The Evolution of a Family of Propellant Tanks Containing Propellant Management Devices

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ABSTRACT

Space systems operators have used propellant tanks with propellant management devices (PMDs) to enable space flight since the 1970s. Thousands of satellite missions had relied on PMD tanks for in orbit operations. ATK developed many of the past and current generation PMD tanks. This extensive heritage includes hundreds of derivative tank designs that evolved from the original qualifying designs to serve new customer needs.

In an ideal world where funding is plenty, schedule is of no concern, hardware space is unlimited, and component mass is unimportant, custom-designing a pressure vessel for space flight is always the best way to optimize pressure vessel performance. In reality, funding limitation, envelope constraint, tight delivery schedule, mass limit, and risk minimization are often major constraints on space programs, and developing derivative tanks can be an effective way to reduce cost, embed heritage, minimize risk, and protect program schedule. The concept of a derivative tank could include derivative tank shells, derivative PMDs, or both. As space programs become more cost constrained, the authors have noted an increasing tendency towards developing derivative tanks in recent years. In this summary paper, we present examples of derivative tank developments, with a special focus on a family of 1150 mm (45.29 in) inside diameter (ID) satellite tanks.

There are four sections to this summary paper. Section 1 is an introduction to the different approaches of pursuing derivative tanks, with specific focus on PMD tank applications. In Section 2, we describe the design and qualification of a new family of 1150 mm ID PMD tanks to establish the baseline for discussion. In Section 3, we describe the development of several branches of derivative tanks, and explore the motives and rationale for taking the derivate tank approach. In Section 4, we conclude with a summary of recent development activities for derivative PMD tanks at ATK Space Systems.

INTRODUCTION

Space systems operators have used propellant tanks with surface tension PMDs to support space flight since the 1970s. Thousands of satellite missions had relied on PMD tanks to operate in low-g or zero-g environments. Mission planners use surface tension PMDs to support maneuvers such as orbit transfer, orbit insertion, station keeping, and deorbit. Missions enabled by PMDs included launch vehicle upper stage, low Earth orbit (LEO), medium Earth orbit (MEO), geostationary orbit (GEO), lunar, and interplanetary missions.

The largest group of users of surface tension PMD tanks is commercial satellite fleet operators. GEO commercial satellite platforms such as Airbus Eurostar; Boeing 601 and 702; Lockheed Martin S3000, S5000, S7000, and A2100; MELCO DS200, Orbital Star 1, Star 2, and Star 3; SSL FS1300 and LS1300; and Thales Alenia Spacebus all contain propellant tanks with surface tension PMDs. Many LEO satellites also contain PMD tanks, including dozens of the first generation Iridium satellites and hundreds of Earth observation satellites. Note there are many other types of PMDs, including elastomeric diaphragms and bladders. In this paper, the authors shall focus on tanks containing surface tension PMDs only. In subsequent paragraphs, all references to PMDs relate to surface tension PMDs.

The primary purpose of a PMD is to supply propellant to thrusters upon demand. In addition, satellite operators have different degrees of tolerance for propellant slosh and propellant Center of Mass (CoM) movement, and PMD designers must consider slosh and CoM requirements when designing a PMD. PMD designers must also consider operational constraints, such as ground handling, ground transportation, launch pad sway environment, and launch operations environment [1]. One example is designing a PMD that accommodates launch vehicles with horizontal handling or transport, such as Proton, Zenit, or Falcon. Finally, programmatic constraints might also affect PMD design, including funding limitation, short development cycle, customer requirement for heritage hardware, and a low mass target. The key challenge to designing a PMD is often finding an optimal solution amongst the conflicting constraints of low mass, low cost, high performance, good manufacturability, high reliability, and schedule compliance.

A PMD tank designed for one mission is rarely a perfect tank solution for another mission. Variables such as propellant volume requirement, mission profile, ground handling conditions, orbital environment, and a customer's operating philosophy could contribute to different tank size and PMD configuration. Typically, ATK conducts trade studies and present various options prior to finalizing the PMD design [2]. The goal of a trade study is to help the customers optimize the design solution for the entire mission instead of a narrower focus of the PMD tank design only. We have experiences with a common theme in which a mass saving of a few kilograms on tanks often contribute positively toward structural or operational elements of a new spacecraft design.

In the same context of optimization, using a universal PMD design approach is not practical and not beneficial to space tank development. As an example, a universal PMD adopting the gallery arms solution might be heavier than a PMD solution with lower mass elements such as vanes or sponges. In general, the further the travel out to space, the more focus on mass. Our GEO Commercial satellite customers go through exhaustive efforts to reduce tank mass. On lunar missions, tank mass becomes even more critical. Recently, an ATK customer funded a PMD tank development program to maximize PMD performance and to reduce the PMD mass by two kilograms. When making decisions involving the business case, a lowest mass and custom-designed PMD is usually the optimal approach for a new mission.

A pressurized propellant tank is an important component of a spacecraft propulsion system. Similar to a PMD development, the development of a propellant tank shell for space flight must also take into account technical, commercial, and programmatic elements to optimize its overall value. The same objectives for designing an optimal PMD, such as high performance, low mass, and so on also apply to tank shell design. In addition, adherence to features with flight heritage is often highly desirable. Finally, mission operators use propellant tanks under pressurized conditions while carrying corrosive fluids. In response, tank shell designers must consider additional factors such as material compatibility, material strength, and material properties such as elongation and corrosive behavior when designing or evaluating a tank shell.

The development and qualification of a new PMD propellant tank could be an expensive and time-consuming endeavor. Assuming there are no pre-existing assets to support a new tank design, tank designers must develop a long list of items to facilitate tank qualification. Over the past several decades, the list of developmental items expanded and contrasted, and finally evolved into a streamlined process identified below:

- Tools for domes
- Tools for machining
- Tools for PMD assembly
- Tools for tank shell assembly
- Tools for tank shell heat treatment
- Tools for PMD heat treatment
- Tools for testing
- Tools for inspection
- Tools for cleaning
- Fixture for vibration testing
- Simulator for slosh testing
- A forging qualification program
- A tank shell heat treatment qualification program
- A PMD weldment qualification program
- A tank shell girth weld qualification program
- A tube weld qualification program
- A PMD quality verification program
- A tank shell quality verification program
- A PMD tank qualification program
- A preliminary design review data package
- A critical design review data package
- A drawing package for tank shell assembly and PMD assembly
- A set of manufacturing planning to guide manufacturing operations
- A Composite overwrap development program if applicable
- A set of compliance documents
- A forging qualification report
- A weld qualification report
- A PMD performance report
- A PMD tank qualification report

Inherent in the list is an assumption that the tank shell material and the PMD material are compatible with the intended propellant and that long-term design and compatibility data exist to support analytical validation. If such an assumption is not valid, as in the case of new tank shell material (e.g. tank shell made from additive manufacturing) or new propellant (e.g. green propellants such as LMP-103s or AF-

M315E), then engineers and scientists must collect additional data that might include:

- long-term compatibility data for tank shell material and the intended propellant,
- fracture data in support of tank shell fracture mechanics analysis,
- propellant material data (e.g. surface tension, contact angle, density, viscosity) to support PMD functional analyses.

