A Detailed Historical Review of Propellant Management Devices for Low Gravity Propellant Acquisition

Jason W. Hartwig[1]

NASA Glenn Research Center, Cleveland, OH, 44135, USA

This paper presents a comprehensive background and historical review of Propellant Management Devices (PMDs) used throughout spaceflight history. The purpose of a PMD is to separate liquid and gas phases within a propellant tank and to transfer vapor-free propellant from a storage tank to a transfer line en route to either an engine or receiver depot tank, in any gravitational or thermal environment. The design concept, basic flow physics, and principle of operation are presented for each type of PMD. The three primary capillary driven PMD types of vanes, sponges, and screen channel liquid acquisition devices are compared and contrasted. For each PMD type, a detailed review of previous applications using storable propellants is given, which include space experiments as well as space missions and vehicles. Examples of previous cryogenic propellant management are also presented.

Nomenclature

Bo = Bond number
D_P = Pore diameter [μm]
EE = Expulsion efficiency
g = Gravity, [m/s^2]
L_C = Characteristic length
$V_{residuals}$ = Residual volume of liquid remaining inside the tank at PMD breakdown, [m^3]
V_{tank} = Volume of the propellant tank, [m^3]
γ_{LV} = Surface tension, [N/m^2]
ΔP_{BP} = Bubble point pressure, [Pa]
ρ = Density, [kg/m^3]
θ_C = Contact angle

I. Introduction

Gravity affects many processes in space, such as the separation of the liquid and vapor phases within a propellant tank. In general, the lowest achievable potential energy state within a tank governs the location of the liquid/vapor (L/V) interface. In the standard gravity field of Earth, fluid density dictates this location because the heavier liquid settles to the bottom and the lighter vapor rises to the top. In the microgravity conditions of space however, surface tension becomes the controlling mechanism for the phase separation because the liquid tends to wet the walls, leaving a gaseous core in the center. To meet vapor-free transfer requirements for both in-space cryogenic engines and cryogenic fuel depots [1], any one of a number of Propellant Management Devices (PMDs) may be required inside the tank.

Figure 1 illustrates why liquid acquisition devices (LADs) are required for successful engine operation. In this paper LADs are used synonymously with PMDs. On the ground or during launch, LADs are generally not required because vehicle thrust and high-g levels can maintain phase separation within the propellant tank. In microgravity

---

[1] Research Aerospace Engineer, Propellants and Propulsion Branch, 21000 Brookpark Road, MS 301-3, Cleveland OH, 44135, Senior Member.

however, in the absence of settling thrusting maneuvers to favorably position the liquid, there is no way to guarantee vapor-free propellant flow out of the tank without using a LAD. After sufficient time, in an unsettled environment, liquid and gas phases will combine such that a two phase mixture may cover the outlet. At a bare minimum, a mixture of gas and liquid sent to the engine will cause combustion instabilities, and at worst cause complete engine failure.

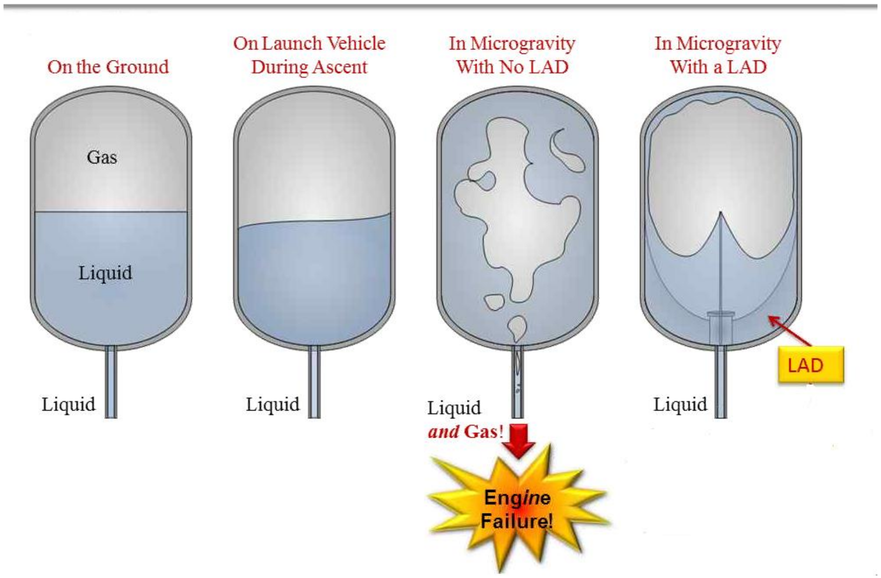

Figure 1 – Illustration of Why Liquid Acquisition Devices are Required

The purpose of a PMD is to separate liquid and gas phases within a propellant tank and to transfer vapor-free propellant from a storage tank to a transfer line en route to one of two customers, an engine or receiver tank (depot application), in any gravitational or thermal environment. The generic system architecture for propellant transfer is shown in Figure 2. Complete propellant transfer from a storage tank to the customer is divided among the following four stages:

1) Vapor-free liquid extraction from the storage tank
2) Chill-down of the transfer line
3) Chill-down of the receiver system
4) Fill of the receiver system

PMDs therefore represent the first step in the propellant transfer process.

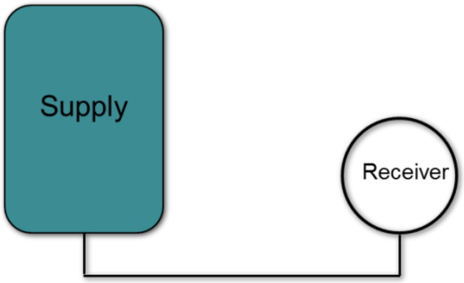

Figure 2 – Generic Supply and Receiver System where the Downstream Customer is Either an Engine or Receiver Tank

PMDs were born out of the desire to perform engine restarts in a low-g environment [2, 3]. PMDs must be designed and implemented to ensure that there is always communication between the PMD and liquid anywhere within the tank, and to ensure that the tank outlet is sufficiently covered with liquid during any phase of the mission. In the 1-g field of Earth, transfer of liquid is easy because the L/V interface in the tank is always such that the heavier liquid resides at the bottom of the tank and the lighter vapor rises to the top; a simple hole in the bottom of the tank is sufficient. In reduced gravity environments (10^{-2} – 10^{-4} g), at high liquid levels, settling thrusting maneuvers can be used to favorably position liquid over the tank outlet. At low liquid levels, simple bubble arrestors or sumps can be inserted over the tank outlet to prevent vapor ingestion into the transfer line in order to drain the remaining liquid residuals.

In the low Bond number microgravity environment of space however, where Bond number is defined as:

$$Bo = \frac{\rho g L_C^2}{\gamma_{LV}} \tag{1}$$

where ρ is the liquid density and L_C is the characteristic length of the system, single phase liquid extraction becomes a challenge because surface tension forces generally become the driving force for phase separation and liquid flow. Liquid tends to wrap the outer walls, leaving a gaseous core in the center of the tank. Multiple PMDs may be required to sufficiently cover the outlet with liquid to counteract low g-levels. Full communication PMDs, or devices that maintain communication between liquid, PMD, and tank outlet at all times, are often required in microgravity systems so that propellant can be accessed from anywhere within the tank. When supplying cryogenic liquids to the outlet of the tank, low gravity fluid control acquisition is further complicated over storable liquid due to the low surface tension and high susceptibility to parasitic heat leak associated with cryogenic propellants.

PMDs come in numerous styles and designs, each with its own specific purpose. Multiple PMDs are often required to meet the demands of a particular mission, whether using storable or cryogenic propellants. PMDs have been used extensively in chemical storable propulsion systems and can even be implemented in electric propulsion systems [4]. PMD performance is determined by three primary characteristics; PMD system mass, demand mass flow rate, and expulsion efficiency *EE*, which is defined as:

$$EE = \frac{V_{residuals}}{V_{\tan k}} \tag{2}$$

where $V_{residuals}$ is the residual liquid propellant left in the tank when the PMD breaks down and admits vapor into the transfer line, and $V_{\tan k}$ is the internal volume of the tank. Therefore EE is a measure of how much of the tank is drained through the LAD before the LAD breaks down. The emphasis of this paper is on full communication, flexible, and robust capillary driven PMDs, which are actually the most commonly used systems for flight [5]. The three most popular capillary driven PMDs are vanes, sponges, and screen channel LADs [6-10], but there are many other non-capillary systems which have been used in previous years.

II. Non-Capillary Propellant Management Devices

The simplest PMD is simply a hole at the bottom of the tank. If acceleration levels are high enough, or if the propellant tank resides in reduced gravity ($10^{-2} – 10^{-4}$ g), there may not be a need for a special PMD. If mission requirements will allow, there are numerous non-capillary driven PMD types which can be implemented for control and extraction of single phase liquid propellant.

Over the years, many missions have incorporated tanks with positive expulsion devices, which include pistons, diaphragms, and bladders. Positive expulsion devices are used primarily to maintain the interface between pressurant gas and propellant through the presence of a barrier [11]. Pistons have been used as PMDs to divide the pressurant gas from the propellant, but leakage and low EE led to the desire for better devices.

The bladder was one of the devices developed to replace the piston PMD on the Corporal [12]. The bladder PMD resembles a balloon, where the propellant is located inside the membrane with a narrow opening leading to the tank outlet as shown in Figure 3 [13]. Because the bladder must encompass the entirety of the propellant, it is heavier than the diaphragm and so tank size is again limited. Also, the pressurant gas can potentially cause folding of the membrane, reducing EE unless a support structure is added. However, the bladder maintains a smaller sealing area than the diaphragm, which needs to be welded to the entire circumference of the tank, allowing for easier installation and removal. Bladders were also used in the Mercury and Gemini missions [14].

A diaphragm differs from the bladder in that it is composed of a flexible membrane to separate pressurant gas and liquid propellant [15, 16]. Figure 4 shows a diaphragm which uses an elastomeric barrier for phase separation [12]. Like bladders, diaphragms are also advantageous in systems that require effective slosh control and elimination of reactions between pressurant gas and propellant. Because bladders and diaphragms span across the entire tank, the mass of the diaphragm may rival the mass of the tank walls, making these PMDs impractical in large scale applications. In addition, elastomeric material is not well suited for long life missions [17].

Newer missions tend to employ surface tension PMDs that can be built to be lighter and more reliable than positive expulsion devices. However, the diaphragm remains effective at maintaining gas free flow to the outlet and eliminating propellant slosh. For example, the Space Shuttle used three diaphragm tanks [12] for its Auxiliary Power Unit (APU), Cassini used a diaphragm tank for its RCS [18], and recent computational analysis performed on diaphragms show they are good at dampening slosh [19].

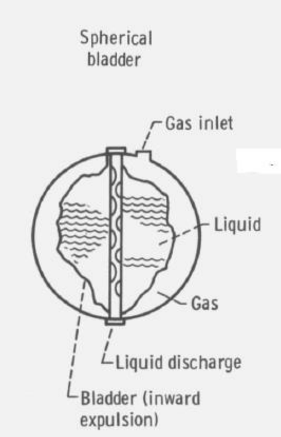

Figure 3 – Schematic of a Spherical Bladder Lying Just Within the Tank Shell from [13]

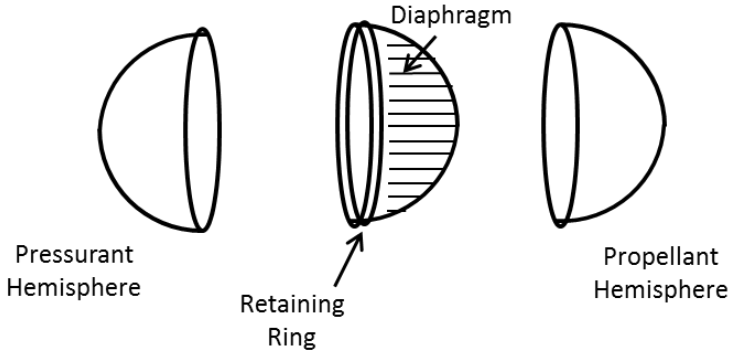

Figure 4 – Schematic of a Diaphragm Assembly. The molded diaphragm is welded between the two hemispheres.

