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Propellant Management Device Conceptual Design and Analysis: Traps and Troughs

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ABSTRACT

While surface tension devices have been used in liquid propellant tanks for over thirty years, the conceptual design process and the analytical methods used to verify performance have been closely held by propellant management device (PMD) designers. This paper is the third in a series which will address the process and the techniques developed and used by PMD Technology to design and verify two PMD components - traps and troughs.[1, 2]

All areas of concern inherent in trap and trough 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 trap and trough 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.[3] By definition, control PMDs provide gas free propellant delivery by controlling propellant within the tank. Both traps and troughs are such devices.

Traps. A trap device is defined as a closed structure which holds and provides a specific quantity of propellant using the surface tension forces. A trap may or may not be refillable. Traps, unlike sponges and troughs, cannot refill in zero g and must use porous elements, such as screen or perforated sheet, to hold liquid.

Both a refillable and non refillable trap is illustrated in Figure 1. Both traps offer a reservoir of propellant usable during high acceleration maneuvers.

Often, refillable traps are referred to as ‘start baskets’ since they are used to ‘start’ engines. The first PMD, used in the Agena upper stage, employed a start basket. The Agena start basket replaced solid ‘ullage’ rockets previously employed to settle the propellant prior to main engine ignition. Refillable traps use the hydrostatics and dynamics created by the main engine settling acceleration to eject the gas ingested during ignition; refilling the trap.

Non refillable traps are found in many PMDs and are used for limited events; such as capturing the gas ingested into gallery arms during launch or providing propellant during a once-in-a-lifetime maneuver. The propellant in the trap is replaced by gas which resides in the trap for the remainder of the mission; the trap is non-refillable and the volume available is limited by the trap’s size.

Troughs. A trough device is defined as an open structure which a) holds and provides a specific quantity of propellant using hydrostatic forces and b) is zero g refillable. Troughs, unlike sponges and traps, do not use surface tension forces to retain propellant but instead use hydrostatics. As a result, troughs are not acceleration limited (though the pick up assembly within the trough may be acceleration limited). A trough is illustrated in Figure 2.

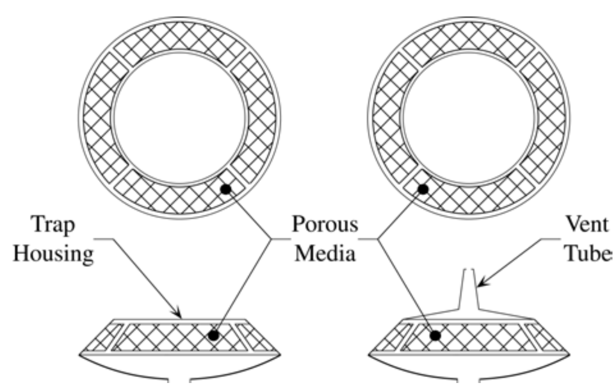

Figure 1. Non Refillable and Refillable Traps

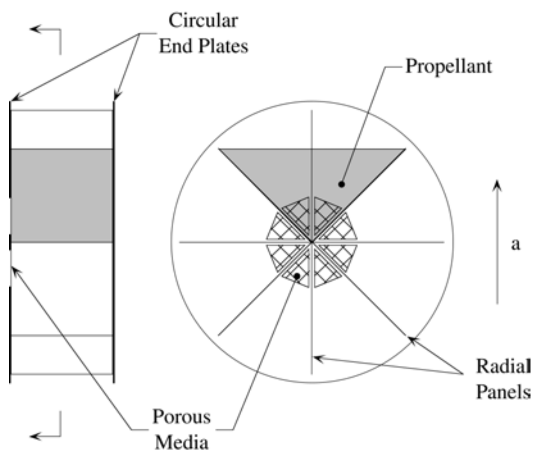

Figure 2. Troughs

As a zero g refillable device, troughs compete with sponges in PMD designs. Typically, troughs can provide more propellant than sponges at higher accelerations, but can require more space and more metal mass. Troughs are more sensitive to acceleration direction than sponges but are useful when the volume or the acceleration increases beyond the capabilities of a sponge.

The PMD design process starts with the evaluation of the mission requirements to determine whether a trap or a trough is suitable. Once suitability is established, the design configuration and the design details are explored. Finally, with the design established, a thorough analytical investigation is conducted to verify performance. This last step is important since typical performance verification relies entirely on analysis.

This paper progresses along the same track as the design process. Section II addresses the physics of traps and troughs and presents the basic equations. Section III describes the uses of traps and troughs and establishes the requirements leading to them. 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 trap and trough design.

II. PHYSICS

The physics of traps and troughs is straightforward. A trap retains liquid even when horizontal or inverted by using the surface tension forces present in a wetted porous element. The trough functions as most one g containers function - solid walls are used to contain the liquid.

Traps. Propellant will remain within the trap against the hydrostatic forces only if the bubble point of the porous element is not exceeded. If the maximum pressure difference across the porous element established by surface tension (the bubble point) is insufficient to balance the hydrostatics and flow losses, gas will enter the trap through the porous element and the trap will leak. By choosing a smaller pored porous element, higher accelerations and/or larger distances can be accommodated.

The pressure difference across the gas-liquid interface within the porous element resulting from the surface tension forces is defined by the Laplace equation:[4]

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

Typically, the bubble point pressure is not estimated using equation (1) because the geometry and the statistics are complex whereas bubble point testing is straightforward. The bubble point is measured by increasing the pressure differential across a porous element until gas penetrates.

In a trap, the loads attempting to push gas through the element are:

$$\Delta P_{hydrostatic} = \rho\ a\ \Delta z \qquad (2)$$

$$\Delta P_{flowlosses} = f\left(Q, \rho, \nu, A, Element\right) \qquad (3)$$

Very simply, one can equate the bubble point to the sum of the loads:

$$BP \geq \rho\ a\ \Delta z + f\left(Q, \rho, \nu, A, Element\right) \qquad (4)$$

This is the minimum allowable bubble point for the porous element covering the trap.

In the case of the refillable trap, the bubble point of the vent window must be exceeded to force the gas from the trap:

$$BP < \rho\ a\ \Delta z - f\left(Q, \rho, \nu, A, Element\right) + \frac{\rho}{2}\left(\frac{Q}{A}\right)^2 \qquad (5)$$

The physics of trap propellant retention are shown schematically in Figure 3. In addition to retention, propellant within traps must be accessible to the outlet. Therefore, both internal pick up assemblies and trap shape are important.

Troughs. Figure 4 shows the physics of trough holding for two types of troughs: a radial trough which can leak and a cylindrical trough which cannot.

