Chapter 6 Vacuum Pumps

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6.1 Introduction to Vacuum Pumps

Exactly how do we produce a vacuum? Many different kinds of vacuum pumps exist, each with their own application. In this chapter we shall examine some of the more common types of pumps and also will discuss vapor traps and cold traps which are auxiliary items with pumps.

The most common types of pumps are the rotary pump for reaching rough vacuum, and the diffusion pump for reaching high vacuum. These will be discussed first followed by other pumps.

For each pump we need to discuss several things:

1. How it operates.
2. What pressure range it operates in.
3. Its pumping speed.
4. Type of gas flow (viscous or molecular).
5. Effects of pumping on different types of gas.
6. Advantages and disadvantages.

Three methods of drawing vacuum components are common. The first uses sketches that are approximately realistic. You can see an example of this in the typical vacuum system shown on the left hand side of Figure 5.5 in the previous chapter. The second method uses standard symbols of the American Vacuum Society. The third method uses standard symbols found in Europe. We will show these symbols as we go through the discussion of the pumps.

6.2 Classifications of Pumps

We can classify pumps in different ways; by their range of pressures, their means of operation, their cleanliness, their ability to pump a continuous gas flow, and their ability to pump different gases. We will next discuss each of these classifications and summarize the several types of pumps in Table 6.1.

Pressure Range Roughing pumps can evacuate a chamber from atmospheric to about 10^{-3} Torr. Examples include the rotary pump, the aspirator, and the sorption pump. Hi-vac pumps provide much lower pressure, as low as 10^{-11} Torr, but can only start to operate when the pressure is below about 0.1 Torr. Thus they require a roughing pump to back them up. In addition to the common oil diffusion pump, the turbomolecular, ion, titanium sublimation, and cryopumps are hi-vac pumps.

Booster pumps span the range of pressures between the roughing and hi-vac pumps and serve to increase the overall speed of the system in reaching low pressures. The Root's blower and the oil ejector are examples. The pressure range is 10^{1} to 10^{-5} Torr. Figure 6.1 gives the ranges of various pumps and pump combinations.

Method of Operation Mechanical Pumps such as the rotary vane, Roots blower, and turbomolecular use rotating parts (macroscopic!) to reach vacuum.

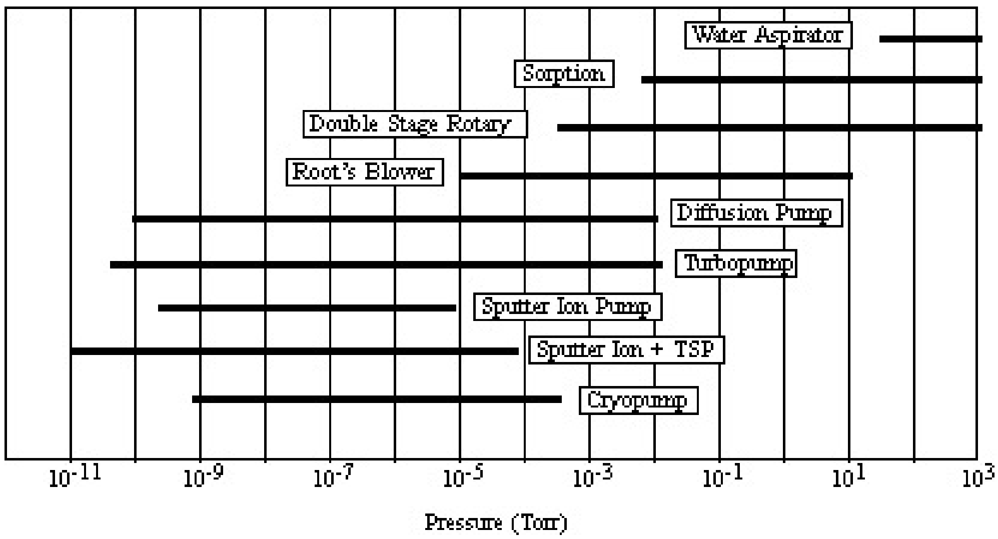

Figure 6.1: Pressure Ranges of Vacuum Pumps

Table 6.1: Properties of Pumps

Pump type	Range	Method	Clean?	Gas sensitive	Continuous?
Aspirator	Rough	Bernoulli	No	No	Yes
Rotary vane	Rough	Mech.	No	No	Yes
Sorption	Rough	Entrain	Yes	Some	No
Roots	Boost	Mech.	Yes	No	Yes
Oil Ejector	Boost	Vapor	No	No	Yes
Turbo-molec.	Hi-vac	Mech.	Yes	Slight	Yes
Diffusion Hi-Vac	Vapor	No	No	Yes	
Sputter-ion	Hi-vac	Entrain	Yes	Some	Semi
Ti sublimation	Hi-vac	Entrain	Yes	Yes	Semi
Cryopump	Hi-vac	Entrain	Yes	Slight	No

Vapor pumps, the diffusion and oil ejection pumps, use a stream of liquid or vapor to create the vacuum.

The aspirator works on Bernoulli's principle.

Entrainment pumps, the sorption, cryo, ion and titanium sublimation pumps, create surfaces onto which vapor and gas molecules will stick by condensation, adsorption or other mechanisms.

Cleanliness Certain pumps are cleaner than others, and this is very important in some applications such as the microelectronics industry.

"Dirty" pumps have a fluid, usually oil, which may travel into the working chamber by a process called backstreaming. These pumps include the rotary vane and oil diffusion pumps.

"Clean" pumps add very little or no vapors to the system. Sorption, turbomolecular, ion, titanium sublimation, and cryopumps are clean.

Continuous Operation? In applications such as gas lasers and sputtering we need a continuous flow of gas at low pressures. Sorption pumps and cryopumps have difficulty with this type of load, while ion and titanium sublimation pumps must have elements periodically replaced. The other pumps can handle continuous gas flows.

Sensitivity to Different Gases Different gases are pumped with different efficiencies by all pumps. Noble (inert) gases and low-mass gases cause the most problem. The problem is more severe with entrainment pumps than with other types of pumps.

Table 6.1 should help to sort out the various pumps and properties.

Compression Ratio Mechanical pumps can also be thought of in terms of their compression ratio, the ratio of the pressure at the outlet to the pressure at the inlet. For "dry pumps" such as Root's blowers the ratio might be small such as 10 to 50. Oil sealed rotary pumps can have compression ratios of 100 000. Turbo-pumps have compression ratios of 2 x 10^7. Diffusion pumps have ratios at or above 10^9.

6.3 Rotary Pump—760 Torr to 10^{-4} Torr

Rotary vane pumps (usually called rotary pumps) take a volume of gas at a low pressure, compress it so that the pressure becomes slightly higher than atmospheric, and vent the gas to the atmosphere. They are very similar in principle to the ideal pump introduced in the previous chapter except that they are rotary.

A typical rotary pump is shown in Figure 6.2. The vacuum chamber is connected to the inlet, and the pressure in region I is about the same as that of the chamber. Region I is an expanding volume. As the rotor moves it eventually traps a relatively large volume of gas at chamber pressure. In the diagram this is region II. This region is decreasing in volume. The rotor continues to move and region II is made accessible to the outlet valve. In our diagram this

