# CREATING A VACUUM

Although creating a vacuum is really an incredibly complex concept, the subject can be simplified down to a single question and a single rule:

> THE QUESTION:   What are you trying to do?
> THE RULE:           Don't make any mistakes!

Hiding within this simplified concepts are myriad pitfalls requiring a good deal of thought and care to avoid, but they can be successfully avoided by staying within the concept. Keep in mind that, in a practical sense, nobody in his or her right mind creates a vacuum without a reason. Before getting into reasons, though, we need a simple definition. A vacuum is any pressure below atmospheric and that requires something to keep it in (chamber) and a means of reducing the pressure (pump.)
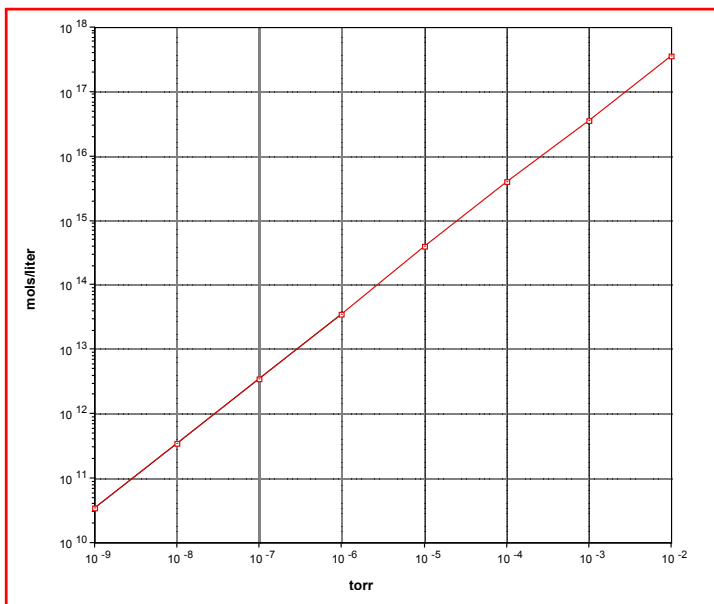


Figure 1.  Number of molecules/liter vs. pressure in torr.

So, what we are talking about here is removing gas molecules from a chamber. Figure 1 shows the mind-numbing number of molecules involved. Whatever the process or product that requires a vacuum, there is a maximum amount of molecules that can exist within the chamber if the product or process is to successfully produced or carried out. The first stages, then, of answering the "What are you trying to do?" question is to define a product/process and a target pressure. At this point, the single rule comes into play in that every component and procedure involved in creating the vacuum must be chosen or done properly or the result will be failure to achieve the target pressure.

This can be restated as Danielson's Dilemma because the complexity of a vacuum system is greater than the complexity of the sum of its parts. A correct choice of a component will not matter unless its interaction

## Anatomy of a Pumpdown

In general, a vacuum is created by starting with air at atmospheric pressure within a chamber of some sort. A vacuum pump is attached to the chamber with the intention of removing enough gas molecules from the chamber to reach the maximum allowable number (pressure) to satisfy the target pressure established under the question, "What am I trying to do?" Since air is a mixture of gases, it will be necessary to consider the relative gas composition later in this discussion, so the composition of atmospheric air is shown in Figure 2.

**Composition of Atmospheric Air**
(50% Relative Humidity at 25°C)

| | | |
|---|---|---|
| $N_2$ | 78.08 | $5.94 \times 10^2$ |
| $O_2$ | 20.95 | $1.59 \times 10^2$ |
| Ar | 0.93 | 7.0 |
| $CO_2$ | 0.033 | $2.5 \times 10^{-1}$ |
| Ne | $1.8 \times 10^{-3}$ | $1.4 \times 10^{-2}$ |
| He | $5.24 \times 10^{-4}$ | $4.0 \times 10^{-3}$ |
| $CH_4$ | $2.0 \times 10^{-4}$ | $1.5 \times 10^{-3}$ |
| Kr | $1.1 \times 10^{-4}$ | $8.4 \times 10^{-4}$ |
| $H_2$ | $5.0 \times 10^{-5}$ | $3.8 \times 10^{-4}$ |
| $N_2O$ | $5.0 \times 10^{-5}$ | $3.8 \times 10^{-4}$ |
| Xe | $8.7 \times 10^{-6}$ | $6.6 \times 10^{-5}$ |
| $O_2$ | $7.0 \times 10^{-6}$ | $5.3 \times 10^{-5}$ |
| $H_2 O$ | 1.57 | $1.19 \times 10^1$ |

Figure 2.



