HPR Research - Static Port Holes from Nescience to Science

The characteristic of scientific progress is our knowing that we did not know.
Gaston Bachelard

Purpose

In 1997 I was inspired by a television program showing individuals launching large rockets in western US deserts. At the end of the program Tripoli was listed in the credits, I found the web site on the internet, and joined the national organization as well as my local prefecture. I as many of you did this hoping to recapture the excitement of my youth – the space race along with a love of technology, engineering, and science. Although I've been able to rekindle much of this excitement over the years and recognize that this is a leisure pursuit, I have been somewhat frustrated and disappointed with the lack of engineering discipline and scientific methods exhibited in our hobby. This extends not only to the various official and unofficial forums but also to commercial materials. Undeniably, a few individuals have produced very informative web sites, some of which include experimental data along with results and conclusions.

The intention of this and subsequent articles is to dispel some of the misinformation propagated in our hobby through the use of scientifically derived material. The illusion of science as currently propagated is dangerous as it gives those using it a false sense of safety and security when applying such methods. It also steers these individuals down false paths when attempting to ascertain the root cause of failures (by steering them away from possible sources of the failure). This inevitably leads to an inability to identify or the misidentification of the root cause thereby eliciting future failures and safety issues. I repeatedly witness such churning when mentoring high school and collegiate rocket teams for the NASA Student Launch Program as well as the Experimental Sounding Rocket Association programs and as Technical Advisor for the Midwest High-Power Rocket Competition. Additionally, I see this with experienced rocketeers since they also assume that the prevailing material has been derived and tested using scientific methods.

Finally, I believe that three of Tripoli's organizational goals are to eliminate injuries and property damage, preserve and enhance our relationships with government agencies, and to curb insurance rates. By improving the information available to the membership we can reduce our failure rates and thereby improve safety which will help us accomplish all of these goals.

Prevailing Static Port Computations

The proper sizing of static port holes is critical to the correct operation of altimeters and thereby electronics based recovery processes. As many of you may know recovery system failures account for roughly 73%[1] of all flight failures and of these roughly 31.5%

[1] Launching Safely in the 21st Century – Final Report of the Special Committee on Range Operation and Procedure to the National Association of Rocketry (October 29, 2005). Retrieved from http://www.nar.org/wp-content/uploads/2014/08/launchsafe.pdf. Admittedly the data in this report is

are due to motor or electronic ejection system failures (≈23% of total flight failures). Although a number of different computational methods are published to size static ports they all share one or more of the following deficiencies:

1. Unknown derivation of equation (validity cannot be assessed)
2. Unjustified assumptions
3. Limited in scope (restricted set of volumes or number of static ports)
4. Equations contain undefined numerical factors

Some of this material takes the form of equations while other information is provided in tabular form. Let's examine some of prevailing material propagated over the internet as well as those available through commercial sources.

In the discussion below the following symbols will be used:

d_s – Diameter of the Static Port Hole(s)
l – Length of Avionics (AV) Bay
n – Number of Ports (restricted to positive integers)
r – Internal Radius of AV Bay

Equation 1

$$d_s = \frac{\pi r^2 l}{400} \; where\; n = 1 \; and \; \pi r^2 l \; \leq 100 \; in^3$$
$$d_s = \frac{2\pi r^2 l}{400n} \; where\; n > 1 \text{ and } \pi r^2 l \; \leq 100 \; in^3$$

This particular equation suffers from deficiencies 1, 2, 3, and 4.

Equation 2

$$d_s = 2r\sqrt{\frac{a_{ref}\, l}{v_{ref}\, n}} \;\; for\; n \geq 1 \; where$$

a_{ref} – Static port hole area of reference (recommends a ¼" hole - .049087 in^2)
v_{ref} – AV Bay volume of reference (recommends 100 in^3)

When substituting the recommended values one arrives at the following forms also found in the literature:

$$d_s \cong .04431\mathrm{r}\sqrt{\frac{l}{n}} \cong 2\sqrt{\left(\frac{.04908\pi r^2 l}{100\pi\mathrm{n}}\right)} \;\cong\; 2\sqrt{\left(\frac{\pi r^2 l}{6397.71\mathrm{n}}\right)}$$

This equation's derivation is demonstrated but suffers from deficiency 2 by using a widely popular rule of thumb that one should use a ¼" hole for every 100 in^3.

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skewed toward low and mid power rocketry; never the less it demonstrates that recovery is a significant cause of failure.

Equation 3

$$d_s = 0.2\mathrm{r}\sqrt{\frac{l}{19.68n}}\ for\ n \geq 1$$

This equation also suffers from deficiencies 1, 2, and 4.

Equation 4

<a>

$$d_s = .0016(4r^2)l\ where\ n = 1$$
$$d_s = .0008(4r^2)l\ where\ n = 4$$

<b>

$$d_s = .006(2r)l\ where\ n = 1$$
$$d_s = .006rl\ where\ n = 4$$

Both of these equations suffer from deficiencies 1, 2, 3, and 4.