III. Partial Communication Capillary Propellant Management Devices

Traps, troughs, baffles, and vortexes are considered capillary PMDs that are used as simple control devices, and not full communication devices. Traps use porous elements such as screens to trap gas outside of the structure while allowing liquid to flow through the trap and out of the tank [20, 21]. Porous traps also allow the PMD to hold propellant at high accelerations. Traps are generally reliable and can be constructed out of lightweight materials. However, since most traps cannot passively reacquire propellant in low gravity environments, they are primarily used in systems which experience one-time maneuvers, such as launches or station keeping maneuvers. Traps have been given consideration inside the Arianne-5 upper stage tanks for restart [22, 23]. A custom built trap PMD was used in the famous Apollo service module for liquid retention during adverse accelerations such as those caused by the RCS [17, 24]. The capillary driven trap allowed the tank to hold liquid over the outlet while simultaneously preventing large gas bubbles from entering the engine feed line.

Troughs are highly reliable control PMDs that use hydrostatic forces to maintain control of liquid, although they can be designed to use surface tension to refill [21, 25]. An example of a trough is depicted in Figure 5. Troughs differ from traps in that they are passively refillable. They are effective at providing large quantities of propellant for high acceleration maneuvers beyond the capabilities of sponge PMDs. However, since they encompass the liquid that they hold and must be constructed of solid metal, they require more space and metal mass than sponges, and are thus less efficient at lower accelerations.

Baffles are control PMDs primarily used to reduce sloshing [26]. Baffles can include a wide variety of shapes, but all function to limit propellant movement. Shown in Figure 6 is an example of a baffle. The two baffles welded into the propellant tank resembled flattened rings that span the diameter of the tank with a hole in the center.

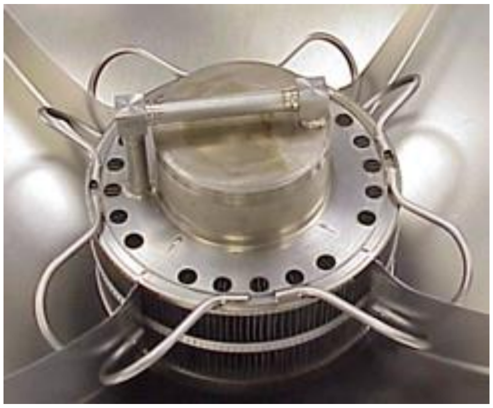

Figure 2.5 – Example of a Trough

Figure 2.6 – A Baffle Welded to the Interior of a Propellant Tank

Meanwhile a vortex suppressor is meant to reduce vortices at the tank outlet that appear during high mass flows. This allows the system to operate well under higher flow rates. The development of a vortex suppressor was needed for the Near Earth Asteroid Rendezvous (NEAR) oxidizer tank as shown in Figure 7 [27].

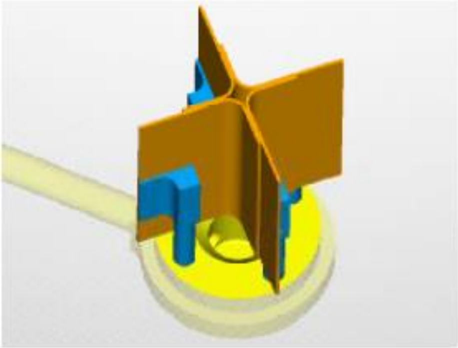

Figure 2.7 – Three Dimensional Image of a Vortex Suppressor. The yellow represents the tank outlet and outflow tube.

IV. Vanes

The three primary total communication capillary driven PMDs include vanes, sponges, and screen channel LADs. Of the three, the simplest and most reliable PMD is the vane. Relative to screen channel LADs, vanes are open acquisition PMDs which allow for a much simpler design at the cost of not being able to sustain or supply higher flow rates. Vanes have rich flight heritage in storable propulsion systems but none in cryogenic systems.

A. Design Concept, Basic Flow Physics, and Principle of Operation

As shown in Figure 8, vanes are generally designed as thin metal plates that are mounted perpendicular to the tank walls so that distinct corners are formed between PMD and the wall [7, 28]. The metal plates can be tapered from "short" to "tall" from the center of the tank to the tank outlet as shown. This tapering allows the vane to utilize a weak capillary pumping force to move liquid from the center or aft end to the tank outlet in the absence of gravity. The size and number of vanes is determined by the flow rate requirements and EE.

Figure 8 – Total Communication Vane with Center Post

Vanes are sized and numbered so that there is always communication between the propellant pool and vane. As shown in Figure 8, a center post can be used as an additional flow path for liquid to creep towards the exit. Vanes can be constructed out of the same metal as the tank wall, allowing for a very simple and lightweight design. For added robustness, a double vane or ribbon vane can be used to increase vane flow area, and thus flow rate out of the tank.

Detailed steady state analysis of vanes is available in [7]. The basic flow physics and principle of operation for vanes are as follows [29, 30]: In flight systems, vanes closely follow the contours of the tank walls. In low gravity, liquid naturally sticks to the vanes and walls in the absence of accelerations. The liquid propellant wets the plate surfaces, and surface tension causes the liquid to form a rounded fillet in the corners, thus enabling liquid to be transported along the fillet toward the outlet. Capillary forces then push liquid from one end of the vane to the other near the poles of the tank. Liquid from the pole opposite the tank outlet is carried across the tank along a center post (not shown) using similar weak capillary forces. These flow paths are depicted with blue arrows in Figure 9.

Because vanes are open PMDs, they cannot block gas ingestion into the outlet. As propellant is removed via the tank outlet, the weak capillary pumping force can only replace liquid over the tank outlet. This renders stand-alone vanes useless except for liquid resupply in very low acceleration environments with high surface tension propellants, since they are incapable of controlling or holding liquid over the tank outlet. To circumvent this problem, vanes are often used in conjunction with small control devices mounted over the tank outlet to provide a very robust PMD. There is a critical flow rate beyond which vanes cannot supply liquid to the outlet in a continuous outflow environment; this is quantified for a small scale LH_2 tank in [31].

B. Advantages and Disadvantages

Perhaps the biggest advantage to choosing vanes over sponges or screen channel LADs is simplicity. Vanes are often constructed out of very thin sheet metal and are generally very easy to build, shape, and install into propellant tanks. The simplest design solution which meets experimental requirements is the best solution, so vanes are often the first choice. Second, vanes are also much lighter than sponges and gallery arms. For example, thin Titanium (Ti) sheet vanes can be installed into most storable propulsion systems that employ Ti tanks. Third, as a result of the simplicity in design, vanes are cheaper to manufacture over sponges and screen channel LADs. Finally, vanes are highly reliable. Because of the open flow path, vanes can generally achieve very high EE before gas ingestion into the outlet.

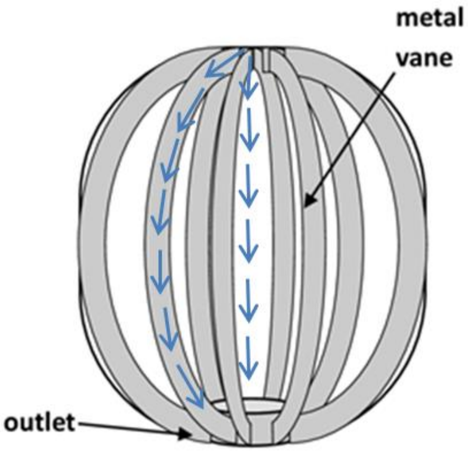

Figure 9 – Schematic of Vane Flow Patterns in Low Gravity

The two disadvantages of a vane PMD are that it cannot supply nor sustain medium to large demand flow rates and it cannot sustain liquid-only flow under medium to high adverse accelerations due to the weak capillary pumping force relative to sponges and galleries. This limits vanes to be implemented in systems that experience low g-levels and require very low demand flow rates. For future cryogenic engines and cryogenic depot applications, it may be difficult to scale up the vane to meet the projected higher flow rate demands.

C. Storable Propellant Historical Examples

Vanes have a rich flight heritage in storable propulsion systems in flight experiments as well as in numerous vehicles and missions. Vanes are particularly beneficial in satellite systems requiring periodic station keeping maneuvers because satellites only require occasional access to propellant over the course of a long duration mission. The lightweight vane is also ideal to reduce the size and system of the satellite. General examples of vane designs are available in the literature [32-34].

1. *Space Experiments*

Historically, there are two space experiments which employed a vane type PMD. The Fluid Acquisition Resupply Experiment-II (FARE-II) tested a vane type LAD using a simulant fluid onboard of the Shuttle mission STS-57 as its primary PMD [35, 36]. The secondary PMD resembled that of a sponge. The purpose of the experiment was to establish vane performance limits in terms of maximum achievable expulsion efficiencies under adverse acceleration levels. A snapshot of the FARE-II experiment is shown in Figure 10 [36]. This was a very successful mission which generated useful low-g data.

A vane type PMD was also used for the Vented Tank Resupply Experiment (VTRE) onboard the Shuttle mission STS-77 [37]. Twelve outer and twelve inner vanes were mounted inside a small scale see-through tank to conduct outflow tests using Refrigerant-113. A vane type PMD was also planned to be used in the Skylab mission [38].

2. *Vehicles and Missions*

Many different variations of vanes have been used in numerous storable propulsion flight vehicles and missions. In 1975, the company Radio Corporation of America (RCA) launched several communications satellites (SATCOM) into orbit [39]. The mission objective was the provision of commercial satellite coverage to all fifty of the United States. A tank with a vane PMD was used to provide the propellant necessary for orbital insertion, regular station keeping, and to access propellant during coasting in low-g. Four vanes sprouted from the tank outlet and tapered all the way up to the other hemisphere of the tank, allowing the vanes to contact both tank ends.

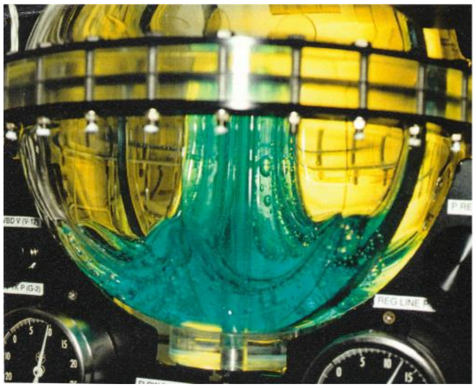

Figure 10 – Fluid Acquisition and Resupply Experiment-II Vane and Sponge with 10% Liquid Remaining in the Tank from [36].

The HS 601 Block I satellite was developed in 1987 as a commercial satellite [40]. The tank assembly was comprised of several PMDs, but vanes were the primary system used to resupply propellant to a sponge and trap during low-g coasts [41]. This satellite also only required small station keeping maneuvers, which were easily achievable with the vane. The HS 601 Block II satellite design completed in 1997 used a simple four vane arm PMD in its main propellant tank [40]. This design was similar to its predecessor, except the longer cylindrical tank required longer vane arms and a slightly more complex trap assembly.

Vanes were used in the Orbital Communication (ORBCOMM) satellites, which were responsible for handling low data transfer, limiting the communications to non-time sensitive information. These satellites allowed two-way data communication, position determination, emergency alerting, and alphanumeric messaging [42]. The design of the satellite was a simple disk with deployable solar panels and antenna [43]. Vanes were used primarily for low thrust station keeping.

Many geosynchronous satellites also employ vanes. For example, a tank and vane PMD was developed in early 2000 for a commercial satellite [29]. This particular system had hemispherical vanes which were not connected along the walls, but connected with a center post. Another example of a geosynchronous satellite was the Star-2 system which used a bi-propellant system with a single fuel tank and two oxidizer tanks [44]. Vanes were chosen because of the desire to achieve very high EE and maintain very low residuals. The Boeing 601 was yet another example of a geosynchronous satellite employing a simple vane PMD [45].

