Vacuum System Overview: Pressure, Mass-Flow and Conductance.

A vacuum pump literally pulls (and pushes) gas molecules out of the vacuum chamber and then does not let them go back in. In this way, it establishes a pressure gradient that causes gas molecules further away to diffuse toward the pump inlet. One could almost say that the pump acts like a one-way road for gas molecules allowing them to travel out of the chamber but not back into it. The earliest vacuum pumps did this by: 1] first allowing gas within the chamber to fill a volume inside the pump, 2] closing off that volume and squeezing it to raise the pressure, 3] followed by expelling that squeezed "high pressure" gas out of the pump to some other location. Pushing volumes of gas from inside the chamber to the outside by compressing them along the way is what "rotary vane", "rotary piston" and other mechanical pump designs still do today. Given this method of pushing molecules out of a chamber, it is quite natural to define a pumps' ability to remove gas in terms of its' pumping "speed." (The units are liters/second or l/s.) We would say that a pump has the ability to remove X liters of volume from the chamber every second if it is an "X-l/s pump." The pressure of the gas inside the chamber then determines how many gas molecules actually reside inside those X liters! The pumping speed is usually denoted as S_p. Figure 1 shows the pumping speed curves for 3 different pumps: a rotary vane pump, a dry pump and a turbo-molecular pump. Note that the pump curves for the Turbo-molecular pump are rapidly decreasing as the pressure goes above about 10^{-2} mbar (7.6 mTorr). Turbo-molecular pumps (TMPs) are not nearly so efficient at pumping when the pressure is large because the gas load slows down the pump vanes. On the other hand, a rotary vane pump (RVP) with its oil sealing of the rotating vanes, has a good pumping speed all the way up to atmoshperic pressure. It has difficulty pumping under high vacuum conditions as can be seen in Fig. 1. It begins to lose pumping speed below 1 Torr where the Turbo-molecular pump can begin to take over. For this reason, the two are used in conjunction to pump a chamber down from atmospheric pressure to low vacuum (the RVP) and from low vacuum to high vacuum (the TMP.)

When talking about gases, however, the terminology must change. It is no longer worthwhile to simply keep track of the volume of gas being moved by a pump; instead one must discuss the QUANTITY of gas molecules being moved by that pump. The quantity of gas molecules is usually denoted as "N" and from the ideal gas law is given by: $N = (PV)/(k_BT)$. Where P is the gas pressure, V is the gas volume, k_B is Boltzmann's constant and T is the gas temperature. k_BT is often considered to be a constant throughout the whole system and for the whole time period of interest (although there are cryogenic vacuum pumps where an imposed temperature gradient gives one the pumping action.) For this reason, we often place k_BT on the left hand side of the equation and describe the pumping of gas (the "throughput" of gas) as:

$$Q = \text{"Gas Throughput"} = d(PV)/dt.$$

The units of gas throughput are Pascal meters-cubed per second (Pa-m^3/s). It is important to note that this unit is identical to a Watt! Throughput describes the amount of gas energy (thermal energy) involved in transporting these molecules per second. It turns out that this unit is rarely used in plasma processing terminology in the USA. Instead, Pa-l/s, slm and sccm units are used under most circumstances. A Pa-l/s is 0.001 Pa-m^3/s since a liter is 0.001 m^3. In addition, the units slm and sccm stand for "Standard Liter per Minute" and "Standard Cubic Centimeter per Minute." The "standard" used denotes gas at 1 atmosphere pressure (760 Torr or 101,323 Pa) and at 0° Celsius. One slm is about 1,690 Pa-l/s and 1 sccm = 1.69 Pa-l/s.
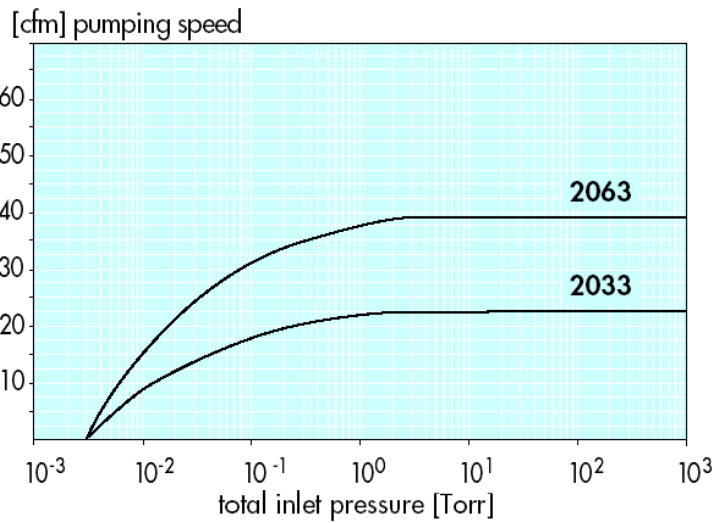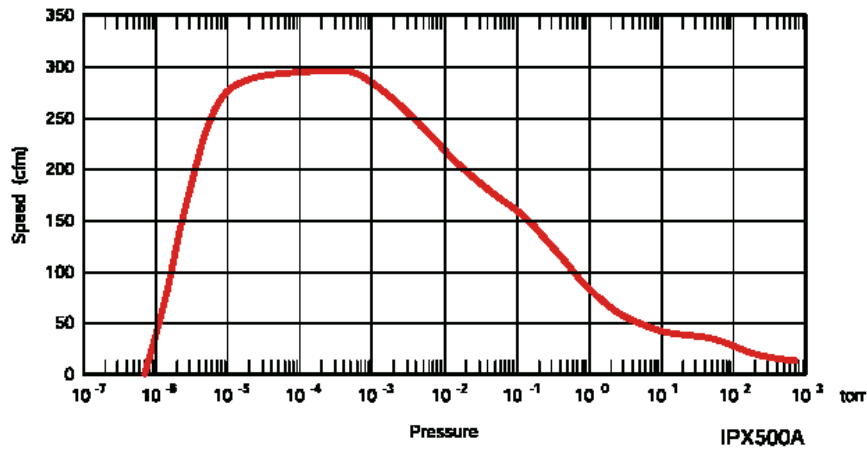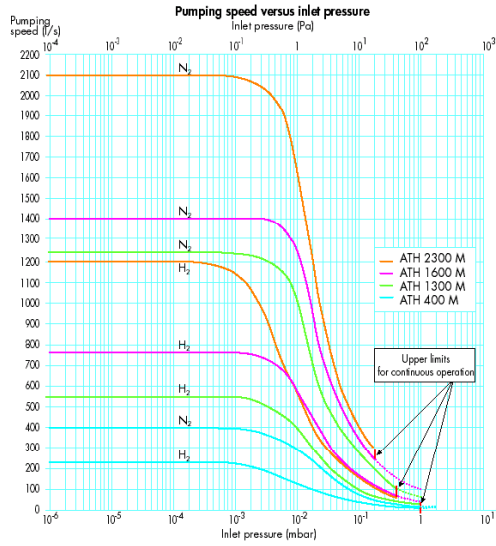
Figure 1. Pumping curves for three types of vacuum pumps. Upper: Turbomolecular Pumps. We have the ATH400 on Holly and Indy. Center: a dry pump. Lower: Rotary vane pumps. We have the 2063 on all 4 of our systems.

This brings up a side point. Temperature does NOT have to be held constant in these systems. In fact, it is quite common for the temperature of a gas to rise as it is compressed! It could also be forcibly lowered. What we are noting is simply that one can easily add or remove energy (Watts) from the gas as it is being pumped! Therefore, PV is a quantity that does not have to be conserved throughout a system. The amount of PV can vary in time and with location far too easily. What IS conserved is MASS. (We ordinarily think that the numbers of molecules is also conserved, but reactions of smaller molecules to form larger molecules can sometimes change the total number of molecules in the gas while the total mass of molecules remains the same! Mass is conserved, molecules are not.) Consequently, one can measure the amount of mass flowing through the system or the number of molecules flowing through the system (if molecules are conserved). The first is called "mass flow" and has units of kg/s. The second is called molecular flow and has the units of molecules/second. Mass flow is written as:

$$N' = MQ/(N_0 k_B T) \quad \text{in kg/s.}$$

While molecular flow is written as:

$$N^* = Q/k_B T \quad \text{in molecules/s.}$$

Here, N_0 is Avogadro's number (6.022×10^{26} molecules) and M is the molecular mass in amu. As a conserved quantity, the amount of mass flowing into the vacuum system is always the same as that "flowing" out of the gas phase in the system provided the pressure is constant in time.