Although other equations may exist these are sufficient to illustrate the prevailing propagation of misleading information.

In order to assess these equations we need to recognize that the volume of a cylinder is simply the area of its circular base times its length (Figure 1):

$$area\ of\ a\ circle\ A = \pi r^2$$
$$volume\ of\ a\ cylinder: V = \pi r^2 l$$

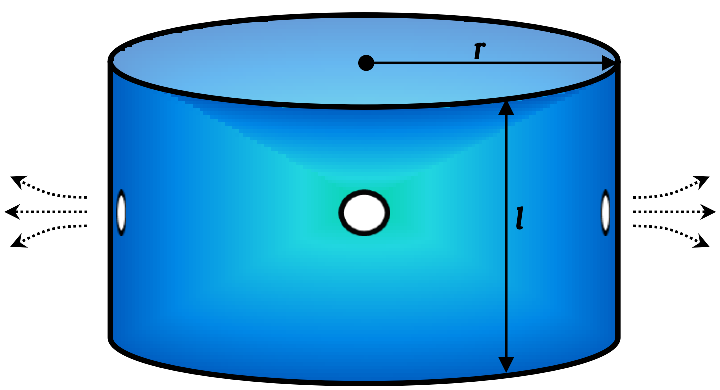

Figure 1 – AV Bay Pressure Equalization

Now let's examine the above equations. It should be obvious that the size of the static ports must be proportional with the volume of the AV Bay and that any reasonable equation would reflect this relationship. All of the equations above do this with the exception of 4b. It should also be apparent that any equation computing the static port size should result in a single value for a specific volume. If we use the following values:

$r_1 = 2$, $l_1 = 4$ then $V = 50.27$ in^3, $d_{s1} = .096$ in and $d_{s4} = .048$ in
$r_2 = 4$, $l_2 = 2$ then $V = 100.53$ in^3, $d_{s1} = .096$ in and $d_{s4} = .048$ in
$r_3 = 1$, $l_3 = 8$ then $V = 25.13$ in^3, $d_{s1} = .096$ in and $d_{s4} = .048$ in

This example shows that when doubling or halving the volume of the AV Bay the size of the static port hole(s) remains the same in both the single and the four port cases: clearly demonstrating that Equation 4b does not adequately account for variations in AV Bay volume. Consequently, Equation 4b should never be used.

Now let's look at the results generated by the remaining equations for the single port case (Figure 2) and the four port case (Figure 3).