The fracture data collection could take approximately one year to complete [3]. The propellant data collection could be a multiple-year endeavor, with much of the time spent on securing regulatory approvals [4]. These efforts could involve large expenditures on labor and material, with costs reaching hundreds of thousands of Euros. Furthermore, in strict compliance to analytical approaches using A-basis allowables, it would be necessary to invest funds to collect dozens of data points that require significant financial commitment.

The exhaustive verification and documentation process described above ensures compliance to requirements and the delivery of reliable space flight hardware, but at a high cost. Eliminating some items on the list by using derivative tanks could achieve many programmatic advantages, including reduced cost, shortened development schedule, assured reliability, and imbedded heritage. Given the severe cost-constrained environment in many commercial and institutional programs, developing derivative tanks had been a primary approach on most of the tank development programs at ATK.

There are many approaches in developing derivative PMD tanks, including:

Approach 1 - Using a qualified PMD tank as is, or with minor modifications. This is the least expensive approach to acquire a tank for a new mission. In most cases, a structural analysis, a PMD validation analysis, and sometimes a protoflight vibration test are sufficient to qualify the tank for flight. However, few missions are exactly alike. A PMD tank developed for one mission is seldom applicable to another mission. From 1970s to 2016, we were able to use this approach only once by adapting a qualified P/N 80430 PMD tank for use on the NASA GLAST mission. We incorporated a modification to the tank outlet tube only. There were no other changes to the tank shell or the PMD. However, most other programs required more adaptations than a simple tube change.

Approach 2 – Modifying (Lengthening or Shortening) an existing PMD tank. This approach is applicable to cylindrical tank shells with PMDs that can accommodate varied tank lengths. We developed many GEO commercial satellite tank families using this approach to reduce qualification cost [5] – [7]. Typically, we qualify the longest tank by qualification testing because the longest length is usually the worst-case. We then qualify the shorter tank or tanks by similarity to the longest tank. We used this approach on several PMD tank families on commercial satellite platforms, including A2100, FS1300, 702 MP, and Star 3, as well as on tanks for LEO platforms. We adopted this approach on a recent green propellant tank development program by reducing the length of an existing P/N 80421 [4]. Conversely, we can also lengthen the tank, and use qualification or protoflight qualification approaches to develop derivative tanks.

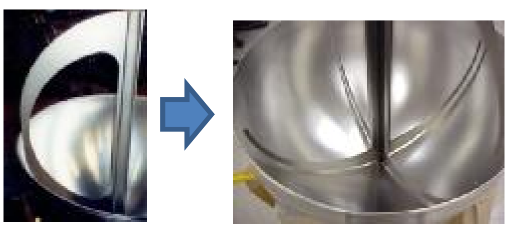
Approach 3 - Installing an existing PMD onto another qualified shell. This approach is valid if all conditions are favorable – good fit, good adaptability, and good performance. The advantage of this approach is achieving cost savings on the drawing package and the manufacturing planning package. In practice, it is usually not the optimal solution because the potential for compromised performance, high residual, and extra mass often prevent this option from proceeding beyond the conceptual stage. Although we often included this approach on many PMD tank trade studies, we never had an opportunity to pursue this approach in practice.

Approach 4 – Modifying an existing PMD design and installing it onto another qualified shell. Unlike Approach 3, we have adopted this approach to support missions. For example, in a recent lunar lander program, we took the PMD from our P/N 80435 [8], eliminated unnecessary features to reduce mass, and incorporated the modified PMD onto the P/N 80474 tank shell [9]. The PMD adaptation had a higher than the optimal residual as compared to a custom-designed PMD, but the design approach facilitated a fast track schedule in support of a fixed launch deadline. The slightly modified PMD retained many of the original component parts, thus reducing the cost of updating drawing package and manufacturing planning package. Although Option 4 was not an optimal tank solution, it was a good solution for the mission by using an approach that balanced performance, schedule, cost, and mass targets.

Before 2010, we had few opportunities to apply Approach 4. As we complete more PMD developments and accumulate more qualified PMD designs in our product inventory, the opportunity for applying Approach 4 increases. As of first quarter of 2016, we have more than 55 qualified PMD designs, and several more in work. We also find ourselves applying Approach 4 more frequently in trade studies and on actual programs.

Approach 5 – Incorporating a custom-designed PMD into a qualified shell. This is a common approach in derivative tank development. ATK has many qualified tank shells, thus making this approach feasible on a wide range of tank sizes. Some examples include:

1. using an existing Iridium PMD tank shell as is [10], but installing a custom-designed PMD to support the NFIRE mission. See Figure 1. A tank shell structural analysis, a PMD functional analysis, and a protoflight vibration test were sufficient to qualify the new PMD tank for flight.



Iridium PMD NFIRE PMD

Figure 1: The Iridium PMD and the NFIRE PMD in the same shell

2. modifying an existing P/N 80352 Mars Observer tank shell, and incorporating a custom-designed PMD to support the NASA SDO mission. See Figure 2. A PMD structural test, a tank shell structural analysis, a PMD functional analysis, and a protoflight vibration test were sufficient to qualify the new PMD tank for flight [11].

Figure 2: The SDO PMD installed in a modified PMD tank shell

3. modifying an existing diaphragm tank shell, and installing a custom-designed PMD to support the Orbital Express on orbit fluid transfer experiment. See Figure 3. We conducted a tank shell structural analysis, a PMD functional analysis, and a protoflight vibration test to qualify the new PMD tank for flight [12].

Figure 3: The Orbital Express PMD installed in a modified diaphragm tank shell

Developing a custom-designed PMD is typically the optimal approach to achieve highest performance and lowest mass. It is also a higher-cost approach as compared to approaches 3 and 4. The higher cost is the result of a new PMD design and the design review process, with the accompanying new drawing package, new manufacturing planning package, and a set of new PMD assembly tools. Customers often chose this approach because the value of optimal performance, lowest residual, and lowest PMD mass would outweigh the high development cost.

