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HYBRID PROPELLANT TANKS FOR SPACECRAFT AND LAUNCH VEHICLES

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ABSTRACT

Within the last ten years, the commercial communications satellite industry has seen increasing demand for satellites with larger capacity and longer on-orbit life. Both requirements lead to the development of propellant tanks with increasing volumetric capacity. However, due to the size limitation of launch vehicles, satellites and, therefore, satellite propellant tanks, can only grow in length rather than girth. As the traditional monolithic titanium tanks grew longer, they became less mass efficient, and technical, economical, and compliance issues demanded a new approach to the design and fabrication of satellite propellant tanks.

In response to this challenge, Pressure Systems, Inc. (PSI) developed a new generation of lightweight "hybrid" propellant tanks. These tanks have a blend of the characteristics of low-pressure, monolithic titanium propellant tanks and of high-pressure, Composite Overwrapped Pressure Vessels (COPV's).

This paper introduces the seven hybrid tanks developed by PSI, to date. Five of these tanks belong to the 35-inch diameter family of fuel tanks. The other two tanks were developed as the wrapped tank technology evolved to include an oxidizer tank and a launch vehicle diaphragm tank.

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INTRODUCTION

PSI has been a leading supplier of spacecraft propellant tanks since the 1960's. Of the more than 4,800 tanks delivered by PSI to date, over 95% are titanium tanks constructed of monolithic Solution Treated and Aged (STA) 6AL-4V titanium alloy. The analytical approaches, design methodologies, and manufacturing technologies of STA 6AL-4V titanium tanks have matured after decades of practical applications. These low weight, highly reliable tanks are well known by the Aerospace Industry. An example of a spherical propellant tank made from monolithic STA 6AL-4V titanium is shown in Figure 1.

Figure 1, a Spherical Tank Made From Monolithic STA 6AL-4V Titanium

Monolithic tanks are most weight-efficient when they are spherical. When a cylindrical center section is added to increase volumetric capacity, it becomes less weight efficient. Figure 2 shows a tank with two hemispherical heads and cylindrical center section.

Figure 2, a Tank with a Cylindrical Center Section

As commercial spacecraft becomes increasingly larger, the demand for tanks with higher capacity inevitably follows. Due to the diametric constraints of launch vehicles, satellites can only grow in height rather than girth. Consequently, satellite propellant tanks grow by adding cylindrical center sections or increasing the length of the center sections rather than increasing their diameters. As tanks grew longer, technical, economical, and compliance issues demand a new approach to the design and fabrication of aerospace propellant tanks.

In 1995, PSI began development of a new generation of "hybrid" propellant tanks for aerospace application. These new hybrid tanks were a mixture of monolithic tanks and Composite Overwrapped Pressure Vessels (COPV's). Each tank contains a metallic liner that's partially overwrapped with high performance composite. However, typical aerospace COPV's are fully wrapped, high-pressure pressurant tanks designed to maximize performance and minimize weight (high PV/W). For these hybrid propellant tanks, only the center section is overwrapped with composite. A summary of basic features of these hybrid propellant tanks is provided below:

- STA 6AL-4V titanium heads machined from forgings;
- Annealed cylinder made from rolled and welded 6AL-4V titanium sheets;
- Welded propellant tank liner made from multiple, high performance, GTA girth welds;
- Composite overwrapped cylindrical section.

The term "hybrid" appropriately describes these tanks which contain characteristics of both monolithic titanium propellant tanks and COPV pressurant tanks.

PSI P/N 80391

PSI P/N 80391 is the first hybrid propellant tank designed for a 3-axis stabilized, commercial geosynchronous communications satellite. The design requirements are shown in Table 1.

At the time of design, this tank was the longest tank ever built by PSI. The tank has a cylinder section that's over 71 inches long, resulting in a L/D ratio of greater than 3. There are also four mounting tabs that must be incorporated onto the cylinder to allow installation of the tank to the spacecraft structure. To fabricate this long cylinder using traditional manufacturing approaches, namely machine and mill from ring forgings, would make the cost of this tank prohibitively expensive. Additionally, the all-metal tank approach would not be able to meet the stiffness requirement without paying a significant weight penalty. Thus a less expensive and more weight efficient solution was developed in the form of a hybrid tank.

