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DESIGN AND MANUFACTURE OF A LIGHTWEIGHT FUEL TANK ASSEMBLY

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ABSTRACT

A fuel tank assembly is required for a commercial spacecraft. This tank must be light weight and provide gas-free expulsion of hydrazine propellant in a low gravity environment. An internally mounted surface tension propellant management device (PMD) is utilized to achieve this goal. The vane trough/trap type PMD, constructed of titanium, was custom designed for the spacecraft mission.

The tank shell is partially overwrapped with carbon fiber. To minimize cost, an existing tank shell liner was selected as baseline design and slightly modified for the mission.[1] No modification was done to the tank membrane. The propellant tank shell is constructed of solution treated and aged (STA) 6AL-4V titanium alloy. This material provides excellent strength to weight characteristics and is widely used in the aerospace industry for its excellent material properties and manufacturability. The overwrap and integral mounting skirt are fabricated from T-1000 carbon fiber for high strength and low weight. The PMD is constructed of annealed 6AL-4V titanium and commercially pure titanium material.

Stress and fracture mechanics analyses were performed to validate the tank shell for the spacecraft mission. PMD performance analysis was conducted to design the PMD. Qualification testing was conducted including pressure cycles, random and sine vibration and burst pressure testing.

INTRODUCTION

Pressure Systems Inc. (PSI) was contracted to provide propulsion system tanks for a commercial geosynchronous communications satellite. The spacecraft utilizes a dual mode propulsion system, and new hydrazine fuel and nitrogen tetroxide oxidizer tanks were developed.

The new hydrazine fuel tank is designed to store hydrazine propellant and gaseous helium pressurant, and provides this propellant to a complement of bipropellant thrusters via propellant manifolds during the three-axis stabilized velocity increment from geotransfer to geosynchronous orbit. It also provides hydrazine propellant to monopropellant thrusters for station keeping activities. The tank operates under a pressure regulated mode. A custom-designed, multi-element, internally-mounted surface tension propellant management device (PMD) ensures gas-free expulsion of propellant upon demand in this low gravity environment. A sketch of this tank is shown in Figure 1. One fuel tank is required per spacecraft. The propellant tank specification requirements are listed below in Table 1.

Figure 1: Fuel Tank Assembly

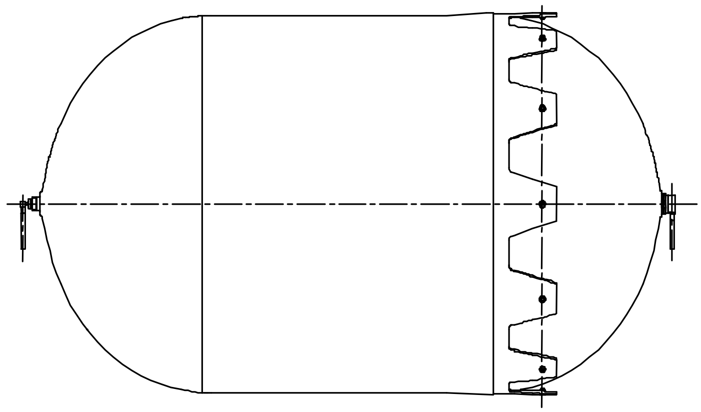


Table 1: Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	MEOP is 300 psia @ 50°C (122°F), 50 cycles
Proof Pressure	375 psia @ 50°C (122°F), 12 cycles
Burst Pressure	450 psia minimum @ 50°C (122°F)
Materials of Construction	Membrane: 6Al-4V titanium, solution treated and aged Overwrap: T1000 carbon fiber, amine resin Inlet/outlet ports: 3Al-2.5V titanium PMD: CP and 6Al-4V titanium
Expulsion Efficiency	99.75%
Propellant Weight	1980 lbm (898 kg) maximum hydrazine
Propellant fill fraction	65% minimum, 95% maximum
Tank Capacity	57,215 in^3 minimum
Internal dimension	35.25” ID x 69.2” long
Overall Length	75.1”
Tank Weight	70.0 lbm maximum
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 psia
Natural Frequency	> 30 Hz in lateral direction > 70 Hz in thrust direction
Failure Mode	Leak Before Burst
On-Orbit Temperatures	50 to 122 °F (10 to 50 °C)
Shelf Life	3 years minimum
On Orbit Life	15 years minimum

To minimize the overall program cost, an existing, flight qualified tank shell liner was selected as the baseline design, and modified to meet the specification requirements. This is a popular design approach widely used by PSI to maximize value and minimize cost. The cost reduction is the result of (1) eliminating the need to conduct a weld development and qualification program, (2) minimizing the number of new engineering drawings, shop travelers, and NC programs, and (3) maximizing the use of existing tooling. This design approach also provided schedule assurance to the customer. However, complete stress and fracture mechanics analyses were conducted to validate the tank shell in the new operating environment. A Qualification tank was constructed and testing was performed.

All completed flight tanks require acceptance testing prior to delivery. This testing includes a static load test as a validation of the workmanship in constructing and bonding the composite skirt to the tank shell.

TANK ANALYSES

The tank analyses included stress analysis and fracture mechanic analysis for the tank shell, stress analysis for the PMD, and the PMD performance analysis. Since the PMD is completely enclosed within the tank shell, by definition a fracture mechanics analysis is not required for the PMD. All analyses used assumptions, computer tools, test data and experimental data utilized on a majority of the pressure vessels and PMD's successfully designed, fabricated, tested and qualified during the past three decades. Conservatism was used throughout the analysis process, and the worst case scenarios were analyzed.

TANK SHELL STRESS ANALYSIS

A stress analysis was performed to establish that the tank meets the hydrazine tank specification requirements. The analysis took into consideration the requirements such as:

- Temperature environment;
- Material properties, STA titanium;
- Material properties, annealed titanium;
- Material Properties; carbon composite;
- Volumetric requirements;
- Mass properties of tank shell material;
- Mass properties of tank fluids;
- Fluids used in the tank;
- Tank pressurization history;
- External loads;
- Girth weld offset and weld suck-in;
- Size of girth weld bead;
- Resonant frequency;
- Tank boundary conditions;
- Residual stress in girth weld;
- Load reaction points; and
- Design safety factors.

This stress analysis validated the use of the existing tank shell liner design, new carbon mounting skirt and overwrap, for the new mission requirements. The analysis dynamic model provided predictions on the first resonant frequencies of the tank.

The analysis concluded that there are positive margins of safety for all design parameters, as summarized in Table 2.

