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Propellant Management Device Conceptual Design and Analysis: Sponges

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PROPELLANT MANAGEMENT DEVICE CONCEPTUAL DESIGN AND ANALYSIS: SPONGES

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ABSTRACT

While surface tension devices have been used in liquid propellant tanks for almost thirty years, the conceptual design process and the analytical methods used to verify performance have been closely held by propellant management device (PMD) designers. With the proliferation of micro computers, the sophistication of these analytical techniques has greatly advanced. These advances have gone largely unpublished. This paper is the second in a series which will address the process and the techniques developed and used by PMD Technology to design and verify one PMD component - the sponge.[1]

All areas of concern inherent in sponge design and implementation will be addressed - starting from the dictating requirements, proceeding into the design configuration choice, and ending with required performance analysis. The result is a cohesive process by which one may design and verify sponge PMD components.

I. INTRODUCTION

Surface tension forces are negligible in most engineering problems. However, in the low gravity environment of orbiting vehicles, surface tension forces are significant and often dictate the location and orientation of liquid within vessels, conduits, etc. By carefully designing structures within a propellant tank, one can utilize these forces to ensure gas free propellant delivery. These structures have come to be known as propellant management devices or PMDs.

Traditionally PMDs are designed for each specific mission scenario and tank size. As a result PMDs can be found in numerous sizes and configurations. PMD components can be classified into two broad categories: control devices and communication devices.[2] By definition, control PMDs provide gas free propellant delivery by controlling propellant within the tank. The sponge type PMD is such a device.

For this paper, a sponge device is defined as an open structure which a) holds and provides a specific quantity of propellant using surface tension forces and b) is refillable. This definition excludes other control devices such as troughs - which do not use surface tension to hold propellant, traps - which are not refillable, and start baskets - which are not open structures. Because all conventional propellants wet, propellant tends to cling to crevices and form fillets in the spaces between sponge panels. Figure 1 illustrates the propellant within a conventional sponge under a lateral acceleration. A conventional sponge is defined as a device consisting of planar panels separated by a tapered gap.

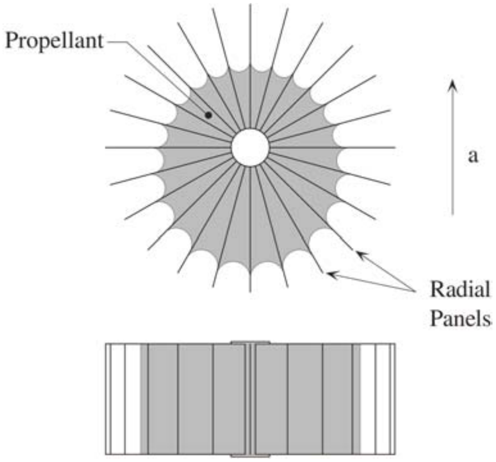

Figure 1. A Conventional Sponge with Liquid Attached

The sponge design process starts with the evaluation of the mission requirements to determine whether a sponge, or sponges, are suitable. Once suitability is established, the design configuration and the design details must be explored. Finally, with the design established, a thorough analytical investigation is conducted to verify performance. This last step is particularly important since sponges are not ground testable and performance verification relies entirely on analysis.

This paper progresses along the same track as the design process. Section II addresses the physics of sponge holding and presents the governing equations. Section III describes the uses of sponges and establishes the requirements leading to sponges. Section IV presents the major design choices and discusses the utility of each option. Finally, Section V presents the analytical techniques used by PMD Technology to verify sponge design.

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II. PHYSICS

The propellant illustrated in Figure 1 will remain within the sponge against the hydrostatic forces only if the upper radius is sufficiently smaller than the lower radius. In basic terms, the pressure difference in the liquid created by the surface tension forces will be balanced by the hydrostatics and the flow losses through panels. If the pressure difference in the liquid is insufficient to balance the hydrostatics, the sponge will leak or drip. A simplified set of equations follows.

The pressure difference across the gas-liquid interface resulting from the surface tension forces is defined by the Laplace equation:[3]

$$\Delta P \equiv P_{gas} - P_{liquid} = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{1}$$

Thus, the pressure difference within the liquid from the lower to the upper side of the sponge is approximately:

$$\Delta P_{st} \equiv P_{low} - P_{up} = \left[P_{gas} - \sigma\left(\frac{1}{R_{low}}\right)\right] - \left[P_{gas} - \sigma\left(\frac{1}{R_{up}}\right)\right]$$

$$\Delta P_{st} = \sigma\left(\frac{1}{R_{up}} - \frac{1}{R_{low}}\right) \tag{2}$$

The radii, R_{up} and R_{low}, can be approximated as the fillet radii occupying the gap between sponge panels as illustrated in Figure 1, or more exactly, as the mean Gaussian radii of curvature. For this presentation of the basic equations, the radii are equal to one half the sponge panel gap and the errors associated with one dimensionality are accepted (if the gaps are quite large relative to the sponge size this assumption will not be accurate).

Assuming negligible flow losses, the surface tension pressure difference is opposed only by the hydrostatic pressure difference.

$$\Delta P_{hydrostatic} = \rho\ a\ \Delta z \tag{3}$$

As an approximation, one can equate the surface tension pressure difference to the hydrostatic pressure difference. Given a specific sponge, and thus a relationship between R and Δz, the resulting equation can be solved for one of the two independent variables, R_{up} or R_{low}:

$$\sigma\left(\frac{1}{R_{up}} - \frac{1}{R_{low}}\right) = \rho\ a\left(z_{up} - z_{low}\right) \tag{4}$$

Given a specific sponge, one can compute the propellant surface location above (or below) the sponge center with R_{low} (or R_{up}).

While the physics of sponge holding can be explained by a relatively simply equation, the implementation of the equation within the bounds of a real sponge with boundaries (creating edge stable fillets), finite thickness panels (complicating the computations), and three dimensional geometry, is not as simple. In addition, other sponge phenomenon must be examined to determine sponge viability including leaking, dripping, gas bubble ejection, propellant location stability and, of course, propellant consumption. This basic force balance, relating R_{up} and R_{low}, is a good tool for estimates and feasibility studies.

The following aside presents an example of how this approach could be applied to a specific sponge.