Gas flows from one location to the next by diffusion. Diffusion is a process whereby the random thermal motion of molecules moves them from regions of high density to adjacent regions of lower density. There is net movement of molecules simply because there are fewer molecules in the region of lower density going back towards the region of higher density than from higher to lower. As a consequence there is a net motion of molecules from the region of higher density (higher pressure) toward the regions of lower density. This is also why throughput has the units of energy flow (Watts). Each molecule that moves takes its energy with it. A net movement of molecules from regions of high density to regions of low density means that there is also a net flow of chemical and thermal energy!

The speed at which these molecules flow from one region to the next, the "throughput," will depend on both the pressure difference between the two locations, as well as on the geometry of the chamber in between. One can imagine the importance of geometry rather easily using Fig. 2. The throughput will be restricted and tiny if the hole through which the molecules must flow to reach the low-pressure region from the high-pressure region is very small. On the other hand, the throughput will become larger as the opening between the low-pressure and high-pressure

High Pressure | Low Pressure   High Pressure | Low Pressure

→ Small Q   Large Q

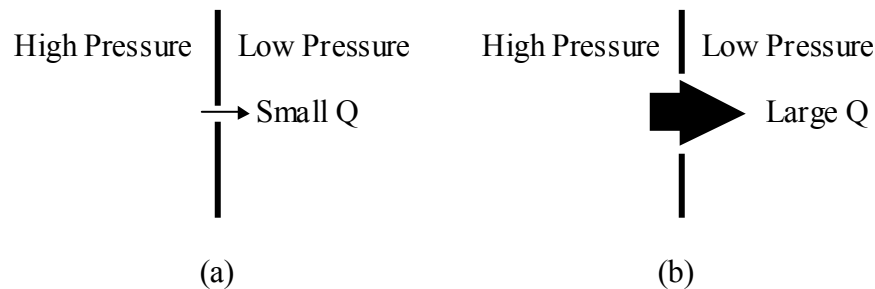(a)   (b)

Figure 2.   The gas throughput for (a) a small geometry orifice between regions of differing pressure and (b) a large orifice between the same regions. The gas flow through the large orifice is larger simply due to its increased size.

regions is widened. The factor which accounts for this geometry difference is called "conductance" and is defined as:

$$\text{Conductance "C"} = Q/(\Delta P) = Q/(P_2-P_1)$$

The conductance is always positive. For short round orifices, the conductance can be modeled as

$$C = (v/4)A \ \ l/s$$

provided the pressure is in the molecular flow regime (Kn > 1). Here v is the average molecular velocity = Sqrt($8k_BT/\pi M$) and Kn is Knudsen's number. In the other extreme, where the pressure is large and molecular collisions in the gas phase are very important, the conductance can also be modeled under various conditions, but the equations are both long and tedious. J. F. O'Hanlon's book describes these relationships under various conditions in Chapter 3 and the reader is directed to that source for further information. (J. F. O'Hanlon, "A User's Guide to Vacuum Technology, 2nd Edition, John Wiley and Sons, New York, NY, 1989. ISBN: 0-471-81242-0.)

Another common situation is pumping through long tubes. Here the equations that have been developed are simpler for both the high-pressure laminar flow regime and the molecular flow regime at very low pressures. O'Hanlon's book gives a good overview of these equations too. In particular, at large pressures, the Hagen-Poiseuille equation applies and the conductance is given by:

$$C = (\pi d^4)/(128\eta l)*(P_1+P_2)/(2).$$

When the pressure is very low so that molecular flow conditions prevail inside the tube (Kn>1) the conductance is given by:

$$C = (\pi v d^3)/(12l)$$

Here d is the tube diameter and l is the tube length. Note that the conductance decreases rapidly with decreasing tube diameter, falling as d^{-3} and d^{-4}. It doesn't decrease nearly so fast with tube length! The conductance simply decreases as l^{-1} in both cases. Both of these equations strongly indicate that the length of the line is not nearly as important as the diameter of that vacuum line and increasing the diameter of vacuum piping will make a large difference in the conductance.