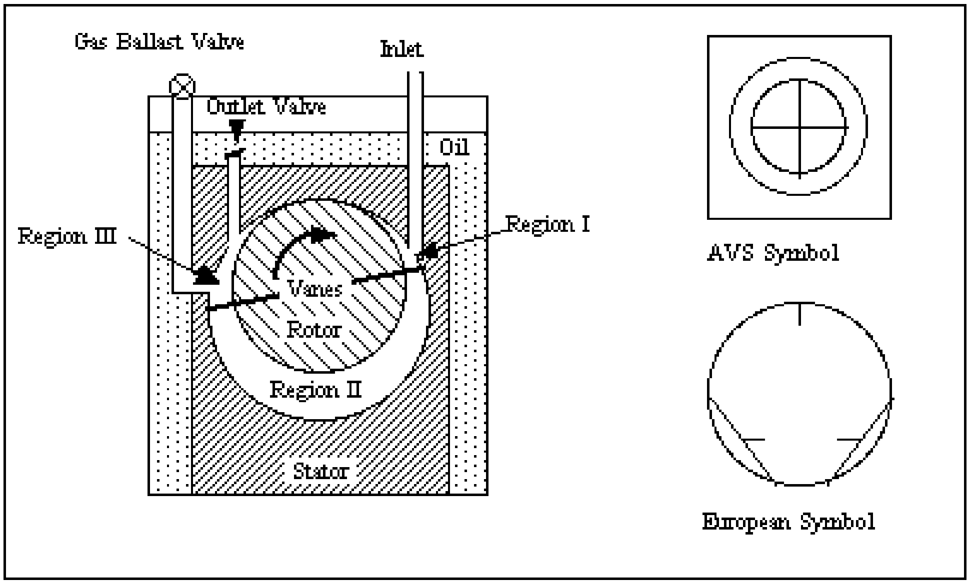

Figure 6.2: Rotary Mechanical Pump. A single stage is shown. The output of this is connected to a similar second stage in two stage pumps. Standard AVS and European symbols are shown.

is the region III. Region III continues to be compressed in volume, and thus its pressure rises. Eventually the pressure exceeds atmospheric and the gas is expelled through the outlet valve and through the oil into the room.

The low-pressure limit on this pump is determined by the leakage of gas around the seals and by gas dissolved in the oil. For a single-stage pump this is at about 50 mTorr, while a two-stage pump has a base pressure of about 0.1 mTorr. In a two-stage pump the vent of one stage goes to the inlet of the other stage. Adding more stages has no practical benefit.

Roughing pumps such as the rotary pump have a problem if they pump on a chamber that contains condensable vapors. The most common condensable vapor is water vapor. As the low-pressure gas from the inlet is compressed, we may reach a pressure where the water vapor will condense into a liquid. At 30°C the vapor pressure of water is 32 Torr. When, upon compression in the pump, the partial pressure of the water vapor exceeds 32 Torr, the vapor condenses into liquid prior to the opening of the outlet valve. The liquid dilutes the oil, and may corrode the pump. For some vacuum applications there is a large vapor load such as freeze drying (water vapor), Chemical Vapor Deposition (HCl), or plasma etching (organics) and large quantities of condensable liquids are possible. To prevent the condensation in moderate vapor loads we use gas ballast.

The gas ballast valve, GB, adds a small

amount of dry gas such as nitrogen to region III. This reduces the amount of compression that the vapor undergoes and thus reduces the condensation problem. The ultimate pressure of the pump is not as low when we use gas ballast.

The oil that surrounds the stator serves to seal the outlet valve from leaks, and also lubricates the moving parts since some oil gets inside the pump. Good rotary pump oils must have low vapor pressures and yet be viscous enough to form a seal across the rotary vanes. In addition, the oil must be chemically stable. The stability of the oil depends on the type of gas passing through the pump. The cheapest and most common oil is a highly refined or synthetic hydrocarbon oil. If we are continually pumping large amounts of oxygen, we must not use a hydrocarbon oil since it may become explosive. More expensive synthetic oil is needed. In addition the pump must be modified to eliminate seals impregnated with hydrocarbon oils. Other uses of pumps may involve the pumping of corrosive materials such as acid vapor, and appropriate modifications of the pumps should be made, usually in consultation with the manufacturer. Rotary pump oils cost between $10 and $1000 per liter.

Rotary pumps are available with speeds ranging from 0.25 to more than 80 L/s. Older rotary pumps are usually belt driven, with the pump and the motor separate and connected by a fanbelt. This means that the belts must be regularly checked. Newer pumps are direct drive, with the motor and pump connected by a shaft.

The dependence of pumping speed on pressure is shown in Figure 6.3. Clearly the speed is not constant but at higher pressures, some average speed may be used without much error. The conductances of the piping and outgassing will mask some of the variations in pumping speed. Usually the pumping speed for roughing pumps is given in L/min or cubic feet per minute, cfm.

$$\text{speed in L/min} = \text{speed in cfm} \times 28.32 \tag{6.1}$$

At low pressures, the speed drops off rapidly, and the ultimate pressure is likely to be somewhere in this drop-off region. The ultimate pressure will depend on the vapor pressure of the oil and on the rate of outgassing and leaks in the system.

Throughout most of the operation of the rotary pump the gas is in either turbulent flow or viscous flow. Below about 100 mTorr the flow becomes molecular for typical piping sizes. When molecular flow occurs, some of the oil molecules in the roughing pump can backstream into the working chamber to cause unwanted contamination of the system by the roughing pump oils. Hence we wish to avoid operation of the roughing pump below 100 mTorr, or else we need to put in a trap to limit backstreaming. Typically we would stop using the rotary pump at about 70 mTorr and switch to a high vac pump.

We can compute approximate pump down times from the equation $P = P_0 \exp -(S/V)t$ using an average value of S. The effective speed at the chamber must be used since it includes the effects of piping conductance.

Example A Varian SD-201 pump is used to evacuate a chamber through a pipe

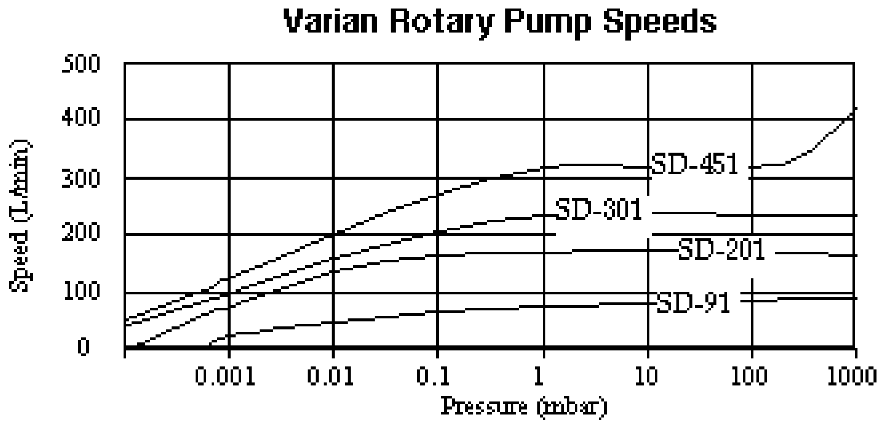

Figure 6.3: Rotary Pump Speeds for Some Varian Rotary Pumps

of conductance 0.50 L/s. How long will it take to pump the chamber down to 1.0 mTorr? The chamber has a volume of 40 L.

The effective pumping speed at the chamber is $S_{eff} = S/\left(1 + (S/U)\right)$.

From the previous chart, the pump has an average speed of 120 L/min = 2 L/s. $S_{eff} = 2/\left(1 + (2/0.50)\right) = 0.40$ L/s.

Now $P = P_0 \exp - \left(S_{eff}/V\right) t$. Let $P_0 = 760$ Torr, $P = 1 \times 10^{-3}$ Torr. Solving for t,

$t = -\left(V/S_{eff}\right) \ln(P/P_0) = -\left(40 \text{ L}/0.40 \text{ L/s}\right) \ln\left(1 \times 10^{-3}/760\right) = 1354$ s.

In practice the pumping time is likely to be larger than this, since the chamber walls will be outgassing.

The pump is relatively cheap and mechanically sturdy. It can operate from atmospheric pressure down, and is thus used before many of the higher vacuum pumps. It is commonly referred to as a *roughing pump* (to get rough vacuum), a *backing pump* (back behind the diffusion pump), or a *fore pump* (before the diffusion pump).

Other types of mechanical pumps are available that work on slightly different principles. These include rotary piston pumps, dry scroll pumps, and trochoid pumps. The rotary piston pump can have larger speeds, up to 500 liter/second. For more information on these refer to the book by O'Hanlon or to the notes in the Leybold Heraeus catalog.

The rotary pump requires some routine maintenance. If the motor-to-pump connection is made by fan belt, the belts must be checked and periodically replaced. Some oil is lost during the process of pumping. The oil level must be checked regularly and maintained at the proper level. Periodic oil changes are necessary, especially if condensable vapors are pumped in large amounts.