Aside - Section II

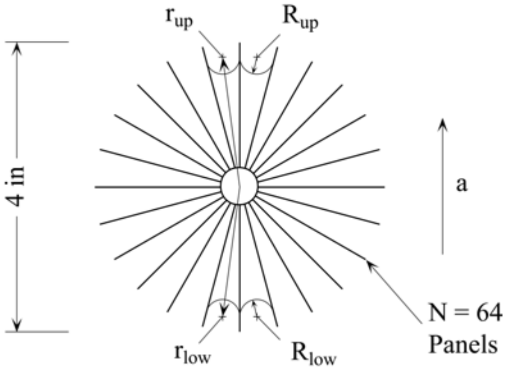
Assume:

a) the propellant is NTO (lower surface tension than MMH and therefore the worst case),
b) the lateral acceleration is 0.005 g,
c) the sponge is illustrated in Example Figure 1, and
d) the upper radius, R_{up}, is 0.05 inches (r_{up} = 1.02 inches)

For this type of sponge - one where the panels are radial, the approximate relationship between Δz and R can be substituted into equation (4) yielding:

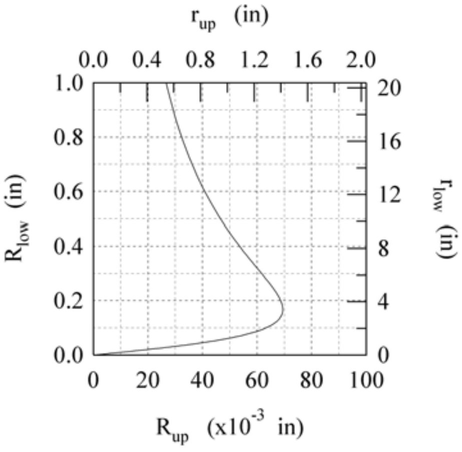
$$\sigma\left(\frac{1}{R_{up}} - \frac{1}{R_{low}}\right) = \frac{\rho\ a}{\sin\frac{\pi}{N}}\left(R_{up} + R_{low}\right)$$

Here, N is the number of panels and gaps. Given an R_{up} of 0.05 inches, the lower radius (R_{low}) of the propellant clinging to the sponge is 0.0625 or 0.449 inches. Two solutions result from the nature of the equation. These radii of curvature are equivalent to r_{low} = 1.27 inches at R_{low} = 0.0625 inches and r_{low} = 9.15 inches at R_{low} = 0.449 inches. One of these two solutions lies on the surface curve containing the initial point, 0.05 inches, while the other is disconnected and not on the same surface curve.



Example Figure 1. Example Sponge

Example Figure 2 shows the relationship between the upper and lower radii of curvature for this sponge. Note that no solutions exist for R_{up} greater than 0.069 inches ($r_{up} > 1.41$ inches above the center of the sponge). Thus, one could surmise correctly that if r_{up} is greater than 1.41 inches, no stable surface exists and the sponge will drip.



Example Figure 2. R_{up} vs. R_{low} & r_{up} vs. r_{low}

The maximum volume per unit height of sponge can be roughly estimated by averaging the radii, r_{up} and r_{low}, at the limiting case, and computing the circular area based upon this mean radius. For this example, a rough estimate of the maximum volume per unit height is:

$$\frac{V}{h} = A \approx \pi r_{mean}^2 = \pi\left(\frac{1.4 + 3.4}{2}\right)^2 = 18 \text{ in}^2$$

This may not be the maximum volume per unit height if the sponge radius is less than r_{low}. In this example, the sponge radius is 2.0 inches and r_{low} is 3.4 inches. Therefore, the actual deliverable volume per unit height will be less than 18 in^2 (which should have been anticipated since the total sponge area is less than 13 in^2).

This simple examination of a particular sponge illustrates how a sponge holds propellant against adverse accelerations but does not address all of the issues. Other issues include edge stability, the propellant location throughout the sponge, leakage, gas bubble ejection, and the flow characteristics within the sponge.

III. USES

The principal advantages of surface tension PMDs over diaphragms or positive expulsion devices are low mass, reliability (no moving parts), and compatibility (100% Titanium designs are possible). However, diaphragms can deliver gas free propellant in any attitude, in any quantity and at almost any flow rate or acceleration. While sponges can deliver propellant in any attitude, they can deliver only specific quantities at limited accelerations.

Traditionally, the three principal uses of sponges are in: settling thrust systems requiring propellant access during engine ignition, systems requiring repeated use of a specific quantity of propellant for a specific maneuver (such as stationkeeping), and systems requiring some propellant (and thus center of gravity) control in zero or low g. Sponges are in use in both monopropellant and bipropellant systems.

This section will address these uses and describe how viability is determined for each system. Before embarking upon the design of a sponge device, the requirements should be evaluated to determine if a sponge is viable and if the subsequent design effort is justified.

Ignition Systems

Ignition systems require gas free delivery during engine ignition while propellant is settling over the tank outlet. In this instance, the PMD must deliver a specific amount of propellant to the outlet. This amount depends upon the reorientation time and the demand flow rate.

Repeated delivery of a specific quantity of propellant requires the PMD designer to look at refillable partial control devices - ones that can control a specific quantity of propellant for delivery to the outlet and can be refilled. These include sponges, start baskets (also known as venting traps), and possibly vanes. The sponge PMD is the simplest, least costly, and most reliable of these PMD options. Unfortunately, sponge PMDs are unable to hold propellant during moderately high adverse accelerations so their viability is more limited than start baskets.

Figure 2 illustrates a sponge device used for engine ignition in a typical propellant tank. A large porous element is located under the sponge to provide flow area for the higher propellant flow rates typical of main engine firing.

Often, ignition systems use separate main thrust and attitude control systems. A sponge used in the main tanks must hold, but not deliver, propellant during the adverse accelerations produced by the attitude control system (as well as during any drag accelerations). The sponge must hold enough propellant for main engine ignition. This quantity equals the demand flow rate multiplied by the reorientation time. For the viability determination, the reorientation time can be estimated as three to five times the free fall time, if the tank Bond number is greater than ten.[4]

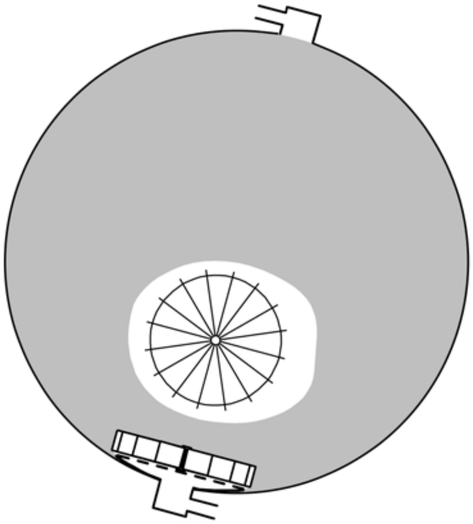


Figure 2. Sponge Concept for an Ignition System

Given the propellant volume required during reorientation and the maximum lateral acceleration, sponge viability can be determined by examining a conventional sponge. The sizing process is iterative. A sponge design is chosen and the deliverable volume computed. If the volume is insufficient, a larger sponge with more panels is assumed and the process repeated. A sponge is not viable is the demand volume cannot be met. Please note that if the sponge must hold against adverse accelerations as well as lateral accelerations, an examination of those accelerations must be conducted as well.