If the trough has a leak path, propellant will remain within the trough only if the pressure within the trough pick up is less than the tank pressure (a negative pressure differential). If the pressure differential were positive, the trough would leak via its own pick up assembly. To maintain a negative pressure differential, the flow losses through the porous element must exceed the pick up hydrostatics:

$$f\left(Q, \rho, \nu, A, Element\right) > \rho\ a\ \Delta z \qquad (6)$$

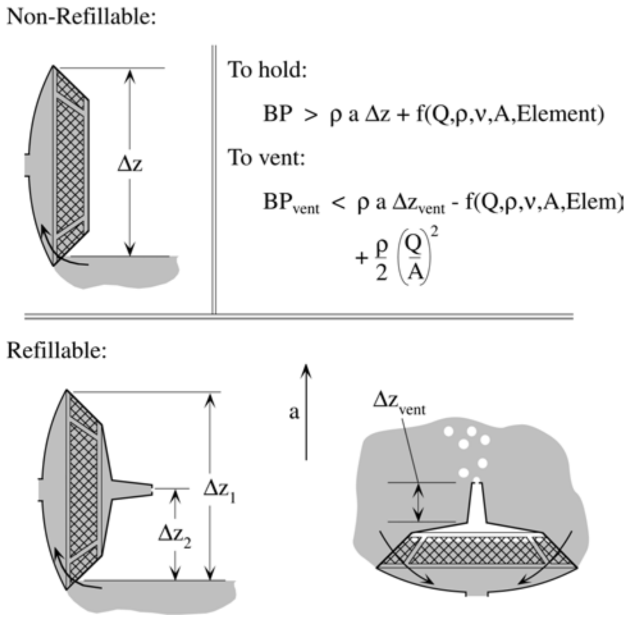

Figure 3. Trap Physics

To prevent leaking, the trough access windows must be small. However, the bubble point must not be exceeded to ensure gas free flow at low trough levels:

$$BP > f\left(Q, \rho, \nu, A, Element\right) \qquad (7)$$

As illustrated in Figure 4, a trough can be designed without a leak path. Here, the exposed porous elements are above the trough propellant ensuring a negative pressure differential. The trough holds and delivers its propellant gas free if the exposed porous element bubble point is not exceeded:

$$BP > f\left(Q, \rho, \nu, A, Element\right) + \rho\ a\ \Delta z \qquad (8)$$

Once the trough propellant is consumed, the trough can be refilled either with a vane system in zero g or with a settling acceleration.

The physics of traps and troughs are straightforward. Traps will hold propellant as long as the porous element bubble point is not exceeded. Refillable traps will refill if the vent window bubble point is exceeded with little gas left in the trap. Troughs will not leak if no leak path exists or if the pressure differential along the leak path is always negative. Troughs can be refilled with a zero g vane re-supply system or with a settling acceleration

III. USES

The principal advantages of surface tension PMDs over diaphragms or positive expulsion devices are low mass, high reliability (no moving parts), and good 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 and acceleration. Traps and troughs can deliver only specific quantities at limited accelerations and, in most cases, in limited directions.

Traditionally, the two principal uses of traps are in: settling thrust systems requiring propellant access during engine ignition and systems requiring one time use of a specific quantity of propellant for a specific maneuver (such as vehicle despin or flat spin recovery). Traps are used in both monopropellant and bipropellant systems.

The two principal uses of troughs are in: systems requiring repeated use of a large quantity of propellant for a specific maneuver (such as stationkeeping) or systems requiring a high g phase of mission where the trough can prevent propellant from leaking from a trap or other PMD component. Troughs are primarily found in bipropellant systems but are applicable to monopropellant systems as well.

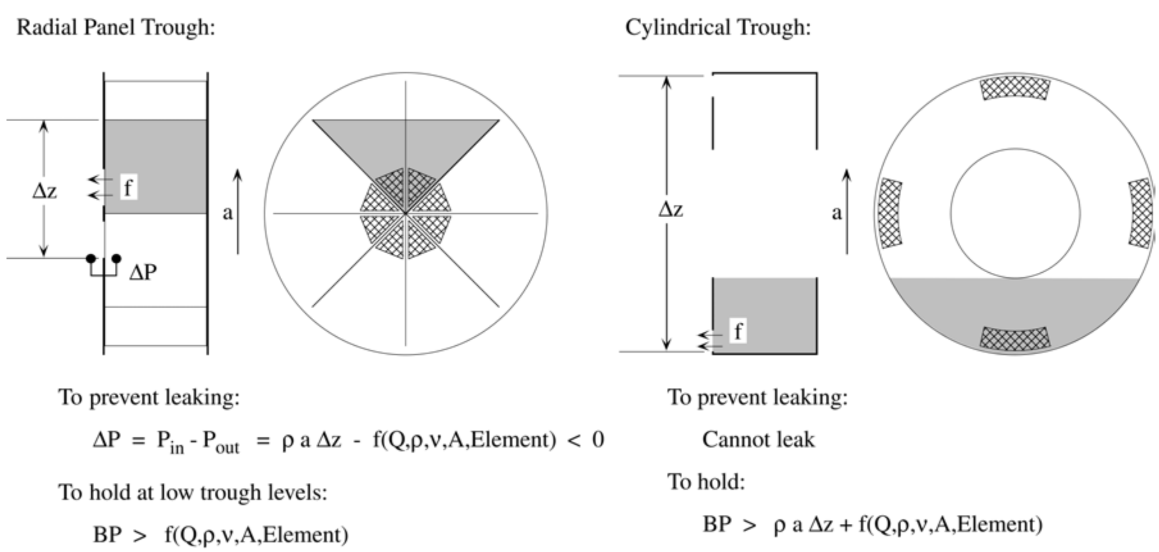

Figure 4. Trough Physics

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

Ignition Systems using a Trap

Ignition systems require gas free delivery during engine ignition during which propellant is reorienting over the tank outlet. In this instance, the PMD must deliver a specific amount of propellant to the outlet. This amount depends upon the propellant 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, and sometimes vanes. The start basket PMD provides the most capability in terms of the maximum tolerable adverse acceleration. Conversely, start baskets are the most complex PMD option so their use is limited to vehicles with relatively high adverse accelerations; such as launch vehicle upper stages.

Figure 5 illustrates the start basket used for engine ignition in a typical propellant tank. The large porous element located on the trap may have to be pleated to provide adequate flow area for the higher propellant flow rates typical of launch vehicle upper stages.

