The Evolutionary Forces and the Design and Development of Propellant Management Devices for Space Flight in Europe and the United States

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ABSTRACT
Propellant management devices (PMDs) applying surface tension phenomena are in use to enable spacecraft propulsion in the orbital environment. The heritage of propellant tanks with surface tension PMDs dates back to the 1960s. Legacy programs included Apollo and Space Shuttle orbital maneuvering system (OMS) and reaction control system (RCS) propellant tanks. The introduction of geostationary (GEO) commercial satellite fleets in the 1980s brought surface tension PMDs into prominence. Today, all the major GEO commercial satellite platforms use PMD tanks to support flight operations. Cumulatively, there are thousands of PMDs supporting space flights on board launch vehicle upper stages, satellites, and exploration spacecraft.

In the past five decades, engineers and scientists designed dozens of PMDs in Europe and the United States. PMD design and development evolved in response to market needs, technology advancements, cost and schedule constraints, and other driving factors. In this summary paper, the authors will explore the two parallel but independent paths of PMD design activities in Europe and the United States, and recount some milestone events that shaped the PMD design evolution.

There are five sections to this summary paper. Section 1 is an introduction of the changing business and institutional environments that affected PMD design and manufacture in Europe and the United States. In Sections 2 and 3, the authors will describe the evolution of PMD design processes in Europe and the United States, respectively. In Section 4, we review the two PMD markets from a historical perspective, and compare and contrast the similarities and differences in the two markets. In Section 5, we conclude with an outlook towards future activities.

INTRODUCTION
Space flight is the result of vision, innovation, commitment, and sacrifice by a group of talented space professionals. Each successive generation of administrators, engineers, and scientists stood on the shoulder of giants to meet ever bigger and more far-reaching challenges. Humanity went from a small sphere called Sputnik in 1957 to a continuously occupied International Space Station (ISS) with sound logistics support in 2000 – an amazing achievement unparalleled in the history of exploration. However, we did not achieve these accomplishments by accident. There were external forces at work that shaped the space industry of today, and there are market conditions already in place molding our industry of tomorrow.

Government sponsorship was crucial to the early development of space systems. Space agencies and institutions are instrumental in initiating and sustaining interest and activities in space systems development. Business managers organize talents and resources, and optimize their organizations to compete efficiently and effectively in a fiercely competitive space industry environment. University researchers and educators train generations of engineers and scientists to meet the demand for talents in space sciences and technologies. As space technologies mature, space systems are no longer the domain of government agencies and large technology firms. Privatization is an emerging trend. While Space X activities capture newspaper headlines, small start-ups such as Astrobotic in the United States and Axiom in India are developing space systems to land on the moon. These are all important developments that mold the space industry regionally, nationally, and globally.

Market forces also shape the paths of PMD design activities in Europe and the United States. PMD designers take advantage of propellant surface tension properties to design PMDs in support of space flight in low g or zero g environments [1] - [6]. The heritage of propellant tanks with surface tension PMDs dates back to the 1970s. Legacy programs using PMD tanks
included Apollo and Space Shuttle OMS and RCS tanks. The introduction of 3-axis stabilized GEO commercial satellites in the 1980s brought surface tension PMDs into prominence and wider use. Today, all the major GEO commercial satellite platforms use PMD tanks to support flight operations. Thousands of PMDs are in flight or have already flown.

In the past five decades, engineers and scientists had designed dozens of PMDs in Europe and the United States. PMD design and development evolved in response to market needs, technology advancements, cost and schedule constraints, and other driving factors. Interestingly, PMD design activities in the two markets progressed in parallel but independent of each other because of different market conditions. In this summary paper, the authors recount many of the market forces that shaped the PMD design evolution. Some transformative events in Europe and the United States included:

The transition from an institutional environment to a business environment with a mix of institutional & commercial programs.

Institutional space programs are important to PMD designers. PMD designers take advantage of the occasional opportunities to design unique PMDs on challenging institutional missions, and value the opportunities to further develop their tools and hone their skills. Nevertheless, institutional programs alone were insufficient in generating PMD design work. The introduction of commercial satellite fleets was the market force that brought sufficient work content for PMD designers. From a historical perspective, the ratio of institutional PMD design programs to commercial PMD design programs is approximately 2 to 3. From a tank quantity perspective, there are over 2,000 commercial PMD tanks in flight, as compared to only hundreds of institutional and governmental PMD tanks in operation.

The de-centralization and centralization of PMD design and manufacture.

Before the 1980s, only large technology companies had the expertise and the resources to participate in PMD design and manufacture. Beginning in the late 1980s, satellite manufacturers such as Hughes (later Boeing), Ford Aerospace (later SSL), Martin Marietta (later Lockheed Martin), and Orbital Sciences (later Orbital ATK) started to transfer PMD design responsibilities to a small and independent tank manufacturing firm called Pressure Systems Inc. (PSI). This shift in the marketplace enabled satellite manufacturers to focus on their primary task of satellite integration. It also allowed PSI to consolidate PMD tank design activities, accumulate its knowledge base, and become more efficient. From the late 1980s to the present time, the same small tank manufacturing organization has been responsible for an overwhelming majority of PMD tank design and qualification activities in the United States. The de-centralization of PMD design by satellite integrators, coupled with the centralization of PMD design and fabrication at PSI (now ATK Space Systems under Orbital ATK), enabled the PSI organization to accumulate a large array of qualified space hardware designs. The large inventory of qualified products in one organization allowed customers to take advantage of the market-derived synergy and develop derivative tanks that benefited the entire space industry [7]. In retrospect, a fractured tank industry might not have served the space industry as efficiently or effectively.

The transition from spin-stabilized to 3-axis stabilized GEO commercial satellites in late 1980s.

The once-popular spin-stabilized spacecraft do not require PMD propellant tanks. However, they also cannot take advantage of large solar arrays for power generation. As spacecraft grew in size and power requirement, the market demand for spin-stabilized spacecraft diminished, replaced by an increasing need for 3-axis stabilized spacecraft using PMD propellant tanks. The transition in the marketplace, especially on GEO commercial satellite platforms, brought PMD tanks into prominence. For example, the HS 601 spacecraft was the most popular commercial satellite platform in the 1990s, and each HS 601 propulsion system contains four PMD propellant tanks [8] [9]. In retrospect, PMD tanks played an important role in facilitating the growth of GEO commercial satellite capability, complexity, and mission life. Today, PMD tanks are the baseline on the Airbus Eurostar [10] [11], Boeing, Lockheed Martin A2100 [12] [13], Loral LS1300 and FS1300 [14], MELCO D2000 [15], Orbital Star 1, 2, and 3 [16]-[18], and the Thales Alenia Spacebus [19] satellite platforms. The abundance of design experience and flight heritage paved the way for expanded use of PMD tanks for space flight.
The introduction of launch vehicles requiring horizontal handling and transport in the 1990s.

