

DESIGN AND MANUFACTURE OF A PROPELLANT TANK ASSEMBLY

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ABSTRACT

ATK-SSI has designed, manufactured, and fully qualified a new 30 inch diameter thin walled titanium propellant tank with a sponge type propellant management device for use by the Naval Research Laboratory for the DARPA Micro-satellite Technology Experiment (MiTEx) Upper Stage (US) program.¹ MiTEx demonstrated a new upper stage for the Boeing Delta II 7925 launch vehicle using a high-performance bi-propellant system that successfully transferred two small satellite payloads from a geosynchronous transfer orbit to geostationary orbit.

ATK-SSI Part Number 80474-1 Propellant Tank Assembly is an all metal, welded spherical pressure vessel, mounted by threaded holes on polar bosses. The Propellant Tank Assembly is fabricated from 6AL-4V titanium with a nominal wall thickness of 0.020 inch. The tank contains a simple internally-mounted sponge type propellant management device (PMD), with perforated sheet, fabricated to maintain separation of liquid propellant and gaseous pressurant. The PMD design provides predictable gas-free liquid propellant expulsion from the tank under low or zero gravity conditions.

Stress and fracture mechanics analyses were conducted to verify the design of both the tank shell and the PMD. A performance analysis of the PMD was conducted and included ground, boost and on-orbit operations.

The tank fabrication utilized existing, reliable, and proven manufacturing technologies and inspection techniques. The tank program was

developed to minimize overall program cost, schedule, and risk.

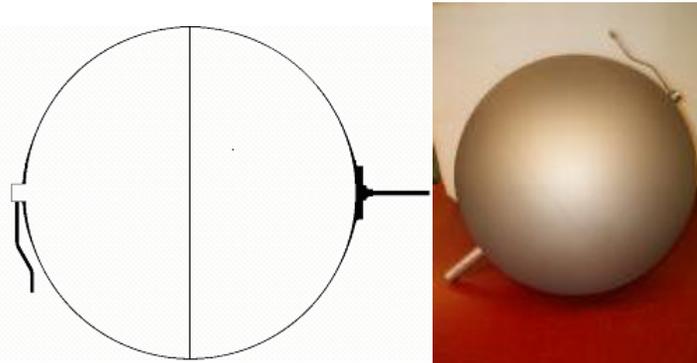
A qualification test program validated the tank design. The qualification program included pressure cycles, vibration testing, and a final burst pressure test compliant with range safety requirements of EWR-127-1 and Mil-STD-1522A. Extensive design, analysis, and testing efforts were performed by ATK-SSI, PMD Technology, and NRL to support this program, and these efforts are summarized in this paper.

INTRODUCTION

The propellant tank assembly is designed for the Naval Research Laboratory Upper Stage (US) program supporting the Defense Advanced Research Projects Agency (DARPA) MiTEx program. The US is a three axis stabilized bi-propellant (MMH & NTO) stage launched by the Delta 7925 launch vehicle. 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 is shown in Figure 1. Four tanks are required for the US.

The PMD and the tank shell are custom designed to meet the mission requirements. Analyses were conducted to design the tank shell and the PMD. A series of qualification tests were performed to establish the qualification status of the new tank. All flight tanks were subjected to acceptance testing. The production program was completed in December 2004, one year from contract award.

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 (MEOP)	250 psig @ 55°C, 100 cycles
Proof Pressure	312.5 psig @ 20°C, 20 cycles
Burst Pressure	375 psig minimum @ 20°C
Material of Construction	Membrane: 6Al-4V titanium, solution treated and aged Inlet/outlet ports: 3Al-2.5V titanium to 304L stainless steel transition tubes
Expulsion Efficiency	99% minimum
Propellant Weight	705.6 lbm maximum NTO
Propellant fill fraction	98% maximum
Tank Capacity	13,750 in ³ minimum
Size	30.060" OD maximum
Overall Length	31.580"
Tank Weight	21.0 lbm maximum
Propellant	MMH or NTO
Fluid Compatibility	NOVEC Engineered Fluid HFE-7100, NTO, MMH, Helium, Nitrogen D.I. water and isopropyl alcohol
Shell Leakage	<1x10 ⁻⁶ std cc/sec He @ 250 psig
Natural Frequency	> 45 Hz axial and > 25 Hz lateral
Structural Design	Safe Life, Stress and Fatigue, Analyses per EWR-127-1, and Leak Before Burst Assessment
On-Orbit Temperatures	20 ±7°C
Shelf Life	5 years minimum
On Orbit Life	180 days 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 with the tank shell, a fracture mechanics analysis is not required.

The tank design analysis approach used assumptions, computer tools, test data and experimental data utilized on the majority of the pressure vessels and PMD's successfully designed, fabricated, tested, and qualified during the past four decades. Conservatism was used throughout the analysis, and the worst case scenarios were analyzed.

TANK SHELL STRESS ANALYSIS

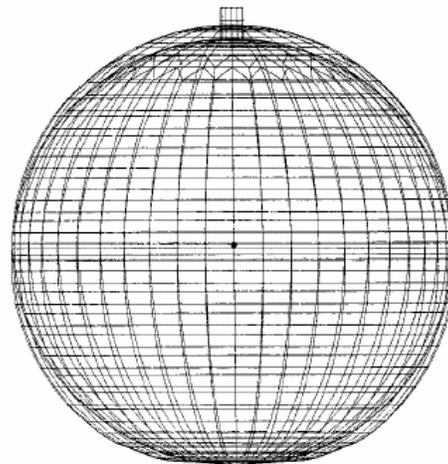
A stress analysis was performed to design and analyze the tank shell. The analysis took into consideration the design requirements such as:

- 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.

