# DESIGN AND MANUFACTURE OF AN OXIDIZER TANK WITH A SURFACE TENSION PMD

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#### **ABSTRACT**

A new oxidizer tank assembly is required for a new commercial satellite. Due to its high L over D ratio, a state-of-the-art tank shell, with its cylinder section reinforced with composite overwrap, was designed to meet the tank requirements. This tank was designed to accommodate low fill fraction horizontal ground handling with unlimited upright-to-horizontal cycles, and to provide gas-free expulsion of oxidizer propellant in low or zero-g environment. A lightweight, high performance, and highly reliable Propellant Management Device (PMD) was developed to meet this requirement.

To minimize risk, the heritage approach was utilized to design and manufacture the tank shell and the PMD. The tank shell construction is entirely based on existing, qualifed shell designs with flight heritage. Likewise, the PMD design utilized all PMD elements previously designed and qualifed for similar missions.

Stress and fracture mechanics analyses were conducted to design the tank shell. Finite element modeling technique was utilized to assist detail designs. A structural analysis was conducted to validate the PMD, and a PMD performance analysis was conducted to design and validate the PMD. A complete

qualification test program is required to qualify this tank. The qualification testing program is not yet complete at the time of publication.

# **INTRODUCTION**

ATK PSI Operations (ATK PSI) was contracted to design and develop a new family of tanks for a commercial satellite propulsion system. The tanks being developed include a Fuel Tank<sup>1</sup>, an Oxidizer Tank, which is the subject of this paper, and a pressurant tank<sup>2</sup>. This effort marked the first time in the company's 40year history where all the tanks being developed for a new spacecraft are either fully or partially wrapped with composite. Another major program challenge was to design and fabricate Propellant Management Devices (PMDs) for both fuel and oxidizer tanks that are capable of horizontal ground handling at low propellant fill fraction, in addition to its traditional role of providing gas-free propellant to satellite thrusters in low or zero-g environment.

Each spacecraft propulsion system contains a hydrazine fuel tank, two nitrogen tetroxide oxidizer tanks, and two pressurant tanks. The two oxidizer tanks are identical in construction and fully interchangeable. A picture of this oxidizer tank is presented below in Figure 1.

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Figure 1, An Oxidizer Tank Assembly

The oxidizer tank specification requirements are listed below in Table 1:

Table 1: PSI P/N 80435 Propellant Tank Assembly Design Requirements

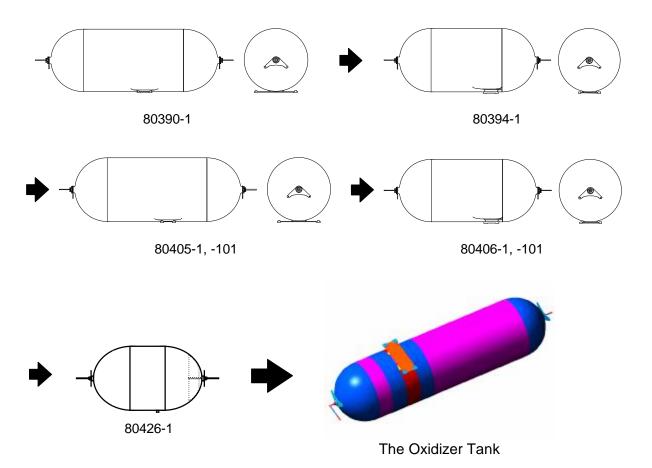
Parameters	Requirements	
Operating Pressure	300 psia, 50 cycles	
Proof Pressure	375 psia, 12 cycles	
Burst Pressure	450 psia, minimum	
Material of Construction	Liner: 6AL-4V Titanium, STA Heads, Annealed cylinder Inlet/outlet Ports: 3Al-2.5V titanium tubes Composite Wrap: G40-800 carbon fiber Sidemount and Flexplate: 6AL-4V Titanium PMD: 6AL-4V and CP Titanium	
Membrane Thickness	0.028 minimum on STA titanium heads	
Tank Mount(s)	Bonded sidemount and upper & lower flexplates (for struts)	
Expulsion Efficiency	99.9% minimum	
Propellant Load	1,339 lbm (608 kg) @ 97% Fill Fraction	
Design Fill Fraction	24% minimum	
Tank Capacity	26,266 in <sup>3</sup> minimum	
Internal Dimensions	21.25" ID x 81.6" long	
Overall Length	90.05" nominal	
Tank Weight	64.7 lbm (29.4 kg) maximum design weight	
Propellant	MON-3 oxidizer	
Fluid Compatibility	MON-3 oxidizer, GAr, GHe, GN <sub>2</sub> , D.I. water, Isopropyl alcohol	
Shell Leakage	<1x10 <sup>-6</sup> std cc/sec He @ 300 psia	
Natural Frequency	> 35 Hz, both lateral and thrust	
Failure Mode	Leak Before Burst / Fracture Mechanics Safe-Life	
Temperature Environment	-20°F to 160 °F (-29 °C to 71 °C)	
Shelf Life	5 years maximum	
On Orbit Life	15 years minimum	

