DESIGN AND MANUFACTURE OF A PROPELLANT TANK ASSEMBLY

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ABSTRACT

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

To minimize the non-recurring program cost, an existing tank shell design was selected for the mission. This tank shell was slightly modified at the bosses to allow mounting to the spacecraft structure. No modification was done to the tank membrane to maintain qualification-by-similarity.

The propellant tank shell is constructed of annealed 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 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 not required, but a qualification-by-similarity analysis was performed to validate the tank shell. A protoflight test program, including vibration testing, was performed on the first flight tank.

INTRODUCTION

A propellant tank assembly is designed to provide hydrazine for a geosynchronous communications satellite. This tank uses an internally mounted surface tension propellant management device (PMD) to provide gas-free expulsion of propellant upon demand in a low gravity environment. A sketch of this tank, with an outline of the PMD, is shown in Figure 1. Two tanks are required per spacecraft.

The PMD is custom designed to meet the mission requirements. However, the tank shell is based on an existing design to minimize overall program cost. The selection of tank shell is primarily based upon cost, capacity, mounting capability, and adaptability to qualification-by-similarity (QBS).

Analyses were conducted to validate the tank shell and design the PMD. A QBS analysis was performed to maintain the qualification status of the new tank. The first flight tank was subjected to a series of protoflight tests. All subsequent flight tanks were subjected to acceptance testing. The production program was completed in January 2000.

The propellant tank was designed to the requirements in Table 1:

Figure 1: Propellant Tank Assembly

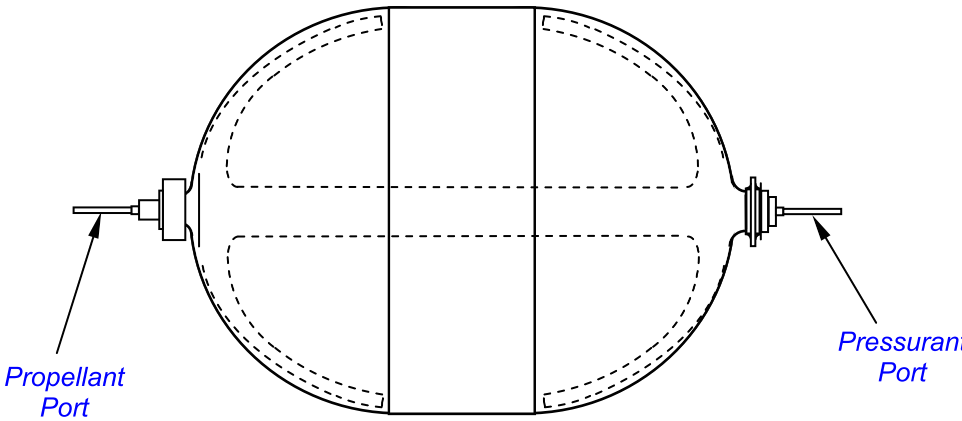


Table 1: Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	400 psia @ 50°C, 50 cycles
Proof Pressure	500 psia @ 50°C, 12 cycles
Burst Pressure	600 psia minimum @ 50°C
Material of Construction	Membrane: 6Al-4V Titanium, annealed Inlet/outlet ports: 3Al-2.5V titanium to 304L stainless steel transition tubes
Expulsion Efficiency	99.6% minimum
Propellant Weight	251 lbm maximum Hydrazine
Propellant fill fraction	60% minimum
Tank Capacity	9200 in^3 minimum
Size	22.14” ID x 31.41” long,
Overall Length	40.17”
Tank Weight	20.5 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 @ 400 psia
Natural Frequency	> 43 Hz, both lateral and thrust
Failure Mode	Leak Before Burst
On-Orbit Temperatures	54 °F to 104 °F
Shelf Life	5 years minimum
On Orbit Life	12 years minimum

DESIGN ANALYSES

The tank design 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.

The tank design analysis approach 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, and the worst case scenarios were analyzed.

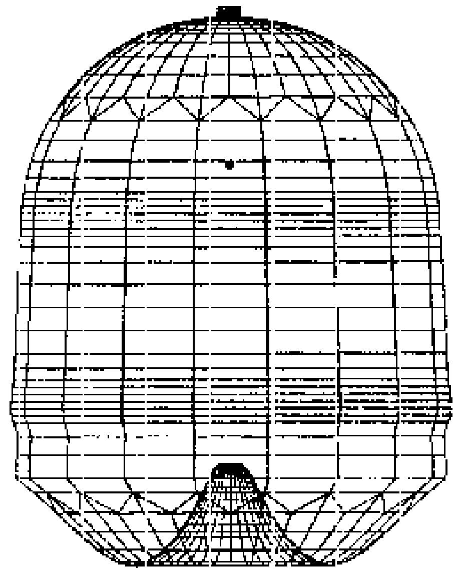
TANK SHELL STRESS ANALYSIS

A stress analysis was performed to design and analyze the tank shell. The analysis took into consideration the design requirements such as:

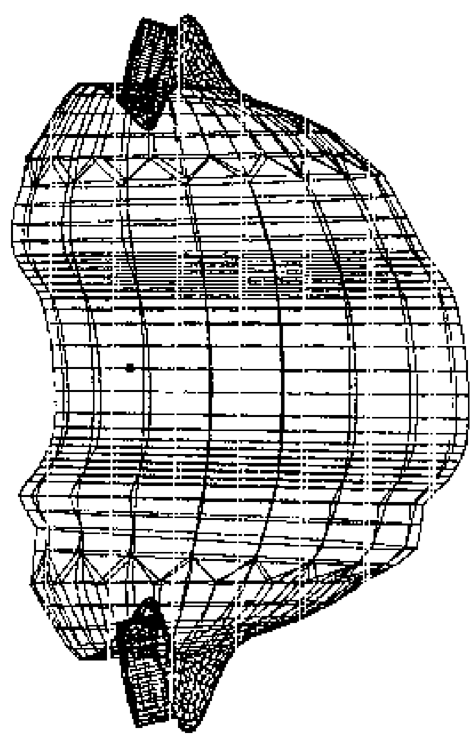
- Temperature environment;
- Material properties;
- Volumetric requirements;
- Mass properties of tank shell material;
- Mass properties of fluid;
- Fluids used by the tank;
- Tank pressurization history;
- External loads;
- Girth weld offset and weld suck-in;
- Size of girth weld bead;
- Resonant frequency;
- 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 design, plus the modified mounting features, for the new mission requirements. The analysis also provided predictions on the resonant frequencies. Figure 2 shows some of the vibration modes from the analysis. The analysis concluded with positive margins of safety for all design parameters, as summarized in Table 2.

Figure 2: Some Vibration Modes



Mode 1



Mode 2

Table 2: Propellant Tank Safety Margins

Characteristics	M.S.
Membrane, sphere, burst	+0.088
Membrane, sphere, proof	+0.205
Membrane, cylinder, burst	+0.100
Membrane, cylinder, proof	+0.210
Boss area, burst	+0.040
Boss area, proof	+0.150
Weld area, burst	+0.110
Weld area, proof	+0.210
Lines, burst	+5.300
Lines, proof	+4.900
Tank external loads, yield	+0.150
Tank external loads, ultimate	+0.090

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 may 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 sizes that can be detected by such special fracture critical inspections were 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.

PMD STRESS ANALYSIS

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

Table 3: PMD Safety Margins

Characteristics	M.S.
Dry random, PMD post, yield	+6.70
Dry random, PMD post, ultimate	+6.30
Wet random, PMD post, yield	+6.50
Wet random, PMD post, ultimate	+6.10
Slosh, PMD post, yield	+11.90
Slosh, PMD post, ultimate	+11.30
Vane, yield	+0.56
Vane, ultimate	+0.48
Pressurant end fitting, yield	+9.40
Pressurant end fitting, ultimate	+8.90
Propellant end fitting, yield	+1.43
Propellant end fitting, ultimate	+1.31

PMD ANALYSIS AND DESIGN

A 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 is designed specifically for the spacecraft mission. The PMD is designed to provide propellant during nutation control, despin, thruster ignition, steady state firing, and pulsed thruster activity during all orbital operations.

Figure 8: PMD Operational Sequence (Pt 1 of 3)

