Bringing a PMD Propellant Tank Assembly to the Marketplace: A Model of US-Europe-Industry-Academia Collaboration

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Abstract

LMP-103S is a new-generation green propellant originating from Sweden. After a successful technology demonstration flight onboard the PRISMA spacecraft, the new propellant was poised for introduction into the marketplace in 2010. However, as is typical for most new technologies, the process of commercial introduction entailed many challenges. First, the space industry infrastructure was not in complete alignment with LMP-103S utilization. Second, the new propellant had to compete with decades-old entrenched technology. Third, the marketers must overcome industry stakeholders' psychological dependency on the heritage approaches. Additionally, hardware designers must obtain new design data to facilitate hardware design. Specifically, in the area of propellant storage and supply, critical LMP-103S propellant properties were unavailable to support the design and analysis of a propellant management device (PMD). An intensive three-year collaborative effort ensued to bring a PMD propellant tank assembly into the marketplace. The collaborative effort involved organizations from the United States and Europe. Key participants included members from government, industry, and academia. Multiple professional disciplines participated in the collaboration, including researchers and engineers in both academia and industry. Other professionals supporting this endeavor included transport, storage, legal, and safety experts. ATK delivered three PMD propellant tank assemblies to ECAPS in 2013. The successful delivery of these PMD propellant tanks demonstrated the economic viability of the new LMP-103S propellant by retaining existing propulsion system architectures, component manufacture methodologies, and skillsets used on conventional hydrazine blow-down systems. The industry response reflected a high degree of capability, adaptability, and robustness throughout the space community supply chain.

Introduction

LMP-103S is a new-generation storable green monopropellant originated from Sweden [1]. After a successful flight demonstration onboard the PRISMA spacecraft, the new green propellant was poised for commercial introduction in 2010 [2]. The process of commercialization had many challenges. First, the space industry infrastructure was not in alignment with LMP-103S utilization. Organizations throughout the process chain, including component providers, spacecraft integrators, launch vehicle providers, and launch support organizations were initially unfamiliar with the properties of the new propellant. Significantly, processes and procedures for LMP-103S application were not widely spread outside ECAPS, and dedicated efforts were necessary to institute new disciplines for LMP-103S utilization. Second, any new propellant had to compete with decades-old entrenched technology. Foremost among the many challenges of confronting the incumbent technology was overcoming the high cost barrier to entry. Third, the marketers had to overcome the industry stakeholders' psychological

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dependency on heritage approaches. The most effective way of achieving this goal was through the application of sound scientific practices supported by empirical test results. Additionally, some hardware design data were unavailable, such as propellant properties to facilitate hardware design analysis. The acquisition of new design data required extensive research and development. The qualification of a PMD propellant tank assembly for LMP-103S application was especially representative of these stated challenges. In this paper, the authors describe the many challenging tasks confronting organizational managers, system and component engineers, university researchers, and experts in the regulatory community throughout the process of bringing a propellant tank assembly for the in-space storage and supply of LMP-103S to the marketplace. The effort represented a multi-year collaboration between industry and academia within the U.S. and Europe.

Background - PMD Propellant Tank for Space Missions

Micro-gravity environments present unique challenges to the designers of propellant management devices (PMDs) for spacecraft and rockets [3] [4]. In space, viscous and capillary forces can dominate the body forces (gravity/acceleration) such that propellant tank and PMD designs must take into account these effects within a micro-gravity environment. Additionally, propellant slosh and wicking effects can contribute to significant trajectory changes, vehicle dynamics behavioral changes, cyclic wear, draining problems and tank overpressure events [5]-[7]. In order to mitigate risks to a mission, the PMD design must facilitate appropriate control of the fluid behavior. The design of such PMDs relies on precise knowledge of the fluid's properties, such as the fluid's surface tension and contact angle with propellant tank internal surfaces. Surface tension in micro-gravity conditions and the contact angle of propellant on PMD or tank surfaces can strongly influence liquid-vapor interface's shape and, therefore, fluid distribution within the tank [8]. Hence, empirical data on surface tension forces and contact angle behaviors are critical to any PMD design endeavor.

