

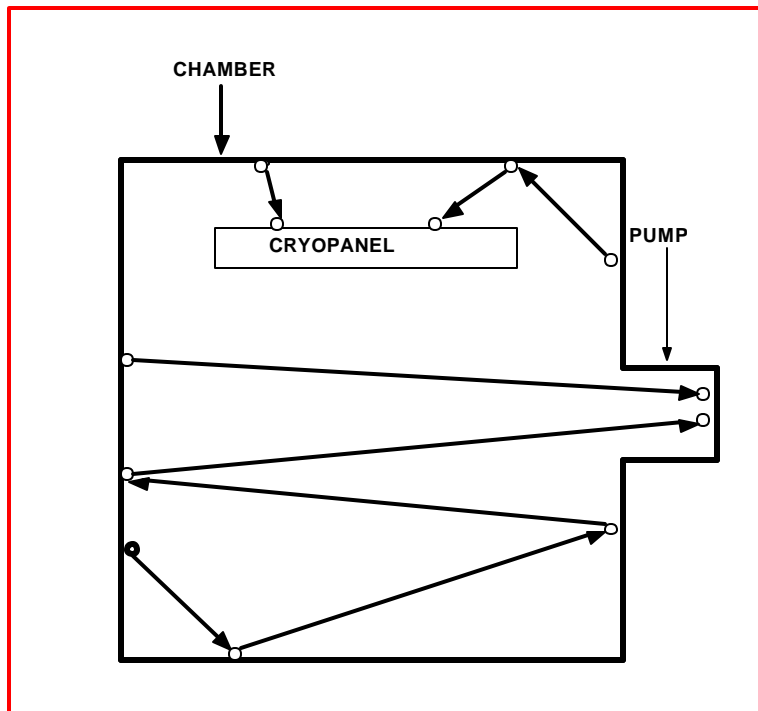
## Pumping Water Vapor

Although vacuum technology is replete with problems and concerns in terms of achieving ever better vacuum levels and reaching them faster, none is more ubiquitous or frustrating than that of having to deal with water vapor. The pumpdown process is relatively easy to understand when we think of the gases making up most of the gas mixture we call ambient air. Dominated by the concentrations of oxygen and nitrogen, we can think of ambient air as a permanent gas. Using the fundamental relationship  $Q$  (gas load) =  $S$  (pumping speed)  $\times$   $P$  (pressure), we can easily see that the gas load will be determined by the volume of the chamber to be evacuated, and that the gas load will become smaller and smaller as the chamber is evacuated. The rate of evacuation (pumpdown curve) that results, within a given chamber volume, will be determined by the speed of the pump. We can easily picture gas molecules bouncing, at random, around inside the chamber while a statistically controlled number of molecules enter the pump where they are removed from the chamber. The pumpdown will then proceed in a fairly straightforward fashion as more and more gas molecules are removed from the chamber. This relatively simplistic picture will suddenly become much more complex when we begin to consider polar molecules such as water vapor which not only stick to surfaces but are also condensable.

The subject of water vapor, in terms of processes, breaks down into two major segments. In some cases, the process itself is to remove water vapor. Examples would be such processes as vacuum drying of materials or any of the many freeze drying process variations. In other cases the process requires that a certain amount of water vapor be removed from the residual gases before the process can be successfully initiated and carried out.

Processes that are designed to remove water from materials will, obviously, result in extremely high gas loads of water vapor that result in a pumping problem that's traceable to the gas laws in that it's necessary to compress the vapor in order to pump it away. Compressing a condensable gas causes it to liquefy whenever it's compressed beyond the critical point. In some cases, steam jet or water ring pumps that are able to easily deal with condensate are used, but they are limited in the ultimate vacuum levels they are able to produce. If the drying process requires that lower ultimate vacuums be achieved at the end of the process, positive displacement-type oil-sealed rotary vane or rotary piston pumps are usually used. If

the process is hydrocarbon sensitive, the oil-sealed pumps are replaced with oil-free pumps such as roots, screw, hook-and-claw, or scroll pumps. All positive displacement pumps will respond to water vapor by loading up with liquid water which reduces their pumping efficiency to an unacceptable extent. In some cases, a refrigerated trap, often dry ice-cooled, is interposed between the chamber and the pump to freeze and hold the water before it reaches the pump. In other cases, it is necessary to gas-ballast the pump by bleeding a dry gas through it to remove the condensate as it forms. Although these are difficult and maddening problems, the real complexity occurs when the process requires that a low partial pressure of water vapor within the chamber be achieved before initiating the actual process.