The key to a high performance wrapped tank is a lightweight, well-defined, and dimensionally consistent liner. The titanium liner for P/N 80391 was designed to such requirement. It consists of two rolled and seam welded annealed titanium cylinders, and two STA 6AL-4V titanium hemispherical heads. The heads include short cylindrical sections, so that the head/cylinder welds are overwrapped with composite. The liner is assembled with three girth welds. A completed liner is shown in Figure 3.

Figure 3, Titanium Liner for P/N 80391

High quality girth welds are crucial to a successful liner and a compliant wrapped tank. The weld technology to assemble the liner was developed and refined over many year of welding thin-wall tanks and COPV pressurant tank liners.[1,2,3,4] A close-up of this liner weld is shown in Figure 4.

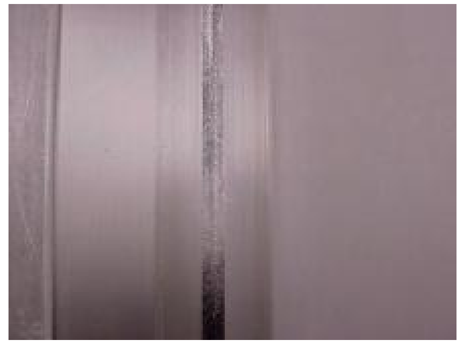


Figure 4, A Typical Liner Girth Weld

One of the major challenges faced by engineers and designers was the design and fabrication of the mounting tabs. The all-titanium solution would make the mounting tabs integral with the tank shell. For P/N 80391, however, a more cost effective solution was devised. The final design included four metallic sidemounts that are bonded to the tank after the liner is overwrapped with composite and then composite doilies are bonded over the side mounts, as shown in Figure 5.

Figure 5, 80391 Tank with Bonded Sidemounts

The tank acceptance test includes the standard proof and leakage tests, as well as a static load test to validate the bonding between mounting tabs and the tank shell. A picture of the completed P/N 80391, installed in test fixture, is shown in Figure 6. Upon delivery, all tank sidemounts are fully tested and meet all the specification requirements.

Table 1: PSI P/N 80391 Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	300 psig, 50 cycles
Proof Pressure	375 psig, 12 cycles
Burst Pressure	450 psig minimum
Material of Construction	Liner: 6AL-4V Titanium, STA Heads, Annealed cylinder Inlet/outlet Ports: 3Al-2.5V titanium tubes Composite Wrap: T1000 Sidemounts and Flexplate: 6AL-4V Titanium PMD: 6AL-4V and CP Titanium
Membrane Thickness	0.027 minimum on STA titanium heads
Tank Mount(s)	Bonded sidemounts (4 each, 90º apart) and upper flexplate (for struts)
Expulsion Efficiency	99.9% minimum
Propellant Load	3,198 lbm (1,451 kg) maximum Hydrazine
Design Fill Fraction	95% maximum
Tank Capacity	92,073 in^3 minimum
Internal Dimensions	35.26” ID x 106.56" long
Overall Length	111.41” nominal
Tank Weight	122 lbm (55.4 kg) maximum design weight
Propellant	Hydrazine
Fluid Compatibility	N_2H_4, GAr, GHe, GN_2, D.I. water, Isopropyl alcohol
Shell Leakage	$<1x10^{-6}$ std cc/sec He @ 300 psig
Natural Frequency	> 35 Hz, both lateral and thrust
Failure Mode	Leak Before Burst / Fracture Mechanics Safe-Life
Temperature Environment	-20°F to 160 °F (-29 °C to 71 °C)
Shelf Life	5 years maximum
On Orbit Life	15 years minimum