Propellant tank PMDs come in many varieties such as wicking geometries and surfaces, baffles, and slosh suppressing inner tank structures. Figure 1 is an example of a PMD with many such features. Typically, a PMD must be custom-designed for a specific mission and the propellant(s) of choice in the spacecraft propulsion system. For example, the PMD shown in Figure 1 was custom-designed for a geosynchronous commercial satellite carrying either monomethylhydrazine (MMH) fuel or nitrogen tetroxide (NTO) oxidizer.

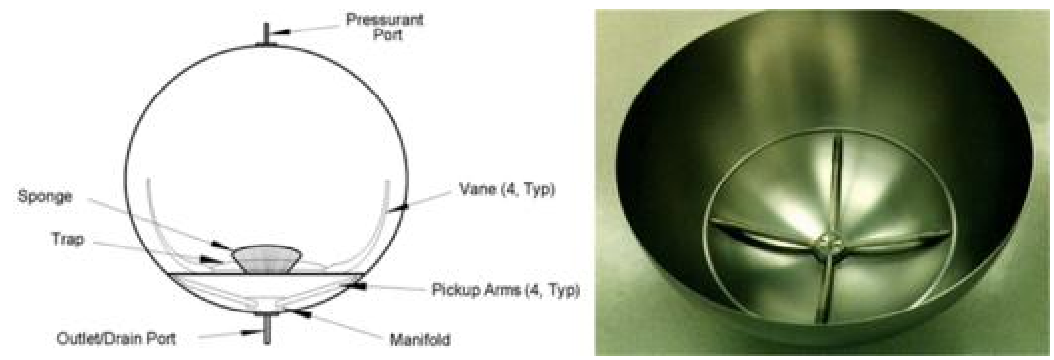

Figure 1: Satellite propellant tank with propellant management devices [9] [10]

The Figure 1 spherical tank has a PMD mounted on the outlet hemisphere above the outlet port. The baffle is welded directly to the tank wall to form a trap, and there are PMD elements both above and below the baffle [9] [10]. The various PMD elements work together to provide gas-free propellant delivery during spinning maneuvers, limited duration on orbit maneuvers, repetitive maneuvers such as station keeping, and once-in-a-lifetime maneuvers such as long duration station change and low fill fraction de-spin. Empirical propellant properties data on MMH and NTO supported the design of each PMD element. However, at the time of its commercial introduction, empirical data on LMP-103S propellant properties were still unavailable.

LMP-103S Propellant Development and Technology Demonstration

Hydrazine had been a space propulsion workhorse for many decades. The primary drawback of hydrazine is its high toxicity. Driven by a combination of safety and environmental concerns, several space organizations invested significant resources to develop green substitutes for hydrazine [1] [21]. Furthermore, there are also initiatives to develop new high performance green propellants with improved performance and reduced mission costs as compared with traditional propellants [11]-[20].

In 1995 and on behalf of the Swedish National Space Board, the Swedish Space Corporation (SSC) began a study of suitable propulsion systems for orbital maneuvering of small scientific spacecraft. Since these spacecraft would fly as secondary payloads from launch sites around the world, they could not impose any risks to the primary payload. Furthermore, to enable delivery of the propellant to every foreseeable launch site in the world on relatively short notice the new propellant must meet the requirements of low or no toxicity, non-carcinogenic, and specific impulse performance equal to, or above, monopropellant hydrazine. SSC thus formulated the new propellant to meet the many demands of the marketplace rather than focusing on maximizing performance only.