At the end of the Cold War, the Russians converted their Intercontinental Ballistic Missiles to commercial launch vehicles. While U.S. launch vehicles Atlas and Delta had upright handling only, the new Russian Proton launch vehicle required horizontal handling and transport of payload on a railroad track. Later introduction of Sea Launch Zenit and Space X Falcon launch vehicles also require horizontal handling and transport. During horizontal handling and transportation, the orientation of the propellant tank might expose the tank outlet to premature gas ingestion. In addition, horizontal transportation on a railroad track or on a boat could induce propellant slosh within a tank, with further risk of premature gas ingestion into the tank outlet. After the introduction of the Proton launch vehicle, all PMD tank designs must consider mission requirements as well as ground handling and transport requirements in response to the changes in the launch vehicle market [12] [13].

The introduction of tight Center of Mass (CoM) requirements to minimize spacecraft disturbances in the 2000s.

As payload instruments become more capable and thus more sensitive to flight disturbances, tight CoM control of propellant within flight tanks are becoming important in some missions. Example of such missions includes the NASA Solar Dynamics Observation (SDO) [20], NASA James Webb Space Telescope (JWST), and some observation missions. Tank manufacturers are receiving more requests to design PMD tanks with tight CoM control capability or precise CoM knowledge than in the past. The added requirement is an addition to the already challenging optimization tasks of reducing mass, improving expulsion efficiency and minimizing residual, optimizing heritage, and reducing cost.

The continuing development of satellite servicing capabilities, including on orbit fluid and gas transfer.

Designing, building, and launching satellites into orbit are expensive and time consuming endeavors. Institutions and private firms continue to explore automated satellite servicing as a way to extend the mission life of valuable assets in space. Satellite servicing missions might require technologies that include tracking, formation flying, docking, and propellant transfer. The capability of propellant tanks is critical to the success of satellite services operations. One example of the satellite servicing demonstration project was the Defense Advanced Research Projects Agency (DARPA) Orbital Express mission. In the 2007 on orbit demonstration mission, engineers and scientists conducted on orbit demonstrations of satellite servicing technologies, including liquid propellant and gaseous pressurant transfer from spacecraft to spacecraft using PMD tanks [21]. The technology demonstration was an important validation of the PMD tanks' capacity to support future demand for satellite servicing missions.

The evolution of resupply missions to the International Space Station (ISS).

The retirement of the space shuttle fleet in 2011 left a capability gap for the United States to deliver cargo and crew to the ISS. Space organizations around the world have developed capabilities to meet the challenge of ISS resupply. ESA's Automated Transfer Vehicle (ATV), Japan’s H-II Transfer Vehicle (HTV), Orbital ATK's Cygnus spacecraft, and SpaceX's Dragon spacecraft are all recently developed resupply cargo ships incorporating PMD tanks. NASA’s goal of using commercial resupply services for ISS gave PMD designers opportunities to develop a new class of tanks that meet challenging mission requirements. With favorable features such as low mass, high performance, and proven reliability, PMD tanks have emerged as the product of choice for this particular kind of space missions.

The new requirement to meet wind-induced slosh on launch pad.

In recent years, a number of satellite integrators have developed a keen interest in the ability to launch spacecraft under adverse launch conditions. One of the adverse conditions that became a tank design requirement is the severe propellant slosh inside a PMD tank assuming the tank is at the top of a launch vehicle stack assembly. Tank designers must ensure that the PMD survives severe slosh loads with large amplitude, high or low frequency, and long duration. Fluid slosh might intensify into swirl that further complicates the PMD design and the method of structural validation. While it is possible to model slosh behavior within tanks, testing is often necessary to validate the structural durability of the PMD. To meet the new challenge of mechanical validation, a dedicated slosh test facility is becoming a necessity for PMD tank design validation [22].
Using PMD design to facilitate propellant gauging.

Propellant availability is the key to mission life. Satellite operators must ensure the accountability of precious fuel before terminating a mission, and a precise knowledge of propellant volume within a tank is critical to asset value optimization and mission success. PMD designers can design a PMD structure to locate the propellant within a tank precisely at any given fill fraction at steady state zero g conditions. Some space systems operators have already incorporated such a propellant gauging system by taking advantage of the PMD design, and others are exploring its potential applications.

The applicability of PMDs for cryogenic propulsion systems.

Cryogenic fluid management is of essential interest since the 1960s, driven by the need to master the ballistic flight phases of cryogenic upper stages [23]. Cryogenic PMD technologies are crucial to future human exploration missions to Mars and Asteroids because of their potential for achieving highly efficient propulsion systems. A number of studies thus focused on the behavior of PMD technologies and their applicability to cryogenic liquids [24]-[27]. Recent developments concerning cryogenic propellant management devices included Ariane 5 upper stage A5ME. In this context, researchers developed, built, and tested PMDs for LH2 and LOX and reached a TRL level of 5 to 6 [28]-[30]. The developments included an in-orbit experiment on TEXUS 48 that successfully demonstrated PMD technologies with liquid nitrogen [31]. Despite the need to consider cryogenic PMD technologies for human exploration missions, it is only an alternative technology for upper stages. The number of main engine restarts for upper stages is limited. For example, RCS is carried out with cold gas from the propellant tanks. Main engine start-up is frequently done with a settling thrust using the RCS. In Europe, cryogenic PMD technology is again coming into focus with the goal of obtaining a more favorable thermal environment on upper stages. Since PMDs collect the liquid near the outlet, especially when the fill level is low, the liquids may also expect a reduced warm-up over time. In this context, it is possible to consider PMDs as thermal devices.

The development of reusable spaceflight vehicles.

Space vehicles capable of multiple launches and returns to Earth have some obvious advantages. Designing PMD tanks for multiple launches and reuse require considerations such as multiple fill and drain, multiple launches, multiple mission operating cycles, and multiple depletions. In addition to meeting functional requirements, the PMD tank must have the structural integrity to survive multiple life cycles, each with severe mission loads. Conventional qualification testing must test the qualification tank to 4 times the single-mission life. On reusable PMD tanks, the life cycle testing must subject the qualification tank to 4 times the multiple-mission cycles, making the design and test of a PMD tank for such a purpose a significant challenge.

The adaptation of synergistic approaches for PMD design to meet commercial and competitive goals.