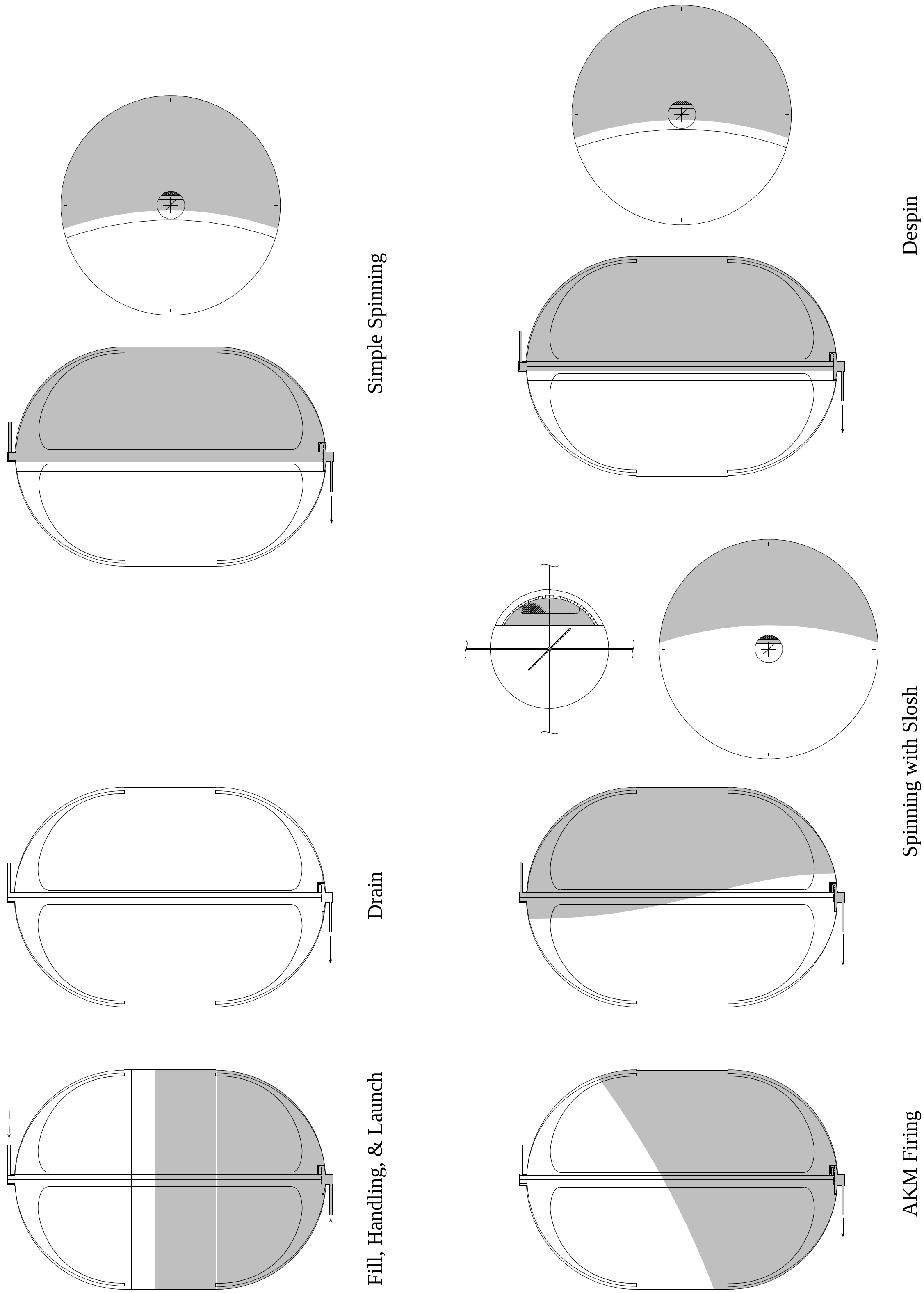


Figure 8: PMD Operational Sequence (Pt 2 of 3)