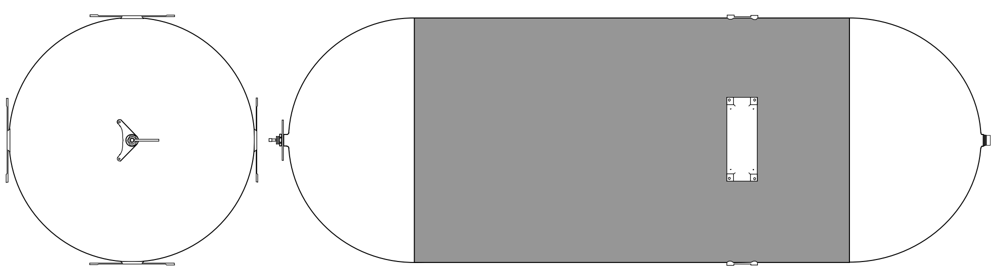


Table 2: PSI P/N 80395 Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	300 psig, 50 cycles
Proof Pressure	375 psig, 12 cycles
Burst Pressure	450 psig minimum
Material of Construction	Liner: 6AL-4V Titanium, STA Heads, Annealed cylinder Inlet/outlet Ports: 3Al-2.5V titanium tubes Composite Wrap: T1000 Mounting Tabs: 6AL-4V Titanium PMD: 6AL-4V and CP Titanium
Membrane Thickness	0.027 minimum on STA titanium heads
Tank Mount(s)	Bonded side tabs (4 each, 90º apart) and upper flex plate (for struts)
Expulsion Efficiency	99.9% minimum
Propellant Weight	2,233 lbm (1,012 kg) maximum Hydrazine
Design Fill Fraction	95% maximum
Tank Capacity	64,524 in^3 minimum
Internal Dimensions	35.26” ID x 78.34" long
Overall Length	83.19” nominal
Tank Weight	93.2 lbm (42.3 kg) maximum design weight
Propellant	Hydrazine
Fluid Compatibility	N_2H_4, GAr, Ghe, GN_2, D.I. water, Isopropyl alcohol
Shell Leakage	<1x10^{-6} std cc/sec He @ 300 psig
Natural Frequency	> 35 Hz, both lateral and thrust
Failure Mode	Leak Before Burst / Fracture Mechanics Safe-Life
Temperature Environment	-20°F to 160 °F (-29 °C to 71 °C)
Shelf Life	5 years maximum
On Orbit Life	15 years minimum

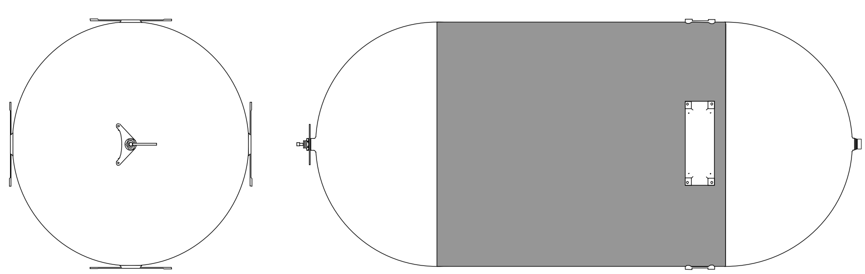


Figure 6, P/N 80391 in Test Fixture

Due to the heavy propellant load, the qualification vibration testing also posed significant challenges. Because the energy required to conduct the vibration test could not be supplied by a single vibration exciter (shaker), a dual-shaker setup was developed for the vibration testing, as shown in Figure 7. Many issues during testing, such as keeping the two shakers in phase, preventing overtest, and minimizing the wear and tear of the hardware, had to be overcome.

Figure 7a, Vibration Testing - Lateral

Figure 7b, Vibration Testing - Axial

P/N 80391 also contains a passive, all-titanium Propellant Management Device (PMD), whose function is to provide gas-free propellant delivery to the spacecraft thrusters. However, since the PMD is not the focus of this paper, the development of the PMD is not presented.

