

REVIEW AND HISTORY OF ATK SPACE SYSTEMS COMMERCE - THE PAST 15 YEARS

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ABSTRACT

ATK Space Systems – Commerce (ATK Commerce), formerly known as Pressure Systems, Inc. (PSI), has been supplying pressure vessels to the aerospace industry for over 45 years. Its first 3 decades of existence can be characterized by the maturing of its tank technologies and the securing of its market niche. The primary focus at that period of time was on maintaining its foothold in the aerospace industry, and less emphasis was given to developing breakthrough technologies. However, beginning in the early 1990's and under new leadership, ATK Commerce has introduced a string of new technologies in the design and fabrication of its pressure vessels. Many innovations were industry firsts. They demonstrated dynamic use of materials to achieve the various design goals of low mass, low cost, excellent packaging efficiency, and exceptional performance. This paper summarizes some of these innovations, which include:

- Hybrid tank shells;
- Bonded brackets or skirts for mounting large propellant tanks;
- Titanium lined, composite overwrapped pressurant tanks;
- Propellant Management Devices (PMDs) adapted for launch vehicle horizontal handling;
- PMD for on-orbit fluid transfer;
- PMD for Center-of-Mass control;
- “Uni-body” Integrated tank and structure.

INTRODUCTION

ATK Commerce has been a leading tank supplier in the space industry for 45 years. The space industry is by nature hugely conservative, and ATK Commerce is no exception. Our first three decades can be best described as developing and maturing our design and analytical techniques and building a large inventory of qualified tanks to ensure competitiveness and survivability. Because the customer needs were satisfied by the available technology, breakthrough innovations were seldom pursued. Additionally, because pressure vessels are high risk items with no redundancy, customers were frequently risk adverse and most would defer technology developments in favor of traditional solutions.

However, starting in the early 1990's, continuously upgraded launch vehicle capacities and new and more demanding mission requirements led to a surge in new tank innovations not seen in the previous three decades. This was in part driven by the demands of a changing market place and sponsors in search of new technologies for a new generation of challenging space applications, and in part due to new company leadership that was willing and able to take on these challenges. Consequently, the past 15 years at ATK Commerce can be defined by transforming technologies. This paper summarizes some of the innovative products that were developed during this dynamic period.

Hybrid Tank Shells

By the early 1990's, composites were already in extensive use on launch vehicles such as rocket motor cases, and on spacecrafts such as solar array substrates, bus structures, panels, and stable structures. Pressurant tanks operating at very high pressure also adopted composites to achieve very significant mass savings. However, propellant tanks that operate at (relatively) low pressure did not find the use of composites beneficial until the early 1990's.

The hybrid - half metal, half composite - tank shell was the product of necessity. Near the mid-1990's, ATK Commerce was contracted to design and qualify a propellant tank for a geosynchronous commercial satellite platform. This propellant tank had a very unique configuration - it was a relatively long tank with a large length-to-diameter (L/D) ratio. At that time none of the traditional design and manufacturing techniques could produce a tank that meets both the (low) mass and stiffness requirements. The solution for this problem was to employ composites ⁽¹⁾. The development of the hybrid tanks has already been documented in AIAA 2003-4607 and need not be repeated here. However, the significance of this innovation cannot be understated. The successful development of the hybrid tanks had proved fortuitous for many tank users. For example, the utilization of inexpensive titanium sheets for the tank shell cylindrical center sections had drastically softened the impact of the steep titanium price increase from 2005 to 2007. The hybrid design is extremely flexible. Once a long cylinder has been qualified, all tank shells with equal or shorter cylinder sections can be qualified by similarity, with minimal non-recurring expenses. This feature allows the establishment of a family of tanks all with the same domes but varied cylinder lengths to support the modular construction of the various commercial satellite platforms. It took only a few years to develop the hybrid tanks into a mature – and best selling – product line. To date 9 hybrid tanks have been qualified, and 3 more are in various stages of development and qualification. Tank size ranges from 530 mm (21 inch), 580 mm (23 inch), 890 mm (35 inch), 1143 mm (45 inch), to 1270 mm (50 inches) in diameter. Dozens of hybrid tanks have already been delivered, and many are currently in flight.

For the many spacecrafts that must carry propellant tanks with high L/D ratio, the hybrid tanks indeed provide the enabling technology. From a programmatic standpoint, the hybrid propellant tanks offer many significant contributions in meeting design requirements, providing design flexibilities and design simplicity, and reducing the recurring unit price. Several families of hybrid tanks are shown in Figure 1.