LMP-103S is a blend of Ammonium DiNitrimide (ADN), water, methanol and ammonia. SSC conducted the first performance calculations of monopropellants based on ADN in May 1997. The actual formulation of LMP-103 began in May 2001, and SSC fixed the formulation after three years of testing before presenting it as the final candidate for further qualification (i.e. LMP-103S). The combination of LMP-103S propellant and the thrusters developed by ECAPS constitutes the foundation of ECAPS' High Performance Green Propulsion (HPGP®) technology.

Since 2003, the LMP-103S propellant has undergone extensive ground testing with respect to performance, sensitivity, thermal characterization, compatibility, radiation sensitivity and storability as part of the qualification for transport classification and long-term storability. Test results on LMP-103S indicated that compared with monopropellant hydrazine, the specific impulse is 6% higher and propellant density is 24% higher, resulting in a 30% increase in density-specific impulse.

LMP-103S is long-term compatible with most materials used in conventional propulsion systems (e.g. titanium and stainless steels) and commercial off-the-shelf (COTS) fluid components such as valves, filters, pressure transducers, etc., thus enabling the utilization of hardware with extensive flight heritage. The new propellant is long-term storable and, unlike hydrazine, not sensitive to contact with air and humidity. LMP-103S has been successfully demonstrated as having a shelf life of 2.5 years within its standard shipping container, and has also been stored for almost 9 years (test is ongoing) in a flight-representative propulsion system during an end-to-end ground test without any indications of propellant degradation or pressure build up. LMP-103S is transport classified according to UN Class 1.4S, enabling its air transport in passenger and cargo carriers. All of the constituents of LMP-103S are registered in the REACH system. Self-Contained Atmospheric Protective Ensemble (SCAPE) suits are not required while handling LMP-103S [22].

ECAPS has built and tested more than 60 HPGP thrusters with thrust levels ranging from 0.5 N to 220 N. Demonstrations of the HPGP technology includes the in-space demonstration of a 1 N HPGP propulsion system on the PRISMA mission, which was launched in 2010 and is still operational [23]. Hot-firing demonstrations for NASA and various commercial aerospace firms have been successfully performed with a 5 N HPGP thruster by ATK in Elkton, MD on numerous occasions in 2012 using LMP-103S blended in the U.S., shown in Figure 2.

Figure 2: 5 N HPGP Thruster (Courtesy ATK)

ECAPS' 1 N HPGP thruster has been validated during the PRISMA mission. Scaled-up versions for 5 N and 22 N are under development in order to form a suite applicable for satellite propulsion systems for attitude, trajectory and orbit control of small to medium size spacecraft. Designed for operation in steady-state and pulse mode, these HPGP thrusters are aiming to replace hydrazine thrusters in conventional monopropellant propulsion systems by offering significant density impulse improvement. A 200 N HPGP thruster has successfully demonstrated the feasibility of scaling the HPGP technology to higher thrust levels and the application of this technology for reaction control systems on launch vehicle upper stages [24]. Furthermore, within the Ariane 5 ME technology program, an ECAPS designed and built 200 N demonstration thruster was successfully hot-fire tested at ECAPS facilities in Sweden and by Airbus (formerly Astrium) in Lampoldshausen, Germany.

LMP-103S Commercialization – The Business Case

Hydrazine fuel has been the predominant monopropellant supporting spaceflight for much of the space age. It is a highly dependable fuel with well-established performance characteristics. Over the past five decades, space organizations around the world have created an elaborate infrastructure to ensure safe storage, transportation, handling, transfer, and utilization of hydrazine for space flight activities. In addition, there is a large collection of space hardware supporting hydrazine propulsion systems. Under this industry environment, it had been difficult for any new propellants to gain a foothold in the marketplace.