PSI P/N 80395

P/N 80395 was developed concurrently with P/N 80391. See Table 2 for tank requirements. This tank is 28 inches shorter than 80391. The only difference between the two shells is the length of the center section. Otherwise all other features are identical. The PMD in this tank is also identical to 80391 PMD, except shorter. Qualification was by similarity to P/N 80391, supported by a protoflight vibration test on the first flight tank. This approach of qualifying tanks with shorter center sections by similarity allows the customer added flexibility in packaging the spacecraft for optimal efficiency and performance without the added cost of a qualification program.

Both the 80391 and 80395 tanks are currently operating successfully in orbit.

PSI P/N 80425

PSI began development of P/N 80425 in 1999. This tank was also designed for a 3-axis stabilized, commercial geosynchronous communications satellite. The tank requirements are listed in Table 3.

P/N 80425 contains the same liner components as P/N 80391, except the liner is shorter and requires only one rolled and seam welded cylinder. This approach of designing derivative tanks using existing components significantly reduces the non-recurring cost of a new program, providing considerable savings on non-recurring items such as drawings, tooling, and process and manufacturing documentation. The total saving on this program was hundreds of thousand dollars.

The liner requires only two girth welds. Only minor modifications were made to the 80391 liner, such as tube length and orientation, to customize it for this new tank. A picture of the 80425 liner is shown in Figure 8.

Figure 8, PSI P/N 80425 liner in X-ray inspection.

The composite portion of P/N 80425, however, is very different from P/N 80391. This tank is skirt-mounted, and a lightweight composite skirt, shown in Figure 9, forms an integral part of the composite structure. The pre-fabricated composite skirt is first bonded to the metallic liner. The entire cylinder, including the bonded portion of the skirt, is then overwrapped with composite. A completed P/N 80425 tank is shown in Figure 10.

Figure 9, Composite Skirt for P/N 80425

Figure 10, P/N 80425 with Composite Skirt

Similar to P/N 80391 tank, the acceptance testing of each P/N 80425 flight tank includes a static load test to validate the bonding of the composites. Qualification testing included qualification level vibration test. Again, due to the high loads, a dual shaker setup was developed to test the Qualification Tank. A picture of the test setup is shown in Figure 11.

Figure 11, Dual Shaker Qualification Vibration Test for P/N 80425

Table 3: PSI P/N 80425 Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	300 psia, 50 cycles
Proof Pressure	375 psia, 12 cycles
Burst Pressure	450 psia, minimum
Material of Construction	Liner: 6AL-4V Titanium, STA Heads, Annealed cylinder Inlet/outlet Ports: 3Al-2.5V titanium tubes Composite Wrap: T1000 carbon fiber Mounting Skirt: T1000 carbon fiber PMD: 6AL-4V and CP Titanium
Membrane Thickness	0.027 minimum on STA titanium heads
Tank Mount(s)	Bonded composite skirt (12 tabs, equally spaced) and upper flex plate (for struts)
Expulsion Efficiency	99.75% minimum
Propellant Load	1,979 lbm (898 kg) maximum Hydrazine
Design Fill Fraction	95% maximum
Tank Capacity	57,215 in^3 minimum
Propellant Capacity	54,354 in^3 (95%)
Internal Dimensions	35.26" ID x 70.574" long
Overall Length	75.1" nominal
Tank Weight	70 lbm (31.75 kg) maximum design weight
Propellant	Hydrazine N_2H_4
Fluid Compatibility	N_2H_4, GAr, GHe, GN_2, D.I. water, Isopropyl alcohol
Shell Leakage	$<1x10^{-6}$ std cc/sec He @ 300 psia
Natural Frequency	> 70 Hz thrust, > 30 Hz lateral
Failure Mode	Leak Before Burst / Fracture Mechanics Safe-Life
Temperature Environment	50°F to 122°F (10°C to 50°C)
Shelf Life	3 years maximum
On Orbit Life	15 years minimum