Approach 6 – Develop a custom-designed PMD for a custom-designed shell using existing tooling. This approach does not fit the traditional definition for derivative tanks as it involves both tank shell and PMD qualification. However, we developed several GEO commercial satellite tank families using this approach, including ∅540 mm (∅21.25 in), ∅896 mm (∅35.26 in), ∅1027 mm (∅40.44 inch), ∅1150 mm (∅ 45.29 in), and ∅1242 mm (∅48.9 inch) diameter tanks. Lower cost and shortened delivery schedule are usually the driving factors for choosing this approach. Some notable examples include:

1. developing our ∅1242 mm (∅48.9 in) [13] and ∅1150 mm (∅ 45.29 in) tank families to generate savings on high price items such as forging tooling, forging qualification, machining mandrel, weld fixture, test fixture, and vibration test fixture. See Figure 4. Not having to design and fabricate these large and expensive tools could also reduce production schedule and minimize program risk. On a large diameter tank, a set of forging dies alone could generate more than

€250,000 in cost savings, and eliminate the 4 to 6 months of lead-time to fabricate the tools. Customers trying to develop new tanks often take into account the available tooling to minimize tank development risk and compress schedule. Given that a spacecraft delivered into orbit has revenue-generating capacity in the millions of Euros a month, this intense focus on accelerated tank development is understandable.

Figure 4: The Astrolink shell took advantage of existing 35 inch PMD tank tooling

2. developing an ultra-lightweight MESSENGER tank shell by modifying an existing diaphragm tank shell and installing a custom-designed PMD. See Figure 5. We conducted a tank shell configuration trade study, followed by a tank shell structural analysis, a PMD functional analysis, and a full set of qualification tests to qualify the new tank [14].

Figure 5: The MESSENGER shell manufacture took advantage of existing 22 inch diaphragm tank tooling

In summary, there are many approaches toward developing derivative PMD tanks. Most customers prefer approaches that do not require a qualification test program in order to minimize cost. This is especially true as the tank diameter becomes larger and new tooling becomes more expensive. In cases where new qualification test programs become necessary, many customers still prefer to take advantage of existing assets such as tooling, qualified forgings, qualified welds, and qualified processes and so on to minimize cost and optimize heritage. In the following sections, we shall explore the actual approaches we used to develop several derivative branches of our Ø1150 mm (45.29 in) PMD tank family. The development of space systems hardware must incorporate the application of technical knowledge while exercising sound business judgment. The examples we present in the subsequent sections are models of good engineering and business practices. They are effective and mutually beneficial for our organization and our customers.

SECTION 2, DEVELOPMENT OF A NEW PMD TANK

In 2007, a GEO commercial satellite manufacturer tasked ATK to design and qualify a new family of PMD tanks for a new propulsion system. The tank family consisted of five configurations from Ø1150 mm x 939.8 mm long (Ø45.29 in x 37 in long) to Ø1150 mm x 1498.6 mm long (Ø45.29 in x 59 in long). The system designers chose these five configurations to support a modular spacecraft construction approach. All tanks in the family have identical upper and lower domes. The only differences between tanks are the varied lengths of the tank shell center section and the PMD vanes. Table 1 is a summary of some key parameters of the five tanks.

At program start, we conducted trade studies to determine the optimal tank shell and PMD configurations. Trade space for the tank shell included dome shape (ellipsoidal or hemispherical), material of construction (6Al-4V titanium, CP titanium, composite, all-metal, hybrid, or fully wrapped), dome manufacturing method (forged or spun), shell construction (number of welds, types of welds), size and envelope (dome diameters and cylinder length), mounting methods, cost, risk, mass, and development schedule. See Figure 6. The trade space for the PMD included component type, performance, mass, and cost.

Table 1: Summary of Volume, Lengths, and Masses of P/N 80507 Tank Family

ATK P/N	Tank Volume	Tank Length	Tank Mass
80507-1	673.39 L (41,093 in^3)	939.8 mm (37.00 in)	30.31 kg (66.82 lb_m)
80507-2	837.74 L (50,756 in^3)	1092.2 mm (43.00 in)	34.81 kg (76.75 lb_m)
80507-3	990.11 L (60,420 in^3)	1244.6 mm (49.00 in)	38.07 kg (83.92 lb_m)
80507-4	1,148.45 L (70,083 in^3)	1397.0 mm (55.00 in)	41.52 kg (91.53 lb_m)
80507-5	1,254.54 L (76,525 in^3)	1498.6 mm (59.00 in)	43.82 kg (96.60 lb_m)

A primary goal of the trade study was to enable customer participation in the tank configuration development. We analyzed dozens of configuration options in the initial trade, and the customer was an integral part of the design evolution by providing feedbacks on which options to pursue and which options to eliminate.

At the conclusion of the trade study, the customer selected a design that was neither the lowest cost nor the lowest mass. The final design was optimal based on a holistic design approach that included considerations for operational factors such as system integration support, operational simplicity, overall robustness, mission life, and overall risk.

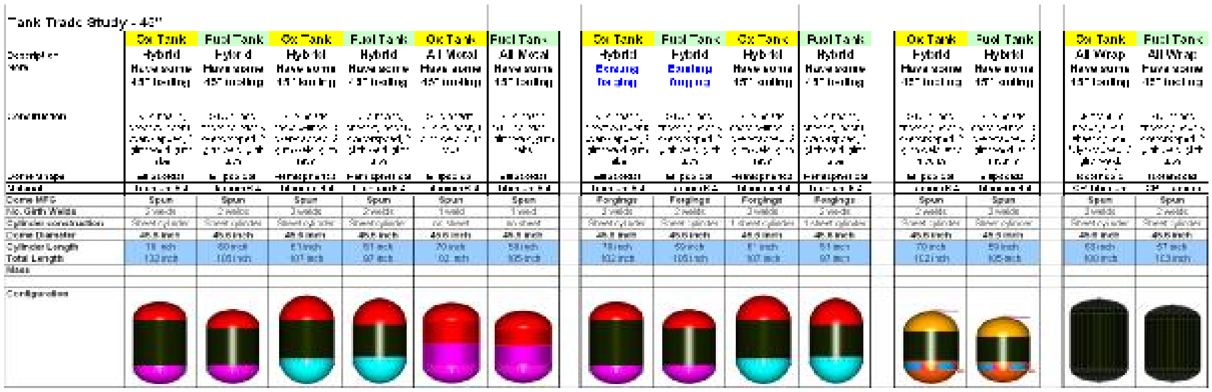


Figure 6: 1150 mm (45.29 in) tank shell trade study

A description of the optimal tank shell configuration, as determined by the tank shell trade study, is as follows:

- A hybrid construction with metal domes and composite wrapped cylinder section.
- Two ellipsoidal domes machined from solution treated and aged 6Al-4V titanium forgings.
- A mounting skirt machined from solution treated and aged 6Al-4V titanium ring forging and electron beam welded to the propellant dome.
- A cylinder section consists of a metallic liner made from rolled and seam welded 6Al-4V titanium sheet stock, and overwrapped with high performance composite. The composite consists of G40-800 fiber and a heritage-based resin system.