Table 2: Propellant Tank Safety Margins

Characteristics	M.S.
Pressurant sphere, proof, yield	+0.13
Pressurant sphere, burst, ultimate	+0.01
Propellant sphere, proof, yield	+0.06
Propellant sphere, burst, ultimate	+0.11
Cylinder- liner, proof, yield	+0.43
Cylinder- liner, burst, ultimate	+0.28
Cylinder- composite, burst, ultimate	+1.90
Weld, proof, yield	+0.16
Weld, burst, ultimate	+0.05
Composite skirt, burst, bondline	+0.49
Outlet/inlet tube, yield	+28.41
Outlet/inlet tube, ultimate	+12.24

TANK SHELL FRACTURE MECHANICS ANALYSIS

A fracture mechanics analysis was performed to establish whether the growth of an initial flaw in the anticipated cyclic and sustained pressure environment as well as the dynamic environment might cause a failure in the tank shell. The analysis was performed using external and internal stresses from the stress analysis, and using NASA/FLAGRO with minimum thicknesses as parameters. Special fracture critical dye-penetrant and radiographic inspections are required to detect flaws. The minimum flaw size that can be detected by such special fracture critical inspections was used as initial flaw size for this fracture mechanics crack propagation analysis. The analysis was performed at:

- Girth welds and heat affected zones;
- Maximum pressure stress location in the hemisphere;
- Maximum stress location in the cylinder;
- Maximum stress location in the hemisphere/cylinder transition;
- Intersection between the hemisphere and the pressurant boss;
- Intersection between the hemisphere and the propellant boss; and
- Maximum external load stress in the hemisphere near the pressurant and the propellant bosses.

The fracture mechanics analysis established the leak-before-burst (LBB) characteristics of the propellant tank. This analysis concluded that the existing tank shell meets all the fracture mechanics requirements. The special NDE requirement established by this fracture mechanics analysis include:

- Special fracture critical dye-penetrant on all surfaces; and
- Special fracture critical radiograph of welds.

These requirements were instituted as part of the tank fabrication requirements.

PMD STRESS ANALYSIS

A PMD stress analysis was also performed to validate the structural integrity of the PMD design. The analysis took into consideration design requirements such as material properties, fluid properties, vibration loads, and design safety factors. The PMD stress analysis concluded that there are positive margins of safety for all design parameters, as summarized below:

Table 3: PMD Safety Margins

Characteristics	M.S.
Long Vane	>0
Trap Sphere	.02
Trap Cylinder	2.08
Center Post	.32
Outlet Side, Bridge	1.60
Outlet Side, Vertical	2.69
Trap Housing Weld	.28
Trap Housing Base	.06

PMD PERFORMANCE ANALYSIS AND PMD DESIGN

A comprehensive PMD performance analysis was performed to design and validate the PMD. The passive, all titanium, surface tension propellant management device was designed to provide gas-free hydrazine delivery throughout the spacecraft mission. As with most PMD's, this PMD was designed specifically for the spacecraft mission. The PMD is designed to (a) survive spinning operations, (b) provide gas-free propellant delivery throughout mission, including system priming, LAE ignition, and LAE steady state firing, and (c) provide gas-free propellant for station keeping.

The PMD was designed to be installed into the tank shell outlined in Figure 1, with 17.63-inch radius hemispherical heads and a 33.62-inch long cylindrical center section. It was designed for use with hydrazine propellant. Additional features were incorporated into the design to provide optimal service. First, because the PMD is a passive device with no moving parts, the design is inherently reliable. Second, the design is constructed entirely of titanium. Thus the PMD is lightweight and offers exceptional compatibility, long life, and reliability. Finally, the PMD was designed not only to provide propellant during steady flow conditions but also to allow some operation in some off design conditions, thus providing additional operational safety.

A sketch of the PMD is provided in Figure 2. The key components of this PMD are:

1) The center post and vanes,
2) The ring baffle,
3) The trough/trap housing,
4) The trough/trap entrance window,
5) The spin baffle,
6) The fins,
7) The liner, and
8) The perforated sheet windows.

All PMD components are located over the tank outlet.

The PMD is designed for use with hydrazine (N_2H_4). The design incorporates a center posted vane device[2] and a trough/trap[3] with integral pickup assembly. The PMD is constructed entirely of titanium. The center post and trough/trap assembly is welded into the propellant end of the tank and is restrained in the X and Y axes at the pressurant end of the tank. The pressurant hemisphere vanes are welded into the pressurant hemisphere.

The Vanes and Centerpost: The four vanes in each hemisphere are positioned on the ±X and ±Y axes and provide a flow path from the side of the tank to the tank outlet or pressurant end of the tank. The center post consists of a cruciform with 6 radial pieces of sheet metal and runs from the pressurant end of the tank to the trough/trap entrance. The center post provides a direct flow path from the pressurant end of the tank to the trough/trap entrance window. The vanes and center post are designed for on orbit operations (the center post also provides fuel during LAE ignition).

The Trough/Trap: The trough/trap is located over the tank outlet. The only entrance into the trough/trap is through a window at the top of the trough/trap, immediately below the center post. Just outboard in this window is a ring baffle designed to limit radial flow near the window. The trough/trap entrance window uses perforated sheet as a capillary barrier. Inside the trough/trap is a spin baffle, fins, and a perforated sheet liner. The spin baffle is a solid plate just below the trough/trap entrance window. The spin baffle contains openings at the outboard edge of the trough/trap housing. Several fins are mounted over each liner perforated sheet window and run up to the spin baffle. The liner is a solid sheet metal housing located just above the bottom of the trough/trap. The perforated sheet window is to allow flow into the outlet. Directly over the outlet is a last perforated sheet designed to minimize residuals. The trough/trap is designed to survive 60 rpm Z axis spin and provide propellant during all subsequent spinning operations.

The Perforated Sheet: The perforated sheet is located over the tank outlet, inside of the trough. This is the only location of a porous capillary barrier in the PMD design. This PMD contains no perforated sheet. The perforated sheet was chosen to have low flow losses while maintaining a bubble point in excess of twice the loads applied. The perforated sheet is fabricated from titanium sheet with electron beam drilled holes.

PMD OPERATIONS

The fuel tank PMD is designed to provide gas-free propellant to the tank outlet throughout the mission. During ground operations, the PMD has been designed to enable tank filling, tank handling, and tank draining. During launch, the PMD does not function and has been designed to maintain propellant over the trough/trap and not be adversely affected by the launch conditions encountered. During the final stages of ascent, the spacecraft is spun up to 60 rpm during which a large solid rocket upper stage motor is fired (AKM Firing). Subsequently, the spacecraft is despun from 60 rpm to <5 rpm without using any hydrazine. The PMD is been designed to provide gas-free hydrazine to despin the vehicle from 5 rpm to 0.1 rpm maximum about the Z axis. The PMD is also been designed to provide gas-free hydrazine during LAE firing and during lateral on orbit hydrazine thruster firing.

FLOW PATH THROUGH THE PMD

The flow path through the PMD is illustrated in Figure 3. The propellant flows up the vanes to both ends of the tank. The propellant flowing toward the pressurant end of the tank (opposite the outlet) will flow down the center post to the trough/trap entrance window. The propellant flowing toward the outlet of the tank will flow up the trough/trap housing and through the radial baffle to the trough/trap entrance window. After entering the trough/trap, the propellant flows around the spin baffle. Once in the main trough/trap compartment, propellant flows along the fins to the liner perforated sheet windows, through the windows and into the liner. The propellant then flows to the center of liner, through the outlet perforated sheet, and out the outlet.