The marketplace demand for lower recurring and non-recurring tank development cost is intense and persistent. In response to the unrelenting pressure, PMD designers are designing new PMDs by applying pre-existing concepts and hardware to gain or retain competitive advantage. Adaptation of pre-existing PMD components or concepts has the benefit of reducing the number of drawings, minimizing engineering drawing hours, and using existing tooling. It has an added advantage of embedding design and flight heritage. In addition to mastering the technical aspects of PMD design, present-day PMD designers must also consider other programmatic factors during the PMD design process. These considerations have evolved to include cost, mass, schedule, performance, and overall value [7].

Spacecraft deorbit to meet space debris mitigation requirements.

Space debris is becoming an increasingly critical problem for the space industry. NASA researchers projected that the number of debris objects will continue to grow [32]. There were four confirmed in space collisions since 1991 [33], including the well-publicized destruction of the Iridium 33 satellite in 2009 [34]. Space systems integrators are already designing spacecraft that meet de-orbit requirements. PMD designers are anticipating more PMD design activities that support satellite de-orbit. This could include assisting the development of space tug-like spacecraft that facilitate de-orbiting of decommissioned satellites. To approach, dock, and de-orbit a large passive satellite require a series of complex maneuvers. There will be a strong emphasis on the spacecraft maneuverability, and consequently on the PMD design. One example in this context is the anticipated de-orbit of the ESA Envisat satellite.
The maturing of green propellants.

Green propellant development is reaching product maturity. Currently, two major brands of green propellant are penetrating the space propulsion market. The Swedish Green Propellant LMP-103s has already undergone in flight demonstration [35] [36]. The commercial satellite constellation SkySat has PMD tanks on board its first-generation satellites [37]. Researchers at the U.S. Air Force Research Laboratories (AFRL) also developed a new green propellant formulation named AF-M315E. A flight demonstration of the AF-M315E propellant capabilities will take place on board the Green Propellant Infusion Mission (GPIM) satellite. The launch of GPIM satellite will take place in late 2016. As the propulsion market migrates towards green propellant usage, PMD tank design activities will inevitably follow this market direction.

The maturing of analytical tools

The advancement in computing capabilities had greatly simplified the task of PMD design. Software developed for computational fluid dynamics analysis included Flow 3D and Surface Evolver. These analytical tools have been integral to PMD design and analysis in the past three decades. In Sections 2 and 3, we shall touch upon the impact of analytical tools on the process of PMD design and analysis.

The different paths to PMD design and validation in Europe and the United States.

The different market conditions in Europe and the United States had led to different design and validation approaches. In the next two sections, we shall explore the commonalities and differences in the two primary PMD tank markets – Europe and the United States.

SECTION 2, EVOLUTION OF PMD DESIGN PROCESSES IN EUROPE

After the termination of the Apollo Space Program in 1972, a cooperative endeavour developed between the Europe and the United States upon the start of the Space Shuttle program. One objective of the collaboration was to advance the basic understanding of space sciences. A major European contribution from the collaboration was the Spacelab laboratory launched in 1983 on STS-9.

The space laboratory was valuable for carrying out fluid dynamic experiments in a zero-g environment. Researchers conducted theoretical and experimental studies to expand their fundamental knowledge because it was new technology in Europe at that time. One important study was to collect data on fluid properties that eventually led to applications on surface tension PMD tanks for space flight. The studies included measurements of a propellant’s surface tension and contact angle on metal surfaces, including screens. The measurements took into account different surface roughness in a wetted state while in orbit. Researchers from a German research organization named Fraunhofer Gesellschaft at Stuttgart conducted most of the measurements that characterized the contact angle and surface tension properties of fluids. One important outcome was the measurement of Hydrazine properties. Hydrazine has a relatively high surface tension. Measurements at metallic probes indicated a surface tension of 60mN/m instead of 70mN/m.

Scientists at MBB/ERNO (predecessors of Airbus DS) further elaborated the theoretical basics to characterize the static and dynamic conditions of the fluid behaviour. They used the Laplace Equation to evaluate the location at the liquid-gas interface for static characterization. Further development of dedicated analytical tools enabled the characterization of the interface condition in both 2D rotational symmetry and 3D. One major function of these tools is to estimate the amount of liquid statically present at the reservoir or in the vanes. Figure 1 and Figure 2 are examples of the fluid characterization.

![Figure 1. Rotational symmetric characterization of the interface and the corresponding liquid volumes](image1)

![Figure 2. Equilibrium conditions for the second generation of surface tension tanks (OST-2) in 3D (0.0003 g lateral disturbance, 1.5L is kept around reservoir near the outlet)](image2)
Many of the dynamic analyses contributed to the development of CFD tool FLOW-3D by Flow Science [38]. FLOW-3D has since become the standard CFD tool at Airbus DS.

2.1. The first generation surface tension PMD tanks (OST-1 tank family)

After acquiring the basic principles of surface tension behaviour of propellants, European scientists developed the main PMD elements and tested them on the ground with neutral buoyancy tests using liquids of equal density. Upon successful test validation, surface tension PMDs became the primary fluid control devices in MMH and MON propellant tanks on board GEO satellites developed in Europe. These satellites required a directed acceleration for orbit insertion in its apogee that consumed about 70% to 80% of the propellant. Satellite operators used the remaining liquid to stabilize the satellite in orbit throughout the mission life.

The first application of PMD propellant tank was on the TV-SAT/TDF-1 program in 1987. It was the first satellite containing the first generation of European surface tension PMD tanks (OST-1). Figure 3 is a sketch of the OST-1 surface tension tank and its PMD components. Figure 4 is a photo of the OST-1 screen system components.

The OST-1 is a compartmented tank, with a conical intermediate bottom dividing the tank into two compartments. See Figure 3. The PMD design implemented a baffle cross in the upper compartment at the conical intermediate bottom to stabilize the propellant. Screen elements in the middle of the conical structure would enable propellant passage from the upper to the lower compartment during draining. The bottom compartment is in use during orbital operations. It contains a number of screen adapters connected via tubes to a sump. The sump contains additional screened windows to facilitate propellant flow. The PMD design ensured that at least one screen adapter is in contact with the bulk liquid propellant throughout the mission, thus enabling the draining of propellant under all operational conditions, see Figure 5.

Driven by a customer request, researchers conducted a PMD functional demonstration on a 1:1 scale mock-up in 1g conditions while applying realistic flow rates around all axes. Figure 6 is the experimental set-up of this test. The location of the outlet was in accordance with North-South or East West attitude control maneuver. The location of the liquid-gas interface was under 1g conditions, and at least one adapter was always covered with liquid during draining. See Figure 7.
Researchers also conducted experiments to verify the functionality of the new PMD propellant tank. The test environments included:

a) parabolic flights;
b) Space Shuttle flight. Researchers conducted experiments using the ERNO MAUS Tank Experiment (EMTE) platform on board the Space Shuttle STS-S16 in 1986 [5] [6]. Figure 8 is a photo of the EMTE platform.