Figure 7 is a photo of the P/N 80507 hybrid tank shell with the metallic domes and composite overwrapped cylinder section. This hybrid shell construction has embedded flight heritage. ATK developed the first hybrid tank shell in 1995 for a GEO commercial satellite platform [5] [15]. As of 2016, we had qualified seven tank families with hybrid shells on mostly GEO commercial satellite platforms.

There are several inherent advantages in the tank shell design:

- The ellipsoidal domes optimized the fuel-carrying capacity within the available envelope [16] with an acceptable increase in tank mass.
- The cylinder construction enabled a qualification-by-similarity (QBS) approach for smaller volume tanks with identical domes but shorter cylinder lengths (Approach 2).
- The use of composite overwrap was a cost-effective solution to meet tank equipment specification requirements.
- The PMD design was adaptable to the varied cylinder length with minimal cost impact.
- The metallic skirt mount was efficient, robust, reliable, and heritage-based.

Figure 7: The P/N 80507 hybrid shell with metal domes and composite overwrapped center section

One of the items on our customer's "shopping list" was to maximize the propellant-carrying capacity within a defined envelope. This requirement led to a new tank size requiring a set of new tools. The tooling cost for this new tank size was substantial and well in excess of $1 million Euros. In addition, ATK must conduct a forging qualification campaign to qualify a new forging configuration. The only heritage items inherent in the tank design were the qualified seam weld and the dome-to-cylinder girth weld. ATK must develop all other items for the new tank, and the non-recurring cost for the new tank development was relatively high as compared to many other tank development efforts.

We traded a number of PMD options during an initial PMD trade study. The PMD trades concluded with a custom-designed PMD to optimize propellant tank performance. The PMD must ensure gas free propellant delivery during all phases of the mission, including:

- Separation recovery while spinning about any axis.
- System priming.
- Engine burns.
- Lateral firing.
- Various contingency spins.

Figure 8 is the PMD concept for P/N 80507. The PMD assembly includes PMD elements such as sponge, vanes, and a pick up assembly. The length of the PMD vanes is adjustable to accommodate five different tank lengths, and the tank volume change would not affect other PMD components such as sponge and pick up assembly.

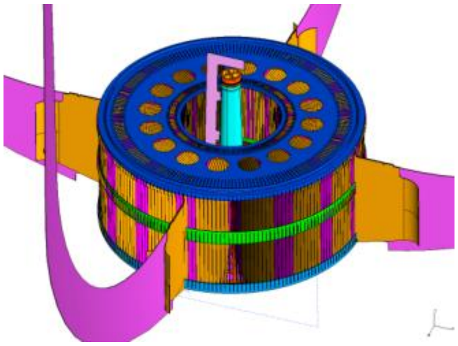


Figure 8: the PMD Concept for P/N 80507

The PMD performance analyses included considerations for the following:

- Ground operations: filling, draining, and both horizontal (see Figure 9) and upright handling.
- Ascent operations: launch, system priming, pressurization, contingencies, and spin recovery.
- Orbital operations: thruster firings, contingencies, and deorbit.

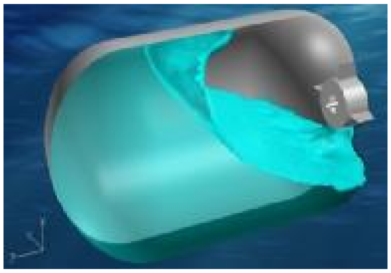


Figure 9: P/N 80507 tank horizontal handling analysis

One unique challenge during PMD design was that the new propulsion system has two different size tanks. The Ø1150 mm (Ø45.29 in) P/N 80507 tank is for a family of large tanks. There was another family of smaller tanks with P/N 80506 designation having a tank diameter at ∅684 mm (∅26.94 in) and different tank lengths. In addition, the modular propulsion system approach must accommodate a 5-tank and a 3-tank combination of fuel and oxidizer tanks depending upon mission requirements. The PMD design must accommodate various tank & PMD orientations during horizontal and upright handling as well as orbital operations. Figure 10 is a photo of the P/N 80507 PMD installed in the finish machined tank shell.

Figure 10: the P/N 80507 PMD installed in a finish machined tank shell

ATK developed a family of five tanks with five dash numbers as summarized in Table 1. The longest tank of the family, P/N 80507-5, underwent a complete qualification test program. The functional, structural, and environment qualification tests included the following:

- Volumetric verification
- Proof test
- Proof pressure (see Figure 11)
- Proof pressure cycles
- MEOP pressure cycles
- Flow rate
- Vibration test (see Figure 12)
- PMD bubble point
- Non-destructive examinations – radiography and dye penetrant
- External leakage
- Collapse pressure
- Burst pressure (see Figure 13)

Qualification of the four shorter tanks (80507-1, -2, -3, and -4) was by similarity to the longest Qualification Tank. ATK often use the QBS approach to qualify the shorter members of a tank family [4]. Some examples include P/Ns 80391 (∅896 mm or ∅35.26 inch), 80434 (∅896 mm or ∅35.26 inch), 80425 (∅896 mm or ∅35.26 inch), 80390 (∅540 mm or ∅21.25 inch), 80405 (∅540 mm or ∅21.25 inch), 80426 (∅540 mm or ∅21.25 inch), and 80435 (∅540 mm or ∅21.25 inch) GEO commercial tank families.