Vanes were also used to supply propellant for the Near Field InfraRed Experiment (NFIRE) for station keeping [31]. The satellite was launched in 2007 [46] which carried two payloads: a Track Sensor Payload [47] to detect and track missiles, and a Laser Communication Terminal (LCT) [48] to test laser communication with the German made TerraSar-X satellite. Vanes have also been used in the Iridium constellation [49], the INSAT satellites [50-52], and the Arabsat television satellites [53].

V. Sponges

The second total communication capillary driven PMD is the sponge. A sponge is defined as an open structure PMD that has the ability to maintain and refill propellant at the tank outlet [8]. Of the three, the sponges by far have the most flight heritage in storable propulsion liquid acquisition systems. Relative to vanes, the sponge is heavier and slightly more expensive; relative to screen channel LADs it is a much simpler design. Like vanes, sponges have no flight heritage in cryogenic propulsion systems.

A. Design Concept, Basic Flow Physics, and Principle of Operation

Similar to vanes, a sponge is composed of an array of fins or plates made from ultra-thin, lightweight metal. The distinguishing factor between vanes and sponges is that sponge fins or plates emanate from the center of the tank over the tank outlet while vanes are mounted alongside the tank wall. By this distinction, many of the vanes reported in the literature are actually sponges. Sponges also differ from vanes in that they can be designed to control the location of both the liquid and gaseous phases within the propellant tank; a wall mounted vane with center post can be used to position the both liquid and ullage but not nearly as efficiently as the sponge. Because the sponge is centrally located, and because it forces liquid to be centrally located, sponges are favorable for applications where tight center of mass control of the spacecraft is desired. Sponges are open PMDs and thus do not use porous elements or enclosures like traps or screen channel LADs.

Sponges can be designed in various ways, and generally consist of perforated, angled plates in contact with the tank outlet. Sponges are also designed to favorably position the ullage bubble; the plates can even be angled is such a way to drive bubbles away from the outlet and towards the aft end of the tank. Figure 11 shows a radial sponge where liquid is "absorbed" or drawn into the gaps between plates and then driven down toward the outlet by capillary forces [54]. Many of the basic flow principles that apply to vanes also apply to sponges.

Figure 11 – Small Scale Total Communication Sponge

The size and number of plates is determined by the desired flow rate, EE, and whether or not access to ullage is desired. Plates are often perforated to reduce mass of the PMD, but this can also lead to a less efficient device. Depending on the size and number of holes, propellant acquisition can be greatly reduced and vapor ingestion can thus become an issue. Therefore, sponge mass is often traded with performance to determine the optimal design for a particular mission.

Sponges are most often employed for resupply for engine ignition, engine restart, or short duration maneuvers requiring a small quantity of propellant. For all of these applications, the sponge is sized to ensure there is sufficient propellant covering the outlet to carry out the restart or burn; afterwards, vehicle acceleration is sufficient to maintain liquid over the outlet. Sponges are also often used as control devices even though they are open PMDs. Sponges can easily be used as refill devices to maintain position of the liquid during minor slosh events or adverse accelerations in between engine burns to hold propellant for the next burn.

B. Advantages and Disadvantages

The primary advantage for choosing sponges over vanes is robustness. The sponge can handle the same low flow rates as vanes, but can also be used to control both ullage and liquid within the propellant tank. Second, sponges can be used to control the location of liquid under slightly higher adverse accelerations relative to the vane by increasing the number of sponge plates to decrease gap thickness. Relative to screen channel gallery arms, sponges are lighter weight, easier to fabricate, and more reliable. Higher reliability is achieved because of the simpler open PMD design. Sponges can be constructed from lightweight Aluminum (Al) or Ti sheet metal, making them inherently less expensive.

The disadvantage to using a sponge over a vane is higher system mass. For the same desired EE, vanes are always the lighter design solution. The first and biggest disadvantage to using a sponge over a gallery arm is lower performance; sponges cannot supply medium to high flow rates and cannot control liquid position in medium to high adverse acceleration levels under either steady flow or restart conditions. Second, sponges simply do not scale with the projected size of larger propellant tanks because the size and mass of the sponge PMD rivals the size and mass of the propellant tank walls. Third, neither sponge nor vane performance is verifiable in ground tests prior to flight, making PMD design for both completely dependent on analysis.

C. Storable Propellant Historical Examples

Sponges have quite the rich flight heritage in storable propulsion systems in flight experiments as well as in numerous vehicles and missions. Sponges have particular success in missions that require refill, or for higher frequency station keeping maneuvers. General examples of sponge designs are available in the literature [54-58].

1. Space Experiments

Sponges were employed as secondary PMDs on both the FARE-II and VTRE Shuttle experiments. Figure 12 shows the location of the sponge in the center of the VTRE tank. The sponge completed the mission objective of venting the tank in microgravity without losing precious liquid [37].

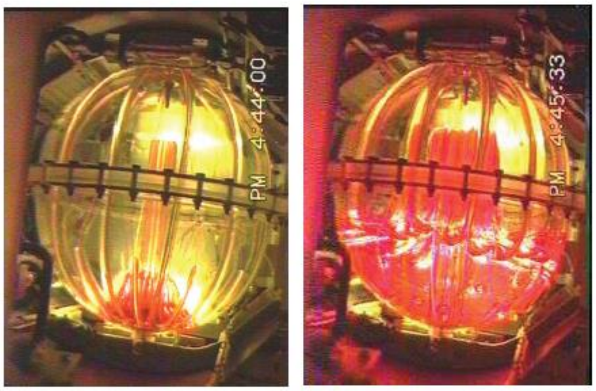

Figure 12 – Sponge Type Vane inside the Vented Tank Resupply Experiment from [37]

In addition, sponges were also the PMD of choice for the recent Orbital Express mission in 2007 [57, 58]. Orbital Express was a demonstration mission to test resupply of satellites with propellant in microgravity [59]. The sponge consisted of 16 Ti plates that radiated from a central pickup assembly.

2. Vehicles and Missions

Sponges were the first ever PMD to obtain flight heritage in storable propellants. The Agena Upper Stage Rocket, first launched in 1959 [60], used a simple sponge composed of a hemispherical array of metal fins that fanned above a screened trap [17, 61, 62]. The sponge also had a venting tube to allow any trapped vapor to be vented towards the aft end of the tank while liquid was moved toward the tank outlet. Agena flew on 361 successful launches, making it one of the most popular upper stage engines.

Sponges were used in an ion propulsion engine using liquid cesium propellant for an auxiliary station keeping thruster [17]. The propellant feed system required a surface tension PMD to transport the liquid from the reservoir to a vaporizing surface. A small storage tank incorporating a 120 fin compact sponge in the reservoir was used to acquire liquid, and then a porous rod transferred the cesium to the vaporizing surface.

Sponges were also the first surface tension PMD to be incorporated in an interplanetary mission [63-67]. Launched in 1975, Viking-1 and Viking-2 were a set of robotic orbiters and landers sent to explore the surface of Mars [68]. Because the Viking orbiters required controlled orbits around Mars, a sponge was chosen to ensure sufficient liquid to perform station keeping and coasting. It was also chosen to maintain a stable center of mass as the spacecraft orbited around the planet [66]. As shown in Figure 13, this particular sponge was very large and tall so that liquid was always positioned near the center of the propellant tank [69]. Both orbiters outlived the expected mission lifespan of 510 days; both orbiters exceeded 1000 days, with Viking-1 lasting 1700 days [70, 71].

The British Aerospace EUROSTAR system featured a rather unique sponge PMD [72, 73]. The system of communication satellites designed by Lockheed Martin employed a simple vane, sponge, baffle, and trap, with the sponge being the primary PMD. The vanes were used to refill the sponge during low-coast times until propellant was needed for another maneuver. The interesting feature of the EUROSTAR tank was that the sponge was placed off center of the vehicle axis, facing radially outward away from the spin axis [74]. During in-flight vehicle spin, the trap inlets were completely submerged in propellant, allowing for lower residual propellant delivery.

The Mars Global Surveyor (MGS) was launched in 1996 to continue the mission of the failed Mars Observer [75]. Compared to its predecessor, MGS was smaller, lighter, and cheaper. Two identical propellant tanks contained PMD structures of a large sponge and an anti-slosh baffle. In order to control propellant slosh during spin, a ring baffle was installed around the inner circumference of the tank, at the midpoint. The 8 paneled sponge provided control of propellant for center of gravity purposes, and to keep propellant near the tank outlet, even under unfavorable conditions such as attitude control.

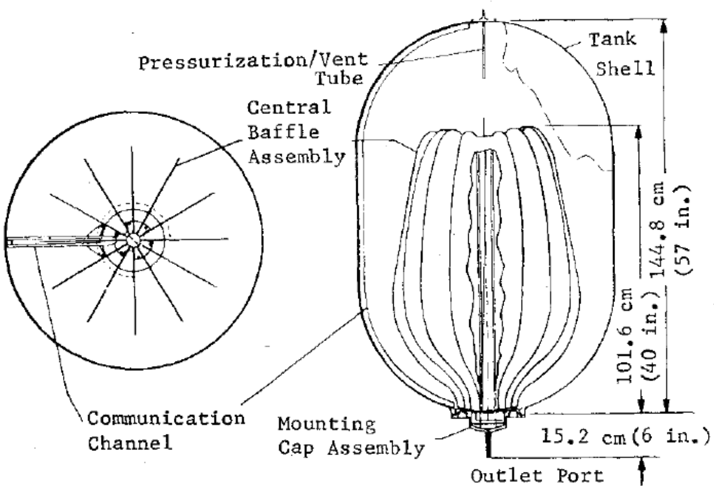

Figure 13 – Mars Viking Propellant Management Device

Sponges were the PMD of choice for the prestigious and successful Cassini Huygens mission to Saturn, which launched in 1997. The original purpose of Cassini was to analyze the rings of Saturn and probe the surface of the moon Titan [76-84]. It has since provided surface and atmospheric data of numerous other bodies within the Saturn system. The main propellant tanks used large, 8 paneled sponge PMDs [18]. The main purpose of the PMD was to maintain the position of the propellant and ullage while in low-g environments as well as for basic thrust control [85].

Sponges were employed in the 1999 Chandra x-ray telescope, where access to both liquid and gas was required. Chandra was launched into LEO and orbited Earth between 10,000 km and 140,000 km above the surface to provide unobstructed, deep space sight into the depths of the universe [86, 87]. Although the Chandra PMD contained a center post, baffles, and trap along with the 8 paneled sponge, the primary PMD was the sponge, because mission requirements dictated the need to control both phases [88]. Half of the triangular panels were used to dislodge trapped bubbles, and the other half extended outward into the baffles to reacquire liquid.

Launched in 2010, the Solar Dynamic Observatory (SDO) was an Explorer-class mission which achieved geosynchronous orbit in order to observe the Sun [89]. SDO required a large amount of propellant, close to half of the overall mass of the vehicle [90]. The PMD used on this satellite was a sponge because maintaining a propellant center of mass and reducing liquid slosh were the two main objectives for PMD design.

Sponges were also used in the recent Messenger mission to Mercury in 2011 [91-93]. A sponge will also be employed for the recently conceived James Webb Space Telescope (JWST), a collaborative effort by NASA, the European Science Agency (ESA), and Canadian Science Agency (CSA). The purpose of JWST mission is to study the evolution of galaxies and the birth of stars and planets from the Earth-Sun LaGrange-2 point [94, 95].

In addition to basic science missions, sponges have rich heritage in geosynchronous satellites. A sponge PMD originally built for the oxidizer tank of a 1988 Mars exploration vehicle was reused for military satellites [54]. The Space Systems Loral 1300 bus, which employed simple sponges, was modified for use in the Intelsat-V, Geostationary Operational Environmental Satellites (GOES), and DIRECTV satellites [96-98] to manage the fuel in the bipropellant tanks. The Boeing 601HP of 1995 [99] and Boeing 702HP of 2009 [100] were satellites designed to carry implements for DIRECTV [45]. The later Boeing 702MP spacecraft used a hybrid of bipropellant and electric propulsion systems. The chemical propulsion system was used for boosting [101] while the Xenon fueled electric system was used to achieve geosynchronous orbit and maintain station keeping [102]. The chemical stages employed a sponge PMD.