Auxiliary items for the rotary pump include mist eliminators, foreline traps, and filtration systems. On each pump-down from atmospheric, a considerable amount of oil vapor is expelled from the exhaust of the pump. For safety, and for cleanliness, this vapor should be vented to the outside. If such venting is not possible, mist eliminators should be used. These prevent the fine oil droplets from leaving the pump. Instead they condense and run back into the pump, greatly reducing the loss of oil from the pump.

Foreline traps will be discussed in more detail shortly. They act to prevent oil from backstreaming from the rotary pump into the chamber, and thus prevent contamination. The level of backstreaming can be reduced by properly switching from rotary to diffusion pump at a pressure near 70 mTorr when the gas flow is not yet molecular.

Vapors that condense in the system can contaminate the oil. This may lead to corrosion of the pump, or degradation of the oil leading to gumming of the working parts of the pump. Frequent oil changes or using gas ballast can reduce these problems. An oil filtration system can be added to the system which will continually remove particulates from the oil and neutralize acids dissolved in the oil, thus extending its useful lifetime, and the life of the pump.

If the vacuum system and pump are shut down and left under vacuum, the oil in the pump will be sucked back into the vacuum lines. Normally the pump is vented to atmospheric pressure when it is shut off. If a fan belt breaks, this problem will occur. Solenoid activated pressure relief valves may be added to the system that will close off the chamber and vent the roughing pump when a broken fan belt or a loss of electrical power occurs.

Malfunctions of a roughing pump rarely cause permanent damage to the pump itself. However high vacuum pumps beyond can be severely damaged if the roughing pump fails to operate, so inspect the roughing pump regularly!

What information is available from the manufacturer? Table 6.2 taken from a Varian catalog is typical. The entries are fairly self-explanatory. Free-air displacement is the speed of the pump when pumping at 1 atmosphere.

Source: `http://www.varianinc.com/cgi-bin/nav?products/vacuum/pumps/rotvane/specs\&cid=QNNHHIPFIH`

6.4 Diffusion Pump–100 mT (throttled) to below 10^{-10} Torr

In outline the diffusion pump is very simple: see Figure 6.4. The pump consists of a cylinder called a "pumping stack". High purity oil at the bottom of the pump is heated and evaporates. The stack confines the oil, and when the oil leaves the stack it moves in a downward direction, colliding with gas molecules and driving them towards the bottom of the pump. At the bottom of the pump the gas pressure is high enough that a rotary pump can remove the gas to atmosphere. The oil vapor hits the sides of the pump that are cooled by water pipes, and

Table 6.2: Specifications for Varian Rotary Pumps: All use KF25 1 inch quick flange connections

	Units	DS 102	DS202	DS302	DS402	DS602
Free Air Displacement	L/min	114	192	285	410	605
Ultimate Pressure	mbar	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
P_{ult} with ballast	mbar	2×10^{-2}	2×10^{-2}	2×10^{-2}	1×10^{-2}	1×10^{-2}
Max Water Vapor	mbar	15	15	20	30	30
Water vapor capacity	g/h	60	100	160	350	550
Oil capacity (max)	L	0.5	0.6	0.6	1	1
Motor Power 1ϕ	kW	.55	.55	.55	.9	.9
Rotation speed	rpm	1800	1800	1800	1800	1800
Weight	lb	48	55	55	77	77

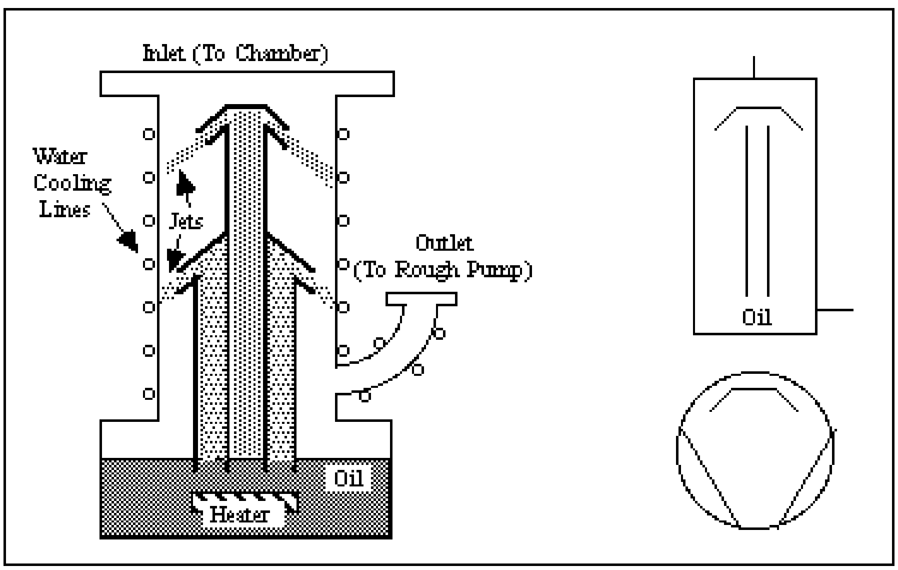

Figure 6.4: A Two Stage Diffusion Pump AVS and European symbols are shown.

the condensed oil runs to the bottom of the pump to be reheated.

At the inlet to the diffusion pump the pressure must be low, well below 100 mTorr. At the outlet the pressure is much higher than at the inlet, typically as high as 600 mTorr. In modern pumps the working fluid is an oil, historically mercury was used. Under normal conditions the pressure at the inlet may be anywhere from 10^{-4} to 10^{-10} Torr, and the pressure at the outlet may be 1 mTorr, which means that the compression ration may be as high as 10^{10}.

The heater creates a vapor pressure of oil (or mercury) of about 1 to 3 Torr. This heating is confined in the center of the pump, underneath the pumping stack. The oil is heated to a temperature of about 250°C. At this temperature the heavy oils have reasonable high speeds of about 300 m/s. The hot vapor molecules move up the stack at high velocity where they are deflected downwards by the shape of the exit nozzles in the stack.

The high-speed vapor jets shoot downwards toward the walls of the pump which are water cooled. Molecules arrive at the top of the pump randomly according to molecular flow. The vapor jets sweep the molecules down towards the ejector stage. Thus each vapor jet produces a pressure differential from above it to below it. The oil vapor condenses on the water-cooled walls and runs back to be heated again.

The vapor stream works because it imparts a preferred downward direction to the system molecules that it strikes. Because of the high temperature of the vapor, the molecules have a high average speed. In collisions between the oil vapor molecules and the system molecules both tend to move in the original direction of the oil vapor. Thus the system molecules are driven downwards where they eventually are removed by a mechanical pump.

When the inlet pressure of gas is too high the diffusion pump fails to operate. At high pressures the oil vapor will have a short mean free path and make several collisions before reaching the wall. The preferred direction of the oil vapor molecules is then lost and gas molecules will migrate backwards in the pump, from the higher pressures at the bottom of the diffusion pump towards the vacuum chamber. The gas molecules will also carry some of the oil vapor with them, contaminating the system. The critical value of inlet pressure is about 100 mTorr. Usually the critical pressure is specified at the output (foreline) because of the location of gauges. The maximum allowable foreline pressure may be in the range of 300 to 600 mTorr.

The foreline pressure at the outlet of the diffusion pump is a good indicator of trouble. Under no circumstances should the foreline pressure exceed the allowable maximum. I generally use a margin of safety so that if the manufacturer says the maximum allowable forepressure is 500 mTorr, I try never to exceed 250 mTorr.

Various mistakes can lead to a sudden overpressure in the diffusion pump and the results are rather catastrophic! Large amounts of oil vapor can suddenly fill the chamber coating the substrates and walls of the chamber, and even blowing things off of supports. A high pressure will raise the boiling point of the oil (that is how a pressure cooker works) and as the heaters raise the temperature of the oil, the oil may decompose. The decomposed oil will deposit on the hot surfaces of the diffusion pump as a varnish and these surfaces must later be cleaned, not an easy task! Synthetic (and expensive) oils are more resistant to cracking than simple hydrocarbons. All in all, it is best to avoid all these problems by proper operation of the system.