Figure 3. Molecular mean free path in feet as a function of pressure in torr.

At atmospheric pressure, the gas molecules are very close together; and as they are in constant motion, the distance between molecule-to-molecule collisions is very short. This distance is known as *mean free path* . As molecules are removed by the vacuum pump, the distance between collisions becomes greater and greater. Figure 3 shows the mean free path as a function of pressure. As molecules are removed, there are fewer other molecules for a given 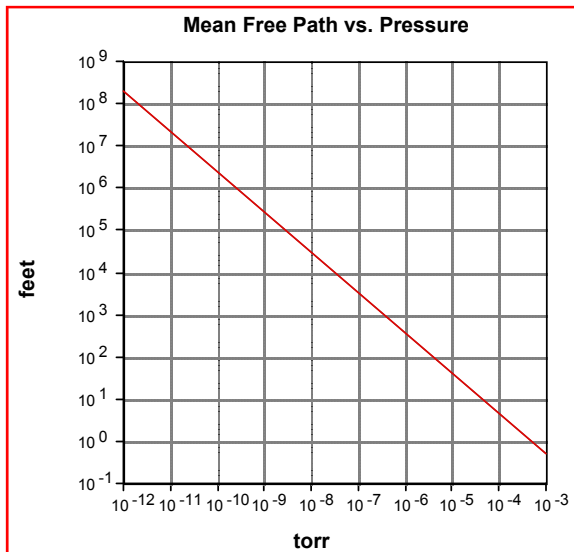molecule to collide with the distance becomes longer and longer as the pressure is reduced. This concept, though fairly obvious, is important in understanding vacuum technology in that the behavior and flow of molecules is almost the whole subject.

When the pumpdown is started at atmospheric pressure, the gas molecules are in a flow regime condition called *viscous flow*. This means that the constant molecule-to-molecule collisions will cause the population of molecules within a given volume to even out immediately when some molecules are removed. This behavior is what most people think of as the effects of pressure differential since there seems to be a driving force to move molecules. This can be seen more clearly as we begin to remove molecules from the chamber.

Starting from atmospheric pressure, molecules are most commonly removed with a mechanically actuated *positive displacement pump* of some sort. This can be anything from an oil-sealed rotary pump to an oil-free diaphragm, piston, or scroll pump. The overall idea is the same in that the gas in the chamber to be evacuated is expanded into a fixed volume where it is isolated and then mechanically compressed to a point where it is expelled into another stage or directly into the atmosphere. The exposure and subsequent isolation of the molecules in the chamber to the fixed volume continues at a high rate and more and more molecules are removed. However, two things are happening.

1. As more and more molecules are removed, the mean free path increases and that results in a slightly longer and longer time to achieve equilibrium in molecular population so that the apparent driving force of pressure is reduced, and

2. Fewer and fewer molecules are removed with each cycle of the pump since there are fewer molecules available to be pumped.

During this process of molecular removal, the makeup of the air as gas mixture remains pretty much the same in terms of relative ratios as is shown in Figure 2, and the total molecular depopulation continues as above until the mean free path becomes long enough that a given molecule is more likely to impact the chamber wall than another molecule. At this point the entire behavior of the molecules changes and the process enters another flow regime entirely. Since the molecular behavior is based on the effects of mean free path which is a function of the molecular concentration, the physical size of the container (chamber) begins to come into play. At this point, it becomes necessary to consider the flow regimes that have and will come into play as the pumpdown progresses.

## Flow Regimes

As a pumpdown from atmospheric pressure to high vacuum is accomplished, the behavior of the molecules in the chamber is affected and controlled by three separate flow regimes. Since, as we have already seen that pressure and chamber dimensions both come into play, Figure 4 shows the boundaries of the various flow regime parameters.