When there are several different elements of a vacuum system placed in series or in parallel, the overall value for the system conductance is found in a similar fashion to that used in finding the overall capacitance in an electrical network. That is to say: parallel conductances simply add
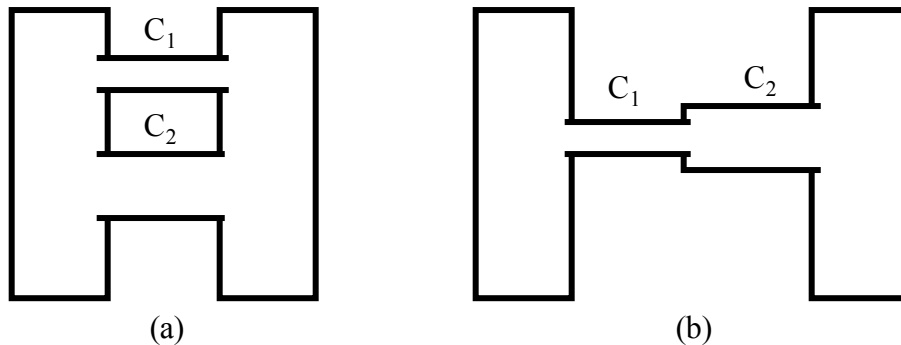

(a)   (b)

Figure 3. Examples of parallel (a) and series (b) conductances are shown in this plot. Gas flowing through conductance C_1 in part (b) will "beam" into conductance C_2 changing the overall conductance from the simple series addition explained in the text.

($C_{total} = C_1 + C_2 + \ldots$) while conductances placed in series add as inverses ($1/C_{total} = 1/C_1 + 1/C_2 + \ldots$) This latter formula assumes that there is no direct coupling between adjacent elements causing the gas to be "beamed" from one element into the next. This is precisely what is happening in the drawing of Figure 3 for the two series elements. In that case, the conductances do not quite add as inverses and things get complicated all over again!

The gas throughput, the pumping speed and the chamber volume determine the time dependence of the pressure at any location in the vacuum system. The relationship between these factors is set in the following equation.

$$\frac{dP}{dt} = \frac{Q - P_P S_P}{V}$$

Here P_P is the pressure at the vacuum pump inlet. The pressure above the pump inlet, at steady state, will always equal the throughput divided by the pumping speed. $P_P = Q/S_P$. The above equation is combined with the relationship between the throughput, Q, the conductance between any two locations, C and the pressure differential between those locations, $Q = C(P_2 - P_1)$. Together these equations prove useful in understanding the full vacuum system.

For example, imagine we have the simple vacuum system shown in Figure 4. The main chamber is separated from the pump by a variable conductance, C_{VAR}. Gas flows into the main chamber at a throughput, Q. The vacuum pump is known to be a 1000 l/s turbo-molecular pump that can pull the chamber to a base pressure of 10^{-5} Pa (7.5×10^{-8} Torr). We could ask: At what flow rate (throughput) will the pressure at the pump be equal to 1 Pa (7.52 mTorr)?

First, we note that the total gas throughput consists of 2 parts: 1] that gas purposely placed into the chamber by the mass flow controller from the gas bottle and 2] that gas coming into the chamber due to out-gassing from the walls and through the vacuum seals. This out-gassing is what causes the base pressure to be 10^{-5} Pa instead of zero and since it is a steady state phenomenon we can write (at base pressure):

$$\frac{dP}{dt} = 0 = \frac{Q_{outgas} - P_P S_P}{V} \quad or \quad Q_{outgas} = P_P S_P$$