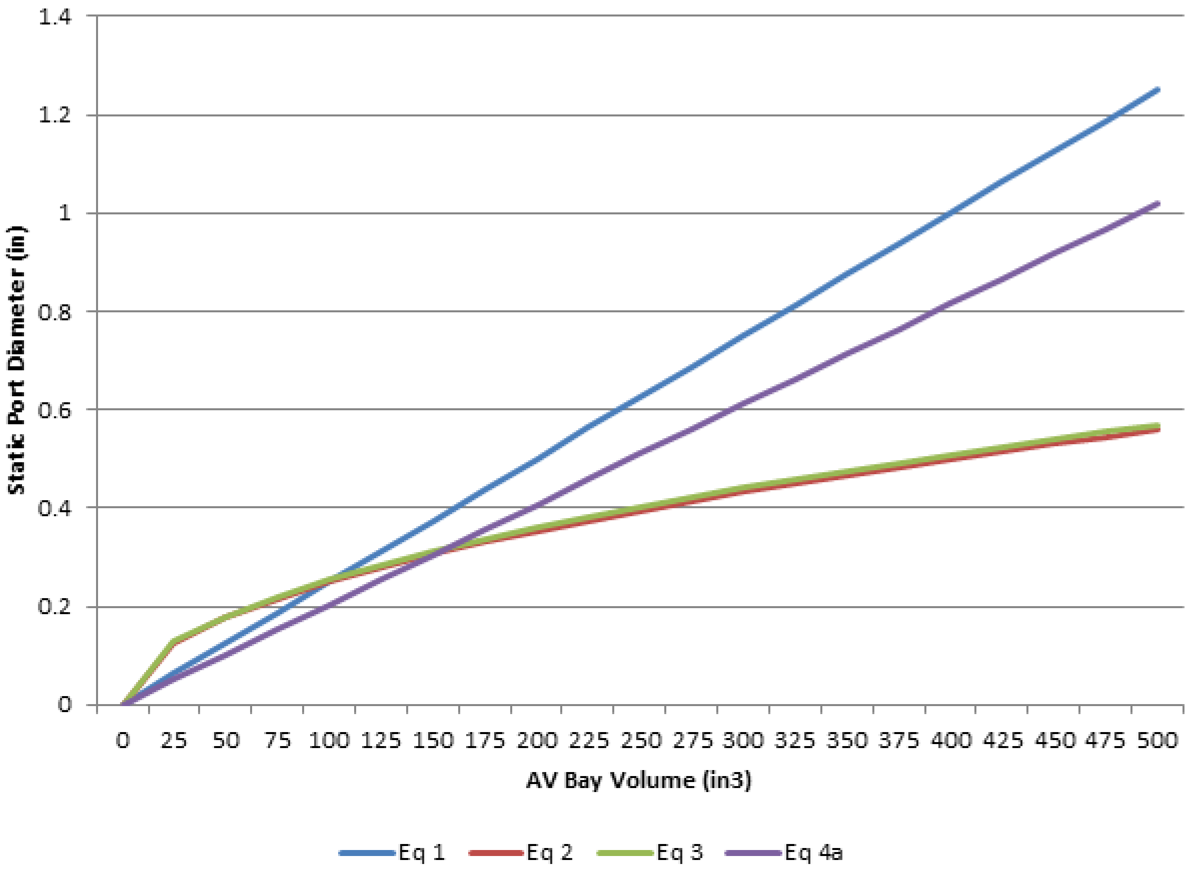

Figure 2 – Single Static Port Sizing

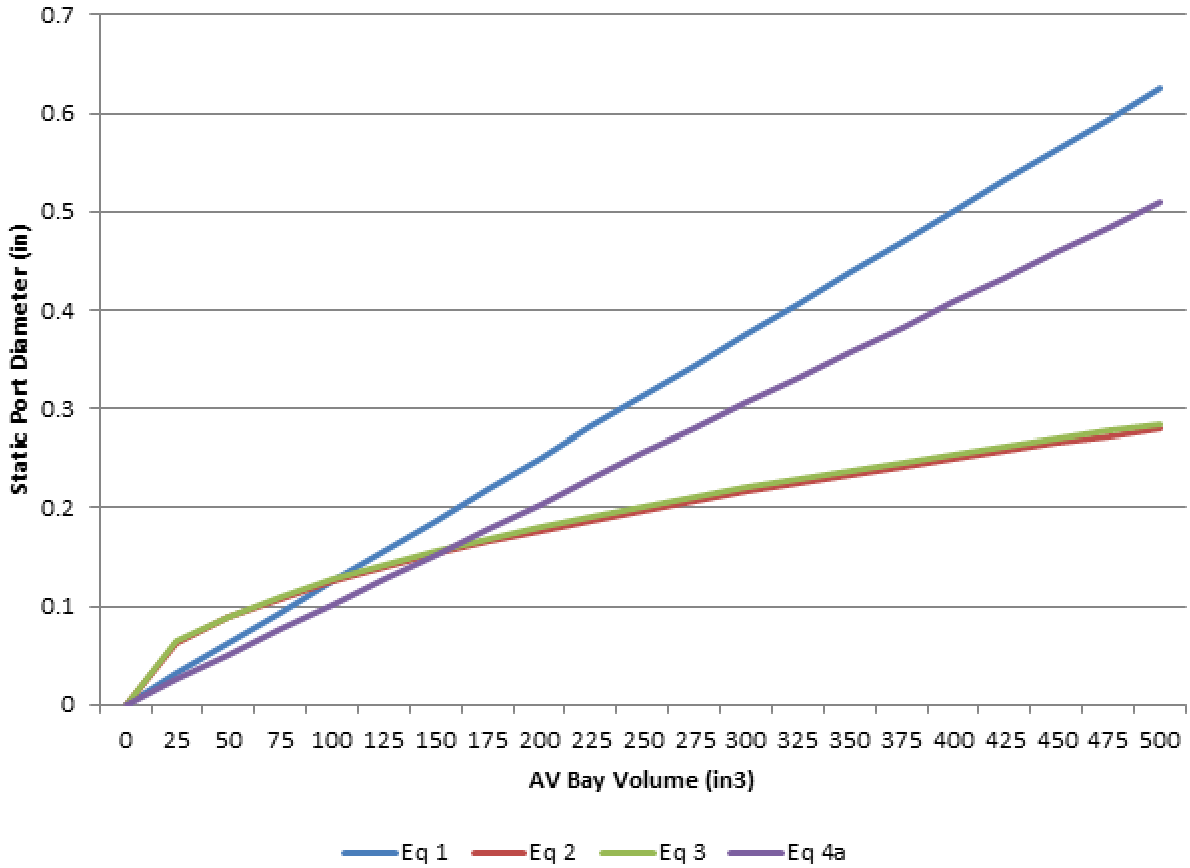

Figure 3 – 4 Port Static Port Sizing

Upon examination of these charts one can see that Equation 1 is an algorithmic expression for the rule of thumb of using a ¼" port for every 100 in^3. Furthermore, we also note that Equation 1 will always produce the same static port hole size for one or two ports which is clearly unrepresentative model of depressurization. Also notice that Equation 4a produces a port size that increases linearly with a linear increase in volume albeit at a reduced rate relative to Equation 1. As the volume of an AV Bay increases it is evident that the area of the static port hole(s) must also increase linearly in order to evacuate the air at the same rate. Considering that port area is proportional to the square of the hole diameter it is clear that Equations 1 and 4a do not accurately predict the static port hole sizes over a range of values in either single or multiple port scenarios.