## Viscous Flow

Viscous flow, as discussed above, occurs when the mean free paths are short and molecule-to-molecule collisions are constant. This provides the impetus to spread the molecule population evenly and results in flow conditions much like a liquid.
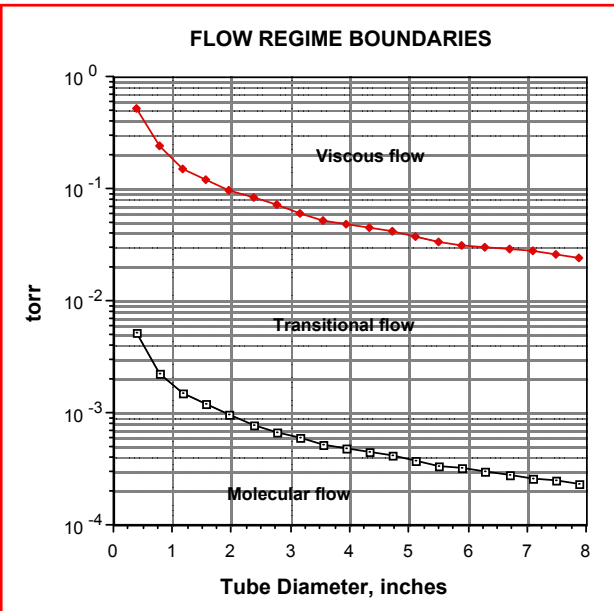
**FLOW REGIME BOUNDARIES**



*Figure 4. Flow regimes as a function of pressure and chamber dimensions.*

### Transition Flow

Transition flow is an extremely complex condition that occurs in a band between viscous and molecular flow. Since it is usually quickly traversed in a normal pumpdown, it can be safely ignored in most cases.

### Molecular Flow

Molecular flow begins to occur when the mean free path of the molecules that are left within the chamber is longer than the internal dimensions of the chamber. This means that the moving molecules are statistically more likely to impact a chamber wall than they are to impact another molecule. This means that there is no longer any flow in the usual sense of being caused by pressure differential because the molecules are now bouncing around entirely at random and flow from chamber to pump is based entirely on the random chance of a molecule wandering into the pump.

### Avoiding Mistakes

It is relatively easy to avoid process fatal mistakes during the pumpdown through the viscous flow region, but that relative ease departs and becomes ever more elusive once the molecular flow region is entered and the pressure becomes lower and lower. Fore example, a tiny leak that would be easily ignored in terms of pumpdown time or ability to reach an ultimate pressure can suddenly become too big as the pressure drops. Ultimately, it can become an intolerably large leak as the target pressure drops into the high or ultrahigh vacuum pressure regions. The same can be said for materials of construction, seals, or other hardware where contamination (gas) emanating from a component part might be too great at one pressure and negligible at a higher pressure.

When the change from viscous to molecular flow occurs, the entire thinking process of gas flow changes. Consider *conductance* which can be most easily described as the amount of volume flow that will pass through vacuum line. There is a formula for each:

Viscous Flow: $C = F \times P_a D^4 / L$
Molecular Flow $C = F \times D^3 / L$
C = Conductance in liters/sec.
F = factor in inches, 2950 for Viscous Flow and 78 for Molecular Flow

L =Length of the line in inches
D= Diameter of the line in inches
$P_a$= Average Pressure in torr (Viscous Flow only)

If we take a line of 1 inch in diameter and 36 inch long, we calculate
C= 31,139 liters/sec. for viscous flow at an average pressure ($P_a$) of 380 torr, and
C=2.2 liters/sec. for molecular flow.

This huge disparity in flow merely points up the fact that all parts or components that make up a vacuum system become more and more important as the pressure drops.  One bad choice or decision can easily negate all the right choices and decisions.  This, of course, can make the entire difference between meeting a target performance or total failure.