Figure 1: Hybrid Propellant Tanks



Bonded Brackets or Skirts For Mounting Large Propellant Tanks

An extremely important by-product of the hybrid tank was the successful development of bonded tank mounts such as brackets or skirts shown in Figure 1. This new technology was a drastic departure from the traditional all-metal construction where mounting features are welded to or integrally machined from the metal shell. For a tank designer whose comfort zone was in metal fabrication, the utilization of bonded mounting brackets was initially counter-intuitive. This was especially true on tanks containing large propellant mass with severe flight environments. To ensure highest workmanship, quality, and reliability, these drastically unconventional design features were extensively tested⁽²⁾. Several ATK Commerce hybrid tank designs indeed took advantage of these available options, including bonded composite skirt ⁽³⁾ (over metal) and bonded metallic brackets⁽¹⁾ (over composite). To date five (5) different types of bonded bracket designs have been qualified, and many tanks with bonded tank mounts have flown. Figure 2 shows a closeup picture of an adhesive bonded bracket.

Figure 2: A Bonded Bracket



An added benefit of the bonded brackets emerged soon after the initial development program. The preliminary trade study on a tank shell requiring off-axis mounting features confirmed that a hybrid shell with bonded brackets would be less expensive to manufacture than an all-metal shell with integrally machined tank mounts. A hybrid construction allowing bonded brackets was subsequently incorporated into the final tank design. This additional option, feasible on design-to-cost programs, provides further validation of the value of this new innovation.

Titanium Lined, Composite Overwrapped Pressurant Vessels

ATK Commerce began manufacturing fully-wrapped pressure vessels in the early 1990's. At that time Composite Overwrapped Pressure Vessels (COPVs) were already widely used in the aerospace industry. However, at the time the customer base was unsatisfied with the quality and mass performance of the available products, and ATK Commerce was contracted to develop several high performance COPVs that would provide improvements in these areas.

The COPVs developed by ATK Commerce were indeed "high end" pressure vessels. Commercially pure titanium was the base metal for the liners⁽⁴⁾. The liner domes are precision machined from titanium forgings, and the liner center section is made from rolled and seam-welded titanium sheet stock. A closure weld with a smooth transition - no weld crown and no mismatch – was developed to assemble the liner assembly. See Figure 3. The liner components and the welded liner assembly are fabricated to extremely tight tolerances. This combination of precision machined components and high quality assembly welds generate the ideal, and highly repeatable, substrates to apply the composite overwrap. Automated filament wrap process is employed to produce COPVs that are consistent with the intended high performance design, with mass efficiency ratio (pressure times volume divided by weight) in the range of 1.5×10^6 inches.

Figure 3: Standard COPV Weld Joint



Several titanium-lined COPVs were developed for xenon storage. Xenon is a heavy gas. Under pressure its density is closer to a propellant than a pressurant. During launch, significant loads are exerted on the xenon tank, especially at the mounting interfaces. We have found that titanium material, with its high strength-to-mass ratio and excellent low- and high-cycle fatigue capabilities, is also an ideal liner material for xenon COPVs⁽⁵⁾.

A titanium-lined COPV certainly has its disadvantages. First and foremost, it is expensive. For example, a typical spun-formed aluminum liner costs only a few hundred dollars to manufacture. In comparison, a precision machined and welded titanium liner costs tens of thousands of dollars to fabricate. Second, it takes many months to process a titanium-lined COPV, as compared to a few weeks to fabricate a spun aluminum liner. For these reasons, titanium-lined COPVs can only serve a niche market where they generate significant savings on launch cost. On programs where mass efficiency is not as critical, such as Low Earth Orbit satellites or launch vehicle applications, titanium-lined COPVs simply do not create value. For example, assuming an average price of €57,600 (\$90,000) per tank, and an average launch cost of €19,200 per kg (\$30,000 per pound) for a geosynchronous communications satellite, a 3 pound mass savings from a titanium-lined COPV would literally pay for the tank itself. Because of its high mass efficiency, this recent innovation will continue to serve a key segment of the space industry where they offer the best overall value to the customers.

PMD for Horizontal Ground Handling

Prior to the mid-1990's, Propellant Management Devices (PMDs) in propellant tanks were designed for upright ground handling only, primarily on launch vehicles such as Delta, Atlas, and Ariane. The upright handling naturally positions the propellant over the tank outlet to prevent gas ingestion, and ground handling is seldom a contributing factor during PMD design.

