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# Review and History of ATK Space Systems Surface Tension PMD Tanks

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**Keywords**

Propellant management device, PMD, PMD tank

**Acronyms**

CFD = Computational Fluid Dynamics
CoM = Center of Mass
GEO = Geosynchronous
LEO = Low Earth Orbit
MEO = Medium Earth Orbit
NTO = Nitrogen Tetroxide
PMD = Propellant Management Device
QBS = Qualification by Similarity

**Abstract**

Surface tension Propellant Management Devices (PMDs) have been an enabler of space systems since the 1960s. Space missions of all kinds, including geosynchronous (GEO) communications satellites, medium Earth orbit (MEO) satellites, low Earth orbit (LEO) satellites and constellations, lunar and planetary explorers, and space-based observatories had all incorporated surface tension PMDs in propellant tanks to meet operational requirements. Thousands of PMDs had supported a multitude of space missions, and new mission scenarios with demanding requirements continue to emerge to challenge PMD designers.

In this paper on heritage, we go beyond tallying of delivered hardware to include a review of PMD tank developments from a historical perspective. However, we confine the scope to our organization's background and experience only. We explore the influence of market forces that drove organizational changes, and recount the approaches we took to persevere in a highly dynamic environment. We highlight our heritage from the perspectives of design methodology, hardware configuration, program history, and business approach, and share the depth and breadth of our tank development experience.

There are four sections in this summary paper. Section 1 is an introduction to PMDs, including history, PMD elements, and PMD design considerations. Section 2 is a summary of design, hardware, and program heritage. In Section 3, we present several PMD design stories to highlight the circumstances and the different approaches we use to design and manufacture PMDs for various missions. In Section 4, we conclude with an outlook towards future PMD design approaches.

## 1. Introduction

ATK Space Systems Inc. is a wholly owned subsidiary of Orbital ATK. Founded in 1963 as Pressure Systems Inc. (PSI), the business entity underwent several ownership changes and took on business names including TRW PSI and ATK PSI Operations. Throughout its long history of services to the space industry, the organizational focus has always been on tank design and manufacture. Operations take place in a dedicated tank factory with vertically integrated capabilities from design to machine, weld, heat treat, clean, non-destructive inspection, and test. As of April 2018, tank delivery exceeded 6500 units with a record of zero in-flight failure.

Given the criticality of heritage emphasized by the customer base, it becomes necessary to document our organizational and product heritage periodically. In this summary paper, we provide updates on two key aspects of our heritage. The first is product heritage on PMD tanks. The second is design heritage on PMDs. We composed this paper to answer many heritage questions related to the following:

- When did we start manufacturing PMD tanks?
- What types of PMDs have we designed and manufactured?
- What types of programs use PMD tanks?
- What is our design philosophy?
- What are our PMD design practices?
- What PMD elements have flight heritage?
- Why do customers select PMD tanks amongst many other options?
- How many PMD tanks we designed and manufactured had completed end-of-life?

The answers to these questions would define our PMD product line and outline our long-standing approaches to PMD design and manufacture.

### 1.1 Overview

In 2016, revenue from global satellite services was $127.7 billion [1]. Space systems have become a vital part of our global economy and an integral part of our daily lives. Many space systems, especially large GEO communications satellites, rely on surface tension PMD tanks to reach and function in orbit. Surface tension PMDs have been an enabler of space systems since the 1960s [2]. Spacecraft of all kinds, including GEO communications satellites, MEO satellites, LEO satellite constellations, space-based observatories, and lunar and planetary explorers had incorporated propellant tanks with surface tension PMDs to meet operational objectives. Thousands of PMDs had been integral to a multitude of space missions [3], and new mission scenarios with demanding operational requirements continue to emerge to challenge PMD designers and manufacturers.

PMD tanks, within the context of this summary paper, are pressure vessels for storable propellants such as monomethyl hydrazine (MMH), nitrogen tetroxide (NTO), hydrazine ($N_2H_4$), and new green propellants such as LMP-103s and AF-M315E. A majority of ATK tanks are titanium or titanium-lined, composite overwrapped pressure vessels. For material compatibility as well as achieving low mass and embedding manufacturing heritage, we also make PMDs out of titanium. PMD tanks are suitable for all flight missions: LEO, MEO, GEO, lunar, and interplanetary. The advantages of PMD tanks include:

- Suitable for bi-propellant, monopropellant, and green propellant propulsion systems.
- Lightweight: As tanks become larger in diameter and longer in length, diaphragms become heavier, and PMDs have a distinctive mass advantage as tank size increases.
- Inherently reliable: PMDs do not rely on moving parts and are inherently reliable.

A PMD must function from mission start through propellant depletion. A successful depletion maneuver is the final verification that a PMD had functioned as designed. For PMD designers, this final depletion maneuver may not take place until years after initial design. For example, commercial satellite design life is typically 15 years, and a PMD designer might not receive final design validation until nearly 20 years after the initial design. Additionally, supporting a satellite's final thruster firing burn and achieving low propellant residual are important goals of any tank design. They are achievable only through good PMD design practices. Consuming all the available propellant ensures the longest possible spacecraft mission. On commercial satellites, prolonging the spacecraft mission equates to additional revenue and higher return on investment for the spacecraft operators.

The primary purpose of a surface tension PMD is to ensure gas-free propellant delivery in a low g or zero g environment throughout the spacecraft mission. Unlike positive expulsion devices such as diaphragms or bladders, surface tension PMDs are passive devices with no moving parts to force propellant flow. In the low g or zero g environment of space, fluid surface tension becomes a dominant force in steady state conditions. PMD designers would take advantage of the surface tension forces inherent in a propellant, along with other elements such as propellant contact angle and device geometries, to design PMDs that meet mission objectives.

The notion of using surface tension PMDs for propellant management in space was already in place at the beginning of space age [2]. In the United States, the basic research on the science of surface tension phenomena took place from early 1960s to 1970s. By the late 1970s, engineers and scientists had applied the scientific knowledge into multiple PMD designs to support space flights. The discipline of PMD design continued to gain maturity throughout the 1980s after more than two decades of flight validation [2] [4].

During the 1980s, several developments in the industry had affected the field of PMD design in the United States. First, many large technology firms that engaged in PMD development underwent consolidation. During the organizational shuffle, PMD design competencies within many firms had diminished. Second, as space systems gained complexity, the large technology primes that sponsored PMD research and design began to shift their organizational focus towards system design and integration. The task of component design and manufacture, including PMD design, became the domain of component manufacturers. Third, there had been significant advances in computational fluid dynamics (CFD) capacity and capability [3]. The iterative PMD design efforts that took months or years in the past had been shorten dramatically to a few weeks. Most importantly, the task that took a team of engineers and scientists to perform became manageable by a single analyst. In response to this new market direction, PSI and PMD Technology formed an alliance in 1986 to offer the system primes an end-to-end solution for PMD tanks. The long alliance had been mutually beneficial. As of April 2018, this alliance has served the space industry for more than 30 years with over 60 PMD solutions for a wide range of missions. We continue to be the market leader in PMD tank solutions for customers around the globe, with more than 1560 PMD tanks delivered as of April 2018.

