9% of the air from the chamber.



A thin film of oil makes the final seal in these pumps. Therefore, base or ultimate pressure is partly determined by the vapor pressure of the oil. If the oil becomes loaded with water, or other impurities, these contaminants increase the vapor pressure. Then it is impossible to reach satisfactory low pressures. The oil is a very important part of your mechanical pump. Dirty pump oil is usually the reason why the pump is not performing well.

gas ballast

Use of the gas ballast feature of the mechanical pump may help to clean up the dirty oil if condensable vapors such as water are the problem. Opening the *gas ballast* valve allows a quantity of air to be admitted during the compression cycle. This causes the exhaust valve to open each and every cycle, sweeping out condensable vapors before they condense inside the pump.

When an oil-sealed mechanical pump is operated at low pressure, it tends to backstream oil vapor into the roughing line. This oil will migrate into the vacuum system and may contaminate the process. There is even more backstreaming if molecular flow conditions are present in the roughing lines. Remember that molecular flow happens when either the pressure is low enough or the diameter of the pipes is small enough.

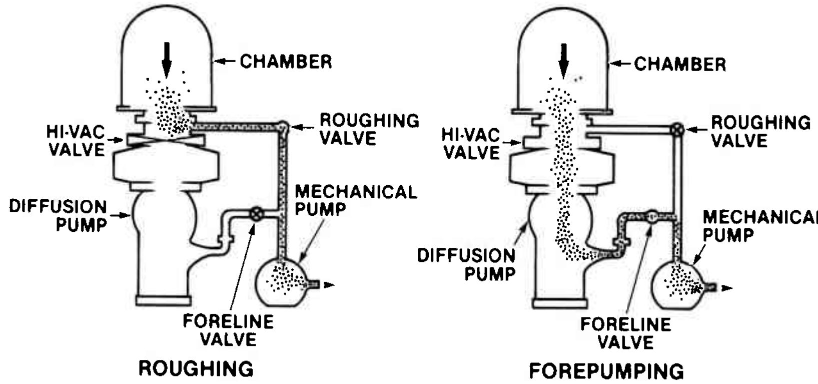
Oil migration can be controlled by using proper traps in the lines. One such trap is the molecular sieve type discussed in the maintenance section. Remember, if you can smell oil in the vacuum chamber, it is most likely coming from the mechanical pump.

Vacuum System Use

forepump

backing pump

Mechanical pumps are generally used two ways. They are used to rough pump the chamber. They may also work with vacuum pumps such as diffusion, blower and turbomolecular pumps. This is because these pumps can't discharge directly into the atmosphere. Instead, they must exhaust into a mechanical pump. The mechanical pump further compresses the gases, then expels them to the atmosphere. When mechanical pumps are used to exhaust another pump, they are called a *forepump* or *backing pump*.



Maintenance

Regular oil changes are an important part of good pump maintenance. The oil level and the oil color should be checked regularly. If the oil is frothy or milky in color, the pump may be kept running while the gas ballast valve is kept open for about one half hour or the oil may be changed.

Over time, pump components will wear out and eventually the pump will need to be rebuilt. Minor or major overhaul kits are available for this purpose from most manufacturers.

molecular sieve trap

backstreaming

When the chamber must be kept free of oil, a useful addition to the roughing pump is a *molecular sieve trap.* It prevents mechanical pump oil *backstreaming.* The trap will restrict the gas flow (less conductance), however. These traps must be periodically baked to 250°C to remove the accumulated oil and water vapor.

There are also other types of traps which are used. Typically they are packed with brass, copper, stainless steel or glass wool. Don't forget that all traps become a *source* of oil if they are neglected. The traps must be regularly cleaned, or replaced.

All oil-sealed vacuum pumps we have talked about have oil in them for a number of distinct functions: as a lubricant for sliding surfaces, as a sealant to prevent back leakage of compressed gas into the inlet part of the pump, as a coolant of internal rotors (oil is continuously circulated in and out of the pumping mechanism by a variety of ingenious methods), as a filler of "dead" space under the discharge valve, and as a hydraulic fluid to operate certain valves. All of these functions are necessary for obtaining satisfactory performance.

The most basic requirements are: a more or less constant pumping speed at a wide range of inlet pressures, ultimate pressure near 1 mtorr (without auxiliary traps), tolerance for a certain amount of water vapor and, of course, reasonable longevity and cost. A variety of such pumps are available in very practical, reliable models. However, the presence of the oil which assures the satisfactory performance also produces certain disadvantages. Among these are: the possibility of contaminating the vacuum system by backstreaming oil, solution of pumped gases in the oil which limits the ultimate pressure and the possibility of chemical reactions between the pumped gases and the oil. In recent years, certain processes using corrosive gases have been producing considerable difficulty in operation of the oil-sealed vacuum pumps. Now let's look at a pump with *no* oil.

Dry Vacuum Pump

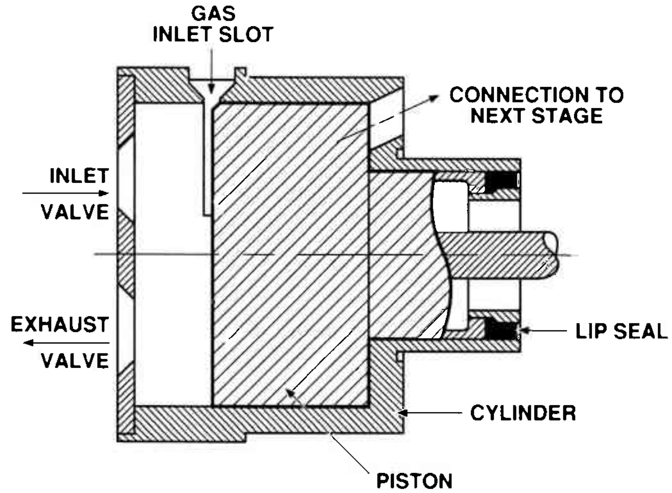
A dry vacuum pump removes gases by a simple compression stroke of a piston in a cylinder. Four stages of compression are used.

The pump is totally oil-free, making it well-suited for use on vacuum systems with ultraclean operating requirements.

The use of composite nonmetallic materials on the moving surfaces allows the pump to work without the use of sealing or lubricating fluids. Thus, the oil backstreaming found with rotary vane, oil-sealed mechanical vacuum pumps is eliminated. Dry pumps need no conductance-limiting foreline traps.

Components

Dry pump components are much the same as those found in a simple engine—a series of pistons and cylinders with appropriate valves for inlet and exhaust. The first two pistons work in parallel; from there on the gas is compressed, exhausted to the next stage and compressed again until the pressure is just a bit more than atmospheric pressure.



Pistons

A typical piston is shown above. The stepped design has a few advantages. The smaller diameter at the atmospheric side helps to reduce the atmosphere leakage because of the smaller outer area of the seal.

The step provides a convenient arrangement for connection to the next stage and a convenient location for the final exhaust valve.

All of the cylindrical surfaces of the piston are lined with special low-friction polymeric material (essentially reinforced polytetra-fluoroethylene but without glass, metal, or graphite fillers).

At the end of the piston is a lip seal that helps to minimize the atmospheric leakage into the pump.

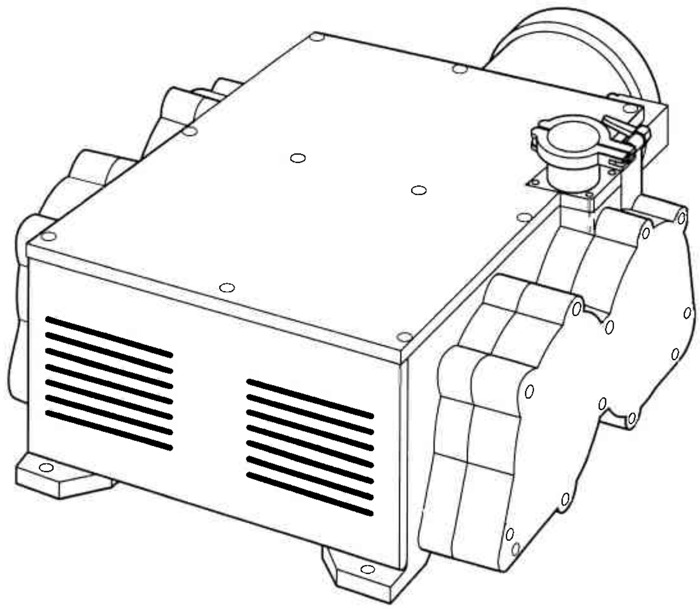
Dual Valve System

When the inlet pressure is high, the two valves placed at the top of the cylinder work in the normal fashion as in an ordinary compressor; that is, they open and close due to pressure of the air which develops as the piston moves in and out. However, when the pressure becomes too low to open the valves, the inlet valves remain closed. The gases flow through the slots in the cylinder which are uncovered at the end of the piston travel. The discharge valves are forced open by soft pads on the face of the piston which bump the valve at the end of the stroke. Only the final exhaust valve at the end of the last stage is opened by the pressure of slightly compressed air, compressed only to the point of overcoming the force of the valve spring.

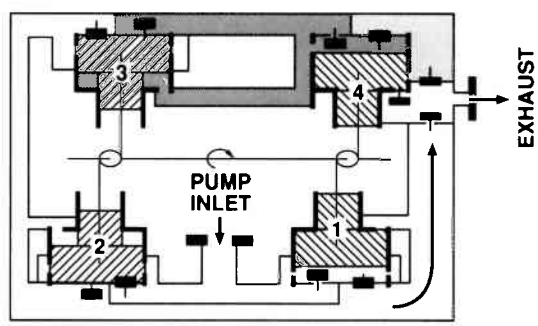
How the Pump Works

Operation

A reciprocating piston design was chosen primarily because it allows a convenient method for cooling the internal moving parts. In the rotary pump, it is very difficult to cool the rotor without using some heat transfer medium. In addition, it is difficult to keep the shaft seals sufficiently cool because their sliding friction surface areas are rather small.



In the reciprocating piston design, the inside of the piston is exposed to air and the atmospheric seals slide over a large area which is periodically exposed to room temperature air. In addition, all moving parts, bearings, connecting rods, and the main shaft are also in atmospheric air.