Often, ignition systems use separate main thrust and attitude control propulsion systems. A start basket used in the main tanks must hold, but not deliver, sufficient propellant for ignition during the adverse accelerations produced by the attitude control system (as well as during any drag accelerations). This required quantity may be estimated by multiplying the demand flow rate 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.[5]

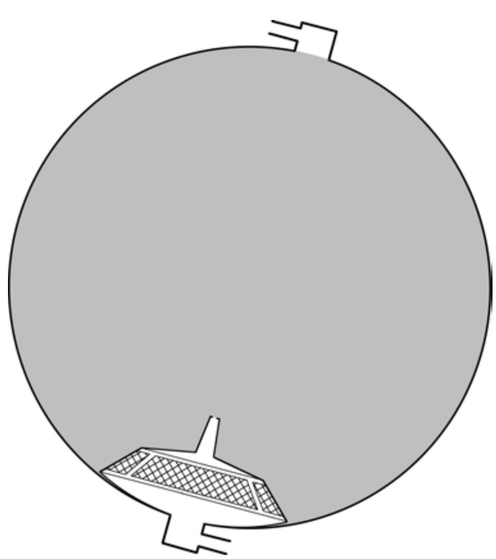

Figure 5. Start Basket Concept for an Ignition System

Given a) the propellant volume required during reorientation, b) the maximum lateral acceleration, and c) the minimum fill fraction at the last ignition, start basket viability can be determined by the examining the hydrostatics of lateral holding and axial venting. The design process is iterative. A start basket shape of the correct volume is chosen and the vent window bubble point boundaries computed using equations (4) and (5). If the boundaries overlap and therefore provide no viable solution, a higher start basket must be examined. A start basket is not viable if a vent window, at the minimum ignition fill fraction, cannot be designed to hold during lateral accelerations and vent during settling accelerations. Typically, this will occur if the lateral accelerations are on the same order of magnitude as the axial accelerations.

The propellant quantity demanded during engine ignition varies greatly so it is difficult to present a typical case. However, start baskets are useful generally for engine ignition if the lateral or adverse accelerations are less than 0.5 g with fine stainless steel screen or 0.05 g with titanium screen. Acceleration limits are dictated by the ability to manufacture small pore porous elements with low flow losses.

Specific Demand Systems using a Trap

The other use of traps is in specific demand systems. Specific demand systems require the one time use of a specific quantity of propellant. An example is vehicle despin after a spinning transfer orbit. The once-in-a-lifetime despin may use 5 lbm of propellant or more and the PMD may experience centripetal accelerations on the order of 0.1 to 0.5 g. Traps are employed for many limited use maneuvers. A specific mission may have a despin, two engine ignitions, a station change maneuver, and a contingency requirement, all relying on trap volume.

To meet specific demand, the designer should consider four PMD components: a) a trap, b) a sponge, c) a trough or d) a communication device such as a gallery. For intermediate to high g operation and/or large demand quantities, the best option is a trap or a gallery. A trap is preferred as it is lighter, cheaper, and more reliable than a gallery (which often uses large quantities of fine, delicate screen at the sacrifice of reliability and cost). Galleries are required if the demand volume dictates a prohibitively large trap.

A specific demand trap must hold propellant during adverse accelerations and must deliver propellant during all maneuvers. This differs from ignition systems that require delivery during settling accelerations but not during adverse accelerations.

A trap concept designed to meet a specific demand is illustrated in Figure 6. In this illustration, an internal pick up assembly allows access to propellant during lateral and settling maneuvers. The trap inlet window is small and

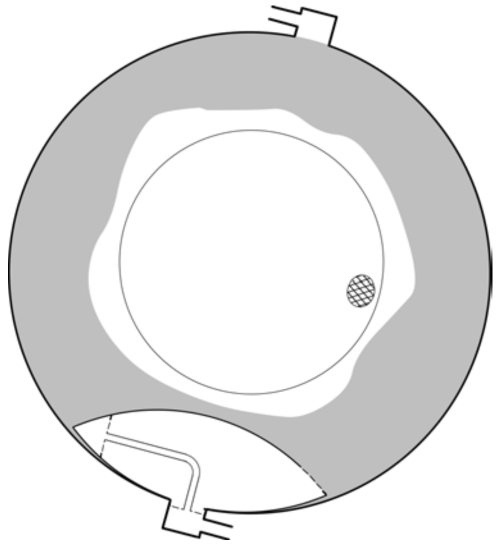

Figure 6. Trap Concept for a Specific Demand System

positioned to one side for propellant access during spinning operation. The smaller window size is dictated by the demand flow rates, which are usually much less than those encountered in an ignition system.

Viability is determined by comparing the trap size and mass required to hold the volume demanded* to the mass of a gallery device. Typically, trap volumes which are less than 10% of the tank volume are more mass efficient than galleries; although this is not a firm limit. In addition, the loads on the trap window(s) must be compared to existing porous element bubble points. Capillary loading of the porous element is rarely a driving requirement but a check is simple and straightforward.

Typically, a safety factor of two is applied to the volume. To determine the trap volume, the propellant demanded, the propellant residuals within the trap, and gas trapped during filling (including subsequent expansion during blow down - if applicable) must be considered. In gallery systems, traps are implemented to accommodate the gas ingestion into the galleries during filling and launch. Any limited volume use can be accommodated by a trap.

For example, if 300 in^3 is required from the trap for despin and a gas bubble of 50 in^3 at minimum operating pressure is trapped during filling, the trap should hold and deliver at least 700 in^3 (2 x [300+50]). If this is less than 10% of the tank volume, a trap is the better choice over a gallery. If the demand volume of 300 in^3 were smaller - on the order of 150 in^3 or less - a sponge or trough would be a better choice; especially if a sponge or trough is required for other mission maneuvers. The choice of device really depends upon mass and complexity since each is capable of meeting the performance requirements.

Repeated Specific Demand Systems using a Trough

Typically, troughs are used in repeated specific demand systems. These systems require repeated use of a specific quantity of propellant. A common example is stationkeeping on communication satellites where burns may use up to 20 lbm of propellant, produce lateral acceleration on the order of 0.01 g, and occur only once every week or so. Trough use in specific demand systems is not limited to stationkeeping maneuvers and may occur for any repetitive maneuver.

To meet intermittent demand, the designer should consider three PMD components: a) a trough, b) a sponge, 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. However, a trough can provide more propellant at higher accelerations than sponges.

A trough concept designed to meet a repeated specific demand is illustrated in Figure 7. Vanes are required to refill the trough during the zero g coast that separates maneuvers.

Viability is determined by establishing that a conventional sponge cannot hold a sufficient quantity of propellant to meet demand.[2] As always, a safety factor of two is applied to the volume. Thus, if 150 in^3 is required from the trough for the maneuver, the trough should hold and deliver at least 300 in^3. The sizing process is iterative. First, a trough's dimensions are assumed and then the deliverable volume is determined.