It is specified that Equation 1 is limited in range, but to meet our safety and failure reduction goals we need a way of accurately computing the proper static port hole sizes over a broad range of AV Bay volumes. Although, we have not assessed whether the values produced in its limited range accurately predict the needed static port size these reasons are sufficient to discard Equation 1.

One also observes that Equations 2 and 3 are identical (accounting for a minor constant adjustment). Interestingly, the resultant port size does not expand linearly with a linear increase in volume. Upon examination of Figure 4 we can see that port areas generated from Equations 2 and 3 do expand linearly with volume so these equations behave as expected (-x indicates the number of ports in the figure) However, we still need to assess whether these equations produce the values that will properly evacuate our AV Bays.

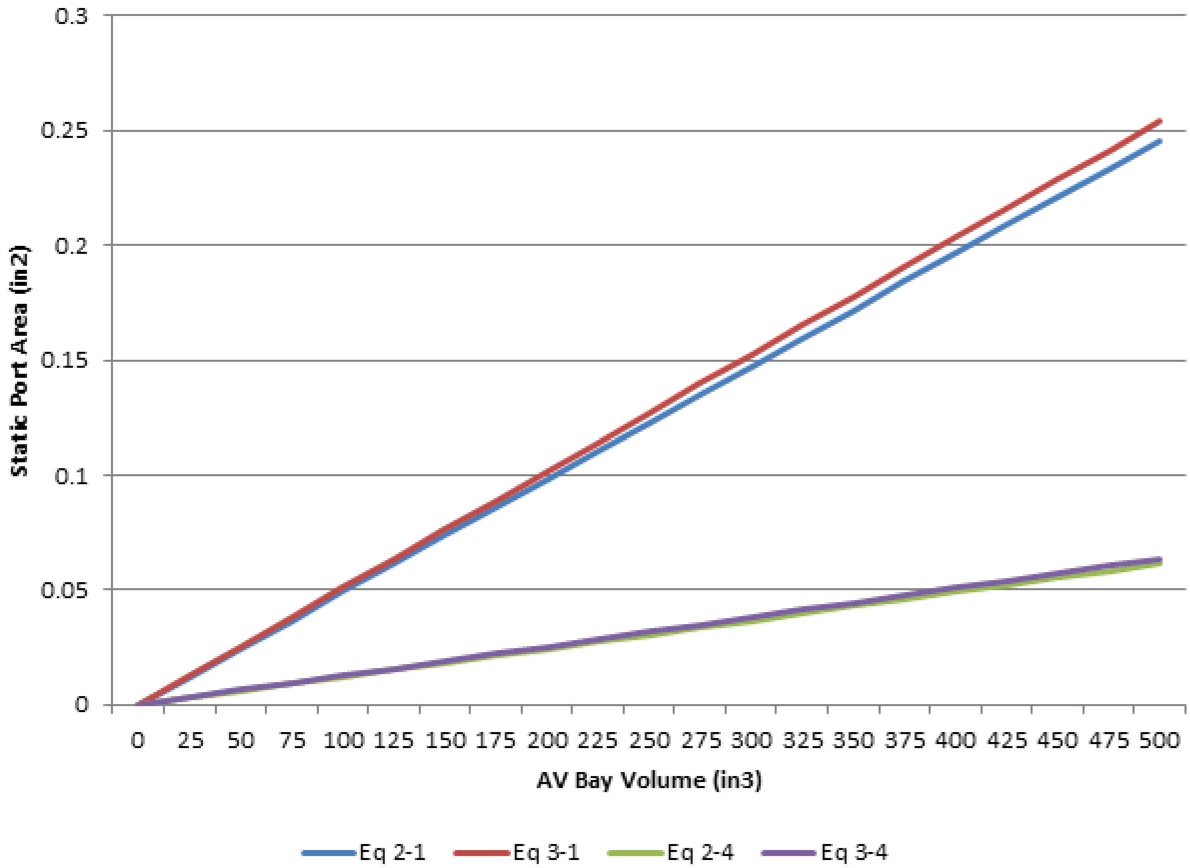

Figure 4 – Port Area vs AV Bay Volume

Although the derivation of Equations 1, 3, 4a, and 4b is unknown in some cases they may still be related to one another. Equation 3 appears to be in a similar form and produces similar results to Equation 2. By substituting the values recommended for Equation 2 we get the following:

$$d_s = 2r\sqrt{\frac{a_{ref}l}{v_{ref}n}} = 2r\sqrt{\frac{\pi\left(\frac{.25}{2}\right)^2 l}{100n}} = .2r\sqrt{\frac{\pi(.125)^2 l}{n}} = .2r\sqrt{\frac{l}{20.37n}}$$