The operating problems that can be encountered include:

- Opening the hi-vac valve without opening the foreline valve.
- Opening the hi-vac valve too quickly.
- The seal on the hi-vac valve leaks.
- There is a leak in the foreline.
- The diffusion pump is left isolated for too long a period of time.

Consider the first two problems. The roughing pump must remove the gas concentrated at the outlet of the diffusion pump. If the hi-vac valve is opened too rapidly the high-speed diffusion pump will create a high throughput from its inlet to its outlet, and will create a very high pressure at the outlet of the diffusion pump. The roughing pump, being much slower, cannot match the throughput. Hence the pressure in the diffusion pump increases, the problems outlined above occur, and in addition the "piston" of gas rebounds from the bottom of the diffusion pump back into the system, carrying oil vapor with it. This whole process is called "rapping the pump", for it can actually make a loud noise! The problem can be avoided by opening the hivac valve slowly while monitoring the foreline pressure to see that it does not rise above 250 mTorr. Once the foreline pressure begins to drop, the hi-vac valve can continue to be opened.

When properly designed a diffusion pump can have speeds ranging from 100 L/s to 10^5 L/s, and can operate between pressures of 100 mTorr (throttled) and 10^{-9} Torr. The ultimate vacuum pressure is dependent on the pump fluid used, the system design (especially baffles and traps), and of course on leaks.

A typical pumping speed curve for a diffusion pump is shown in Figure 6.5. The curve consists of three main parts. In the very low pressure range the pump speed drops off since some gas will be able to diffuse back into the chamber. Over the useful operating range of pressures, the pump has a constant speed. At pressures above a critical point the speed begins to drop again. This last region is called the overload region. The pressures where the speed begins to drop, and the value of the speed will depend on the type of gas pumped as will be discussed shortly. Table 6.3 is the spec-sheet for a Varian VHS6 Diffusion Pump.

In the overload region the pump is saturated and the throughput is constant. Figure 6.5 includes graphs of speed and throughput versus pressure for a VHS-6 diffusion pump. The product of speed and pressure is the throughput, plotted using the right-hand axis. Notice that the speed is constant at 1550 L/s below a critical pressure of 1×10^{-3} Torr. The throughput is starting to level off at high pressures, and for the good health of this pump we want to keep this below 3.0 Torr L/s.

Table 6.3: Spec Sheet for Varian VHS-6 Diffusion Pump

Pumping Speed	1550 L/s Air	Warmup Time 10 min
	1930 L/s H_2	
Max Throughput:	2.4 T·L/s operating range	Cooldown Time 10 min
	3.0 T·L/s at 0.01 T	
Operating Range	1.5×10^{-3} to	Fluid Charge 500 cc
	5×10^{-9} Torr	
Max Forepressure	0.65 Torr No Load	Power 2200 W
	0.55 Torr full load	
Backing Pump Speed	≥ 17 cfm	Cooling Water 0.25 gpm at 70°C
Backstreaming	$< 5 \times 10^{-4}$ mg/cm^2/min	

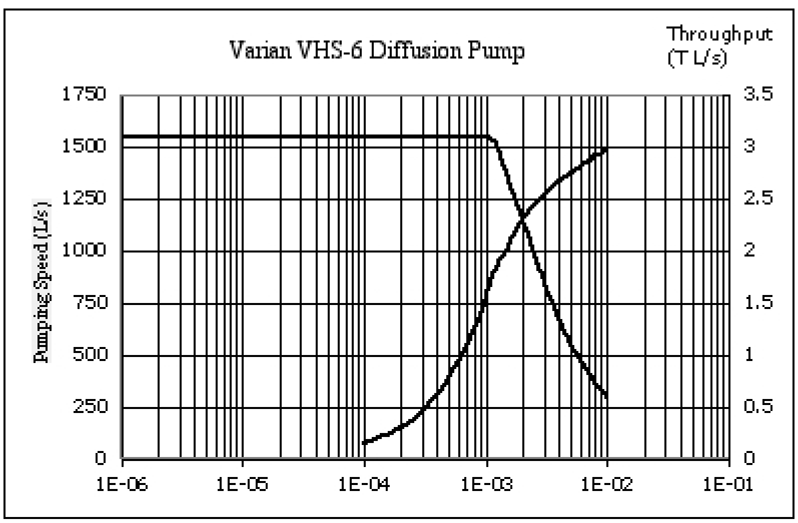

Figure 6.5: Speed and Throughput for a Varian VHS-6 Diffusion Pump

The throughput at high pressure tells us the size of rotary pump that we must consider. The rotary pump must handle the throughput of the diffusion pump, and must maintain the foreline pressure below the maximum allowable. For the VHS-6 pump, a maximum throughput of 3.0 Torr-L/s at the maximum allowable forepressure of 0.55 Torr implies that the rotary pump must have a speed of S= 3.0/0.55= 5.5 L/sec = 12 cfm. For safeties sake we may choose a larger pump—Varian suggests 17 cfm.

Pumpdown times will again be given by $P = P_0 \exp -(S/V)t + P_{ultimate}$ if S is roughly constant and if the leakage rate is constant. The actual pump down time when using the diffusion pump may be much larger than what this equation suggests since considerable amounts of gas may outgas from the chamber walls. In a small research coater the pressure may drop from 0.1 Torr to 1×10^{-5} Torr in a couple of minutes and then require an hour to reach 1×10^{-6} Torr.

The diffusion pump properties depend on the molecular weight of the gas being pumped. The speed is larger for low mass gases than for high mass gases. For the VHS-6 pump the speeds are listed as 1550 L/sec for air and 1930 L/sec for hydrogen and helium. The lighter gases can more easily diffuse backwards through the pump however, and so the ultimate pressure is higher for helium than for air.

Notice that the pump fluid vapor must be pumped also to prevent backstreaming into the chamber. Initially the vapor is heading downwards, but some of the molecules will make many collisions and perhaps be moving upwards. These molecules must be driven down by other oil vapor molecules. The ultimate pressure of the pump will be determined by the type of oil as well as by the types of cold-caps and cold-traps used on the system. These will be discussed shortly.

In many cases the diffusion pump is used to pump on chambers that are at quite high pressures, above the critical pressure of the diffusion pump. This is the case for example in sputtering systems. In order to operate the pump safely, a throttle is used between the chamber and the pump, thus reducing the effective pumping speed at the chamber.

As an example of throttling consider the VHS-6 pump, unthrottled speed of 1550 L/s and maximum throughput of 2.4 Torr ·L/sec at an inlet pressure of 2×10^{-3} Torr. If we want to sputter at a pressure of 50 mTorr, we must throttle the pump so that the pressure at the inlet of the pump remains below its maximum allowed value. The required effective speed is

$$Q = 2.4\,T \cdot \mathrm{L/s} = \left(50 \times 10^{-3}\ \mathrm{Torr}\right) \mathrm{S_{eff}}$$
$$S_{eff} = 48\ \mathrm{L/s}.$$

Since the effective speed is much much less than the speed of the diffusion pump, we know that the conductance of the throttle is approximately 48 L/s, and this can be achieved by inserting a plate with a 1 inch hole between the pump and the chamber. In current vacuum systems the throttle is adjustable to allow greater control over the system.

The diffusion pump approaches the ideal pumping speed closely that is the speed is given by $(v\,A/4)$, where v is the average speed of the molecules and A is the opening to the pump. In standard practice manufacturers specify the size of the pump by the size of an ideal pump of the same size. Thus a "6 inch" diffusion pump has the speed of an ideal 6-inch pump, but actually has an inner diameter of 7.88 inches. The effective speed of the pump will be reduced substantially by the nitrogen traps and high-vac valves used with it.

In proper use the amount of oil vapor that backstreams into the chamber is rather small, but in some applications like the semiconductor industry, any oil is too much. To reduce the amount of backstreaming proper pump design is essential. All modern diffusion pumps use some sort of "cold cap" just above the stack. This condenses vapors and the liquid drips back into the pump. The cold traps that will be discussed in the next section will also reduce the amount of backstreaming.

