A Quantitative Examination of Venting Trapped Volumes Due to Fasteners

By Charles E. Bryson, III, (Chuck), CEO,
Apparati Inc., Hollister, CA

Why We Care

The need addressed here is the problem of pumping out internal volumes in vacuum systems that may be blocked by construction methods. Vented screws are a common approach to reducing this problem. This discussion will focus on evaluating the magnitude of the problem and various solutions. Calculations on conductance for vented and unvented screws and some accessories will be given. These conductance values will be used to model different common configurations that have different amounts of trapped volumes.

The conclusions are clear, vented screws and venting accessories are essential.

Summary

The direct measurements on un-vented screws tested were flawed because the screws tended to seal to varying degrees underneath the head of the screw. A use of a vented washer helped but the leak rate was hard to measure because of variability. Direct comparison to calculations is difficult because of the tolerances in screw fasteners. There are large differences in conductance because of the clearance between the screw and the mating fixtures. Calculating the ranges of conductance that can be expected for unvented screws, venting channels, showed this. Ranges in excess of a factor >15 were encountered for a single definition of a particular fastener. Some comparisons with data shed insight to the nature of the task.

The result is a "set of ground rules for design" based on the quantitative information derived. Examples are given for different designs with different parameters in terms of vacuum performance.

Scope of Problems

The use of fasteners in vacuum system results in voids between the parts being restrained, threads and incompletely filled holes. Often these voids are partially sealed or if sealed the seals may break in time. The result is the presence of virtual leaks in the vacuum system, which extends the time to obtain a desired vacuum. Virtual leaks mean a leak that cannot be found for activities out side of the vacuum chamber. The differences in pumping rate for different gasses can induce undesired impurities. The areas that involved are described in **Table 1** and shown in **Figure 1**.

Table 1. Voids encountered when pumping residual volumes with fastener parts and related solutions needed for good performance.

Symbols	Names	Descriptions
Voids		
FT	Filled Threads	Voids in the screw threaded portion
CV	Clear Volume	Clear hole between Parts
EV	End Volume	Volume between screw & hole end
Solutions		
1	Threaded Screw	Helps clear all volumes
2	Vented Washer	Increases pumping of CV
3	Vented Hole	Increases pumping of EV

A Summary of the Results Reported

There are several ways to limit the impact of this problem. First, one can make sure all holes that will have screws are through drilled to areas with-in the vacuum chamber. Obviously this cannot be done when the other side of the part is outside of the chamber. Next, one can use vented screws that connect the End volume, (EV), and Filled threads, (FT), with the vacuum chamber. A vented washer also ensures the trapped volumes, CV, are not partially sealed by the fastener head. In the design of a fastener it is best to use the minimum length of thread engagement and the least percent thread used consistent with the strength needed. Fewer threads per unit length will also help. Obviously the design must not limit utility of the system by pushing these last items so far that their strength is compromised.

The importance of virtual leaks is dependent on the use of the vacuum system. One use of vacuum systems is to allow particles to transfer some distance without hitting a gas molecule. The vacuum level needed can be quite modest, pressure = to 10^-7 torr, for some items like SEM's where the electrons travel fast. For synchrotrons the pressure needs to be much lower, 10^-11, since the particle path length is often quite long, hundreds of meters.

Another common use of vacuum systems is to control gas material reactions. An example where higher pressures are accepted and some impurities are acceptable is where deposition rate processes are very high with material being put down at high rates, microns per minute. In this case the deposited material is being covered faster than the problems associated with the slowly removed gases like the water and CO2, mentioned above, can affect the process. For lower rate processes, such as, the Atomic Layer Deposition, (ALD), or Molecular Beam Epitaxy, (MBE), the impurities in the vacuum system pressures must be very low.