Figure 2: PMD Configuration

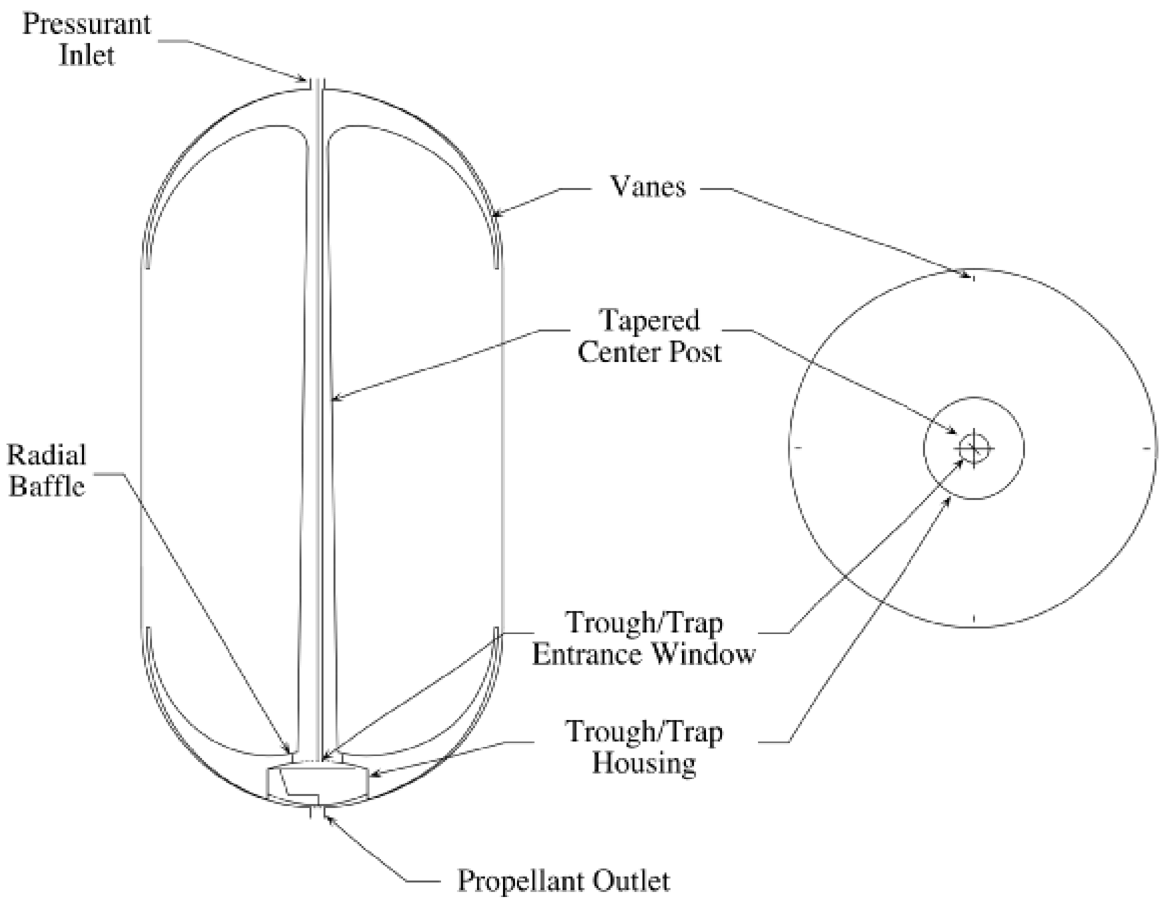
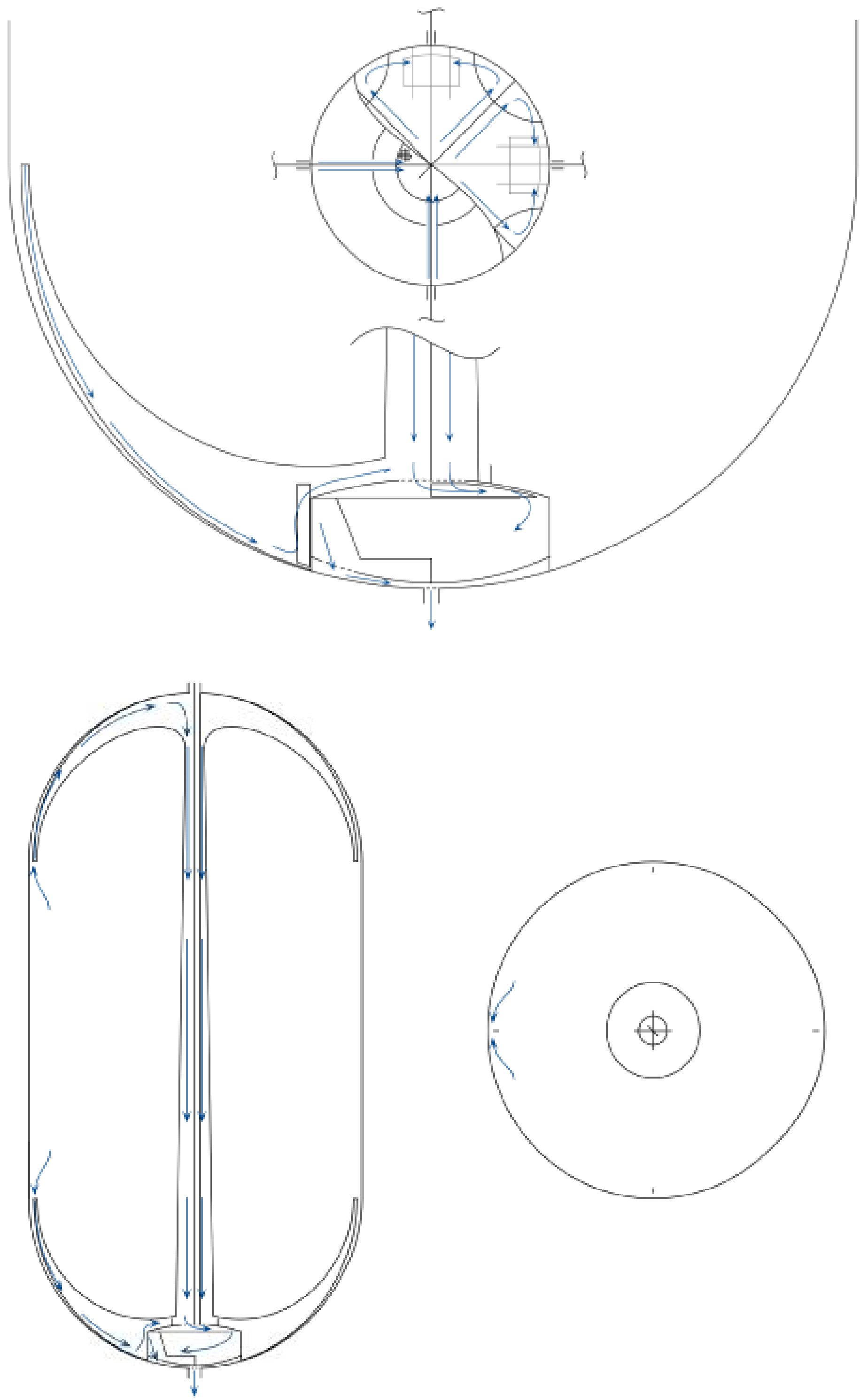