## Molecular Flow Pumpdown

Although the pumpdown through the viscous flow region generally maintains the same ratios of gases that are given in Figure 2 for air, this begins to change as soon as the molecular flow region is entered.  As the pumpdown moves through the high millitorr region (1,000- 1millitorr,) the overall makeup of the partial pressures of the gases remaining in the chamber undergo a number of important changes.  At the high end of this region, little change is noted; but as the pressure approaches 1 millitorr, the permanent gases in the air,i.e. oxygen, nitrogen, carbon dioxide, etc. begin to disappear dramatically while water vapor begins to dominate.  In fact, the total pressure from roughly $10^{-4}$ to $10^{-7}$ torr is almost entirely water vapor.

## Water Vapor

The permanent gases mentioned above are all gases that were existing within the volume of the chamber, so removing them with the appropriate pump is a fairly straightforward matter.  Suddenly, though, we find them essentially gone, and find water vapor instead.  That's the difference in that we have now switched from a condition dominated by volume gas to one that's dominated by surface or wall gas.  The water vapor has been there all the time as a small percentage of the overall gas composition, but now that same amount of water has become important in a relative sense.

The source of all this water vapor  is from the inner surfaces of the chamber where it had originally sorbed when the chamber had been at atmospheric pressure.  The polar nature of the water molecule results in attachment to the surfaces and to itself in water-to-water bonds that are fairly weak.  This means, then, that the water vapor must desorb before it can be pumped away.  The desorption rate of the water vapor is shown in Figure 5.  Since the desorption rate drops off slowly, we can easily see that the total amount of water vapor that needs to be

desorbed will control the pumpdown. The only way to traverse this desorption rate controlled region is to wait long enough for the water vapor to desorb as shown in Figure 5 or to increase its desorption rate artificially through heat or UV energy.
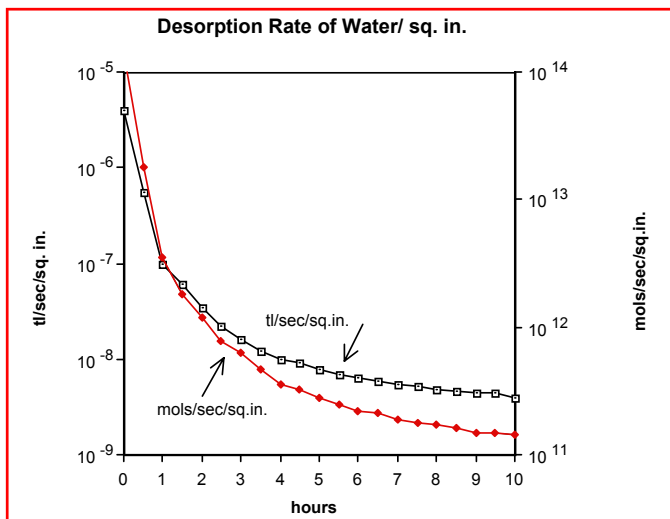


**Desorption Rate of Water/ sq. in.**

*Figure 5. Desorption rate of water vapor in torr liters per second per square inch as a function of time in hours.*

## Chamber Criteria

As the pumpdown moved into molecular flow, our thinking needs to change in several ways in addition to the conductance and gas flow criteria discussed above. In viscous flow, the main criteria was the chamber volume since the job was, at that point, to remove the volume of gas within the chamber; but in molecular flow, the volume of gas within the chamber becomes trivial when compared to the chamber's surface area which is now the main source of gas to be pumped away. This, then, requires a major mode shift in the "thinking about creating a vacuum" process. Additionally, we can see how a previously trivial source of pumpdown problems can suddenly become a controlling source of gas.

## Below 10$^{-7}$ torr

As the amount of water vapor is finally reduced, the pressure can be lowered by continued pumping assuming that the pump is capable of achieving lower pressures and that there is enough pumping speed to do so. In terms of the partial pressures of residual gas makeup, hydrogen will slowly become the dominant gas. The hydrogen is also surface area dependent since it arises from a complex series of sources on the chamber's surface.

## Conclusions

Creating a vacuum within a chamber is a fairly complex process that does not allow a single thinking process to dominate across the whole pressure range. Instead, it goes through a series of processes that can be successfully dealt with by breaking up the thinking process into stages based upon the breakdown discussed here. Although a single mistake can negate the expected performance; applying a completely thought through, in terms of expected performance, analysis can avoid mistakes that might occur.