Considering that Equation 3 originates from an area that uses the metric system the closest drill bits size that does not undersize the static port to .25” is 6.5mm. Substituting this value into the equation and converting 100 in^3 to mm^3 we get:

$$d_s = 2r\sqrt{\frac{\pi\left(\frac{6.5}{2}\right)^2 l}{1638706.4n}} = .2r\sqrt{\frac{\pi(3.25)^2 l}{16387.064n}} = .2r\sqrt{\frac{l}{493.8381n}}$$

Noting in the Entacore documentation that they recommend 500mm (not 493.8381) presumably since this is more convenient to compute and then performing the metric to imperial conversion we get:

$$d_s = .2r\sqrt{\frac{l}{493.8381n}} \approx .2r\sqrt{\frac{l}{500n}} = .2r\sqrt{\frac{l}{19.68n}} \approx \ .2r\sqrt{\frac{l}{20.37n}}$$

Equations 1 and 4a also appear to be related:

$$d_s = \frac{\pi r^2 l}{400} = \frac{4\pi r^2 l}{4(400)} = \left(\frac{\pi}{1600}\right) 4r^2 l = \ .0019635(4r^2)l \ \approx \ .0016(4r^2)l$$

Since the four hole case of Equation 4a is simply the single hole value divided by two it also corresponds to the four hole version of Equation 1. It appears that all of these equations are using a rule of thumb of ¼" per 100 in^3 as their basis (although you can vary this with Equation 2 but it is not specified under what circumstance you should do so nor is any guidance given on how to make such variations). Where did this rule of thumb come from and does it have any scientific basis? I do not know and will leave that to a High Power Rocketry (HPR) historian or archeologist to uncover.

Improved Static Port Sizing

Consider that an avionics bay is simply a container traveling through space where the atmospheric pressure steadily decreases or increases based on the direction of travel. Also note that the external atmospheric pressure rate of change is dependent upon the vertical velocity of the rocket. Finally, note that the rate of pressure equalization between the avionics bay and the atmosphere is dependent upon the pressure differential between them. Alternatively, this can be modeled as a static pressure vessel where the external atmospheric pressure is reduced or increased. For the following discussion I will be employing the following assumptions:

1) Incompressible air flow
2) Bernoulli effects are negligible
3) Atmospheric pressure and temperature changes during flight are disregarded

Unlike the earlier equations our model should account for internal/external pressure differential, gas density, among other factors. Discharging of a gas through an orifice is a specialty in fluid dynamics and as depicted below has been modeled as part of this discipline.[234] When a gas is discharged through an opening into the atmosphere the gas

[2] "Perry's Chemical Engineers' Handbook", Seventh Edition, McGraw-Hill Co., 1999. Retrieved from http://files.rushim.ru/books/spravochniki/Perrys-Chemical-Engineers-handbook-1999.pdf.

velocity through that opening (static port) may be choked (the gas has reached the maximum velocity limit) or non-choked. Choked velocity (aka sonic velocity) is reached when the ratio of the absolute source pressure to the absolute ambient pressure is greater than or equal to:

$$\left(\frac{k+1}{2}\right)^{\frac{k}{k-1}} \textit{ where k is the specific heat ratio of the discharge gas}$$

In our case the specific heat ratio of air is 1.401 (may vary with temperature and pressure by ±.001) and the choked threshold from the above equation is 1.8935. This implies that the choked velocity occurs when the source pressure (AV Bay) is 1.8935 times greater than the external atmospheric pressure. Assuming one is launching from sea level under standard atmospheric conditions this implies that if an AV Bay were perfectly sealed one would not need to be concerned with choked velocity until attaining an altitude equal to or exceeding 16,636.4 feet. It should be noted that by starting at sea level we have generated the most conservative altitude difference. Starting at higher altitudes would result in slightly larger altitude separations prior to attaining a pressure difference for choked flow. Clearly, since AV Bays are open to the atmosphere and high power rockets are not traveling at velocities which would prevent pressure equalization in the allotted travel time (more on this momentarily) we need not concern ourselves with choked air flow.