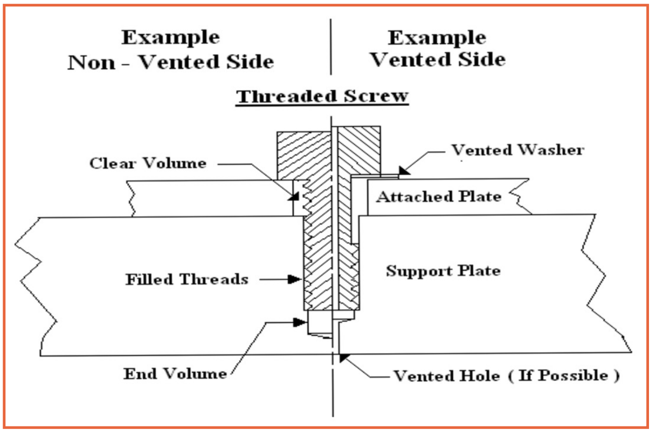

Figure 1. The sketch shown in this figure illustrates the areas that are a problem when pumping systems have internal mechanical construction. Also included are labels showing where solutions can be implemented.

Operation Situation or Stages in Vacuum Systems

There are three situations in vacuum chamber operation [1]. First there is rough vacuum pumping when the pressures are high enough that gas interactions dominate the material flow. This is called laminar flow. Then in transition pumping the gas-wall interactions as well as gas-gas interactions inhibit material flow. In the final stages, molecular flow is where all gas interactions are with the walls and gas molecules do not interact in a way to effect pumping. The Molecular flow condition is where the system is being used and the gas flow is slowest. The good news is that if there is any open aperture between the blocked regions and the vacuum chamber large quantities of the trapped gas (but not all) will be pumped away in the rough pumping and transition stage. The bad news is that once pressure drops all the way to the molecular flow level the removal of unwanted gasses is slower and hence, a bigger problem. Some materials, explicitly water, carbon dioxide and Hydrogen will remain trapped for a long time. This inhibited pumping is due to the length of time each molecule stays on the interior walls or diffusion of gas out of the walls.

Transition Pressures Between Different Modes

The mean-free-path of the gas molecules determines when the pumping modes change. The mean-free-path is proportional to gas pressure and is also a function of gas composition and temperature. In this Laminar flow region the pumping speed is very high. When the shortest dimension between walls approach the mean free path, the roughing stage is beginning to switch over and the transitional stage starts. When the mean-free-path approaches the longest distances between walls the transitional stage passes into the molecular flow. These changes are not abrupt at a particular pressure but occur over a range of pressures near the point defined above. A simple estimate of the transition pressures is to use atmospheric gas and room temperature (see **Table 5**). The major use for this discussion is to recognize that the time to reach the molecular flow range is relatively short, typically up to a day, compared to the time to reach lower pressures, which can be weeks to months. The lowest pressures often require baking and the use of vented fastener assembles reduces the bake time required.

The pressure at the beginning of the molecular pumping stage is a way to estimate the gas load that needs to be evacuated from trapped volumes. The important point is that the gas load is strongly dependent on the volume and surface area of the trapped volume. The mass of gas bound to the surface, as a film, is much larger than the mass of free gas in the trapped volume.

Conclusion 1

The conclusion is the more complete venting method used by combining vented screws, vented washers and alternate access to the trapped volumes the better a vacuum can be achieved. More importantly the time required to establish a vacuum goal will be lower and less time will be spent trouble shooting the vacuum system.

Determining the Solutions Provided by Vented Screws and Washers

The first method was to examine some pumping systems with non-vented holes to establish some of the pumping rates for higher pressure near one atmosphere. The lack of reproducibility made it clear that there is a wide variation in the results obtained. One is the partial seal between the screw cap and the hole with the tapped threads. Since this effect can be easily eliminated with vented washers or screws with a venting slot in the screw head, we addressed the screw part directly. The other source of variability was also due to the variations induced by the tolerances in the fastener parts. The tolerances are set to make the strength of the fastener consistent. However, these same tolerances resulted in a very wide rang of values for the spaces between the fastener components. This effect is described more clearly in the molecular flow calculations that follow.

The first observation with measurements is that when a SS screw is tightened into an Al part the screw head can seal the part to a leak rate less than 10^-4 torr-liter per second. Further more the existing leak rate is not necessarily going to stay that low as the unit is being used. As the screw loosens on the order of a few degrees in the screw angle along its length, the leak rate goes in to the 10^-3 range. In fact the leak rates were very different from one experiment to another.