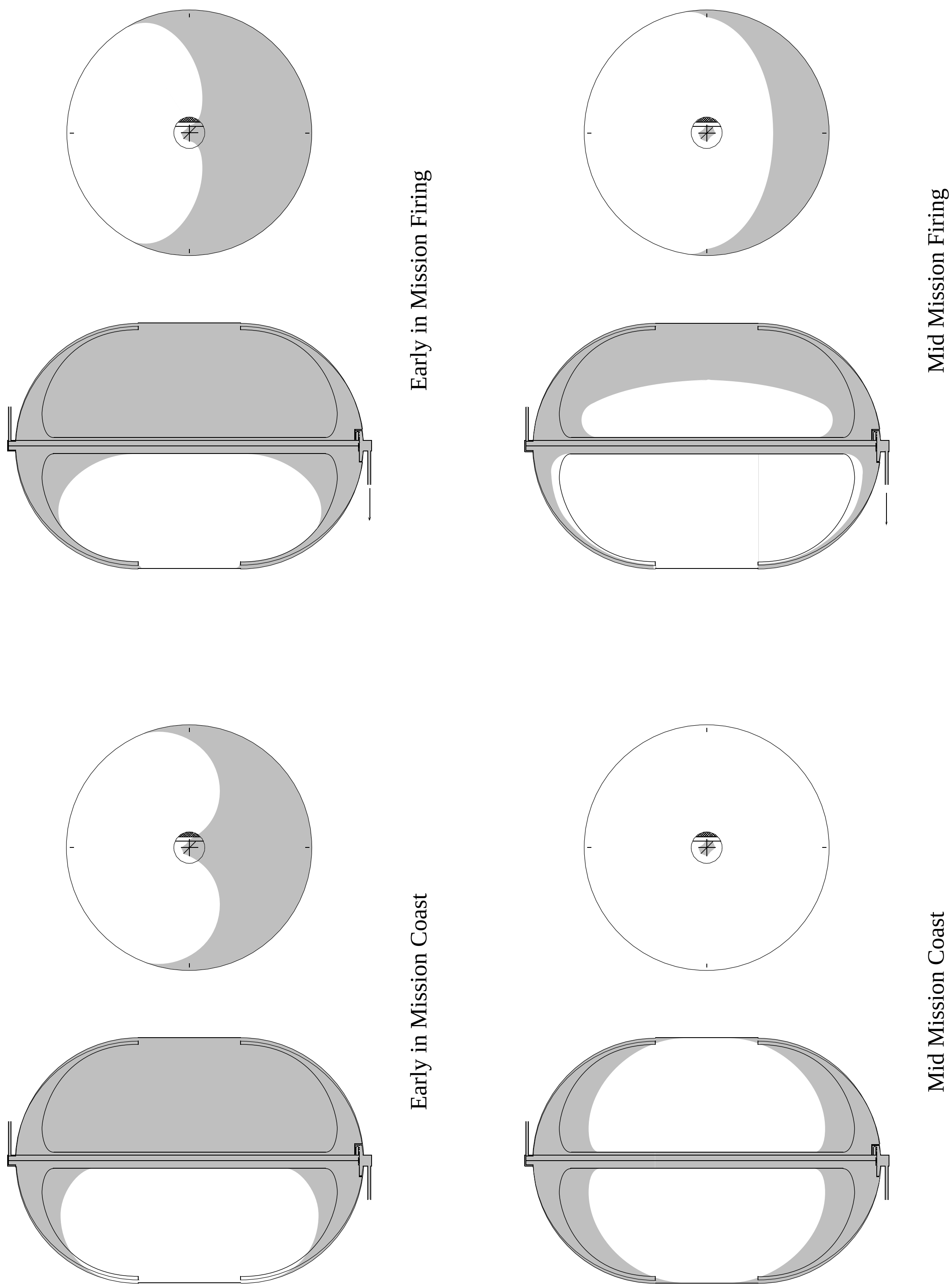
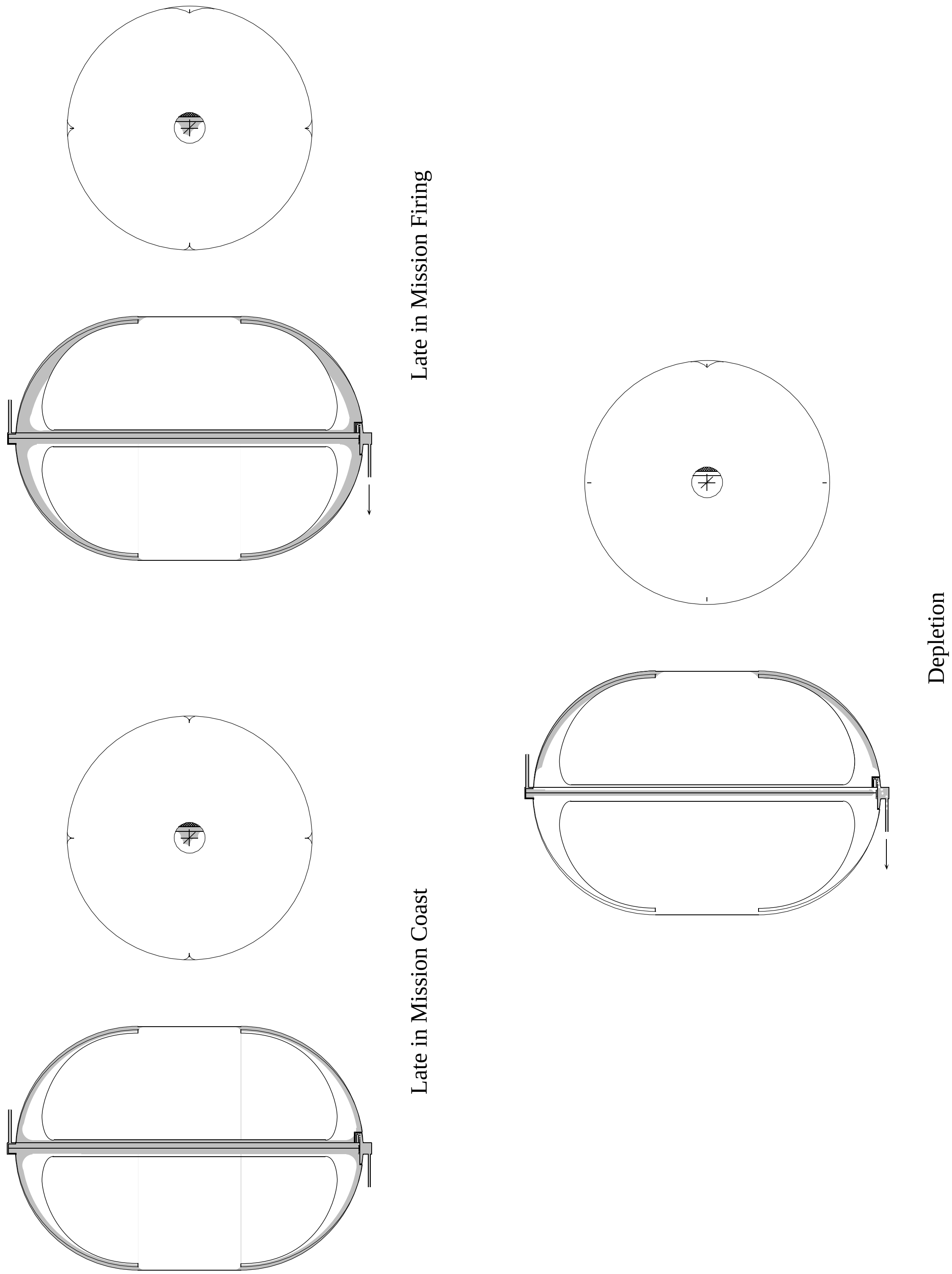


Figure 8: PMD Operational Sequence (Pt 3 of 3)



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. The operational sequence presented in Figure 8 shows these ground operations.