High Acceleration Retention using a Trough

The second use of troughs is in systems requiring a trap or other PMD component to retain propellant during high accelerations. For example, a trap in a tank required to be handled horizontally in one g may be exposed to higher

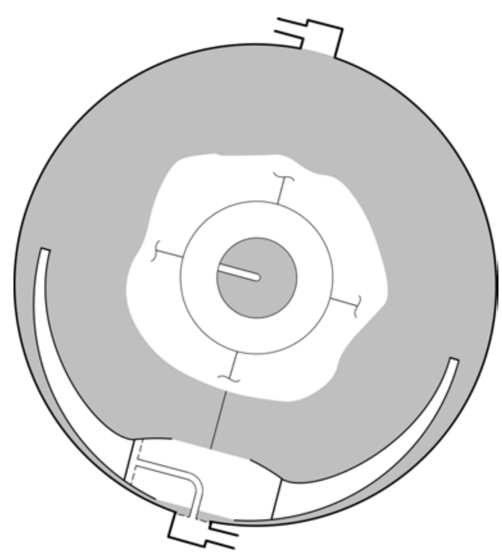

Figure 7. Trough Concept for a Repeated Demand System

* The trap volume required may be less than the volume demanded if other PMD components can deliver some propellant. For example, a sponge positioned over the trap inlet might provide some propellant before the trap volume is required.

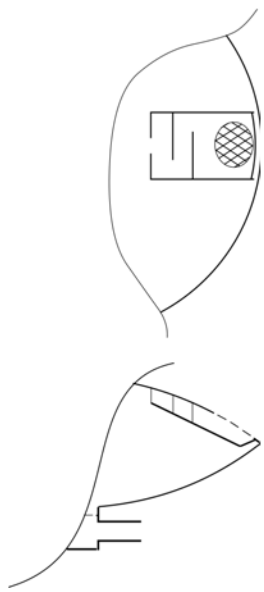

Figure 8. Trough Concept for High g Trap Retention

hydrostatic loads than its trap inlet window can accommodate. A trough, located over or under the trap inlet window, can prevent gas ingestion into the trap. This is accomplished by providing a tortuous flow path which troughs liquid over the trap opening.

An example of a trough device fitted onto a trap is illustrated in Figure 8. In this example, lateral handling in most, but not all directions, is possible. Please note that the trough retains the trap propellant but the propellant is not usable during the high g phase without gas ingestion.

Viability depends on space limitations. In a new PMD design, implementation is straightforward as space is easily allocated. In an existing design, space may be at a premium.

IV. DESIGN

The simple traps and trough illustrated in Figures 1 and 2 are only some of numerous possible designs. This section will address qualitatively the various design issues including size, shape, internal structure, and porous element placement.

Trap Shapes

Traps are usually cylindrical, conical, clam shell shaped or a combination but may be any shape. However, when considering maneuver direction and other PMD component placement, some shapes are more efficient. Various trap shapes are illustrated in Figure 9.

The dictating factors in trap shape are a) ensuring propellant access at the trap inlet window when trap propellant is not required, b) ensuring propellant access within the trap at all times, c) minimizing trap size by reducing trapped gas and residuals d) providing space for sponge, trough, or gallery attachment outside of the trap, e) designing for manufacture, and possibly f) reducing (or increasing) viscous dissipation during spinning operation.

To provide bulk propellant access, the trap inlet window should be either in the bulk propellant or covered by an alternate means of supply (such as a sponge, a trough or a gallery). For example, if spinning transfer orbit is required, the trap inlet window should be placed outboard enough to reach the bulk propellant throughout the transfer orbit. In addition, upright ground draining is usually required and the trap inlet window must be as low as possible. In this case, to ensure trap access for both ground draining and spinning transfer orbit, a shallow trap, like the clam shell shape illustrated in Figure 9, is best.

In start baskets, which operate during settling accelerations, the trap inlet window must be as low as possible to minimize residuals. Venting can be aided by the reorientation dynamics if the propellant impacts the window directly. A shallow cylinder would be best for this application.

The second issue is propellant access within the trap. Propellant must be accessible during all maneuvers, whether trap propellant or bulk propellant is being used. In those acceleration directions where low trap volume operation is required, the trap should be small to maximize propellant depth and minimize residuals. For example, if the trap depletes during an axial unsettling maneuver, the top of the trap ought to be narrow. The conical trap would be ideal. A conical trap is also well suited for lateral depletion but is not well suited to axial depletion. This is illustrated in Figure 10.

Typically, tanks are not vacuum filled in order to minimize shell mass. Thus, if the trap window is not at the highest point in the trap, some gas will be trapped during filling. This gas must be retained throughout mission which increases the required trap size and mass. Therefore choosing a trap shape which reduces the volume above the porous element will save weight. For example, a cylinder with the inlet window near the bottom is a less efficient shape than a shallow cone if gas ingestion during fill is a significant trap size driver.

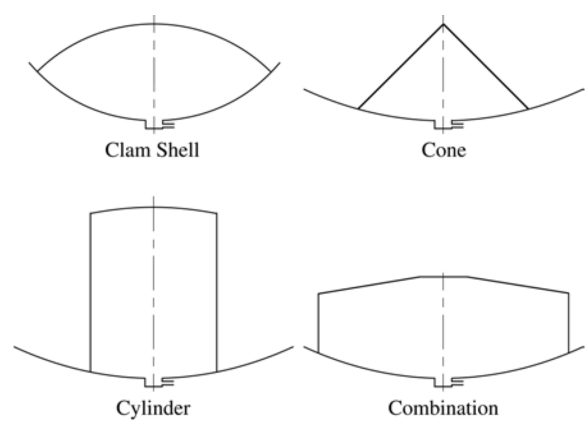

Figure 9. Trap Shapes

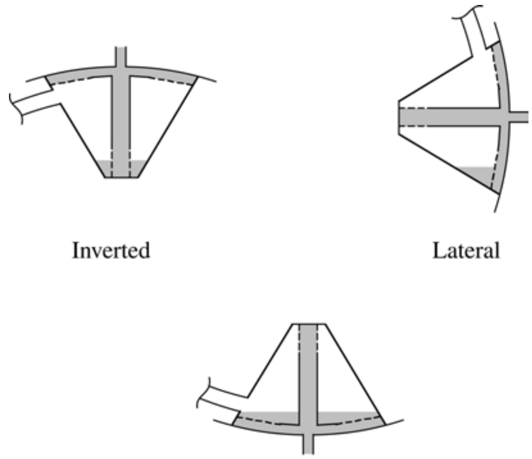

Figure 10. Trap Shape for Minimum Residuals

Integration and manufacturing often impact trap shape. The least expensive and lowest weight trap is usually the best choice. For example, a cylindrical trap more readily lends itself to the attachment of other PMD components and can be cheaper and simpler to build (not always). If a large sponge is required, a cylindrical trap might easily fit in the core of the sponge. As manufacturing techniques change and improve, trap shape will continue to evolve.