*Water vapor moves through a chamber in a desorb-sorb-desorb cycle until it enters the pump. The desorbing water vapor moves from sorption site to sorption site until it finally enters the pump unless the cycle is interrupted by an internal cryopanel.*

When a chamber is pumped to a pressure of  $10^{-3}$  torr or below, most of the chamber's volume gas has been pumped away and water vapor becomes the predominant gas within the chamber. The source of the water vapor, at these pressures, is not from humidity in the volume gas but from the internal surfaces of the chamber, elastomer O-rings, and process work load materials. At this point in the pumpdown process, the rate of pressure reduction becomes controlled by the rate of water desorption from the surfaces instead of the amount of gas within the chamber's volume. The

highly polar water molecules are sorbed on the surfaces with relatively weak bonds, and the molecules will only desorb as fast as they can absorb enough energy to exceed the bonding force. In a simple and common pumpdown scenario, the required energy comes from the slow flow of heat from the room temperature chamber walls to the sorbed molecules. The desorption rate will then be proportional to both the bond strength and the total number of sorbed molecules. This, then, means that the chamber's total desorption rate will be proportional to the internal surface area. The only way to increase the pumpdown rate is to increase the

desorption rate temporarily by supplying additional energy to the molecules. The two most common methods of energy transfer are heating the chamber or by UV bombardment from an internal source. As desorbed water molecules are pumped away, the rate of total desorption drops and so does the pressure.

The mental picture of gas molecules within the chamber constantly entering the pump and being removed, such as is workable for permanent gases, becomes untenable when we consider water molecules. The same mechanism that sorbed the water to the surfaces originally causes an additional complexity. A desorbing water molecule might leave the surface in any direction, move through the chamber's volume in a straight line, and impact another surface, or it might move directly into the pump. The statistical chances of the molecule directly entering the pump depend upon the diameter of the pumping throat which controls the effective pumping speed at the chamber. It's much more likely that any given desorbing molecule will impact another surface site instead of entering the pump. The impacting molecule will then re-sorb on the surface. The sojourn time of the molecule on the surface will depend upon its energy transfer with the surface. For example an impact with a warm, or hot, surface will not allow the molecule to transfer its energy to the sorption site, but will, in fact, transfer energy to the molecule so that it will have a sojourn time so short that it can be viewed as a bounce. The mental picture that can be employed, under these conditions, is a single molecule going through a number of desorb-sorb-desorb cycles before it enters the pump. As the pressure drops during the pumpdown, more molecules have desorbed and been pumped away. This means that more sorption sites are available for impacting molecules to sorb onto surfaces, and this means, in turn, that the sojourn time increases. At this point, the desorption rate vs. time curve will be almost flat, and the vacuum practitioner will assume that the system is in a state of equilibrium. This is an erroneous assumption, but, in a practical sense, there would seem to be little that can be done to improve the system's pumpdown performance short of adding energy by heating or UV. Of course, adding pumping speed would seem to be another solution. After all,  $Q=SP$ , and that means that more S would lead to a lower P. Well, sort of.

Installing a higher speed pump will have an effect, but not as much as would intuitively seem to result. A faster pump would entail a bigger diameter pumping port, and that would mean that more molecules would enter the pump. This is true enough, but in a practical sense, there isn't all that much improvement in performance. The additional molecules entering the pump aren't really enough to seriously impede the quasi-equilibrium of the desorb-sorb-desorb cycle within the chamber. This was borne out in a series of experiments on a metal-sealed chamber where a number of small turbo-pumps could be added one at a time onto the chamber. As each additional pump was placed onto the system, the pumpdown curves and ultimate pressure improved, but the improvements indicated that a condition of diminishing returns was reached. This generated a rough rule-of-thumb ratio that can be called "critical pumping speed" where the pumping speed is

ratioed to the total internal surface area of the chamber. If the pumping speed is increased beyond this critical speed, little improvement can be expected. The ratio is 0.011 Liters/sec./cm.<sup>2</sup> of internal surface area. This ratio does not take into account the desorption rate of water vapor emanating from O-rings, but each linear cm. of Viton O-ring will be equivalent to about 50 cm<sup>2</sup> of surface area, and the equivalent surface area can be easily calculated and added to the actual surface area and allow a workable and practical ratio to be calculated.

The critical pumping speed limitation can be overcome by mounting a pumping surface, such as a cryopanel, within the chamber or directly within the pumping port. This pumping surface disrupts the quasi-equilibrium of the desorb-sorb-desorb cycle by removing molecules before they can impact onto a surface that will allow them to only sorb temporarily.

When water vapor is differentiated from the volume gas within a chamber, and its peculiarities taken into account, a better understanding of the practical workaday performance of vacuum systems can provide a better choice of pumps, pumping speeds, and pump installation techniques.

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