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 under screen. A high flow rate during fill will push the gas through the screen and out of the outlet region. In addition, 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.

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 screen. Gas will not enter 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 screen (the PMD itself will act as a baffle preventing gas from reaching the screen). The integrity of the PMD's functionality is assured. Upright handling is illustrated in Figure 8, the operational sequence.

Ground draining may have to be accomplished with propellants 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. It is desirable to minimize this quantity of liquid. The tank should be drained in the outlet down position. A small tilt may slightly increase ground drain residuals as liquid is trapped in a pool near the outlet. The ground drain residuals will be minimized by preventing significant tilt of the tank assembly during draining. Ground draining is not seen as a difficulty.

Ascent Operations: Ascent operations can be divided into four stages: launch, 65 rpm spinning, AKM firing, and despin. The PMD has been designed to withstand the structural loads during these stages of ascent.

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 outlet pick up assembly (downstream of the screen). Slosh is not foreseen as a force substantial enough to drive gas to the screen. In addition, the positioning of the center post above the pick up assembly provides a fluid stagnation region where fluid velocities will always be small. Even if gas were driven down toward the pick up assembly by slosh, the center post and the screen itself will prevent the gas from penetrating into the outlet. Launch is illustrated in the operational sequence with the propellant position identical to ground handling.

After the initial launch, the vehicle is spun up to 65 rpm about a spin axis parallel to the tank centerline and 33 inches away. Propellant is not used to spin up the vehicle but is required subsequently. System priming is not anticipated and, therefore, the propulsion system is operational after the initial launch. During simple spinning, the propellant is positioned outboard by the centripetal forces. The propellant interface is cylindrical and the trough entrance is submerged by at least 1 inch of propellant (2 inches of submergence depth is recommended). Propellant access is straightforward with propellant flowing from the bulk space, into the trough, through the screen and out the outlet. Simple spinning at the minimum fill fraction and at the recommended fill fraction is illustrated in the operational sequence.

While the vehicle is spinning at 65 rpm, AKM firing occurs, producing a large axial acceleration. The propellant reorients in the tank with the surface being a paraboloid of revolution. Propellant access is not required during AKM firing but is possible with this PMD. The propellant motion created by the extremely high g environment causes high loads on the PMD center post. The center post has been designed to accommodate these loads. The propellant position during steady state AKM firing is illustrated in the operational sequence.

After AKM firing and after other undefined disturbances, the propellant slosh will result. Propellant may move away from the outlet region during this slosh as illustrated in the operational sequence. Propellant access is assured by the trough. The trough hold sufficient propellant to supply the maximum thruster demand rate throughout the period when the bulk propellant is away from the outlet. As the propellant sloshes back over the outlet, the trough refills, readying it for the next half cycle.

After AKM firing, the vehicle is despun using propellant from these tanks. During spinning operation including despin, less than 5 kg of propellant per tank is consumed. Like simple spinning, the trough entrance is submerged by at least 1 inch of propellant (2 inches recommended) and propellant access is straightforward. The tangential acceleration created by the thrusters is insignificant compared to the centripetal acceleration and, therefore, the propellant location is identical to simple spinning. Despin is illustrated in the operational sequence.

After the ascent, the spacecraft is separated from the last launcher stage and the vane system becomes operational. Separation is assumed to pose no operational difficulties for the PMD.

Orbital Operations: Once separated from the booster's last stage, the PMD vane system becomes operational and has been designed to provide gas free propellant delivery during all maneuvers. The PMD's sole purpose is to deliver gas free propellant during the lateral accelerations produced by thruster operation. These small accelerations and low flow rates make gas free propellant delivery possible using a simple vane device.

The operational sequence shows the propellant configuration during coast and during a steady state lateral firing early in mission, in mid mission, and later in mission. During coast, the gas will occupy a position minimizing the gas-liquid interfacial energy. This occurs when the sum of the reciprocals of the principal radii of curvature are identically equal everywhere on the surface. Without boundaries, this would result in a spherical gas bubble. Only if the tank were very close to full would this occur. During a nominal mission, when the tank begins operation at a 60% fill fraction, a spherical gas bubble cannot reside within the tank; it is distorted by the center post, vanes and tank walls. Early in mission, the gas ullage bubble will be asymmetrically oriented on one side of the tank. Toward the end of mission, the gas will be axisymmetrically distributed around the tank during coast. With intermediate fill fractions, the gas could occupy an asymmetric position or axisymmetric position depending upon the preceding maneuver, drag accelerations, and the fill fraction. In all cases, the outlet region is completely submerged and ready to supply gas free propellant upon thruster ignition.