The last issue deals with the transition to flat spin. If a vehicle separates from a lower stage with a spin and cannot use the propulsion system immediately for nutation control, transition to flat spin is possible. A trap which is on the spin axis will minimize viscous dissipation and maximize the time to transition to flat spin. This rarely affects the trap design but should be considered if required.

When choosing the vent tube shape in a start basket, two requirements must be considered: a) the porous element at the top of the tube must be kept wet between maneuvers and b) the gas remaining in the vent tube after venting should not be allowed to migrate into the start basket. These are competing requirements which result in a myriad of vent tube designs. A straight tube with a tapered internal fin running its length is ideal. The fin is tapered to keep the gas in the vent tube but also ensures that the porous element is always wet.

Trap Internal Structure and Porous Element Placement

Structure is implemented within traps to access propellant during operation. This structure is generally another PMD component, e.g. galleries, pick up tubes, liners, or even sponges or vanes. Since the trap is essentially a tank within a tank, any PMD component can be found inside a trap. Occasionally, a trap within a trap is implemented.

The most common structure within a trap is a communication device such as a screen covered tube, galleries, or perforated sheet on the end of pick up tubes. Without exploring all the possibilities, three important considerations must be incorporated into the internal structure design: a) the propellant access window(s) must be located where propellant will be during operations (ground operations should not be forgotten), b) the pick up assembly bubble point must not be exceeded and c) in zero g, both the trap inlet and internal propellant access windows should be covered with propellant to prevent thermal gradients from causing gas ingestion. This consideration is often overlooked but a robust PMD design will have all porous elements in liquid in zero g. Fins can be implemented to ensure propellant contact with porous elements.

Positioning of the trap inlet porous elements must consider the location of the propellant during required access and the gas ingested during fill. Obviously, the inlet window(s) should be placed where the liquid resides; for example outboard if spinning access is required or low for ground draining.

As previously described minimizing trapped gas during fill will minimize trap mass. The accomplish this, the trap inlet window should be placed at the highest point in the trap to minimize trap weight. However, positioning the window away from the bulk propellant might increase weight of other PMD components which are required to reach the propellant. One option is a vent window for gas venting during fill and a trap inlet window for propellant access. This dual window trap has the disadvantage of less lateral acceleration capability due to the large separation between windows.

Once trap shape, internal structure and inlet window position has been designed the trap can be fully analyzed.

Trough Shape

Like traps, troughs can be any conceivable shape. However, when considering maneuver direction and volume used, some shapes are more efficient. Various trough shapes are illustrated in Figure 11.

Troughs can be divided into two categories: leaking and non-leaking. Leaking have the advantage of being able to accommodate larger accelerations since the pick up assembly porous elements are closer together (lower Δz). Non-leaking troughs have the advantage of not having to worry about proper sizing of the pick up assembly windows. Non-leaking troughs should be preferred unless large accelerations must be accommodated.

The dictating factors in trough shape are a) ensuring propellant is retained during all pertinent maneuvers, b) ensuring the trough will refill during zero g, c) minimizing size and mass, and d) designing for manufacture.

An upside down bucket will not hold propellant in one g and a poorly designed trough will not hold sufficient propellant during spacecraft operation.

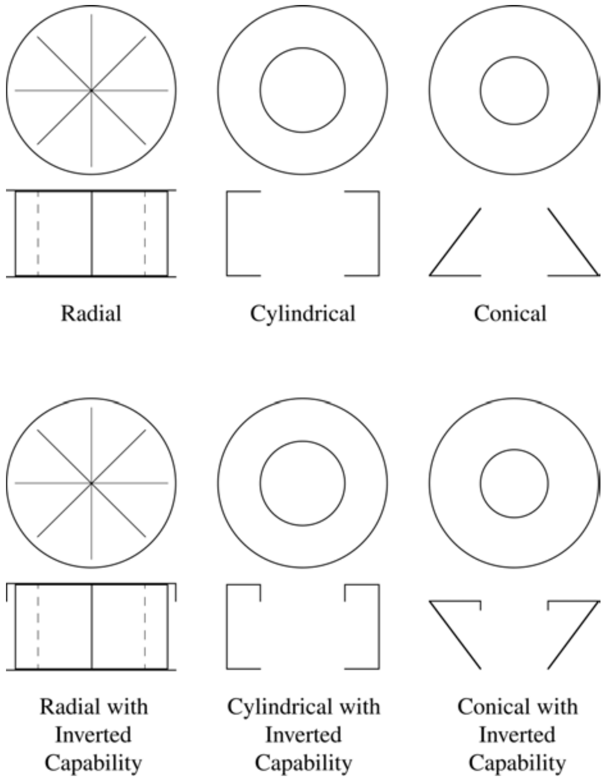

Figure 11. Trough Shapes

When designing a radial trough as illustrated in Figure 2, the number of radial panels used depends upon the number of lateral maneuver directions anticipated and the results of a mass/cost trade. A trade must be completed which weighs diameter and height vs. number of panels. Increasing the number of panels, the height of the trough, or the diameter of the trough will increase the trough's deliverable volume. Therefore, more panels will allow a smaller trough and conversely a larger trough will allow the reduction in the number of panels.

The radial paneled trough illustrated in Figure 2 cannot hold propellant during axial accelerations and therefore is not suitable for missions requiring non settling axial maneuvers. One could modify the radial trough as illustrated in Figure 11 to accommodate non settling axial maneuvers. Both a pick up assembly at the top of the trough as well as an inverted cup shaped barrier ensures some propellant is troughed during high g non settling accelerations.

The second dictating factor, refilling in zero g requires that the gas will be pushed out of the trough by incoming liquid. In radial panel sponge, no obstructions exist for gas ejection and therefore this shape is ideal. The gas is pushed from the trough by the taper created between panels. In the case of a closed trough, such as the cylindrical trough, the central opening must be large enough to ensure that refilling occurs.