As is typical for most new technologies, the commercialization of LMP-103S faced significant challenges on multiple fronts. In addition to validating its technical performance, there was the added necessity of ensuring its economic validity. To overcome the cost barrier to market entry, the LMP-103S propulsion system development adopted existing industry infrastructure as much as practical to minimize cost and establish competitiveness in the marketplace. Similarly, engineers and business managers kept hardware development to a minimum to control cost. One highly favorable characteristic was the compatibility of LMP-103S with both titanium and CRES 304/316. There exists in the marketplace a large pool of flight-qualified space hardware made from these materials, and LMP-103S' compatibility ensures an ample supply of flight-qualified components with minimal development cost. Nevertheless, when ECAPS first approached ATK in 2010 to discuss propellant tank options for LMP-103S storage, both organizations encountered non-trivial regulatory, technical, schedule, and cost challenges.

Propellant Tank Development

One of the key success factors in business is the ability to position the right product in the right place at the right time. Successful timing in product introduction must not depend on chance. It requires visionary foresight, considerable planning, diligence, and perseverance to bring a new product to the market upon demand. The development of the propellant tank assembly for the first commercial LMP-103S propulsion system exemplified these attributes.

Propellant tank selection for a space mission is subject to multiple constraints. Typical constraints include pressure rating, tank volume, propellant volume, available envelope, type of tank mount, propellant and pressurant interfaces, mission environment, program schedule, and cost, [25]. Early tank trade studies performed by ECAPS and ATK revealed that tanks containing PMDs or elastomeric diaphragms were both good candidates for LMP-103S' inaugural commercial satellite mission. Recognizing that fundamental scientific research was necessary to bring either tank type to the market, ECAPS and ATK embarked upon a focused research and development project to collect scientific data far in advance of any contractual go-ahead. Ultimately, ECAPS selected a PMD propellant tank assembly for its satellite mission. In this paper, the authors shall focus on the R&D efforts in support of design and analysis activities on a PMD propellant tank assembly.

Propellant Properties Acquisition

The design and analysis of a propellant tank assembly containing a surface tension PMD requires propellant properties data such as contact angle, surface tension, and bubble point. In 2010, propellant properties data were not yet available for LMP-103S. Researchers at the Florida Institute of Technology (Florida Tech) ***A***erospace ***S***ystems ***A***nd ***P***ropulsion (***ASAP***) Laboratory started developing experimental tools to measure relevant propellant properties associated with LMP-103S in July 2010. Consistent with most research projects, the Florida Tech researchers initially conducted an extensive literature review to identify the state-of-the-art measurement techniques used to acquire contact angle, surface tension and bubble point. A literature search revealed a large body of prior research, [26–37] on both fluid properties and measuring techniques, although these techniques were typically applied to water as the fluid. Additionally, only limited information was available on contact angle of water on both non-passivated and passivated titanium. A 2-year effort ensued, in which the Florida Tech researchers repeatedly practiced measuring techniques and replicated published fluid properties of water and isopropyl alcohol on various material surfaces. The researchers then extended these measurements to water and isopropyl alcohol on titanium samples representative of the actual tank material and internal surface treatment. The repeated practices led to further advancements in measuring techniques and additional insights in fundamental physical properties of LMP-103S.

In 2011, Florida Tech researchers developed a preliminary set of fluid properties data from an initial shipment of LMP-103S. During data collection, the researchers encountered propellant evaporation at ambient conditions because of the small sample volume. For this reason, it became necessary to construct an environmentally controlled test chamber to ensure the accuracy, reliability, and repeatability of data. Throughout 2012, Florida Tech researchers devoted considerable efforts to design and implement the propellant property measurement platform. The platform is a remotely operated apparatus that can contain a positive pressure inert atmosphere for determining surface tension and contact angle of a given fluid on a given material. The platform can rotate ± 180° from vertical, and can maintain any incremental angle. This capability allows the acquisition of images on advancing and receding contact angles. The platform also has the capability to contain both lighter and heavier than air atmospheres without the need to pull a hard vacuum or switch components. The platform has an operational range of 82 bar at -29 to 38 °C to 69 bar at 100 °C. The platform was designed for use with hazardous fluids including non-cryogenic liquid-phase gases, monopropellants, refined petroleum products and alcohols. A top-view and a side-view of the propellant property measurement platform are shown in Figure 3.