During a lateral acceleration, the fluid will reorient into a pool on the tank wall opposite the direction of the acceleration. The pool will form along one of the four vanes. The surface of the liquid in the pool is highly curved due to the surface tension forces and small accelerations. As depicted in the operational sequence, the propellant will cling to the vane. This is caused by the surface tension forces and provides a flow path for propellant, thereby allowing access to the propellant in the pool during lateral thrust. During early in mission lateral accelerations, the fill fraction is above 50% and the outlet pick up assembly must be submerged in propellant. The PMD becomes more active as propellant is consumed. At low fill fractions, the fluid climbs the vane and the radius of surface curvature decreases as the fluid rises. When analyzing the vanes, low fill fractions are worst case and will be thoroughly examined. End of life (EOL) accelerations and flow rates are worst cases.

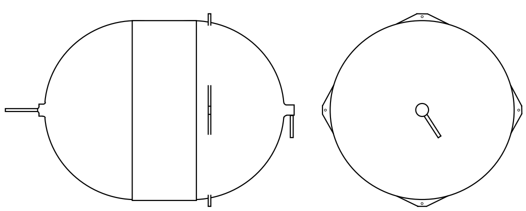
Finally, depletion is illustrated in the operational sequence. During a steady long duration burn, the highest residuals occur. This is because the acceleration is applied for a sufficient period to reorient the propellant from its distributed location to a pool along a vane. As propellant is consumed, 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. The burn will continue until the center post can no longer supply the propellant necessary to meet the added demand. Finally, because the center post and the vanes combined cannot meet flow demand, the propellant in the outlet trough will be consumed. Eventually, as the screen flow area decreases, gas will be pulled through the screen. 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 0.4%.

DESIGN HERITAGE

As stated previously this is a derivative tank whose tank shell is based on tank shells previously built and qualified[1]. It belongs to PSI's family of 22.1-inch diameter propellant (diaphragm and PMD) tank product line. See Figure 9. The QBS is based on similarity to PSI P/N 80309-1, 80281-1, 80229-1, and 80212-1, all of which have identical tank shells. Modifications are limited to the propellant and pressurant ports and the internal PMD. The PMD in this tank is more sophisticated than the PMD's in its predecessor tanks and offers significantly more capabilities.

Figure 9: Propellant tank heritage.

80212-1



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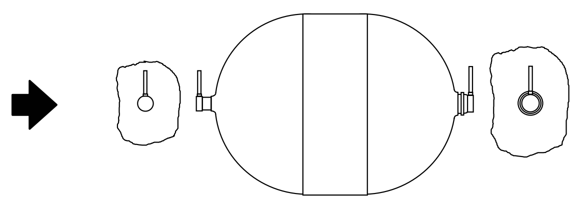

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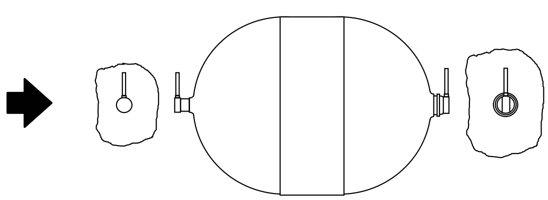

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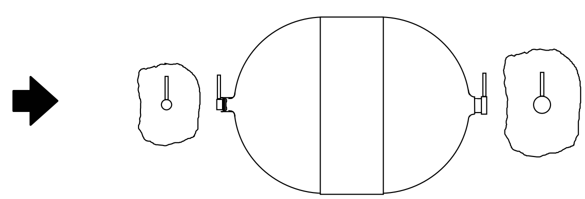

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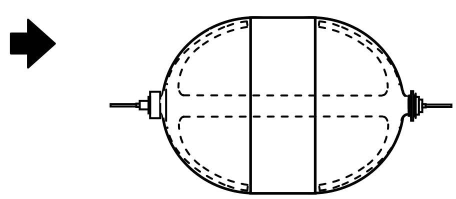


PROPELLANT TANK DESIGN AND FABRICATION

To reduce the overall cost to the program, an existing tank shell design was baselined, and qualification-by-similarity approach was utilized. This approach minimized the non-recurring expenditures such as engineering, documentation, and tooling. It eliminated the need for weld development and qualification test programs. The tank shell also provides flight heritage, which is an added advantage.

To maintain QBS, the propellant tank membrane was not changed. Modification to the tank shell is limited to the propellant and pressurant port mounting features. This tank is polar mounted to the spacecraft structure, and the pressurant port was fitted with a mounting bracket, while the propellant port was fitted with a gimbal assembly.

The propellant tank shell consists of two hemispherical heads and a cylindrical center section. Both the hemispheres and the center section ring are machined from 6AL-4V titanium alloy forgings. Each forging is machined to the tank shell thickness as required by the stress analysis. The as-delivered hemispherical forgings have a nominal thickness of 0.57 inch, and the finished tank shell membrane has a nominal thickness of 0.032 inch. The entire machining process removes over 95% of the forging material. Figure 10 shows a machined hemispherical head, and Figure 11 shows the machined cylindrical center sections.