The EMTE test results were qualitative only. Comparisons with CFD results were not possible because the software was not yet sophisticated enough to consider surface tension forces at that time. Figure 9 is an image taken with the EMTE film camera. PMD designers used these crude but valuable early images to gain confidence in their design practices.

In addition, researchers conducted draining tests on the EMTE platform. Although the video images were not high resolution, researchers were able to study the video and distinguish the liquid from the gas. The video evidence from the draining experiments enabled the verification of the PMD functionality in zero g.

In summary, sixty-four OST-1 tanks went into orbit on board satellites. Some of the PMDs included adaptations to the intermediate bottom to enhance performance on board the DFS, EUTELSAT, INSAT, and ITALSAT satellites. Although the OST-1 PMD concept was functional, researchers learned that the PMD concept had its disadvantages. The geometrical adaptations were complex because of the design limitations of the intermediate bottom. The integration cost was high, and the tank mass was relatively high. These disadvantages did not facilitate continuous use of the PMD concept for a large number of satellites. A new concept became necessary, and intermediate bottom PMD became obsolete as PMD designers developed the second-generation OST-2 tanks for the Spacebus tank family.

### 2.2. Second generation of surface tension tanks (OST-2 / Spacebus tank family)

The desire to lower the cost of surface tension PMD tanks was difficult to meet using the two-compartment concept of the OST-1 PMD. For the second-generation OST-2 tank, PMD designers used a partial retention device to keep only a portion of the propellant in a refillable reservoir (PRR) at the tank outlet. Introduced in 1988, the OST-2 PMD became the standard PMD for the Spacebus tank series. From its introduction to 2016, 140 OST-2 tanks had launched aboard satellites. The development of the PRR PMD concept benefited from improved software and the use of a new drop tower ZARM in Bremen for test.
validation. The reservoir is adjustable to fit within a large variety of tank shells without the need to adapt the reservoir’s shell geometry. The new OST-2 PMD has a lower mass as compared to the two-compartment OST-1 PMD. Figure 10 is the OST-2 PMD concept [19].

Figure 10. OST-2 surface tension PMD tank

Figure 11 is a detailed view of the PRR. The reservoir has a volumetric capacity of approximately 6 liters. The 6-liter propellant volume is sufficient for all anticipated spacecraft maneuvers.

Figure 11. Details of the OST-2 refillable reservoir, with the top lid removed for clarity

The four guide vanes, equally spaced and attached to the conical house, are inside the PRR. Functionally, these four guide vanes facilitate the capillary pumping of propellant towards the four upper screen adapters. In the zero-g environment, surface tension forces would drive the propellant to collect inside the PRR. On demand, the propellant is pumped via screen adapters to the outlet.

The parallel mounted capillary vanes inside the tank (Figure 10) would refill due to capillary effects. A propellant bridge inside the capillary gap interconnects the bulk volume with the propellant in the reservoir. Whenever the propellant reaches the inlet of the reservoir, the capillary vanes and grooves would pump the fluid into an annular wedge formed by two cones to provide a concave surface in the tank. The annular wedge affects a lower pressure than ambient in its gap, thus sucking the fluid into the reservoir. The outlets are located at the upper end of the annular. Metal screens cover the outlets to provide bubble-free propellant flow while keeping the pressurization gas from leaving the tank via the outlets. The pressure drop at the screens has to be lower than the bubble point pressure, otherwise bubbles may penetrate the screen. The PRR would refill with propellant automatically via propellant acquisition vanes [39].

At the time of the OST-2 maturation, PMD designers conducted a larger number of experiments to verify the functionality of the PMD concept because the state-of-the-art of CFD tools was not yet adequate. The designers expended significant effort to test each new PMD concept. In the following paragraphs, we present the different experiments conducted in the 1990s. One major focus was the verification of the filling and draining behavior of the reservoir. Initial testing took place in the ZARM drop tower in Bremen, and later in a Mini-TEXUS sounding rocket flight in 1995. Figure 12, Figure 13, and Figure 14 are photos of the different tests carried out in the drop tower.

Figure 12. Reorientation of the liquid after a station keeping maneuver using a scaled PRR

Figure 13. Testing the refilling of the PRR connected to the bulk liquid with guide vanes

Figure 14. Test vessel used for testing of the initial refilling phase in scale 1:1
PMD designers performed a final experimental verification of the OST-2 PMD tank in 1995 on a Mini-TEXUS sounding rocket. The focus of the experiment was on the filling and draining of the PRR. The microgravity duration of the experiment was 3.7 minutes. Figure 15 is a photo of the experiment set-up.

![Figure 15. Mini-TEXUS experiment set-up](image)

The experiment included an expulsion of the liquid from the reservoir, followed by a refilling phase to verify that the PRR could empty and fill frequently. In Figure 16, we show photos taken during the refilling phase of the experiment. Some photos showed the expulsion of a gas bubble through the venting hole as intended.

![Figure 16. Photos taken during the refilling phase showing the expulsion of a gas bubble through the venting hole](image)

### 2.3. Third generation of surface tension tanks (OST-3/Globalstar tank family)

The third generation satellite PMD tank is the Globalstar tank. These are PMD tanks used on smaller satellites with low Bond numbers and low hydrazine flow rates in contrast to the larger OST-1 and OST-2 tanks. The OST-3 tank has a total retention surface tension PMD with four guide vanes similar to the OST-2 PMD. The guide vanes connect directly to the outlet port. The vanes are able to pump propellant continuously towards the outlet if the accelerations and the flow rates are sufficiently low. Designers initiated this concept based on the good experience gained from the OST-2 PMD. Figure 17 is a conceptual view of the Globalstar PMD tank.

![Figure 17. OST-3 Globalstar PMD tank](image)

PMD designers at Airbus DS used the heritage-based guide vane design on the OST-3 PMD. The guide vane has a shape that facilitates high pumping capability as shown in Figure 18 below with the different menisci. The lower horizontal line denotes the tank wall.

![Figure 18. Guide vane shape](image)

The liquid flows between the tank wall and the guide vane. When the liquid covers the area 4 below the vane, the propellant flow along the vane would reach the critical flow rate. Higher flow rates would lead to a collapse of the menisci below the guide vane and the vane would stop pumping. It is therefore essential to have a good knowledge of the pumping capability of the vane as a function of different vane-wall distances. To gain this critical knowledge, PMD designers conducted dedicated drop tower experiments. See Figure 19. Based on the drop tower test data, PMD designers were able to derive the rise time from a differential equation based on an impulse equation.
2.4. ATV tank

The ATV is the European supply vehicle to the ISS. Four ATVs have flown between 2008 and 2015. Initially, tank designers intended to use eight tanks with metal bladders for the bipropellant propulsion system. However, a number of difficulties with the bladder tank led to a PMD tank solution. Two PMD tanks of equal design were set in series. Figure 20 is the concept and photo of ATV PMD.