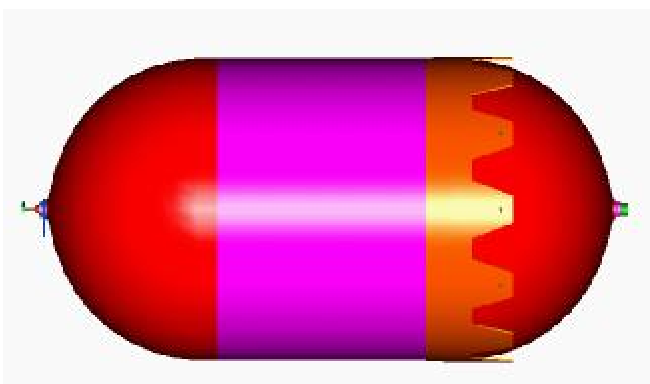
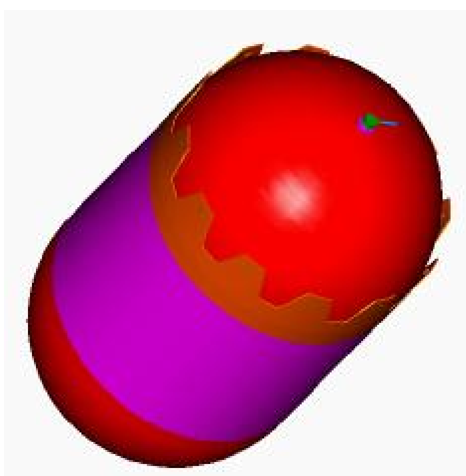


Table 4: PSI P/N 80432 Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	300 psia, 50 cycles
Proof Pressure	375 psia, 12 cycles
Burst Pressure	450 psia, minimum
Material of Construction	Liner: 6AL-4V Titanium, STA Heads, Annealed cylinder Inlet/outlet Ports: 3Al-2.5V titanium tubes Composite Wrap: T1000 carbon fiber Mounting Skirt: T1000 carbon fiber PMD: 6AL-4V and CP Titanium
Membrane Thickness	0.027 minimum on STA titanium heads
Tank Mount(s)	Bonded composite skirt (12 tabs, equally spaced) and upper flex plate (for struts)
Expulsion Efficiency	99.75% minimum
Propellant Load	1,802 lbm (817 kg) maximum Hydrazine
Design Fill Fraction	95% maximum
Tank Capacity	52,335 in^3 minimum
Internal Dimensions	35.26" ID x 65.574" long
Overall Length	70.1" nominal
Tank Weight	65.5 lbm (29.71 kg) maximum design weight
Propellant	Hydrazine N_2H_4
Fluid Compatibility	N_2H_4, GAr, GHe, GN_2, D.I. water, Isopropyl alcohol
Shell Leakage	$<1x10^{-6}$ std cc/sec He @ 300 psia
Natural Frequency	> 70 Hz thrust, > 30 Hz lateral
Failure Mode	Leak Before Burst / Fracture Mechanics Safe-Life
Temperature Environment	50°F to 122°F (10°C to 50°C)
Shelf Life	3 years maximum
On Orbit Life	15 years minimum



A new PMD, custom designed for the spacecraft mission, was developed for P/N 80425. The passive, all-titanium PMD was designed to accommodate multiple launch environments. The development and qualification of this tank, including the PMD, is presented in detail in Reference 5.

PSI P/N 80432

PSI P/N 80432 was developed concurrently with P/N 80425. The tank requirements are listed in Table 4. This tank is 5 inches shorter than P/N 80425. It also contains a similar but shorter PMD. Qualification of this tank is based on similarity to P/N 80425. A picture of 80432 is shown in Figure 12.

Figure 12, Liner for P/N 80432

PSI P/N 80434

PSI P/N 80434 is the newest member of the 35" diameter family of wrapped propellant tanks. At 136.7 inches in length, this tank is also the longest tank ever fabricated by PSI. The tank requirements are listed in Table 5.