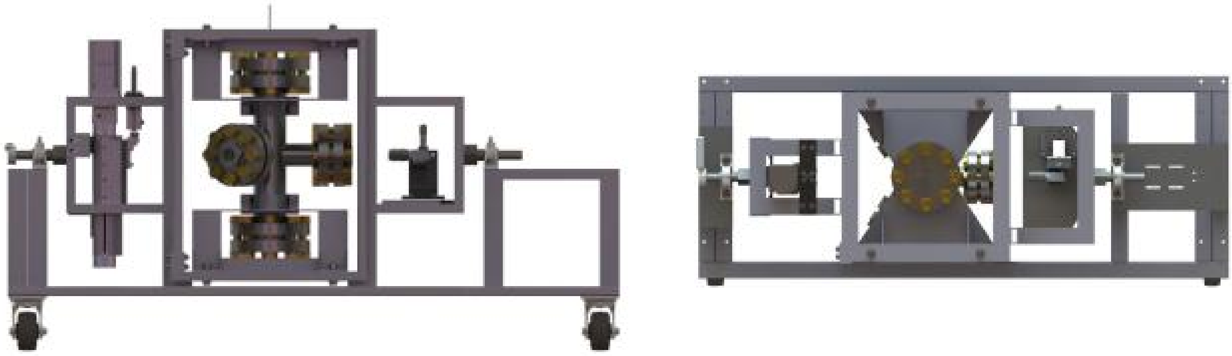

Figure 3: Side-view (left) and top-view (right) of the propellant property measurement platform

The platform is controlled using a LabVIEW capable PC. This virtual instrument (VI) continuously acquires images from 2 cameras, 6 thermocouples, and 2 pressure transducers. The control panel is shown in Figure 4.

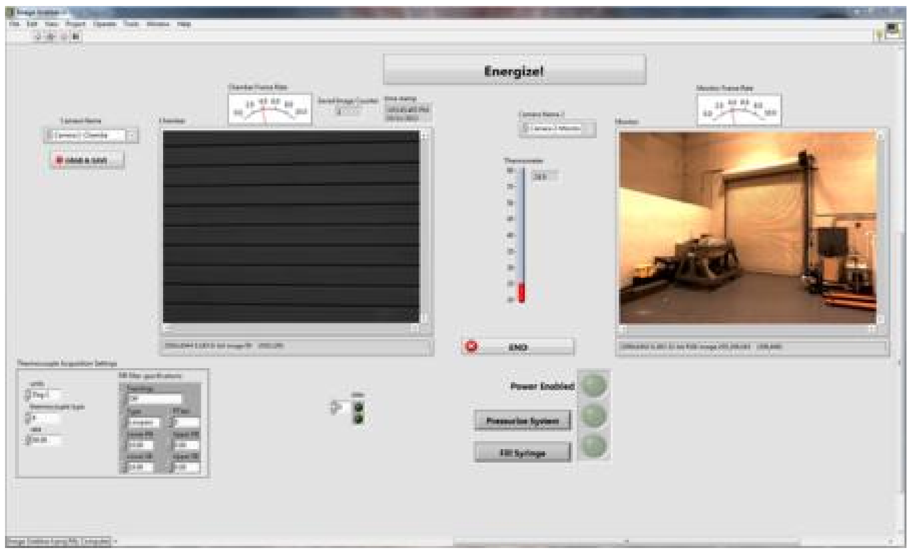

Figure 4: LabVIEW VI front panel control interface

The user determines when to save a captured droplet image, and the droplet is stamped with the date and time, as well as the environmental conditions within the chamber at the time of image capture.

Examples of the types of measurements made using the platform are shown in Figure 5. The schematics and images in Figure 5 show examples of contact angles of various fluids, including LMP-103S, on various surfaces. The images show examples of low wettability (high contact angle) and high wettability (low contact angle), which depends on the combination of fluid and surface.