Figure 10: A Machined Hemispherical Head

Figure 11: Machined Cylindrical Center Sections.

Unlike most tank shells fabricated by PSI which have STA properties, this tank shell has annealed Ti 6Al-4V properties only. This selection results in a less than minimal tank weight, but provides our customer with the best overall contract value.

The PMD installation is performed in two phases. Phase 1 installs the PMD pick up assembly onto the propellant port, and phase 2 assembles the PMD vane assembly and installs the vane assembly above the pick up assembly. See Figure 12.

Two girth welds are required to assemble the tank. The first weld joins the propellant hemisphere and the cylindrical center section. After the installation of PMD, a second girth weld joins together the hemisphere/cylinder assembly to the pressurant hemisphere to complete the tank closure. Both girth welds are subjected to radiographic and dye penetrant inspections. After closure the tank assembly is stress relieved in a vacuum furnace to remove residual stress from the weld operations. A final machine operation is also performed prior to acceptance testing. After the completion of the acceptance tests, the mounting bracket and the gimbal assembly are installed prior to final clean and delivery.

TANK WEIGHT

The propellant tank weight per the specification is not to exceed 20.5 lbm. The actual tank weight for the first two production tanks are 19.40 and 19.62 lbm, respectively. These actual weights are consistent with the predicted nominal weight of the tank.

Figure 12: Propellant Tank Assembly

PROTOFLIGHT TEST PROGRAM

The tank shell is qualified by similarity and a tank qualification program is not required. However, the first flight tank underwent protoflight testing to verify the tank shell and PMD design. Protoflight test consists of the following tests:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure
- Post-proof volumetric capacity
- PMD bubble point test
- Vibration test
- Differential pressure test
- Expulsion efficiency test
- PMD bubble point test
- External leakage test
- Penetrant inspection
- Radiographic inspection
- Mass measurement
- Final examination
- Cleanliness

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 consists of acceptance type external leak tests and non-destructive evaluations conducted at intervals throughout the test program.

Volumetric Capacity Examination: The capacity of the propellant tank is measured utilizing the weight of water method, using clean, 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 (500 psia, normalized for test temperature) for a pressure hold period of 2 minutes.

PMD Functional Test: The tank assembly level PMD bubble point test is intended to verify the capillary integrity of the screened PMD element. Successful completion of the PMD bubble point test after the proof pressure testing validates the PMD workmanship.

Protoflight Vibration Test: The protoflight vibration test is designed to verify the workmanship of the PMD and the integrity of the tank shell. There are four phases of the protoflight vibration testing: wet random, wet sine, dry random, and dry sine. All three principal axes are tested at each phase. The vibration spectrum is listed below in Table 4. For wet random vibration, the protoflight tank is loaded with 251 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 fixed-end propellant boss is restrained in all directions during all vibration testing. The free-end pressurant boss is free to move in the tank longitudinal axis but is restrained in all other directions during test. The fixture is also sufficiently stiff to be considered rigid for the test frequencies.

Control accelerometers are placed on the vibration test fixture near each attachment boss to control energy input. Three tri-axial response accelerometers are used to monitor the tank responses: two on the tank center and one near the free-end pressurant boss. The vibration test setup is presented in Figure 13.

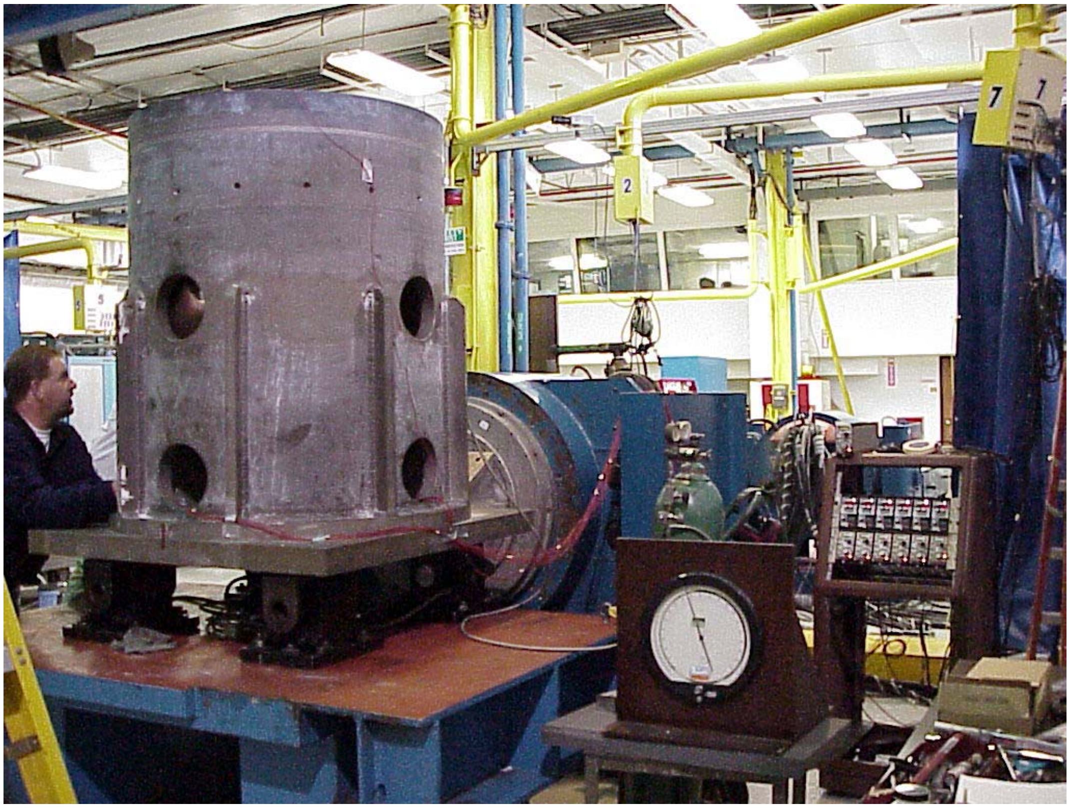
Table 4a: Protoflight Random Vibration Levels