To eject gas, the surface tension forces within the trough must exceed the surface tension forces of an interface at the opening. The surface tension forces are dictated by the surface curvature. For an empty cylindrical trough, the pertinent parameter is the surface tension pressure as function of the trough height and diameter:

$$\Delta P = \sigma\left(\frac{1}{R_1}+\frac{1}{R_2}\right) \cong \sigma\left(\frac{2}{H}+\frac{2}{D}\right) \tag{9}$$

For a circular opening, the surface tension pressure as a function of the radius of the opening is:

$$\Delta P = \sigma\left(\frac{1}{R_1}+\frac{1}{R_2}\right) = \sigma\left(\frac{2}{r}\right) \tag{10}$$

Thus to ensure trough refilling, the following inequality must be valid:

$$\left(\frac{2}{H}+\frac{2}{D}\right) > \left(\frac{2}{r}\right) \quad \text{or} \quad r > \frac{H\,D}{H+D} \tag{11}$$

One can either a) increase the forces within the trough by adding fins and/or decreasing trough size or b) decrease the forces associated with the opening by increasing the size of the opening. Figure 12 shows an insufficient opening with two options making the trough refillable in zero g. Please note that the inadequate opening will function properly during most refills but if slosh were to move liquid over the trough as illustrated, refilling will not occur.

Trough shape is determined by trial and error. Alternative shapes are examined in terms of their manufacturability, weight and cost. Clearly, many different troughs can hold the required volume just as many different drinking glasses can be found in all kitchens. The most efficient design is the lowest weight and/or the least costly.

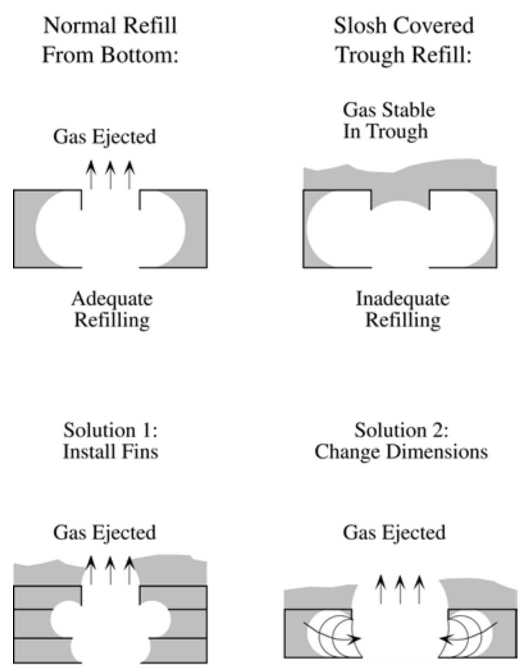

Figure 12. Zero g Trough Refilling

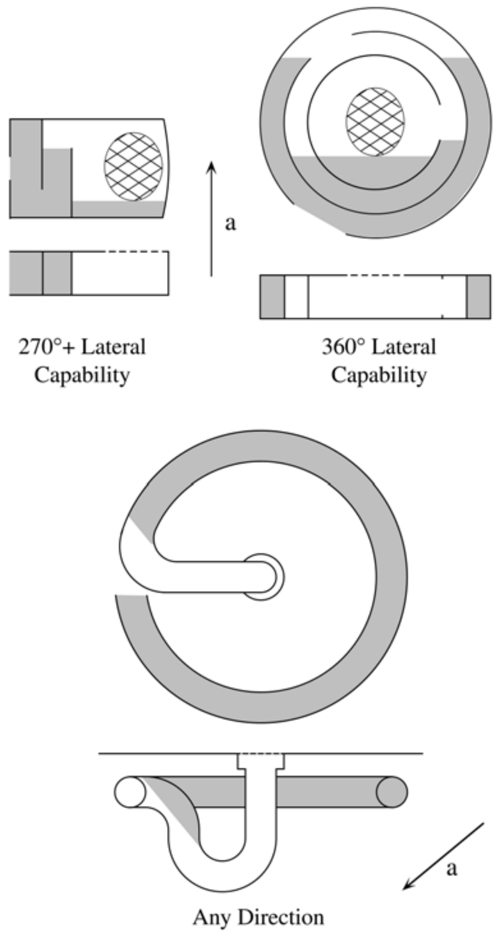

Figure 13. Trough Designs for Propellant Retention

Trough Internal Structure and Porous Element Placement

Structure is implemented within troughs to a) access propellant during operation and b) to ensure zero g refilling.

Since troughs are primarily used for high g retention, galleries or screened pick up assemblies are most often used to access propellant. As with traps, three important considerations must be incorporated into the internal structure design: a) the propellant access window(s) must be located where propellant will be during operations (ground operations should not be forgotten), b) the pick up assembly bubble point must not be exceeded and c) in zero g, the windows should be covered with propellant to prevent thermal gradients from causing gas ingestion.

As previously stated, fins may be implemented to ensure gas expulsion and zero g trough refilling. The fins can be configured in almost any manner so long as a) the gas is pushed toward and out of the central opening and b) propellant flow to the trough pick up assembly is not significantly inhibited. Orienting the fins parallel to the flow direction or perforating the fins alleviates this concern.

Trough Design for Trap Entrances

When designing a trough for a trap entrance, the trough should be as small as possible to minimize potential residuals and metal mass.

The dictating factors in trough shape are a) ensuring propellant is retained during all pertinent maneuvers, b) minimizing size and mass, and c) designing for manufacture.

Retaining propellant requires that the direction and frequency of the relevant maneuver be identified. A trough is directionally sensitive and may allow a small amount of gas to enter the trap during each adverse maneuver. If the maneuver repeats, the gas would accumulate in the trap and the trap must be sized to accommodate it.

It is possible to design a trough which allows omnidirectional retention. An example is a spiral tube which travels in one axial direction and then reverses to travel in the opposite direction. This bent tube trough will prevent a trap from losing propellant during handling or thrusting in any direction. However, simple troughs are possible if the omnidirectional capability is not required. Figure 13 shows a variety of trough concepts for trap propellant retention.

Providing a tortuous path which requires gas to travel down while liquid flows up is all that is required to create a trough. Mass, cost and manufacturability will dictate individual designs.

V. ANALYSIS

PMD Technology uses the techniques presented in this section to verify trap and trough compliance with the operating requirements. The main requirement of a partial control device is to hold and deliver propellant during adverse accelerations. The pertinent performance characteristic is the available or deliverable volume. In general, this volume is computed using a simple, conservative analysis and a significant safety factor. Sophisticated models can be used to refine the predicted available volume but generally are not required.

Analysis of traps and troughs is more straightforward than other PMD components. When analyzing traps, the goals are to ensure a) adequate available volume, b) gas free delivery, c) zero g submergence, and, in the case of start baskets, d) adequate venting. Analyzing troughs has similar goals: to ensure a) adequate available volume, b) gas free delivery, and c) zero g refilling.