Figure 3: Flow Path Within the PMD



GROUND OPERATIONS

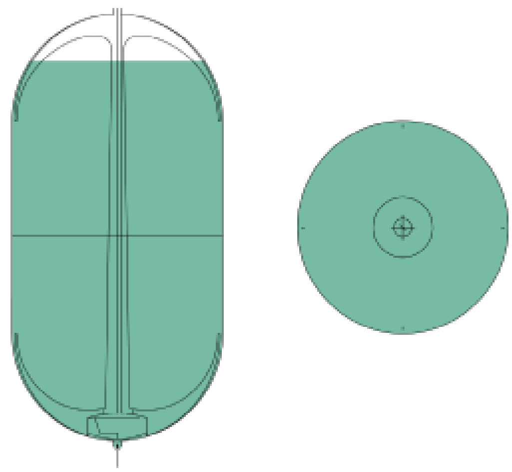
The ground operations can be divided into three parts; filling, handling, and draining. These are important not only from a flight standpoint but also from a testing standpoint. One must be able to fill the tank in a reasonable time when following a standard procedure. Similarly, handling and ground draining must be accomplished without excessive effort. Figure 4 shows these ground operations.

Filling: Filling occurs with the tank upright in the outlet down position. The tank is at atmospheric pressure when propellant is introduced into the tank through the propellant outlet line. During the filling process, a small quantity of gas may be trapped in the liner under the perforated sheet. Nominally, no gas should be trapped but if one assumes worst-case fill conditions, a small bubble may exist. This gas is compressed significantly during pressurization and is likely to be dissolved into the unsaturated propellant. In any case, the gas quantity is too small to be a concern. The filling process is straightforward and should introduce no difficulties either to the technician or to the PMD.

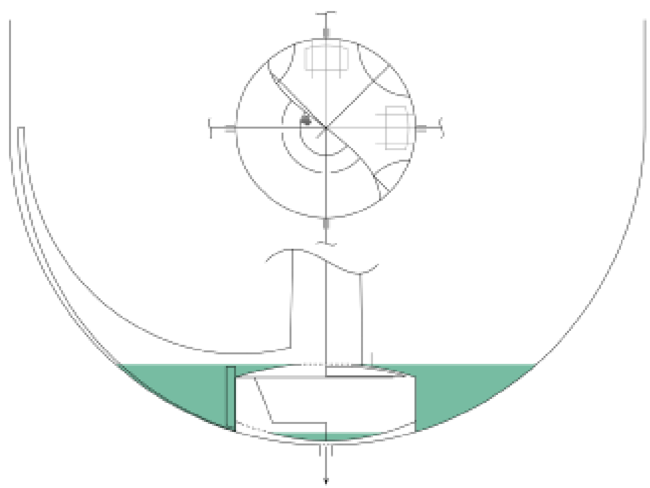
Handling: Typical handling occurs with the tank in the outlet down position. The tank can be tilted significantly before gas will come into contact with the trough/trap inlet perforated sheet. Gas will not enter the trough/trap or the outlet during handling. The slosh amplitude required to compromise the PMD functional design is so large that it is unlikely gas will come in contact with the perforated sheet (the center post will act as a baffle preventing gas from reaching the perforated sheet). The integrity of the PMD's functionality is assured.

Draining: Ground draining may have to be accomplished with hydrazine and certainly will occur with test fluids. The liquid remaining in the tank at the end of ground draining will have to be evaporated from the tank. The ground drain residuals are relatively large. As illustrated in the operational sequence a liquid pool outside the trough/trap and below entrance window will be left behind. Since the entrance window is elevated, this volume is relatively large. It was decided that PMD simplicity and functional reliability were more important than minimizing ground residuals. The tank will be drained in the outlet down position. Ground draining is not seen as a difficulty.

Figure 4: Ground Operations



Ground Fill
Ground Handling
Launch



Ground Drain

ASCENT OPERATIONS

Ascent operations can be divided into five stages: launch, 60 rpm spinning, AKM firing, despin to 5 rpm and 5 rpm spinning. The PMD has been designed to withstand the structural loads during these stages of ascent as well as provide gas-free propellant to the tank outlet during system priming, despin to 0.1 rpm, and LAE firings.

Launch: The PMD is designed to be launched in the outlet down position. Similar to upright ground handling, there is no perceived danger of ingesting gas into the trough/trap and/or outlet. Slosh is not foreseen as a force substantial enough to drive gas to the perforated sheet. In addition, the positioning of the center post above the trough/trap entrance window provides a fluid stagnation region where fluid velocities will always be small. Even if gas were driven down toward the trough/trap entrance window by slosh, the center post and the perforated sheet itself will prevent the gas from penetrating into the trough/trap. Launch is illustrated in the operational sequence (with filling and ground handling).

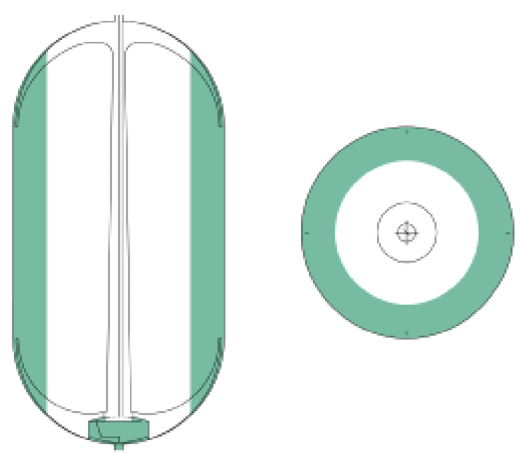
Simple Spin: After launch, the vehicle is spun up to 60 rpm about a spin axis parallel to the tank centerline. Fuel is not used to spin up or spin down the vehicle from 60 rpm. During spinning, the propellant is positioned outboard by the centripetal forces. The propellant interface is cylindrical and the trough/trap entrance is exposed to gas. The trough/trap entrance perforated sheet bubble point may not prevent gas from penetrating into the trough/trap. Any gas entering the trough/trap will be limited in volume by the spin baffle, which is solid near the tank centerline and open only outboard. The configuration of the trough/trap with a single entrance located on the tank centerline (spin axis) allows the device to act as a trough; holding liquid as a cup holds liquid in one g. The PMD has limited nutation angle capability at 60 rpm due to this spin baffle configuration (no nutation is required). Spinning at the minimum fill fraction is illustrated in Figure 5.