The equation for the initial instantaneous mass flow rate of non-choked (i.e. sub-sonic) gas velocity with the source gas at a specific temperature and pressure is:

$$Q = ca_s\sqrt{2\rho P\left(\frac{k}{k-1}\right)\left[\left(\frac{P_A}{P}\right)^{\frac{2}{k}} - \left(\frac{P_A}{P}\right)^{\frac{k+1}{k}}\right]} \langle Eq\ 5\rangle$$

Q - mass flow rate (kg/s or lbm/s)
c - discharge coefficient (dimensionless, 0.62 for sharp edged orifices in thin plates)
a_s – discharge (static port) hole area (m^2 or ft^2)
ρ – gas density at temperature and pressure (kg/m^3 or lbm/ft^3)
P – source absolute pressure (Pascals or $lbm/ft\text{-}s^2$)
P_A – ambient absolute pressure (Pascals or $lbm/ft\text{-}s^2$)
k – c_p/c_v of the gas (dimensionless, isentropic expansion coefficient) which is equivalent to (specific heat at constant pressure) / (specific heat at constant volume). For air at the typical temperatures and pressures we operate at the value is 1.401±.001 (increases with temperature decreases and/or pressure

[3] "Risk Management Program Guidance For Offsite Consequence Analysis", U.S. EPA publication EPA-550-B-99-009, April 1999. [Equation (D-1), Section D.2.3, and Equation (D-7), Section D.6, Appendix D. Retrieved from http://www2.epa.gov/sites/production/files/2013-11/documents/oca-apds.pdf].
[4] "Methods For The Calculation Of Physical Effects Due To Releases Of Hazardous Substances (Liquids and Gases)", CPR 14E, Third Edition Second Revised Print, The Netherlands Organization Of Applied Scientific Research, The Hague, 2005 [Equations (2.22), (2.25), and (2.28a) on pages 2.68-2.69]. Retrieved from http://www.bib.ub.edu/fileadmin/fdocs/PGS2-1997.pdf.

increases and conversely decreases with temperature increases and/or pressure decreases).

We will use the mass flow rate equation to solve for the static port hole area and then derive the hole diameter using the area of a circle equation for n holes.

$$a_s = \frac{n\pi d_s^2}{4} \; where\; n\; is\; a\; positive\; integer \; \langle Eq\ 6\rangle$$

We will estimate the mass flow rate by calculating the air mass within the AV Bay and then applying a discrete pressure differential based on altitude and time. In order to calculate the mass flow rate we will use the following equation:

$$Q_E = \frac{\pi r^2\, l\rho\left(\frac{P-P_A}{P}\right)}{t} \; \langle Eq\ 7\rangle$$

During the following discussions I will use Standard Atmospheric[5] values at sea level. In Equation 7 $\pi r^2\, l$ is simply the volume of the AV Bay. However, in order to compute the mass flow rate we need to know the mass of the fluid (gas) so we will multiply the volume of the gas by its density where $\rho = 1.225$ kg m^{-3}. Next we need to understand the difference in pressure between the AV Bay and the ambient environment. To do this let's make a simplifying assumption that the pressure changes discretely every meter of altitude (obviously the change is continuous). Given that the percentage change varies with altitude and temperature we will choose a conservative value of .0126% (sea level is .0113%). Finally, we need to select a time period over which the chamber is evacuated. This would be done by assessing the velocity at which the rocket is changing altitude. Let's assume we are travelling vertically at 400 m/s (≈Mach 1.2). In this case we would then want to evacuate the AV Bay every .0025 sec (the time it takes to travel a meter). What happens if we don't empty the AV Bay fast enough? The relative differential pressure will surge and the rocket will experience a lag in its barometric sensor readings (and derivative computations) until it slows down enough for the AV Bay pressure to equalize with the atmosphere.

By combining Equations 5, 6, and 7 to solve for d_s and substituting Q_E for Q we get:

$$d_s = \sqrt{\frac{4Q_E}{\pi n c\sqrt{2\rho P\left(\frac{k}{k-1}\right)\left[\left(\frac{P_A}{P}\right)^{\frac{2}{k}} - \left(\frac{P_A}{P}\right)^{\frac{k+1}{k}}\right]}}} \; \langle Eq\ 8\rangle$$

Upon examination of Figure 5 we see that the Equation 8 results in static port sizing that follows the appropriate curve (the area not the diameter changes linearly with volume)

[5] "The Engineering ToolBox", Retrieved from http://www.engineeringtoolbox.com/standard-atmosphere-d_604.html

and generates a static port diameter that is smaller in size than the other equations. After a cursory assessment one may determine that the differences are immaterial. However, after examining Figure 6 and Figure 7 it must be concluded that such an assessment would be shortsighted. Specifically,

1) Optimal static port sizes vary based on the absolute pressure differential between the AV Bay and atmosphere. This differential is dependent upon the velocity since it dictates the rate of evacuation.
2) Optimal static port sizes also vary slightly based on altitude and temperature