The advancement in CFD tools and design techniques led to important changes in PMD design practices. It enabled PMD designers to rely solely on analytical tools without ground test validation. It facilitated shortened product development cycle, accelerated qualification schedule for new PMD tanks, and contributed to the accelerated introduction of satellites systems to the marketplace. The improvement was especially beneficial for the commercial satellites market where a new PMD design is achievable within a short development period of three to six months. New hardware introduction could be as short as 12 months after receipt of order. The shortened PMD tank development schedule allows frequent capability upgrades for satellite primes, thus enabling our customers to meet their marketplace commitments.

Moreover, the use of CFD tools had eliminated the need to design PMDs for ground test validation. Designing PMDs to accommodate ground testing at 1g could prevent optimized PMD design and performance in zero g. In addition, PMD ground testing could be costly and time consuming while delaying product introduction. Furthermore, PMD ground tests such as neutral buoyancy test may produce inaccurate or misleading results. By the late 1970s, PMD designers in the United States had mostly abandoned PMD ground test validation [4]. The only ground level PMD validation testing would be in-process bubble point tests of the porous elements to ensure the structural integrity of the PMD. Decades of successful flights, supported by feedbacks on operational, off-nominal, and end-of-mission maneuvers continued to lend justification to the analysis-only design approach [5] [6] [7] [8].

### 1.2 Elements of a PMD Assembly

To generate an optimal PMD solution, PMD designers must trade multiple PMD options [9]. During the PMD configuration trade, PMD designers often consider the following factors and capabilities:

- Mission performance
- Mass versus performance
- Flow rate versus performance
- Non-recurring development cost
- Recurring unit cost
- Slosh damping capability
- Center of mass control
- Off-nominal event recovery
- Propellant residuals
- Length of development schedule
- Manufacturability
- Reliability
- Risks

PMD designers use a number of basic elements to design PMD assemblies. These basic elements include vanes, traps, troughs, sponges, galleries, horizontal handling slosh control devices, and perforated elements such as screens and perforated sheets [10] - [19]. Most PMD assemblies include some or all of these PMD elements to meet performance objectives.

Vane PMDs are communication devices with open flow paths [10]. In zero g, propellants tend to adhere to the structure surfaces, and PMD designers use vanes to facilitate propellant flow along a flow path towards a desired location. Figure 1a is a model of an all-vane PMD.

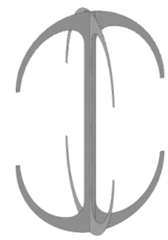


*Figure 1a: PMD Element – Vanes*

Vane PMDs are suitable for missions with relatively low accelerations [10]. The absence of features that might trap propellant contributes to low residual propellant for vane-type PMDs. We cut vanes from thin sheet metals. Their lightweight and simple constructions are typically lower cost as compared to other PMD elements. Figure 1b are some examples of vane PMDs. Few PMDs are all-vane PMDs. Vanes often supplement other PMD elements. For example, a common use of vanes is to fill and re-fill sponges or traps [10].

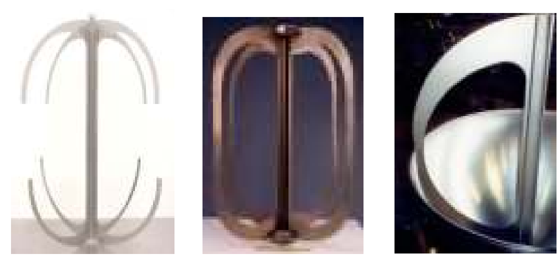


*Figure 1b: All-vane PMDs of Various Configurations*

Gallery PMDs are communication devices with closed flow paths [17]. In zero g, propellant would enter the galleries through screen-covered openings and travels along the gallery to a collection point downstream. The screen covers function as a barrier to prevent gas ingestion into the galleries. Figure 2a is a model of a gallery arm PMD.

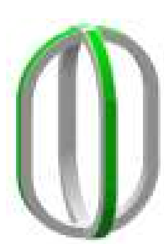


*Figure 2a: PMD Element – Galleries*

Gallery PMDs are suitable for missions with intermediate accelerations [17]. Compared to vanes, galleries have higher performance capabilities, but are heavier, more complex in construction, and more costly. For example, the gallery arms in Figure 2b (left photo) took more than two years to develop at substantial cost. This long component development cycle was longer than the overall program schedule for most PMD tank development programs. Gallery PMDs tend to have higher residuals than vane PMDs at around 1% to 2%. Compared to vanes, galleries are more expensive to construct as galleries must conform to the curvature of the tank shell, and a curved tubular structure is always more expensive to construct than cutting a vane from a flat sheet. Figure 2b and 2c have additional examples of PMDs with gallery arms. Few PMDs are all-gallery PMDs. Galleries often complement traps, as shown in Figure 2b.

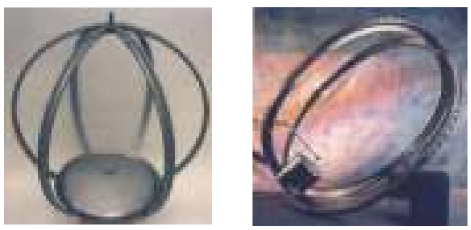


*Figure 2b: PMD Assemblies with Gallery Arms and Traps*

*Figure 2c: A PMD Assembly with Gallery Arms*

Sponge PMDs are control devices [14]. A sponge PMD is a refillable open structure that holds a specified amount of propellant using surface tension forces. Figure 3a is a model of a sponge PMD.

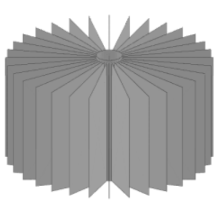


*Figure 3a: PMD Element – Sponge*

Sponges are suitable for refilling at low to medium accelerations [14]. Two types of sponges are most prevalent. The sponges depicted in Figure 3b are partial control devices. Partial control sponges are useful when positioned above or adjacent to trap inlet windows to refill traps, or directly above the tank outlet to supply propellant during the thruster firing burns. The large sponges depicted in Figures 3c are total control devices frequently used for slosh damping and propellant center-of-mass (CoM) control. These large sponges could control both the propellant pool and the gas bubble, and PMD designers could use this unique characteristic to design PMDs that meet tight CoM requirements [20].

*Figure 3b: Partial Control Sponge PMDs*

*Figure 3c: Total Control Sponge PMDs*

A trap is a control device. It retains a fixed amount of propellant for specific applications such as a contingency recovery maneuver or a long duration burn [15]. See Figure 4a. Figure 4b has some examples of traps in communications satellite PMD assemblies. A horizontal handling slosh control device (SCD) is a variant of a trap. Its function is to prevent gas from entering other PMD elements during horizontal handling from launch vehicles such as Proton, Sea Launch, and Falcon. See Figure 4c for a photo of a SCD.

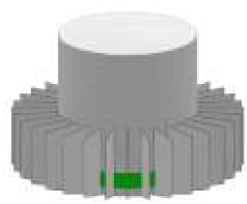


*Figure 4a: PMD Element – Trap*

*Figure 4b: Trap PMDs of Various Configurations*

*Figure 4c: A Horizontal Handling Slosh Control Device*

Similarly, a trough is a control device, but with an open structure [15]. A trough could hold a specified amount of propellant using hydrostatic forces. See Figure 5a. Figure 5b is an example of a trough in a GEO communications satellite tank PMD [21].