We are given $P_P = 10^{-5}$ Pa and $S_P = 1000$ l/s. So the out-gassing throughput is $Q_{outgas} = 10^{-2}$ Pa-l/s. Remaining at steady state then, we must find the total throughput required to make the $P_P =$
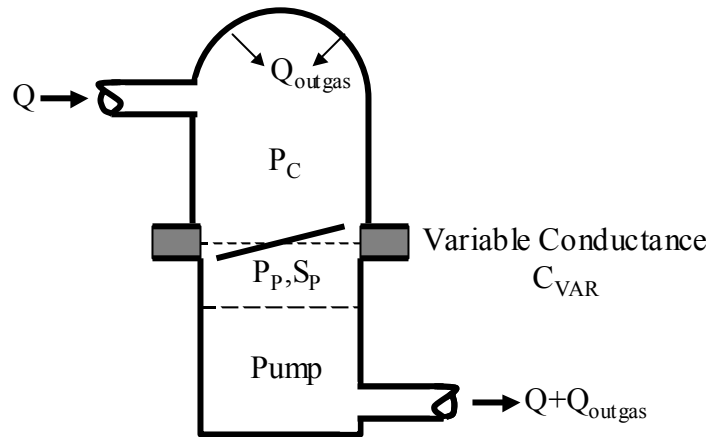

Figure 4. A plot of a simple vacuum system used to illustrate the concepts in the text. P_C is the chamber pressure, P_P is the pressure at the pump inlet, S_P is the pumping speed and C_{VAR} is the conductance set by a variable conductance element called a "throttle valve."

1 Pa. The answer is that $Q + Q_{outgas} = P_P*S_P$ or $Q = P_P*S_P - Q_{outgas} = 1*1000 - 10^{-2}$ Pa-l/s. We must supply a throughput of approximately 1000 Pa-l/s.

    Alternatively, we could place a limiting conductance between the main chamber and pump if we desired to set the chamber pressure to 5 Pa and while only flowing 1 Pa-l/s of gas. This variable conductance could be used to set the chamber pressure to any value (within some limits) without having to change the gas throughput at all. To solve for the required conductance in this case, we must use both of the steady state relationships outlined above. In particular: $Q+Q_{outgas} = C_{VAR}(P_C-P_P)$ and $Q+Q_{outgas} = P_P*S_P$. Plugging in the known constants we find that we have two equations in two unknowns.

$$Q + Q_{outgas} = 1 + 10^{-2} = 1.01 = C_{VAR}(5 - P_P)$$

$$1.01 = P_P*1000$$

Solving these equations is really very simple and results in $P_P \approx 10^{-3}$ Pa while $C_{VAR} \approx 2$ l/s. By placing a series conductance in front of the pump, the effective pumping speed can be reduced (dramatically in this case from 1000 down to 2 l/s) and the pressure of the chamber can be controlled independently from the gas flow.

Homework Problems:

1) A vacuum chamber has a turbo-molecular pump connected directly to it, which has a 360 l/s pumping speed. The base pressure of the chamber is 2.4×10^{-5} Pa after it has been fully baked and as a consequence, the gas throughput caused by out-gassing from the chamber walls is very small. After venting the system for loading a new substrate the base pressure remains at 5×10^{-4} Pa until the system is baked again.
   a. Find the leak rate (throughput) in the system after baking.
   b. Find the increase in the leak throughput caused by the venting and loading procedure.
   c. What could one do to reduce the increase in leak throughput?
2) Pumps typically have a pumping speed that is a function of pressure. The pumping speed curve for a typical rotary vane-pump (2063) is shown in Figure 1. Find the ultimate pressure for a system pumped using this pump that has a leak rate of 3.4×10^{-4} Pa-l/s.
3) The typical pumping speed for a rotary vane pump is shown in Figure 1. What will be the pressure at the pump inlet for a gas throughput (flow) of 100 sccm? Our Roots pumping package on Cappy has a typical pump speed of 171 CFM or 290 m³/hr. What will be the pressure at the pump inlet for a gas throughput (flow) of 100 sccm?
4) A throttle valve is very often placed above a turbo-molecular pump in semiconductor processing equipment.
   a. Why is this a good idea despite the fact that the throttle valve will always limit the pump speed and consequently lower the maximum gas flow rate that can be used for the process?
   b. What conductance should the throttle valve be set to (on Indy) to maintain a pressure of 1 mTorr at 200 sccm? Use the pumping speed curves for an ATH400 turbo-molecular pump shown in Fig.1 and assume the gas flowing through the system is Nitrogen.
5) A vacuum chamber has a turbo-molecular pump on it that is connected to a rotary vane "roughing" pump by a very long fore-line (50'). The design engineer can choose to make the tube either 1.5"diameter (at $10/foot of length) or 4" diameter (at $40/foot). The process requires a gas throughput of nitrogen up to 300 sccm total and the fore-line pressure must remain below 0.1 Torr. Should he save the money and purchase the 1.5" tubing or not? Why? (Hint, you must outline very specific and correct reasoning here.)
6) Figure P1 shows four pump-down curves for various Alcatel roots pumps. For the curve that decreases the fastest, estimate the pumping speed for pressures well above the base pressure of the pump.
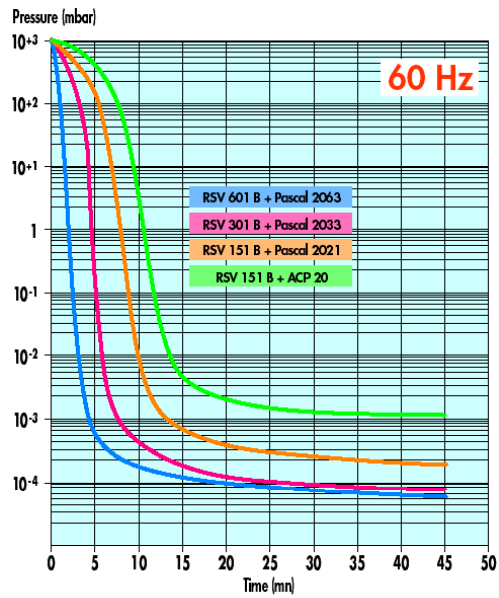
Figure P1. Pump down curves for some Alcatel roots pumps. The curve which drops the second fastest (the RSV301B + 2033) is typical for the pump system on Cappy. These curves plot pressure as a function of time as the various roots pumps evacuate a 1 m³ chamber.