AKM Firing: While the vehicle is spinning at 60 rpm, AKM firing occurs producing a large axial acceleration. The propellant reorients in the tank with the surface a paraboloid of revolution. Propellant access is not required during AKM firing. The propellant motion created by the high g environment causes high loads on the PMD center post. The center post has been designed to accommodate these loads. AKM firing is not shown in the operational sequence.

Despin from 60 rpm: After AKM firing, the vehicle is despun to between 60 and 5 rpm very rapidly. The tangential acceleration created by the rapid despin is large compared to the centripetal acceleration and the propellant will move circumferentially in response to the acceleration. No hydrazine is required and the PMD is unaffected by despin. Despin from 60 rpm is not illustrated in the operational sequence.

5 rpm Spin: Following despin (and after separation from some launch vehicles), the spacecraft is spinning about the Z axis at up to 5 rpm. At 5 rpm, the propellant location is nearly identical to 60 rpm spinning. Within the trough/trap, the fins above the spin baffle cause propellant to rise and wet the perforated sheet. With the perforated sheet wetted, it will prevent any additional gas ingestion. The trough/trap is now acting as a trap, with a porous element preventing gas ingestion (thus the name trough/trap). It is possible that the spacecraft could enter a flat spin where the spin axis lies in the XY plane. The transition to flat spin and flat spin itself will not cause additional gas ingestion into the trough/trap.

Figure 5: Ascent Operations



60 rpm Z Axis Spinning

ORBITAL OPERATIONS

System Priming: System priming of the fuel lines occurs while a) spinning at up to 5 rpm about the Z axis, or b) spinning at up to 5 rpm about an axis in the XY plane, or c) in zero g. The propellant position during the three cases of system priming is illustrated in figure 6. The trough/trap entrance window may or may not be submerged with propellant. In worst-case, the trough/trap entrance window is exposed and gas is ingested into the trough/trap during system priming. The gas is kept away from the perforated sheet windows by the fins over the windows. The trough/trap is designed to retain this gas throughout mission.

Despin: Following system priming, the hydrazine propulsion system is active and the vehicle is despun from 5 rpm to 0.1 rpm about the Z axis using hydrazine. Again in the worst-case, the trough/trap entrance is exposed to gas and gas is drawn into the trough/trap during despin. Gas-free propellant is supplied to the outlet by the perforated sheet windows in the liner. The fins keep the windows submerged in propellant. The trough/trap has been sized to retain this gas throughout mission. Despin from 5 rpm to 0.1 rpm is illustrated in the operational sequence.

While spinning about the Z axis at 0.1 rpm, the propellant reorients into its zero g configuration. The low spin rate coupled with a small spin radius and the relatively high surface tension of hydrazine makes the 0.1 rpm Z axis spin negligible. With a Fill Fraction of 95%, the ullage bubble is very close to a sphere but is distorted by the center post. The bubble is pushed toward the top of the tank by the taper in the center post. At 47.7% FF, the ullage bubble can be in one of two equilibrium positions. In one position, the bubble is axisymmetric with each end of the bubble close to hemispherical but slightly distorted by the center post. The bubble will be pushed to the top of the tank by the tapered center post. In the second position, the bubble is asymmetric, not quite wrapping all the way around the center post. Both of these positions, as well as the 95% fill fraction fluid position, are illustrated in the operational sequence as early coast.

LAE Ignition and Firing: The initial and major use of propellant is for LAE ignition and firing. The LAE produces a settling acceleration reorienting all the propellant into a pool over the tank outlet. During the initial reorientation, propellant falls down the outer tank walls until it is forced upward at the tank centerline. A geyser results. Propellant in the center post will fall against this upward moving propellant; limiting the geyser height. The center post will provide gas-free propellant during LAE ignition. After the geyser is damped out, the propellant will be settled over the trough/trap entrance window and gas-free propellant is easily supplied. LAE ignition is illustrated in the operational sequence.

Station Keeping: After LAE firing, the spacecraft is on orbit where maneuvers primarily consist of lateral hydrazine thruster firings. The PMD vane system becomes operational and is designed to deliver gas-free propellant during the lateral accelerations produced by thruster operation. Small accelerations and low flow rates make gas-free propellant delivery possible using a simple vane device. These firings produce a relatively low lateral acceleration and require propellant delivery at low flow rates.

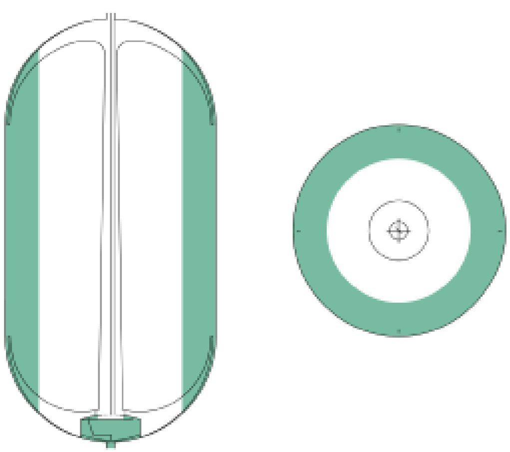
During thruster firings, the propellant will reorient to the cylinder sidewall as a result of the acceleration. However, the surface tension forces are sufficiently high that propellant surface will be highly curved. The propellant easily climbs up the vanes in a fillet formed in the tank wall/vane corner. Early in mission, the bulk propellant surface curvature will reach and submerged the entrance perforated sheet. Within the trough/trap, the fins will keep the perforated sheet submerged. Gas-free propellant delivery for unlimited duration lateral firings is assured. Early in mission lateral firing is illustrated in the operational sequence.

Zero g coast: During most of the spacecraft on orbit life, zero g coast is encountered. During zero g coast, the propellant will occupy a position minimizing the gas-liquid interfacial energy. This occurs when the sum of the reciprocal of the principal radii of curvature are identical. Most of the propellant will reside on the center post or around the center post and trough/trap tank wall intersection. In addition, a fillet of propellant will be adhere to the vanes. Within the trough/trap, the gas bubble is positioned inboard and upward by the fins.

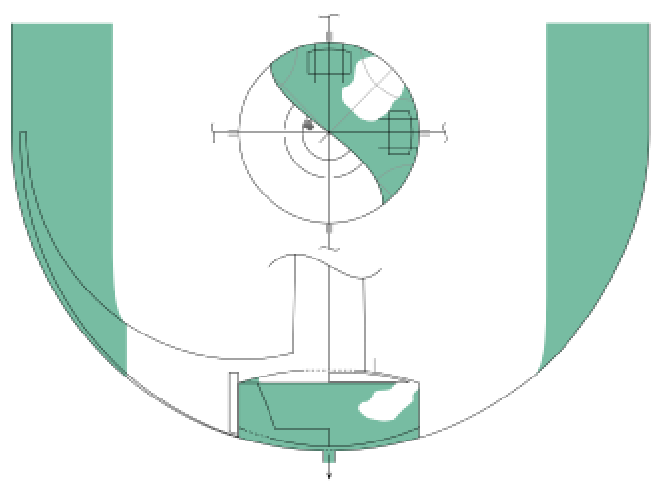
As propellant is consumed, a pool no longer forms on the tank cylinder wall during lateral firings. All the propellant is retained by the vane system. Propellant flows along the pressurant hemisphere vanes to the center post and down the center post to trough/trap entrance window. Alternately, the propellant flows along the propellant hemisphere vanes, up the clips that run up the trough/trap housing, and across the radial baffle to the trough/trap entrance window. The vast majority of propellant can be found on center post. A late lateral steady firing is illustrated in the operational sequence.