After the Cold War, Russian-made rockets were converted to commercial launch vehicles such as Proton and Sea Launch. Prior to a Proton launch, the spacecraft is integrated into the launch vehicle and transported horizontally via railway to the launch site. On the Sea Launch, the spacecraft and the launch vehicle are transported horizontally, by boat, on a long sea voyage to a launch site near the equator. The horizontal transportation and handling present a much greater chance of exposing the propellant outlet to gas ingestion, unless the tank is equipped with a horizontal handling PMD or filled to a very high fill fraction. However, unnecessarily filling all the propellant tanks to higher fill fraction may be a simple but certainly not a very cost effective approach to solve this recurring problem. In response to the new market demand, PMDs capable of horizontal transportation and handling⁽⁵⁾ at low propellant fill fraction were custom-designed to fill the need. This new innovation was developed with the dual functionality of preventing gas ingestion at one g as well as enabling orbital operations at zero g, without significant impact to schedule and cost. To date ATK Commerce has designed and manufactured eleven (11) PMDs capable of horizontal transportation and handling. A picture of such a PMD is shown in Figure 4.

Figure 4: PMD for Horizontal Handling



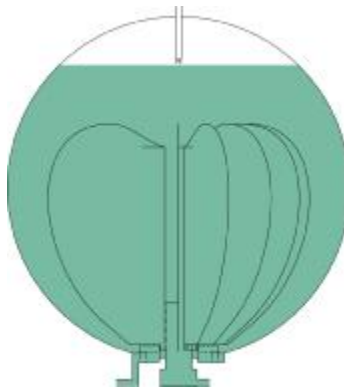
Many of the current generation of commercial geosynchronous communication satellite platforms are equipped with these custom-designed PMDs. Although the non-recurring cost of developing such a PMD is relatively high, the real savings on each recurring launch would more than pay for the development cost. Far more important, these horizontal handling capable PMDs allow the customers the flexibility to select the best launch vehicle for its spacecraft, thereby providing value over and above its on-orbit performance capabilities.

PMD for On Orbit Fluid Transfer

For decades, spacecrafts are launched with only sufficient fuel for the intended missions. The duration of each mission is limited by the amount of available fuel on board. The mission must terminate when the fuel is depleted, regardless of the health of the payload. It is entirely possible that upon propellant depletion, the asset onboard the spacecraft may still be perfectly functional but must be discarded. To add insult to injury, many satellites must use the precious remaining fuel to perform the final de-orbit operation. The commercial geosynchronous satellite operators face this reality whenever their multimillion dollar satellites are near propellant depletion. An elaborate set of procedures must be followed to allocate sufficient fuel for the final burns that relocate the satellites to their final orbit. In comparison, it may be a lot less expensive to re-fuel a spacecraft than to replace it with another spacecraft. For satellites with highly valuable assets, the ability to refuel and extend the service life can be a very desirable feature.

The design of a refillable PMD tank presents some interesting challenges. The traditional role of a PMD is to supply gas-free propellant to spacecraft thrusters upon demand. The PMD is typically designed to facilitate the expulsion (outflow) of propellant. To enable tank refuel on orbit, the PMD must be designed to permit propellant flow in the reverse direction as well. This dual functionality adds a new level of complexity to the already difficult design effort. To further complicate the task, the PMD tank must allow the transfer of pressurant into the propellant tank. Such a PMD tank has recently completed an on-orbit fluid transfer experienment with 100% mission success. See Figure 5. The fluid transfer from one PMD tank to another PMD tank was the first of its kind. Its success is a crucial first step which will pave the way for further research in the area of on-orbit propellant delivery.

Figure 5: PMD for On-Orbit Fluid Transfer



There are many potential benefits of on-orbit refueling. A commercial satellite can carry less fuel and fly more instruments to generate more revenue, thus increasing the value of this space asset and providing its owner higher Return on Investment. Refueling could extend the useful life of a satellite already on orbit, reduce waste, lower replacement cost, and increase operating profit. The same principle applies to both civil and military satellites. Wider use of this capability will one day reduce the amount of space debris. Although on-orbit refueling is not commercially available at this time, efforts are now being made to develop this exciting new technology that will benefit the future generations.

PMDs for Center-of-Mass Control

Two fundamentally different types of propellant management techniques are employed in propellant tanks. In a diaphragm tank, a reversing elastomeric diaphragm actively pushes the propellant out of the tank. In a PMD tank, however, a non-moving metallic PMD uses surface tension forces to direct propellant to the tank outlet. If a diaphragm uses brute force during propellant expulsion, a PMD achieves the same goal using the technical equivalent of gentle persuasion.

Within a diaphragm tank, the elastomeric diaphragm provides a physical barrier between the propellant and the pressurant, and the whereabouts of the propellant is always known. Although the mere mention of a PMD conjures up images of propellant sloshing uncontrollably within the tank, PMDs can in fact be designed to provide varying degrees of center-of-mass control, depending upon the mission requirements.