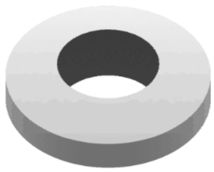


*Figure 5a: PMD Element – Trough*

*Figure 5b: An Example of a PMD Trough*

Each space mission is unique. Depending upon the launch vehicle, payload mass, thruster choice, available envelope, mission profile, mission duration, and many other factors, the propellant tank and PMD solution could vary widely from mission to mission. In Figures 6a, 6b, 6c, and 6d, we present photos of various custom-designed PMDs.

Traditionally, the most effective PMD solution had been custom designing a PMD for a specific mission. Custom designing a PMD ensures optimal performance, lowest mass, and lowest propellant residual. Given that mission profiles usually differ from mission to mission, custom designing a PMD had often been the best technical and commercial solution. However, it is also the most expensive approach with extensive expenditures on analyses, reviews, drawings, tooling, and manufacturing planning. Alternatively, developing derivative PMD designs are possible but the PMD solution might not be optimal.

*Figure 6a: Examples of PMD Assemblies with Multiple PMD Elements (Vanes and Sponge)*

*Figure 6b: Examples of PMD Assemblies with Multiple PMD Elements (Vanes, Sponge, Trap, Horizontal Handling Slosh Control Device)*

*Figure 6c: Examples of PMD Assemblies with Multiple PMD Elements (Vanes, Sponge, Bulkhead for Trap)*

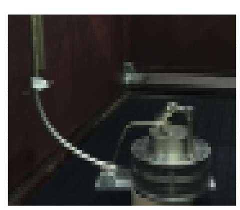


*Figure 6d: An example of a PMD Assembly with Multiple PMD Elements (Gallery Vane, Sponge, Trap, and Horizontal Handling Slosh Control Device)*

For decades (from 1970s through 2000s), custom-designing PMDs was necessary because there were insufficient qualified PMD designs for derivative PMD considerations. However, after accumulating more than 60 PMD designs by mid-2010s, ATK is now in a position to offer adaptations of existing PMD designs as a valid technical and commercial solution. Adaptation of an existing PMD design might not facilitate optimum performance, minimum mass, or minimum residual, but it is nevertheless an effective method of reducing non-recurring expenses and imbedding design and flight heritage. The frequency of using this lower cost approach has increased dramatically in recent years.

From 2015 through 2018, we took the derivative PMD approach on a majority of PMD design efforts, including four international lunar programs and several proprietary programs. On one lunar lander program, we baselined an existing PMD (for P/N 80435, 540 mm or 21.25 inch diameter), eliminated an unnecessary feature, and adapted the PMD to a 757 mm (29.8 inch) diameter shell. The solution met the performance requirements, but was not optimal for mass and residual. Nevertheless, it was the best cost solution given the customer's funding constraints. On a second lunar lander program, we took the same P/N 80435 PMD as a baseline, and adapted it to a 562 mm (22.14 inch) diameter tank shell. The changes to the baseline PMD was more extensive than the first example. The technical solution resulted in a lowest mass solution desired by the customer at a higher development cost. On one of the proprietary programs, we adopted the same P/N 80435 PMD elements, but customized the PMD for a 668 mm (26.3 inch) diameter shell. In all three cases, we generated our PMD solution in response to customers' cost, schedule, mass, envelope, or performance constraints, and embedded design and flight heritage with validated performance.

In summary, there are four distinctive phases to the ATK PMD tank heritage:

- Phase 1: design and fabrication of PMD tanks with customer-designed PMDs prior to 1986
- Phase 2: custom designing tank shells and PMDs for GEO commercial satellite fleets
- Phase 3: custom-designing PMDs for existing shells or custom-designed shells
- Phase 4: adapting existing PMDs for existing shells or custom-designed shells

As we accumulate more PMD designs, adapting existing PMD designs will become our standard practice in response to market forces and direction. This evolved approach will only help our customers reduce risk, reduce cost, and ensure reliability.

### 1.3 Other PMD design considerations

PMD designers often consider the PMD-to-tank-shell interface when generating a PMD solution. The most common mounting method is a cantilever mount having the PMD attachment at the tank outlet boss as shown in Figure 7. Other common PMD mounts include having attachment points at both the upper and lower polar bosses as shown in Figure 8. This design is suitable for PMDs with high profiles that are subject to the influence of propellant slosh loads. Occasionally, it might be necessary to design PMDs with attachment points along the tank membrane as shown in Figure 9. This attachment method is common on gallery arm PMDs. A PMD attached to the tank wall adds cost to the tank shell manufacture because milling on tank shell interior becomes necessary. A fourth PMD attachment scheme is a full circumferential weld along the tank wall as shown in Figure 10. This attachment method is common on PMD bulkheads or full enclosure traps. Tank mounting decisions could affect the tank shell configuration and influence tank cost. It is important to include tank mount in the initial design trade study to generate the optimal PMD solution.

*Figure 7: A PMD Mounted at the Tank Outlet Boss (one attachment point)*

*Figure 8: PMDs Mounted at the Tank Inlet and Outlet Bosses (two attachment points)*

*Figure 9: A PMD with Attachments on the Tank Shell (multiple attachment points)*

*Figure 10: A PMD Baffle Welded to the Tank Shell (attached circumferentially)*

Pressure vessels often grow axially and laterally during pressurization. Typically, a PMD is not part of the tank structural membrane. However, there are exceptions. A welded PMD bulkhead could become an integral part of the tank membrane, with the space enclosed by the tank wall and the bulkhead becoming a PMD trap [22] [23]. Another example is having the PMD mounting features be an integral part of the tank shell membrane [24]. For these cases, PMD designers must consider tank shell growth during PMD design and performance evaluation. As PMD design could affect tank shell design, close coordination between PMD designer and tank shell designer is critically important.

After the introduction of launch vehicles with horizontal handling and transport, the scope of PMD design must include additional consideration for horizontal ground handling requirements [3]. ATK incorporated an innovative solution with a standardized slosh control device that prevents premature gas ingestion after multiple elevation cycles. In addition, new design requirements such as ground transportation slosh and pad slosh have influenced our PMD designs. Our responses to these new design considerations include both structural reinforcements and new and innovative PMD design solutions.

For decades, spacecraft integrators had inquired about the feasibility of a universal PMD that meets all possible mission objectives. An all-gallery arm solution could be such a PMD. The advantage of a universal PMD is a one-time non-recurring expenditure for design and analysis for potentially multiple mission applications. Nevertheless, incorporating an all-gallery PMD still incurs the cost of drawings and manufacturing planning when changing tank size or gallery arm size. The most disadvantageous aspect of a universal PMD is higher mass. For example, if a 2 kg vane PMD design is sufficient in meeting mission objectives, incorporating a 15 kg gallery arm PMD design to reduce the cost of PMD analysis might not be justifiable. In addition, an all-gallery arm PMD has more welds and, therefore, is inherently a higher risk PMD solution than a vane PMD. Finally, an all-gallery arm PMD is more expensive to manufacture than a vane PMD. Given all these disadvantages – higher cost, higher mass, higher risk – we always recommend a PMD approach that incorporates multiple PMD elements to meet mission objectives optimally.