Sponges were used in countless military applications as well. For example, in 2007, The Defense Advanced Research Projects Agency (DARPA) designed the Micro-satellite Technology Experiment (MiTEx) as a test to demonstrate upper stage capabilities [103-104]. The goal was to deliver two small satellites into geostationary orbit using an upper stage vehicle. For the MiTEx upper stage, a small sponge, a set of baffles, and a trap were used in the propellant tank. Two baffles, an axial baffle above the sponge, and a radial baffle around it, were installed to control propellant motion around the sponge. The sponge was small, with many panels leading to a center post as shown in Figure 14. Many of the other designs of military PMDs are classified and thus cannot be discussed in this work.

Figure 14 – Sponge used in the Micro-satellite Technology Experiment

VI. Screen Channel Liquid Acquisition Devices

The third total communication capillary driven PMD is the screen channel liquid acquisition device or gallery arm. A screen LAD is defined as a closed channel with three solid walls and one porous wall. Screen channel LADs use the same basic capillary pumping force as vanes and sponges, but offer a much more robust solution to liquid acquisition over a wider range of thermal and gravitational conditions. The primary difference between screen channels and vanes and sponges is that the channel creates an internal and closed flow path for liquid to flow from the bulk propellant in the tank to the outlet of the tank. The presence of the screen allows for relatively higher flow rates under more adverse accelerations and promotes higher resistance to gas ingestion, at the cost of a more complex and expensive design. Screen channel LADs have flight heritage in storable propulsion systems, and are the only PMD type to ever be used in a flight cryogenic system.

A. Design Concept, Basic Flow Physics, and Principle of Operation

For flight missions, screen channel LAD design is classified into two categories [105-108], namely start baskets and total communication devices. Start baskets, sumps, traps, start tanks, and pleated tubes [109] are considered small LADs that confine sufficient liquid over the tank outlet to start engines until relatively large vehicle accelerations can adequately settle the liquid for the large flow rates required for engine operation. Shown in Figure 15, start baskets are simply sized to ensure liquid covers the outlet, and are designed as the last line of defense against gas ingestion as a bubble arrestor. They allow liquid to flow across the screen but also act as a barrier to vapor ingestion if gas comes in contact with the screen, essentially trapping liquid inside the basket and preventing gas from entering. Start baskets are much simpler to design than full communication devices and are used in systems that experience large acceleration changes and demand high flow rates over short time scales. The particular sump shown in Figure 15 can also be used to feed the mixing pump located on top of the basket to recirculate stratified liquid within the tank.

Meanwhile, total communication devices are much more complex designs than start baskets, because they are required to ensure communication between propellant and outlet during all phases of a mission. As shown in Figure 16, total communication screen channel LADs, or gallery arms, run the full length of the propellant tank. These LADs are designed and manufactured in a variety of styles, sizes, and geometries. Typically they are rectangular shaped channels. Total communication devices, such as channels, distributors, and tank liners, are used in systems that experience small acceleration changes and demand lower flow rates over longer time scales.

The basic flow physics and principle of operation for total communication screen channel LADs is as follows: In flight-like systems, these LADs tend to closely follow the contour of the propellant tank wall and can have different cross section geometries (typically a triangular or rectangular shape). The channel side that faces the wall has openings covered with a tightly woven fine mesh screen, which produces very small pores (10 – 100 µm). The other three sides of the channel are solid metal. Because the propellant naturally tends toward the tank walls in low gravity environments, the screen side usually faces the wall. During either quiescent or transient flow environments, the screen serves three purposes.

1. To maintain communication between tank outlet and propellant during all phases of the mission. When liquid approaches the porous screen, the screen admits liquid into the channel.
2. To separate and control phases. When pressurant gas or vapor approaches the screen, liquid surface tension forces within the screen pores block vapor admittance.
3. To rewet portions of the screen that dry out due to exposure to warm pressurant gas; the screen can wick liquid along the screen.

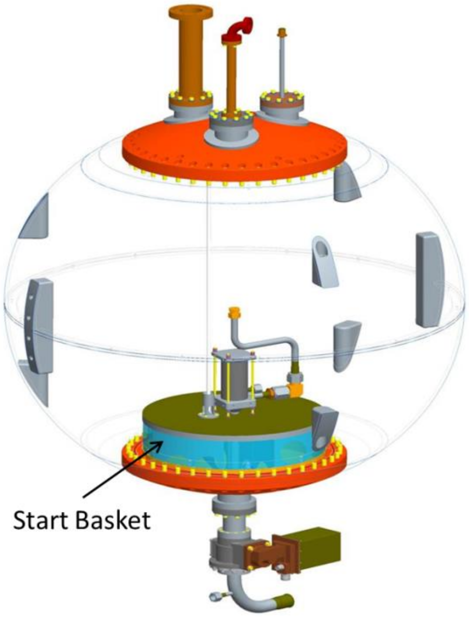

Figure 15 – Example of a Screen Channel Start Basket/Sump

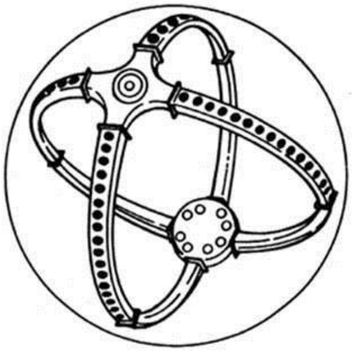

Figure 16 – Example of a Total Communication Screen Channel Liquid Acquisition Device

The channels all converge to a common location at the tank outlet in order to ensure that there is communication between propellant and tank outlet during the mission. As liquid is withdrawn from the tank and vapor approaches the screen, surface tension forces block vapor entrance into the channel, but allow the liquid to flow freely. Screen channel LADs succeed in preventing gas ingestion so long as the pressure differential across the screen does not exceed the bubble point pressure.

B. Mesh and Metal Type

The choice of screen for a particular mission is dictated by the mission requirements, which include gravitational and thermal environments, as well as desired demand flow rate. LAD screens are classified by the geometry, size, number of pores, and manufacturing style, which is compactly expressed as the screen weave. The screen weave refers to the number of wires per inch in each direction and the weave pattern used during manufacturing.

Figure 17 displays a Scanning Electron Microscopy (SEM) image of a commonly used 200x1400 Dutch Twill screen mesh where there are 200 larger warp wires and 1400 smaller shute wires per square inch of screen material. The warp wires are not visible in Figure 17.

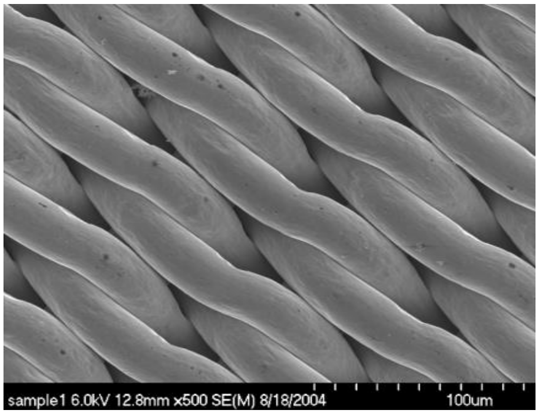

Figure 17 – Scanning Electron Microscopy Image of a 200x1400 Dutch Twill Screen

The screen weave is the most important parameter affecting the choice of screen channel LADs since certain weaves are capable of producing much finer pore sizes than other weaves. For example, finer screen meshes are desirable to ensure adequate resistance to vapor ingestion. However, they tend to generate large hydraulic pressure losses during propellant outflow. In addition, the smaller pore sizes also make finer screens more susceptible to potential clogging due to impurities that may exist within the propellant liquid.

In order of increasing complexity, the types of screen weaves available for screen channel LADs are Plain Square, Twilled Square, Plain Dutch, Reverse Dutch, and Dutch Twill. 3D models of the Twilled Square, Plain Dutch, and Dutch Twill weaves are shown in Figure 18, taken from [110]. Each weave type has a different weave pattern of its larger warp (shown in red) and smaller shute wires (shown in gray), which run perpendicular to each other. The Plain Square weave is the simplest design because the warp and shute diameters are the same size, and the wires simply pass over and under each other in a square pattern. Pore sizes are generally large for this mesh.

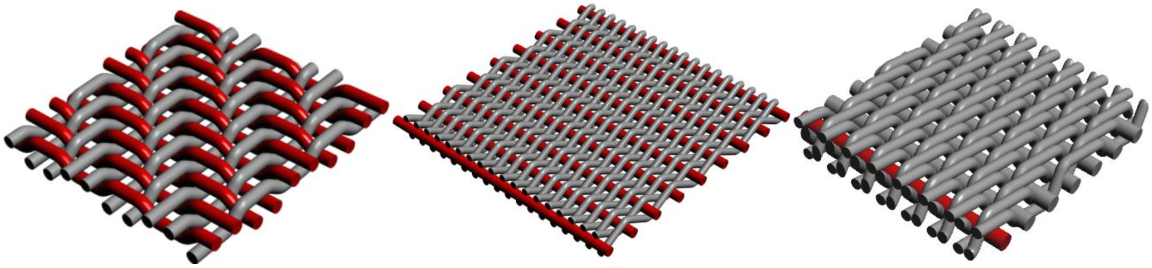

Figure 18 – Three Dimensional Models of a) Twilled Square, b) Plain Dutch, and c) Dutch Twill Weave Styles. Warp wires are denoted in red and shute wires are denoted in gray.

The Twilled Square weave is the second most complex style; the warp and shute wires are also the same diameter, but each shute wires passes over two warp wires before going under the next two warp wires. The pattern then repeats. The Plain Dutch weave has the same pattern as the Plain Square, but the warp wires are larger in diameter than the shute wires, which creates smaller pore sizes. The Reverse Dutch weave is the inverse of the Plain Dutch; the shute wires are larger than the warp wires. Lastly, the most complex screen weave is the Dutch Twill. This weave combines properties of both Plain Dutch and Twilled Square; it has the same weave pattern as the Twilled Square but has larger warp than shute wires like the Plain Dutch. Each shute wire again passes over one warp wire before passing under the next two warp wires. The Dutch Twill weave creates the smallest pore diameters and the most tortuous flow path for gas ingestion, thus making it an attractive candidate for low surface tension cryogenic liquid acquisition systems. A full list of all 40 available screen meshes where data is available is in [31].

The type of metal also affects screen selection, and thus LAD channel design and mass. Coarser meshes are available in many different metals, such as Titanium (Ti} and Aluminum (Al), while finer meshes are generally only available in heavier metals such as stainless steel (SS). As with vane and sponge PMDs, a screen channel LAD designer must often trade performance for system mass.

The ability to wick liquid along the screen makes woven screen superior to perforated plate. Pore sizes much smaller than 10 µm are achievable using advanced laser drilling or machining techniques on a solid piece of metal. However, for flexible liquid acquisition systems, both the size and the number of holes affect performance. The number of pores in a woven wire screen is proportional to the product of the number of the warp and shute wires. Perforated plates are structurally more stable than woven screens at the cost of higher flow resistances due to fewer holes. However since perforated plates cannot wick liquid to areas that dry out due to evaporation, they are not recommended as a primary PMD in future cryogenic propulsion systems.

C. Advantages and Disadvantages

LAD screens are almost always in direct contact with liquid fuel, and can acquire propellant in almost any situation. This means that regardless of spin, direction, or acceleration, screen channel PMDs maintain contact with liquid and can continue to deliver that liquid to the outlet. This makes screen channels likely the most flexible PMD across a range of mission requirements [9]. Unlike other PMDs such as traps, sponges, or vanes, they can supply vapor-free liquid under much higher accelerations, and then sustain high flow rates due to rapid reacquisition of liquid. Until the pressure drop across the screen exceeds the screen bubble point pressure, vapor-free propellant will continue to the outlet. Because of these advantages, gallery arms are optimal PMDs for flights requiring high flow demands. Flexibility, robustness, the ability to maintain low, medium, or high flow rates, and the ability to acquire and supply liquid under very high adverse accelerations render the screen channel LAD advantageous over the vane and sponge type PMD.