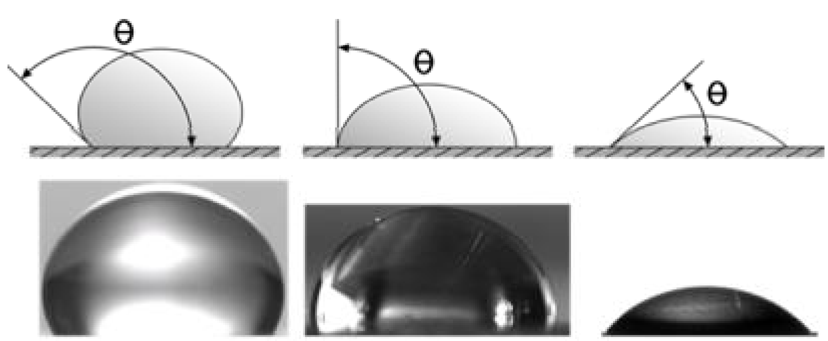

Figure 5: Contact angles of various fluids, including LMP-103S, on various surfaces

In December 2012, ATK received a contract from ECAPS for the design and fabrication of a PMD propellant tank assembly for LMP-103S storage and delivery. At the time of contract go-ahead, the propellant properties acquisition effort had been on-going for nearly 29 months, and a full set of data was still unavailable. The early phase of PMD functional analysis utilized preliminary propellant properties supplied by Florida Tech researchers. The full set of design data became available in February 2013. The propellant properties data arrived just in time to support the propellant tank preliminary design review. In retrospect, the timely support from the researchers at Florida Tech was instrumental in the successful PMD propellant tank development. It is important to note that this hardware development success was not coincidental. Team members at ECAPS, Florida Tech, PMD Technology, and ATK all realized the significance of conducting research and development ahead of actual hardware need date. Had Florida Tech not started the data acquisition effort prior to contract go-ahead, it would have been impossible for both ATK and ECAPS to support the mission schedule.

Propellant Tank Design, Analysis, and Construction

The propellant tank assembly for LMP-103S storage and delivery is a derivative of a flight-qualified tank, ATK P/N 80421-1. P/N 80421-1 was previously designed and qualified for hydrazine storage and delivery. Both the tank shell and the PMD are of all-titanium construction. Physical modifications from P/N 80421 included shortening the tank shell, shortening the PMD, and modifying the tank interfaces, as shown in Figure 6.

ATK P/N 80421-1 **New PMD tank, ATK P/N 80568, for LMP-103S storage**

Figure 6: The new PMD propellant tank is an adaptation of an existing tank design

In support of a common goal to minimize development cost, ATK, ECAPS, and the satellite end user agreed upon a qualification-by-analysis approach for the LMP-103S propellant tank. The tank qualification regime included structural analysis and PMD functional analysis. ATK stress analysts conducted structural analysis using traditional analytical techniques while taking into consideration the LMP-103S physical properties. One important consideration during structural analysis was the higher density of LMP-103S. Fortunately, the heritage P/N 80421-1 is a 29 inch long tank while the derivative LMP-103S tank is much shorter at 13 inch overall length. The effect of 55% length reduction had offset the impact of 24% increase in fluid density, and ensured the qualified tank loads would envelope the worst-case load conditions on the new tank. The tank structural analysis yielded typical analytical outputs as shown in Figure 7.