Figure 11: the P/N 80507 Qualification Tank during pressure testing

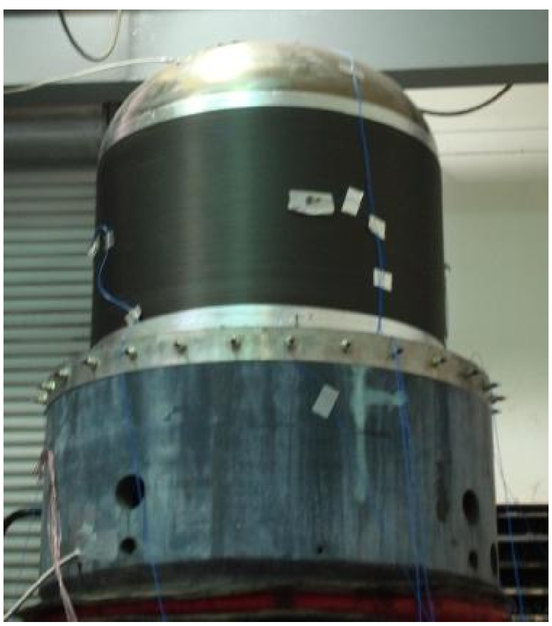


Figure 12: the P/N 80507 Qualification Tank during vibration testing

Figure 13: the P/N 80507 Qualification Tank after the destructive burst test

The concept of QBS is important in derivative tank development. It enables the engineers and managers to justify eliminating a dedicated qualification tank and removing an expensive qualification test campaign to achieve cost and schedule savings. Figure 14 is a photo of P/N 80507-1, the shortest member of the P/N 80507 tank family. We used the QBS methodology to qualify the 80507-1 through 80507-4 tank configurations without conducting additional qualification testing on these shorter tanks.

Figure 14: P/N 80507-1 is the shortest version of the 80507 tank family

Table 2 is a summary of design parameters for P/N 80507 family of tanks. ATK completed the Qualification Program in 2008. The tanks are currently in production. We delivered several shipset of tanks in support of space flight programs.

Table 2: P/N 80507-5 Design Parameters

Parameters	Requirements
Operating Pressure	18.7 bar (271 psig)
Proof Pressure	23.3 bar (338 psig)
Burst Pressure	>28.3 bar (>410 psig)
External Pressure	2,0 – 3.0 psig, Actual Collapse: 2.50 psig
Material of Construction	Shell: Solution Treated and Aged (STA) 6AL-4V Titanium Heads Inlet/Outlet Ports: 6AL-4V titanium tubes PMD: 6AL-4V and CP Titanium
Tank Mount(s)	Mounting skirt consists of 28 equally space mounting tabs
Inside Diameter	∅1150 mm (∅ 45.29 in) ID
Skirt Interface Dimension	∅1177 mm (∅ 46.321 in) with 28 equally spaced tabs
Propellant Capacity	Qualified to 1754 kg (3,866 lb_m) NTO for P/N 80507-5
Natural Frequency	64 Hz axial, 39 Hz lateral
Shell Leakage	$<1x10^{-6}$ std cc/sec He max @ MEOP
Actual Burst Pressure	Tank ruptured @ 34.7 bar (503 psig). Normalized burst pressure @ 28.5 bar (413 psig).

SECTION 3, DEVELOPMENT OF DERIVATIVE TANKS

After the successful qualification of P/N 80507 tank family, we added these tanks to our general catalog. During the ensuing years, several ATK customers took note of the available assets and funded additional programs to develop derivative tanks. In this section, we describe these derivative tank development efforts and highlight some of the common practices preferred by our customers.

3.1. Derivative tank P/N 80520

In 2009, some characteristics of P/N 80507 tank caught the attention of engineers from a satellite manufacturer. After some initial trade studies, the satellite manufacturer tasked ATK to develop a new PMD tank for a non-commercial satellite propulsion system application. Our initial trade studies concluded with a derivative tank approach using the existing P/N 80507 assets to develop the tank shell while custom-designing a PMD for the new mission. The new tank, ATK P/N 80520, has an all-metal construction. See Figure 15. The tank has a similar size and envelop as P/N 80507-5, but operates at 24.1 bar (350 psi) Maximum Expected Operating Pressure (MEOP). The design burst safety factor must be >1.5 x MEOP. We designed a thicker membrane to accommodate the higher MEOP. In addition, we incorporated a metallic cylinder made from STA 6AL-4V titanium ring forging, configured a set of new mounting tabs to facilitate tank integration, and custom-designed a PMD to support the satellite mission.

Figure 15: ATK P/N 80520-1

There were several advantages in adopting a derivative tank approach in this PMD tank:

- using an existing qualified forging eliminated the costs of forging tooling and forging qualification;
- adapting existing tooling for machining, welding, heat treat, and testing generated cost savings for the tank development program;
- adapting the metallic skirt mount generated cost savings and embedded design heritage
- adapting existing tooling reduced tank development schedule and ensured quality and reliability.

The immediate financial advantages included cost savings in excess of €1,000,000. In addition, the customer also recognized the value of reduced program risk from using the available assets, as well as the inherent schedule advantage.

Table 3 is a summary of P/N 80520 design parameters.

Table 3: P/N 80520 design characteristics

Parameters	Requirements
Operating Pressure	24.1 bar @ 48.9 °C (350 psig @ 120°F)
Proof Pressure	30.2 bar @ 48.9 °C (438 psig @ 120°F)
Burst Pressure	>36.2 bar @ 48.9 °C (>525 psig @ 120°F)
Material of Construction	Shell: Solution Treated and Aged (STA) 6AL-4V Titanium Heads and Cylinder Inlet/Outlet Ports: 6AL-4V titanium tubes PMD: 6AL-4V and CP Titanium
Tank Mount(s)	Mounting skirt consists of 28 mounting tabs
Expulsion Efficiency	>99.5%
Design Fill Fraction	50-70%
Tank Capacity	1254.54 liters (76,525 in^3, same as P/N 80507)
Inside Diameter	∅1150 mm (∅ 45.29 in) ID, same as P/N 80507
Skirt Interface Dimension	∅1183 mm (∅ 46.570 in) with 28 tabs, not equally spaced
Tank Mass	Maximum mass is 61.7 kg (136 lb_m), actual Qualification Tank mass is 60.8 kg (134 lb_m)
Propellant Capacity	889 kg (1960 lb_m)
Shell Leakage	<1x10^{-6} std cc/sec He max @ MEOP
Burst Pressure	Tank ruptured @ 45.7.5 bar (663 psig). Normalized burst pressure @ 39.1 bar (567 psi). Burst margin = +4%.

P/N 80520 contains a PMD custom-designed to ensure gas free propellant delivery during all phases of the mission, including:

- System priming.
- Lateral firings.
- High acceleration and flow rate firings.
- Spin recovery.