## 2. Heritage Summary

ATK's PMD tank heritage dates back to the 1970s. In those early years of spaceflight, large technology firms such as Lockheed and Martin Marietta were involved in the research and development of basic sciences associated with surface tension phenomenon and generated PMD concepts for manufacture [2]. As a third tier component supplier, ATK (previously PSI) converted the PMD concepts provided by the customers into production PMDs. We also designed and manufactured the tank shells that incorporated these PMDs. The PMD tank product line complemented our diaphragm tank product line, enabling us to accumulate a large inventory of qualified tank shells. We even adapted some qualified diaphragm tank shells for PMD tank applications [6] [25] [26].

By the 1980s, basic research on surface tension phenomena had mostly ended within space firms in the United States. The science of surface tension phenomena became graduate-level course material taught at academic institutions throughout the world. More importantly, PMD design was becoming an engineering discipline and a subset of tank design activities. As the space industry underwent consolidation, the number of organizations involved in PMD design activities had dwindled down to less than five in the United States. The limited number of space programs created an economic constraint, and few large technology firms in the U.S. could justify maintaining PMD design and manufacture capabilities of a propulsion component in house. Increasingly, spacecraft primes focused on system integration, and subcontracted tank design and manufacture to component suppliers. As our organization gained expertise in tank design and manufacture and built up our tank factory, most spacecraft integrators are outsourcing tank shell and PMD design activities to us.

From the 1980s until the publication of this article, ATK had manufactured multiple GEO communications satellite platform tanks, including 376, 601, 601HP, 702 MP, A2100A, A2100AX, A2100AXL, A2100 TR, DS2000, FS1300, LS1300, NeoSat, S3000, S5000, S7000, Star1, Star 2, and Star 3. In addition, we manufactured PMD tanks for LEO, MEO, and other critical missions both domestic and international. They are a combination of new qualification tanks and derivative tanks. As we accumulate ever larger number of tank shell designs, multiple customers would take advantage of these existing designs. Most customers welcome the market-derived synergy because increasing production volume leads to reduced tank prices. For example, four customers are using our 1.25 meter (49 inch) shells, and three customers are using our 1.15 meter (45 inch) shells. With savings on design and tooling often amount to more than $1M dollars on new developments, it is easy to understand why customers embrace this market-derived synergistic approach to PMD tank development.

In Table 1, we present our PMD tank heritage. It is a partial list only, but sufficiently comprehensive on commercial and civil programs. We summarize our program heritage, as well as heritage on PMD elements. With regard to heritage on design approaches, we rely on CFD tools exclusively, and do not design PMD assemblies to satisfy 1 g PMD functional test requirements. As noted previously, the only PMD validation tests are bubble point tests conducted to verify the structural integrity of the PMD throughout the PMD construction.

## 3. PMD Development Stories

Every PMD tank development program has a story. These stores are experiences from which we build our heritage and accumulate knowledge. In this section, we review several PMD tank development programs from historical, performance, and heritage perspectives. As a precursor, it is noteworthy that throughout our organization history, both tank shell and PMD design methodologies remain consistent. We used the same design principles for tank shell structural analyses, and we used CFD tools to design PMDs and analyze their functionalities without ground test validation. This consistency continues to play a key role in our organizational success.

### 3.1 The HS601 GEO Commercial Satellite PMD Tanks

The HS601 satellites were the most popular GEO communications satellite systems in the 1980s and 1990s. We developed a spherical and a cylindrical version of PMD tanks for various versions of the satellite bus [22] [23]. Other non-commercial missions using the 601 bus included Tracking and Data Relay Satellites (TDRS) and proprietary programs. ATK delivered 267 tanks over a 25-year span in support of this highly successful platform.

Three off-nominal HS601 missions are worth noting from a PMD design perspective. The first resulted from an underperformed launch vehicle depositing a satellite at a lower than planned orbit. To recover the spacecraft, the PMD designer worked with mission planners in real time to maneuver the satellite into a usable GEO orbit [5]. The second was a well-publicized AsiaSat 3 salvage mission to raise a stranded satellite from an initial useless orbit to a final usable orbit using lunar flybys gravity assist [27]. The third mission was the recovery of the Tracking and Data Relay 9 (TDRS 9) satellite [28]. In all three off-nominal missions, confidence in the PMD functionalities beyond initial design parameters was a contributor to recovery mission execution. Supported by CFD analysis runs, the satellite recovery teams operated the PMD at performance levels far beyond the design parameters listed in the equipment specification. Their successful outcomes were indicative of the robustness of the PMD design, and served as a convincing confirmation to the analysis-only performance validation methodology.

### 3.2 The 1242 mm (48.9 inch) Diameter PMD Tanks

ATK started manufacturing the all-metal 1242 mm diameter PMD tanks in 1991 [29]. Several generations of upgrades ensued to increase tank volume and enhance PMD performance. Multiple tank shell developments had resulted in a family of five different volumes from 1000 liters to 1710 liters. Both government and commercial customers from domestic and international markets had used tanks from this tank family for applications that included GEO commercial and interplanetary exploration missions. Four satellite integrators had bought tanks of varying sizes from this tank family to take advantage of the synergy created in the marketplace. The 1242 mm family of tanks is the longest-running tank fabrication program in our company history with over 26 years of continuous production. We delivered over 330 tanks as of April 2018, with dozens of tanks in the orders backlog. It is currently the most popular family of tanks in production.

The evolution of the 1242 mm tank family is indicative of the market shift we experienced in the 1980s and 1990s. In 1991, the PMD design was a customer responsibility. In subsequent tank developments, we became responsible for the end-to-end solution, including both PMD and tank shell design and manufacture. Another market driven development was a series of PMD upgrades to accommodate horizontal handling in response to the introduction of the Proton and Soyuz into commercial launch service [3] [30]. Figure 11 shows the evolution of PMD designs to accommodate horizontal handling for tanks with low initial fill fraction.

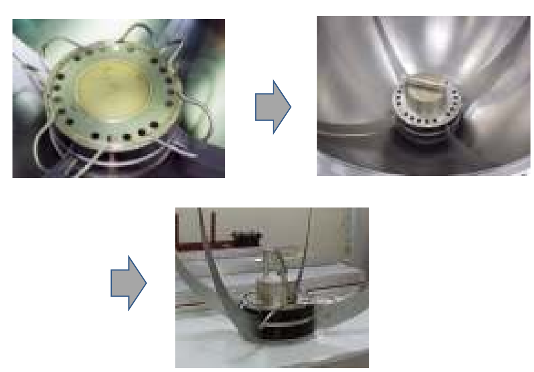
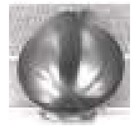
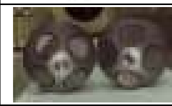
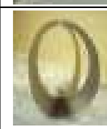
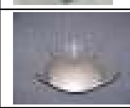
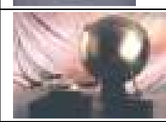
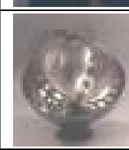
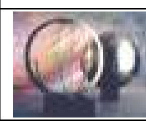
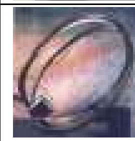
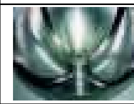
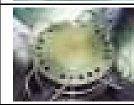
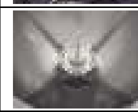
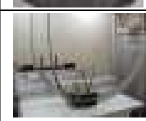
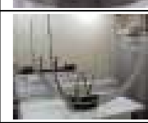
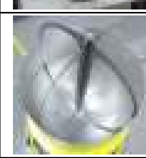
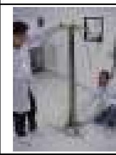
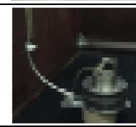
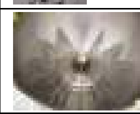
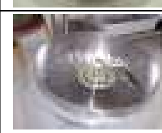
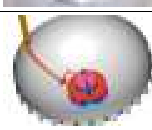