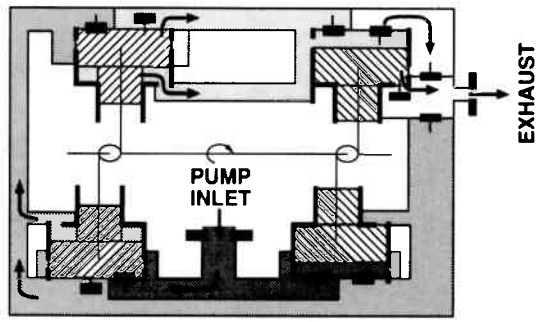


PUMP OPERATING NEAR
ATMOSPHERIC PRESSURE

The four pistons are arranged in pairs 180° apart. The first two are connected in parallel simply to obtain a higher pumping speed at high pressure. The third piston is used as the second stage of compression and the fourth piston has two compression stages, one in front and one in the back.

The backs of the first three pistons are always pumped by the pistons of the next stage. This reduces the amount of atmospheric leakage and improves the compression ratio in each stage.

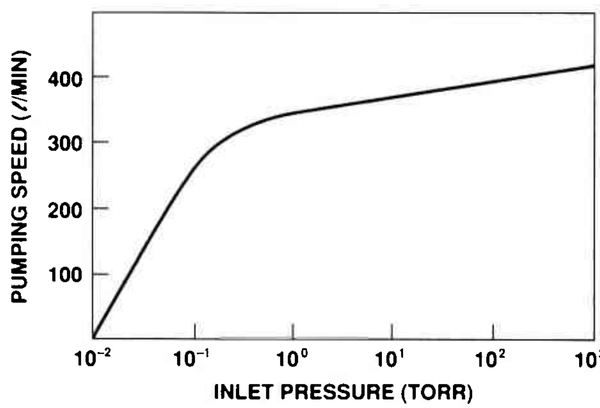
Additional interconnections shown in the pump schematic serve to reduce the amount of gas subjected to compression. That is, when the inlet pressure is high, most of the gas is exhausted through intermediate valves rather than passing through all four stages. In other words, when the inlet pressures are high, the pump functions as a single-stage pump. This reduces the amount of power needed to operate the pump and the degree of heating. Thus, a 20 cfm pump requires only a one horsepower motor (at 1,200 rpm).



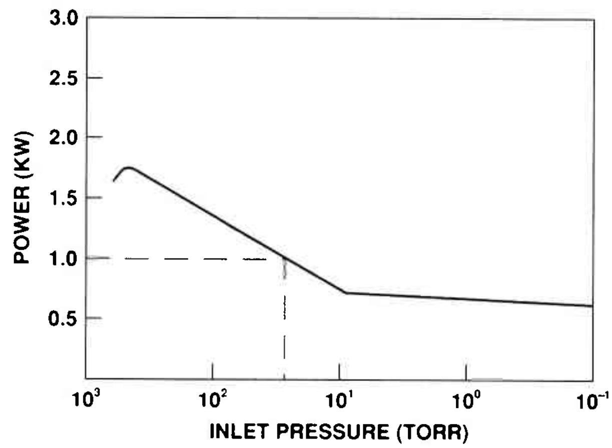
PUMP OPERATING AT
LOW PRESSURE

The dry pump has two interstage exhausts and, in addition, the flow into the *last cylinders* is proportioned by controlling the conductances of ducts.

Performance

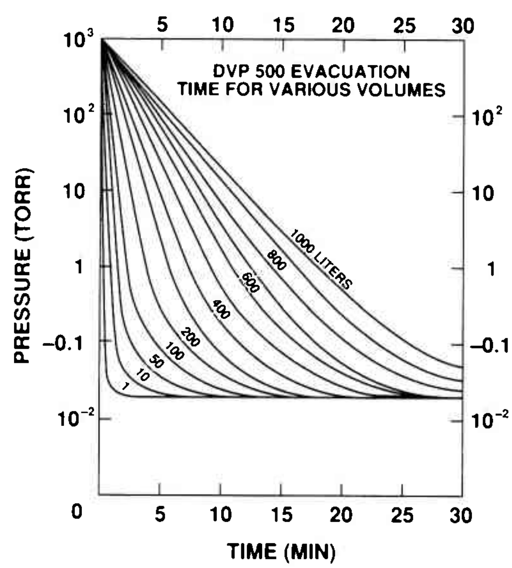


The basic pumping performance of the dry pump is shown in the form of a traditional pumping speed curve. The shape of the curve is very similar to the typical curves obtained with oil-sealed pumps. The gradual decline in speed toward the lower pressure is due to the changes in volumetric efficiency and the switching of the flow from the regular valves to the inlet slots. The final decline toward 10 mtorr is due to residual leakages which produce the limiting compression ratio.



The power requirement at various inlet pressures (or, in other words, at various flow rates) is shown above. The shape of the power curve depends on specifics of design, such as stage matching and the interstage exhaust valve system, but the general relationship is not unlike the one obtained with the conventional pumps. The peak demand occurs typically anywhere between one third and one atmosphere, depending on design.

It is evident from the power curve that for continuous operation and a one horsepower motor, the inlet pressure should be limited to a 30 torr maximum. For evacuation of large chambers, a one horsepower motor is sufficient to handle about a 1,000 liter volume. The evacuation process of various chambers is shown in the figure below.



Vacuum System Use

The ideal use for the new pump is pre-evacuation of vacuum systems which then are pumped by cryopumps, turbo pumps or ion pumps or any other oil-free high vacuum pump. These applications are described in chapter 7, Systems.

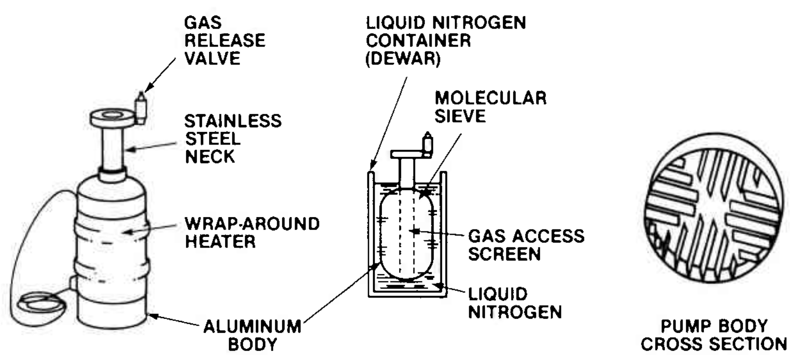
Maintenance

The pump does not need any maintenance under normal conditions for a period of approximately one year. Depending on severity of use, replacement of piston liners and some bearings may be required.

Sorption Pump

This pump operates on a totally different principle than those we have previously discussed. That is, there is no mechanical compression. The sorption pump is a capture pump. That is, it pumps gases by trapping or capturing them within the molecular sieve material. It is usually used for roughing ultrahigh vacuum systems where there can't be any oil— not even a trace.

Components



molecular sieve

The sorption pump has an aluminum body with internally extruded heat transfer fins (see cross section). The pump is filled with a very porous material known as *molecular sieve.* A pressure relief tube is mounted on the connecting flange. The pump is placed in a dewar containing liquid nitrogen (LN_2).

The LN_2 dewar may be either expanded polystyrene or stainless steel. The polystyrene is a solid foam-like material and the stainless steel dewar is double-walled and evacuated like a thermos bottle. Both provide good thermal insulation properties to keep the LN_2 from boiling away too rapidly. The liquid nitrogen cools the pump body to about −196°C. This helps the pumping process. Let's see how it works.

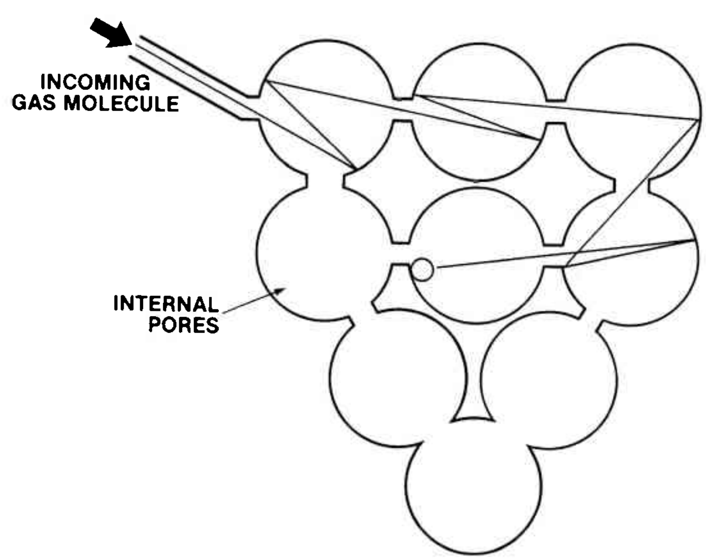
How the Pump Works

Gases are trapped on cold surfaces in two ways— by cryocondensation and by cryosorption.

cryocondensation

Cryocondensation is the trapping of gases that are condensable at liquid nitrogen temperature (–196°C). The cold trapping surfaces in the pump are the molecular sieve material. The porous molecular sieve provides acres of surface area. By chilling the material with liquid nitrogen at –196°C, the pumping or trapping action is very effective.

You're familiar with condensation!

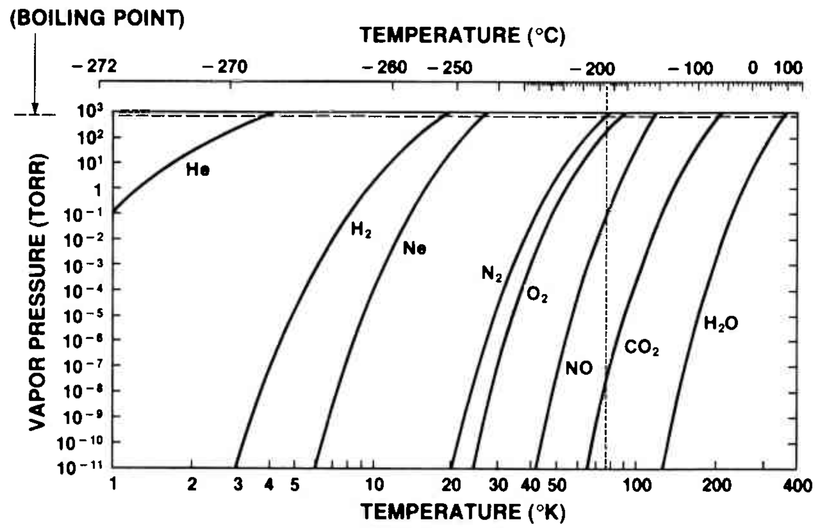


cryosorption

Cryosorption is the trapping of gases not readily condensed or pumped at LN_2 temperature. Cryosorbed gases are trapped in the pump's molecular sieve material.