#### **TANK SHELL HERITAGE**

The oxidizer tank is a member of a family of tanks with common 21.25" diameter hemispherical heads and central cylinders of various lengths. See Figure 2. All the heritage tanks presented in Figure 2 are oxidizer tanks previously developed for commercial satellite propulsion systems. The subject oxidizer tank is a third-generation oxidizer tank with a state-of-the-art hybrid tank shell, containing both metallic titanium and composites. Prior to the design and development of this oxidizer tank, all the tanks in this family were of all-titanium construction.

The oxidizer tank shell consists of solution treated and aged (STA) 6AI-4V titanium heads, a cylinder section fabricated from rolled and seam welded titanium sheets, and composite overwrap applied over the cylinder section, thus the term "hybrid". The application of the hybrid shell is not new to ATK PSI. Several 35" diameter hybrid tanks for commercial satellites have been developed in the last 10 years<sup>1,3</sup>. However, this oxidizer tank is the first 21.25" tank that required the hybrid shell construction. Thanks to the matured technology, manufacturing process developments such as girth weld, liner preparation, adhesive application, and filament wrap were not needed.

Figure 2: Oxidizer Tank Heritage



# TANK ANALYSES

tank analyses included stress analysis, fracture mechanic analysis, and dynamic analysis for the tank shell, structural analysis for the PMD, and the PMD performance analysis. Because 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. published material properties, test data and experimental data utilized on a majority of the pressure vessels and PMD's successfully designed. manufactured, 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 oxidizer tank specification requirements. The analysis took into consideration the requirements such as:

- Temperature environment;
- Material properties, titanium;
- Fiber allowable:
- Laminate Moduli for epoxy;
- Adhesive properties;
- Volumetric requirements;
- Mass properties of tank shell material;
- Mass properties of fluid;
- Fluids used by the tank;
- Line and fitting pressure;
- Tank pressurization history;
- Negative pressure requirement;
- 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.

The stress analysis verified that the new tank design meets all the stress requirements. The analysis concluded with positive margins of safety for all design parameters, including collapse pressure. Some of the analytical safety margins are summarized in Table 2.