Regardless of the care taken in design and assembly of the pumping system, proper operation is essential to prevent excessive backstreaming. The major problem that occurs in routine operation is the switchover between the roughing pump and the diffusion pump. Backstreaming will become important for the rotary pump at pressures below 100 mTorr, and for the diffusion pump at pressures above 1 mTorr. Normally we switch from rotary to diffusion at a pressure close to 100 mTorr, and rely on the high speed of the diffusion pump to limit the region of high backstreaming to a very short time. Of more concern is misoperation of the system. Problems occur when

- foreline pressure exceeds the maximum allowable forepressure.
- high inlet pressure makes the throughput higher than the maximum allowable for extended time.

The book by O'Hanlon, "A User's Guide to Vacuum Technology" discusses backstreaming and its prevention in detail.

In choosing the oil for a diffusion pump two factors must be considered. The ultimate pressure that the pump can reach will be limited by the vapor pressure of the oil, so the vapor pressure should be low. If chemical vapors are pumped the oil must be compatible with them. Most diffusion pump oils nowadays are synthetic rather than natural hydrocarbons.

Common types are silicon based oils such as Dow Corning 704 and 705, and polyethers such as Santovac and Fomblin. The properties of these oils are given in Table 6.4 taken from O'Hanlon. All oils from DC704 down have excellent oxidation resistance. Certain oils (Octoil, Invoil, Santovac, Fomblin) are suitable for mass spectrometer systems since they do not polymerize to an insulating film upon electron bombardment.

Little maintenance is needed for a diffusion pump. The oil level must be maintained. Good synthetic oils are rugged and should not decompose except under extreme conditions. If the oil level drops too rapidly it may indicate improper operation of the pump. The heaters may occasionally fail, and in some designs only one heater of a group may fail. This will degrade the performance of the pump. The cooling water is an essential component of the pump. Modern pumps have thermal interlocks to shut off

Table 6.4: Properties of some diffusion pump oils. Taken from O'Hanlon. Low vapor pressures should lead to low ultimate pressures. Replacing the pump oil may require modifying the heaters to reach the proper boiler temperature.

Trade Name	Chemical Name	MW	Vapor Pressure at 25°C (Torr)	Boiler Temp °C
Convoil 20	Hydrocarbon	400	5×10^{-5}	210
Balzers 71	Hydrocarbon	425	3×10^{-6}	210
Octoil S	Bis(2-ethyl-hexyl) sebacate	427	3×10^{-6}	220
Invoil	Bis(2-ethyl-hexyl) phthlate	390	3×10^{-5}	200
DC-704	Tetraphenyl-tetramethyl siloxane	484	3×10^{-6}	220
DC-705	Pentaphenyl-trimethyl trisiloxane	546	4×10^{-8}	250
Santovac 5	Mixed 5-ring polyphenylether	447	6×10^{-8}	275

heaters when the temperature of the housing becomes too hot. Additionally, water flow indicators may be used to close valves if the water flow is interrupted. Normally the water enters at the top of the diffusion pump, near its inlet, and exits at the bottom at the outlet. The temperature of the exiting water should be warm, between 40C and 70C (104F to 160F), for optimum performance of the pump.

Cost for 500 mL of DC704: \$195, DC705: \$285, Santovac 5: \$1129.

6.5 Vapor Traps and Baffles

A baffle is a device that condenses pump fluid vapors and returns the liquid to the pump. A trap acts as a pump for the vapors temporarily or permanently removing them from the system. The terms baffle and trap are frequently used interchangeably. A baffle can be placed in a vacuum line to prevent backstreaming of oil in a diffusion pump or a rotary pump. Their only disadvantage is that they limit the conductance of the pipes. The baffle may be refrigerated to increase its effectiveness. Some typical designs are in Figure 6.6.

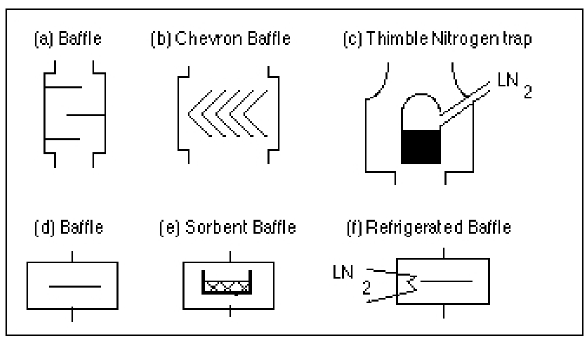

Figure 6.6: Some Traps and Baffles. The bottom row (d to f) are standard AVS symbols.

High vacuum traps are somewhat similar in function and design. They are refrigerated, typically to liquid nitrogen temperatures (77 K). At this temperature many of the vapors present in a gas will "freeze" onto the surface of the trap as will be described in the cryopump. Water vapor is frozen out very effectively.

These traps are essential if we want to reach ultra high vacuums of 10^{-9} Torr or less. The nitrogen is added prior to opening the hi-vac valve and should last several hours. The design of baffles and traps is complicated by creep of oil along their surfaces. With proper design and proper operation back-streaming from a diffusion pump can be reduced to exceedingly low values corresponding to monolayer formation times on the order of years!

Foreline traps are typically made with a "molecular sieve" material that will pass the small gas molecules, but will trap the large molecules of the pump oils. Periodically the molecular sieve must be revitalized by heating in order to release the trapped oil molecules.

6.6 Other Mechanical Pumps

6.6.1 Root's Blower

Root's pumps or Root's blowers, symbols in Figure 6.7, consist of two figure-eight rotors mounted on parallel shafts and rotating in opposite directions at speeds of about 3000 rpm. In order to rotate this rapidly, the rotors have a clearance of about 0.2 mm and use no oil.

The rotors provide a compression of gas from the inlet to the outlet. The compression ratio (outlet pressure/inlet pressure) reaches a maximum at about 1 Torr. It can operate between 20 Torr and 10^{-5} Torr.

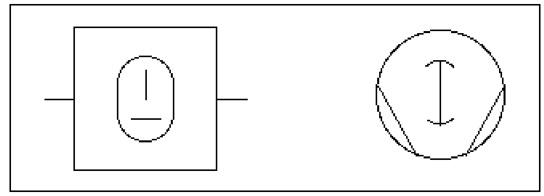

Figure 6.7: AVS and European symbols for Roots Blower

The Root's pump is a booster pump. It typically is found on a large system between a diffusion pump and a rotary pump. The rotary pump is permitted to operate in its high speed, high throughput pressure (typically above 0.1 Torr) and at the same time the diffusion pump is allowed to operate at its high speed, high throughput pressure (typically below 0.5 mTorr).

Thus the Root's blower acts to maximize throughput in a pumping system and minimize the pumpdown time. It becomes cheaper to buy a Root's pump and be able to use a smaller rotary pump, than to buy a larger rotary pump of sufficient throughput by itself. The speed of the combination of Root's pump and rotary pump is usually what is specified, and depends on the speed of the rotary pump.

Since the rotors do not use oil to form a seal, they can rotate at high speed, 3000 to 4000 rpm. This also means that the maximum compression ration of the Root's blower itself is rather small (10 to 50 over the operating range) since air can be carried around on the rotors into the vacuum side and then outgas. Also the gap allows some gas to backstream past the rotors. The size of the gap will depend on the temperature. As the pump warms up the rotors expand. In order to keep the expansion below a dangerous level the maximum differential pressure is given, and is usually in the 10 to 50 Torr range.

The Root's Blower cannot then be used to pump down starting at atmospheric, but must be coupled with a rotary pump which typically has a speed of 1/5 to 1/10 of the speed (displacement) of the Root's pump.

In practice one of three things is done.

1. The Root's Blower is bypassed at high pressure. When the chamber pressure approaches the maximum differential pressure the bypass is closed and the gas flow is through the Root's Blower and on to the rotary pump.
2. The Root's Blower is allowed to freewheel and pumping occurs through the Root's Blower even at atmospheric pressure.
3. The Root's Blower is operated at a low rpm at higher pressure allowing it to help the rotary pump even at higher pressures.

Consider the Leybold-Heraeus WA 2000 Root's Blower which has a theoretical speed given in the spec sheet as 1383 cfm. We would look for a rotary pump of speed 140 cfm to 280 cfm. Leybold's E250 pump fits the criterion with a rated speed of 171 cfm, or a S400F with rated speed of 301 cfm.