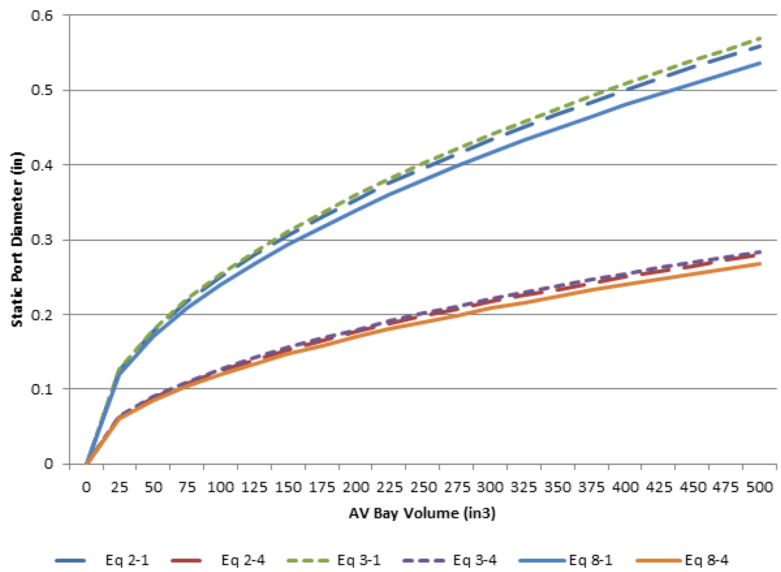

Figure 5 – Equation Comparison @ Mach 1.2

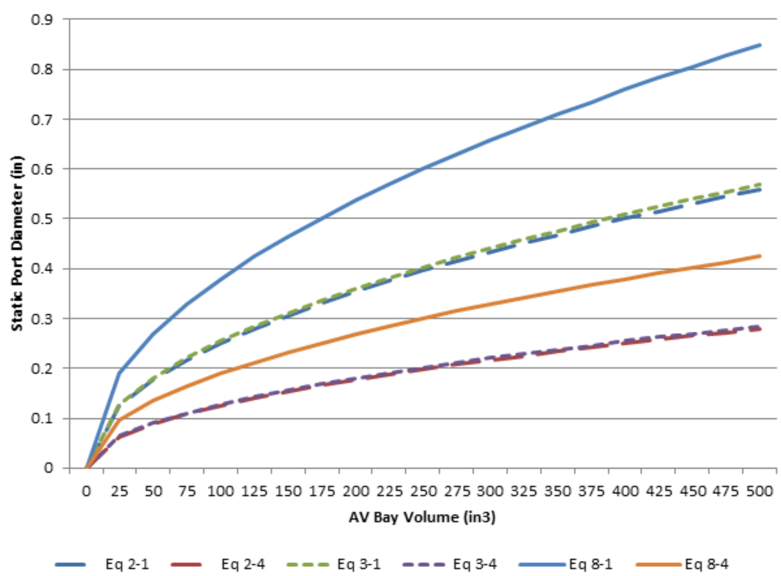

Figure 6 – Equation Comparison @ Mach 3

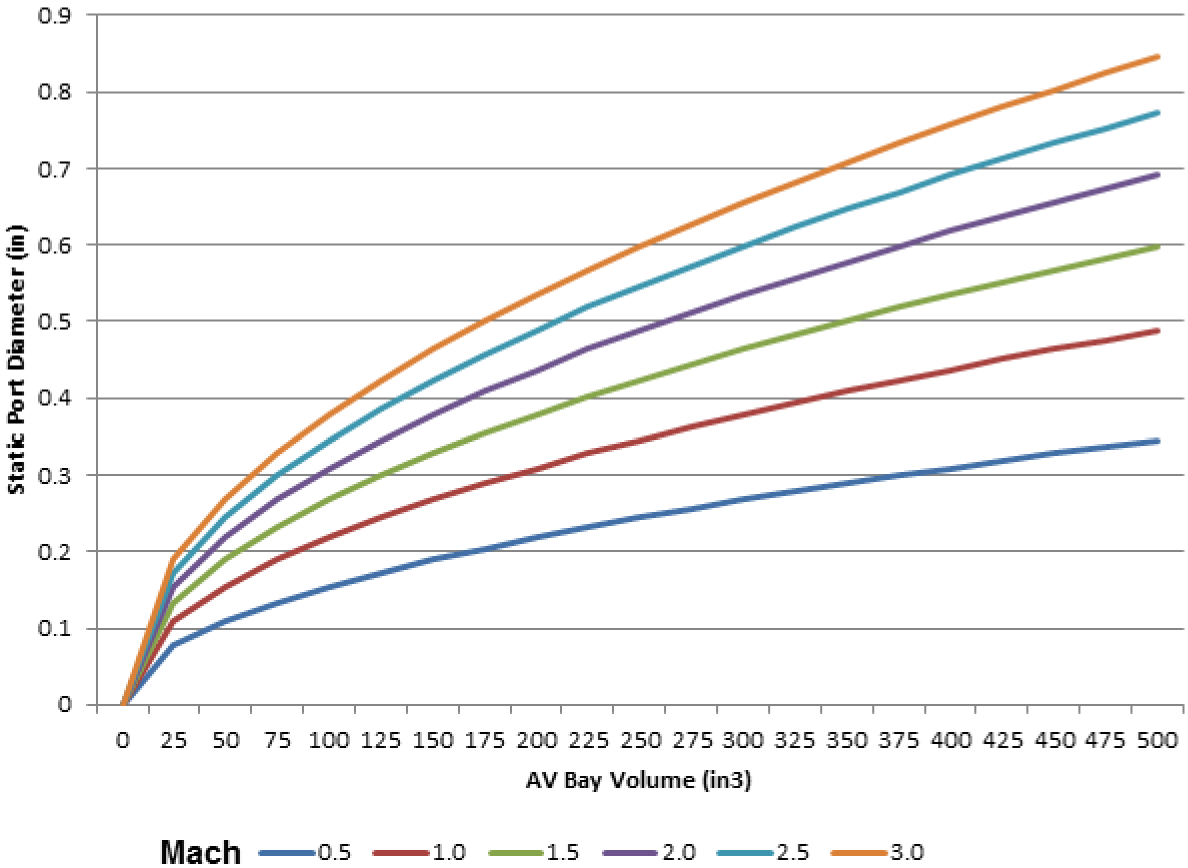

Figure 7 – Single Port Size by Mach Velocity

At the beginning of this discussion we made three assumptions. Incompressible flow is reasonable until your rocket begins traveling above Mach 0.3. Above these speeds we need to minimize the effects of pressure waves and turbulence. Therefore, the static ports must be positioned without obstructions in the airstream above them in order to maximize the possibility of laminar flow. Since compressibility may affect the air density this is an area for improvement of the provided equations. Bernoulli effects caused by the flow of a gas over an opening would typically result in a decrease in ambient pressure effectively creating an increase in pressure differential resulting in more rapid evacuation of the chamber. Again further analysis is required but this effect may counter the compressible flow effects to a small or perhaps large degree. Finally, the continuous variations in atmospheric pressure and temperature as well as AV Bay chamber pressure during the flight might be accounted for through the application of calculus but I have not performed such inferences.

During the course of our discussion we also disregarded choked flow. This would be a concern under the following scenarios:

1) Static ports are undersized
2) High velocities

Under sizing of static port holes is not recommended as this would result in a reporting lag by the barometric sensors in the AV Bay which may negatively impact altimeter operations. Excessively high velocities (in excess of Mach 15) may result in choked flow situations. I am unaware of any amateur rocket flying at these velocities so I have not included those equations in this document.

Equations 7 and 8 have been used successfully for the past four years to design and implement static ports with the collegiate teams as well as others I've advised. No deployment failures have been traced back to inadequate static port sizing. Admittedly the equations are not as simple to use as earlier albeit inaccurate ones. Therefore, I have provided a spreadsheet accessible to any who desire it in the Resources section of my web site: www.offwegorocketry.com.

Recommendations