The ATV PMD has 11 screen adapters placed near the tank shell at different locations such that under all mission constraints, also for very low fill levels, at least one screen adapter is in contact with the bulk liquid. The screen adapters, made from pleated 200x1400 mesh, are connected to the outlet via pipes. The ATV PMD has two conical baffles whose primary function is to suppress sloshing motions while approaching the ISS. These conical baffles also ensure that liquid is always next to the vicinity of the adapters under zero g conditions at very low fill levels. See Figure 21.

Owing to the success of ATV PMD tank, PMD designers baselined parts of the ATV tubes and screen adapter designs on the European Service Module’s (ESM) propellant tanks for the Orion Spacecraft [40]. The Orion ESM PMD tank is now in the manufacturing phase.

2.5. Eurostar tank

Matra Marconi Space (today Airbus DS) and British Aerospace (today BAE Systems) engineers started the development of propellant tanks for the generic Eurostar platform in 1983. The first successfully qualified tank was the 257 liter Eurostar 2000 propellant tank. This tank contains a flat membrane with a communication tube to be compatible with a spin stabilized apogee transfer. The tank contains a tilted PMD as shown in Figure 22 [10].

Figure 19. Capillary pumping of the vane with a flow rate of 13ml/s

Figure 20. The ATV PMD

Figure 21. Zero g configuration in the ATV tank for low fill levels

Figure 22. Eurostar 2000 (257 liter) propellant tank [10]
The basic Eurostar 2000 design then underwent optimization to enlarge tank volume and meet 3-axis stabilized operational requirements. In 1997, engineers concluded qualification on two larger Eurostar 2000+ tanks, first for a 393-liter tank, and later for a 406-liter tank. The Eurostar 2000+ PMD has relocated to sit directly above the tank outlet. In 2000, a next-generation propulsion tank onboard the new Eurostar 3000 bus completed qualification. The Eurostar 3000 tank evolved from the Eurostar 2000+ tank, but with increasing length and diameter to meet higher but variable volume requirements of 517 to 590 liters. Figure 23 is the conceptual sketch of the Eurostar 3000 propellant tank. The Eurostar 3000 PMD contains the same functional items as the Eurostar 2000+ PMD. A stretched version of the Eurostar 3000 tank, named Eurostar 3000 LX for large capacity with a tank volume of 650 liters, completed development in 2006. A second stretching of the Eurostar 3000 LX tank grew the tank volume to 745 liters [10].

Figure 23. Eurostar 3000 propellant tank [11]

2.6. Alphabus tank

To respond to larger satcom applications, the ALPHABUS propellant tank became a joint development effort between MT Aerospace AG and Airbus DS. The ALPHABUS propellant tank is a carbon fiber overwrapped pressure vessel (COPV), including a titanium liner developed by MT Aerospace AG [41] and a PMD designed by Airbus DS [42]. See Figure 24. The ALPHABUS tank is 1.6 meter in diameter. The ALPHABUS PMD is a derivative of the Eurostar PMD. However, unlike the Eurostar PMD, the ALPHABUS PMD does not contain an inner membrane. The PMD’s refillable reservoir at the bottom of the tank is similar to the Eurostar 3000 PMD, but an enhance PMD design enables horizontal transport at all fill levels [42].

Figure 24. Alphabus propellant tank (1910 liters) [42]

SECTION 3, EVOLUTION OF PMD DESIGN PROCESSES IN THE UNITED STATES

In this section, we examine the PMD design evolution in the United States. It is appropriate to characterize the PMD design evolution in phases, from early research and development phase to the most current refinement and new applications phase.

3.1. The 1960s: Research and Development

The introduction of surface tension PMDs in the United States came out of necessity. Early upper stages such as Centaur and Agena had solid rockets to settle propellant before igniting the main liquid engine. These solid rockets were failing at an unacceptable rate, leaving many satellites stranded in useless orbits. For example, Centaur restart solid rockets failed on December 11, 1964, April 7, 1966, and August 10, 1968. There was no published history of the Agena upper stage, but we suspect it had a similar failure rate. It became necessary to develop a PMD solution to support main liquid engine restart, and the first PMD used on the Agena upper stage to restart the main liquid engine in 1964 became the generally acknowledged first PMD from the United States.

The development of the Agena PMD started at Lockheed in 1962. Because of the newness of the technology, researchers used ground tests and drop tower tests to validate all aspect of PMD function. Engineers used a drop tower at the University of Santa Clara for low g experiments, and developed 1 g test facility for the ground tests. These studies used academia and large corporate resources to ensure success. This fundamental
space-related research continued for nearly two decades. As the research moved forward in the 1960s and early 1970s, the Agena PMD performance improved as PMD designers gained knowledge. Figure 25 has several renditions of the Agena PMDs. Over 375 Agena missions used surface tension PMDs to supply gas free liquid for engine restart.

As an aside, one humorous story came out of the Agena testing. To study the reorientation of the propellant at ignition and the refilling of the Agena start basket, researchers conducted a full-scale test campaign under one g conditions using a 1.5 m diameter by 3 m long (5 feet diameter by 10 feet long) full-scale simulator tank. The simulation had the liquid in the tank suspended at the top of the tank. Researchers accomplished this with a screen stretched horizontally across the tank near the top of the cylindrical section, and relied on surface tension forces to hold the liquid above the screen. A rap on the tank would destabilize the liquid, thus allowing the liquid to penetrate the screen and falling to the bottom of the tank to refill the PMD. The side of the simulator tank had an access port to enable access to the PMD before and after testing. In one test, a problem developed and a PMD designer entered the tank through the access port to address the problem. While the PMD designer was in the simulator, the suspended water released and drenched the PMD designer. It was unclear whether his colleagues had anything to do with the liquid reorientation, but the story became one of the endearing tales of early PMD development.

The research and testing conducted in the 1960s provided confidence that surface tension would be useful for propellant management in space. Besides Lockheed, researchers in other companies within the space industry were actively pursuing research into PMDs. A symposium on propellant management held in Los Angeles in 1968 had many industry participants showing interest in using surface tension as a means to control liquid in space [43]. A panel discussion on PMDs included participants from TRW, Lockheed, Rockwell and NASA Marshall. The researchers who published papers on surface tension PMDs in this period came from technology companies such as Martin, GD, Lockheed, Western Filter, TRW, GE, RCA, McDonald Douglas, NASA Marshall, NASA Glenn, and Bell. Researchers in more than a dozen companies were conducting fundamental research, and many were collaborating with academia. Their research included PMDs such as start baskets, sponges, gallery arms, and vanes.