The propellant quantity demanded during engine ignition varies greatly and no typical case can be presented. However, sponges are generally useful for engine ignition if the demanded propellant quantity is less 250 in^3 and the lateral or adverse accelerations are less than 0.007 g in bipropellant systems. Slightly higher accelerations are acceptable in hydrazine systems. These limits are dictated by the capability to manufacture and place straight panels in proximity to one another.

These acceleration and volume limits are by no means exact; they are meant as guidelines. If an application requires holding against a 0.1 g adverse acceleration then a sponge is probably not viable, but at 0.01 g a sponge may be viable if the volume required is small.

After ignition, the propellant is settled over the outlet and the sponge must allow flow to reach the outlet. The sponge only functions to reduce or eliminate surface dip and vortexing. Since ignition system flow rates generally are high, the propellant access window is large and located under the sponge. Once the burn ends, the sponge must hold propellant against adverse accelerations in order to be ready for the next engine ignition. Since propellant is settled over the sponge by the main thrust acceleration, the sponge has been refilled for the next ignition. Refilling requires no other PMD component.

Specific Demand Systems

Another use of sponges is in specific demand systems. Specific demand systems require repeated use of a specific quantity of propellant. The most popular example is stationkeeping on communication satellites where burns may use 5 lbm of propellant, produce lateral acceleration on the order of 0.01 g, and occur only once every week or so. Sponge use in specific demand systems is not limited to stationkeeping maneuvers and may occur during any repetitive maneuver.

To meet intermittent demand, the designer should consider three PMD components: a) a refillable sponge, b) a trough or c) a communication device such as a gallery. If viable, a sponge is the best choice since it is lighter, simpler and more reliable than the alternatives.

A sponge must not only hold propellant during lateral accelerations but also must deliver propellant. This differs from ignition systems that require delivery during settling accelerations but not during the lateral accelerations.

A sponge concept designed to meet a specific demand is illustrated in Figure 3. Vanes are required to refill the sponge during the zero g coast that separates maneuvers.

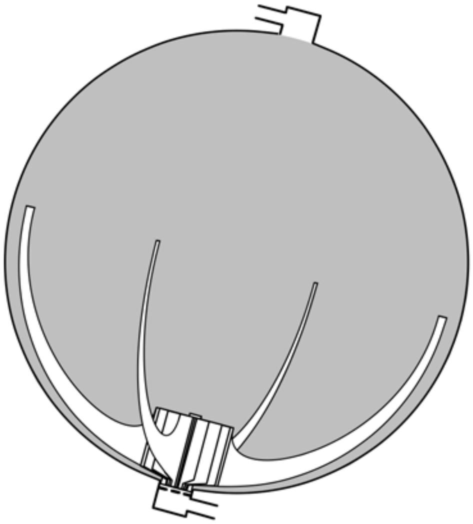


Figure 3. Sponge Concept for a Specific Demand System

As before, viability is determined by establishing that a conventional sponge can hold a sufficient quantity of propellant to meet demand. Typically, a safety factor of two is applied to the volume. Thus, if 30 in^3 is required from the sponge for the maneuver, the sponge should hold and deliver at least 60 in^3. The sizing process is iterative. First a sponge's dimensions are assumed then the deliverable area determined. With the deliverable area known, the required sponge height can be computed. If the height is unacceptable, new dimensions are assumed and the process repeated. Sponges should not be allowed to be too high if the access window is located under the sponge as this will result in large sponge propellant residuals.

Propellant Control Systems

The last use of sponges is in systems requiring control over the propellant for pointing or other reasons. If a sponge is designed on the order of the tank size, it will hold the majority of the propellant. The propellant in the tank can be preferentially located or controlled with such a sponge. One can even design a sponge to push the gas bubble into a preferred location - i.e., centered at the top of the tank.

Such a sponge was used in the Viking Orbiter bipropellant tank.[5] The sponge was designed a) to minimize propellant disturbances resulting from reorientation during main engine ignition and b) to position the gas bubble over a venting tube to enable depressurization should thermal conditions drive the tank pressure dangerously high.

An example of a sponge device fitted into tank for use in a propellant control system is illustrated in Figure 4.

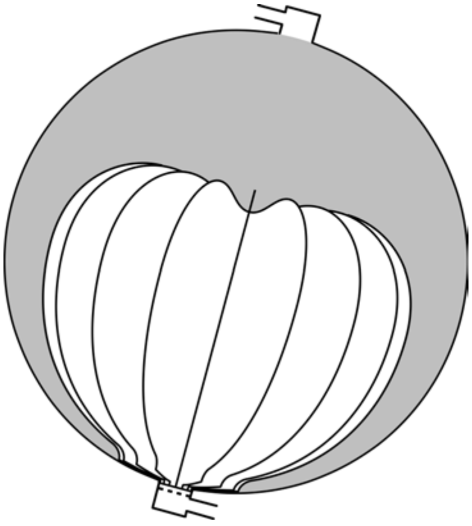


Figure 4. Sponge Concept for a Propellant Control System

Obviously as the sponge grows in size, the number of panels must be reduced to keep the mass reasonable. Thus the lateral holding capability is much lower than smaller sponges (on the order of 1 x 10^{-5} g in bipropellant systems and slightly higher in monopropellant systems). Higher lateral accelerations are possible with less propellant control.

In addition to analyzing propellant holding by the sponge, the position of the gas bubble must be addressed by examining the position of the sponge panel edges in relationship to the tank wall. First, a taper should exist between the tank wall and the panel edge to force the bubble to the preferred location (at the top of the tank in Figure 4). Second, the distance from the panel edge to the tank wall must be large enough to ensure that the gas bubble will not break up into smaller bubbles that are more difficult to center.

Though very interesting, these requirements for bubble centering are beyond the scope of this paper and must be addressed at a later date.

IV. DESIGN

The simple sponge illustrated earlier in Figure 1 is only one of numerous possible sponge designs. This section will address qualitatively, and in some cases quantitatively, the various design issues. The design choices can be divided into four categories: sponge panel placement and the resulting gap taper, sponge panel porosity, sponge location relative to other components, and propellant access window position.

Sponge Panel Placement and Resultant Gap Taper

Sponge panels need not be placed, as previously illustrated, extending radially and linearly from the sponge center. In fact, most sponges do not use radial panels. Radial sponges are used as examples in this paper because they are simpler to analyze and illustrate. A sponge could be designed with panels in a variety of positions: with panels that taper away from a plane, with panels which are accordionned to produce tapers in two directions, with panels which are conical producing a gap between cones, or with panels corrugated to create triangular slots. Panels may be positioned in any position that provides a taper to hold propellant and reject gas. Various sponge panel placements are illustrated in Figure 5.