Traps

To ensure adequate volume, one must first determine the required volume. If the trap is used in a specific demand system, the specification will state the required volume for each maneuver. All maneuvers must be examined to determine if trap propellant is required. If trap propellant is not required, the trap inlet window must be submerged. Determining propellant location during each maneuver requires that the surface tension's effect on the liquid gas interface be accounted for. Methods for computing the two dimensional surface curvature and stability are presented in Ref. 1. and Ref. 6.[6] Although typically not required, static three dimensional surfaces can be modeled using Evolver, a three dimensional surface, minimum energy solver.[7] Determining the propellant's location during each mission phase is required for correct trap sizing.

Each volume required from the trap must be adjusted to the minimum operating pressure (maximum trap use volume) via the perfect gas law:

$$V_{maximum} \cong V_{required} \frac{P_{at\,ingestion}}{P_{minimum}} \tag{12}$$

Other considerations will add volume to that computed above. The appropriate questions are:

1) If galleries are attached to the trap, what is the volume of gas trapped in the galleries during launch?
2) If the trap is used during thrust ignition (start basket or non refillable trap), what is the reorientation time and volume of propellant consumed?
3) If the trap inlet window is not at the highest point in the trap, how much gas is trapped during fill?
4) How much residual propellant will reside in the trap?

These volumes and the specification required volume determines the total volume required from the trap. Typically, a safety factor of two is applied. The methods used to compute each volume follow. Please note that each gas volume must be adjusted to the minimum operating pressure.

Conservatively, the gallery gas volume (item 1) is the volume in the gallery arms above the minimum launch fill fraction (adjusted to the minimum operating pressure).

To determine the volume required during thrust ignition (item 2), one must model the bulk propellant reorientation. First, a rough estimate is completed and if this volume is small, and therefore has little impact, a large safety factor is applied and no more analysis is required. However, if the estimated volume is large, a more elaborate analysis producing a more precise volume is warranted.

To obtain an estimate, one first must determine if surface tension has a role in the reorientation. The Bond number is the ratio of inertial forces to surface tension forces. If the Bond number is greater than 10, surface tension is negligible when computing the reorientation time:[5]

$$Bo = \frac{\rho a r^2}{\sigma} > 10 \tag{13}$$

With surface tension negligible, the propellant will reach the trap inlet in the free fall time (approximately). The time required to completely settle all the propellant can be estimated as three times free fall. This is conservative as propellant will begin to be accessible at the free fall time.

$$t_{estimate} \cong 3\, t_{free\,fall} = 3 \sqrt{\frac{2\,\Delta h}{a}} \tag{14}$$

If a more precise reorientation estimate is required, a two or three dimensional model should be constructed. Both RIPPLE, a two dimensional free surface computational fluid dynamics (CFD) model or FLOW-3D, a three dimensional free surface CFD model are adequate for the task.[8, 9] Effects such as geysering can be fully explored using these models.

If surface tension is not negligible, an estimate can be attained by using the data presented in NASA TN 3005 but a RIPPLE or FLOW-3D CFD model is warranted.[5,8,9] Both of these CFD codes can estimate the effects of surface tension but great care must be exercised to obtain accurate results.

Once the reorientation time is determined, the volume required is simply the reorientation time multiplied by the demand flow rate (adjusted to the minimum operating pressure). This is conservative because some propellant will be available as soon as the bulk propellant reaches the trap.

The volume of gas trapped in the trap during fill (item 3) is the physical volume of trap above the highest trap inlet window. Fortunately, this volume is captured at a pressure typically much less than the minimum operating pressure. Therefore, the trap volume required is smaller than the physical volume and is adjusted via equation (12).

The residual volume (item 4) is the trap volume required to deliver gas free propellant. This volume is unavailable for use and must be excluded from the total trap volume. The residual volume depends upon the EOL maneuver direction. If specified, only one direction need be examined, otherwise all possible directions must be examined to determine the maximum residual volume.

The residual volume is computed by determining the minimum porous element area required to provide gas free flow. As a trap is depleted, the porous element area submerged decreases. Eventually, the flow losses across the porous element increase beyond the bubble point and gas is ingested. The area at which the flow losses exceed the bubble point (minus any hydrostatic pressure) dictates the trap residual volume:

$$f\left(Q, \rho, \nu, A, Element\right) = \frac{BP}{SF} - \rho\, a\, \Delta z \tag{15}$$

Accounting for the above volumes allows one to verify that the trap volume safety factor is sufficient (two is the goal):

$$SF = \frac{V_{trap} - V_{residual}}{V_{spec} + V_{gallery} + V_{ignition} + V_{gas}} \tag{16}$$

Now that one has sufficient volume in the trap, access must be confirmed. If a gallery or pick up assembly is used, a gallery or pick up analysis is required. Analyzing galleries is beyond the scope of this paper but in summary the following analyses must be completed: a) the propellant location determined during each maneuver to ensure access, b) the steady state loads compared to the bubble point to ensure gas free flow, c) the surface dip and vortexing analyzed to ensure gas free flow, and d) the transient conditions of both propellant motion and thrust ignition examined to demonstrate no transient gas ingestion.

For start baskets, surface dip and vortexing must be explored both inside and outside of the trap to ensure adequate coverage of the perforated sheet. Vortexing should be prevented either by employing a cruciform vortex suppresser both inside and outside of the start basket, or by reducing the flow velocities to levels producing negligible dynamics. Surface dip can be estimated by equating the hydrostatics to the dynamics (surface tension is ignored for conservatism). Assuming cylindrical potential lines, the resulting equation describes the surface height, h, as a function of the height far from sink, h_∞, the radial distance, r, the flow rate, Q, and the acceleration, a:

$$h^2\left(h_\infty - h\right) = \frac{Q^2}{8\pi^2 a r^2} \tag{17}$$

Using this equation one can determine the gas core diameter at low fill fractions and the required porous element diameter. For conservatism, a safety factor should applied to the flow rate. Figure 14 shows an example surface dip computed with equation (17).

By properly placing and sizing porous elements, gas free propellant flow is assured.