Again maintaining the heritage developed previously, the same liner components in P/N 80391 are used to fabricate the new liner. However, due to its length, the new 80434 liner requires 3 rolled and seam welded cylinders, as shown in Figure 13. The liner requires four girth welds.

Figure 13, Liner for P/N 80434

Similar to P/N 80391 and 80395, this tank also includes four sidemounts that are bonded to the composite portion of the tank after the liner cylinder is wrapped. A completed tank is shown in Figure 14.

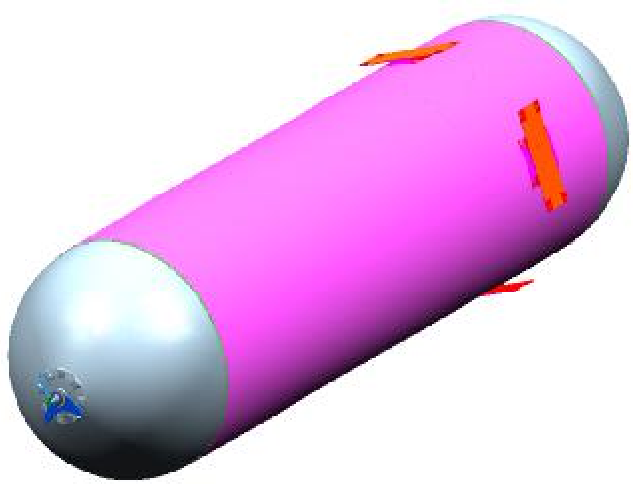
Figure 14, P/N 80434 in inspection

This tank contains a new PMD that's custom designed for the spacecraft mission. The passive, all-titanium PMD was designed to allow horizontal handling of the propellant tank and to accommodate multiple launch environments, including multiple erections and de-erections.

The qualification of this tank is not yet complete, as the program was terminated prior to the completion of qualification testing.

Table 5: PSI P/N 80434 Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	300 psia, 50 cycles
Proof Pressure	375 psia, 12 cycles
Burst Pressure	450 psia, minimum
Material of Construction	Liner: 6AL-4V Titanium, STA Heads, Annealed cylinder Inlet/outlet Ports: 3Al-2.5V titanium tubes Composite Wrap: G40-800 carbon fiber Sidemounts and Flexplate: 6AL-4V Titanium PMD: 6AL-4V and CP Titanium
Membrane Thickness	0.027 minimum on STA titanium heads
Tank Mount(s)	Bonded sidemounts (4 each, 90º apart) and upper flexplate (for struts)
Expulsion Efficiency	99.7% minimum
Design Fill Fraction	45% minimum
Tank Capacity	115,855 in^3 minimum
Internal Dimensions	35.26" ID x 131.35" long
Overall Length	136.702" nominal
Tank Weight	207.2 lbm (94.2 kg) maximum design weight
Propellant	Hydrazine N_2H_4
Fluid Compatibility	N_2H_4, GAr, GHe, GN_2, D.I. water, Isopropyl alcohol
Shell Leakage	$<1x10^{-6}$ std cc/sec He @ 300 psia
Natural Frequency	> 35 Hz, both lateral and thrust
Failure Mode	Leak Before Burst / Fracture Mechanics Safe-Life
Temperature Environment	-20°F to 160 °F (-29 °C to 71 °C)
Shelf Life	5 years maximum
On Orbit Life	15 years minimum



PSI P/N 80435

Unlike the previous five tanks, P/N 80435, at 22 inches in diameter, belongs to a different family of tanks. However, other than the difference in diameter, P/N 80435's design and construction is similar to the 35-inch diameter tanks. Its design requirements are presented in table 6.

Similar to the larger fuel tanks, this tank also has STA 6AL-4V titanium heads. There are two center sections made from rolled and welded 6AL-4V titanium sheets. The entire liner is assembled with three (3) girth welds, as shown in Figure 15. Because the liner thickness is the same as the 35-inch diameter tank, the same weld schedule is used, and weld development was not required.