The reasoning depicted in this paper has not only demonstrated that the sizing of static port holes is critical to the evacuation of AV Bays but that the solutions derived from existing models are inadequate for a broad range of scenarios. Therefore, the following recommendations are made:

1. Use Equations 7 and 8 as described in this paper to determine the minimum static port hole size required based on your AV Bay size and maximum expected velocity. Discontinue the use of Equations 1, 4a and 4b under all circumstances and Equations 2 and 3 particularly when conducting supersonic flights.
   This paper has not addressed the gas flow within AV Bays resulting from the use of static ports. This is left for another and may require the use of Computational Fluid Dynamics to assess whether oversizing static ports truly results in increased turbulent flow within AV Bays. Until that time it is recommended to size the static ports as closely to the size needed as specified by the supplied equations. It is not recommended to undersize the static ports due to the inevitable lag in sensor readings.
2. Ensure that all static port holes are drilled cleanly with square edges. If they are not the value of the discharge coefficient will change and/or the static port hole area is reduced (consider fiber strands blocking the airstream).
3. At a minimum use three static ports evenly spaced around the circumference of the AV Bay.
   As stated in recommendation 1 this paper has not addressed the gas flow within AV Bays resulting from the use of static ports. Again this requires further analysis; however, all my tests have been conducted with three or more static ports. Conventional wisdom is that multiple evenly spaced static port holes will reduce the amount of turbulence experienced inside of an AV Bay.

Conclusion

It has been shown that the prevailing computations for static port sizing do not model the AV Bay evacuation process accurately and at worst will provide flyers with a false sense of security that may result in repeated flight failures. Consequently, their propagation does not support Tripoli's safety goals. Finally, it has been shown that Equations 7 and 8 can be used to more accurately predict static port sizes particularly those with large AV Bays and/or travelling at high velocities thereby leading to improved safety.

Acknowledgements

The author wishes to thank Dale Hagert (#11958) for his review of this article and insightful comments.

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