During zero g, the porous elements should be submerged with propellant. Fins are often used to accomplish this. Qualitatively, one can examine each porous element to ensure that any gas exposed to it will be ejected in zero g. Little quantitative analysis is required. If necessary, the two or three dimensional propellant surface location can be determined using computational methods.[1, 6, 7]

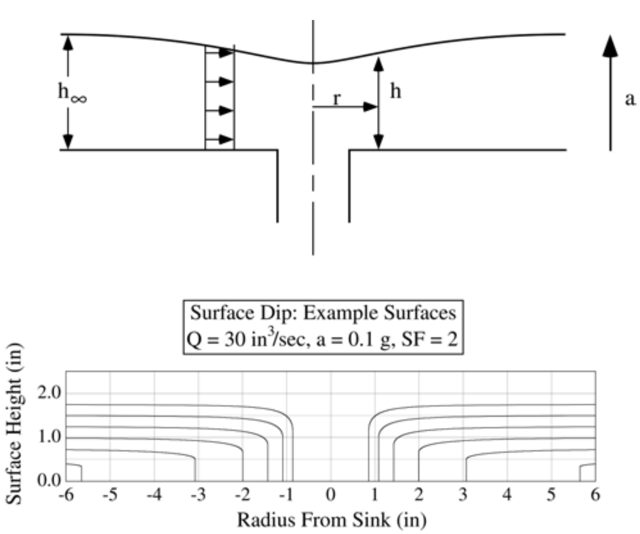

Figure 14. Example of Computed Surface Dip

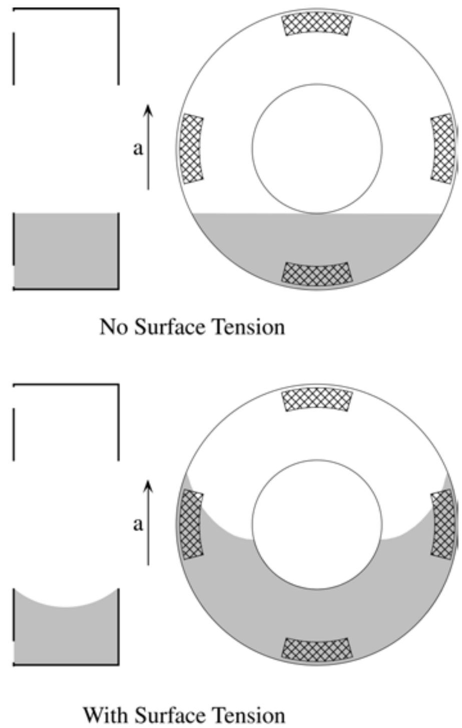

Figure 15. Trough Holding Volume

For non-refillable traps, no more analysis is required. Completing the preceding demonstrates the ability of the trap to deliver the required volume gas free. For refillable traps, venting must be analyzed. The Physics section of this paper addresses the criteria for venting. The analysis need only confirm that venting will occur. The dynamics should be ignored for conservatism.

Troughs

To ensure adequate trough volume, one must first determine the required volume. In the case of a trough, the required volume is given in the specification as the maximum volume demanded for each repetitive maneuver. Other concerns, such as gas ingested during fill, are not relevant to troughs. Once given the required volume, one must compute the available trough volume as the trough holding volume minus the trough residual volume.

Since troughs are typically used to provide propellant during high g maneuvers, surface tension forces are ignored in most cases. The trough holding volume is the volume in the trough below the lowest solid wall. This is illustrated in Figure 15. Also illustrated is the propellant location assuming surface tension is not negligible. The surface was estimated using methods described in Ref. 1. In this case assuming negligible surface tension is conservatism.

The available volume will be reduced if the trough leaks. Leaking should be prevented by creating flow losses across the pick up porous element which a) exceed the hydrostatics and b) are less than the bubble point (with a safety factor). Demonstrating the inequalities in equations (6) and (7) will verify that the trough will not leak.

Determining the holding and residual volumes allows one to verify that the trough volume safety factor is sufficient (two is the goal):

$$SF = \frac{V_{holding} - V_{residual}}{V_{spec}} \qquad (18)$$

To ensure gas free delivery of the available trough propellant, the pick up windows must be properly positioned and sized. In addition, fins incorporated into the design must be perforated to allow propellant to reach the windows.

The trough pick up windows should be low in the trough to minimize residuals. Residuals are computed as previously indicated for traps and must be shown to be less than required.

The windows should be sized to ensure gas free propellant delivery. Verification requires demonstrating compliance with equation (8) with a safety factor (preferably two over acceptance test criteria). If the flow path in the pick up assembly is small (such as in a gallery device) transients also must be examined.

If fins are used in the trough, they should be perforated and the flow losses through the perforations shown to be negligible. The flow losses can be measured or conservatively estimated.

Having verified a) propellant access at the trough pick up windows, b) that the porous element bubble point is not exceeded and c) that flow can reach the pick up window through the fins, gas free propellant delivery is assured.

Once the trough propellant is used, zero g coast is encountered and the trough must refill. A vane system can deliver propellant to the trough. One must verify that a) the vane system can deliver sufficient propellant to refill in the allocated time, b) the propellant will flow into the trough once it reaches the trough and c) that the gas will flow out of the trough.

A vane analysis as outlined in Ref. 1 is required to show that propellant can be delivered to the trough in the required time. Propellant must be able to flow into the trough once the vane system has delivered it.

To verify proper trough refilling, one has to show that a flow path exists into the trough. In the case of a radial trough, each section must be connected to the vane supply system. This must be accomplished without compromising the individual trough sections. Extending the vane system around the outer circumference would suffice. In the case of a non leaking trough, the vane system must extend into the trough. This is typically accomplished by using the region under the trough and a fin circumscribing the inner trough edge. Whatever the method, the vane system analyzed must include a path into the trough.

As previously described, a trough can be designed which does not properly refill as a result of propellant sloshing over the trough. One must verify that gas will be ejected from the trough in this unlikely event. If the opening in the trough is circular, one can use equation (11) (or a similar one for non-cylindrical but axisymmetric troughs) to show that the surface tension forces within the trough exceed the surface tension forces of the interface at the trough opening. For more complex geometry a three dimensional modelling code like Evolver can be used.

The trough's operational performance is adequate if the required propellant is delivered gas free and the trough refills in the allocated time.

Analysis Summary

A number of assumptions were incorporated into the analysis presented to keep it simple and straightforward. These assumptions have been chosen to be conservative.

One might argue that, with a safety factor of two on trap or trough volume and a conservative analysis, the resulting device is over designed. Depending upon the circumstances, this may or may not be true. However, the approach taken guarantees a robust design which easily meets requirements and provides some additional capability. Typically, the impact of any 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 PMD component which will meet requirements.

Also, reducing the safety factor is not recommended. The safety factor is not only incorporated to accommodate uncertainty in the analysis, but also to accommodate uncertainty in manufacturing. 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 (which in some cases is possible though not required), 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.

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NOMENCLATURE

Greek

ρ ≡ liquid density
σ ≡ absolute surface tension
ν ≡ liquid kinematic viscosity

Δ ≡ change

English

a ≡ acceleration
h ≡ height
r ≡ radius (of opening, of tank, or from centerline)
t ≡ time
z ≡ height relative to acceleration vector

A ≡ area
Bo ≡ Bond number
D ≡ trough diameter
H ≡ trough height
P ≡ pressure
Q ≡ volumetric flow rate
R ≡ principal radius of curvature
SF ≡ safety factor
V ≡ volume

Subscripts

∞ ≡ at an infinite radius

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NOTES