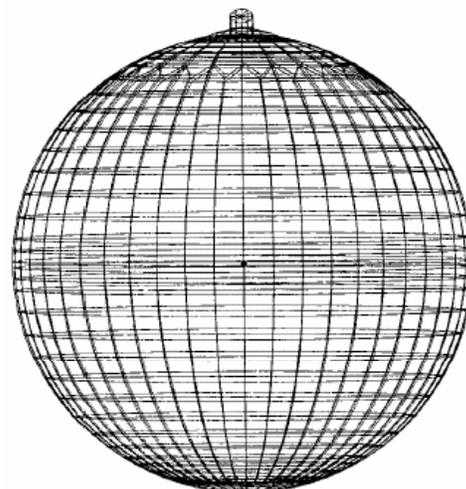
This stress analysis validated the tank shell design for the new mission requirements. The analysis also provided predictions on the resonant frequencies. Figure 2 shows some of the vibration modes from the analysis. The analysis concluded with positive margins of safety for all design parameters, as summarized in Table 2. A tank buckling analysis under the expected flight loads was

performed to validate the pressure stabilized design. The conservative analysis showed positive margins with improved stiffness and geometrical spherical uniformity at a pressure of 80 psid.

Figure 2: Some Vibration Modes



Mode 1



Mode 2

Table 2: Propellant Tank Safety Margins

Characteristics	M.S.
Membrane, sphere, burst	+0.04
Membrane, sphere, proof	+0.08
Inlet Boss external loads, yield	+0.64
Inlet Boss external loads, ultimate	+0.75
Outlet Boss external loads, yield	+0.31
Outlet Boss external loads, ultimate	+0.12
Weld area, burst	+0.03
Weld area, proof	+0.12
Outlet tube, yield	+7.10
Outlet tube, ultimate	+7.50
Tank external loads, yield	+1.59
Tank external loads, ultimate	+1.80

TANK SHELL FRACTURE MECHANICS ANALYSIS

A fracture mechanics analysis was performed to establish whether the growth of an initial flaw subjected to four times the expected histogram 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 the fracture mechanics crack propagation analysis. The analysis was performed at:

- Girth welds and heat affected zones;
- Maximum pressure stress location in the hemisphere;
- 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 safe life capability of the propellant tank and concluded that the tank shell meets all EWR-127-1 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:

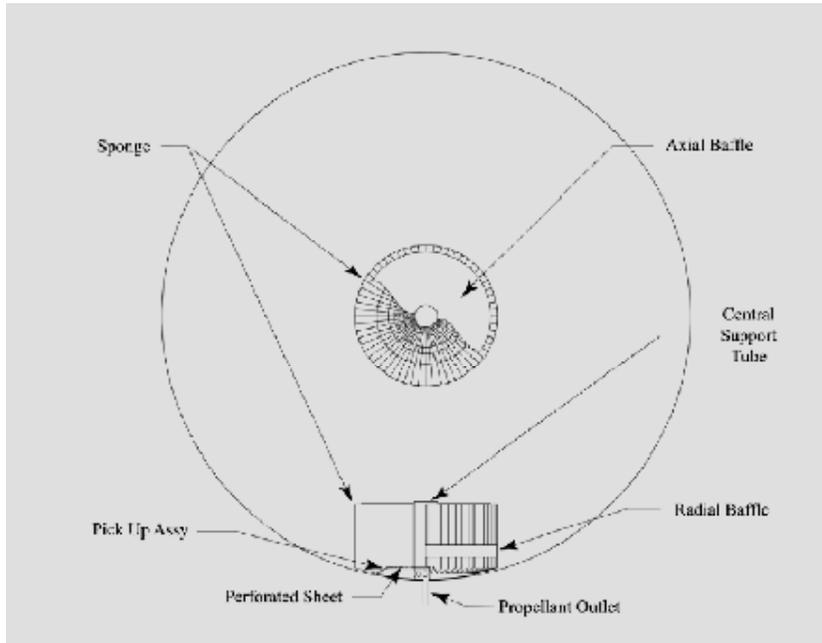
Table 3: PMD Safety Margins

Characteristics	M.S.
PMD post, axial load, yield	+12.5
PMD post, axial load, ultimate	+12.6
PMD post, lateral, yield	+0.69
PMD post, lateral, ultimate	+0.71
Panel, weld to plate, yield	+45.0
Panel, buckling, ultimate	+3.98
Weld, top plate to post, ultimate	+12.4
Trap, top plate, ultimate	+27.5
Trap, bottom cone, ultimate	+6.70
Post threads, ultimate	+9.40
Panel lateral loads, yield	+0.88
Panel lateral loads, ultimate	+0.60

PMD DESIGN

A passive, all titanium, surface tension propellant management device was designed to provide gas-free propellant 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 system priming, separation recovery, main engine firings, rotations, and deorbit.

Figure 3: PMD Configuration



The PMD was designed to be installed over the propellant outlet in the propellant hemisphere as shown in Figure 3. It is designed for use with MMH and NTO. Several additional design considerations were also incorporated into the PMD. First, because the PMD is a passive device with no moving parts, the design is inherently reliable. The design is constructed entirely of titanium, thus the PMD is lightweight and offers exceptional compatibility, long life, and reliability. Finally, the PMD is designed not only to provide propellant during steady flow conditions but also to allow operation in some off-design conditions, thus providing additional operational margin of safety. The PMD is welded into the propellant end of the tank as shown in Figure 4.

The key components of the PMD design are a sponge with integral propellant motion baffles, a perforated sheet, Pickup Assembly and an outlet region. See Figure 5 for a cut-away view of the PMD and its component parts.