In 1971, a paper titled “A Survey of Current Developments in Surface Tension Devices for Propellant Acquisition” summarized seven different PMD designs having flight heritage with altogether 391 devices flown [44]. The PMDs included the Agena start basket as well as small devices on the Apollo Service Module, Apollo LEM, and the first vane PMD developed by designers at RCA on an experimental ATS Cesium Ion Propulsion System. Researchers had studied almost all types of PMDs in drop towers around the United States. Figure 26 has many of the PMDs in development prior to 1971.
3.2. 1970s and Early 1980s: First Flights of a Broad Range of PMD Types

Researchers in the United States devoted the 1960s to research and development, and began to realize the fruits of their labor in the 1970s. Virtually all of the PMD types in use today flew onboard spacecraft in the 1970s and early 1980s. These PMDs included galleries by Lockheed and Martin Marietta, vanes by both Lockheed and RCA, start baskets by Lockheed and McDonnell Douglas, and sponges by Lockheed and Martin Marietta. Seminal PMDs developed in the 1970s included the Shuttle RCS gallery arm PMD, the Shuttle OMS start basket, the Peacekeeper start basket, the vane PMDs, the HOE sponge, and the Viking Orbiter sponge. These early PMDs became the basis for most of the current-generation PMDs.

Figure 26 includes a gallery arm PMD developed at Lockheed and supported space flight around this timeframe, and the Shuttle RCS gallery arm PMD that supported Shuttle flights for 30 years starting 1981. The advantage of a gallery arm PMD is that the screen covered gallery arms could support gas free propellant in any orientation [4]. The disadvantages include higher cost, higher risk, and higher mass as compared to other types of PMDs. The development of the Lockheed gallery arm PMD included extensive drop tower testing. What was unusual about the Lockheed gallery PMD was that it had no trap in the PMD design. Present-day gallery arm PMDs always
contain a trap to contain the gas that will be in the arms during launch and prevent it from entering the outlet. Lockheed researchers conducted extensive drop tower testing to prove that after launch, once the vehicle entered zero g, the liquid would rise faster inside the gallery than outside, thus rejecting the gas in the arms into the bulk space. In retrospect, this approach was risky because if the screens were wet from slosh or condensation, the PMD would fail. PMD designers do not take this risk in the present-day. The Modern-day approach is to minimize risk through conservative design, and PMD designers always include a trap in a gallery arm PMD. The Shuttle RCS gallery arm PMD developed at Martin Marietta incorporated a trap to capture the launch gas as well as to perform other functions. Designers at Martin Marietta had used fine screens that would allow limited ground testing of the flight articles. In current practice, using fine screens for the purpose of allowing ground testing is deemed risky from a manufacturing perspective because the finest screens are structurally weak.

extended the concept to their GEO satellites in the 1970s and early 1980s. The principal difference between the Lockheed and RCA PMD designs was that the Lockheed designers used a center post to provide a flow path from the top of the tank directly to the outlet, whereas the RCA designers used vanes along the tank wall to direct the propellant to the outlet. Lockheed’s design had the advantage of being easily scalable while retaining its structural integrity upon scaling. RCA’s design advantage was that all the liquid was on the walls to facilitate heating. Researchers cannot use ground testing to validate vane PMDs [1]. Designers at Lockheed used a drop tower to validate the basic physics of a vane PMD, but used analysis to validate the actual PMD. It is unclear how RCA validated their vane PMDs, but it is the author’s opinion that analysis likely played a major role in the RCA PMD validation.

Figure 27. Early Gallery Arm PMDs

Figure 28 has photos of vane PMDs developed at RCA and Lockheed in the 1970s. Researchers at RCA flew the first vane PMD in the 1960s and Figure 28. Early Vane PMDs

Figure 29 includes the Peacekeeper start basket and the Shuttle OMS start baskets, both developed at McDonnell Douglas [45] [46]. These were the last start baskets developed for a long while as new upper stages with PMD tanks were uncommon. McDonnell Douglas researchers used ground testing to validate the start basket PMDs.
Figure 30 includes the HOE sponge PMD developed at Lockheed and the Viking Orbiter sponge PMD developed at Martin Marietta. The HOE sponge PMD was unusual because it was an accordion sponge. Ford Aerospace designers used an accordion sponge PMD in the mid-1980s, but we have not seen an accordion sponge PMD again since that time. The advantage of the accordion sponge PMD is that it is structurally self-supporting. Unfortunately, it has higher residuals and is not as efficient as other sponges. This inefficiency was the contributing factor for its disappearance from current-generation PMD designs. The Viking Orbiter PMD was probably the most important PMD of the era [47]. It was novel in many respects. First, the PMD was the first stand-alone sponge PMD to support space flight. (Note: the Agena PMD included a sponge in combination with a start basket). Second, the Viking Orbiter PMD was the first to enable access to the gas in the tank by positioning the gas bubble at the top of the tank. This PMD design enabled ullage pressure venting if the tank was to overheat, although there was no in-flight demonstration of this capability that we are aware. Lastly, the Viking Orbiter PMD became the basis for several Martin Marietta and later Lockheed Martin PMDs, including the PMD for the Cassini mission, the PMDs used on some Mars missions, and others [48].

3.3. The 1980s: Consolidation and Opportunity

By the early 1980s, PMDs supporting space flight began to resemble PMDs developed today. This is in part because the most efficient designs were more prolific but also because the industry was consolidating. By the mid-1980s, only two U.S. PMD design groups remained active: the team at Lockheed in Sunnyvale and the team at Martin Marietta in Denver. The approaches of these two teams were different.

In the late 1970s and early 1980s, Lockheed began selling PMD tanks to Ford Aerospace and British Aerospace (BAE). These PMDs were unique, and developed and validated entirely by analysis. These included PMD tanks for the Insat and Arabsat GEO spacecraft for Ford Aerospace, and the Eurostar and Inmarsat GEO spacecraft for BAE [49]-[51]. Figure 31 includes photographs of these PMDs. Lockheed used the analytical techniques developed over the previous 20 years to validate these PMDs. The analysis-only approach, with no validation testing involved,
proved viable. The analysis-only approach was essential for commercial space programs that could not and did not want to spend the time and money on research, development, and testing. Lockheed designers also transitioned to analysis-only PMD validation on all its government programs at around this time. Testing was no longer deemed necessary and was completely abandoned by Lockheed by 1981.