Laboratory procedure:

1] Measure the approximate **volume of the chamber** by flowing 2.5 sccm of argon into the chamber, measuring the base pressure with this gas flow and measuring the time required to rise from that base pressure to 0.5 Torr after the gate valve has been closed. Take a pressure measurement using the capacitance manometer every 15 seconds until the pressure has reached 0.5 Torr. Re-measure the chamber volume using an argon gas flow of 5 sccm and the same procedure. Do the two estimated volumes match?

2] Next measure the approximate outgas throughput for the chamber by closing the gate valve and monitoring the chamber pressure for 15 minutes. Record the pressure measurement using the capacitance manometer each and every minute. What is the outgassing flow rate like compared to the 2.5 and 5 sccm gas flow rates used in Part 1 of this lab?

3] Estimate the conductance of the main pump line by measuring the pressure as a function of the gas flow rate with **the gate valve full open**. (Assume the pressure at the pump remains at less than 1% of the chamber pressure at all flow rates. In actuality, the roots pump has a pump speed of about 171 CFM or 290 m³/hr.) In addition, measure the pressure at the halfway point of the pump line using the Pirani gauge there. Under what conditions is the 1% approximation valid? What is the conductance of the pump line to the halfway point?

4] Set the gate valve to **85% closed** and re-measure the conductance. (Assume the pressure at the pump remains at less than 1% of the chamber pressure at all flow rates again.) How much has the overall conductance changed due to the nearly closed gate valve? In addition, measure the pressure at the halfway point of the pump line using the Pirani gauge there. Under what conditions is the 1% approximation valid now? What is the conductance of the pump line to the halfway point? Has it changed?

5] Set the gate valve to **95% closed** and re-measure the conductance. (Assume the pressure at the pump remains at less than 1% of the chamber pressure at all flow rates again.) How much has the overall conductance changed due to the nearly closed gate valve? In addition, measure the pressure at the halfway point of the pump line using the Pirani gauge there. Under what conditions is the 1% approximation valid? What is the conductance of the pump line to the halfway point now?   Has it changed?

6] Close the gate valve and **open the "soft pump" valve**. Measure the conductance again. (Assume the pressure at the pump remains at less than 1% of the chamber pressure at all flow rates.) How much has the conductance changed due to using the slow pump tube (the 0.25" line)? In addition, measure the pressure at the halfway point of the pump line using the Pirani gauge there. Is the 1% approximation valid? What is the conductance of the pump line to the halfway point now? Does it dominate over the conductance of the second half?