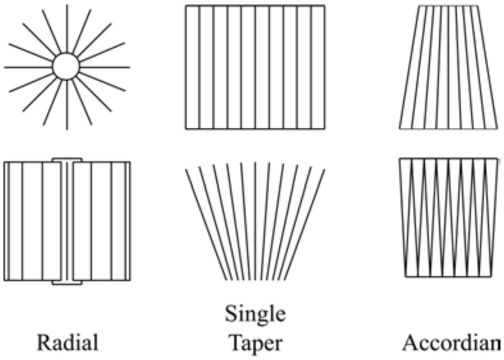


Figure 5. Possible Sponge Panel Positions

The dictating factors in panel placement are a) ensuring propellant access, b) providing sufficiently large gap tapers, c) providing sufficiently small gaps, d) designing for manufacture, and e) minimizing hydrostatics.

To provide propellant access, the ideal panel position should locate the smallest gaps over the propellant access window and provide a taper extending away from the access window. As propellant is consumed and gas is drawn into the sponge, the propellant access window will remain covered with propellant at the lowest possible levels, thereby minimizing sponge residuals. Of course, positioning the panels with the smallest gaps over the access window is not essential, but additional residual can be expected if the window is located elsewhere.

The second issue in panel position is the magnitude of the taper. If the taper is too small for the given holding acceleration, gas entering the sponge will not be ejected by the taper.

This could result in the isolation of some propellant within the sponge.

This is illustrated in Figure 6. To ensure that the taper is sufficient, one must either verify that the taper can reject gas bubbles even when the acceleration is trying to push them into the sponge, or design the sponge with gap tapers perpendicular to the acceleration.

One should design and verify sufficient tapers. Designing a sponge with tapers perpendicular to the acceleration is difficult when more than one acceleration direction exists.

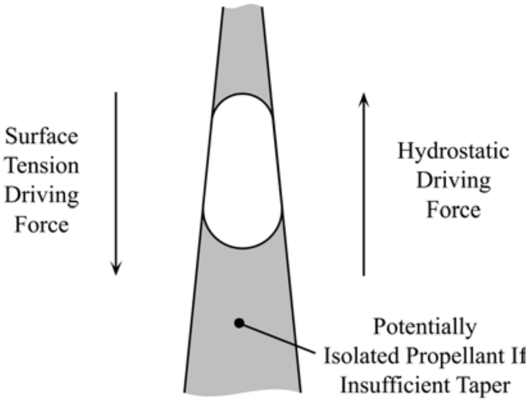


Figure 6. Gas Bubble Ejection

To ensure that a sponge can reject gas bubbles, the surface tension forces acting on the bubble must exceed the opposing hydrostatic forces. Equation (4), rewritten as an inequality, is differentiated and rearranged to yield:

$$\frac{dg}{dz} > \frac{1}{2}\frac{\rho}{\sigma}\,a\,g^2 \qquad (5)$$

One should try to design with at least this minimum taper. If a desired sponge does not provide the necessary taper, designing the sponge with accordion panels may solve the problem. Large radial sponges often cannot meet the taper requirement and accordion panels can resolve this difficulty. Sponges that surround cylindrical traps often must use accordion panels. Accordion panels have the disadvantage of leaving additional residual in the sponge or requiring larger access windows.

The third and fourth issues deal with the size of the panel gaps. If the gaps are too large, most of the propellant in the sponge will leak, causing the sponge mass to be used inefficiently. On the other hand, if the sponge gaps are too small, manufacturing will be difficult and/or the sponge metal will occupy a majority of the sponge volume - using mass inefficiently.

The sponge mass can be optimized by iterating across various panel gap sizes. Placing panels closer than 0.04 inches with an accurate and consistent gap is quite difficult and should not considered. In many cases even 0.04 inches is too close for optimal sponge mass.

Finally, sponge panel placement should address the direction of the acceleration vector. Ideally, the sponge dimensions should be minimized along the acceleration vectors. For a sponge designed to hold during lateral maneuvers, the lateral dimensions should be reduced for the smallest possible sponge. However, making the sponge taller to reduce the lateral dimensions can increase sponge residuals. The optimal sponge is tall enough to achieve maximum deliverable volume at minimal mass.

Sponge Panel Porosity

If the sponge panels are positioned so that propellant is drawn toward the access window, the cross flow between panels will be minimized. However, if the access window only has access to some of the panel gaps, flow between panel gaps will be required.

Even in sponge designs not requiring cross flow, the ability to accommodate panel cross flow is desirable. It allows uniform draining and access to propellant in gaps that are not perfectly tapered. Manufacturing thin, straight, and perfectly placed panels is difficult and accommodating cross flow may allow access to more propellant.

To accommodate cross flow, the panels must be perforated. Generally, the perforations are relatively large and are produced by chemical or mechanical machining. A typical pattern may include 0.050 inch diameter holes spaced on 0.100 inch centers on a 60° array. This pattern produces roughly a 20% open area which is usually sufficient for cross flow.

One should examine the losses across panels and show them to be significantly lower than the surface tension forces. This eliminates the need for a detailed flow analysis. Increasing open area may be necessary in unusual circumstances where the flow rate is large.

Sponge Location Relative To Other Components

Sponges are designed to hold propellant against adverse accelerations. A sponge can accomplish this only if it cannot drain via a leak path.

A PMD sponge draining via a leak path is analogous to a wet household sponge positioned on top of a stack of paper towels. After a period of time, most of the water in the household sponge will leak into the paper towels. The sponge's ability to hold water will have been compromised. However, if the sponge were suspended a fraction of an inch above the paper towels, no leaking would occur. (Dripping, a different phenomenon, may occur.) For this reason, it is important that PMD sponges be placed with accuracy in proximity to other PMD components.

The best example of a sponge and leak path is a sponge designed for a specific demand system and the vanes designed to refill the sponge. Figure 3 illustrates such a PMD design. Each vane provides a path to refill the sponge as well as a leak path which may drain the sponge. Note that the vanes are notched in the illustration. These notches cause the sponge to be isolated from the vane system and prevent excessive leakage during a lateral or adverse acceleration.

The size of the notch must be designed to optimize sponge metal mass against liquid residual mass. A large notch advantageously decreases sponge mass but disadvantageously increases residual propellant mass. During leaking, a larger notch will cease the flow of propellant from the sponge earlier than a small notch. Therefore, the sponge will retain more liquid and can be designed smaller than a sponge designed for a small notch. A larger notch results in a smaller, lighter sponge. However, a larger notch means that more propellant remains on the vane system when it can no longer deliver propellant to the sponge because it has become isolated from the sponge by the notch. So a larger notch increases the amount of propellant residual attached to the vane system.