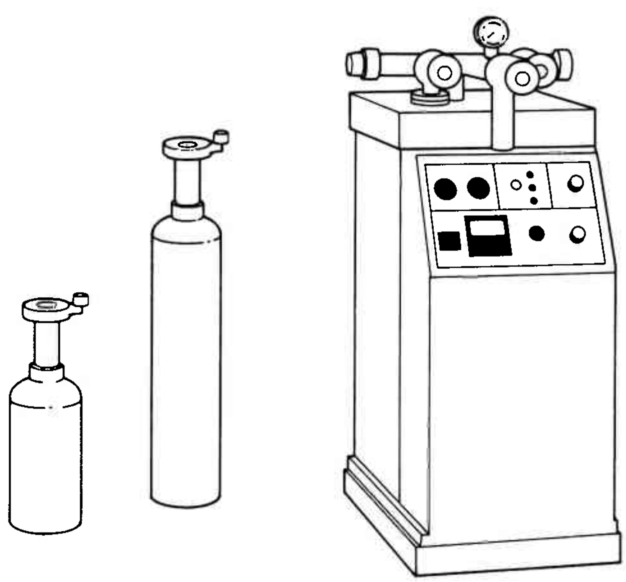
The molecular sieve material is very porous (giving tremendous surface area). Gases that are not readily condensed at LN_2 temperature bounce around within the sieve, losing heat. They are finally trapped (cryosorption). Other gases such as hydrogen, helium and neon are never truly trapped by either condensation or sorption. If we try to pump too long or to too low a pressure, these gases will tend to wander back out of the pump.

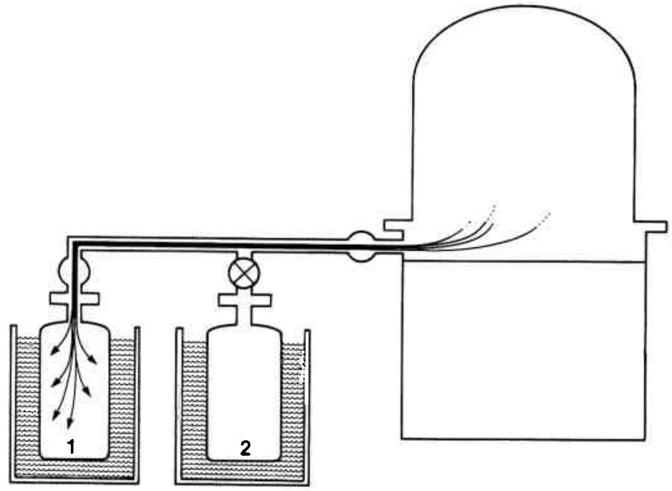
The vapor pressures of the incoming gases are reduced because of the cold temperature. Those that condense have greatly reduced vapor pressures, as shown in the following chart.



VAPOR PRESSURES OF COMMON GASES

Variations on the Varian sorption pump include a double-sized pump, and an automatic roughing system. The automatic system includes a Venturi pump and an array of five triple-sized sorption pumps.

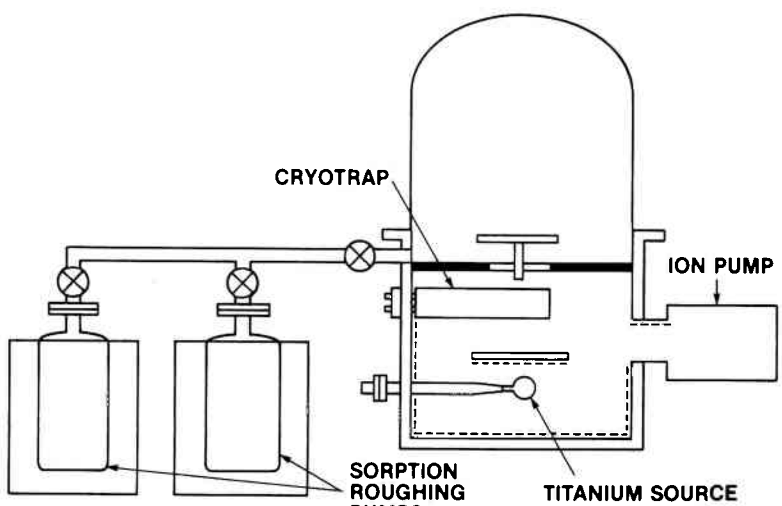




The actual operation goes something like this:

The pump body is pre-chilled for about 20 minutes. Then the valve is opened and pumping begins. The inrush of air carries all gases into the pump. Condensable gases, of course, are trapped on the cold fins and sieve material. Gases that are not condensable at liquid nitrogen temperatures are pumped by sorption or can begin to migrate back into the chamber. When two pumps are used, the first is valved off at a relatively high pressure to prevent back-migration of pumped gases. The second pump then takes over to continue rough pumping. Ultimate pressures of 10 mtorr or less are possible.

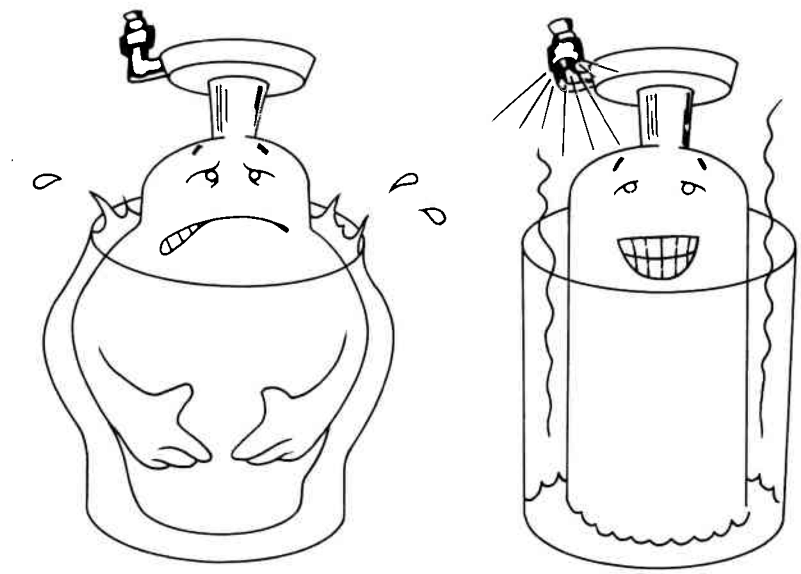
Vacuum System Use



Sorption pumps are very clean. They have no moving parts and do not use oils in their operation. For this reason, they are typically used in ultrahigh vacuum systems. This system configuration includes sorption roughing pumps, a titanium sublimation pump, and an ion pump.

Maintenance

Because the pump is a storage pump, it will eventually get full. Pumping will slow down and then stop. Because of this, the pump must be emptied or "regenerated" before the pumping action stops.



regeneration

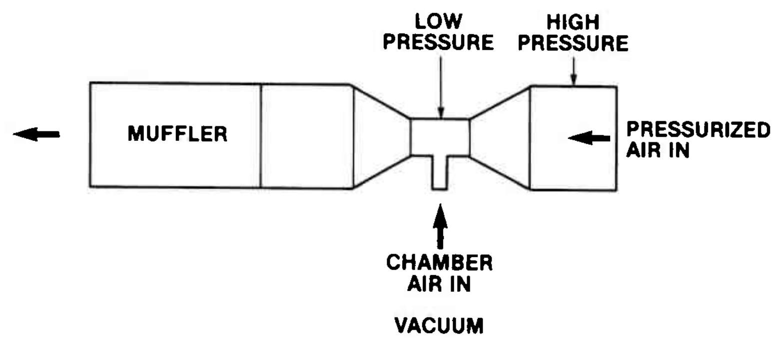
Regeneration consists of warming the pump. As the liquid nitrogen boils away, the pump and sieve material warm up. Now the trapped gases come off the surfaces of the pump and sieve material, build up pressure, and escape through the pressure relief valve. Water vapor, which does not escape so readily, must eventually be driven off by electrically heating the pump body. Typically, the pump is heated to around 250°C. It is very important not to obstruct the pressure relief valve in any way. Otherwise, dangerous pressures could build up in the pump.

For good sorption pump maintenance, the sieve material should be changed once a year. At that time, the inside of the pump and its components should be cleaned. Early degeneration of the sieve due to contamination will cause the pump to require more frequent cleaning.

Venturi Pump

The Venturi pump pumps gases by creating a low-pressure volume into which chamber gases are drawn and expelled to atmosphere. It is usually used along with sorption pumps to extend the time between regenerations.

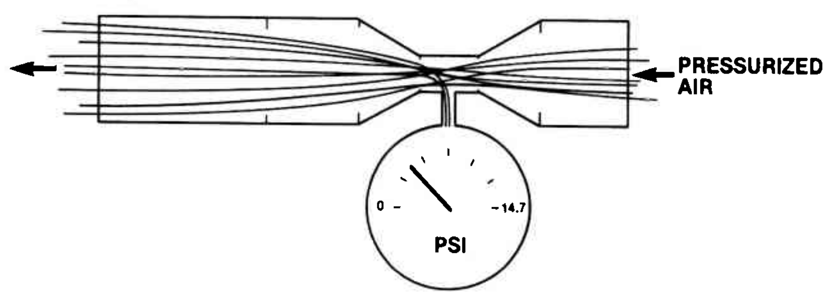
Components



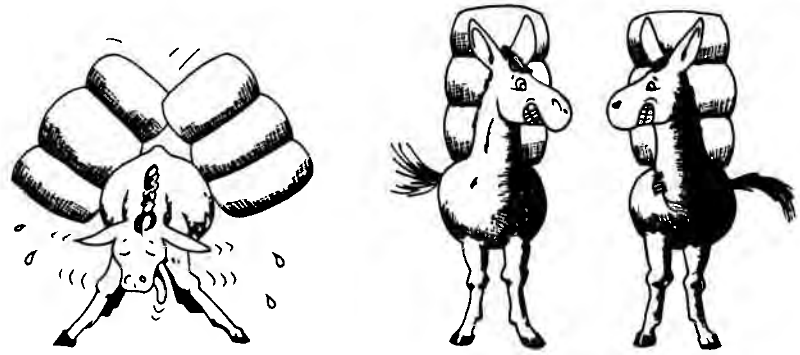
A Venturi pump is simply a tube with a pinched midsection. The tube has an inlet from the work chamber, a pressurized air inlet, and an exhaust. A muffler at the tube exhaust reduces the noise level during pumpdown.