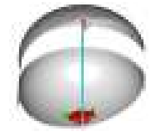
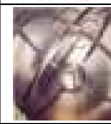
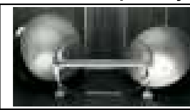
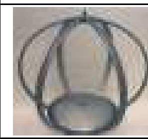
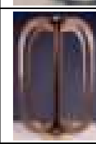
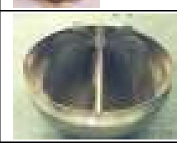
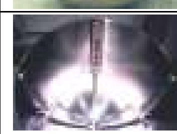
*Figure 11, Evolution of PMDs to Accommodate Horizontal Handling*

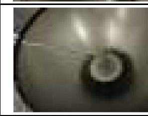
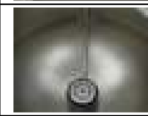
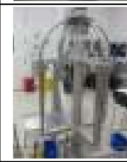
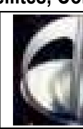
Table 1, PMD Heritage Summary

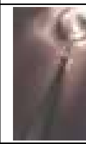
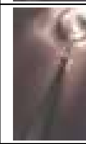
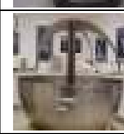
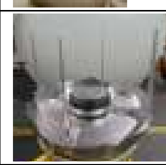
| Program Type | Program Name | PMD Element: | | | | | PMD photo | Propellant | Reference P/N | End of Mission | Publication | Notes & delivered quantity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sponge | Vane | Trap | Gallery | Other | | | | | | |
| | **GEO Commercial Satellites** | | | | | | | | | | | |
| Communications satellite | INSAT | | Yes | | | |  | MMH, NTO | 80277, 80283 | | AIAA 83-1273 [31] | |
| Communications satellite | INSAT (auxiliary tank) | | | | | Liner |  | NTO | 80292 | | | |
| Commercial Communications satellite | Satcom K, -Star, DBS, BS-III, S3000, ACTS | | Yes | | | |  | Hydrazine | 80296, 80304, 80313, | | | PMD concept provided by the customer |
| GEO commercial | Arabsat, INSAT-1D | Yes | Yes | Yes | | Trough |  | MMH, NTO | 80301 | Yes | AIAA 84-1480 [32] | PMD concept provided by the customer |
| GEO commercial | Eurostar, InMarSat | Yes | Yes | Yes | | Liner |  | MMH, NTO | 80310 | | AIAA 89-2641 [33] | PMD concept provided by the customer |
| GEO commercial | HS601, HS601HP | Yes | Yes | Yes | Yes | |  | MMH, NTO | 80350, 80399, 80415 | Yes | AIAA 96-2748 [22] AIAA 98-3199 [23] | |
| GEO commercial | S5000 | Yes | Yes | | | |  | Hydrazine | 80339 | | | PMD concept provided by the customer |
| GEO commercial | S5000 | | | | Yes | | | | 80340 | | | |
| GEO commercial | S7000 | | Yes | Yes | Yes | |  | MMH, NTO | 80373 | | | PMD concept provided by the customer |

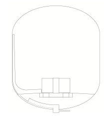
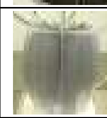
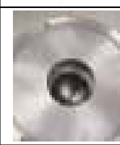
| Program Type | Program Name | PMD Element: | | | | | PMD photo | Propellant | Reference P/N | End of Mission | Publication | Notes & delivered quantity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sponge | Vane | Trap | Gallery | Other | | | | | | |
| GEO commercial | 702MP | Yes | Yes | | | Venting Pickup |  | Hydrazine, NTO | 80507. 80576, | | SP2016_3124654 [34] | |
| GEO commercial | 702MP | Yes | Yes | | | Venting Pickup |  | Hydrazine, NTO | 80506 | | | |
| GEO commercial | FS1300, LS1300, | | | Yes | Yes | |  | MMH, NTO | 80363, 80367 | | AIAA 95-2527 [27] | |
| GEO commercial | FS1300, LS1300, | | | Yes | Yes | |  | MMH, NTO | 80366 | | AIAA 95-2527 [27] | |
| GEO commercial | FS1300, LS1300, | Yes | Yes | Yes | | |  | MMH, NTO | 80380 | Yes | AIAA 96-2749 [35] | |
| GEO commercial | FS1300, LS1300 | Yes | Yes | Yes | | Horizontal Handling Device |  | MMH, NTO | 80403, 80422 | | | |
| GEO commercial | FS1300, LS1300 | Yes | Yes | Yes | | Horizontal Handling Device |  | MMH, NTO | 80441, 80442, 80501, 80502, 80517, 80601, 80602 | | | |
| Technology demonstrator | Engineering Test Satellite VIII | Yes | Yes | yes | | Horizontal Handling Device |  | MMH, NTO | 80411 | | AIAA 2001-3826 [30] | |
| GEO commercial | DS2000, MTSAT, Himawari, | Yes | Yes | Yes | | Horizontal Handling Device |  | MMH, NTO | 80482, 80535, 80601, 80602 | | | |
| GEO commercial | Star 1, BSAT | | Yes | | | Trough |  | Hydrazine | 80420 | | AIAA 2000-3444 [36] | |

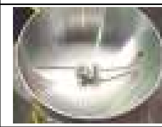
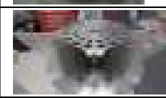
| Program Type | Program Name | PMD Element: | | | | | PMD photo | Propellant | Reference P/N | End of Mission | Publication | Notes & delivered quantity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sponge | Vane | Trap | Gallery | Other | | | | | | |
| GEO commercial | Star 2 | | Yes | Yes | | Liner |  | Hydrazine | 80425, 80432, | | AIAA 2003-4606 [37] | |
| GEO commercial | Star 2 | Yes | | | | Anti-geyser baffle |  | NTO | 80426 | | AIAA 2001-3825 [21] | |
| GEO commercial | Star 3 | Yes | Yes | Yes | | Horizontal Handling Device |  | Hydrazine | 80563 | | | |
| GEO commercial | Star 3 | Yes | Yes | Yes | | Horizontal Handling Device | | NTO | 80564 | | | |
| GEO commercial | A2100A, A2100AX | | Yes | Yes | | |  | Hydrazine | 80391, 80395 | | | |
| GEO commercial | A2100A, A2100AX | Yes | | Yes | | |  | NTO | 80390, 80394, 80405, 80406 | | | |
| GEO commercial | Astrolink, A2100AXL | Yes, | Yes | Yes | | Horizontal Handling Device |  | Hydrazine | 80434 | | AIAA 2004-3505 [38] | |
| GEO commercial | Astrolink, A2100AXL | Yes | | Yes | | Horizontal Handling Device |  | NTO | 80435 | | AIAA 2005-3734 [39] | |
| GEO commercial | A2100 TR | Yes, | Yes | Yes | | Horizontal Handling Device |  | Hydrazine | 80570 | | SP2016_3124654 [34] | |