Figure 15, Liner for P/N 80435

The same processes and procedures used for the 35-inch diameter tanks are also applicable to the P/N 80435 liner and tank, including bonding of a single mounting tab. A completed 80435 tank is shown in Figure 16.

Figure 16, A Completed P/N 80435

P/N 80435 is an oxidizer tank. Two of these tanks are used in conjunction with P/N 80434 fuel tank. These tanks are installed adjacent to the P/N 80434 tank in the spacecraft.

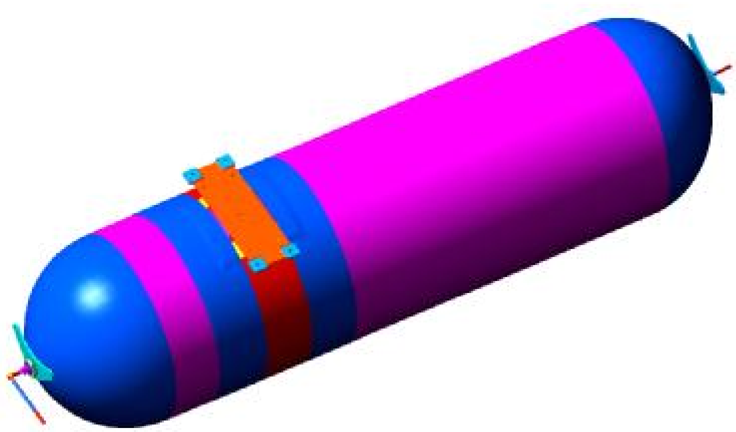
The 80435 tank contains a custom-designed PMD for the oxidizer tank application. The passive, all-titanium PMD was also designed to allow horizontal handling of the oxidizer tank and to accommodate multiple launch environments, including multiple erection and de-erections.

The selection of the tank diameter is based on heritage. The same STA titanium heads are used on several other tanks. Therefore, the tank shell required no development since all design and manufacturing technologies have been developed. The only development effort required was for the new PMD.

Similar to P/N 80434, the qualification of this tank is not yet complete. The program was terminated prior to the completion of qualification testing.

Table 6: PSI P/N 80435 Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	300 psia, 50 cycles
Proof Pressure	375 psia, 12 cycles
Burst Pressure	450 psia, minimum
Material of Construction	Liner: 6AL-4V Titanium, STA Heads, Annealed cylinder Inlet/outlet Ports: 3Al-2.5V titanium tubes Composite Wrap: G40-800 carbon fiber Sidemount and Flexplate: 6AL-4V Titanium PMD: 6AL-4V and CP Titanium
Membrane Thickness	0.028 minimum on STA titanium heads
Tank Mount(s)	Bonded sidemount and upper flexplate (for struts)
Expulsion Efficiency	99.9% minimum
Propellant Load	1,339 lbm (608 kg) @ 97% Fill Fraction
Design Fill Fraction	24% minimum
Tank Capacity	26,266 in^3 minimum
Internal Dimensions	21.25" ID x 81.6" long
Overall Length	90.05" nominal
Tank Weight	64.7 lbm (29.4 kg) maximum design weight
Propellant	MON-3 oxidizer
Fluid Compatibility	MON-3 oxidizer, GAr, GHe, GN_2, D.I. water, Isopropyl alcohol
Shell Leakage	$<1x10^{-6}$ std cc/sec He @ 300 psia
Natural Frequency	> 35 Hz, both lateral and thrust
Failure Mode	Leak Before Burst / Fracture Mechanics Safe-Life
Temperature Environment	-20°F to 160 °F (-29 °C to 71 °C)
Shelf Life	5 years maximum
On Orbit Life	15 years minimum



PSI P/N 80427

The previous six tanks presented thus far are all satellite propellant tanks containing PMD's. P/N 80427, however, is the first tank to deviate from this norm. The tank requirements are shown in Table 7. This is an unique tank in several respects:

- It is a launch vehicle propellant tank.
- It contains an AF-E-332 elastomeric diaphragm. See Figure 17. This tank is the newest diaphragm tank developed by PSI. The elastomeric diaphragm has a hemispherical section plus a cylindrical section. This design allows a fully reversable diaphragm.