How the Pump Works

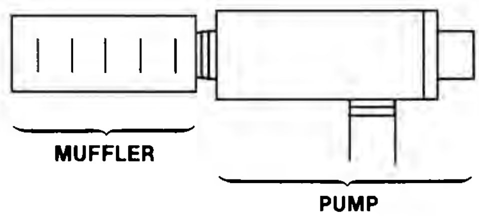
The pinched section of the Venturi tube causes an increase in the speed of the incoming pressurized air. These fast-moving air molecules tend to remove gas molecules from the small side opening. More molecules rush into the side opening from the chamber, only to be removed also.



Pressurized air at about 60 psig entrains air from the work chamber and exhausts it through the noise muffler. The chamber is evacuated to about 60 torr, then a sorption pump continues rough pumping. It's a very rough roughing pump, but it does offer this advantage:



The Venturi pump takes some of the load off the sorption pump. It removes about 90% of the air. Therefore, saturation of the sorption pump doesn't occur so readily, and regeneration is required less frequently.

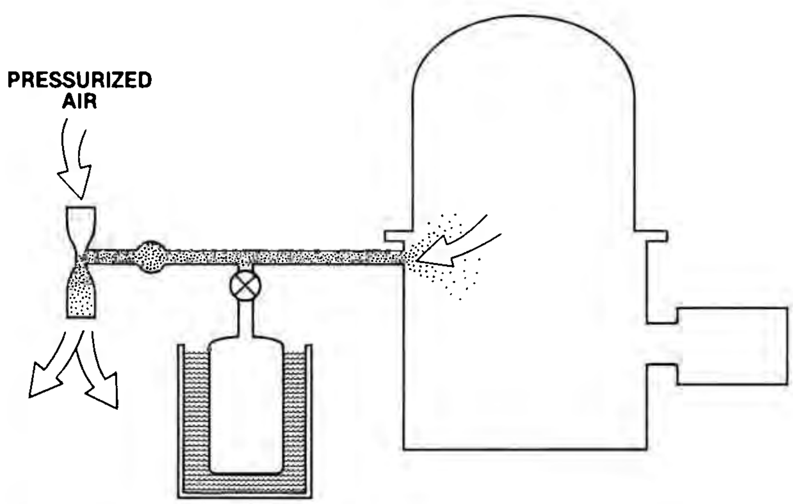


The Venturi pump is quite small, about 5 inches long and 1 inch in diameter.

Vacuum System Use

All you need to do to "operate" it is to connect a high-pressure air line to its air inlet and open the valve. It's not even necessary to connect the line with any kind of permanent coupling.

Next, you simply close off its valve to prevent outside air from re-entering the chamber, and remove the source of pressurized air.



Maintenance

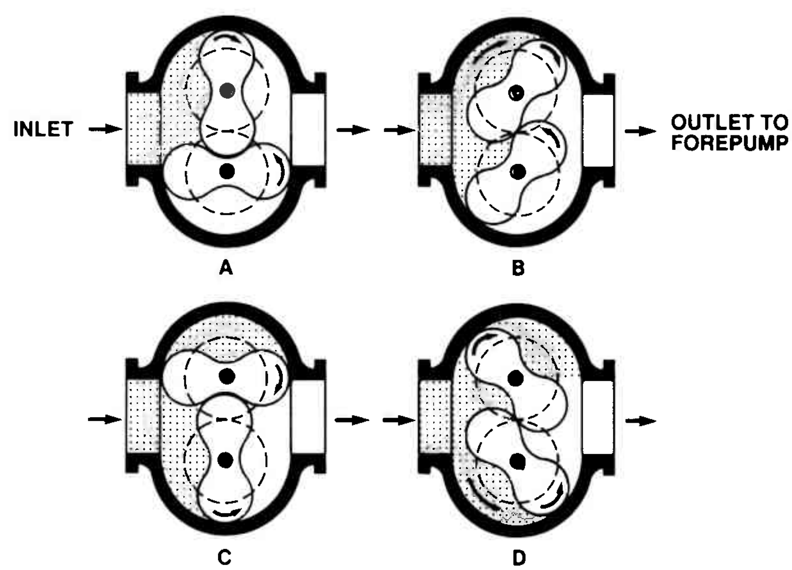
The Venturi pump is simple, and is virtually maintenance-free. However, be sure that the air used is properly filtered. Also, the muffler should be periodically checked for particulates or debris that might restrict gas flow.

Blower/Booster Pump

The blower or booster pump (sometimes referred to as a "Roots™" pump) is a high throughput, low-compression pump. This pump is usually used on systems where a large volume of gas must be pumped. It is also used with a mechanical pump to forepump large diffusion pumps, turbomolecular pumps, or even other Roots type of pumps.

Components

The pump consists of two figure eight-shaped rotors or lobes mounted axially on parallel shafts, as shown in the drawing below. These rotors are synchronized by gears to prevent physical contact and damage, and rotate in opposite directions. This rapidly displaces gas from the inlet to the outlet.



How the Pump Works

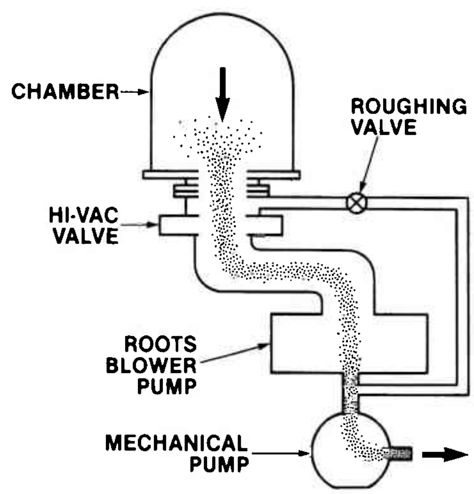
These rotors are designed so that while spinning, they approach each other and the housing within several thousandths of an inch. Rotor speeds vary from 2,500 to 3,500 rpm. Because of the high speeds and close tolerances of the rotating lobes, booster pumps are usually not started until roughing pressures of about

10 torr have been reached. The typical blower "windmills" at atmospheric pressure, producing much heat and very little pumping action. They are most useful between the 10 torr to 10^{-4} torr pressure range. They are always backed by a mechanical pump as a result. Operating at high pressures will cause heating and expansion of the lobes. This can result in damage to the pump. No oil is used to seal the stator/rotor gap. Oil is used in the forevacuum section of the pump to lubricate the gears and bearings located there.

Vacuum System Use

Operating procedure consists of turning the mechanical pump on, then the blower. Usually the mechanical pump has lowered the pressure sufficiently for the blower to begin pumping by the time the blower has reached operating speed. A bypass valve around the blower is sometimes used for high-pressure roughing.

Blowers are commonly used where large volumes of gas need to be pumped. They are used when the lowest pressure needed is 10^{-4} to 10^{-5} torr. They also are used to help the mechanical forepump or backing pump maintain a low pressure and help reduce the possibility of oil backstreaming.



Maintenance

The mechanical components and external drive mechanisms must be kept properly lubricated and cleaned. Consult the maintenance information provided by the manufacturer.

You have seen that there are several different kinds of roughing pumps, each with some advantages and also some disadvantages. Some are much cleaner than others. Let's go on now to high vacuum pumps, where we will see some different ways to produce a vacuum.

3 High Vacuum Pumps

Here is a list of things we think you should be able to do after reading this chapter:

You should be able to—

1. Describe the major components of each type of high vacuum pump.

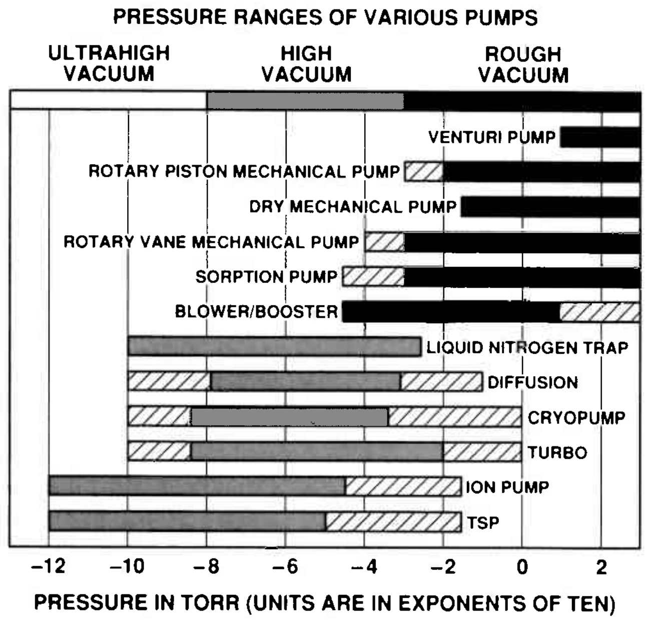
2. Explain how the major types of high vacuum pumps work.

3. Describe the place of these pumps in vacuum system use.

4. Describe in general how these pumps are maintained.

Introduction

In this chapter we will explain how high vacuum pumps work and the general ways they are used. We will also discuss the major pump components and how the pumps are maintained. We will give an overview of how they fit into vacuum systems. System operation is explained in more detail in a later chapter.



This chart shows typical operating ranges for a variety of vacuum pumps. See the beginning of chapter 2 for a brief discussion of pressure ranges of pumps.

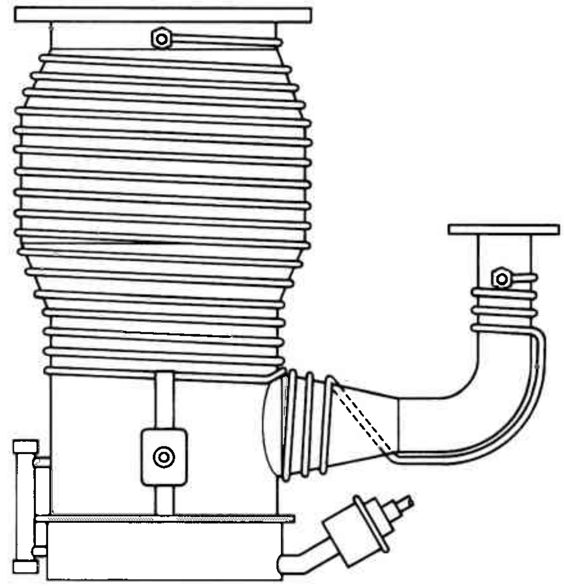
The liquid nitrogen trap is not really a pump but is often used with other high vacuum pumps to collect condensable vapors such as oil or water vapor. The other three high vacuum pumps operate marginally or briefly above their normal range.