Depletion: Finally, depletion is illustrated in the operational sequence. During a steady long duration burn, the highest residuals occur. This is because a) the acceleration is applied for a sufficient period to reorient the propellant from its distributed location to the ends of the vanes and b) the flow losses cause a radius of curvature reduction near the trough/trap entrance window. The depletion transient is multistaged: as propellant is consumed, the radius of curvature along the vane decreases until the flow area on the vane near the center post can no longer supply the steady demand. At this point, the propellant on the center post will begin to be consumed to complement the inadequate flow up the vane. As the burn continues, the center post will no longer supply the propellant necessary to meet the demand and the propellant in the trough/trap will begin to be consumed. Eventually, as the liner perforated sheet flow area decreases, gas will be pulled through the liner perforated sheet, the liner propellant will be consumed and gas will be pulled through the outlet perforated sheet and into the outlet line. The ingestion of gas into the outlet line indicates depletion. The PMD has been designed to provide gas-free propellant to the tank outlet during the required conditions until the fill fraction of the tank falls below 0.5% maximum.

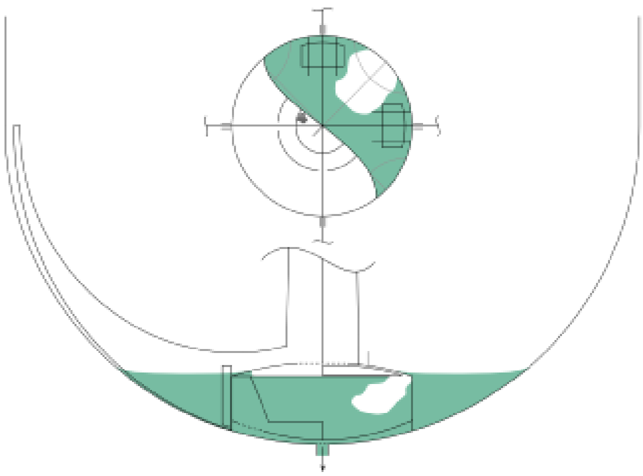
FIGURE 6: ORBITAL OPERATIONS



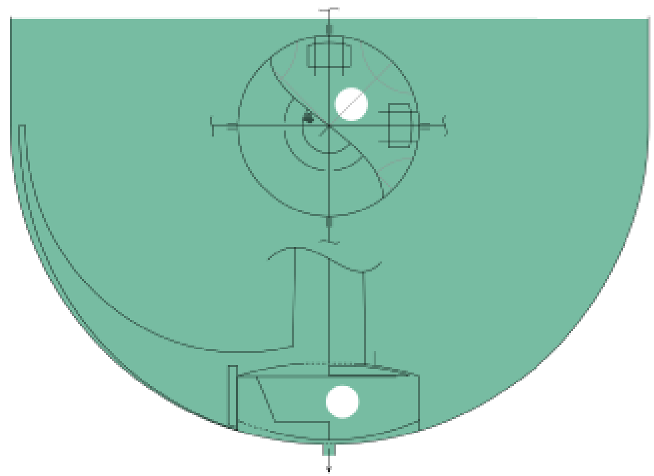
60 rpm Z Axis Spinning



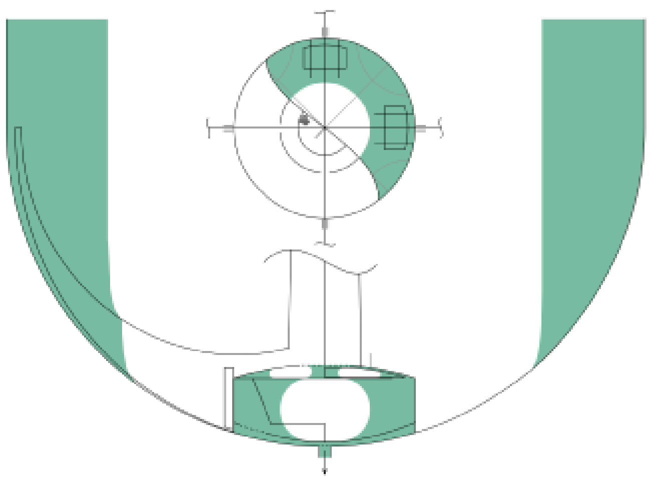
System Priming During 5 rpm Z Axis Spin



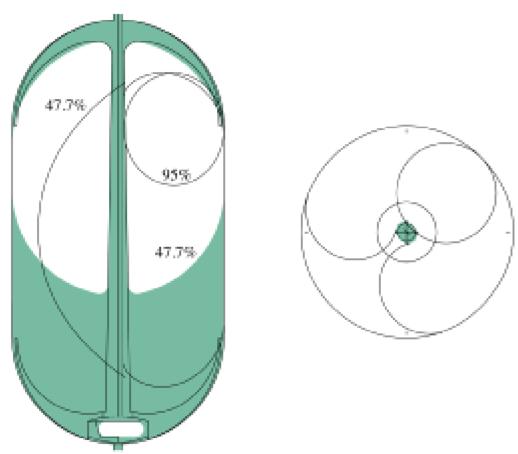
System Priming During Flat Spin



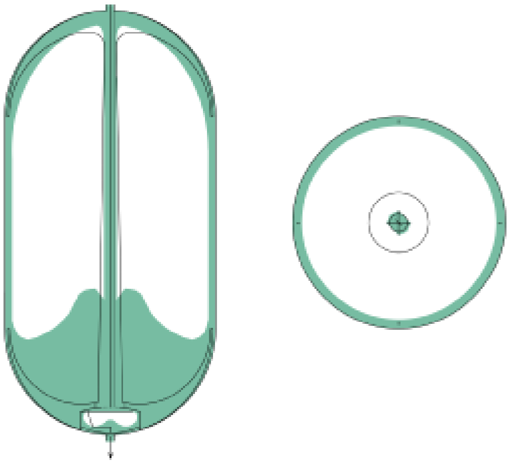
System Priming During Zero G



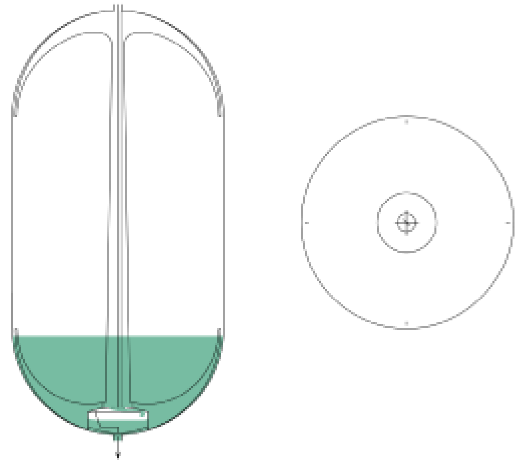
Despin From 5 rpm to 0.1 rpm



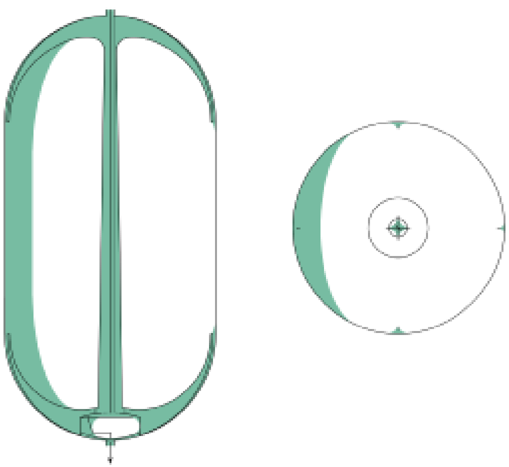
Early Coast



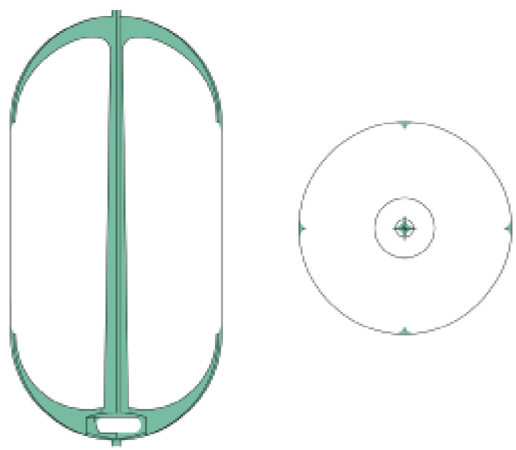
LAE Ignition



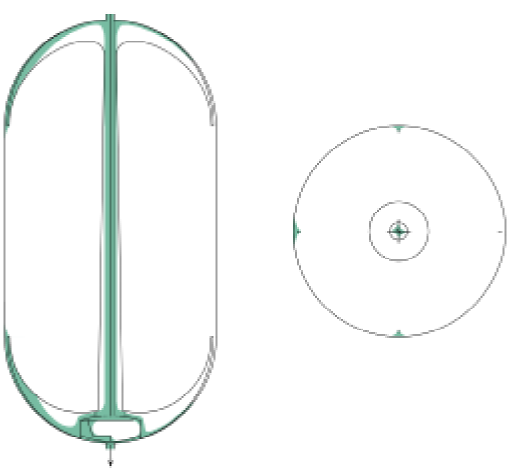
LAE Firing



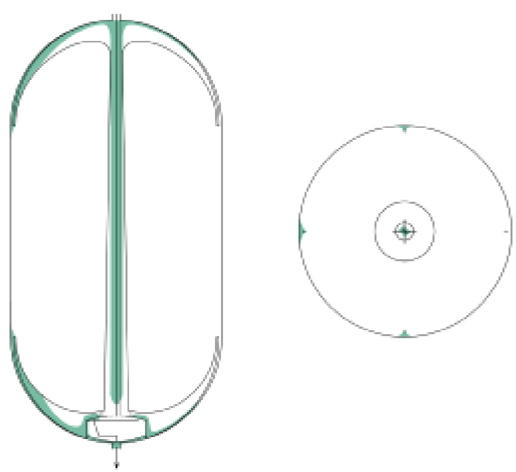
Early Lateral Steady Firing



Late Coast



Late Lateral Steady Firing



Depletion

TANK SHELL DESIGN HERITAGE

This fuel tank is a derivative of an existing, flight qualified tank. It belongs to PSI's family of 35.2-inch diameter carbon hoop-wrapped propellant tank product line. The titanium liner is the same as the heritage tanks. The carbon composite overwrap, carbon composite mounting skirt and the internal PMD were designed specifically for this tank. The PMD in this tank is more sophisticated than the PMD's in its predecessor tanks and offers significantly more capabilities. The composite skirt was designed to reinforce the girth weld in the liner as well as mount the tank to the spacecraft. The composite overwrap reinforces the cylindrical section of the liner.