| Program Type | Program Name | PMD Element: | | | | | PMD photo | Propellant | Reference P/N | End of Mission | Publication | Notes & delivered quantity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sponge | Vane | Trap | Gallery | Other | | | | | | |
| GEO commercial | A2100 TR | Yes, | | | | Baffles |  | NTO | 80571 | | SP2016_3124 654 [34] | |
| GEO | GOES | Yes | Yes | Yes | Yes | |  | MMH, NTO | 80338 | | | |
| | **Proprietary Satellites** | | | | | | | | | | | |
| Proprietary | Proprietary | | Yes | | | |  | Hydrazine | 80212, 80281 | | | |
| Proprietary | Proprietary | | Yes | | | | | | 80213 | | | |
| Proprietary | Proprietary | | Yes | | | | | Hydrazine | 80229 | | | |
| Proprietary | Proprietary | | | | Yes | | | Hydrazine | 80317 | | | Breadbasket PMD |
| Proprietary | Proprietary | | | Yes | Yes | |  | MMH, NTO | 80324 | | AIAA 88-2848 [18] | |
| Proprietary | Proprietary | | Yes | | | |  | Hydrazine | 80356 | | | |
| Proprietary | Proprietary | Yes | | | | |  | Hydrazine | 80387 | | AIAA 97-2813 [40] | |
| Proprietary | Proprietary | | | | Yes | |  | MMH, NTO | 80398 | | AIAA 98-3200 [24] | |
| Proprietary | Proprietary | Yes | | Yes | Yes | |  | MMH, NTO | 80472 | | | |

| Program Type | Program Name | PMD Element: | | | | | PMD photo | Propellant | Reference P/N | End of Mission | Publication | Notes & delivered quantity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sponge | Vane | Trap | Gallery | Other | | | | | | |
| Proprietary | Proprietary | Yes | Yes | | | |  | Hydrazine | 80480 | | | |
| Proprietary | Proprietary | Yes | | | | |  | NTO | 80481 | | | Includes a dip tube |
| Proprietary | Proprietary | Yes | Yes | | | |  | Hydrazine | 80520 | | SP2016_3124 654 [34] | |
| Proprietary | Proprietary | | | Yes | Yes | |  | MMH, NTO | 80577 | | | Derivative of P/N 80398 PMD |
| Proprietary | Proprietary | Yes | Yes | Yes | | Horizontal handling device |  | Hydrazine | 80595 | | | Derivative of P/N 80435 PMD |
| Proprietary | Proprietary | Yes | Yes | Yes | Yes | Horizontal handling device | | Hydrazine | 80617 | | | Derivative of P/N 80595 PMD |
| Proprietary | Proprietary | Yes | | | | |  | MMH, NTO | 80474 | | AIAA 2007-5559 [41] | |
| | **LEO Satellites, Constellations, Experiments, and Platforms** | | | | | | | | | | | |
| LEO constellation | Iridium | | Yes | | | |  | Hydrazine | 80375 | Yes | AIAA 95-2529 [42] | |
| LEO space station | Space Station Interim Control Module | | | Yes | Yes | |  | MMH, NTO | 80404 | | | |

| Program Type | Program Name | PMD Element: | | | | | PMD photo | Propellant | Reference P/N | End of Mission | Publication | Notes & delivered quantity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sponge | Vane | Trap | Gallery | Other | | | | | | |
| LEO communications | Orbcomm | | Yes | | | |  | Hydrazine | 80421 | | | U-vane |
| LEO constellation | SkySat | | Yes | | | |  | LMP-103s | 80568 | | SP2014_2978 323 [43] | U-vane, derivative of P/N 80421 |
| LEO Earth observation | DS1000 | Yes | Yes | | | |  | Hydrazine | 80430 | | AIAA 2003-4604 [44] | |
| Observation | DS1000 | Yes | Yes | | | |  | Hydrazine | 80470 | | | |
| LEO Earth observation | DS1000 | Yes | Yes | | | |  | Hydrazine | 80511 | | | |
| Space Technology Demonstration | Orbital Express (propellant transfer experiment) | Yes | | | | |  | Hydrazine | 80454 | | AIAA 2008-5105 [6] | |
| Observation | NFIRE | | Yes | | | |  | Hydrazine | 80462 | Yes | | 4-vane PMD, derivative of P/N 80375 PMD |
| Space Station | Space Station Crew Resupply | Yes | Yes | Yes | | |  | Hydrazine, NTO | 80527 | | | |

| Program Type | Program Name | PMD Element: | | | | | PMD photo | Propellant | Reference P/N | End of Mission | Publication | Notes & delivered quantity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sponge | Vane | Trap | Gallery | Other | | | | | | |
| Space Station | Space Station Crew Resupply II | Yes | Yes | Yes | | |  | Hydrazine, NTO | 80589 | | | Derivative of P/N 80527 PMD |
| | **Space Observatories** | | | | | | | | | | | |
| Space telescope | AXAF (Chandra) | Yes | Yes | | | Baffles |  | | 80393 | | AIAA 97-2812 [45] | |
| Space telescope | GLAST | Yes | Yes | | | |  | Hydrazine | 80466 | | | Same as P/N 80430 PMD |
| Space telescope | SDO (solar observatory) | Yes | | | | |  | MMH, NTO | 80484 | | AIAA 2008-4942 [46] | |
| Space telescope | James Webb Space Telescope (JWST) | Yes | | | | |  | Hydrazine | 80545 | | SP2018_00018 [20] | |
| Space telescope | James Webb Space Telescope (JWST) | Yes | | | | |  | NTO | 80546 | | SP2018_00018 [20] | |
| | **Lunar and Interplanetary Missions** | | | | | | | | | | | |
| Exploration | Mars Observer | | | Yes | Yes | | | | 80353 | | | PMD concept provided by the customer |
| Asteroid exploration | NEAR (asteroid exploration) | | | | | Vortex suppressor |  | NTO | 80379 | Yes | AIAA 95-2528 [25] | |
| Mercury explorer | MESSENGER | | | | | Baffles, vortex suppressor |  | Hydrazine, NTO | 80433 | Yes | AIAA 2002-4139 [26] | |

| Program Type | Program Name | PMD Element: | | | | | PMD photo | Propellant | Reference P/N | End of Mission | Publication | Notes & delivered quantity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sponge | Vane | Trap | Gallery | Other | | | | | | |
| Mars explorer | MER | Yes | | | | Dip tube |  | Hydrazine | 80449 | | AIAA 2002-4137 [47] | |
| Lunar science mission | LADEE (lunar science) | Yes | Yes | | | |  | MMH, NTO | 80540 | Yes | | |
| Lunar lander | Lunar lander | Yes | | Yes | | |  | Hydrazine | 80585 | | | Derivative of 80435 PMD |
| Mars orbiter | EMM | Yes | Yes | | | |  | Hydrazine | 80596 | | | Derivative of 80507 PMD |
| Lunar lander | Lunar lander | Yes | | Yes | | Baffles |  | Hydrazine or NTO | 80599 | | | Derivative of 80435 PMD |
| Lunar Orbiter | KPLO | Yes | Yes | Yes | | | | Hydrazine | 80612 | | | Derivative of 80595 PMD |
| Lunar Lander | Proprietary | Yes | Yes | Yes | | | | | 80621 | | | Derivative of 80435 PMD |