Conclusion 2

The conclusion here is that one should always use a vented washer or a vented screw with a side vent to the threaded area. At this point the trapped volumes will eventually pump out. Next is how long it takes.

The Important Parameters in Leak Rates

There are a number of parameters that have an effect on leak rate from a sealed chamber. Most are commonly understood and include: pumping path length, conductance of the path, cross section size and shape of the path, volume of the chamber being evacuated, side wall area of the volume and path and gas composition.

There are Effects Beyond Ideal Gas Kinetics

The gas composition has an attribute that extends beyond simple kinetic theory of gasses. Most often the mass of the molecules in the gas, their temperature, density and pressure are considered and can be modeled well with thermodynamics. All of the gasses pump on a basis of mass, chemical or thermal reactions or evaporation rates from surfaces. When the pressure drops into the transition flow and more important into the Molecular flow stages the gas wall transaction becomes an additional parameter [2]. There are two parameters that are used: one is the vapor pressure that is commonly stated but the other is the residence time a molecule has when on the surface. When the residence time is long the molecule is often thought of as sticking, i.e. it has a high sticking coefficient. The residence time is related to the adsorption of the molecule to the wall.

There is an attraction of the molecule to the wall that causes the molecule to reside on the wall for some time. This residence time slows down the pumping of gas molecules from a chamber. In fact the composition of the gas in a chamber when the system is in the transition stage or early into the Molecular flow stage is almost 100% water and CO_2 if there are no leaks. The residence times for these gases are very long, up to .001 seconds while resident times for rare gases are down to 10^{-13} seconds. O_2 and N_2 also have very short residence time, much less than water and CO_2. The implication of these thoughts show why the systems have so much water and CO_2 before baking and will be badly influenced by improperly vented voids. The long residence times often force the gas removal to behave like a diffusion problem than a kinetic gas problem.

An early reference on outgasing, A. J. Santeler, JVST A 5(4), July 1987, defines these effects in a general way in terms of diffusion and removal of adsorbed materials on the surface of the system components and absorbed material in the system components.

Conclusion 3

Vented holes are a key in reducing the sticky gases such as water and CO_2 contained in a vacuum chamber because a lower pressure is obtained before going into the Molecular flow mode in addition to the higher pumping speed through the vented part.

Atmospheric Pressure Experimental Measurements Effects Using Vented Washers

As mentioned above the measurements on the leak rate of unvented screws through the threads is difficult because of partial sealing of the thread passage by the screw head. A solution to this problem will be to use vents in the screw body or use washers that have a vent path across their face. This will provide better venting of the threaded region as well as the trapped voids, CV, mentioned above.

Figures 2 and **3** show pressure vs. time for venting a 1 cc chamber through a threaded hole with a 1 inch threaded section filled with a 4-40 screw. In both cases the hole was filled to a

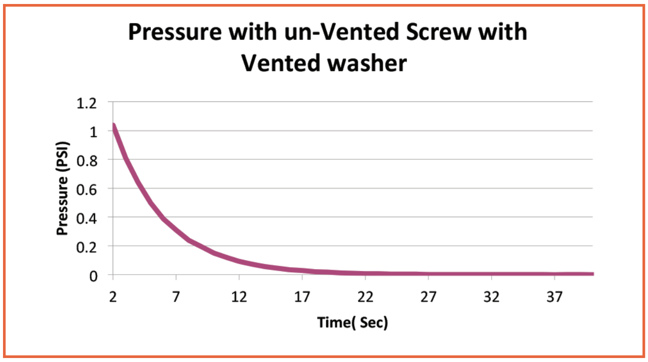

Figure 2.