The WA 2000 pump operates in the bypass mode 1 of the previous paragraph, while the WAU 2000 operates in a mix of bypass mode 1 and freewheel mode 2. Performance curves are given for the Root's Blower in combination with a rotary pump. For the WA 2000 the overall pumping speed jumps up at the point when the Root's Blower is turned on, while the WAU 2000 speed curve gradually increases as the Root's Blower is engaged.

In either case we see that when the Root's Blower is used in conjunction with the rotary pump we get much better overall speed, and the useful range of the pump is extended down to lower pressures.

The Root's pump adds little or no contamination to the system, and in fact reduces backstreaming from the rotary pump into the diffusion pump. Consider pumping down a chamber with a rotary pump/diffusion pump combination with and without a Root's Blower.

With just the two pumps we pump down to 100 mTorr with the rotary pump, then close the roughing line and open the foreline and hi-vac valve. In this process we start to get backstreaming from the rotary pump at pressures below 100 mTorr and have backstreaming from the diffusion pump at the 100 mT to 0.5 mTorr pressure range.

Now add a Root's Blower. We pump via the rotary/Root's combination until the rotary pump is at 100 mTorr. At this foreline pressure, the compression ratio of the Root's Blower is 22 (see Leybold Figure 15.1) and so the pressure at the inlet to the Root's Blower, i.e. the chamber, is 100mTorr/22 = 4.5 mTorr. At this point we close the roughing line and open the line to the diffusion pump. Now the diffusion pump is in a safer operating region and should produce less backstreaming.

The Root's Blower does have oil filled bearings to allow it to rotate at high speed. These are sealed from the working volume, but if the seals fail some contamination of the pump and the chamber is possible.

6.6.2 Turbo-Molecular Pump

The turbomolecular pump or turbopump consists of a rotor assembly, a multi-bladed turbine which rotates at high speed (such as 50 000 rpm), which rotates in a stator assembly, a similar non-rotating turbine. A gas molecule which strikes the blades of either the rotor or stator is more likely, upon reflection, to be ejected than to reenter the system. In order to produce an effective pump between 8 and 20 stages are used, half in the rotor and half in the stator. Symbols are shown in Figure 6.8

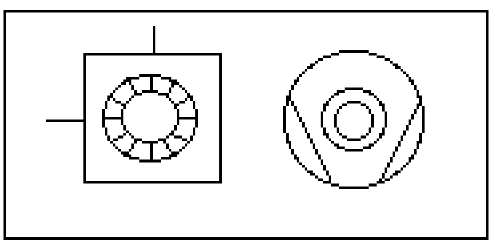

Figure 6.8: AVS and European Symbols for a Turbopump

Turbopumps operate from 10^{-2} to 10^{-10} Torr. They are very clean, with contamination coming only from outgassing and from the oil used in the bearings of the rotor. Magnetic bearings can eliminate the oil contamination. Pumping speeds up to 20 000 L/s are available, with speed relatively equal for most gases. At the ultimate pressure the residual gas left by the turbopump is primarily hydrogen. One can expect slight vibration from the pump, although this is much less than for a rotary pump.

Table 6.5 is a spec sheet for a Varian Turbo-V 701 Navigator Pump.

6.6.3 Newer Mechanical Pumps

With the growth of microelectronics and other applications requiring very clean, oil-free vacuum but with a high throughput of gas the manufacturers have begun to introduce oil-free mechanical pumps that operate from atmospheric down. At present I have no details on the operating principles of these pumps.

6.7 Entrainment Pumps

Entrainment pumps are pumps that work by the interaction of gas molecules with molecules of a surface or vapor in the pump. In one sense diffusion pumps are entrainment pumps, but we will not discuss them again. Instead we will look at pumps that use absorption and adsorption of gases.

Three similar words are used, but they have slightly different meanings. *Absorb* (absorbed, absorption) refers to an atom being taken into the bulk material, such as water being absorbed by a towel. *Adsorb* (adsorbed, adsorption) refers to an atom being bound physically or chemically to the surface of the bulk material. The infamous static

Table 6.5: Specs on Varian V 701 Navigator Pump

Pumping Speed, L/s	790 (N_2)	820 (He)	860 (H_2)
Compression Ratio	1×10^9 (N_2)	5×10^7 (He)	2×10^6 (H_2)
Base Pressure		$< 1 \times 10^{-10}$ Torr	
Rotational speed		38000 rpm	
Start-up Time		< 4 min	
Recommended forepumps		Varian DS-402 Rotary or TS300 Dry scroll	
Cooling requirements		Forced air or water	

cling of a sock to a towel could be called adsorption. *Sorb* (sorbed, sorption) is used when we wish to refer to both absorption and adsorption with a single word.

Two mechanisms of adsorption are *physisorption* and *chemisorption*. These processes occur for any surface, and are the source of molecules for outgassing in a system. Physisorption refers to weaker bonds such as Van der Waal's forces while chemisorption refers to the stronger chemical bonds.

We can qualitatively describe adsorption as follows. A gas molecule approaches an atomically clean metal surface. At some point it begins to feel a weak van der Waal's attractive force that can bind it to the surface. This weak binding is called physisorption. If the molecule can react with the molecules of the surface a stronger bond is formed, and we call this chemisorption. The sorbed molecules can be "desorbed" if they gain enough energy while on the surface. Cooling the surface should reduce the rate of desorption. *Cryosorption* is a term used to describe physisorption to a chilled surface.

An adsorbed molecule can be prevented from desorbing by various methods. The molecule may diffuse into the bulk material of the surface and thus be absorbed. This is unlikely unless the bulk material is heated or very porous. An exception is hydrogen that is easily absorbed into titanium even at room temperature. We can ionize the molecules and accelerate them toward the solid in which case some of them will implant into the surface. And we can bury the molecules under a new layer of material before the molecule can desorb. All these methods have been used in pumps.

How is sorption used as a pumping mechanism? *Gettering* is a word frequently used for the chemisorption version of adsorption. A getter is commonly used in vacuum tubes to provide a continuing pumping mechanism even after the tube is sealed. The metal coating on the inside of the glass envelope of the tube is the getter and not an indication of tube malfunction. Typical gettering metals are barium, titanium, zirconium or thorium. Gettering will be important in the cryopump, the titanium sublimation pump and the ion pump. Molecular sieve material consists of a very porous material which has a large surface area for a given volume. Physisorption occurs between the molecules and the sieve material. Molecular sieves are important in the sorption pump and the cryopump.

6.7.1 Sorption Pump. Atmospheric to 10 mTorr

This is a roughing pump that uses a molecular sieve material. When this material is chilled to liquid nitrogen temperatures, gases in the system are physisorbed (cryosorbed) to the sieve material. Typically a sorption pump is preceded by a Venturi pump (similar to an aspirator) which reduces the pressure to 200 Torr. If the sieve material is pre-chilled, and then valved into the system it will lower the pressure very rapidly to about 1 mTorr. Symbols are shown in Figure 6.9

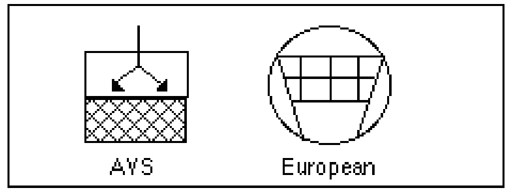

Figure 6.9: AVS and European Symbols for Sorption Pumps

Typical sorption pump installations may use two sorption pumps and a Venturi pump. The Venturi pump reduces the pressure to about 200 Torr. The first sorption stage reduces the pressure to 100 mTorr, and the second stage reduces the pressure to about 1 mTorr where hi-vac pumps can take over. Speeds of sorption pumps are not the major consideration. Instead the pumping capacity is given. Small pumps may have a capacity of about 7×10^4 Torr·liters while large installations may have a capacity of 1.7×10^6 Torr·liters. Speeds equivalent to 5 L/s are easily possible. Much of the time required for this pump to operate is the time needed to chill the sieve material.