TANK FABRICATION

The fuel tank shell consists of two hemispherical heads and a cylindrical center section. The two hemispherical shell components are machined from 6AL-4V titanium alloy forgings. The cylinder is fabricated from 6AL-4V sheet metal. All raw forgings have annealed properties at time of receipt. Each forging is rough machined, solution treated and aged, and finish machined to the tank shell thickness as required by the stress analysis. The solution heat treat process increases the strength of the titanium alloy, thus minimizing the weight of the tank shell. The excellent strength to weight property, coupled with its manufacturability, make this titanium alloy the material of choice for aerospace application. Figure 7 shows a machined hemispherical head.

Figure 7: A Machined Head

Vanes for the PMD are installed in the pressurant hemisphere. The cylinder is then welded to the pressurant hemisphere. Figure 8 shows the vanes inside this inlet assembly.

Figure 8: Inlet Head/Cylinder Assembly

The componenets of the trap/trough are welded into a PMD sub-assembly and bubble point tested. The centerpost assembly is welded to the trap/trough to create the PMD assembly. The PMD assembly is shown in Figure 9.

Figure 9: PMD Assembly

The PMD is installed in the propellant hemisphere over the propellant outlet to create an expulsion assembly. The expulsion assembly is shown in Figure 10.

Figure 10: Expulsion Assembly

Two girth welds are required to assemble the tank. The first weld joins the propellant hemisphere and the cylindrical center section. This is part of the inlet assembly shown in Figure 8. The second girth weld joins together the hemisphere/cylinder assembly to the pressurant hemisphere (with the PMD installed) to complete the tank liner. Both girth welds are subjected to radiographic and dye penetrant inspections. After closure the liner assembly is stress relieved in a vacuum furnace to remove residual stress from the weld operations. See Figure 11.

The composite skirt is manufactured separately and attached to the liner with a paste adhesive and the cylindrical section of the liner is filament wrapped with carbon fiber. The skirt and filament wound tank are shown in figures 12 and 13.

After winding, the pressurant port shear plate is machined and installed. The completed tank is acceptance tested, precision cleaned and shipped to the customer. The completed tank is shown in figure 14.