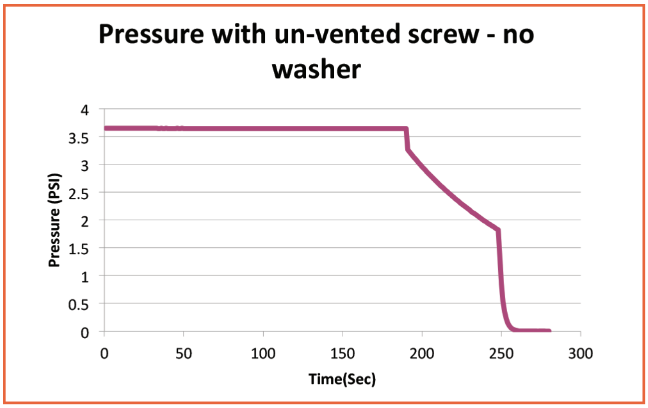

Figure 3.

few psi and then allowed to vent. **Figure 1** was with a vented washer under the head of the screw while **Figure 2** was with the screw-tightened snuggly to the Al test frame. With the tightened screw with no washer the venting was finite and very slow. The screw was loosened in increments of a few degrees to see how the fastener leak behaved when not sealed. This is important because screws in a vacuum chamber can get loose with time, especially if there is any backing or system vibration. The screw was tightened enough to make an imprint into the Al fixture.

The data in **Figure 2** represents pressure reduction through threads of a 4-40 screw mounted with a vented washer.

The data in **Figure 3** represents the pressure reduction through threads without a washer and with successive loosening of the screw the leak rates were obtained by expanding the actual data curves to show the detail pressure vs. time portion for each screw setting.

Table 2 shows the changes in leak rate as the screw is loosened and a comparison to the screw with a vented washer. Earlier measurements showed lower leak rates when the screw was tight.

This data backs up the comment on Conclusion 2 described above. The bigger the volume CV is the more important the vented washer.

Extrapolation of the atmospheric data to the molecular flow regime to allow a more complete description of the need for vented fasteners.

The length of time to reach a good base pressure is more influenced by the molecular flow pumping, because the conductance of tubing is much higher in the laminar and transistion flow region. The molecular flow region is also where the diffusion like extraction of gases is a more difficult problem. Because the pumping time to reach low pressures is longer in the molecular flow range, the next section will contain calculations of the Molecular flow conductance from threaded regions. This will be the dominating effect in calculating the time to reach given low pressures. The time calculations will be based on simple models of the chambers shown in **Figure 1**.

Table 2

Leak Rate (Torr liter/sec)		
Unvented screws with no washer		
Screw Condition	**Gauge Pressure (torr)**	**Leak Rate torr-liter/sec**
Tight	182.4	7.90E-04
10 degree loose	182.4	1.70E-03
20 degree loose	157.1	7.90E-01
30 degree loose	45.6	1.40E+01
Unvented screw with vented washer		
Tight	50.7	1.60E+01

The ConductanceThrough a Fastener is Radically Affected by Manufacturing Tolerances

This part of the discussion will focus on a Sharpe V standard threaded screw based fasteners. There are several references and the one used here is the ASME B1.1 2003, (R2008 Unified inch Screw threads), UN and UNR Thread Form, copyrighted 2011 Industrial Fasteners Institute, [3] In these standards there are documented tolerances that are used for manufacturing the fastener parts, a screw and a nut. In our case, instead of a nut there is a threaded hole that is used instead of a nut. There are three classes of threads that are designated1, 2 and 3 where 1 is for the loose fit tolerances parameters, 2 is for moderate tightness and 3 is for very tight tolerances. The parameters are separated by an additional reference, which is a letter. The screw tolerances are designated by an A and the nut, or hole, tolerance by a B. We have taken the combinations of 2A and 2b as the common standard and added the class 3A with 2B for plated screws. The 3A and 2B combination can have very tight fits.

As described above the standards are used to make the strength of the fastener reproducible but they have a significant effect on the gas conductance through a tightened fastener because the spaces between the parts are of a secondary concern from the point of view of strength.

To illustrate the size of these effects, an example calculation was done on a ¼-20 screw using the 2A2B set and the 3A2B set of tolerances. There are five parameters to define both the screw and the nut. Two numbers define the size and thread pitch. The size may be a reference number or letter or the outer dimension. Either the number of turns per unit length or the length of the pitch defines the pitch. If the number of turns is N and the unit length is L then

$$N = 1 / L.$$

The detail shape of the screw or nut thread is defined by basic parameters defined by the reference listed above. The basic shape is a repeated 60-degree V that has the width defined as the pitch and a defined height (H) set by the angle. Therefore, $H = \cos(30) * P$. The V pattern rotates around the screw so the outer diameter of the pattern is nominally the screw size.