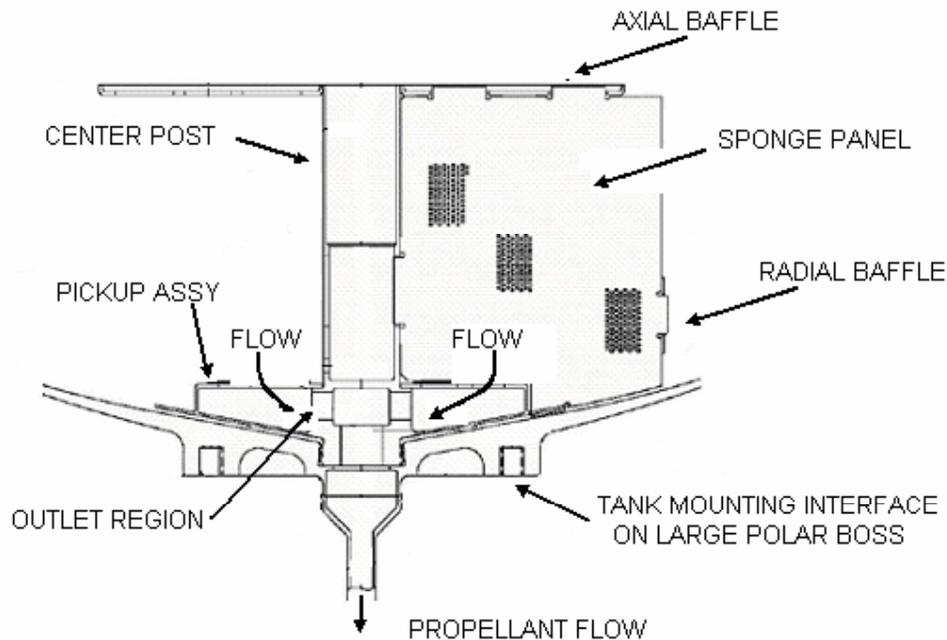
The sponge is located in the bottom of the tank over the perforated Pickup Assembly. The sponge consists of multiple panels of titanium sheet; each separated by a tapered gap and assembled onto the Centerpost Assembly. The sponge has been designed to provide NTO or

MMH to the Pickup Assembly during axial engine firings and during all operations, including rotations, between axial maneuvers. Integral to the sponge are two propellant motion baffles; a radial baffle at the outboard edge of the sponge and an axial baffle on top of the sponge; see Figures 3, 4 and 5.

Figure 4: PMD Assembly.



Figure 5: PMD Cut-Away View



The outlet region (Figure 5) is an annular pathway leading to the centrally located outlet tube. The outlet region is designed so that 80% of the perforated sheet may be exposed instantaneously to gas without gas penetration. The outlet region is designed with worst case assumptions and provides a significant safety factor.

The Pickup assembly design incorporates a porous element to prevent gas ingestion should gas approach the outlet. For this application the porous element must accommodate the flow losses associated with main engine firing flow rates. See Figures 5 and 6.

PMD OPERATIONS

The 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 on the Delta 7925 rocket, the PMD does not function and has been designed to maintain propellant over the perforated sheet and not be adversely affected by the launch conditions encountered. During the final stages of ascent,

the spacecraft is rapidly spun up to 60 rpm (maximum design case was 90 rpm), a solid motor produces large axial accelerations and the spacecraft rapidly spun down to a maximum of 5 rpm.

Figure 6: PMD Center Post and Pickup Assembly.



In addition, the PMD has been designed to prevent gas from penetrating the perforated sheet and exiting the tank during all applied loads. The flow path of the propellant is illustrated in Figure 7. The propellant flows into the sponge radially. The propellant within the sponge flows between and through the sponge panels into the perforated sheet preventing gas penetration.

PMD functional operation is separated into three phases: ground operations, ascent operations, and orbital operations. The various phases of mission that the PMD will encounter and how the PMD will affect the propellant are illustrated in Figure 8, PMD Operational Sequence.

Figure 7: Flow Path Within the PMD

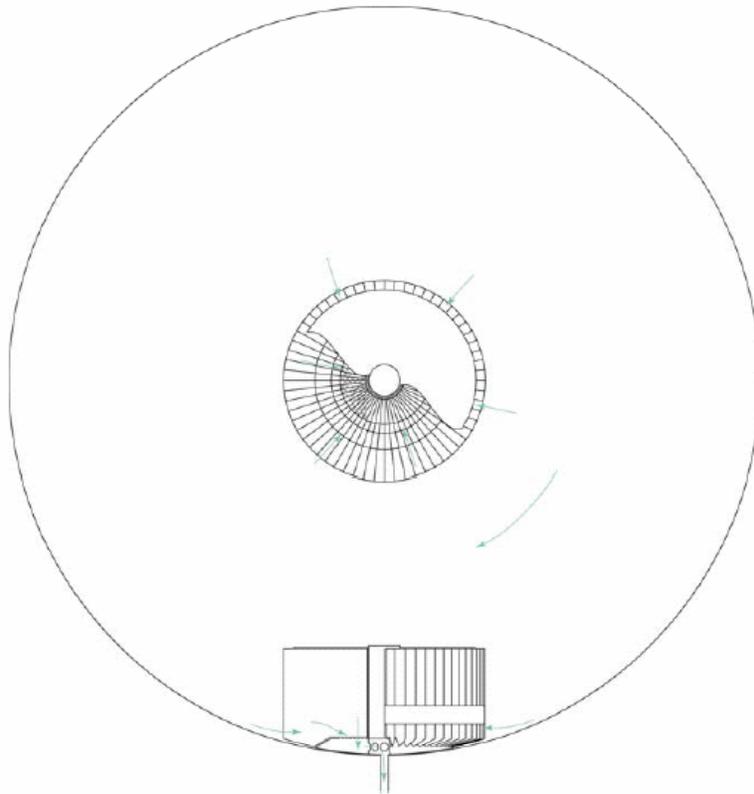


Figure 8: PMD Operational Sequence (Pt 1 of 4)