This trade between vane residual mass and sponge metal mass is completed iteratively by examining various notch depths, the sponge holding volume at each depth, the sponge size required to meet demand and the residuals adhered to the vanes. This can be accomplished at the same time as the sponge sizing iteration. In practice, gaps between 0.25 and 0.75 inches have been used to prevent leaking and allow refilling. At a minimum, the notch depth must be greater than one half the maximum panel gap. Otherwise the vane system cannot be isolated from the sponge.

Notching of vanes is not the only concern. The distance between a sponge and any other fillet forming crevice should be examined and verified not to cause excessive sponge leakage. Areas of concern include trap housing corners, gallery-tank wall gaps, etc. An adequate and inadequate design are illustrated in Figure 7.

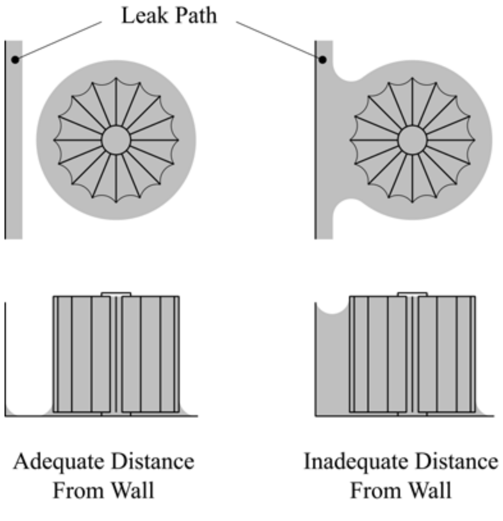


Figure 7. Sponge Distance to Leak Path

Propellant Access Window Position

As mentioned earlier, panel placement should direct propellant toward the access window. Given a specific sponge, an ideal access window location exists. The location is at the smallest gap position. Figure 8 illustrates some ideal window locations. For radial sponges, the ideal location is at the center tube support, for single taper sponges the ideal location is on the plane below the sponge, and for accordion sponges the ideal location is as illustrated.

Placement elsewhere can provide a fully functional sponge but the sponge must be oversized to accommodate increased residuals.

The preceding is only true for systems which require access during lateral or adverse accelerations. For ignition systems which require propellant delivery only during settling accelerations, the access window should be located as low as possible and thus below the sponge. The sponge gap tapers should be designed to accommodate this access window location.

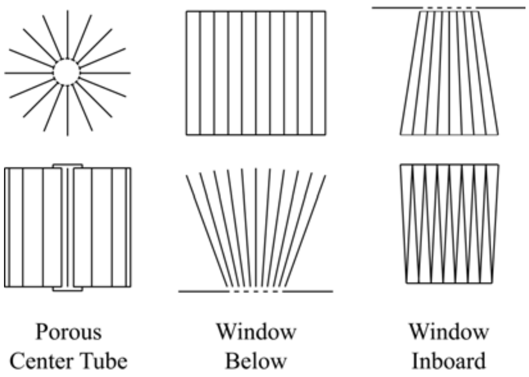


Figure 8. Propellant Access Window Positions

V. ANALYSIS

Besides simple bubble point tests verifying porous element integrity, no performance related quantitative testing in one g is possible. As a result, analysis using relatively large safety factors is required to verify performance.

PMD Technology has developed the techniques presented in this section to verify sponge compliance with the operating requirements. The main requirement of a sponge is to hold and possibly deliver propellant during adverse accelerations. The pertinent performance characteristic is the available and/or deliverable volume. In general, this volume is computed using a simple, conservative analysis and a significant safety factor applied.

Dripping and Leaking

To address propellant retention, one must first address leaking and dripping. Leaking and dripping are the two phenomena which reduce the propellant volume held in the sponge. For instance, one cannot rely on a 4 inch diameter radial sponge 4 inches high delivering its full volume of 50 in^3. It is likely that some of that propellant will leak or drip upon application of an adverse acceleration.

Leaking is the predominate method of volume reduction. However, dripping will occur if the adverse accelerations pull sponge propellant away from the leak paths (or if no leak paths exist). Typically, this is the case if the acceleration is perpendicular to the sponge mounting plane and access window. Dripping is illustrated in Figure 9. The radius of curvature reverses at the edge of the sponge and a drip begins to form.

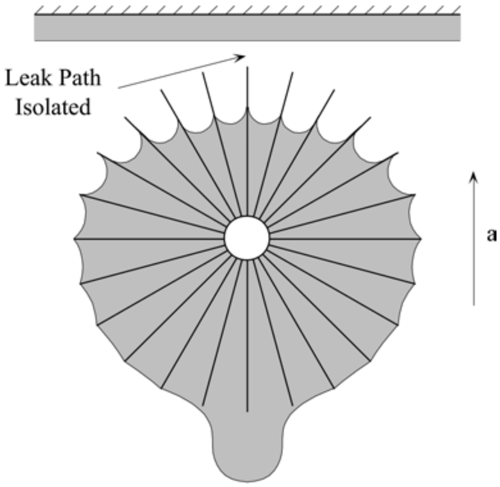


Figure 9. Dripping

If the acceleration were applied infinitely slowly and with no perturbations, the radius at which dripping would occur would be relatively small (and negative) and would depend upon the acceleration. However, for conservatism, one should assume that any negative radius in the sponge will cause dripping.

Leaking will occur if a leak path exists. For a given PMD configuration, the sponge may be connected to other components. If a fillet can exist which connects the sponge and the leak path, the path may allow leaking. The radius of the smallest connecting fillet dictates the maximum sponge holding volume. In the case of a notched vane system, the notch depth is the limiting fillet radius. In the case of the sponge near a wall, as illustrated in Figure 7, the limiting radius is one half the distance to the wall. In any sponge designed with a leak path, the limiting fillet radius should be designed to minimize sponge leakage.

To determine if dripping or leaking is a problem, one must first determine the radius of curvature and the propellant location within the sponge.

Propellant Holding

Equation 4 can be rewritten to apply to any point on the surface of the propellant in the sponge:

$$\sigma \frac{1}{R} - \rho a z = \sigma \frac{1}{R_0} - \rho a z_0 \tag{6}$$

The terms R_0 and z_0 correspond to a given surface.

Given a specific sponge, a relationship between R and z for each gap can be substituted into equation (6) to allow the solution of the surface in each gap. On the sponge boundary, one needs to not allow the radius, R, to dictate a location outside the sponge (as our example did in the Physics section). If the solution dictates a surface outside the sponge, the surface can be placed at the sponge boundary and a radius, R, associated with that location computed from equation (6). The radius, R, can be larger than the gap due to edge stability.