PMDs are always custom-designed to optimize the many conflicting goals of mass, cost, quality, performance, and producibility. If center-of-mass (CoM) control is not a requirement, PMDs are usually designed to tolerate a certain amount of propellant slosh after acceleration events. On the other hand, if CoM is critical and propellant movement must be minimized, PMDs can also be designed to achieve the same. A good rule of thumb is “the more propellant control, the higher the mass of the PMD, and the higher the cost of the PMD”. It is in fact possible to design a PMD with a better anti-slosh capability than an elastomeric diaphragm. However, it will also be a lot heavier and many times more expensive.

Of the more than 50 PMDs we have designed and manufactured to date, only a handful had a CoM control requirement. In recent years, however, more PMDs with tighter CoM control are in demand. This new class of PMD may not be overly difficult to design, but it does entail a great deal more analysis time as more precise knowledge of propellant location is required. Figure 6 shows a PMD designed to suppress propellant slosh and provide center-of-mass control.

Figure 6, PMD Designed for Propellant Center-of-Mass Control



Unibody Integrated Tank and Structure

The “unibody” construction of tank and structure is our most recent innovation. It was introduced to the space community only within the past two years. The new product line was qualified in 2006, with the following unique features:

- The tanks are completely integrated into the spacecraft structure;
- The tanks do not have the traditional mounting features such as tabs or flanges;
- The tanks include custom-designed bi-propellant propellant management devices;
- The composite structure does not have the tradition mounting features such as holes for tank mount;
- Piping is included as part of the unibody design;
- The entire assembly is analyzed as a single unit;
- The entire assembly is tested as a single unit.

The unibody construction represents a radical departure from the traditional approaches of developing the spacecraft composite structures and propellant tanks. Historically, the tanks and composite structures were designed by separate organizations under distinctively different engineering disciplines. For the first time in history these tasks were merged and performed by the same design team. The development of this highly innovative product requires extensive expertise in both pressure vessel and composite structure design, analysis, and manufacture – the same skills we have gained from the development of several hybrid tanks from the past decade. Not surprisingly, the end product completely realizes the vision of our designers and engineers, and offers many advantages that cannot be ignored, such as minimal mass, optimal packaging, no stacking of analytical safety margins, and the delivery of an integrated product that reduces assembly time after delivery to the customer. However, the unibody construction does have limited applications. It is best applied to cylinders or cones, and box structures or panels are not suitable for this application.

When this new product was first introduced to our customer base, the initial reactions were mixed: some were delighted, but others were dismayed or disinterested. This was certainly expected because the concept of unibody construction is somewhat revolutionary within the conservative environment of the aerospace industry. More importantly, it represented a fundamental shift in the division of responsibilities between the customer and the structure manufacturer. For decades, the design of the spacecraft structure has largely been the responsibility of the spacecraft integrator, and the manufacturing would be conducted either in-house or subcontracted as a build-to-print. The new design approach requires the merging of two very different technical disciplines, as well as the transfer of design authority to the tank manufacturer. Many customers are still trying to become more comfortable with this new concept.

The uni-body construction of tank and structure is one of our most advanced innovations to date. Ironically, the greatest obstacle during the introduction of this product was not in conquering the technical difficulties, but rather in overcoming inertia and the reluctance to change. Our challenge ahead is to educate the customer community and increase the awareness of the significant technical and economical advantages of this new product line.

CONCLUSION

Tremendous technical strides have been made in the space industry since the launch of Sputnik fifty years ago. Every year, scientists and engineers continue to find new and better ways to create and utilize space assets. Space systems now touch every aspect of our lives, from communication, navigation, weather monitor and forecast, to education, entertainment, and national defense. In contrast, technology advancement in pressure vessels has been relatively stagnant until recently. This is in part due to the already very efficient and effective heritage technology, and the relatively large investments that are required to gain small, incremental technology improvements. In addition, it has been difficult to overcome the conservative, risk adverse nature of this industry. However, government sponsored space exploration and the utilization of space for commercial activities are now fueling a new generation of tank innovations. We have developed more than twice as many new products during the past 15 years in comparison to our first three decades, and the high demand for new technology continues.

As usual, innovations were developed in response to market needs. These are a mixture of product improvements and new product lines. They represent the high confidence and maturity level of the designers and engineers who succeeded in making technology advances by working beyond their comfort zones. The innovations have already made significant contributions to many commercial, scientific, and government satellites and launch vehicles in the U.S., Asia, and Europe.

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