GROUND & ASCENT OPERATIONS

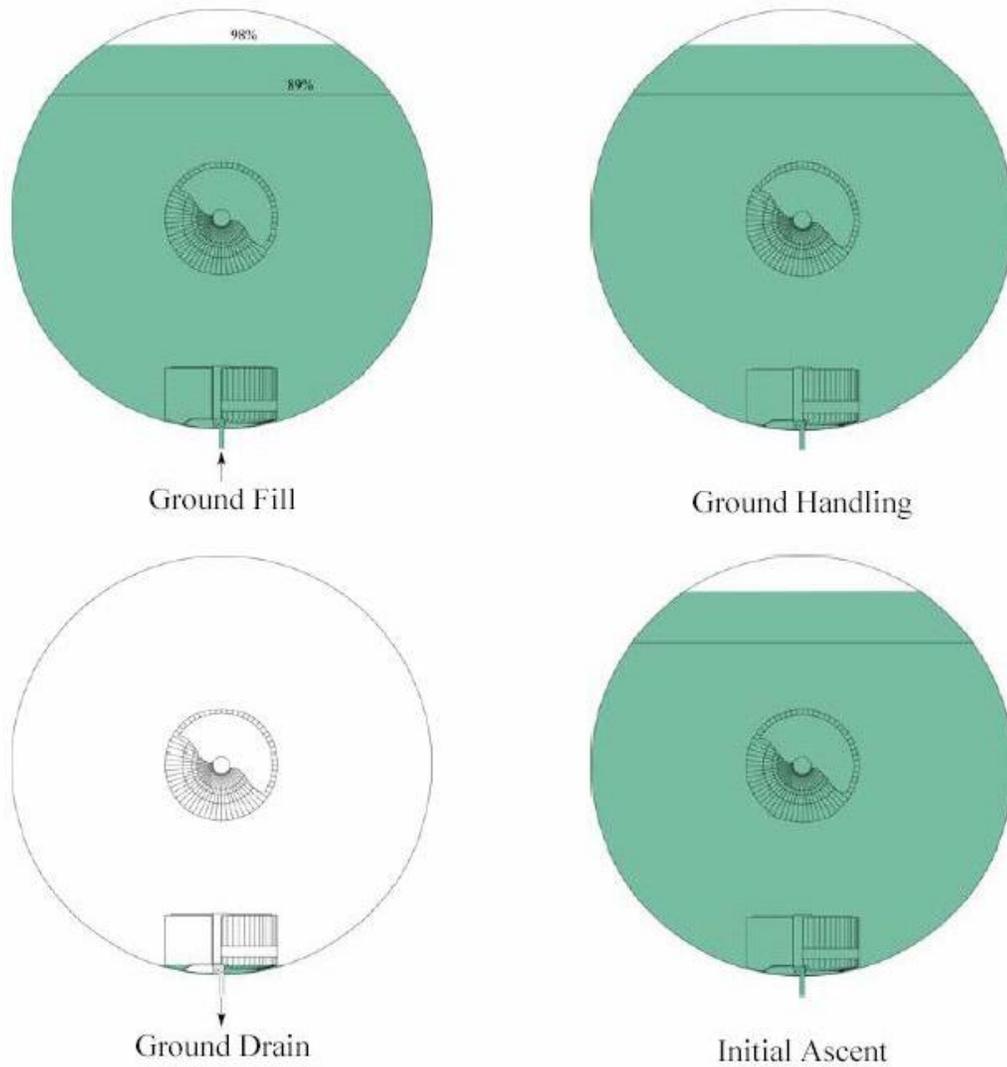


Figure 8: PMD Operational Sequence (Pt 2 of 4)