For example, for a finite radial sponge, a substitution for R and z can be made in terms of the panel thickness, t, distance from the sponge center, r, and the angle from the thrust vector, ϕ:

$$\left.\begin{aligned} R &= r \sin\left(\frac{\pi}{N}\right) - \frac{t}{2} \\ z &= r \cos\phi \end{aligned}\right\} \quad \text{for} \quad r < r_{sponge}$$
$$\left.\begin{aligned} R &= r_{sponge} \\ z &= r_{sponge} \cos\phi \end{aligned}\right\} \quad \text{for} \quad r > r_{sponge} \tag{7}$$

For any sponge, the relationship between R and z can be specified and equation (6) solved for each gap. For sponges which contain gaps with two dimensional tapers (such as radial, accordion sponges), either an approximation can be made to obtain a relationship between R and z or the additional dimension must be included in the analysis.

Equation (6) is the only equation required to evaluate sponge holding. However, it does not immediately tell us how much propellant a particular sponge can deliver.

The propellant quantity a sponge can deliver is the propellant holding volume minus the propellant residual volume. The propellant residual volume is the propellant quantity required to cover the access window sufficiently to prevent gas penetration.

One computes the holding volume by taking the lesser of two volumes: the propellant volume in the sponge when dripping ceases, and the propellant volume in the sponge when leaking ceases. As already stated, dripping ceases when the radius of curvature at the lowest point on the sponge is infinity, and leaking ceases when the radius of curvature at the location of the leak path decreases to a value which isolates the sponge. So given a particular sponge and its position relative to other components, the dripping and leaking sponge holding volume are easily computed.

One should note that dripping occurs very rapidly while leaking occurs relatively slowly. Therefore, it is possible that the sponge will not leak significantly during the short duration of the thruster firing. For conservatism, this analysis has assumed that leaking is instantaneous. However, a less conservative, more accurate approach would be to compute the quantity of propellant which leaks during a given thruster firing. This approach requires an analysis of the flow along the leak path. This is accomplished by vane modeling as presented in reference 1. Assuming instantaneous leaking is conservative and therefore an acceptable approach.

Before the residual volume is computed, the minimum access window flow area required to prevent gas ingestion must be determined. This is dependent upon the window's bubble point, the window's flow losses, and the demand flow rate. For any porous window material, a maximum tolerable propellant flow velocity exists above which gas ingestion will occur. The minimum flow area required is simply the demand flow rate divided by this flow velocity (and a safety factor applied).

Once the minimum required window area is established, the residual volume is computed by solving equation (6) given the R_0 and z_0 corresponding to this minimal window coverage (see the next section for anomalies).

With the initial holding volume and the residual volume, the sponge's deliverable volume is computed by subtracting the residual volume from the holding volume. This procedure must be followed for each adverse acceleration direction. The deliverable volume should be shown to be greater than the demand volume with margin; a safety factor of two is recommended. The holding and residual volumes are illustrated in Figure 10 for a representative sponge.

As indicated throughout the design section, the sponge design is achieved by iterating this process across the independent variables: the leak path radius, the sponge size, the sponge panel gaps, and the sponge panel gap tapers. It is advisable to put this procedure into a spreadsheet or computer code to reduce the iteration time.

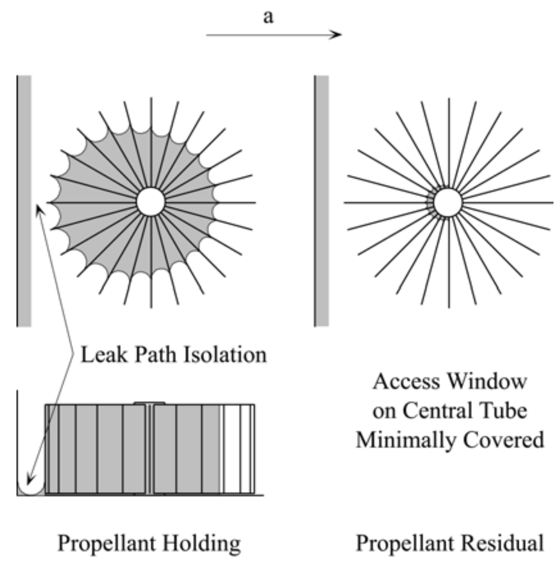


Figure 10. Holding and Residual Volumes

An Anomaly: Sponge Propellant Isolation

The residual propellant volume in the sponge, as calculated above, does not include propellant which might isolated in the sponge. Propellant isolation will result if more than one stable surface exists in a single gap. If the adverse acceleration is higher than the limit for gas ejection for a given sponge gap taper, isolation will occur. The limiting acceleration is defined by rearranging equation (5):

$$a_{limit} = \frac{dg}{dz}\frac{\sigma}{\rho}\frac{2}{g^2} \qquad (8)$$

Thus if the acceleration is maintained below this limit, no sponge propellant will be isolated. If the acceleration is above this limit, some propellant will be isolated within the sponge and special care is required to ensure access to it. The example presented at the end of this section provides a look at sponge performance beyond this limit for a radial sponge.

Propellant Demand

The preceding analysis has dealt only with equilibrium fluid positions and static hydrodynamics. In ignition systems this is all that is required since no demand occurs during adverse accelerations. But in specific demand systems, one must be concerned with demand during the adverse acceleration.

Typically, the flow dynamics within the sponge are much smaller than the surface tension forces and can be ignored. In order to ignore the flow dynamics one must show that the flow losses in panel gaps, the dynamic head in panel gaps, and the flow losses across panels are negligible.

To estimate the flow losses, steady constant width slot flow can be examined. The losses will not accurately represent the tapered gap losses but will be on the order of magnitude of these losses. The flow losses and dynamic head in fully developed slot flow are:

$$\begin{aligned} H_{loss} &= \frac{24}{\mathrm{Re}}\frac{L}{g}\frac{u^2}{2} \\ H_{dyn} &= \frac{u^2}{2} \end{aligned} \qquad (9)$$

The surface tension head is approximately:

$$H_{st} = \frac{\sigma}{\rho}\frac{2}{g} \qquad (10)$$

For the flow dynamics to be negligible, the flow velocity in the sponge must be low enough to ensure that the flow loss head and the dynamic head are much less than the surface tension head:

$$\left(1 + \frac{24}{\mathrm{Re}}\frac{L}{g}\right)\frac{u^2}{2} \ll \frac{\sigma}{\rho}\frac{2}{g} \qquad (11)$$

For example, given a sponge with 4 inch long 0.1 inch wide gaps and NTO as the propellant, the velocity at which the losses are ten times smaller than the surface tension head is roughly 0.5 in/sec. The typical demand flow rate is on the order of 1 in^3/sec or less and thus the sponge velocity is significantly lower than 0.5 in/sec (except near sponge depletion where the flow area decreases and the flow velocity climbs).