However, there are some major disadvantages to screen channel LADs. As described above, there is a bubble point at which the surface tension of the wetted screens will fail and vapor ingestion will occur. Because of the delicacy of the fine mesh screens, reliability is reduced. Also, the sheer mass and size of the arms in relation to other PMDs, such as vanes and sponges, can be a disadvantage. For example, the finer screens can only be constructed from SS and are inherently heavier than coarser builds of Ti. Lastly, screen channel LADs are the most expensive and difficult to manufacture of the PMDs. They require a great deal of materials to construct, tests to analyze bubble points of different meshes, and can be difficult to manufacture. Therefore the high performance of screen channel LADs comes at the added cost, mass, complexity, and less overall reliability relative to vanes and sponges.

D. Storable Propellant Historical Examples

Screen channel LADs have a rich flight heritage with storable propellants. They have been used in both space experiments and flight vehicles. Design of these LADs is well understood for storable systems [111-113]. Galleries have particular success in missions which require flexible demand systems, such as the Space Shuttle.

1. Space Experiments

Screen channel LADs were used in some of the earliest high altitude tests in the mid 1950's. The X-15 spacecraft, while never breaking LEO, was tested as a rocket powered space plane to determine the role of man as a future pilot [114]. Launched from modified B-52 airplanes at high altitude, the X-15 would continue to accelerate and increase in altitude to conduct high altitude entry maneuvers. A total communication gallery LAD was installed inside the propellant tank, which was a simple screen lining the entire interior tank wall, to access propellant throughout the altitude testing [17, 115]. A picture of this unique type of screen channel device is depicted in Figure 19, which was also to be used in the Spacelab experiment onboard the Shuttle [116-118]. As shown, this gallery more closely resembles a group of closely packed vanes.

Galleries were also used in the Boeing Peacekeeper missions. Originally built as an Intercontinental Ballistic Missile (ICBM) [119], the Boeing Peacekeeper was redesigned as an expendable resupply vehicle for space missions, specifically for the International Space Station (ISS). The Boeing Stage IV used a gallery arm to supply propellant for attitude control and also used ring baffles to prevent slosh [120]. Testing was performed in 1-g and aboard a KC-135. 1-g testing was used to evaluate PMD refill and expulsion efficiency and to measure pressure drop across the screen to calculate bubble point pressures at engine startup, while the low-g experiments tested slosh control.

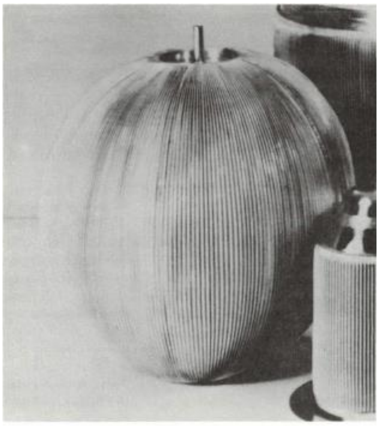

Figure 19 – Spherical Pleated Screen Liner Used for Spacelab

The primary storable propellant space experiment employing screen channel LADs was the FARE-I mission onboard STS-53 [36, 121]. FARE-I tested the fill and EE of a four armed screen channel LAD assembly using the see-through tank shown in Figure 20. The galleries were able to achieve expulsion efficiencies near 98%. Like FARE-II, FARE-I was a very successful mission towards understanding general low-g fluid behavior as well as PMD performance in microgravity.

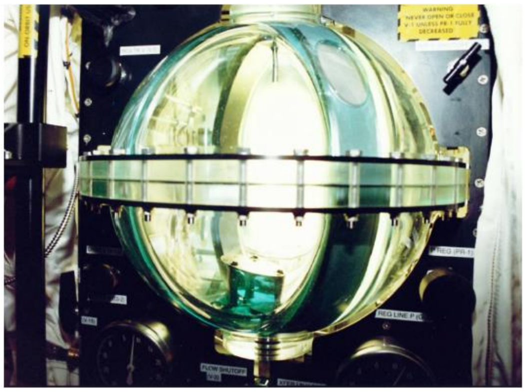

Figure 20 – Fluid Acquisition and Resupply Experiment-I Gallery Arm

2. *Vehicles and Missions*

The Agena Upper Stage Rocket launched in 1959 began using a screened start basket in 1964 [60]. The motivation for the incorporation of the basket was the desire to perform multiple restarts of the engine [17]. The Agena design featured a screened cone at the top of the sump that protruded into the bottom of the tank to allow for both refill of the sump and the preservation of gas free flow to the tank outlet.

Several Geostationary Operational Environmental Satellites (GOES) satellites employed a 200x1400 screen channel LAD. First launched in 1974 [122], GOES satellites were designed to observe weather on Earth, specifically for monitoring storms [123]. Geosynchronous orbits required station keeping maneuvers several times every month using the gallery PMD [32, 122].

Screen channel LADs were also employed in many communications satellites. For example, the bipropellant Intelsat VI, VIIA satellites used for improved phone and television coverage employed four screened gallery arms and a trap to maintain liquid over the tank outlet [124]. The fuel tank used a 200x1400 mesh while the oxidizer used a 165x800 mesh [125]. Space Systems/Loral produced a series of Superbird Satellites for the Japanese owned Space Communications Corporation. Superbird-A was launched in 1992 [126] and provided consistent telecommunications services across a great part of Asia, including China, Japan, and Taiwan. The Superbird satellite utilized a screen channel PMD to allow for liquid acquisition in low-g environments and to maximize EE [126]. The 702B, a recently evolved communications satellite based on the Boeing 702 MP platform, also used a screen channel PMD for its propellant tank. The Milstar satellites, which provided worldwide communication for military personnel, employed a 30x160 mesh screen channel LAD for its PMD [127, 128]. Galleries were also used in the only known NASA mission to have failed in the Mars Observer mission, due to “propulsion and pyrotechnic” problems [129]. However its descendant was the highly successful Mars Global Surveyor [75].

Perhaps the most well-known example of a screen channel LAD in a flight vehicle is in the Space Shuttle Transportation System (STS). Shuttle is well known as NASA’s workhorse vehicle from 1981 – 2011. The purpose of the Shuttle was to transport astronauts, cargo, and space experiments from ground to LEO. STS is the only reusable, winged manned vehicle to achieve orbit in LEO and land back on Earth. Some of the primary accomplishments included transport and assembly of the ISS, ferrying astronauts and supplies to the ISS, return, recovery, and/or repair of satellites, transportation of Spacelab [118], Hubble Telescope [130], Chandra X-ray Observatory [86], and numerous Tracking and Data Relay Satellites (TDRS). Since the destination was LEO, special thrusters were needed to make small adjustments to the vehicle position. STS was equipped with 14 Reaction Control System (RCS) thrusters to change the attitude or direction. Meanwhile, to change orbits for rendezvous docking maneuvers, STS was also equipped with an Orbital Maneuvering System (OMS). Both systems were fueled by nitrous tetra-oxide (NTO) and mono-methylhydrazine (MMH). The Shuttle flew 135 missions in total, 133/133 successful operations with its PMD.

Both RCS and OMS tanks employed very complex total communication 325x2300 screen channel LADs. The RCS LAD was designed to supply propellant during all phases of the mission in LEO, as well as during re-entry. There were multiple sections of windowed screen material in total communication-like arms to access propellant at different acceleration levels, as well as a sump at the bottom of the tank [131]. Meanwhile OMS used both gas arrestors and gallery arms. Design details for both are well represented in the literature [112, 132-137]. Although a non-toxic upgrade to cryogenic propellants was considered for the RCS/OMS systems [138], due to safety considerations it never came to fruition.

E. Cryogenic Propellant Historical Examples

Of all the PMDs, screen channel LADs are the only PMD type to actually have flight heritage with cryogenic liquids. The first attempt at using LADs inside a flight cryogenic propellant tank was in the popular Centaur upper stage. Short duration (< 6 hours) upper stages typically use settling thrust maneuvers and thus vehicle acceleration to drive propellant to the tank outlet [139]. However, because of the sheer number of engine burns required to position propellant, and the possibility of vapor ingestion, the settling system was deemed undesirable for multi-burn mission [140, 141]. Therefore start baskets for both the LOX and LH_2 tanks were designed and tested; the baskets even included passive subcooling systems to further mitigate the likelihood of vapor ingestion into the transfer line [142-148]. While the start basket weighed more than the previous settling system, faster engine preparation and less total number of required engine burns made the start basket the more long term viable option. While Centaur upper stages continue to be used for evolved expendable launch vehicles (EELV), start baskets were never installed into the propellant tanks. Several low-g CFM experiments were proposed [149] and modifications to convert the Centaur upper stage into a cryogenic test bed were conceived, but they never came to fruition [150-152].

The second attempt at using screen channel LADs inside a flight cryogenic propellant tank was in the not well-known Russian Buran. Analogous to the United States Space Shuttle, and very similar in design, the purpose of the Buran was to ferry astronauts and cargo into LEO using a reusable vehicle. The Buran was also developed as a potential military application due to its very large payload capacity. The exact military capabilities are classified. The main difference between the two shuttles was that the Buran employed cryogenic LOX/LH_2 stages for its LEO maneuvering whereas the Shuttle used storable propellants for its RCS and OMS systems. Additionally, the Buran launch stage was four single LOX/kerosene rockets, whereas the Shuttle used a combination of solid rocket boosters and LOX/LH_2 stage. Buran only had a single launch in November, 1988 from the Baikonur Cosmodrome facility. Launched as an unmanned spacecraft on its 206 minute inaugural voyage, the Buran was sent into orbit, completed two full orbits in LEO around Earth, and then landed back in Russia. The Buran was unique because it was the first spacecraft of its size to perform fully automated launching, LEO maneuvers, re-entry and descent, and land back on Earth. The Buran LAD was never tested outside of this inaugural flight.

The third attempt at obtaining flight heritage with LADs in cryogenic liquids was in the successful Superfluid Helium On-Orbit Transfer (SHOOT) small scale experiment onboard STS-57 in June, 1991 [154-160]. The purpose of SHOOT was to demonstrate autonomous transfer of Superfluid Helium (SFHe) between two storage tanks in low gravity, accurate mass gauging, successful operation of a screen channel LAD, as well as demonstrate accurate phase separation with SFHe and normal helium. SFHe, representing a unique fluid with zero entropy and zero viscosity, has applications in quantum solvents, spectroscopy, and cryo-cooling [161, 162]. SHOOT used a 325x2300 screen channel LAD to acquire the ultra-low surface tension SFHe, the details of which are well documented in the literature [163-169]. Although helium is an inert, SHOOT represented a major step in the advancement of cryogenic propulsion system technology development through its simple demonstration mission. While basic experiments have been conducted to analyze liquid positioning, propellant slosh, chill down of hardware through the Saturn IV-B, Centaur, and Titan CFM flight tests, obtaining low-g performance data in cryogenic propellants like LOX and LH_2 still remains to be one of the highest priority objectives for the space flight community [170].

VII. Propellant Management Device Combinations

It is instructive to note that many PMDs are actually combinations of several subsystem devices. Grouping several PMDs together in a single system, a designer can easily overcome the aforementioned disadvantages of each of the stand-alone systems. For example, sponges and baffles are often used in combination with simple vanes for resupply missions, as shown in Figure 21a [171]. Vanes arms can continuously access propellant from the pool in the tank to refill the sponge, while the sponge can be used to hold propellant for the next burn. Meanwhile a series of baffles can help prevent liquid movement within the sponge panels and increase the effectiveness of the sponge at maintaining propellant.

Another combination example is a vane, trap, and trough combination as shown in Figure 21b [30]. Reliable vanes and a center post aid in propellant acquisition from the tank walls, both on the outlet side and the pressurant gas side. Flow is forced from both the vanes and center post through a small hole at the top of a trough/trap combination. A double layer of perforated screen sits above the outlet to reduce vapor ingestion, while the hydrostatic forces used by the trough can keep large amounts of propellant near the outlet during tank spin. Many other examples of combination style PMDs exist in the literature [25, 172-175].