In addition, the PMD must survive high amplitude ground slosh loads during ground operations.

Figure 16 is the PMD concept for P/N 80520. The PMD assembly includes PMD elements such as sponge [17], vanes [18], and perforated elements.

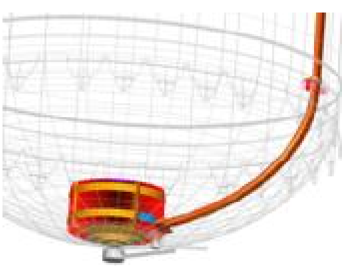


Figure 16: The PMD concept for P/N 80520-1

The PMD performance analyses included considerations for the following:

- Ground operations: filling, draining, and upright handling.
- Ascent operations: launch and system priming.
- Orbital operations: thruster firings, spin recovery, and depletion.

Figure 17 is a photograph of the PMD as installed in the finish machined tank shell. The oval vane is a derivative PMD component derived from prior PMD assemblies. Originally, ATK developed the oval bent tube as gallery arms on the MILSTAR propellant tanks. See Figure 18. We adopted the gallery arm to function as flat vane in the 80520 PMD design to meet high flow rate requirements.

Figure 17: ATK P/N 80520-1 PMD as installed in the propellant dome

Figure 18: The MILSTAR PMD with oval gallery arms

We conducted a stand-alone qualification test program to qualify the new all-metal shell. The functional, structural, and environmental qualification tests included the following:

- Volumetric verification
- Proof pressure
- Proof pressure cycles
- MEOP pressure cycles
- Flow rate
- Pressure drop
- Vibration test, see Figure 19
- Acceleration test, see Figure 20
- Acoustic test, see Figure 21
- PMD bubble point
- Non-destructive examinations – radiography and dye penetrant
- External leakage
- Burst pressure, see Figure 22

The tank development concluded with a successful burst test in 2011.

Figure 19: P/N 80520 Vibration Testing

Figure 20: P/N 80520 Qualification Tank at Pressurized Acceleration Test

Figure 21: P/N 80520 Qualification Tank during Acoustic Test

Figure 22: P/N 80520 Qualification Tank after Burst Pressure Test

Table 4 is a side-by-side comparison of the 80507-5 Tank and the 80520-1 Tank design parameters. Note we designed P/N 80520 to higher pressure but with a lower propellant mass than P/N 80507-5, and made only a small modification to interface dimension of the tank mounting tabs. Unlike the original P/N 80507, we developed only one tank configuration and not a family of multiple tanks. While the P/N 80520 is a new tank design requiring a stand-alone qualification test program, we nevertheless considered it a derivative tank in line with the Approach 6 outlined in Section 1.

Table 4: A Side-By-Side Comparison of P/N 80507 and P/N 80520 Design Characteristics

Feature	**80507-5 Qualified Tank**	**80520 Hydrazine Tank**
Propellant Load	1754 kg (3866 lb_m)	889 kg (1960 lb_m)
Volume	1255 liters (76,525 in^3)	1255 liters (76,525 in^3)
MEOP	17.9 bar @ 45°C (260 psi @ 113°F)	24.1 bar @ 48.9°C (350 psi @ 120°F)
Proof Pressure	22.4 bar @ 45°C (325 psi @ 113°F)	30.2 bar @ 48.9°C (438 psi @ 120°F)
Burst Pressure	>26.9 bar @ 45°C (>390 psi @ 113°F)	>36.2 bar @ 48.9°C (>525 psi @ 120°F)
Natural Frequency	64 Hz axial & 39 Hz lateral	≥ 40 Hz
Interface Mounting	∅1177 mm (∅46.321 in) with 28 equally spaced tabs	∅1183 mm (∅46.570 in) with 28 non-equally spaced tabs
Design Loads	Qualified to 10g axial & 6g lateral	Qualified to 11.25g axial & 7.5g lateral

Inherent in the P/N 80520 tank design and qualification was a conservative approach with preference to heritage hardware. Although the new design necessitated a stand-alone qualification test program, the use of the existing and flight qualified assets was important for the conservative customer. The cost savings from pursuing a derivative tank approach was also an important competitive advantage for ATK and its customer in the marketplace.

3.2. Derivative Tanks P/N 80570 and P/N 80571

In 2013, a GEO Commercial satellite manufacturer was looking to develop a new tank in the 1143 to 1194 mm (45 to 47 in) size range. After an initial trade study, the satellite manufacturer tasked ATK to develop a new family of tanks for a modernized GEO Commercial satellite platform. We assigned part numbers 80570 and 80571 to this new family of tanks. The P/N 80570 was a family of fuel tanks having five distinct sizes. P/N 80571 was a family of oxidizer tanks having two sizes. See Tables 5 and 6. Both tanks have the same internal diameter of 1150 mm (45.29 in). The seven tank configurations would enable the customer to adapt different combination of fuel and oxidizer tanks in support of a modular satellite construction approach.

Both 80570 and 80571 tanks are hybrid constructions with STA 6Al-4V titanium domes and composite overwrapped cylinder sections. The Qualification Tank, an 80570-1 configuration, looks like an extended version of the 80507-5 Qualification Tank. See Figure 23.

Table 5: A Summary of Volumes, Lengths, and Masses of P/N 80570 Tank Family

ATK P/N	Tank Volume	Tank Length	Tank Mass
80570-5	674.8 L (41,163 in^3)	946.2 mm (37.25 in)	34.0 kg (74.96 lb_m)
80570-4	1,096.5 L (66,882 in^3)	1351.8 mm (53.22 in)	46.8 kg (103.18 lb_m)
80570-3	1,514.9 L (92,409 in^3)	1754.1 mm (69.06 in)	58.8 kg (129.63 lb_m)
80570-2	1,829.5 L (111,596 in^3)	2056.6 mm (80.97 in)	67.9 kg (149.69 lb_m)
80570-1	2,194.7 L (133,872 in^3)	2407.9 mm (94.80 in)	78.6 kg (173.28 lb_m)

Table 6: Summary of Volumes, Lengths, and Masses of P/N 80571 Tank Family

ATK P/N	Tank Volume	Tank Length	Tank Mass
80571-2	674.8 L (41,163 in^3)	946.2 mm (37.25 in)	29.6 kg (65.26 lb_m)
80571-1	912.5 L (55,662 in^3)	1174.8 mm (46.25 in)	36.5 kg (80.47 lb_m)

Figure 23, ATK P/N 80570.