Figure 11: Tank Liner Assembly

Figure 12: Composite Skirt

Figure 13: Filament Wound Tank

Figure 14: A Completed Fuel Tank Assembly

QUALIFICATION TEST PROGRAM

Qualification testing consists of the following tests:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- PMD bubble point test
- Vibration test
- External leakage test
- Proof pressure cycle test
- MEOP pressure cycle test
- Differential pressure test
- PMD bubble point test
- External leakage test
- Penetrant inspection of exposed welds
- Radiographic inspection of exposed welds
- Mass measurement
- Final visual examination
- Burst pressure test

Conservatism is exercised throughout the test program, and all pressure testing is temperature adjusted for the worst case operating temperature (50°C). Pass/Fail criteria consist of acceptance type external leakage and PMD bubble point tests conducted at intervals throughout the test program.

Volumetric Capacity Examination: The capacity of the fuel tank is measured utilizing the weight of water method, using filtered deionized water as the test medium. This test is conducted before and after the proof pressure test to verify that the proof pressure test does not significantly alter the tank capacity. A successful validation indicates that the tank shell is manufactured properly and that the tank can operate in the pressure environment under which it was designed for. Typically, the volumetric growth after proof pressure test is zero.

The post-proof test capacity examination also serves to verify that the tank meets the designed volume requirement.

Proof Pressure Test: The proof pressure test is typically the first pressurization cycle applied to the tank after fabrication. It is intended to validate the workmanship by verifying the strength and integrity of the tank shell. The test must be conducted in a “safe” environment to minimize hazards to test technicians. The test is conducted hydrostatically at proof pressure (375 psia, normalized for test temperature) for a pressure hold period of 1 minute minimum.

PMD Bubble Point Test: The PMD bubble point is measured at various times during the test procedure to ensure proper function of the porous elements in the PMD. Testing is conducted using isopropyl alcohol.

Qualification Vibration Test: The vibration test is designed to verify the structural design of the PMD and the integrity of the tank shell. There are two phases of the vibration testing: wet and dry random and wet and dry sine. The three principal axes are tested at each phase. The vibration spectrum is listed below in Tables 4 through 7. For both wet random and wet sine vibration testing, the qualification tank is loaded with 1980 lbm of deionized water. The tank is pressurized to MEOP for all vibration testing.

The vibration test fixture is designed to simulate the tank-to-spacecraft installation interface. The fixture is also sufficiently stiff to be considered rigid for the test frequencies. The vibration test set-up is shown in figure 15.

Figure 15: Lateral Vibration Test Set-up

Control accelerometers are placed on the vibration test fixture at four locations by the composite skirt and near the attachment boss to control energy input. Tri-axial response accelerometers are used to monitor the tank responses.

External Leakage Test: The tank shell is tested at various times during the test procedure for leakage of the shell by pressurizing the tank to MEOP with helium and measuring the leak rate in a vacuum chamber using a mass spectrometer. The tank is placed in a vacuum chamber, evacuated to under 0.2 microns of mercury, and helium pressurized to 300 psia for 30 minutes. The helium leak rate cannot exceed 1×10^{-6} std cc per second after a 10-minute stabilization period.

Proof and MEOP Pressure Cycling: Proof and MEOP pressure cycling is conducted similar to the Proof Pressure Test. A total of 12 Proof cycles and 50 MEOP cycles to show that the tank is capable of surviving four expected life cycles.

Differential Pressure Test: The fuel tank must meet the pressure drop requirement of not-to-exceed 5.0 psid at a maximum flow rate of 0.1 lbm/sec. The test is conducted by measuring the pressure differential between the ullage and the tank outlet while pressurizing the tank (and the test fluid) through the pressurant port. The measured differential pressure was 4.0 psid.

Weld Inspection: All exposed welds (on tubes and outlet fittings) are inspected using radiographic and fluorescent penetrant techniques. Tank shell axial and girth welds are not accessible due to the composite overwrap.

Table 4: Dry Sine Vibration Levels

Axis	Frequency Range (Hz)	Acceleration (g)	Sweep Rate
Spacecraft	4 – 11	0.50" DA*	
Lateral(X, Y axis)	11 – 100	3.1	2 oct/min
Spacecraft	4-9.5	0.50" DA*	
Thrust (Z axis)	9.5 - 100	2.3	2 oct/min

Table 5: Wet Sine Vibration Levels

Axis	Frequency Range (Hz)	Acceleration (g)	Sweep Rate
Spacecraft Lateral (X & Y axis)	4 – 14.4	0.50" DA*	2 oct/min
	14.4 – 50	5.3	
	50 - 100	2.25	
Spacecraft Thrust (Z axis)	10 – 35	0.1597" DA*	2 oct/min
	35 – 50	10.0	
	50 - 100	5.0	

* DA: Double Amplitude

Table 6: Dry Random Vibration Levels

Axis	Frequency Range (Hz)	PSD** Level (g^2/Hz)
X, Y and Z	20 20-50 50-600 600-2000 2000	0.01 +2.1 dB/oct 0.01875 –1.6 dB/oct 0.01
Overall 5.4 G_{rms} Duration: 120 seconds per axis		

Table 7: Wet Random Vibration Levels

Axis	Frequency Range (Hz)	PSD** Level (g^2/Hz)
X, Y and Z	20 20-50 50-600 600-2000 2000	0.0025 +13.4 dB/oct 0.15 –10.2 dB/oct 0.0025
Overall 10.9 G_{rms} Duration: 120 seconds per axis		

**PSD: Power Spectral Density

Burst Test: The qualification tank burst pressure was validated by testing to the required burst pressure of 483 psi. The tank actually burst at 557 psi. The burst tank is shown in figure 16.

Figure 16: Burst Tank

ACCEPTANCE TESTING

After the flight tank is assembled, it is subjected to the following acceptance tests prior to delivery:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure
- Post-proof volumetric capacity
- Static Load
- PMD bubble point test
- External leakage test
- Penetrant inspection of exposed welds
- Radiographic inspection of exposed welds
- Mass measurement
- Final visual examination
- Cleanliness

Acceptance tests are similar to qualification tests previously described with the following additions:

Static Load: The integrity of the bond between the composite skirt ant the titanium liner, and the workmanship of the composite skirt are verified with a series of static load tests. The tank is mounted in a fixture similar to the vibratation fixture, and the tank is externally loaded to simulate flight loads. Successful completion of this test with no damage to the tank is acceptance of the hardware.

Cleanliness Verification: After all testing is complete, the interior of each flight tank is cleaned to the cleanliness level specified below in Table 8:

Table 8: Tank Cleanliness Level

Particle Size Range (Microns)	Maximum Allowed per 100 ml
Less than 5	Unlimited
5 to 10	600
11 to 25	80
26 to 50	20
51 to 100	4
101 and over	0

CONCLUSION

The fuel tank assembly has successfully completed qualification testing. The production program is in progress and five flight tanks have been delivered.

The fuel tank PMD is specifically designed to meet the mission requirements. The PMD is a robust design. It has been qualification tested and shows excellent strength, durability, and reliability.

The fuel tank assembly is lightweight, high performance, and easy to manufacture. The tank assembly is accomplished using standard manufacturing processes and procedures. Special materials and processes are not required.

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