To be able to manufacture screws that have a required strength and such that they will actually rotate together, there are three diameters defined for both the screw and the nut. Both threaded parts have a Major diameter, a Minor diameter and a Pitch diameter. The Major diameter is the largest and is near the Screw size. The reported sizes listed in the references nominally are the maximum and minimum value which parts respect to allow actual use. There are some very minor shape changes that allowed a

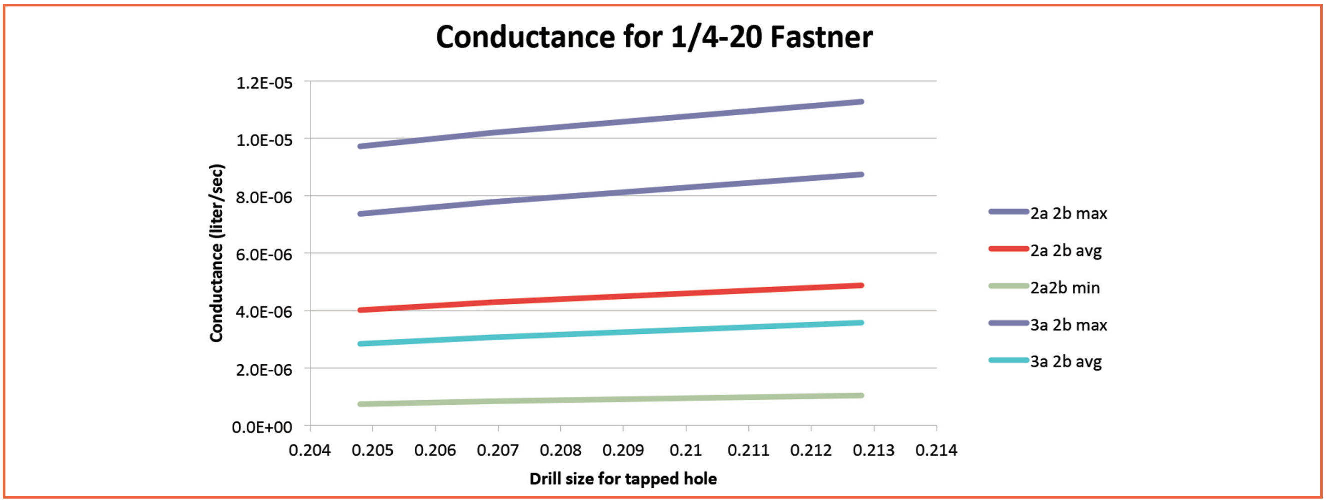

Figure 4.

curved outer cross-section that is not flat and these were ignored. As a note it's important using 3 class parts require pre-selection of some dimensions because if built to the extremes they will bind up in operation.

To use these numbers for conductance calculations we used three combinations of diameter values. One labeled MAX, uses diameters chosen so the gap between the screw and hole are as wide as possible. For MIN conditions we used diameters chosen with the opposite extreme. For a mid range calculation, labeled AVG, we used the average values between the value of the maximum and minimum tolerance. Note we could not use the Minimum extreme for the 3A 3B class because this setup would bind up and not engage.

The first sets of calculations focus on the effect of manufacturing tolerance plus the one additional variable available to a fastener user/designer. This is the pre-tap hole size. This will set the minimum pitch diameter of the hole that is being taped to receive the screw. **Figure 4** contains a plot of conductance vs. pre-tap hole size using the MAX, MIN and AVG for ¼-20 class 2A2B fasteners and Max and AVG ¼-20 Class 3A2B fasteners. This shows the very wide range of conductance one can expect from commercial fastener components.

Figure 4 shows conductance through a threaded fastener for a ¼-20 screw in a ¼-20 threaded hole. The hole diameter varied for 70% thread engagement to a 57 % thread engagement. Most of the differences are due to the allowed thread dimension variations based on references described above.