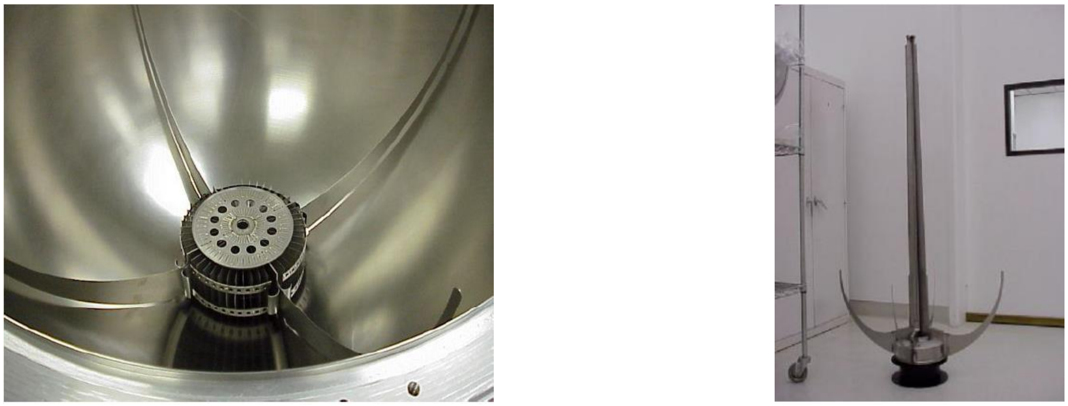

Figure 21 – Combination Propellant Management Device with a) Four Tall Vanes, a Small Sponge, and Baffles Positioned within the Sponge and b) Four Short Vanes, Center Post, Trap, and Trough

VIII. Conclusions

This paper gave a comprehensive review of propellant management devices throughout the past 60 years of spaceflight history. PMDs represent an interesting and robust solution to low gravity propellant acquisition. PMDs were compared and contrasted based on basic flow physics, and design strengths and weaknesses. While PMDs have enjoyed rich flight heritage in multiple science, industry, government, and military missions, work is remaining to fully enable in-space cryogenic flight systems that will employ PMDs. However, from the rich cryogenic LAD technology development program, a robust suite of design and sizing tools can be coupled with heritage design experience to construct flight qualified cryogenic PMDs. Details of the recent cryogenic LAD technology development program, along with future PMD requirements, will be presented in the subsequent journal publication.

Acknowledgments

This work was completed as part of doctoral requirements at Case Western Reserve University. The author thanks Don Jaekle and Dave Chato for their many thoughtful and insightful interactions throughout the past decade.

References

[1] Darr, S.R. and Hartwig, J.W. “Optimal Liquid Acquisition Device Screen Weave for a Liquid Hydrogen Fuel Depot” *International Journal of Hydrogen Energy* Vol. 39, No. 2, 4356 – 4366. 2014.

[2] Radcliffe, W.F. and Transue, J.R. “Problems Associated with Multiple Engine Starts in Spacecraft” *American Rocket Society Journal* Vol. 31, 1408 – 1412. 1961.

[3] Behruzi, P., Dodd, C., and Netter, G. “Future Propellant Management Device Concepts for Restartable Cryogenic Upper Stages” AIAA Paper 2007-5498, July, 2007.

[4] Polzin, K.A., Markusic, T.E., and Stanojev, B.J. “Liquid Bismuth Propellant Management System for the Very High Specific Impulse Thruster with Anode Layer” *NASA-TM-2007-214958*. May, 2007.

[5] DeBrock, S.C. “Spacecraft Capillary Propellant Retention and Control for Long-Life Missions” AIAA Paper 68-465, April, 1968.

[6] Rollins, J.R., Grove, R.K., and Jaekle, D.J. “Twenty-Three Years of Surface Tension Propellant Management System Design, Development, Manufacture, Test, and Operation” AIAA Paper 85-1199, July, 1985.

[7] Jaekle, D.E. “Propellant Management Device Conceptual Design and Analysis: Vanes” AIAA Paper 91-2172, June, 1991.

[8] Jaekle, D.E. “Propellant Management Device Conceptual Design and Analysis: Sponges” AIAA Paper 93-1970, June, 1993.

[9] Jaekle, D.E. “Propellant Management Device Conceptual Design and Analysis: Galleries” AIAA Paper 97-2811, July, 1997.

[10] Purohit, G.P., Ellison, J.R., and Jaekle, D.E. “Propellant Management Device Analysis for Some Off-Design Operational Scecnarios” AIAA Paper 99-2974, June, 1999.

[11] Chu, H.N. and Unterberg, W. “Improvement of Efficiency and Life of Expulsion Bladders” *NAS7-506, R-6762-3*, Rocketdyne, April, 1967.

[12] Ballinger, I.A., Lay, W.D., and Tam, W.H. “Review and History of PSI Elastomeric Diaphragm Tanks.” AIAA Paper 95-2534, July, 1995.

[13] Lark, R.F. “Cryogenic Positive Expulsion Bladders” *NASA-TM-X-1555*. April, 1968.

[14] Biron, J. “An Aluminum Collapsible Bladder Tank for Space Systems” AIAA Paper 90-2058, July, 1990.

[15] Coulbert, C.D., Cuddihy, E.F., and Fedors, R.F. “Long-Time Dynamic Compatibility of Elastomeric Materials with Hydrazine” *NASA-TM-33-650*. September, 1973.

[16] Kreis, A., Kurz, A., Klein, M., and Deloo, P. “Static and Dynamic Modelling of Diaphragm Tanks” *Proceedings of International Conference on Spacecraft Structures, Materials and Mechanical Testing* 2, 845-852. 1996.

[17] DeBrock, S.C., Grove, R.K., Sloma, R.O., Balzer, D.L., Brill, Y., and Yankura, G.A. “A Survey of Current Developments in Surface Tension Devices for Propellant Acquisition” *Journal of Spacecraft and Rockets* 8, 83 – 98. 1971.

[18] Enright, P.J., and Wong, E.C. “Propellant Slosh Models for the Cassini Spacecraft”, *AIAA-94-3730-CP*, 1994.

[19] Lenahen, B., Desai, M., and Gangadharan, S. “A Computational and Experimental Analysis of Spacecraft Propellant Tanks Implemented with Flexible Diaphragms” AIAA Paper 2013-1886, April, 2013.

[20] Giacalone, P.L. “Detail Design of the Surface Tension Propellant Management Device for the Intelsat VII Communication Satellite” AIAA Paper 93-1802, June, 1993.

[21] Jaekle, D. E. “Propellant Management Device Conceptual Design and Analysis: Traps and Troughs” AIAA Paper 95-2531, July, 1995.

[22] Behruzi, P. and Netter, G. “Concept Analysis of PMD Designs for Future Upper Stages” *IAC-03-S.1.07*, 54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, Bremen, Germany, September 29 – October 3, 2003.

[23] Behruzi, K.P. and Michaelis, M. “Development of a Propellant Management Device for Restartable Future Cryogenic Upper Stages” AIAA Paper 2006-5053, July, 2006.

[24] Hines, W.J., Duncan, L.F., Lewin, J.E., and Fettel, B.E. “Apollo SPS Propellant Position Control in Low- and Zero G Environments” *SD-67-655* July, 1967.

[25] Tam, W.H., Drey, M.D., Jaekle, D., and Larsson, L.W. “Design and Manufacture of an Oxidizer Tank Assembly” AIAA Paper 2001-3825, July, 2001.

[26] Tam, W.H., Wiley, S., Dommer, K., Mosher, L., and Persons, D. “Design and Manufacture of the Messenger Propellant Tank Assembly” AIAA Paper 2002-4139, July, 2002.

[27] Tam, W.H., Debreceni, M.J., and Lay, W.D. “Design and Development of the NEAR Oxidizer Tank” AIAA Paper 95-2528, July, 1995.

[28] Tegart, J.R. “A Vane Type Propellant Management Device” AIAA Paper 97-3028, July, 1997.

[29] Tam, W.H., Kawahara, G.H., Jaekle, D.J., and Larsson, L.W. “Design and Manufacture of a Propellant Tank Assembly” AIAA Paper 2000-3444, July, 2000.

[30] Griffin, P.S., Ballinger, I.A., Jaekle, D.E., and Jackson, A.C. “Design and Manufacture of a Lightweight Fuel Tank Assembly” AIAA Paper 2003-4606, July, 2003.

[31] Hartwig, J.W. “Liquid Acquisition Devices for Advanced In-Space Cryogenic Propulsion Systems” Elsevier: Boston, MA, November, 2015.

[32] Debreceni, M.J., Lay, W.D., Newell, J.M., Jaekle, D.J., and Benard, I.J. “Design and Development of a Communications Satellite Propellant Tank” AIAA Paper 95-2529, July, 1995.

[33] Debreceni, M.J., Lay, W.D., and Jaekle, D.J. “Design and Development of a PMD-Type Bipropellant Tank” AIAA Paper 98-3200, July, 1998.

[34] Netter, G., Renner, U., and Dreyer, M. “Design and Verification of a Standard Surface Tension Propellant Tank” AIAA Paper 99-2178, June, 1999.

[35] Dominick, S.M. and Tegart, J.R. “Orbital Test Results of a Vaned Liquid Acquisition Device” AIAA Paper 1994-3027, June, 1994.

[36] Dominick, S.M., Tegart, J.R., Driscoll, S.L., Sledd, J.D., Hastings, L.J. “Fluid Acquisition and Resupply Experiments on Space Shuttle Flights STS-53 and STS-57” NASA-TP-2011-216465, April, 2011.

[37] Chato, D.J., and Martin, T.A. “Vented Tank Resupply Experiment: Flight Test Results” *Journal of Spacecraft and Rockets* Vol. 43, 1124 – 1130. 2006.

[38] Tegart, J.R. “Performance of a Capillary Propellant Management Device with Hydrazine” AIAA Paper 79-1259, June, 1979.

[39] Balzer, D.L., Barksdale, T.R., Bowman, T.E., Gilmore, D.E., Gorman, D.N., Hise, R.E. “Advanced Propellant Management System for Spacecraft Propulsion Systems, Phase 2 – Detail Design” NASA-CR-101913, September, 1969.

[40] Tam, W.H., Jaekle, D.E., and Farokhi, S.A. “Design and Manufacture of the HS 601 Block II Propellant Tank Assembly” AIAA Paper 98-3199, July, 1998.

[41] Tam, W.H., Lay, W.D., Hersh, M.S., Jaekle, D.E., and Epstein, S.J. “Design, Development, Qualification, and Manufacture of the HS 601 Propellant Tank”, AIAA Paper 96-2748, July, 1996.

[42] Decket, M. “ORBCOMM – A Description and Status of the LEO Satellite Mobile Data Communication System” AIAA Paper 94-1135-CP, 1994.

[43] Stoltz, P.M., Krebs, M., and Baltman, R. “ORBCOMM Attitude Determination and Control” AIAA-96-3620, July, 1996.

[44] Rattenni, L. “Design and Performance of the Orbital Star-2 Propulsion Subsystem” AIAA Paper 2001-3394, July, 2001.

[45] Narita, T. and Yendler, B. “Thermal Propellant Gauging System for BSS 601” AIAA Paper 2007-3149, June, 2007.

[46] Ballweg, R. and Wallrapp, F. “EDRS Operations at GSOC- Relevant Heritage and New Developments” 2012.

[47] “Near Field InfraRed Experiment (NFIRE)” *Mda.mil*. Missile Defense Agency, 15 Jan. 2013. Web. 7 Aug. 2013. <http://www.mda.mil/global/documents/pdf/nfire.pdf>.

[48] Smutny, B. and Lange, R. “Homodyne BPSK Based Optical Inter-Satellite Communication Links” AIAA Paper 2006-5460, June, 2006.

[49] Garrison, T.P., Ince, M., Pizzicaroli, J., and Swan, P.A. “System Engineering Trades for the IRIDIUM Constellation” *Journal of Spacecraft and Rockets* Vol. 34, 675 – 680, 1997.