ORBITAL OPERATIONS

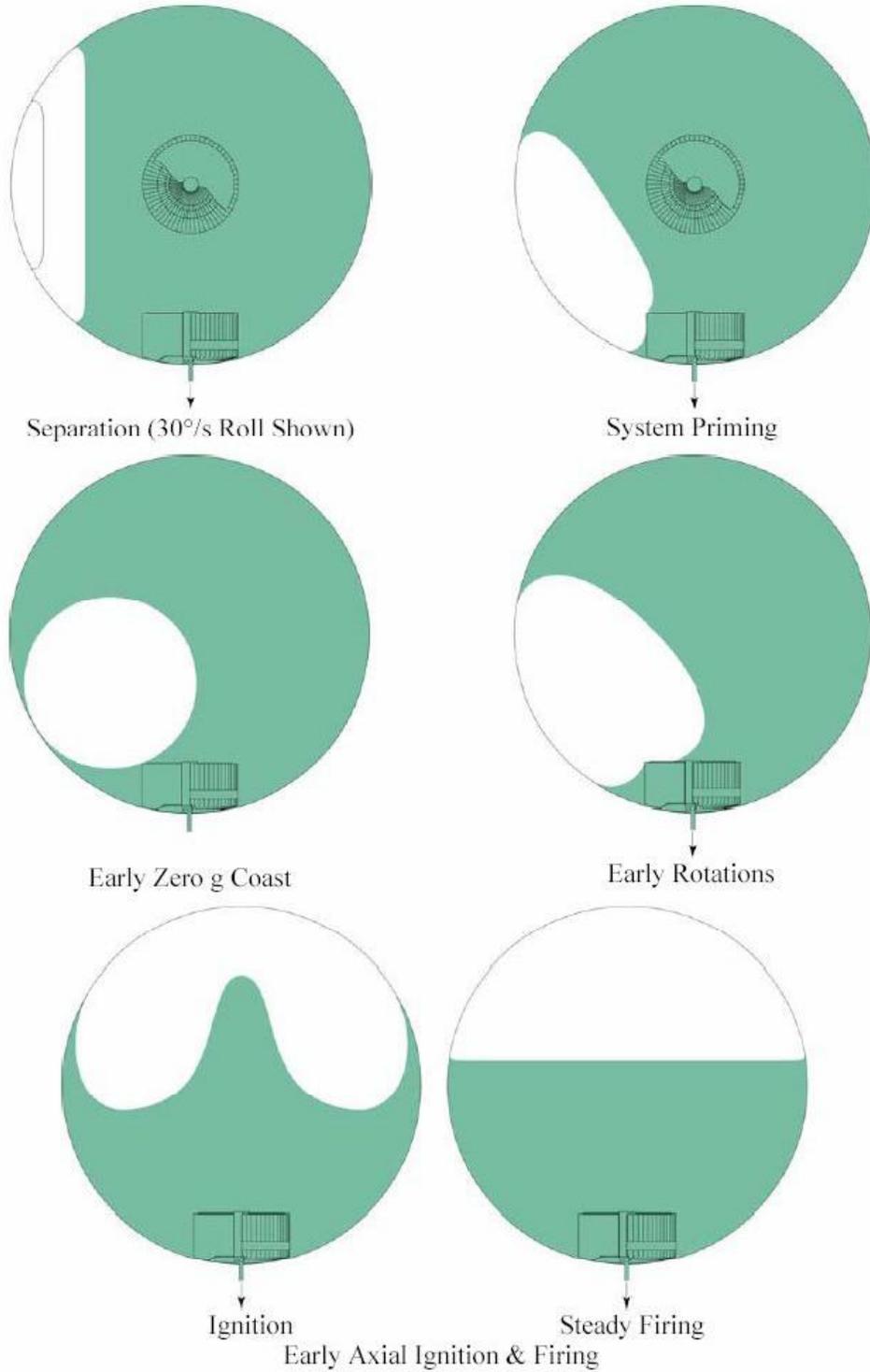
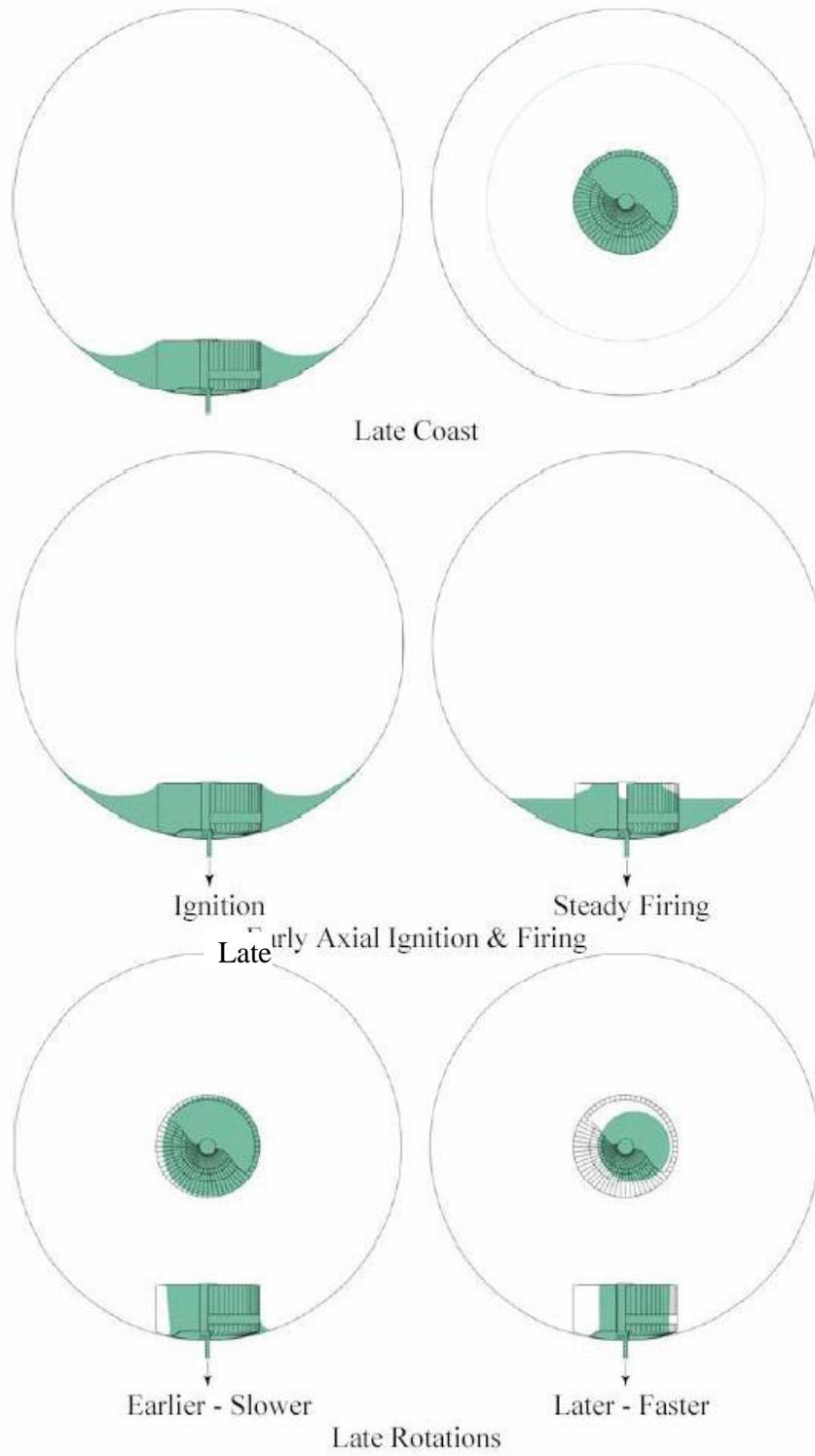


Figure 8: PMD Operational Sequence (Pt 3 of 4)



**Figure 8: PMD Operational Sequence
(Pt 4 of 4)**



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 shows these ground operations in Figure 8.

Filling occurs with the tank upright and 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 the perforated sheet. A high flow rate during fill will push the gas through the perforated sheet and out of the outlet region. In addition, this gas is compressed significantly during pressurization and is likely to be dissolved into unsaturated propellant. In any case, the gas quantity is too small for 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 perforated sheet at the nominal 98% fill fraction. 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 perforated sheet (the PMD itself will act as a baffle preventing gas from reaching the perforated sheet). 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: The ascent operations of the Delta 7925 rocket can be divided into four stages: launch, spinning ascent, solid rocket separation, and despin. The PMD has been designed to withstand the structural loads during these stages of ascent.