The adaptation from the P/N 80507 tank design to make the P/N 80570 tank included the following:

- The new 80570 and 80571 tanks used the same dome forging and the same rolled-and-welded cylinder as P/N 80507.
- We adopted the same internal diameter of 1150 mm (45.29 in) as P/N 80507.
- We adopted the same mounting ring interface dimension of 1177 mm (46.321 in) as P/N 80507.
- We adopted the same number (28) of equally space mounting tabs as P/N 80507.

Concurrent with the P/N 80470 fuel tank development program was a parallel oxidizer tank design and qualification effort. The fuel tank and the oxidizer tank have different lengths, and there were two different PMD concepts for the two tank families. Figure 24 is the PMD concept for the longer Hydrazine Tank. Figure 25 is the PMD concept for the Shorter oxidizer Tanks. For clarity, we will not include the P/N 80571 oxidizer tank PMD in our discussion.

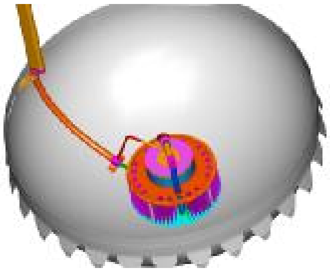


Figure 24: The PMD concept for P/N 80570 Hydrazine Tank

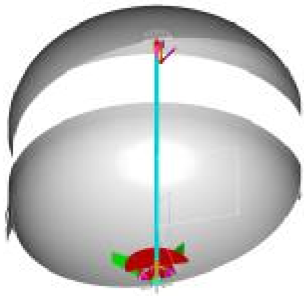


Figure 25: The PMD concept for P/N 80571 NTO Tank

We designed the 80570 PMDs to meet a range of different requirements:

- Both propellant and pressurant ports on the same bottom dome.
- No gas ingestion during horizontal handling.
- Accommodate system priming.
- Supply propellant during various operational burns.
- Supply propellant during contingency operations.

The PMD assembly for the long fuel tank includes the following PMD components:

- Sponge
- A single vane
- A horizontal slosh handling device

The PMD performance analysis included considerations for the following:

- Ground operations: filling, draining, and both horizontal and upright handling.
- Ascent operations: launch, separation, system priming, recovery, engine burns.
- Orbital operations: Zero g coast, thruster firing, and deorbit.

Similar to P/N 80520, we conducted a stand-alone qualification test program to qualify the two new tank families. The Qualification Tank was the longest tank, P/N 80570-1. The functional, structural, and environment qualification tests included the following:

- Volumetric verification
- Proof test
- Proof pressure
- Proof pressure cycles
- MEOP pressure cycles
- Acoustic test, see Figure 26
- Sine vibration, see Figure 27
- Pressure drop
- PMD bubble point
- Weld quality inspection
- External leakage
- Burst pressure, see Figure 28

Figure 26: ATK P/N 80570 Qualification Tank Acoustic Testing

Figure 27: ATK P/N 80570 Qualification Tank Vibration Testing

Figure 28: ATK P/N 80570 Qualification Tank Burst Test Setup

We used the QBS approach to qualify the rest of the shorter tank shells, including the two 80571 oxidizer tanks.

Table 7: P/N 80570 tank parameters

Parameters	Requirements
Operating Pressure	20.68 bar (300 psig)
Proof Pressure	25.85 bar (375 psig)
Burst Pressure	>33.58 bar (>487 psig), actual burst @ 39.3 bar (570 psi)
Material of Construction	Shell: Solution Treated and Aged (STA) 6AL-4V Titanium Heads, Inlet/Outlet Ports: 6AL-4V titanium tubes, PMD: 6AL-4V and CP Titanium
Tank Mount(s)	Mounting skirt consists of 28 equally spaced mounting tabs
Design Fill Fraction	65 to 95%
Tank Capacity	See Table 5
Inside Diameter	∅1150 mm (∅ 45.29 in) ID, same as P/N 80507
Skirt Interface Dimension	∅1177 mm (∅ 46.321 in) with 28 equally spaced tabs, same as P/N 80507
Shell Leakage	<$1x10^{-6}$ std cc/sec He max @ MEOP
Burst Pressure	Tank ruptured @ 39.3 bar (570 psig). Normalized burst pressure @ 39.4 bar (571.7 psig)

Our initial proposal, based on adapting an existing tank design, was in alignment with our customer's desire and expectation. At the onset of the tank development, our customer expressed a strong desire to minimize non-recurring expenditures. We worked with the customer to find ways to reduce cost, and used the cost advantages of the derivative tank approach to optimize savings on engineering, tooling, and hardware manufacture. The fact that there are many parallel design features between P/N 80507 and P/N 80570 was the physical evidence of the derivative tank approach. At the conclusion of the contract, we were able to help the customer meet both the technical goals and the programmatic goals.

3.3. Derivative Tanks P/N 80576

In 2013, the original customer that funded P/N 80507 tank development tasked ATK to extend the length of the longest P/N 80507 tank by another 864 mm (34 inches). The same customer extended the tank length for a second time by another 152 mm (6 inch) in 2014. We assigned part numbers 80576-1 and 80576-2 to these new additions to the tank family. Table 8 is a summary of the new tank parameters. On both tanks, we made two design changes only. For the tank shell, we extended the tank shell by lengthening the cylinder section. For the PMD, we extended the vanes to ensure PMD functionality. ATK conducted product development for the longer PMD vanes to ensure the manufacturability and functionality of the long vanes. Otherwise, we did not perform additional process or product development for the two longer tanks. Figure 29 is a photo of the tank wrapping operation, and Figure 30 is a complete tank after precision clean.

Figure 29: ATK P/N 80576 tank wrap

Table 8: Summary of Volume, Lengths, and Masses of P/N 80576 Tank Family

Part Number	Volume	Length	Mass
80576-2	2309.7 L (140,945 in^3)	2514.6 mm (99.00 in) boss-to-boss	63.9 kg (140.8 lb_m)
80576-1	2151.3 L (131,282 in^3)	2362.2 mm (93.00 in) boss-to-boss	60.6 kg (133.7 lb_m)

Figure 30: ATK P/N 80576 after final clean

The two new tanks might belong to the same P/N 80507 tank family, but they are considerably longer in length. Taking a conservative approach, we conducted a full suite of qualification tests to qualify P/N 80576-1. The functional, structural, and environmental qualification tests included the following:

- Volumetric verification
- Proof pressure
- Proof pressure cycles
- MEOP pressure cycles
- Flow rate
- Pressure drop
- Vibration test
- PMD bubble point
- Collapse pressure
- Non-destructive examinations – radiography and dye penetrant
- External leakage
- Burst pressure, see Figure 31

Figure 31: ATK P/N 80576 tank after burst

The normalized burst pressure of P/N 80576-1 Qualification Tank was 28.4 bar (412 psig), and the normalized burst pressure of the 80507-5 Qualification Tank was 28.5 bar (413 psig). The burst pressure data correlated with the analytical assessment that hoop and axial stresses have no correlation with cylinder length.