Conclusion 4

Use as large a tapped hole as possible given the strength of the fastener needed.

Effects of Fastener Size and Pitch on Conductance

The effect of fastener size and pitch is important but there is clearly a variation based on the particular dimensions of the parts used. A useful conductance can be estimated from the "Average" fastener size and pitch by using the methods that produced the information in **Figure 4**. This estimate will allow some judgment to help select optimum part design.

The conductance for a long complicated path can be found by multiplying the conductance into the path by the probability of the gas leaving the path [4, 5]. The probability is simply the ratio of the area from the exit to the path divided by the total area of the path walls. The cross section, CS, of the path is defined by the description above that contains the tolerances. Since all of these are defined as a function of height and period of the "V" shape in the threshold form the expression for CS is nominally proportional to a constant time period, P, and height, H. This can be expressed as:

CS = k1 * H * P, where k is a constant that depends on units.

In a similar way the path area, PA, is a product of the length of the path and the length around its cross section. This can be expressed as:

PA = K2 * Pi *K3 *N* where K2 is dependent on diameters units and K3 is dependent on the number of threads per inch, where PI stands for pitch diameter.

Because the exit hole has the same cross section as the entry hole of the threads, it will be the sum of CS+PA.

All of this indicates one should use screws with the largest pitch practical and then, use the smallest screw size for that pitch. Based on the simplified expression used here the conductance through the filled thread section is proportional to thread pitch squared divided by the thread size. In fact the data plotted based on published manufacturing specifications shows the tolerances used are not strictly proportional to the period, P because the tolerances are not strictly a function of period. The value of the calculations still provides directions on making a design of fasteners less of a virtual leak.

Conclusion 5

Use as course a thread as possible and the smallest thread size for that pitch, while being consistent with the fastener strength needs.

Different Methods for Venting Fastener Voids Produce Different Results

The calculations for the threaded channel is a limiting conductance that affects all efforts in venting the virtual leaks that are part of a fastener installation. If vented threads and washers are used to access the end volume, EV, and the clear volume near the head of the screw, CV, the volumes will tend to pump to a lower pressure when the molecular flow conditions become important and then pump faster. The remaining volume, FT, is the difficult part that involves pumping through the filled thread.

These issues will be addressed by showing the pumping time constants and the time it takes to reach 10^-9 torr for each volume. The starting pressure for each situation will be the transition pressure for the molecular flow condition. The initial gas volume will include the gas mass for each volume plus the adsorbed species on the fastener system walls.

The venting processes for the end volume, EV, will include screws vented with a central through hole and screw vented with a side slot parallel to the screw central axis. Venting of the clear volume, CV, described above and in **Table 1** will be done using washers with a radial open slot along one side, with a slot on the base of the head that is the end of a screw as in the slot vented screws. **Table 4** contains the sizes used in the model shown in **Figure 1** and **Table I** to calculate the time needed to reach a pressure in the voids of the fastener of $1.0*10^{-9}$

The pumping model used for this analysis is to treat each volume as an independent entity and examine how different venting techniques affect that entity. The entity volumes are shown in **Table 1** as clear volume, CV, end volume, EV and the void in the filled threads, FT. The conductance through the filled treads is much slower than the other conductance path so one can approximate the performance by treating the voids as independent. There is a crosstalk that will improve the performance if all voids are emptied aggressively.

Table 3. The values for fastener dimensions used to calculate the times needed to reach a pressure of $1.0*10^{-9}$ for the different voids in the fastener. There will be some coupling between the different voids but it will be low because the conductance in the filled threads is so low. The time to reduce the effect of adsorbed gas is not included. The adsorbed gas is best removed with baking if they are important. All of the pumping speed increases as the temperature goes up and the vented volumes still pump much faster than unvented volumes.