The PMD has been designed to withstand the structural loads during launch as well as to prevent gas from entering the pickup assembly. 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 Pickup Assembly (downstream of the perforated sheet). 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 Pickup Assembly provides a fluid stagnation region where fluid velocities will always be small. Even if gas were driven down toward the Pickup Assembly by slosh, the center post and the perforated sheet 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.

Orbital Operations: Once separated from the booster's last stage, the PMD becomes operational and has been designed to provide gas free propellant delivery during all maneuvers. The PMD's primary purpose is to deliver gas free propellant during axial thruster firings and rotations. The operational sequence shows the propellant configuration during separation, system priming, coast and rotations during a steady state axial firing early in mission and later in mission.

After ascent, the spacecraft is separated from the launch vehicle with a settling acceleration. After separation, the spacecraft may be spinning at 30°/s about the roll axis and up to 7°/s maximum about the pitch or yaw axis. Separation with a 30°/s roll rate is illustrated in the operational sequence depicted in Figure 8.

Shortly following separation, system priming occurs. During system priming, a high flow rate is demanded from the tanks to fill the evacuated lines downstream of the propellant isolation valve. The PMD has been designed to maintain the gas sufficiently away from the outlet to preclude gas ingestion during this operation.

Most of the US spacecraft's time on orbit will be spent in a zero g coast mode. At high initial fill fractions, the gas bubble in the tank is spherical and free floating. An early mission coast at the nominal fill fraction is illustrated. The worst case bubble location, near the sponge, is illustrated. At all fill fractions in zero g the sponge is filled with propellant and maintains the gas away from the perforated sheet.

The PMD has been designed to provide gas free propellant during two types of maneuvers: 1) axial ignitions and steady state firing; and 2) rotations.

Small thruster firings cause the vehicle to rotate. The maximum rotation rate is 0.5°/s in most of the operational events and the rotation is about any axis passing through the center of gravity, which is in general above the tank. The angular accelerations vary throughout the mission from a low of 1.6°/s² to a high of 7.6°/s². During thruster firings, a settling acceleration component is also present. With the tanks off axis, the rotations can push the gas bubble toward the bottom of the tank. An early in mission rotation is illustrated in the operational sequence showing the gas pushed down toward the outlet. The sponge maintains the gas away from the perforated sheet. Rotations between maneuvers use sufficiently small quantities of propellant that the sponge can easily provide gas free propellant for all maneuvers between long duration axial burns.

Main engine firings and small axial firings settle propellant in the tanks. During thruster ignition, the propellant reorients from zero g configuration into its settled configuration.

During this transient, a geyser may form in the tank. The PMD sponge and propellant motion baffles are designed to ensure that the liquid within the sponge remains in the sponge during the ignition transient. Once the liquid is settled into the tank, propellant access is straight forward. Propellant flows between the sponge panels to the perforated sheet, through the perforated sheet and out of the outlet. The propellant surface is flat except near the tank walls where surface tension has an effect. The surface is flat compared to rotations because of the higher acceleration resulting from the main engine firing. An early in mission firing is illustrated in the operational sequence depicted in Figure 8. Note that the sponge is filled with propellant following a long duration axial engine firing readying it for the subsequent rotations between burns.

The three same conditions, zero g coast, rotation, and axial thruster firing will be encountered throughout the mission at lower fill fractions.

The propellant will reside mainly in and around the sponge late in mission coast. The tank is spherical and therefore no propellant will reside in the upper hemisphere during zero g coast. The perforated sheet will be submerged in propellant and the sponge will be full of propellant and ready for propellant demand.

During late mission rotations, the bulk of the propellant will move in response to the thruster firings and the centripetal acceleration. However, the sponge remains nearly full of propellant and is ready to supply the demand between axial firings as well as during the axial ignition transient. Late mission rotations are illustrated in the operation sequence depicted in Figure 8.

During late mission axial thruster firing, the propellant settles in the tank and access is straightforward. In order to minimize the effects of propellant reorientation within the sponge during short duration axial firings, the smaller axial thrusters are used at very low fill fractions. This precludes the possibility that sponge propellant does not settle but continues to move toward the girth due to the short duration pulses coupled with the low fill fractions. During the ignition transient, the propellant in the sponge is restrained by the surface tension forces and the propellant motion baffles. A late mission axial thruster

firing is illustrated in the operational sequence depicted in Figure 8.

Depletion occurs during a steady state axial firing. As the settled propellant is consumed, the perforated sheet is exposed to gas and the perforated sheet flow area will decrease. The decrease in flow area causes an increase in flow losses. Once the flow losses increase to the bubble point of the perforated sheet, gas will be drawn through the perforated sheet and entrained in the flow into the outlet tube. When gas enters the outlet tube, depletion has occurred. Depletion is illustrated in the operational sequence depicted in Figure 8.

PROPELLANT TANK FABRICATION

Tank Hemispheres

In most cases ATK-SSI is able to select an existing tank shell design that has been previously qualified with some or minimal modifications. This tank design required a completely new tank shell. While every effort was made to minimize cost of tooling and non-recurring engineering a complete new set of tooling including forging dies were required.

The propellant tank shell consists of two hemispherical heads. Both hemispheres 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 0.73 inch, and the finished tank shell membrane has a nominal thickness of 0.020 inch. The machining process removes over 95% of the forging material. Figure 10 shows a machined propellant head, and Figure 11 shows the machined pressurant head.

Like most tank shells fabricated by ATK-SSI, the hemispheres are solution heat treated and aged, resulting in minimal tank weight. Both the propellant and pressurant hemispheres are subject to 100% special level fracture critical NDE after machining.

PMD Fabrication and Installation

The PMD consists of two major sub-assemblies; the Centerpost Subassembly which consists of the Centerpost and the Pickup Assembly; and the Sponge

Subassembly which consists of the sponge panels, radial and axial baffles. Prior to installing the PMD into the propellant hemisphere, the PMD is bubble point tested to verify proper function of the Pickup Assembly. The PMD Assembly installation is performed in a single phase; welding the PMD Assembly directly over the outlet in the finished machined propellant hemisphere forming the expulsion assembly as shown in Figure 12.