Figure 31: PMDs Tanks Sold By Lockheed to Other Primes in the Late 1970s and Early 1980s

At that time, Martin Marietta PMD designers were working less with commercial programs and had more government projects, including interplanetary spacecraft and some cryogenic research. Martin Marietta designers continued to rely on the Viking Orbiter PMD design, modifying it for various tank shapes and sizes. Martin Marietta researchers also carried on a robust test program by flying experiments such as FARE on shuttle and drop tower testing new ideas such as PMDs in toroidal tanks. In Figure 32, we show the PMDs for these programs. Analytical approach played a major role in PMD design at Martin Marietta, but testing continued. However, unlike Lockheed, Martin Marietta did not sell PMD tanks to other aerospace companies.

Figure 32: Martin Marietta PMD Testing Continues

With Lockheed the only purveyor of PMD tanks [52], managers in other aerospace companies had only two options: buy from Lockheed or develop internal capability. It is important to note that Lockheed had internal PMD design capability, but did not build tanks. Lockheed engineers relied on a small independent company called Pressure Systems Inc. (PSI) to build their PMD designs and to develop the tank shells. After procuring the PMD tanks for two spacecraft from Lockheed, managers at Ford Aerospace quietly developed internal capabilities to design their own PMDs. Ford researchers conducted some drop tower testing to validate their analytical models. Hughes, the most prolific communication satellite builder at the time, was using spinning spacecraft in all its applications. Hughes needed to move up to a bigger spacecraft on a three-axis stabilized platform that required surface tension PMDs. Hughes researchers began a program to use the Space Shuttle to conduct PMD experiments.
Unfortunately, the experiments on the ill-fated Challenger mission left Hughes designers without many options. Designers at other aerospace primes such as TRW were looking for PMD design capability. TRW would buy PSI in 1987 to secure PMD tank design and tank manufacture capabilities.

In 1986, D. E. Jaekle Jr., a former PMD designer and analyst at Lockheed, started a PMD design firm called PMD Technology. PMD Technology teamed with PSI, a small tank manufacturing business in Commerce, California with a strong heritage in tank design and manufacture. The team began selling PMD tanks into the aerospace community that continued to this date, and alleviated the PMD supply problem for the space industry. The PMD design approach was validation by analysis only, the same as the one already proven by Lockheed for over a decade prior to 1986. The first two PMDs completed by the PSI and PMD Technology team included a center-posted vane PMD tank for TRW, and a sponge, trap and vane PMD tank for the HS 601 platform [8] [9]. Figure 33 includes photos of these early PMDs. The HS 601 platform was hugely successful. PSI delivered 263 PMD tanks for the HS601 and HS601 HP platforms. See Table 2. Many of these HS601 PMDs had already completed end-of mission maneuvers and provided life cycle validation of the PMD concept.

3.4 1990s and beyond: Refinement of Design and New Applications

PMD development in the United States in the 1990s and beyond focused on design refinement and applying PMDs in new ways – such as for fluid transfer on orbit, for CoM control, and for green propellants. All PMDs designed and developed by PMD Technology and Lockheed Marin used analysis-only design approach.

In 1994, PMD Technology designed a simplified PMD for the SS/Loral LS1300 GEO spacecraft platform. Figure 34 includes photos of the original and current-generation PMDs. The original PMD consists of a sponge, a trap, and vanes. The PMD is small and located in the bottom of the tank with only the cantilevered, flexible vanes extending into the tank. The PMD replaced a heavier gallery arm PMD designed by SS/Loral [54]. After the introduction of the Proton launch vehicle and then Sea Launch, we modified the original PMD to allow for horizontal handling. Over 200 PMD tanks from the LS1300 PMD family are in flight. See Table 2.
Also designed in 1994 was the Iridium vane PMD – one of the simplest PMDs ever constructed [55]. Figure 35 is a photo of this one-vane PMD. The simple PMD consists of three pieces of sheet metal electron beam welded together to form a center post and single tank wall vane. A simple clip retains the PMD over a small circular perforated sheet in the outlet. PSI delivered over 100 Iridium PMD tanks. See Table 2. A majority of the tanks are in flight.

The SS/Loral LS1300 PMD and the Iridium PMD are examples of design refinements on an ongoing basis. One advantage of analysis-only approach is that it allows for the modification of PMDs in a timely fashion. In addition, analysis allows the designer to explore the impact of tolerances on the PMDs performance. As an example, it is possible to explore the impact of waviness on sponge panels without building and testing a litany of possible panels. Similarly, it is also possible to characterize the effect of vane to tank wall gaps without a lengthy test program.

Analysis has allowed the U. S. PMD designers to design and build dozens of different PMDs and fly thousands of PMD tanks. This simply would not be possible if every design had to be tested.

Besides design refinement, recent PMDs have tackled new issues. Figure 36 is a photo of a PMD designed, built, and flown for fluid and gas transfer in orbit [21]. It flew on the Orbital Express experiment with hydrazine transfer from one PMD tank to another and gas transferred in the opposite direction. The PMD concept is similar to the Viking Orbiter PMD concept validated by drop tower testing in the 1970s [47] but never exercised on orbit. The Orbital Express PMD was the first to deliver gas to the pressurant port on orbit. We used Surface Evolver to show that it is possible to access and transfer gas at fill fractions as high as 96% during PMD design. See Figure 37. On orbit performance demonstrated that this predicted limit was correct and precise.

In Figure 38, we show photos of PMDs for two space telescope missions: SDO [20] and JWST. In addition to delivering gas-free propellant to the outlet, the PMDs are also capable of controlling the propellant center of mass and minimizing disturbance during space telescope observations. The SDO PMD is supporting the mission successfully and maintaining the propellant CoM
within 5 mm (0.2 inches) of its zero g location while slewing for observations. The JWST PMDs have even tighter CoM control requirements. For both missions, CoM control validation was solely by analyses.

Figure 38. PMDs with CoM Control capabilities

Figure 39 is a PMD used on the SkySat green propellant propulsion system [37]. It is a simple PMD consisting of a U shaped vane running along the tank wall. The unique aspect of this PMD is that it is functional with a contact angle as high as 60 degrees. The PMD functional validation was by analysis only.

Figure 39. A PMD on a Green Propellant Propulsion System on SkySat

The Orbital Express, SDO, JWST and green propellant PMDs are examples of unique new applications of PMDs. As we write this paper, new missions are emerging, including lunar lander missions that are driving a number of new PMD designs. During the Apollo era, it took a team of engineers and scientists to design the PMDs in support of the Apollo mission. Today, designing PMDs in support of lunar landing missions have the same lead-time and scope as most other commercial PMD design efforts.