If the dynamics are important in the sponge, the analysis is more complicated. The surface location is not dictated solely by hydrostatics. The analytical techniques for this type of analysis are not sufficiently developed for presentation here. Since most sponges do not have significant flow dynamics, a more complicated analysis is typically not required.

If flow through panels is required due to an access window location which is not in contact with all panel gaps, the associated cross panel losses must be examined. They may or may not be significant. If a rough order of magnitude analysis shows them to be significant, the propellant location analysis should decrease the head in each panel gap by the flow loss term. Thus equation (6) must include a flow loss term which reduces the head in each panel gap by the flow losses anticipated. This flow dynamic is easier to include since each gap can be examined separately.

Stability

The assumption that the radius of curvature in each gap is circular is not accurate. However, the effect of the deformation of the surface can be ignored if it can be shown to be insignificant. If the Bond number based on the gap radius is much lower that 1, the surface deformation can be ignored:

$$\mathrm{Bo} = \frac{\rho a r^2}{\sigma} \ll 1 \qquad (12)$$

In fact, this also defines whether the radius is stable. In circular tubes with a wetting fluid, the Bond number must be below 0.84 for stability.[6] If a sponge can hold propellant, then by definition the gap must be stable since the sponge size greatly exceeds the gap radius. This can be verified for any particular sponge with the above inequality.

Three Dimensionality

The last topic in the analysis section is the aspect of three dimensionality. Where panel gaps end, they are either in contact with a surface or open. In both cases three dimensional effects govern the propellant location. At the base of a sponge which is positioned over a solid metal plane, the interaction of the plane with the panel gap must be considered for an accurate assessment of the propellant location. Fortunately these three dimensional effects only propagate a short distance into the sponge; on the order of the gap size. They can be ignored in all sponges with dimensions much greater than the gap size.

However, the three dimensional aspect may become important if propellant is isolated or if adequate window coverage is a concern. In regions where panel gaps end at solid planes, the fluid surface will tend to wet the plane as well as the panels and thus the surface will be elevated. This may provide more window coverage or access to isolated propellant. Tools to analyze these three dimensional surfaces are available and should be employed if these concerns jeopardize the implementation of a sponge. Typically, their use is not required since the safety factor on sponge volume swamps the impact of three dimensionality.

Conclusion

The analysis presented is very simply and straightforward. A number of assumptions were incorporated into the analysis to maintain simplicity. These assumptions have been chosen to be conservative in every way.

One might argue that, with a safety factor of two on sponge volume and a conservative analysis, the resulting sponge is over designed. Depending upon the circumstances, this may or may not be true. However, the approach taken guarantees a sponge design which meets requirements. The impact of over design is minimal.

An alternative approach might be to incorporate in the analysis more accurate, but not necessarily conservative, assumptions. Since fluid mechanics is not an exact science, this approach will a) make the analysis much more difficult and b) not guarantee a sponge which will meet requirements.

Also, reducing the safety factor is not recommended. The safety factor is not incorporated exclusively to accommodate uncertainty in the analysis but also to accommodate uncertainty in manufacturing. It is very difficult to produce flawless sponges; panel warping and uneven gaps are often encountered. In addition, it is very difficult to analyze every manufacturing tolerance. The safety factor provides for these uncertainties as well as analytical uncertainties.

The verification approach using simple, conservative analysis coupled with a safety factor of two a) alleviates concerns of analytical accuracy b) virtually guarantees requirement compliance without ground testing, and c) allows for manufacturing uncertainty. This approach is widely used on all PMD components and has proven itself with no known PMD performance failures to date.

Aside - Section V

Example Figure 3 shows a radial sponge similar to, but larger than, the sponge presented in Aside - Section II. Assume the sponge height is 4 inches, NTO is the propellant, and the access window is located on the central tube support.

Given a panel thickness of 0.010 inches, the gap at the central tube is 0.039 inches and the gap at the outer edge of the sponge is 0.186 inches. The inner gap is very small and is near the limit of manufacturing capability. Increasing the tube diameter can alleviate this difficulty but only at the expense of available sponge volume.

The radius at which the sponge will be isolated from the leak path is 0.5 inches since the distance to the wall is 1 inch. We have assumed that the acceleration settles propellant over the leak path/sponge junction. This assumption produces the worst case volume since the largest radius of curvature will be at the base of the sponge.

To analyze the sponge we will look at the gap taper, the sponge holding capacity, the flow within the sponge, and possible three dimensional effects.

The maximum acceleration during which the gap tapers will reject gas is 0.0081 g via equation (8). Operation above this acceleration may isolate propellant within the sponge.

Substituting equation (7) into equation (6) allows for the solution of the sponge propellant surface in terms of r and ϕ:

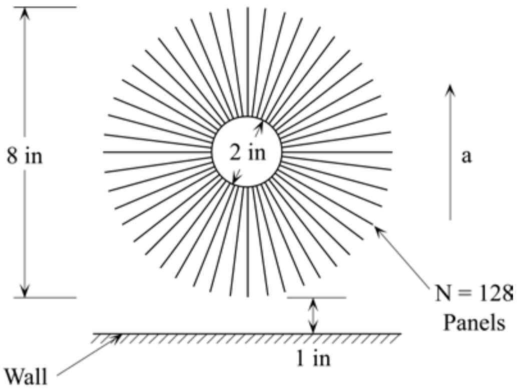
$$\sigma \frac{1}{r \sin\left(\frac{\pi}{N}\right) - \frac{t}{2}} - \rho a r \cos\phi = \sigma \frac{1}{R_0} - \rho a z_0$$

Where r is greater than r_{sponge}, r can be set to r_{sponge} and a radius of curvature, R, computed:

$$\sigma \frac{1}{R} - \rho a r_{sponge} \cos\phi = \sigma \frac{1}{R_0} - \rho a z_0$$

A spreadsheet was used to integrate along the surface curve to obtain a variety of solutions; each corresponding to a different propellant volume in the sponge.

Example Figure 4 shows the surfaces for an acceleration of 0.004 g. The sponge panels are not illustrated but the central tube and sponge diameters are shown. The acceleration is upwards. The largest volume shown corresponds to a radius of curvature of 0.5 inches at the base and therefore is the holding volume. The volume is 178 in^3. The inner three surfaces correspond to 96, 64, and 29 in^3. The residual volume is less than 1 in^3 (not illustrated since the surface is too close to the central tube to be discernible). During a 0.004 g lateral acceleration, this sponge can hold and deliver 88 in^3 of NTO with a safety factor of two on volume.