Figure 10: A Machined Propellant Head



Figure 11: A Machined Pressurant Head



Tank Assembly and Final Machining

A single girth weld is required to assemble the tank as shown in Figure 13. The girth weld is subject to radiographic and dye penetrant inspections. After closure, the tank assembly is final aged in a vacuum furnace. A final

machine operation is also performed prior to acceptance testing. After final machining establishes the final overall length of the tank assembly and drills the interface holes in the polar bosses, the pressure and propellant interface tubes are welded onto the tank. The tube welds are subject to radiographic and penetrant inspection. The tank is now ready for Acceptance Testing.

Figure 12: Expulsion Assembly



TANK WEIGHT

The propellant tank weight per the original customer specification was not to exceed 28.0 lbm. Based on a conservative analysis of the proposed ATK-SSI design the specified weight was lowered to 21.0 lbm. The actual average tank weight for the four flight and one spare tank is 17.68 lbm. The actual weights are consistent with the predicted weight.

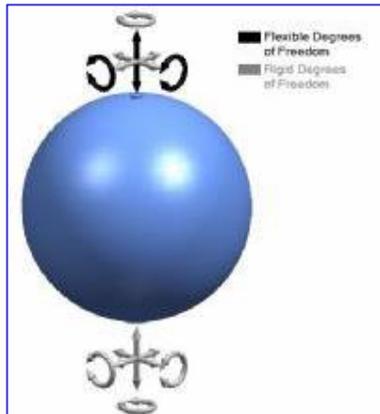
Figure 13: Finished Welded Tank



Tank to Spacecraft Interface Design

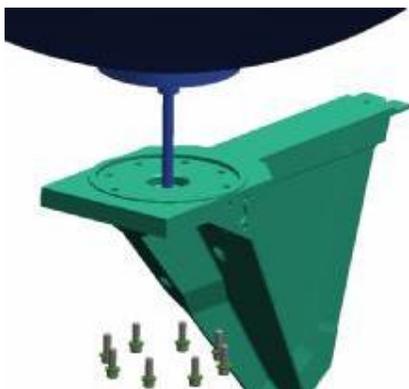
The tank is an all metal spherical pressure vessel with two polar bosses configured to provide tank mounting and fluid interfaces with the spacecraft. The mounting requirements are as shown in Figure 14 with associated loads and moments coordinated between NRL and ATK-SSI for the detailed analysis and testing efforts. The tanks are located 26.5 inches from the US vehicle center of mass.

Figure 14: Tank Mounting Requirements



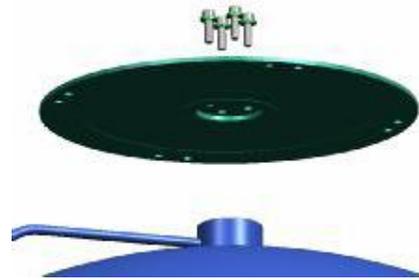
The outlet propellant interface is shown in Figure 15 and is a 0.375 x 0.035 inch wall tube centered on the larger 4.750 polar boss of an Aluminum 7075 tank Pedestal. This outlet boss is the primary load path between the tank and the spacecraft, and uses eight 0.25 inch high strength A286 bolts and a shear lip on the spacecraft with a 0.0005 to 0.0015 inch diametrical clearance and 0.15 inch engagement to provide a rigid 6 degree-of-freedom (DOF) interface.

Figure 15: Pressure Outlet Flexure Mount



The pressurant interface is shown in Figure 16, and is a 0.250 x 0.035 inch wall tube that attaches through the side of the smaller 1.600 diameter polar boss. This boss interfaces with the spacecraft through a Titanium 6AL/4V diaphragm flexure that permits tank motion along the axis through the two bosses, while restricting lateral and rotational movements resulting in 3 rigid DOF including lateral and torsion and 3 flexible DOF axial and lateral moments. Tank attachment is by four 10-32 A286 socket head cap screws and CRES washers.

Figure 16: Propellant Outlet Structural Mount



The final tank flight installation is shown in Figure 17. These interfaces were extensively analyzed at the tank and integrated system levels. The analysis results were used to set test limits and define instrumentation for use during wet random vibration and Design Loads (sine burst) testing. As a result the tank and its spacecraft mounting designs were both qualified during tank testing.

Figure 17: Tank Installed in Spacecraft



QUALIFICATION TEST PROGRAM

This tank was a new design and therefore required a complete Qualification Test program. One tank from the production lot was selected for the Qualification Test program. The Qualification Unit was constructed of the same materials, using the same processes and procedures as the Flight Units. The Qualification Test program consisted of the following tests:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure
- Post-proof volumetric capacity
- Pressure cycle test
- Negative pressure test
- Vibration test (dry and wet)
- Total Design Loads test (sine burst)
- Expulsion efficiency test
- PMD bubble point test
- External leakage test
- Penetrant inspection
- Radiographic inspection
- Burst

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 for which it was designed. The volumetric growth after proof pressure test was zero for all tanks.

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 (312.5 psig, normalized for test temperature) for a pressure hold period of 5 minutes.

Pressure Cycle Test: The pressure cycle test is intended to validate the life of the tank shell. A total of 100 MEOP cycles, 0 to 250 psig at 131°F with a minimum hold of 30 seconds each and 20 proof cycles, 0 to 68°F with a minimum hold time of 30 seconds each is conducted hydrostatically

Negative Pressure Test: The tank was evacuated to a differential pressure of 3.0 psid and held for 5 minutes minimum. The tank was then examined for any evidence of buckling or other damage.

Qualification Vibration Test: The qualification vibration test is designed to verify the workmanship of the PMD and the integrity of the tank shell. There are two levels of vibration testing, acceptance level and qualification level. The qualification unit is subject to both sequentially commencing with the acceptance level. There are three phases of the qualification vibration testing: dry random, wet random, and sine burst. 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 713.2 lbs of NOVEC™ test fluid. The tank is pressurized to 75 psig at 68°F 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 pressurant boss is attached to a flexure plate which allows restricted movement at test. The fixture is sufficiently stiff to be rigid for the test frequencies.