[50] Kale, P.P., Nickelson, R.L., and Sarles, F.W. “A Design for INSAT” AIAA Paper 72-576, April, 1972.

[51] Menon, M.G.K. “INSAT in Perspective” AIAA Paper 72-583, April, 1972.

[52] Netter, G. and Prasad, C.S. “Use of the Surface Tension Propellant Tanks in the Indian Satellite INSAT” IAF Paper 88-237, 39th IAF International Astronautical Congress, Bangalore, India, October, 1988.

[53] Rollins, J.R., Grove, R.K., Lewis, A.H. “Design and Qualification of the Arabsat Propellant Tank” AIAA Paper 84-1480, June, 1984.

[54] Tam, W.H., Ballinger, I., and Jaekle, D.E. “Propellant Tank with Surface Tension PMD for Tight Center-of-Mass Propellant Control” AIAA Paper 2008-4942, 2008.

[55] Spencer, B., Rigollet, R., Fontaine, J.M., and Salome, R. “Qualification and Future Development of Propellant Tanks for Telecommunication Satellites” AIAA Paper 1991-3387, June, 1991.

[56] Tam, W.H., Kuo, J., and Jaekle, D.J. “Design and Manufacture of an Ultra-Lightweight Propellant Management Device” AIAA Paper 2002-4137, 2002.

[57] Tam, W., Ballinger, I., and Jaekle, D.E. “Tank Trade Studies – An Overview” AIAA Paper 2008-4940, July, 2008.

[58] Tam, W.H., Ballinger, I., and Jaekle, D.E. "Surface Tension PMD Tank for On Orbit Fluid Transfer" AIAA Paper 2008-5105, July, 2008.

[59] Dipprey, N.F. and Rotenberger, S.J. "Orbital Express Propellant Resupply Servicing" AIAA Paper 2003-4898, July, 2003.

[60] DiFrancesco, A., and Boorady, F. "The Agena Rocket Engine Story" AIAA Paper 89-2390, July, 1989.

[61] DeBrock, S.C. and Grove, R.K. "Capillary Propellant Management for Integrated Primary and Secondary Propulsion Systems" AIAA Paper 74-1153, October, 1974.

[62] DeBrock, S.C. and Grove, R.K. "Capillary Propellant Management for Integrated Primary and Secondary Propulsion Systems" *Journal of Spacecraft* Vol. 12, 261 – 270. 1975.

[63] Dowdy, M.W. and De Brock, S.C. "Selection of a Surface-Tension Propellant Management System for the Viking 75 Orbiter" *Journal of Spacecraft* Vol. 10, 549 – 558. 1973.

[64] Vote, F.C. and Schatz, W.J. "Development of the Propulsion Subsystem for the Viking 75 Orbiter" AIAA Paper 73-1208, November, 1973.

[65] Stultz, J.W. "Viking Mars Orbiter 1975 Solar Energy Controller" *Journal of Spacecraft* Vol. 14, 294 – 299. 1977.

[66] Dowdy, M.W., Hise, R.E., and Peterson, R.G. "Development and Qualification of the Propellant Management System for the Viking 75 Orbiter" *Journal of Spacecraft* Vol. 14, 133 – 140. 1977.

[67] Morrisey, D.C. "Historical Perspective: Viking Mars Lander Propulsion" *Journal of Propulsion and Power*, Vol. 8, 320 – 331. 1992.

[68] Schmit, D.D., Leeds, M., and Vote, F. "In-Flight Performance of the Viking 75 Orbiter Propulsion System" AIAA Paper 77-894, July, 1977.

[69] Dominick, S.M. and Tegart, J.R. "Low-G Propellant Transfer Using Capillary Devices" AIAA Paper 81-1507, July, 1981.

[70] Schmit, D.D., Anderson, J.W., and Vote, F.C. "A Long Life Bipropellant System Demonstration, Viking Orbiter Propulsion System 4 Years in Space and Operating" AIAA Paper 80-1173, June – July, 1980.

[71] Schmit, D.D., Anderson, J.W., and Vote, F.C. "Long-Life Bipropellant System Demonstration, Viking Orbiter Propulsion System" *Journal of Spacecraft* Vol. 18, 327 – 332. 1981.

[72] Rollins, J.R., Grove, R.K., Miller, J.A., Price, J.D., and Lawrie, A. "Design and Qualification of the EUROSTAR 2000 Propellant Tank" AIAA Paper 92-3606, July, 1992.

[73] Ducret, E., Arnaud, R., and Rigollet, R. "Design and Development of the EUROSTAR 2000+ Propellant Tank" AIAA Paper 96-3289, July, 1996.

[74] Rollins, J.R., Grove, R.K., and Hobbs, L.W. "Design and Qualification of the EUROSTAR Propellant Tank" AIAA Paper 86-1659, June, 1986.

[75] Dominick, S.M. "Design, Development, and Flight Performance of the Mars Global Surveyor Propulsion System", AIAA Paper 99-2176, June, 1999.

[76] Wong, E.C. and Breckenridge, W.G. "An Attitude Control Design for the Cassini Spacecraft" AIAA Paper 95-3274-CP, 1995.

[77] Lee, A.Y. and Hanover, G. "Cassini Spacecraft Attitude Control System Flight Performance" AIAA Paper 2005-6269, August, 2005.

[78] Mitchell, R.T. "Cassini/Huygens at Saturn and Titan" 56th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, 2005.

[79] Sarani, S. "Cassini Attitude Control Configuration for Huygens Probe Release" AIAA Paper 2005-6390, August, 2005.

[80] Vandermey, N. and Paczkowski, B.G. "The Cassini-Huygens Mission Overview" AIAA Paper 2006-5502, June, 2006.

[81] Standley, S.P. "Cassini-Huygens Engineering Operations at Saturn" AIAA Paper 2006-5516, June, 2006.

[82] Burk, T. and Bates, D. "Cassini Attitude Control Operations: Flight Rules and How They are Enforced" AIAA Paper 2008-6808, August, 2008.

[83] Buffington, B., Strange, N., and Smith, J. "Overview of the Cassini Extended Mission Trajectory" AIAA-Paper 2008-6752, August, 2008.

[84] Pilinski, E.B. and Lee, A.Y. "Pointing-Stability Performance of the Cassini Spacecraft" *Journal of Spacecraft and Rockets* Vol. 46, 1007 – 1015. 2009.

[85] Chiang, R.Y., Breckenridge, W.G., and Wong, E.C. "Self-Tuning Thruster Control for Cassini Spacecraft" AIAA Paper 96-3822, July, 1996.

[86] Weisskopf, M.C., Brinkman, B., Canizares, C., Garmire, G., Murray, S., and Van Speybroeck, L.P. "An Overview of the Performance and Scientific Results from the Chandra X-Ray Observatory" *Astronomical Society of the Pacific* Vol. 114, 1 – 24. 2002.

[87] Heffner, K. and Davidson, G. "Performance as Promised: How the Chandra X-ray Observatory Accomplished One of NASA's Most Challenging Missions for Billions of Dollars Less than Originally Planned" AIAA Paper 2004-5935, September, 2004.

[88] Debreceni, M.J., Lay, W.D., Jaekle, D.E., and Graffer, A.C. "Design and Development of the AXAF-IPS PMD and PMD Integration" AIAA Paper 97-2812, July, 1997.

[89] Mason, P. and Starin, S.R. "The Effects of Propellant Slosh Dynamics on the Solar Dynamics Observatory" AIAA Paper 2011-6731, August, 2011.

[90] Willis, W.D. "The SDO Propulsion Subsystem" AIAA Paper 2012-4329, July – August, 2012.

[91] Wiley, S. and Dommer, K. "Design and Development of the Messenger Propulsion System" AIAA Paper 2003-5078, July, 2003.

[92] Wilson, M.N., Engelbrecht, C.S., and Trela, M.D. "Flight Performance of the MESSENGER Propulsion System from Launch to Orbit Insertion" AIAA Paper 2012-4333, July – August, 2012.

[93] Wilson, M.N., Engelbrecht, C.S., and Jaekle, D.J. "MESSENGER Propulsion System: Strategies for Orbit-Phase Propellant Extraction at Low Fill Fractions" AIAA Paper 2013-3757, July, 2013.

[94] Hunter, D.G., Stockman, H.S., and Long, K.S. "The Role of Science and Operations in the James Webb Space Telescope Mission Development" May, 2004.

[95] Gardner, J.P., Mather, J.C., Clampin, M., Doyon, R., Greenhouse, M.A., Hammel, H.B., Hutchings, J.B., Jakobsen, P., Lilly, S.J., Long, K.S., Lunine, J.I., McCaughrean, M.J., Mountain, M., Nella, J., Rieke, G.H., Rieke, M.J., Rix, H-W., Smith, E.P., Sonneborn, G., Stiavelli, M., Stockman, H.S., Windhorst, R.A., and Wright, G.S. "The James Webb Space Telescope" *Space Science* Reviews Vol. 123, Issue 4, 485 – 606. 2006.

[96] Hollingsworth, T.P., van Ommering, G., and Kim, D.J. "Evolutionary Enhancement of SS/L's 1300 Bus for Broadband Payloads" AIAA Paper 2002-1929, May, 2002.

[97] Kim, D.J. and Wilson, J.C. "SS/L-1300 Satellite Optimized for Land Launch" AIAA Paper 2006-5302, June, 2006.

[98] Kim, D.J., Wilson, J., Chiang, J., and Hom, S. "SS/L Historical Trends on Satellite Mass Growth" AIAA Paper 2007-3220, 2007.

[99] "Boeing 601 Fleet." *Boeing.com.* Boeing Company, n.d. Web. August 8, 2013.

[100] "Boeing 702HP Fleet." *Boeing.com.* Boeing Company, n.d. Web. August 6, 2013.

[101] Apfel, S.L. "Optimization of the Boeing 702 for the DIRECTV Mission" AIAA Paper 2006-5300, June, 2006.

[102] Goebel, D.M., Martinez-Lavin, M., Bond, T.A., and King, A.M. "Performance of XIPS Electric Propulsion in On-orbit Station Keeping of the Boeing 702 Spacecraft" AIAA Paper 2002-4348, July, 2002.

[103] Osborn, M., Clauss, C., Gorin, B., and Netwall, C. "Micro-Satellite Technology Experiment (MiTEx) Upper Stage Propulsion System Development" AIAA Paper 2007-5434, July, 2007.

[104] Benton, J., Ballinger, I.A., Jaekle, D.E., and Osborn, M.F. "Design and Manufacture of a Propellant Tank Assembly" AIAA Paper 2007-5559, 2007.

[105] Burge, G.W., Blackmon, J.B., and Klevatt, P.L. "Study and Design of a Cryogenic Propellant Acquisition System, 5th Quarterly Report" *MDC-G4271, NASA-CR-120387,* McDonnell Douglas Company, Huntington Beach, CA, September, 1972.

[106] Burge, G.W. and Blackmon, J.B. "Study and Design of Cryogenic Propellant Acquisition Systems. Volume I: Design Studies" *NASA-CR-120300,* McDonnell Douglas Company, Huntington Beach, CA, December, 1973a.

[107] Burge, G.W. and Blackmon, J.B. "Study and Design of Cryogenic Propellant Acquisition Systems. Volume II: Supporting Experimental Program" *MDC-G5038, NASA-CR-120301*, McDonnell Douglas Company, Huntington Beach, CA, December, 1973b.

[108] Burge, G.W., Blackmon, J.B., and Castle, J.N. "Design of Propellant Acquisition Systems for Advanced Cryogenic Space Propulsion Systems" AIAA Paper 73-1287, November, 1973.

[109] Boraas, S. and LaBruna, A.J. "In-Space Propellant Acquisition with Pleated Screen Tubes" *Journal of Spacecraft* Vol. 13, 377 – 384. 1976.

[110] "3D-Models." *BOPP.com*. BOPP Group, n.d. Web. August 2, 2013.

[111] Schweickert, T.F. "Design of the Aft Propulsion Subsystem for Long Life" JANNAF Propulsion Meeting, New Orleans, May 26 – 28, 1981.