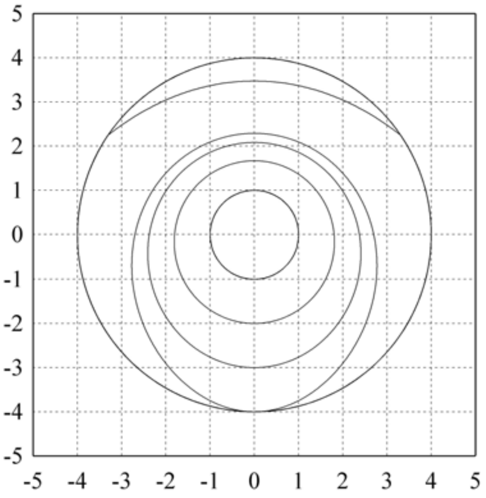
Example Figure 3. Radial Sponge

Example Figure 5 shows the surfaces for an acceleration of 0.0081 g; the limiting acceleration for this gap taper. As in Figure 4, the largest volume shown corresponds to a radius of curvature of 0.5 inches at the bottom and therefore is the holding volume. The volume is 126 in^3. The inner three surfaces correspond to 58, 46, and 23 in^3. Again, the residual volume is less than 1 in^3 and is not illustrated since the surface is to close to the central tube to be discernible. During a 0.0081 g lateral acceleration, this sponge can hold and deliver 62 in^3 of NTO with a safety factor of two on volume.

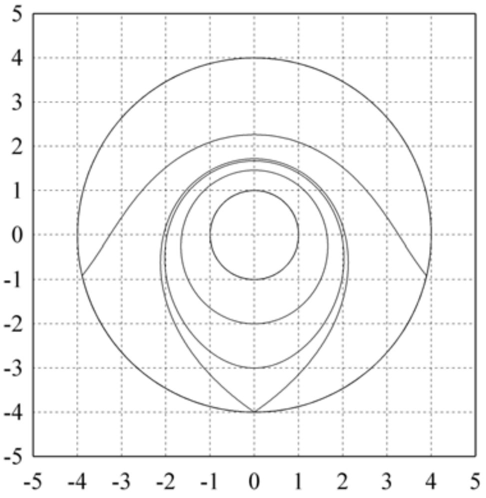
Example Figure 6 shows the surfaces for an acceleration of 0.02 g; significantly above the limiting acceleration for this gap taper. Again, the largest volume shown corresponds to a radius of curvature of 0.5 inches at the bottom and therefore is the holding volume. The volume is 60 in^3. The next inboard surface corresponds to a volume of 35 in^3 and shows the pinching indicative of the upcoming isolation.

When the volume is further decreased by use, some propellant is isolated by the saddle point located within the sponge (as illustrated). The propellant below the lower saddle point separatrices will not be accessible from the access window located on the central tube and must be added to the residual volume. The volume below the lower saddle separatrices is 11 in^3.

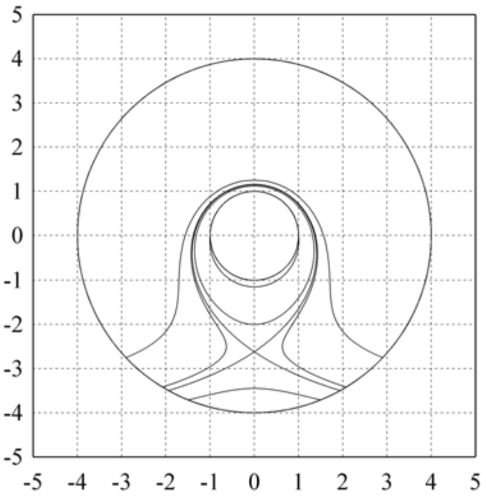
The next surface, just inboard of the saddle, corresponds to a volume of 14 in^3 (the corresponding surface below the saddle is shown but will not occur if propellant cannot be withdrawn from the region below the saddle). The surface clinging to the central tube is the residual volume if the minimum required flow area is one half of the central tube.



Example Figure 4. Propellant Surfaces at 0.004 g



Example Figure 5. Propellant Surfaces at 0.0081 g



Example Figure 6. Propellant Surfaces at 0.02 g

The residual volume is 12 in^3 (including 1 in^3 near central tube and 11 in^3 isolated below the saddle). During a 0.02 g lateral acceleration, this sponge can hold and deliver 24 in^3 of NTO with a safety factor of two on volume.

The flow losses must be shown to be negligible to accept these deliverable volumes. The average gap is 0.11 inches in this sponge. Example Table 1 shows the flow loss and dynamic head of NTO in a 0.10 inch wide slot 3 inches long at a variety of flow velocities. The surface tension head associated with a 0.1 inch gap and NTO is 0.057 inches. Therefore, a flow velocity in a gap of less than 0.6 in/sec will produce flow losses less than one tenth of the surface tension head. With 128 panels, each 4 inches high, the maximum flow rate for which flow losses can be assumed negligible is roughly 12 in^3/sec (= 0.6 x 128 x 4 x 0.039). With less of the sponge flowing, the maximum flow rate is proportionally lower.

Example Table 1
Flow Losses in a Slot

u (in/sec)	$H_{loss} + H_{dyn}$ (in)
0.1	8.52×10^{-4}
0.2	1.73×10^{-3}
0.3	2.63×10^{-3}
0.4	3.56×10^{-3}
0.5	4.52×10^{-3}
0.6	5.50×10^{-3}
0.7	6.51×10^{-3}
0.8	7.54×10^{-3}
0.9	8.60×10^{-3}
1	9.69×10^{-3}

The three dimensional effects are relevant only at the top and bottom of the sponge. The bottom plane will cause the propellant to move outboard and the open space at the top will cause the propellant to move inboard. The net effect will be negligible on the sponge volumes. Because the bottom plane causes propellant to move outboard, it is possible that some of the isolated propellant at accelerations above 0.0081 g can be accessed. Access to much of the propellant is not likely unless the flow rate is unusually low. Using vane modeling codes, an examination of the flow in the fillets formed between the bottom plane and the sponge panels is possible. For conservatism, isolated propellant should be considered residual.

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NOMENCLATURE

Greek

ϕ ≡ angle from acceleration vector
ρ ≡ liquid density
σ ≡ absolute surface tension

Δ ≡ change

English

a ≡ acceleration
g ≡ gap size
h ≡ sponge height
r ≡ radius from center of radial sponge
t ≡ panel thickness
u ≡ flow velocity
z ≡ height relative to acceleration vector

A ≡ area
Bo ≡ Bond number
H ≡ head
L ≡ length of the flow path
N ≡ number of panels
P ≡ pressure
R ≡ principal radius of curvature
Re ≡ Reynolds number
V ≡ volume

Subscripts

0 ≡ reference point
dyn ≡ dynamic
limit ≡ limiting
loss ≡ flow loss
low ≡ lower
gas ≡ pressurant gas
st ≡ surface tension
up ≡ upper

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