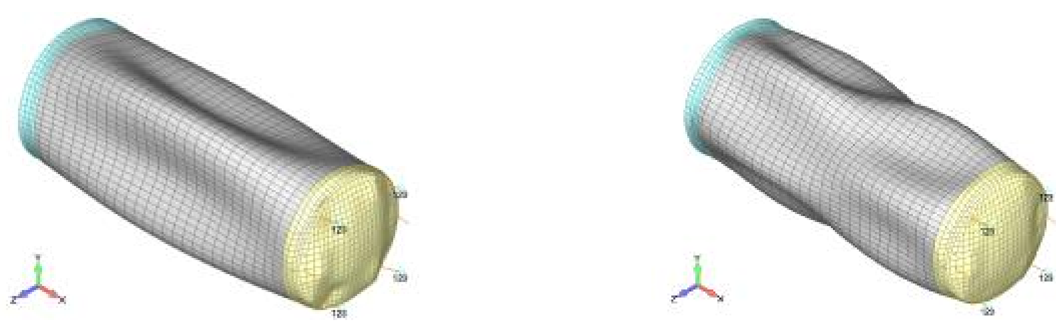

Figure 7: Outputs of PMD tank structural analysis

PMD Technology conducted a conventional PMD functional analysis utilizing the newly acquired LMP-103S material properties data. LMP-103S has different fluid properties as compared to hydrazine. The task of adapting a PMD that was custom-designed for hydrazine for the management of LMP-103S in space was challenging. However, it was fortuitous that the heritage PMD design had built-in features that provided suitable margins of safety for the new propellant. The engineers and designers also traded a taller PMD for fluid management, but the design change became unnecessary after additional analysis. After a comprehensive analytical effort, the only design change incorporated was the shortening of the PMD.

The PMD functional analysis yielded typical analytical outputs as shown in Figure 8 – Figure 10 for 30% propellant fill fraction (left-side images) and 13.6% propellant fill fraction (right-side images). Figure 8 shows the initial conditions, Figure 9 shows the transient propellant motion and Figure 10 shows the steady-state thruster firing condition.

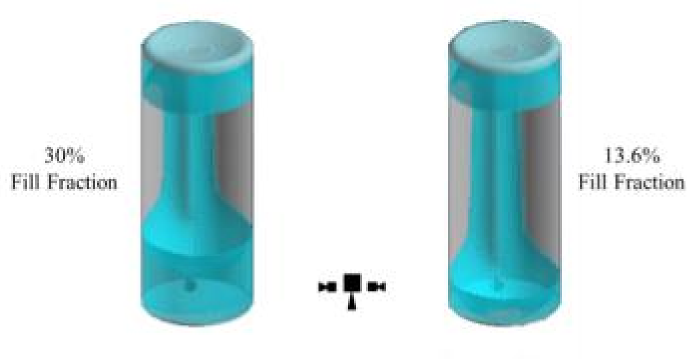

Figure 8: Outputs of PMD functional analysis for 30% and 13.6% fill fractions: initial conditions

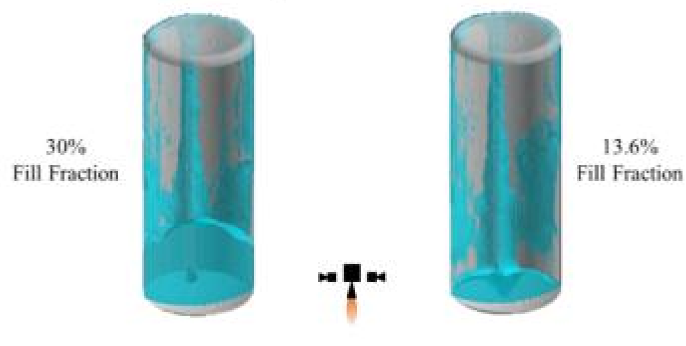

Figure 9: Outputs of PMD functional analysis for 30% and 13.6% fill fractions: transient motion