### 3.3 The 1150 mm (45.3 inch) Diameter PMD Tanks

Another PMD tank family with substantial market-derived synergy is our 1150 mm PMD tanks. Development of the original tank started in 2007, followed by several derivative tanks requiring qualification testing. Variants from this tank family include different tank constructions (all metal and hybrid), different tanks sizes (1255 liters to 2310 liters), and different PMD designs [34]. Multiple satellite integrators use tanks from this tank family for GEO commercial, proprietary, and Mars exploration programs.

We had learned, from analyses of hybrid tanks, that hoop and axial stresses in the cylindrical section of a hybrid tank have no correlation with cylinder length. Test results from two independent burst tests had verified our analytical assessment [34]. This finding made it possible to use a QBS approach to qualify a *longer* hybrid tank shell. Given that PMD qualification for a longer tank is by analysis only, our finding could result in lower qualification costs on future programs involving growth in tank length.

### 3.4 Iridium

Iridium is a LEO voice and data communications satellite constellation. The development of the first generation Iridium satellites took place in the 1990s, with each satellite containing a PMD propellant tank. The emphasis of the tank development program was simplicity. Simplified design and operations supported our customer's market strategy of low cost and a speedy time to market. We custom designed a simple and low mass shell with a simple one-vane PMD [42]. See Figure 12. The PMD tank design facilitated a sustainable high rate of production at one tank per week. We delivered 103 PMD propellant tanks for the Iridium program, and met our customer's integration plan successfully.

*Figure 12, the Iridium PMD and the Iridium Tank*

#### 3.4.1 NFIRE

The Near Field Infrared Experiment (NFIRE) was a space experiment platform launched in 2007. Our customer selected the Iridium tank shell based on its capabilities. However, the Iridium PMD was unable to meet mission objectives, and we custom designed a new PMD to meet NFIRE mission requirements. Unlike the one-vane Iridium PMD, the NFIRE PMD is a 4-vane PMD that facilitates a higher flow rate. The NFIRE PMD tank development was an early example of adopting a derivative tank approach to avoid a qualification test program in order to reduce program cost and schedule. As we qualified more tank shells and PMDs, we were able to apply this tank development approach on more and more programs. Starting in the late 2010s, it has become the primary PMD tank development approach.

*Figure 13, the N-FIRE PMD*

### 3.5 Chandra X-Ray Observatory (AXAF)

The Chandra X-ray Observatory, previously known as the Advanced X-ray Astrophysics Facility or AXAF, is a NASA space observatory launched in 1999. Chandra is orbiting the Earth on a highly elliptical orbit, from 133,000 km (82,646 mi) at apogee to 16,000 kilometers (9,942 mi) at perigee. The observatory is still operational as of April 2018.

The Chandra PMD development was independent of the tank shell development. Our responsibility included designing a PMD that met mission requirements, fabricating the PMD, installing the PMD through a small opening in a customer-furnished tank shell, and welding the tank close [45]. The PMD design was such that an installer could wrap the PMD vanes tightly around a centerpost during installation. After installation, the installer would unfurl the all-titanium PMD, and the vanes would spring back into flight configuration to support the mission. See Figure 14 for a picture of the PMD.

*Figure 14, the Chandra PMD in its Unfurled (and natural) Position*

### 3.6 Space Station Interim Control Module

The intent of the Space Station Interim Control Module (ICM) was to provide the International Space Station propulsive capabilities. The PMD design had two preconditions: design a PMD that met mission requirements, and assemble the PMD into a customer-furnished shell. The tank shell had a small 120 mm (4.75 inch) opening, making the PMD assembly operation extremely challenging. See Figure 15.

The mission profile required a gallery arm PMD design. The design and manufacturing challenges included (1) designing large gallery arms that could fit through the small opening, (2) covering a large area of the gallery arms with screens, (3) assembling the four gallery arms in the tank shell without damaging the delicate screens, and (4) sealing the tank shell. Our designers met all the challenges, and ATK delivered six flight tanks in 1999.

*Figure 15, the Space Station ICM Tank PMD*

### 3.7 GLAST

NASA launched its Gamma-ray Large Areas Space Telescope (GLAST) in 2008 onto a low Earth orbit. The PMD for the hydrazine propulsion tank was a classic sponge and vane PMD previously developed for a LEO earth observation satellite [44]. See Figure 16. The qualified PMD capabilities met all the requirements of the GLAST mission. We made a small modification to the outlet port, but the PMD as is was completely suitable for the GLAST mission. It was a rare opportunity and the only time in the history of the company that an existing PMD tank would be applicable for another unrelated mission.

*Figure 16, the GLAST PMD*

### 3.8 LADEE

NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) mission was to orbit the moon and gather scientific data on the lunar atmosphere and lunar dust. The spacecraft launched in September 2013 and completed its mission in April 2014. The mission profile included lunar orbit insertion, lunar orbiting, deorbit, and a planned impact on the lunar surface. The four PMD tanks in the bi-propellant propulsion system contained a classical sponge and vane PMD as shown in Figure 17. The final impact maneuver of LADEE deposited ATK hardware onto the lunar surface, joining other hardware that had landed on Mars, Venice, Mercury, asteroid, and comet surfaces.

*Figure 17, the LADEE PMD*

### 3.9 Orbital Express

The Defense Advanced Research Projects Agency (DARPA) Orbital Express program was a 2007 flight experiment to demonstrate autonomous on-orbit refueling technology. ATK was under contract to provide the PMD tanks for the fluid transfer experiment. Both the filled supply tank in the servicing satellite (ASTRO) and the empty receiver tank in the serviceable satellite (NEXTSat) had identical large sponge PMDs. See Figure 18 for the PMD configuration. The PMD, designed to enable on-orbit transfer of both gas-free propellant and liquid-free pressurant, had functioned as predicted throughout the mission [6]. The CFD predictions of the fluid behavior had been accurate and precise, and the successful flight experiment served as a definitive proof of our analysis-only approach to PMD validation [8].

*Figure 18, the Orbital Express PMD*

### 3.10 SDO

The Solar Dynamics Observatory (SDO) is a NASA solar observatory in operation starting 2010. The SDO spacecraft has two 1067 mm (42”) diameter spherical PMD tanks in its bi-propellant propulsion system [46]. As a space observation platform, control of the propellant movement was key to mission success, and we developed a large sponge PMD to facilitate tight propellant CoM control. See Figure 19 for the PMD configuration. During PMD development, it became necessary to design a test program to measure the transmitted loads at the PMD attachment interface. The empirical data became critical to the SDO and all future large sponge PMD design efforts.