Frequency (Hz)	Protoflight Level	Units
Wet Tank		
20-50 50-500 500-2000	6 0.16 –3	dB/oct g^2/Hz dB/oct
Overall 13.7 G_{rms} Duration: 60 seconds per axis		
Dry Tank		
20-50 50-500 500-2000	6 0.4 -3	dB/oct g^2/Hz dB/oct
Overall 21.6 G_{rms} Duration: 60 seconds per axis		

Table 4b: Protoflight Sine Vibration Levels

Axis	Frequency (Hz)	Acceleration (g)	Sweep Rate
Wet Tank			
Spacecraft thrust (Z)	5-18	0.5 in DA	4 oct/min
	18-25	12.5	
	25-100	2.5	
Spacecraft lateral (X) and (Y)	5-13	0.5 in DA	4 oct/min
	13-20	12.5	
	20-100	2.0	
Dry Tank			
Spacecraft thrust (Z)	5-13	0.5 in DA	4 oct/min
	13-50	7.5	
	50-100	2.5	
Spacecraft lateral (X) and (Y)	5-13	0.5 in DA	4 oct/min
	13-20	7.5	
	20-100	2.0	

Figure 13: Vibration Test Setup



Differential Pressure Test: The propellant tank must meet the pressure drop requirement of not-to-exceed 5.0 psid at a maximum flow rate of 0.01 lbm/sec. The test is conducted by measuring the pressure differential between ullage and the tank outlet while pressuring the tank (and the test fluid) through the pressurant port. The measured differential pressure is 4.0 psid.

Expulsion Efficiency Test: A ground level expulsion efficiency test is conducted after the differential pressure test. The measured expulsion efficiency is 99.91%.

External Leak Test: The external leak test verifies the integrity of the tank shell and also serves to validate the above vibration testing. The tank is placed in a vacuum chamber, which is evacuated to under 0.2 microns of mercury, and helium pressurized to 400 psia for 30 minutes. The helium leak rate cannot exceed 1×10^{-6} std cc per second after the 10-minute stabilization period.

Non-Destructive Examination: Following the pressure tests, the tank shell is screened for flaws using fracture critical penetrant inspection and fracture critical radiographic inspection techniques. Tank acceptance after NDE marks the successful completion of protoflight testing.

Cleanliness Verification: After the non-destructive examination, the interior of each flight tank is cleaned to the cleanliness level specified below in Table 5:

Table 5: Tank Cleanliness Level

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

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
- Vibration test
- PMD bubble point test
- External leakage test
- Penetrant inspection
- Radiographic inspection
- Mass measurement
- Final examination
- Cleanliness

Acceptance Vibration Test: The acceptance vibration test is designed to verify the workmanship of the PMD and the integrity of the tank shell. Only wet random vibration test is performed on the flight tanks. The test spectrum is listed below in table 6. All three principal axes are tested. The test specimen is loaded with 251 lbm of deionized water and pressurized to MEOP during vibration testing.

All other tests are identical to the tests described under protoflight testing.

A photograph of a completed tank is shown in Figure 14.

Figure 14: A Completed Tank at Final Clean

CONCLUSION

The propellant tank assembly has successfully concluded protoflight testing without failure. The production program is complete and all flight tanks have been delivered.

The PMD is specifically designed to meet the mission requirements. The PMD has a simple, robust design and is easy to manufacture. It has been protoflight tested and shows excellent strength and durability.

Table 6: Acceptance Random Vibration Levels

Frequency (Hz)	Protoflight Level	Units
Wet Tank		
20-50	6	dB/oct
50-500	0.04	g^2/Hz
500-2000	–3	dB/oct
Overall 6.9 G_{rms}		
Duration: 60 seconds per axis		

The propellant 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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REFERENCE

1. W. Tam, M. Debreceni, M. Hersh and C. Nye, "Low Cost Derivative Tanks for Spacecraft and Launch Vehicles", AIAA 99-2831.

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