Today, there are few PMD designers in the United States conducting PMD design and analysis. Very little testing is transpiring for conventional propellants, although currently NASA is continuing testing for cryogenic PMD applications. Lockheed Martin is designing and developing PMDs using analysis-only approach for their own spacecraft. The team of PMD Technology and Orbital ATK continues to build and fly more and more PMDs solely validated by analysis since 1986. In Figure 40, we show some of the PMDs developed by the PMD Technology and Orbital ATK team over the past three decades.

SECTION 4, REVIEW OF THE EUROPE AND U.S. MARKETS FROM A HISTORICAL PERSPECTIVE

The European and U.S. space markets had independent paths for PMD tank development. PMD designers from both markets had developed high competency and extensive experience base. While PMD designers from the two markets might use slightly different nomenclatures (for example, a reservoir in Europe or a trap in the United States), the basic design principles and PMD components in use are the same. A comparison of the two PMD markets yielded the following observations:

- PMD designers in both markets relied on experimentation and tests to develop fundamental understanding of fluid behavior in space.
- The first PMD tank from the U.S. was onboard a launch vehicle upper stage in 1964. The first PMD tank from Europe was onboard a commercial satellite in 1987.
- Both PMD tank markets have global reach, including sales outside of the two primary markets.
- Both PMD tank markets have high sales to GEO commercial satellite programs.
- Both PMD markets, when combined, account for >80% of PMD design activities worldwide.
- The U.S. market had less institutional sponsorship.
- The U.S. market had a higher number of PMD tank development programs. See Table 1 for a partial list of PMD development programs in both markets.
- A few commercial satellite platforms account for a majority of PMD tank deliveries in the two markets, see Table 2.
• The U.S. market has a larger number of PMD tanks delivered. See Table 3 for estimated PMD tank deliveries.
• The U.S. PMD designers converted to analysis-only approach in 1980s.

• Analysis-only is the standard approach in Europe since about 2000.
• PMD testing in Europe is now focusing on PMDs for cryogenic liquids and benchmarking for tool development.

Figure 40: Some of the PMDs developed by the team of PMD Technology and ATK Space Systems
Table 1. A partial list of PMD tank development programs in Europe and the United States.

<table>
<thead>
<tr>
<th>Program Type</th>
<th>Europe</th>
<th>U.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institutional Programs developing PMD Tanks</td>
<td>Alphasat, ATV, Orion Service Module</td>
<td>CASSINI, Chandra, Cygnus, Dragon, GLAST (space telescope), LADEE, JWST (space telescope), JUNO, MAVEN (Mars explorer), MER (Mars explorer), MESSENGER (Mercury explorer), MRO (Mars explorer), SDO (Solar observatory), Space Station Interim Control Module</td>
</tr>
<tr>
<td>Government Programs developing PMD tanks</td>
<td>Classified programs</td>
<td>Classified programs, DS1000, GOES, MILSTAR, MiTex, NFIRE, Orbital Express,</td>
</tr>
</tbody>
</table>

Several commercial satellite platforms had accumulated large tank delivery quantities. In Table 2, we make one important observation on the number of tank deliveries for some very popular spacecraft platforms. In Table 3, we estimate the number of PMD tank deliveries from Europe and from the United States.

Table 2. Commercial platforms with large quantity of tanks delivered

<table>
<thead>
<tr>
<th>Satellite Platform/Constellation</th>
<th>Quantity Delivered</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2100 platform tank families</td>
<td>215+</td>
<td>The production program is continuing. 73 Fuel plus 142 oxidizer tanks delivered.</td>
</tr>
<tr>
<td>Iridium constellation tanks</td>
<td>103</td>
<td>The first generation Iridium tanks are obsolete.</td>
</tr>
<tr>
<td>FS/LS 1300 platform tank families</td>
<td>225+</td>
<td>The production program is continuing.</td>
</tr>
<tr>
<td>HS 601/HS601 HP platform tank families</td>
<td>263</td>
<td>The 601 platform tanks are obsolete, replaced by 702 tank families.</td>
</tr>
<tr>
<td>Spacebus platform tanks OST-2</td>
<td>140+</td>
<td>The production program is continuing.</td>
</tr>
<tr>
<td>OST-1 platform tanks</td>
<td>64</td>
<td>The OST-1 tanks are obsolete.</td>
</tr>
<tr>
<td>Eurostar platform tanks</td>
<td>300+</td>
<td>The production program is continuing.</td>
</tr>
</tbody>
</table>

Table 3. An estimate of PMD tank deliveries from the two primary PMD markets

<table>
<thead>
<tr>
<th>PMD tanks delivered to institutional, governmental, and commercial Programs</th>
<th>Europe</th>
<th>U.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>~800</td>
<td>~2200</td>
<td></td>
</tr>
</tbody>
</table>

SECTION 5, CONCLUSION

The PMD design process in Europe and the United States had reached technical maturity. A large number of governmental, institutional, and commercial programs had relied on PMD tanks to ensure mission success. Hundreds of end-of-mission spacecraft maneuvers had validated PMD’s feasibility, durability, utility, and functionality. The science behind surface tension PMD technology is no longer in doubt.

The PMD design process is an integral part of the PMD tank design and manufacture. PMD tank development requires expertise in fluid dynamics and structural analyses, as well as proficiency in tank manufacture in areas such as thin-wall shell machining, welding, heat treatment, non-destructive examination, and testing. Gaining
expertise in PMD design and manufacture requires years of schooling and many more years of on-the-job training. A combination of institutional, commercial, and government programs fostered the maturity of PMD tank development processes in both Europe and the United States. The PMD tank community will need similar level of support from the customer base to continue its contribution to the space industry.

The outlook for future PMD design activities is intriguing. We are noticing two current trends. The first trend is the maturing of xenon propulsion systems. Some new propulsion systems in development are focusing on either all-electric propulsion or hybrid versions with both electric and chemical propulsions. This developing trend has the potential to reduce the market share of PMD tanks. The second trend is a recent wave of GEO commercial PMD tank development programs focusing on qualifying larger diameter or longer tanks to carry more fuel. The two trends seem to be in conflict with each other, and only time will tell how the future of propulsion market might evolve in the long term.

Nevertheless, new missions requiring PMD tanks continue to emerge. For example, PMD tanks’ low mass and high performance characteristics are ideal for lunar lander missions. There will be one-off scientific or exploration missions that require PMD tanks. In addition, future missions using green propellant propulsion systems or cryogenic propulsion systems will need PMD tanks. We believe that the matured PMD technology will continue to play an important role in spacecraft propulsion, and propulsion markets around the world will continue to benefit from the accumulated knowledge and expertise in PMD design and manufacture.

In this paper, we presented the perspectives from PMD designers in Europe and the United States. For future work, we invite PMD designers from other space faring organizations to share their histories and experiences. Their valuable insights and perspectives could provide additional benefits to members of the space community.

REFERENCES


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