The sorption pump does not work well on He or Ne. It is possible to trap some of the inert gases in a two stage pump. The initial rush of gas into the first stage will sweep some of the inert gases into this stage, and if we close the stage off from the vacuum system the inert gas will be trapped. The sorption pump saturates i.e. a large volume of gas will require many sorption pumps. The sorption pump is an ideal roughing pump for very clean hi-vac pumps since it cannot contaminate the system with backstreaming.

When the sorption pump is allowed to warm back to room temperature most of the sorbed gases are released. Some water vapor is retained and after several pumping cycles the molecular sieve material must be heated up to drive off the water vapor. In a regularly used system this may need to be done weekly.

6.7.2 Cryopump: 10 mTorr to below 10^{-8} Torr

A cryopump, Figure 6.10, uses very cold surfaces to cryocondense and cryosorb most gases in a system. It operates in the range of 1 mTorr to 10^{-10} Torr. As with the sorption pump, the cryopump will eventually saturate. After saturation the pump must be warmed for regeneration, a lengthy task. In the design of a cryopump we must try to make the time between regenerations large. The gas in a system consists of three components: water vapor which is easily removed at liquid nitrogen temperatures, active gases which can be gettered, and inert gases which must be physisorbed.

Typically two stages are used. The first stage is cooled to about 80 K and cryocondenses mostly water vapor. The second stage is cooled to 15 K where it cryocondenses the active gases in the system. A sorbing material such as charcoal is bonded to the 15 K surface and serves to cryosorb hydrogen and helium. These latter two gases are pumped with much less efficiency than other gases, and may not be pumped at all if the sorbant surface is saturated. Three stage designs which add a 4.2 K surface for enhanced pumping of H and He are not in commercial production. A closed cycle helium refrigerator is used to provide the low temperatures, and this accounts for much of the cost of the cryopump.

Cryopump speeds are large (10 L/s and up) and depend on the gas of interest.

The cryopump is very fast and very clean, and these features make it ideal for hi-vac work in analytical instruments and microelectronics applications. Ultimate pressures below 10^{-6} Torr are possible. With careful design UHV pressures down to 10^{-10} Torr are possible.

Table 6.6 presents info on Helix Technology cryopumps (`http://www.helixtechnology.com`). Capacity is a measure of the total number of molecules that can be contained in the pump, given as Capacity $=PV$. For argon the pressure used is 1 atmosphere (760 Torr) while for hydrogen (present in very small amounts in the air) the pressure used is 1×10^{-6} Torr.

Table 6.6: Cryopump specs for Cryo-Torr Cryopump Models 8, 8F, and 10. Capacity $=PV$. For argon the pressure used is 1 atmosphere (760 Torr) while for hydrogen (present in very small amounts in the air) the pressure used is 1×10^{-6} Torr.

Model	8	8F	10
Pumping Speeds			
Water Vapor(L/s)	4000	4000	9000
Air(L/s)	1500	1500	3000
Hydrogen(L/s)	2500	2200	5000
Argon(L/s)	1200	1200	2500
Capacity, PV			
Argon	1000	1000	2000
Hydrogen	12	8	24

6.7.3 Titanium Sublimation Pump: 10^{-2} to below 10^{-11} Torr

The titanium sublimation pump (TSP), Figure 6.11 operates primarily by chemisorption or gettering of active gases. Since it does not pump inert gases it is generally used in conjunction with an ion pump. A filament of a titanium-molybdenum alloy is surrounded by walls which may be left at room temperature or may be cooled by water or liquid nitrogen. Titanium can be sublimated from the filament onto the walls to form an atomically clean surface.

Chemically active gases combine with the freshly evaporated titanium film. The exact reactions depend on the gas. As reactions take place, the Ti film saturates, and a new film must be deposited which buries the molecules previously gettered to the surface. The frequency of evaporations depends on the pressure in the system. At high pres-

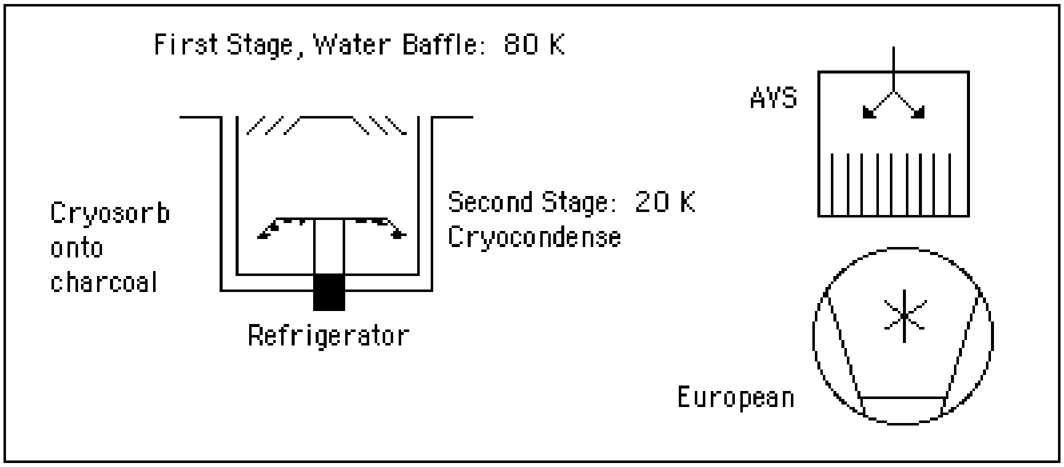

Figure 6.10: Cryopump and Symbols

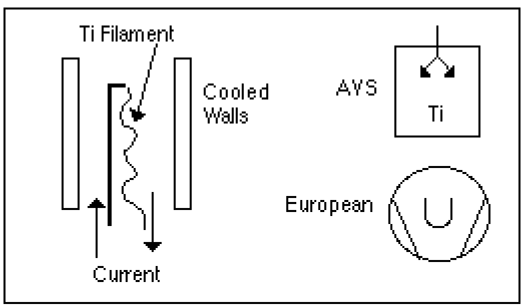

Figure 6.11: Titanium Sublimation Pump (TSP) and Symbols

sures the Ti may need to be evaporated continuously. At low pressures the evaporation may be done but once a day. Eventually the filament will need to be replaced.

The TSP operates from about 1 mTorr to 10^{-11} Torr when used in conjunction with a sputter-ion pump. Pumping speeds at low pressures depend primarily on the area of the active surface, being about 20 L/sec/square inch. The TSP is a very clean pump, however it does not pump the chemically inert gases, and must therefore be combined with another hi-vac pump.

6.7.4 Sputter-ion Pumps: 10^{-4} to 10^{-11} Torr

Sputter-ion pumps use chemisorption, burying, and implanting of gas ions to remove gas. The basic diode ion pump uses a magnetically confined cold-cathode discharge. Between two titanium cathodes is an anode consisting of a large number of hollow cylindrical anodes. A high voltage (about 10 kV) produces a plasma in whatever gases are in the pump. A random electron initiates the plasma. It is accelerated by the large electric field and causes ionization of a gas molecule. In order to maintain the plasma in a low pressure gas each electron must ionize several gas molecules. A magnetic field around the assembly causes electrons to follow spiral paths thereby causing several ionizations before they are captured by the anode. Symbols are in Figure 6.12

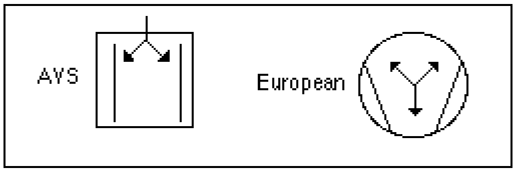

Figure 6.12: Symbols for Sputter Ion Pumps

Table 6.7: StarCell Sputter Ion TSP Combinations Speeds in L/s

Vacion Plus 150	N_2	610
	H_2	1380
Vacion Plus 150	N_2	720
	H_2	1580
Vacion Plus 150	N_2	880
	H_2	1930

The ions are accelerated towards the cathode, and being more massive than the electrons are little affected by the magnetic field. When they strike the cathode they typically bury themselves physically in the cathode, and at the same time eject (sputter) some of the titanium of the cathode. This titanium deposits elsewhere in the system providing a gettering surface for active gases. Thus ions are physically buried during the sputtering. Neutrals and inert gases are trapped either in by gettering with a fresh titanium surface or by being buried by newly sputtered titanium.