*Figure 19, the SDO PMD*

### 3.11 JWST

ATK developed two PMD tanks for the James Webb Space Telescope (JWST) [20]. See Figure 20. The hydrazine tank PMD is a large sponge custom designed for a cylindrical tank. The NTO oxidizer tank PMD is also a large sponge, but custom designed for a spherical tank. We qualified the new hydrazine shell by qualification testing, and used a QBS approach to qualify the spherical NTO tank. The development of these two PMD tanks is an example of the extreme optimization we could exercise to minimize tank mass [20].

ATK conducted extensive structural testing of the PMD and the shell-to-PMD interface in the form of long duration slosh tests [20]. It was an example of the extreme precautions we took to evaluate risk and ensure mission success. Most advantageously, the valuable data we collected are applicable to future PMD designs of similar configuration.

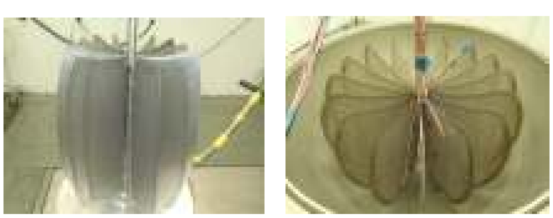


*Figure 20, the JWST Hydrazine and NTO PMDs*

### 3.12 MESSENGER

Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) was a NASA planetary explorer that orbited planet Mercury from 2011 to 2015. We provided all the tanks on the MESSENGER spacecraft, including three custom-designed bi-propellant tanks, a diaphragm tank, and a composite wrapped pressurant tank. The propellant tank development included a yearlong trade study to identify a tank configuration with the lowest mass [26]. The PMDs included two baffle rings for nutation damping during the spinning upper stage flight, and a vortex suppressor at the propellant outlet to prevent gas ingestion. See Figure 21.

During MESSENGER’s on orbit science mission at Mercury, analysts conducted multiple CFD analyses to optimize the thruster firing sequences in order to extract residual propellants adhering to the tank baffles. The CFD predictions on the duration and timing of gas ingestion were consistent and precise [7] [8]. The data feedback confirmed, in real time, the accuracy and validity of the predictive tools, further validating the predictive tools and the analysis-only design approach.

*Figure 21, the MESSENGER Tank PMD*

### 3.13 Gallery Arm PMDs

Gallery arm PMDs are ideal solutions for missions with medium flow rate and continuous propellant supply requirements [17]. Figures 22 and 23 are some classic gallery arm PMDs manufactured for highly demanding mission maneuvers. However, this high performance comes with a cost. The disadvantages of gallery arm PMDs are higher mass, higher risk, and longer development cycles as compared to other PMD solutions. For example, the gallery arms in Figure 22 took over two years to develop, whereas a conventional sponge and vane PMD tank could take less than 15 months to deliver. On each gallery arm, there are screen welds that run the entire length of the gallery arm as seen in Figure 23. As a rule, the more welds in a PMD assembly, the higher the inherent risk. A gallery arm PMD typically has the longest length of weldment, thus the highest inherent risk. Finally, a gallery arm PMD typically has the most metal content, and is typically heavier than a conventional sponge or vane PMD.

*Figure 22, the Special Program Gallery PMD*

*Figure 23, the ICM Gallery PMD*

### 3.14 Lunar Lander PMD Tanks

Two PMD tank programs for lunar lander missions are representative of a recent trend in PMD tank development. Both programs had followed parallel development paths. After trade studies for available options, both customers had selected a derivative PMD development option. The PMDs in both programs are from the same P/N 80435. On one program, the PMD optimization focused on performance and mass, and adapted the PMD originally designed for a 540 mm (21.25 inch) tank into a 562 mm (22.14 inch) diameter shell. On the second program, the PMD optimization focused on cost minimization, and adapted the PMD into a 757 mm (29.8 inch) diameter shell. Figure 24 is a photo of a lunar lander PMD.

After developing over 60 PMD designs, we are now in a position to offer adaptation of existing PMD designs for programs with cost constraints. PMD design efforts are often time intensive and costly. Adapting existing PMDs becomes an effective way to reduce cost and shorten schedule. In the first quarter of 2018, ATK proposed the same development approach and received two additional awards to develop lunar program tanks with derivative PMDs.

*Figure 24, a Lunar Lander PMD*

### 3.15 Green Propellant PMD Tank

ATK developed the first PMD tank that carries the LMP-103s green propellant. The challenge of bringing this PMD tank to the marketplace was not limited to PMD design and analysis. It took several years to design and fabricate a highly complex measuring apparatus before we could collect the basic propellant property data such as surface tension and contact angle. We also overcame numerous regulatory hurdles both in Sweden and within the United States in order to take delivery of the LMP-103s propellant at our research facility [43]. In addition, we supported the collection of fracture data to facilitate fracture mechanics analysis of the tank shell. Figure 25 is a photo of the first PMD tank developed for the storage of LMP-103s. Dozens of these tanks are already in orbit.

*Figure 25, PMD for LMP-103s Green Propellant*

## 4. Conclusion

In this summary paper, the term *heritage* is not merely a numeric count of which tank is on which space mission. Internally, the broader term *heritage* is a reflection of the connectivity amongst design principles, manufacturing practices, inspection disciplines, and test methodologies that culminate in successful hardware development and deployment. Externally, heritage is the recognition of organizational knowledge as well as an acknowledgement of accumulated excellence in produce performance. Our tanks support thousands of space missions worth hundreds of billions of dollars. Their scientific, social, and economic impacts are immeasurable. The acknowledgment of heritage is an indication of the inherent customer trust we earned from the beginning of the space age.

Contrary to some long-held popular beliefs, there is no black magic in PMD design and operations. The process of PMD design and analysis has always been the engineering application of basic scientific knowledge. Hundreds of successful space flights from early 1960s to present had confirmed and validated our design methodology. Nevertheless, PMD design continues to require a human touch. A good PMD designer must be an exceptional scientist, a versatile engineer, an innovative designer, and a good CFD software diagnostician. As with all human endeavors, there could be multiple approaches to PMD tank solutions as demonstrated by our industry colleagues who design PMDs in other parts of the world.

For future work, we encourage the assembly and publication of a body of evidence to validate PMDs designed by CFD tools only and without ground test validation. Such evidence exists with satellite integrators and operators but is not readily available in the literature in an organized form. The availability of this body of evidence in the literature will help future PMD users understand the effectiveness of this design methodology and the benefits it brings.

Having a highly matured PMD design methodology does not permit complacency. We continue to engage institutions and academia to seek process and product improvements. We are developing test data that will reduce design margin to facilitate lower mass PMD tank designs. We continue to accept new challenges on a wide variety of PMD tank programs, including lunar and planetary exploration missions. Increasingly, we take on new PMD tank design challenges by adapting existing PMD and shell designs to imbed heritage, reduce cost, and optimize overall value. As space systems advance and evolve, we intend to rely heavily on our heritage and accumulated knowledge to provide the optimal PMD solution on future missions.

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