[112] Anglim, D.D. "Space Shuttle Aft Propulsion Subsystem" AIAA Paper 81-1511, July, 1981.

[113] Rollins, J.R., Grove, R.K., and Walling, D.R. “Design and Qualification of a Surface Tension Propellant Tank for an Advanced Spacecraft” AIAA 88-2848, July, 1988.

[114] Walker, J.A. and Weil, J. “The X-15 Program” 1963.

[115] DeBrock, S.C. “Surface Tension Devices for Management of Space Propulsion System Propellants” SAE Aerospace Systems Conference, Los Angeles, CA, June 27 – 30, 1967.

[116] Cady, E.C. “Spacelab Cryogenic Fluid Management Experiment” *NAS3-19719 NASA CR-135143,* November, 1976.

[117] Cady, E.C. “Filling of Orbital Fluid Management Systems” *NASA-CR-159405,* August, 1978.

[118] Lord, D.R. “Spacelab: An International Success Story” *NASA-SP-487,* 1987.

[119] Kumpel, A., Barros, P., Burg, C., Villeneuve, F., and Mavris, D. “A Conceptual Design for the Space Launch Capability of the Peacekeeper ICBM” AIAA Paper 2002-5854, October, 2002.

[120] Gaines, R.D. and Orton, G.F. “Recent Developments in Propellant Acquisition Technology” AIAA Paper 84-1477, June, 1984.

[121] Dominick, S. and Driscoll, S., “Fluid Acquisition and Resupply Experiment (FARE I) Flight Results” AIAA Paper 93-2424, June, 1993.

[122] Joselyn, J.A., and Grubb, R.N. “The Space Environment Monitors Onboard GOES” AIAA Paper 85-0238, January, 1985.

[123] Krummann, W. “The Power Subsystem for the Next Generation GOES Satellite” AIAA Paper 2000-2834, 2000.

[124] Purohit, G.P. and Prickett, R.P. “Modeling of the Intelsat VI Bipropellant Propulsion System” AIAA Paper 93-2518, June, 1993.

[125] Debreceni, M.J., Lay, W.D., Kuo, T.K., Bond, D.L., McClellan, R.E., and Yeh, T.P. “Design and Development of the Intelsat VIIA and N-Star Propellant Tanks” AIAA Paper 95-2527, July, 1995.

[126] Murase, K., Doi, M., Fukuda, K., Okuyama, A., and Hososno, N. “Superbird-C Communications Satellite System” AIAA Paper 98-1251, 1998.

[127] Heubush, H. and Pugmire, T.K “Acceptability of Stainless Steel for Nitrogen Tetroxide Propellant Management Devices and Flight Tankage” AIAA Paper 88-3024, July, 1988.

[128] Kwiatkowski, L.F., Daugherty, M.J., Cornell, C.O., King, M.A., and Riley, P.B. “The MILSTAR System” AIAA Paper 94-1013-CP, 1994.

[129] Saulsberry, R., Ramirez, J., Julien, H., Hart, M., and Smith, W. “Mars Observer Propulsion and Pyrotechnics Corrective Actions Test Program Review – 1999” AIAA Paper 99-2305, June, 1997.

[130] Zimmerman, R.F. “The Universe in a Mirror: The Saga of the Hubble Space Telescope and the Visionaries Who Built It” New Jersey: Princeton University Press. 2008.

[131] White, G.P. “Aft Propulsion Subsystem” *Addendum II to TN-E453-244,* 1980.

[132] Fester, D.A., Eberhardt, R.N., and Tegart, J.R. “Space Shuttle Reaction Control Subsystem Propellant Acquisition” AIAA Paper 74-1106, October, 1974.

[133] Fester, D.A., Villars, A.J., and Uney, P.E. “Surface Tension Propellant Acquisition System Technology for Space Shuttle Reaction Control Tanks” AIAA Paper 75-1196, September – October, 1975.

[134] Tegart, J.R. and Fester, D.A. “Space Storable Propellant Acquisition System” *Journal of Spacecraft and Rockets* Vol. 12, 544 – 551. 1975.

[135] Regnier, W.W. and Hess, D.A. “Design and Development of a Passive Propellant Management System” *Journal of Spacecraft* Vol. 15, 299 – 304. 1978.

[136] Hess, D.A. and Regnier, W.W. “Design and Performance Verification of a Passive Propellant Management System” AIAA Paper 78-1029, July, 1978.

[137] Anglim, D.D. “Low-g Testing of the Space Shuttle OMS Propellant Tank” AIAA Paper 79-1258, June, 1979.

[138] Lak, T., Rodriguez, H., Chandler, F.O., and Jenkins, D. “Non-toxic Cryogenic Storage for OMS/RCS Shuttle Upgrade” AIAA Paper 98-3818, July, 1998.

[139] Austad, K.L. “The Common Centaur Upper Stage” AIAA Paper 2001-3842, July, 2001.

[140] Blatt, M.H. and Aydelott, J.C. “Centaur Propellant Acquisition System” *Journal of Spacecraft* Vol. 13, 515 – 521, 1976.

[141] Blatt, M.H., Bradshaw, R.D., and Risberg, J.A. “Capillary Acquisition Devices for High-Performance Vehicles – Executive Summary” *GDC-CRAD-80-003, NASA-CR-159658,* February, 1980.

[142] Blatt, M.H. “Low Gravity Propellant Control using Capillary Devices in Large Scale Cryogenic Tanks. Related IRAD Studies” *GDC-DDB70-009, NASA-CR-102902*, Convair Division of General Dynamics, San Diego CA, August, 1970.

[143] Blatt, M.H. “Low Gravity Propellant Control using Capillary Devices in Large Scale Cryogenic Tanks. Phase I Final Report” *GDC-DDB70-008, NASA-CR-114104,* Convair Division of General Dynamics, San Diego, CA, August 1970.

[144] Blatt, M.H. “Low Gravity Propellant Control using Capillary Devices in Large Scale Cryogenic Tanks. Phase II Final Report” *GDC-DDB70-008, NASA-CR-114104,* Convair Division of General Dynamics, San Diego, CA, August 1970.

[145] Blatt, M.H. “Orbital Cryogenic Acquisition and Transfer” *N71-29611*, 1971.

[146] Blatt, M.H. and Walter, M.D. “Centaur Propellant Acquisition System Study” *CASD-NAS-75-023, NASA-CR-134811*, June, 1975.

[147] Blatt, M.H., Pleasant, R.L., and Erickson, R.C. “Centaur Propellant Thermal Conditioning Study” *CASD-NAS-76-026, NASA-CR-135032*, July, 1976.

[148] Blatt, M.H. and Aydelott, J.C. “Capillary Device Passive Thermal Conditioning” *Journal of Spacecraft* Vol. 15, 236 – 241, 1978.

[149] Chato, D.J. “The Role of Flight Experiments in the Development of Cryogenic Fluid Management Technologies” *Cryogenics* Vol. 46, 82 – 88. 2006.

[150] Kutter, B., Zegler, F., Sakla, S., Wall, J., Saks, G., Duffey, J., Hopkins, J., and Chato, D.J. “Settled Cryogenic Propellant Transfer” AIAA Paper 2006-4436, 2006.

[151] Sakla, S., Kutter, B., and Wall, J. “Centaur Test Bed (CTB) for Cryogenic Fluid Management” AIAA Paper 2006-4603, July, 2006.

[152] Gravlee, M, Vera, C., Wollen, M., McLean, C., and Walls, L. “Micro-gravity Cryogenic Experiment Opportunity” AIAA Paper 2010-8838, August – September, 2010.

[153] Semenov, Yu P, Lozino-Lozinsky, et al., *Mnogorazoviy orbitalniy korabl 'Buran'*, Mashinostroenie, Moscow, 1995.

[154] Lee, J.H., Ng, Y.S., and Brooks, W.F. “Analytical Study of He II Flow Characteristics in the SHOOT Transfer Line” *Cryogenics* Vol. 28, 81 – 85. 1988.

[155] Gille, J.P., Martin, T.A., and McIntosh, G.E. “Fluid System Design for a Superfluid Helium Space Tanker” AIAA Paper 89-0586, January, 1989.

[156] Castellano, T.P., Raymond, E.A., Shapiro, J.C., Robinson, F.A., and Rosenthal, D.A. “Knowledge Based and Interactive Control for the Superfluid Helium On-Orbit Transfer Project” *The 1989 Goddard Conference on Space Applications of Artificial Intelligence*, 3 – 11, 1989.

[157] DiPirro, M.J., Schein, M.E., Boyle, R.F., Figueroa, O., and Lindauer, D.A. “The SHOOT Cryogenic Components: Testing and Applicability to Other Flight Programs” *SPIE Volume 1340 – Cryogenic Optical Systems and Instruments IV*, 291 – 302. 1990.

[158] Kashani, A., Wilcox, R.A., Spivak, A.L., Daney, D.E., and Woodhouse, C.E. “SHOOT Flowmeter and Pressure Transducers” *Cryogenics* Vol. 30, 286 – 291. 1990.

[159] Hopkins, R.A. and Mord, A.J. “A Design and Critical Technology Issues for On-Orbit Resupply of Superfluid Helium” *Advances in Cryogenic Engineering* Vol. 35, 321 – 333. Plenum Press: New York, 1990.

[160] DiPirro, M.J., Shirron, P.J., Volz, S.M., and Schein, M.E. “SHOOT Performance Testing” *Advances in Cryogenic Engineering* Vol. 37B, 1229 – 1236. Plenum Press: New York, 1992.

[161] Hendricks, J.B., Nilles, M.J., and Dingus, M.L. “A Helium-3/Helium-4 Dilution Cryocooler for Operation in Zero Gravity” *NASA-CR-183632*, October, 1988.

[162] Frank, D. “Dynamics of Superfluid Helium in Low-Gravity” *NASA-CR-204755*, June, 1997.

[163] Anderson, J.E. and DiPirro, M.J. “Acquisition System Testing with Superfluid Helium” *Advances in Cryogenic Engineering* Vol. 37, 909 – 916. Plenum Press, New York, 1988.

[164] Anderson, J.E. “Superfluid Helium Acquisition System Development” *Cryogenics* Vol. 29, 513 – 516. 1989.

[165] DiPirro, M.J. “Fluid Acquisition System for Superfluid Helium” *Cryogenics* Vol. 29, 517 – 522, 1989.

[166] Maddocks, J.R. and Van Sciver, S.W. “Pressure Drop and Helium II Flow through Fine Mesh Screens” *Cryogenics* Vol. 29, 503 – 508. 1989.

[167] DiPirro, M.J. “Liquid Acquisition Devices for Superfluid Helium Transfer” *Cryogenics* Vol. 30, 193 – 199. 1990.

[168] Nissen, J.A., Maytal, B., and Van Sciver, S.W. “Pressure Drop in the SHOOT Superfluid Helium Acquisition System” *Cryogenics* Vol. 30, 211 – 215. 1990.

[169] Nissen, J.A. and Van Sciver, S.W. “Thermal Behavior of the SHOOT Gallery Arm” *Advances in Cryogenic Engineering* Vol. 37A, 115 – 121. Plenum Press, New York, 1991.

[170] Chato, D.J. “Experimentation for the Maturation of Deep Space Cryogenic Refueling Technologies” *NASA-TP-2008-214929*. June, 2008.

[171] Debreceni, M.J., Kuo, T.K., and Jaekle, D.E. "Development of a Titanium Propellant Tank", AIAA Paper 2003-4604, July, 2003.
[172] Debreceni, M.J., Lay, W.D., Kuo, T.K., Jaekle, D.E., and Seki, T. "Propellant Tank for an Advanced Communications Satellite", AIAA Paper 2001-3826, July, 2001.
[173] Debreceni, M.J., Kuo, T.K., and Jaekle, D.E. "Development of a Composite Wrapped Propellant Tank", AIAA Paper 2004-3505, July, 2004.
[175] Tam, W.H. and Jaekle, D.E. "Design and Manufacture of an Oxidizer Tank with a Surface Tension PMD" AIAA Paper 2005-3734, 2005.