Clearly the ion pump does not remove the molecules from the system, it either getters or captures them. Thus it has a finite operating lifetime after which it must be "rebuilt" by being cleaned and by having fresh titanium applied to the cathodes. In normal operation this must be done only after several years of operation.

Active gases are both buried and gettered. The noble gases are only trapped by being buried. Thus inert gases are pumped less efficiently than active gases. Gases buried in the cathode can be released at a later time by another sputtering event, and this is especially a problem for the inert gases. "Nobel diode ion pumps" use tantalum on one cathode to better trap the inert gases. Special ion pumps exist for hydrogen as well. Hydrogen diffuses easily through titanium, and so the cathodes are made thicker to absorb greater amounts of hydrogen than the regular pump.

Ion pump "triodes" also exist. These have cathodes which are strips of titanium rather than being a solid sheet. Some of the sputtered titanium then can hit the walls of the pump, and act as a getter there. Gases trapped or buried at the wall are not subject to ion bombardment, and thus will be trapped permanently. Triodes are also slightly better at pumping inert gases for reasons which are beyond the scope of this course.

Sputter-ion pumps are available with pumping rates as high as 7000 L/s and operate between 10^{-2} Torr and 10^{-11} Torr. Anodes and cathodes can be replaced, and a typical lifetime is 50 000 hours at 10^{-6} Torr. The pump is a clean pump.

Often Ion Pumps are paired with Titanium Sublimation Pumps such as the Varian "Vac-Ion Plus"pump.

6.8 Some Typical Systems

Three systems will briefly be described here, a general purpose hi-vac system, an ultra-hi-vac system capable of pressures as low as 10^{-10} Torr, and a high gas-flow system capable high-vacuum base pressures but operated in the 1-100 mTorr range.

6.8.1 General Purpose Hi-Vac System

The system in Figure 6.13 is capable of high vacuum, 10^{-7} Torr, and is relatively clean and inexpensive. It might be used for vacuum evaporation, vacuum sputtering, or plasma physics experiments.

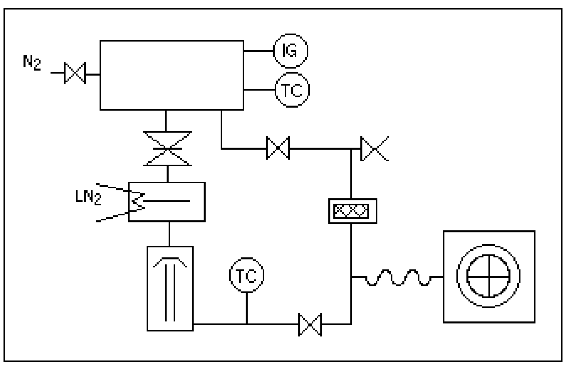

Figure 6.13: General Purpose Vacuum System

6.8.2 Ultra Hi-Vac System

The system in Figure 6.14 is very clean, and reaches ultra-high vacuum. It would be used in surface analysis work such as XPS (X-ray Photoelectron Spectroscopy.)

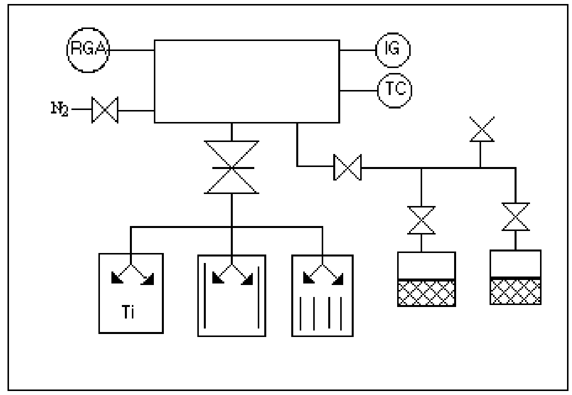

Figure 6.14: An UHV System suitable for low gas flow applications

6.8.3 High Gas Flow System

Figure 6.15 shows a system suitable for very clean, high vacuum applications where a substantial gas flow might be required. It would find application in manufacturing-scale sputtering systems.

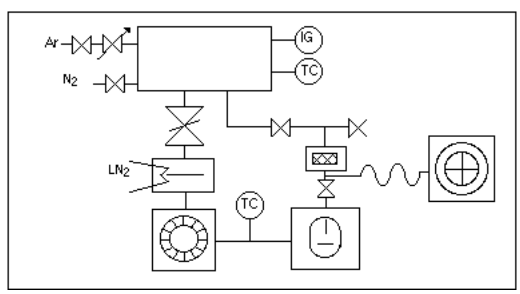

Figure 6.15: Vacuum System for High Gas Flow Clean System

6.9 Capital Costs, Operating Costs

Nothing doesn't come cheap. Here I summarize the 2005 costs of a variety of pumps and accessories. My sources are Varian Vacuum Products and Kurt J. Leskar Company. Other vendors have high quality equipment also, these are chosen for convenience.

Consider a diffusion pump system suitable for a small laboratory chamber of less than 1000 L. A 6-inch diffusion pump system is appropriate. The following are significant items.

For a large system, a Roots blower-rotary pump combination is very effective. A 50 cfm (1300 L/min) rotary pump coupled with a Roots blower makes a combination effective speed of 350 cfm (9300 L/min). The combination (Leskar VBPS350) costs $13 200. This would be appropriate for a production system that might use a 50 000 L/s diffusion pump on a 21 000 L chamber ($7 \times 10 \times 10$ feet).

Instead of a diffusion pump, we might want to use a cryopump because of its cleanliness. Here are costs for a cryopump comparable in speed to the VHS-6 diffusion pump.

Table 6.9: Cryopump System, Helix Technology

Cryo-Torr 10	3000 L/s air	$9 555
Compressor		$10 180
Regenerator		$1 900
Thermometer		$1 300

If we are looking for a small UHV system we use different pumps. These might be appropriate choices.

The prices above are just for the pumping components of a system. We still need to specify and purchase the chamber, vacuum gauges, equipment for the chamber, and assorted plumbing of water lines, pipes, etc.

In addition to the capital costs associated with the pumps, we must consider the operating costs. These include the costs of electricity, cooling water, liquid nitrogen as well as maintenance costs. For an excellent discussion, see O'Hanlon.

6.10 Summary

Several types of pumps have been outlined in this chapter. As mentioned in the introduction, each has certain pressure ranges it operates in and each has advantages and disadvantages.

In choosing a system you must balance factors of cost (both initial purchase price and operating costs), cleanliness, and suitability for your application. By far the most widespread system in use today uses a rotary pump coupled with either a diffusion pump or a turbopump. In certain applications however other types of pumps are the norm.

Spend some time becoming familiar with your pumping system and pay attention to service intervals, safety aspects, and proper operating procedure. Vacuum pumps are generally quite reliable as long as they are not too severely mistreated.

Table 6.8: Small Diffusion Pumped System

Varian SD451	Rotary Pump	450 L/min, 17 cfm	\$3500
Rotary Pump Oil	Leskar TKO-19	VP 8.8×10^{-9} Torr, 4L	\$15
Varian VHS-6	Diffusion Pump	2400 L/s	\$4000
	Cryotrap		\$2400
	Hi-vac gate valve		\$3000
	Roughing valves		\$800
Diffusion Pump Oil	DC704	500 mL workhorse	\$103
	Fomblin Y06	500 mL high oxygen loads	\$138
	Santovac-5	500 mL oxidation resistant	\$1632

Table 6.10: UHV System

Varian Vac-Sorb	Sorption Pump	76 000 Torr-L	\$1 000
Varian Vac-Ion Plus-150	Ion-Pump	150 L/s	\$4 600
	Controller		\$3 200
Varian TSP	Titanium Sublimation		\$3 000
	Controller		\$1 600
Varian V150HT	Turbo Pump	130 L/s	\$5 300
	Controller		\$2 000
	Rotary pump, SD-40		\$1 300