The high vacuum pumps covered in this chapter are:

Oil Diffusion Pump
Baffles and Traps
Turbomolecular Pump
Cryopump

Oil Diffusion Pump

The oil vapor diffusion pump is a compression type of pump that has long been the workhorse of the high vacuum industry. It is generally used where throughput for heavy gas loads is important.



The diffusion pump will not operate at or exhaust to atmospheric conditions. It begins to work at 10^{-3} torr, after the mechanical pump has exhausted most of the air. It therefore must have a backing pump, or forepump, to operate. It, like other high vacuum pumps, cannot successfully operate at atmospheric pressure.

Components

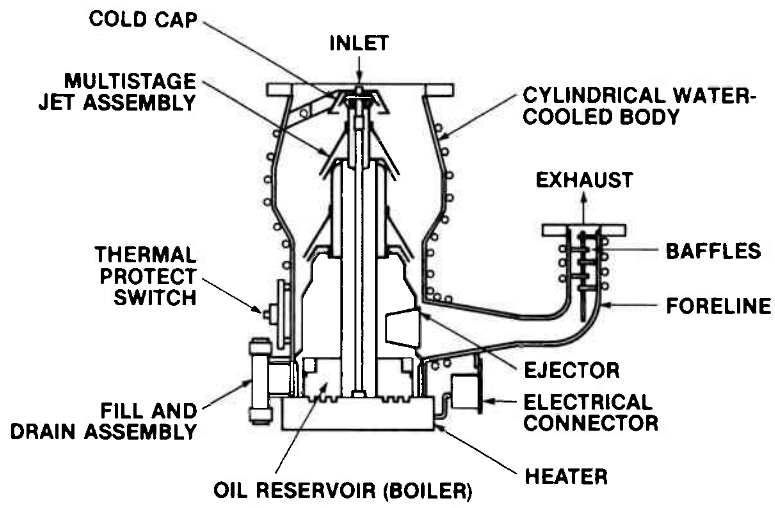
jet assembly

cold cap

The heart of the diffusion pump is the multistage *jet assembly*. The jet assembly is a group of concentric cylinders. These cylinders are capped to leave small openings through which vapor can be deflected down and out toward the pump walls. A *cold cap* may be mounted on top of the jet assembly. This cap helps keep pump fluid vapor out of the chamber.

Other important parts are the water- or air-cooled body and a heater mounted at the bottom. Inside is a reservoir of oil. Many pumps also have a fill and drain assembly and thermal protect switch. The inlet is at the top, and the exhaust is through the foreline. (Early diffusion pumps used mercury as a motive fluid. These pumps are still manufactured today for use in special applications.)

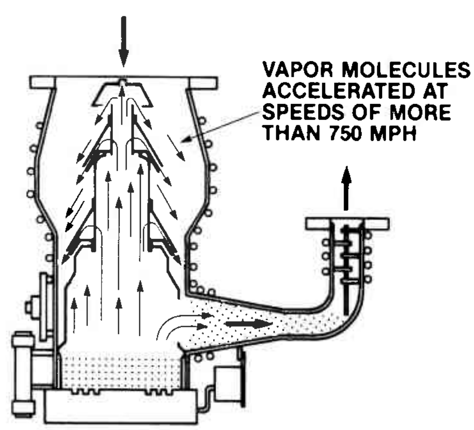
There are no moving parts in this pump.



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!



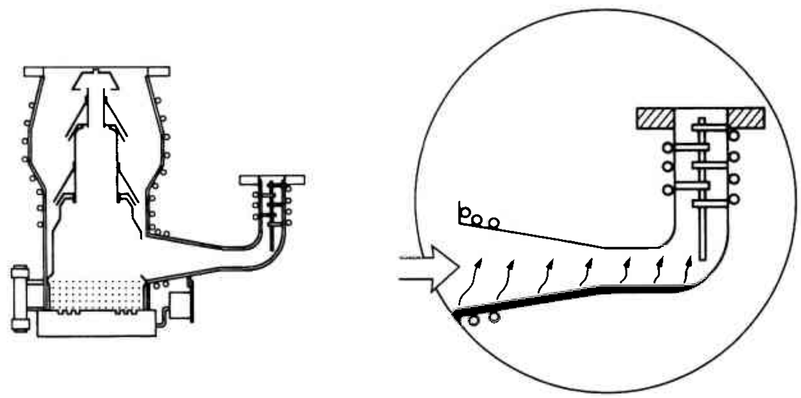
These vapor streams are directed toward the outer walls of the pump. The walls are typically cooled by water. When the vapor hits the cooled walls, it condenses back into a fluid. This fluid then flows downward into the pump boiler for reboiling.

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

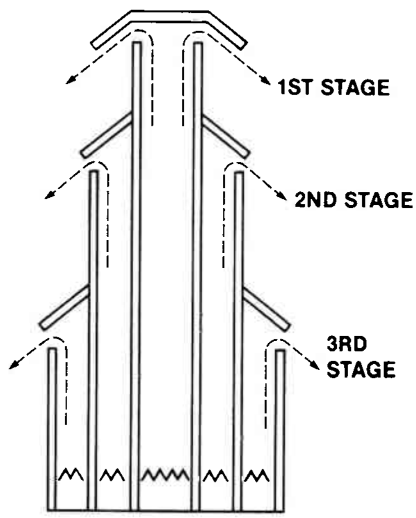
fractionation

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.

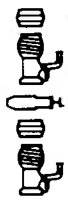


Backstreaming

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* ($mg/cm^2/min$) (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.

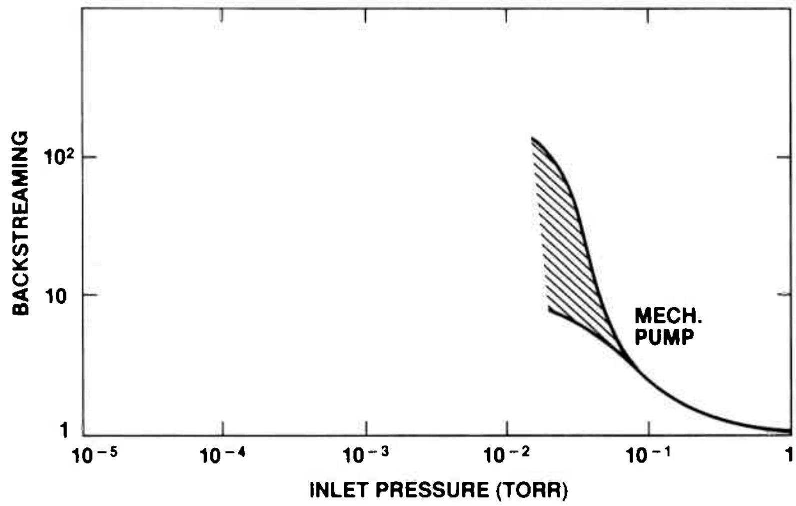
The combination given below reduces pumping speed by approximately 40% (550 ℓ/sec vs. 900 ℓ/sec for valved combinations.) This system may provide added protection against accidental exposure of the diffusion pump to pressures exceeding the normal operating range.

Combinations	Typical Applications	With Cold Cap	With Mexican Hat	With Cold Cap	With Mexican Hat	Using DC-704	Using DC-705 or S-5
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.	$<1 \times 10^{-7}$	$<1 \times 10^{-7}$	$<2 \times 10^{-8}$	$<5 \times 10^{-9}$

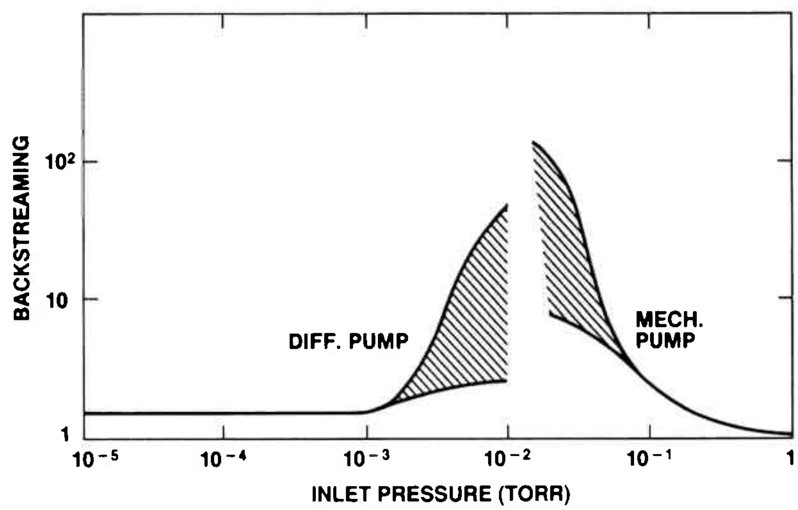
If excessive backstreaming occurs, a major system cleanup may be necessary. Large amounts of oil vapor may end up in the chamber. This results from various causes– sudden pressure bursts in the chamber; opening the high vacuum valve at high pressures; loss of the mechanical forepump as a result of perhaps 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