By the time we designed P/N 80576-2, there was sufficient confidence in the tank design that we took a QBS approach to tank qualification. The QBS process included analyses and a modal test on the P/N 80576-2 First Article. The QBS approach was in accordance with the Approach 2 to derivative tank development, with minimal qualification cost. It was the first time in ATK history that we used a QBS approach to qualify a *longer* tank. Given this new precedence, we expect to lengthen and qualify new hybrid tanks as opportunities arise in the future.

3.4. Final Thoughts on the 1150 mm (45.29 in) Tank Family

Figure 32 is a comparison of the seven 80507 and 80576 tank masses versus the five 80570 tank masses versus the 80520 tank mass. The masses are not-to-exceed numbers based on manufacturing tolerance. Our flight tank masses are usually lower than the not-to-exceed numbers. This chart could enable the extrapolation of tank masses anywhere along the two lines. For tank integrators interested in a derivative tank in the future, this chart could provide appropriate mass predictions.

ATK is now under contract to develop a propellant tank for an upcoming Mars mission. The propellant tank is another derivative of P/N 80507 tank. From the customer's perspective, the tank solution is low cost, low technical and schedule risk, and high performance. From ATK's perspective, we are providing our customer the best value. It is a win-win solution for both parties.

SECTION 4, CONCLUSION

With the maturing of conventional technologies and the advancement of new or enhanced methods and processes, the business of space flight is undergoing a high stake transformation. The *old* is competing with the *new*, but the focus on cost remains. In this summary paper, we provided several examples of derivative tank development to highlight the many advantages of a derivative tank approach. In an ideal environment without funding or schedule constraints, engineers should custom-design all space tanks to optimize performance and minimize risk. Realistically, engineers and managers must cope with multiple constraints such as cost, schedule, and risk when designing a space propulsion solution, and developing a derivative tank is often an effective approach towards addressing these constraints while generating a tank solution most suitable for space flight.

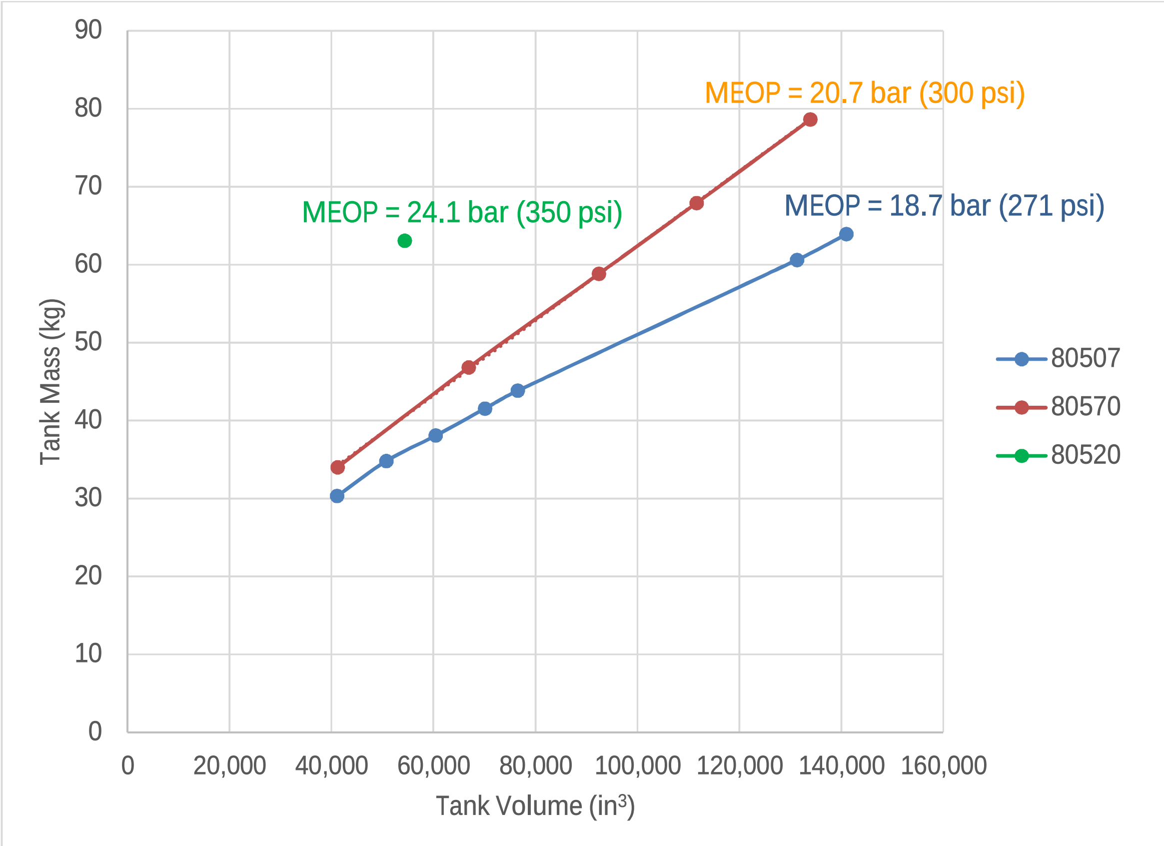


Figure 32: A comparison of the 80507/80576 and 80570 tank families

From ATK's perspective, a majority of our new tanks are derivative tanks. Quantitatively, we worked on 15 PMD design programs within the past five years. Two of these programs involved new tank sizes - the James Webb Space Telescope program, and the GEO Commercial Star 3 program. The rest of the programs, including LEO constellation, GEO Commercial, proprietary, and lunar lander programs all involved derivative shells, derivative PMDs, or both. From the literature, we noticed that the derivative tank approach is also in use at Airbus [19] [20]. From a business perspective, developing derivative tanks is the most effective method of meeting requirements at reduced technical, schedule, or cost risks. We suggest future studies on derivative tanks by other tank manufacturers to explore this tank development perspective.

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