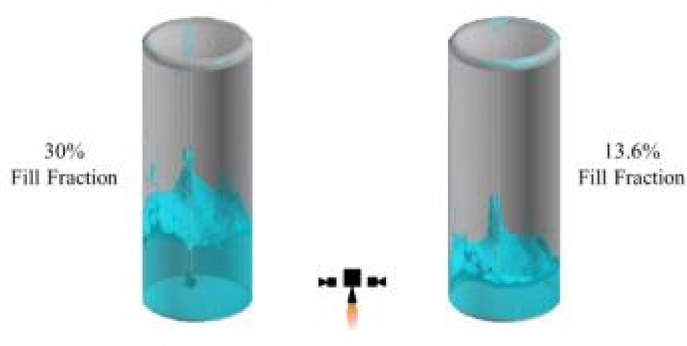

Figure 10: Outputs of PMD functional analysis for 30% and 13.6% fill fractions: steady-state thruster firing

All tank analyses resulted in positive analytical margins of safety which were sufficient to support qualification-by-analysis. The customer did not require additional protoflight testing to support qualification.

Besides the typical programmatic issues associated with development programs, the engineers and business managers did not encounter significant obstacles throughout all phases of tank design and manufacture. ATK executed the development contract and delivered the first set of flight tanks in 2013. The successful tank development led to a follow-on production contract in 2014 with a larger order quantity.

Regulatory Challenges: Shipping, Handling, and Storage of LMP-103S

Participation in LMP-103S introduction included coping with uncommon problems. One example was resolving the regulatory challenges associated with shipping, handling, and storage of the new propellant. An extended network of specialized professionals participated in the management of the regulatory framework.

In 2010, ECAPS and ATK entered into a business arrangement in which ATK, through its Propulsion and Controls Division, became the U.S. distributor of LMP-103S. ATK also performed mixing of LMP-103S under this agreement. In addition, ATK holds the license to sell the thrusters for LMP-103S in the U.S. It became necessary for ATK to secure the necessary licenses for the shipping, handling, and storage of LMP-103s in the U.S.

LMP-103S propellant has many positive characteristics, including low toxicity, insensitivity to shock, and high stability in air and humidity. These positive attributes enabled ECAPS to secure a transport classification of UN and DOT 1.4S for LMP-103S and allowed its transport on commercial passenger aircraft [26]. To expedite interstate shipping of LMP-103S, ATK consulted the United States Department of Justice, Bureau of Alcohol, Tobacco, Firearms and Explosives (BATF). BATF considers LMP-103S a monopropellant and not an explosive. Under this guideline, Federal Explosive Law would not apply to LMP-103S. This classification meant ATK did not need to apply for an explosive license from the State of Florida, and allowed ATK to ship the LMP-103S under Department of Transportation (DOT) license. Securing the licenses to transport LMP-103S was crucial for supporting the research and development effort at Florida Tech. The delivery of two separate shipments of LMP-103S at 25 mg each was sufficient to complete the research and development at Florida Tech.

At Florida Tech, safety officials participated in safety reviews and issued guidelines for the safe handling and storage of LMP-103S within Florida Tech premises. For storage, Florida Tech safety officials required double locks in storage structure to secure the propellant. Florida Tech safety officers also required development of a Standard Operating Procedure and corresponding contingency plan for storage and handling. Additionally, Florida Tech safety office also demanded personnel training for the safe storage, handling, and transport of LMP-103S.

Conclusion

In this summary paper, the authors used propellant tank development as an example to highlight the many dimensions of a technical innovation and its journey toward commercial introduction. The introduction of LMP-103S green propellant marks an important milestone for in-space propulsion. It challenges the current status quo, advances the state-of-the-art, and presents a viable alternative to long-standing practices. This important evolution could not have taken place without vision, planning, dedication, and perseverance by many supportive individuals. The successful introduction of the LMP-103S was the culmination of two decades of collaborative efforts among scientists, engineers, business leaders, academic researchers, government officials, and numerous area experts. The development, qualification, and timely introduction of a propellant tank assembly for LMP-103S' inaugural commercial mission was a reflection of this critical collaborative effort.

Acknowledgments

Individuals from many organizations in the U.S. and Europe participated in the tank development program and made significant contributions toward its successful completion. The authors wish to acknowledge their significant contribution and thank them for their continued support.

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