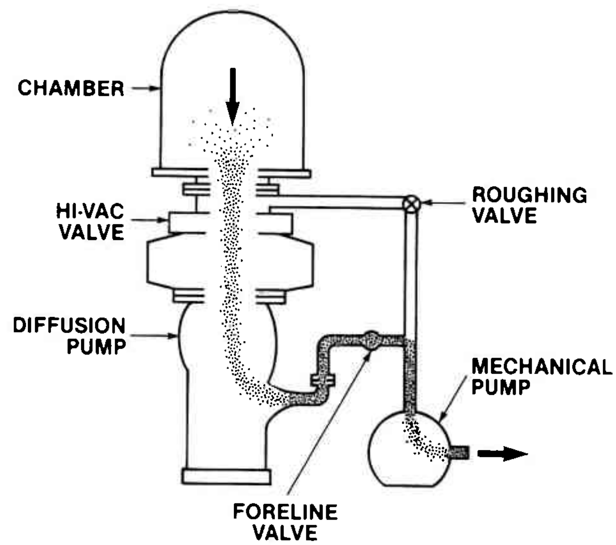


PUMPING AND LUBRICATION FLUID BACKSTREAMING IN THE TRANSITION ZONE BETWEEN DIFFUSION AND MECHANICAL PUMPS

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

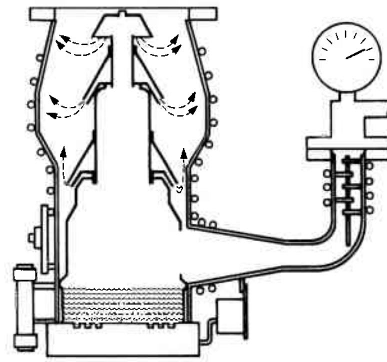
maximum tolerable foreline pressure

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

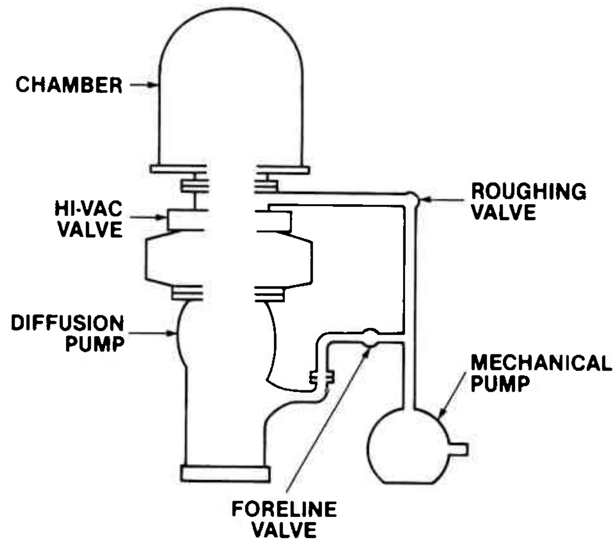
(3) Polyphenyl Ether
- (a) Santovac 5
- (b) Convalex 10

(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.

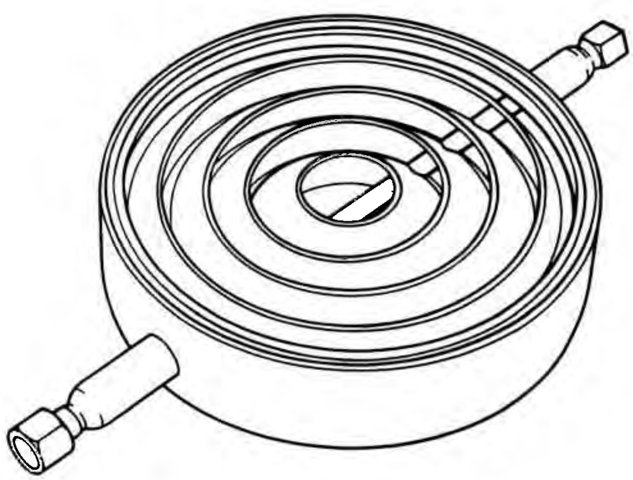
Baffles and Traps

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.

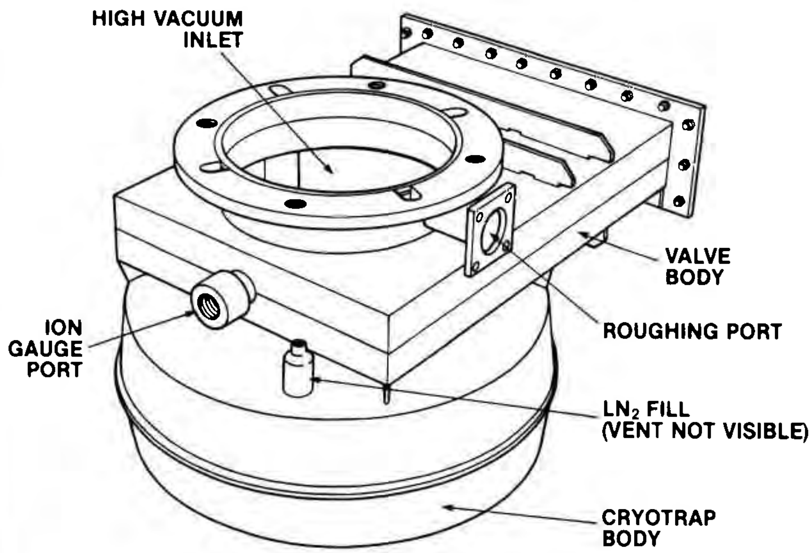
Baffles are composed of arrays of fins that are optically dense. That is, you cannot see through them. These arrays are cooled by continuous water flow through or about their internal components.



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.)



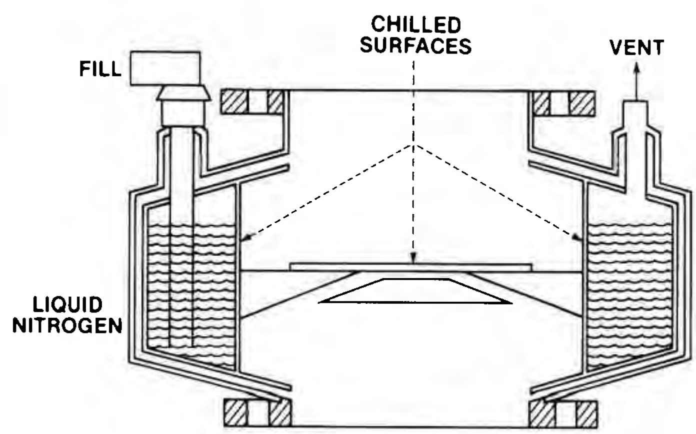
Components

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

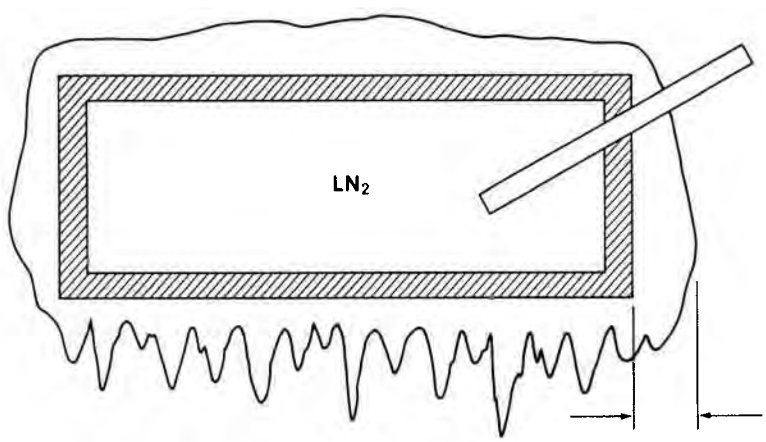
Cryotraps pump gases or vapors by freezing, or condensing, them on their chilled surfaces. This cryocondensation effectively removes them from the work chamber. However, some gases don't condense at liquid nitrogen temperature, or −196°C.

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

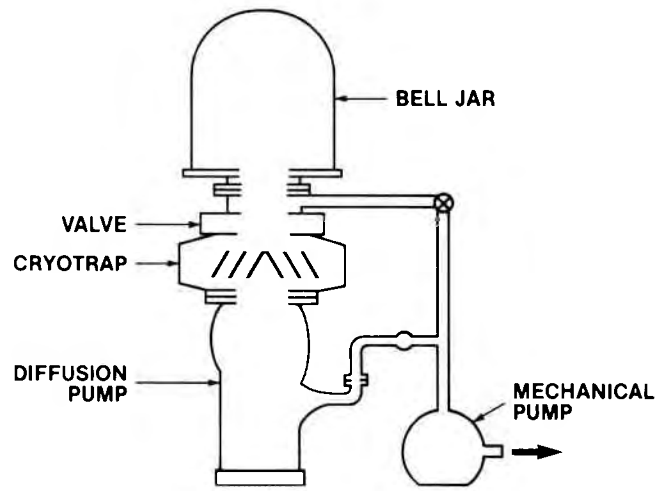
LN_2 traps should be filled after roughing pressures near 50 mtorr have been reached in the area where they are being used. At this pressure, much of the water vapor in the chamber volume has been removed. The mean free path of the remaining gases is long enough to create an insulating vacuum. If exposed 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.

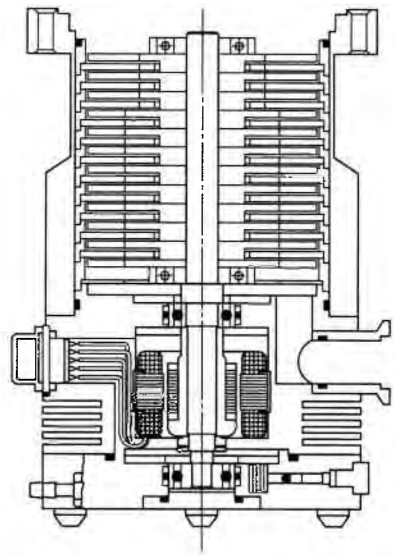
Maintenance

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.

Turbomolecular Pump

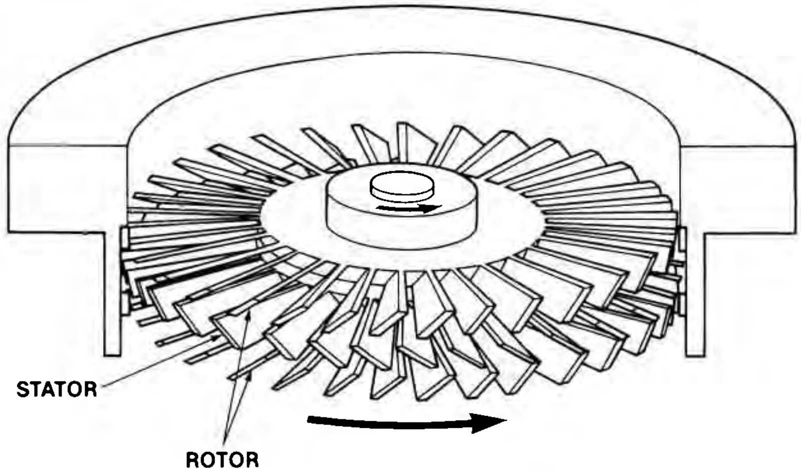
Turbomolecular (turbo) pumps are very clean mechanical compression pumps. They pump by using a high-speed rotating surface to give momentum and direction to gas molecules. They operate smoothly and contribute little vibration to the operating system. They are the only purely mechanical vacuum pump that can reach pressures of less than 5×10^{-10} torr without using traps. (Metal gaskets, and a mild bakeout of the vacuum system are necessary to reach this pressure.)