Figure 17, Diaphragm for P/N 80427

- The tank does not have a high L/D ratio. The application of composite is based on economics. Machining of the angled mounting lugs integral with a rolled ring cylinder forging or welding machined lugs to the cylinder forging would make this tank more expensive.
- It contains two annealed titanium hemispherical heads. Because tank weight is not critical, the use of annealed heads is acceptable. These heads are spun from 6AL-4V titanium sheets. One of the heads is hemispherical. The second head contains both a hemispherical section and a cylindrical section. See Figure 18.

Figure 18, Annealed Heads for P/N 80427

- The tank is mounted on three bonded lugs. The lugs are all individually machined, adhesive bonded to the composite, and overwrapped by composite fiber at the base of the lugs.

Similar to previous hybrid tanks, the composite is applied over the cylinder section only. A completed P/N 80427 is shown in Figure 19.

Figure 19, A Completed P/N 80427

A static load test is conducted during acceptance testing to validate the adhesive bonds. Figure 20 shows the tank in the static load test fixture during acceptance testing.

Table 7: PSI P/N 80427 Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	550 psig
Proof Pressure	690 psig
Burst Pressure	825 psig
Material of Construction	Liner: 6AL-4V Titanium, Annealed Heads, Annealed cylinder Inlet/outlet Ports: 6AL-4V titanium to 321 CRES transition tubes Composite Wrap: T300/T800/T1000 carbon fibers Mounting and Anti-rotation Tabs: 6AL-4V titanium Elastomeric Diaphragm: AF-E-332
Membrane Thickness	0.040 minimum on annealed titanium heads
Tank Mount(s)	Bonded and overwrapped mounting and antirotation tabs (3 ea.)
Expulsion Efficiency	98.25% minimum
Propellant Load	343 lbm (156 kg) Hydrazine
Tank Capacity	10,431 in^3 minimum
Internal Dimensions	22.85" ID x 33.85" long
Overall Length	36.8" maximum
Tank Weight	42 lbm (19.1 kg) maximum design weight
Propellant	Hydrazine N_2H_4
Fluid Compatibility	N_2H_4, GAr, GHe, GN_2, D.I. water, Isopropyl alcohol
Shell Leakage	$<1x10^{-6}$ std cc/sec He @ 550 psig
Natural Frequency	109 Hz axial, 59 Hz & 194 Hz lateral
Failure Mode	Leak Before Burst / Fracture Mechanics Safe-Life
Temperature Environment	-35°F to 160°F (-37°C to 71°C)
Storage Life	10 years maximum

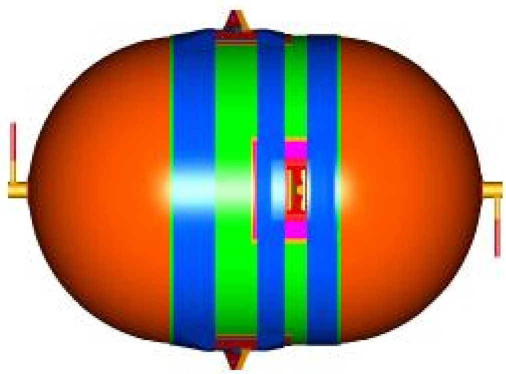


Figure 20, Static Load Test of P/N 80427

CONCLUSION

The hybrid propellant tank is an innovative solution to a new challenge as modern spacecraft evolve. The tank design takes advantage of favorable characteristics of both COPV and monolithic titanium tanks. Tank designers and engineers from both disciplines were involved in the development of this new technology. Several hybrid tanks, including P/N's 80391, 80395, 80432, and 80427, are functioning in orbit or functioned during a successful launch. Their successes demonstrates the feasibility of this innovative hybrid tank design.

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