Dimensions for evaluating leak rates				
Examples - Screw Size	1/4-20	10-24	8-32	
Screw diameter		0.25	0.196	0.167
Thickness of Attached plate	0.25	0.2	0.175	
Thickness of Support plate	0.7	0.5	0.5	
Screw and hole		1/4-20	10-24	8-32 / 2A
Class		2A/2B	2A/2B	2A/2B
Screw length		0.625	0.5	0.375
Hole depth		0.45	0.45	0.4
Hole thread depth	0.4	0.35	0.3	
Engaged thread length	0.375	0.288	0.2505	
Attached plate clear Dia.	0.256	0.196	0.17	

Two other simplifications were made. One is to ignore the pump down time in the roughing stage and the transition stage because it is very fast compared to the molecular flow speed. Another simplification is to treat the condensed gasses on the walls as a separate problem. The basis will be to consider the pumping speed to be set at the high end of the molecular flow stage until the gasses are mostly removed. **Table 5** will shows the initial start pressure for the time calculation and the time in seconds to reach 1×10^{-9} torr.

Table 4 has pump down time for the gas pressure to drop from the switch to molecular flow regime to a pressure of 1.0x10-9 and the initial pressure for the molecular flow region.

Conclusions

The analysis above of the different factors in the way fastener filled holes vent in vacuum systems result in several clear conclusions. The collection of these conclusions is a nice summary that illustrates some concepts that will allow a design to be optimized for better vacuum performance when fasteners are used inside vacuum systems. Some general conclusions are added that came out of the details of the calculations done to illustrate the above data.

The conclusions are:

Conclusion 1

The conclusion is the more complete the venting method used by combining vented screws, vented washers and alternate access to the trapped volumes the better a vacuum can be achieved.

Table 4.

Pumping time for unvented and vented fasteners				
Example		1/4-20	10-24	8-32
Pumping vent	Volume pumped			
	Initial Pres.			
	Time for 1*10e-9			
No vent	Total volume			
	Initial press.	1.26E+00	1.20E+00	2.01E+06
	Time at 1.0*e-9	8.58E+05	8.15E+05	7.53E+05
Vented screw	Total volume			
	Initial press.	3.12E-02	3.79E-02	4.69E-02
	Time at 1.0*e-9	1.08E+01	1.69E+01	1.31E+01
Vented screw	End volume. EV			
	Initial press.	3.12E-02	3.79E-02	4.69E-02
	Time at 1.0*e-9	3.25E+00	6.74E+00	1.98E+02
Vented washer	Clear volume CV			
	Initial press.	1.97E-01	1.97E-01	1.97E-01
	Time at 1.0*e-9	7.64E+02	3.71E+02	1.89E+02
Lock washer	Clear volume CV			
	Initial press.	3.18E-02	4.19E-02	4.92E-02
	Time at 1.0*e-9	1.53E+01	9.10E+00	6.44E+00
Slotted screw	End volume EV			
	Initial press.	1.97E-01	1.97E-01	1.97E-01
	Time at 1.0*e-9	4.90E+02	1.57E+03	6.17E+02
Slotted screw	Volume EV + FT			
	Initial press.	1.97E-01	1.97E-01	1.97E-01
	Time at 1.0*e-9	2.38E+03	4.50E+03	2.00E+03

More importantly the time required to establish a vacuum goal will be lower and less time will be spent trouble shooting the vacuum system.

Conclusion 2

The conclusion here is that one should always use a vented washer or a vented screw with a side vent to the threaded area. At this point the trapped volumes will eventually pump out. Next is how long does it take.

Conclusion 3

Vented holes are a key in reducing the sticky gases such as water and CO2 contained is a vacuum chamber because a lower pressure is obtained before going into the Molecular flow mode.

Conclusion 4

Use as large a tapped hole possible, given the strength of the fastener needed, when prepping for tapping a hole.

Conclusion 5

Use as course a thread as possible and the smallest thread size for that pitch, all to be consistent with the fastener strength needs.

Conclusion 6

Pay careful attention to keeping the volumes that need venting to be as small as practical. These volumes directly increase pump down time

Conclusion 7

Use the least length of engaged-threads because the more threads that are engaged the less pumping speed will be available through the threads.

Conclusion 8

Keep the amount of threads to a minimum in order to keep the amount of surface area in the volumes that need venting to minimize the quantity of adsorbed gasses.

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