When operated correctly, turbo pumps are highly reliable and clean. Because they can operate from steady state inlet pressures as high as 10^{-2} torr to below 5×10^{-10} torr, turbos are used in a wide variety of applications. They are ideal for uses where a vacuum relatively free of hydrocarbons is a must. Turbo pumps offer the advantages of a fast start-up to full pumping speed and a clean, hydrocarbon-free vacuum. They are ideal for all but the most stringent applications (such as molecular beam epitaxy, surface analysis) where even the most miniscule hydrocarbon background cannot be tolerated.

Like the diffusion pump, the turbo pump cannot exhaust directly to atmosphere. Usually a rotary mechanical pump or dry vacuum pump is used to forepump the turbo.

Components



The turbo pump is mainly composed of rotating and fixed disks. These are called rotors and stators, respectively. The rotor disks are arranged alternately with the stator disks. On each disk are blades. A disk may have from 20 to 60 blades. The number of blades on a disk, the blade length, width, spacing and rotational speed determine its ability to pump gases.

Each rotor and stator disk can be called a compression stage. A pump may have as many as ten to forty stages. The rotor is driven by a motor capable of reaching speeds from 9,000 rpm to 90,000 rpm, depending on the size of the pump. The motor is typically powered through a special power supply. Compressed gases are expelled from the pump via a foreline which must be evacuated by some type of forepump.

The primary source of vibration of a turbo pump is the residual imbalance of the rotor assembly. This imbalance causes an acceleration in the radial direction of the pump rotor, appearing as a displacement of the inlet flange "side to side." Typically, this displacement is of the order of 0.02 microns (2×10^{-8} meters) and is inconsequential for the majority of turbo pump applications.

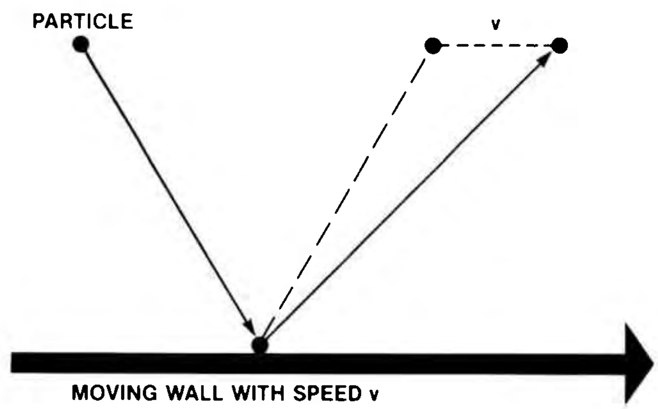
For vibration sensitive applications such as scanning electron microscopes or focused ion beam systems, vibration isolators are available that reduce the vibration level by an additional factor of ten to thirty times.

With turbo pumps, the vibration is at a relatively high frequency (near the controller output frequency) and is much easier to isolate than the low frequency vibration present in other types of mechanical pumps.

How the Pump Works

Pump Operation

When a gas molecule strikes a moving surface, it keeps its own speed. It also picks up a little more speed and a different direction from the contact with the moving surface. By this process, the movement of molecules can be directed, and pumping takes place.



PRINCIPLE OF THE TURBOMOLECULAR PUMP

The turbo pump works much like this; however, it adds blades to the moving surface plus a close-coupled stator. The stator also has blades. Each blade, when moving, will give some momentum to the gas molecules it hits. Each rotor blade, then, acts as a molecular pump. The result? Much greater momentum, speed, and direction are given to gas molecules entering this pump.

In the molecular flow range, the gas particles collide much more often with the moving blades than with each other. The effect of moving blades on the gas particles is highest in the molecular flow range. Pumps operating on this principle are called molecular pumps.

On the stages closest to the inlet, the blades have a large angle so as to pump at a faster rate, because more "open" space allows more access to the chamber. The blades closest to the foreline have a small angle for greatest compression. This works to move the gases from the inlet into the foreline. It also works to keep the gas and oil molecules in the foreline from making their way to the inlet.

Pumping Speed

Turbo pumps typically operate at speeds ranging from 9,000 rpm to 90,000 rpm. For any given turbo pump, variations in the rotational speed will strongly affect the pumping performance.

The pumping speeds and compression ratios achieved with a turbo pump are related to the rotational speed. Unless a manual switch for "low-speed mode" is made by a user, full rotational speed is achieved at pressures lower than 1×10^{-3} torr (1 micron).

The pumping speed of the turbo pump is directly proportional to its rotational speed. For example, if a turbo pump has a rated speed of 300 ℓ/sec (normal rpm) and is switched to a "low-speed mode" that reduces rotational speed to 70% of normal, the turbo pump will pump at 70% × 300 ℓ/sec, or 210 ℓ/sec. The "low-speed mode" allows operation at pressures of several hundred millitorr. This is useful in applications such as sputtering, which require a gas backfill into the millitorr pressure range.

Most manufacturers of turbo pumps give pumping speed specifications for nitrogen, helium and hydrogen.

The pumping speed for a gas species is a function of the velocity ratio of the tip speed of the rotor blade to the thermal velocity of the molecule being pumped. Helium and hydrogen molecules have high thermal velocities, in excess of 1,000 meters/sec, compared with nitrogen molecules which move at approximately 450 meters/sec. This large difference in molecular thermal velocities is why separate pumping speed specifications are given for helium, hydrogen and nitrogen. For other air gases such as oxygen, argon and carbon dioxide, the pumping speed for a typical turbo pump is within 10% of the nitrogen specification.

Compression Ratio

The compression ratio of a turbo pump is equal to the foreline pressure divided by the inlet pressure for a particular gas species. It is an exponential function of the molecular weight of the gas and the rotational speed of a particular turbo pump. The major operational significance of the compression ratio of a turbo pump is that it determines the cleanliness of the vacuum system.

The compression ratio of a turbo pump is a function of the molecular weight of the gas being pumped. In a well-baked UHV system, the compression ratio for hydrogen will limit the ultimate pressure achieved in the system. This is because the residual gas in a baked-out system is typically over 85% hydrogen. The ultimate pressure (P_{ult}) is determined according to the formula:

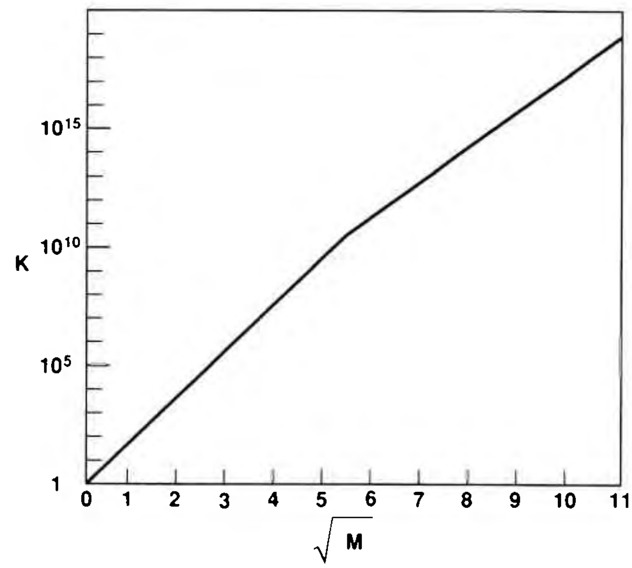
$$P_{ult} = \sum \frac{Q_i}{S_i} + \sum \frac{P_{2i}}{K_i}$$

where Q_i is gas load (for each gas species from outgassing),
S_i is pumping speed for each gas species,
K_i is compression ratio for each gas species,
P_{2i} is partial pressure at the exhaust for each gas species.

With an oil-sealed mechanical pump as the forepump, the foreline partial pressure of hydrogen is approximately 2–5 × 10^{-7} torr due to the hydrogen produced by cracking of the mechanical pump oil vapor. With typical turbo pumps having a compression ratio of 10^3 for hydrogen, the system pressure will contain a hydrogen partial pressure of 2×10^{-10} torr to 5×10^{-10} torr.

To obtain a lower ultimate pressure, into the 10^{-11} torr range, the turbo pump should be backed with another, smaller turbo pump which is then backed by a mechanical pump. This configuration is usually only used when the lowest possible hydrogen partial pressure must be achieved.

Mechanical pump oil typically has a molecular weight of at least 100. From the chart, the compression ratio, K, for this mass is 10^{15}.



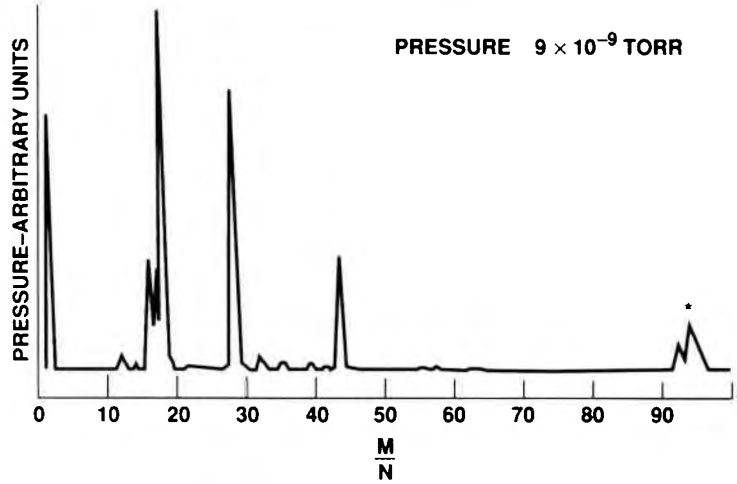
COMPRESSION RATIO (K) VS.
SQUARE ROOT OF THE MOLECULAR MASS

If the forepump is producing a foreline pressure of 1 mtorr (0.001 torr), then the partial pressure of hydrocarbon gas (mechanical pump oil) at the inlet of the pump is

$$= \frac{10^{-3}\text{ torr}}{10^{15}}$$

$$= 10^{-18}\text{ torr}$$

This is why turbo pumps produce virtually hydrocarbon-free vacuum. Only the most sensitive of analytical equipment can detect this level of hydrocarbon vapor.