Control accelerometers are placed on the vibration test fixture near each attachment

boss to control energy input. Response accelerometers are used to monitor the tank responses: six on the tank girth, six on the

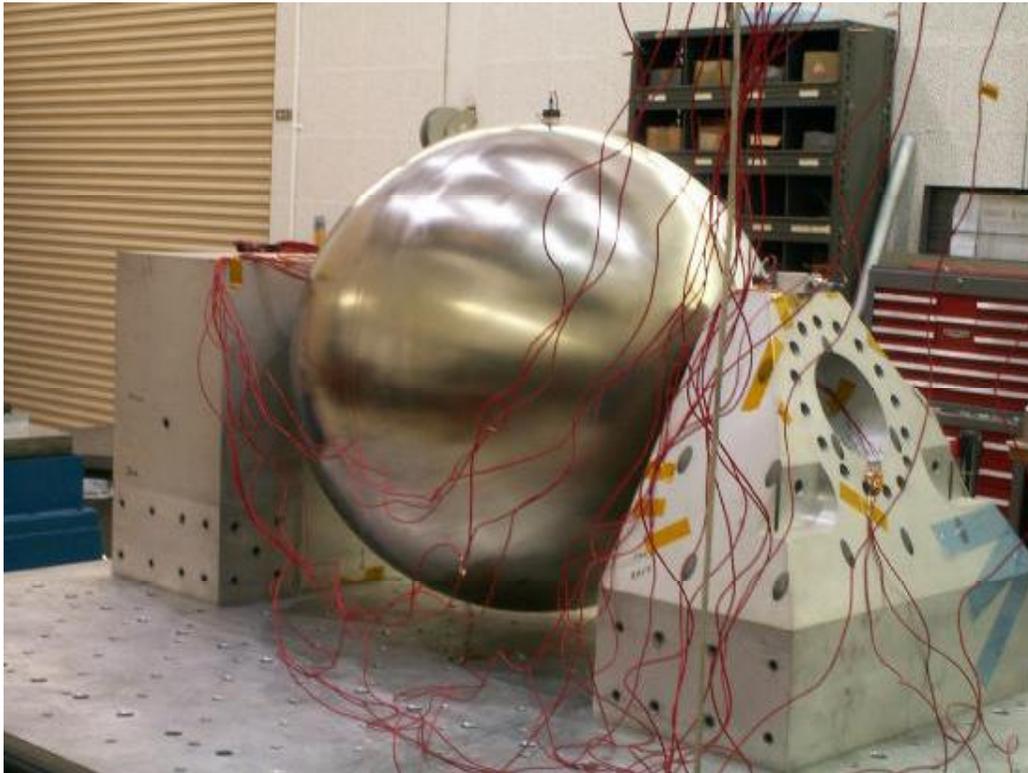
propellant end and nine on the pressurant end. The vibration setup is presented in Figure 15.

Table 4a: Dry Configuration Random Vibration Levels

Frequency (Hz)	Acceptance Level	Qualification Level
Dry Random Vibration		
20	0.004 g ² /Hz	0.008 g ² /Hz
100	0.040 g ² /Hz	0.080 g ² /Hz
200	0.040 g ² /Hz	0.080 g ² /Hz
300	0.020 g ² /Hz	0.040 g ² /Hz
2000	0.020 g ² /Hz	0.040 g ² /Hz
Overall G _{rms}	6.5	9.2
Duration	1 minute	2 minutes

Table 4b: Wet Configuration Random Vibration Levels

Frequency (Hz)	Acceptance Level	Qualification Level
Wet Random Vibration		
20	0.020 g ² /Hz	0.040 g ² /Hz
2000	0.020 g ² /Hz	0.040 g ² /Hz
Overall G _{rms}	6.3	8.9
Duration	1 minute	2 minutes

Figure 18: Vibration Test Setup

Total Design Loads Test (sine burst) The tank was subjected to sine burst testing in all three axes using the same electrodynamic shaker and test setup that was used for random vibration testing. The test input acceleration levels were tailored so that with only single-axis test accelerations applied, the resulting internal stresses matched the critical stresses in the tank generated from the combined design accelerations. The test levels were applied for 6 cycles at 15 Hz. The equivalent CG response was 8.9 g-peak for the two lateral axes, and 9.54 g-peak for the axis through the polar bosses. The tank and the small boss mounting flexure are qualified for the total design loads.

Expulsion Efficiency Test: A ground level expulsion efficiency test is conducted. The measured expulsion efficiency is 99.85%.

PMD Functional Test: The tank assembly level PMD bubble point test is intended to verify the capillary integrity of the perforated

sheeted PMD element. Successful completion of the PMD bubble point test after the proof pressure testing validates the PMD workmanship.

External Leak Test: The external leak test verifies the integrity of the tank shell and 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 250 psia for 15 minutes. The helium leak rate cannot exceed 1×10^{-6} std cc per second.

Non-Destructive Examination: Following the pressure tests, the tank shell is inspected for flaws using fracture critical penetrant inspection and fracture critical radiographic inspection techniques. Tank acceptance after NDE marks the successful completion of 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	1516.0
11 to 25	185.6
26 to 50	67.7
51 to 100	9.7
101 and over	1.0
< 1 mg NVR/ 100ml	

ACCEPTANCE TESTING

After flight tanks are assembled, they are subjected to the following acceptance tests prior to delivery:

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

All the flight units successfully completed all the acceptance tests.

CONCLUSION

The propellant tank assembly has successfully completed qualification 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 qualification tested and shows excellent strength and durability.

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.

All customer specification requirements were met. The qualification testing and the flight units were completed on schedule and the program was completed with the scope of its initial budget.

Figure 19:A Completed Tank at Final Clean



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