MASS SPECTRUM OF UNBAKED TURBO PUMP SYSTEM

*RHENIUM PEAK (FROM FILAMENT IN RGA)

Pump Base Pressure

Ultimate or base pressure is defined as the lowest pressure measured in the standard test dome within 48 hours after the prescribed bakeout is finished, per international test procedures (DIN Norm #28428).

To achieve the lowest base pressure in a system then, it is necessary to bake out the system and the turbo pump. Many people accept the pressure reached without a bakeout as their base pressure.

Care must be taken to ensure the temperature of the turbo pump never exceeds the manufacturer's maximum allowable temperature at the inlet flange, typically 80°–120°C.

Most manufacturers supply heating mantles to give the turbo pump inlet a mild bakeout. The chamber can be baked out with strip heaters or a small clamshell oven.

Potential Problems

The most common failures of turbo pumps are due to particulates, lack of bearing lubrication, and shock.

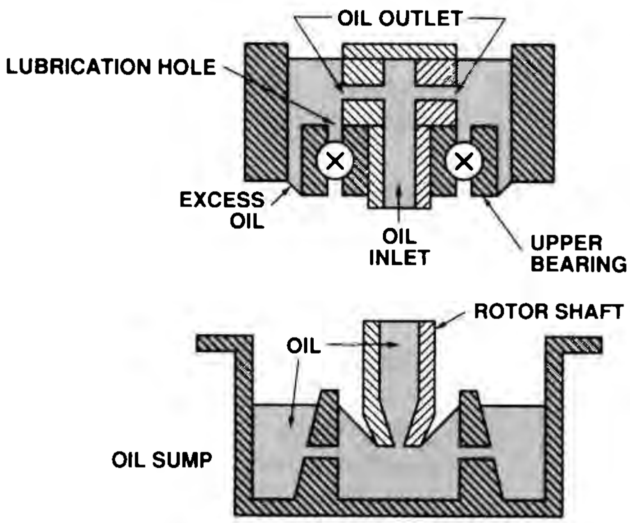
Lubricating Systems

There are a variety of methods used to deliver lubrication to the bearings. The most common are described below.

Circulating Oil

Oil is drawn up the shaft during operation and ejected over the bearings. This method provides a continuous flushing of the bearings, removing any particulates that have accumulated, and provides a continuous flow of lubricating oil. The oil also helps to cool the bearing.

Circulating oil is the most reliable method of bearing lubrication; however, it requires a vertical mounting of the pump and water cooling. In addition to superior reliability, it allows a visible indication of the oil quality and quantity through a transparent oil sump.

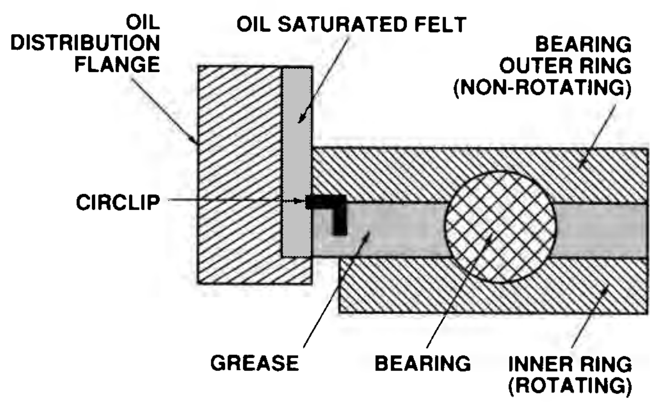


OIL LUBRICATION OF TURBO PUMP BEARINGS

Grease-Lubricated Pumps

In this method, the bearings are packed in grease, which contains a lubricating oil. Periodically, oil must be injected into the pump lubrication port to replenish the consumed oil.

Advantages of this method are that the pumps can be mounted in any orientation and usually can be air-cooled. Disadvantages are that the status of the lubrication cannot be determined as with the oil-lubricated pumps.



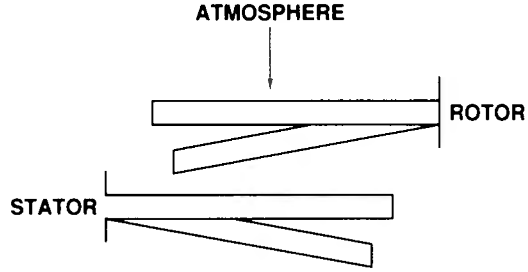
VARIAN GREASE-LUBRICATED PUMP OIL DISTRIBUTION DEVICE (SIDE VIEW)

Shock
Since a turbo pump incorporates a precisely balanced high-speed rotating turbine, it should never be moved or jolted while it is in operation. This will help prevent a catastrophic crash (rotating rotor touching a stator and destroying the turbine).

There are two other modes of shock damage that should be avoided. One mode is that the system dumps to atmosphere while the pump is rotating. The second is improper venting. Let's look at these modes in further detail.

System Dumps to Atmosphere While Pump Is Rotating
Most well-designed turbos can withstand infrequent dumps to atmosphere without suffering a pump crash, although it is certainly recommended that one avoid this whenever possible!

The pump blades will flex when a gas load is dumped into the pump. If the rotor and stator blades come in contact with each other under these conditions, a catastrophic failure mode will occur. This is "fondly" called a crash. Proper valving procedures will help prevent this occurrence.



SYSTEM DUMPED TO ATMOSPHERE
WHILE THE PUMP IS ROTATING

Venting
One should always vent the turbo pump while the rotor is still spinning.

If the pump is still in rotation when vented, rotational lift (like the way a helicopter blade produces lift) will minimize the loading on the bearings. If the balls in the bearings are not rotating, "dimples" can result as the impact on the balls permanently deforms the bearing race. Once this occurs, bearing failure can occur at any time due to the damaged bearing surface.

The proper location for the vent valve is at the turbo inlet, or at an interstage vent port, if available. Venting through the foreline is not recommended, as accumulated mechanical pump oil vapors can be forced into the high vacuum area of the pump by the inrushing air, eventually migrating to the system chamber if done repetitively. This is the prime cause of contamination in a turbo pump vacuum system.

See the chapter on System Operation for more detail on how to vent a turbo pump properly.

Additional Concerns

Turbomolecular pumps must be protected against mechanical damage as well as against the loss of cooling water because the pump is a high-speed device with considerable stored energy. If a large, solid particle enters the rotor or a bearing seizes, serious damage may be done to the pump.

A splinter shield or screen located at the pump inlet adequately protects the rotors and stators from physical damage with some loss in pumping speed. Some pumps are available with side inlet ports. Water cooling is preferred in both oil-lubricated or grease-packed bearings. Proper cooling is necessary to remove heat from the bearings and to extend bearing life.

Turbomolecular pumps will give reliable, trouble-free operation if they are adequately lubricated and protected against cooling-water failure, power failure, mechanical damage, and excessive torque.

Backstreaming of mechanical pump oil can occur. Stopping the pump with the forepump operating and the work chamber under vacuum will result in rapid backstreaming of oil vapors from the foreline to the clean side of the pump. To minimize this back-streaming, you should always vent the turbomolecular pump from the inlet during shutdown.

The pump should be vented with dry gas in such a way that it will flow toward the foreline through at least a portion of a rotor and stator assembly. Oil vapors in the foreline are then flushed away from the high vacuum chamber. The pump must never be vented from the foreline because oil vapors will be forced back toward the pump inlet and the high vacuum chamber.

Vacuum System Use

Most system designs use the turbo pump coupled with a high vacuum valve. This design is similar to a diffusion pump system using a common roughing and foreline pump. It is possible, however, to rough pump a chamber right through the turbo; in this case, the turbo will gain speed as chamber pressure is reduced.

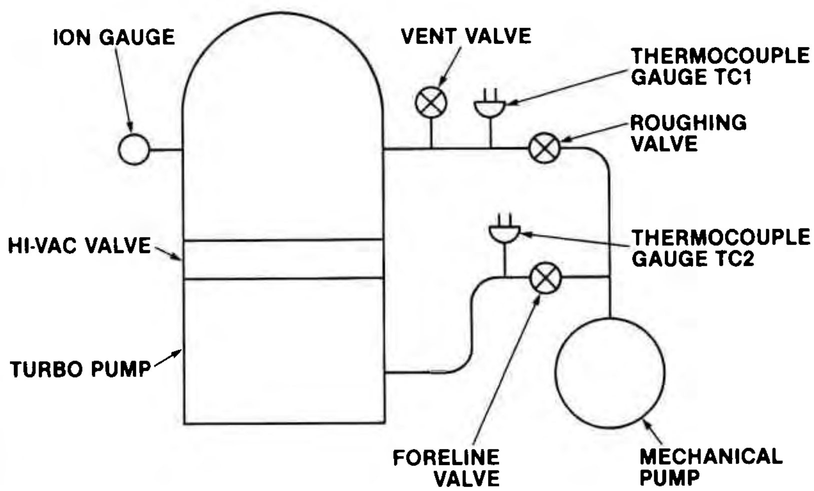
This type of system design shouldn't be used if the work chamber needs to be vented to high pressure very often, or if rapid pump-down to low pressure is required.

Turbo pumps can also be placed in series with cryotraps to promote high-speed pumping of water vapor and other condensables.

It is desirable to use a high vacuum isolation valve to isolate the turbo pump if roughing the chamber through a separate roughing line, similar to the way diffusion pump systems are manifolded.

This is especially true on fast cycling applications such as load locks, where it is desired to cycle the load lock at a rate approaching the start-up time of the turbo pump. To achieve the fastest cycle time, it is necessary first to rough the chamber through a roughing line and then transfer to the turbo pump (which is rotating at full speed). As a general rule of thumb, it is advisable to use a valved system if the chamber is going to be repetitively cycled from atmosphere to vacuum to atmosphere, with a total cycle time of less than ten minutes.

A valved system as shown here should also be used when evacuating a large vacuum chamber. Roughing the chamber through the turbo pump will be slower, since the turbo pump will have rather large conductance losses due to the small exhaust port on the turbo pump.



TURBO PUMP SYSTEM

Turbo pumps allow great flexibility in the choice of vacuum manifolding. For moderately sized chambers, the turbo pump can be mounted directly to the chamber without a high vacuum isolation valve. In this case, the turbo pump is cycled from atmosphere to high vacuum along with the chamber, and the chamber is roughed through the turbo. Usually, the turbo pump and