Table 2: Oxidizer Tank Safety Margins

Characteristics	M.S.
Membrane, hemi, proof, yield	+0.110
Membrane, hemi, burst, ultimate	>+0.004
Membrane, hemi, collapse, ultimate	+6.150
Membrane, cylinder, collapse, ultimate	+2.600
Cylinder liner, proof, yield	+0.240
Cylinder liner, burst, ultimate	+0.130
Girth weld, proof, yield	+0.070
Girth weld, burst, ultimate	+0.040
Prop/pres boss, p+external load, yield	+0.450
Side boss, p+external load, yield	+0.540
Side boss, p+external load, ultimate	+0.560
Flex plate, yield	+0.702
Side plate, yield	+0.560
Side boss, attachment, yield	+0.085
Side mount, bolt, ultimate	+0.000
Side mount, bearing, yield	+0.050
Collapse pressure, head	+6.150
Collapse pressure, cylinder	+2.600

#### FRACTURE MECHANICS ANALYSIS

fracture mechanics analysis 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. analysis was performed using external and internal stresses from the stress analysis, and using NASA/FLAGRO with minimum thicknesses as parameters. Special dye-penetrant fracture critical 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 seam welds and heat affected zones;
- Maximum pressure stress location in the hemisphere;
- Maximum stress location in the cylinder;
- Maximum stress location in the cylinder side mount;
- 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 concluded that the tank shell as designed meets all the fracture mechanics The special NDE requirements. requirement established by this fracture mechanics analysis includes:

- Special fracture critical dye-penetrant on all surfaces; and
- Special fracture critical radiograph on all welds and the spherical shell where thickness is <.030 inch.</li>

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

# FINITE ELEMENT MODEL

A finite element model (FEM) was created to determine the dynamic characteristics of the oxidizer tank. The model incorporated shell thickness variations, composite overwrap, and spacecraft interface stiffness as specified by the customer. The dynamic FEM finite element is presented in Figure 3.

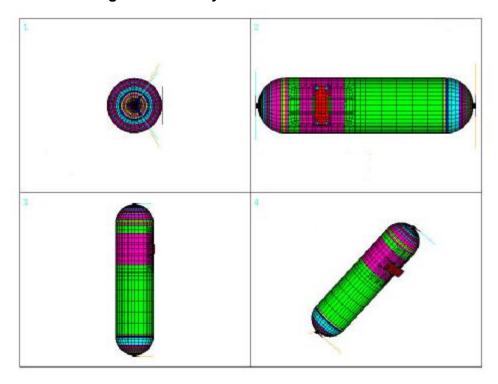


Figure 3a: The Dynamic Finite Element Model

Figure 3b: The Dynamic Finite Element Model, Side Mount

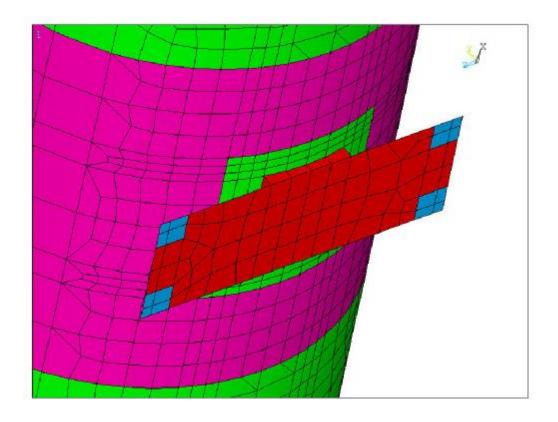
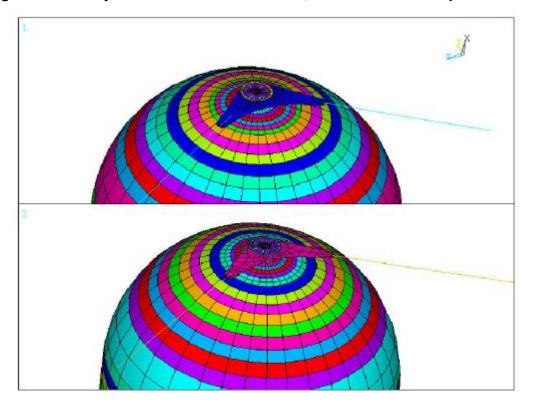


Figure 3c: The Dynamic Finite Element Model, Pressurant and Propellant Bosses



The extensive FEM analysis provided the design details for the composite overwrap as well as tank frequency predictions. The FEM analysis showed that the tank design meets both minimum lateral and longitudinal (axial) frequency requirements. Some representative axial and lateral modes are shown in Figure 4:

Figure 4a: Axial Mode

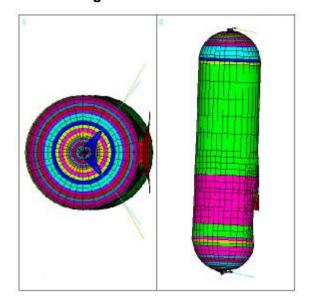
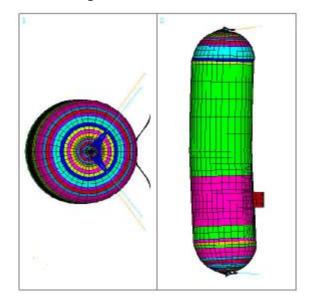


Figure 4b: Lateral Mode



The dynamic model was also used to simulate loads during the qualification vibration testing. The analysis showed that the sine vibration testing is the critical loading case at the following axes:

• Axial - X: ± 16 g's;

• Later - Y: ± 10 g's; and

• Later - Z: ± 10 g's.

The random vibration maximum response of 4.0 g<sup>2</sup>/Hz is less critical and enveloped by the sine vibration loads. Some quasi static loading cases are shown in Figure 5:

Figure 5a: Quasi Static Loading, Axial X @ +16 g's

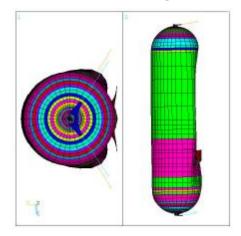
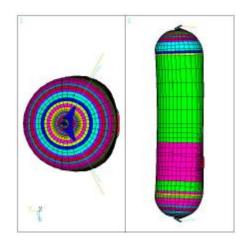


Figure 5b: Quasi Static Loading, Lateral Y @ +10 g's



# **TANK FREQUENCY**

The Oxidizer Tank was designed to a minimum lateral and axial frequency. However, when this tank undergoes qualification, it will be mounted in a test

fixture. In order to correlate test results with analysis, the FEM was conducted for the flight configuration and the test configuration. Table 3 below shows the Oxidizer Tank frequencies and effective masses for these configurations.

Table 3a: Oxidizer Tank Frequencies and Effective Masses, Flight Configuration

Direction	Frequency (Hz)	Mode Number	Effective Mass (%)	Effective Mass (lbm)
X (Axial)	33.0	1	91.8	1273.6
	50.9	3	3.1	42.9
	94.3	6	4.8	66.4
Y (Lateral)	50.9	3	87.9	1220.6
	76.3	4	8.0	111.5
Z (Lateral)	38.0	2	88.7	1231.6
	99.4	7	9.3	129.6

Table 3b: Oxidizer Tank Frequencies and Effective Masses, Test Configuration

Direction	Frequency (Hz)	Mode Number	Effective Mass (%)	Effective Mass (lbm)
X (Axial)	35.0	1	89.1	1236.5
	52.2	3	4.1	56.8
	97.0	6	6.4	88.5
Y (Lateral)	52.2	3	90.9	1261.6
	81.4	4	4.3	60.1
Z (Lateral)	38.7	2	87.6	1216.5
	101.7	7	10.4	143.7

#### PMD STRESS ANALYSIS

PMD stress analysis also was conducted to validate the structural components, integrity of the PMD subassemblies, and assemblies. analysis took into consideration design requirements such as material properties, fluid properties, pressure environments, vibration loads, and design safety factors. The PMD stress analysis concluded with positive margins of safety for all design parameters, as summarized below:

**Table 4: PMD Safety Margins** 

Characteristics	M.S.
Trap, priming pressure, yield	+4.18
Trap, priming pressure, ultimate	+4.22
Trap bottom, priming pressure, buckling, ultimate	+0.33
Trap bottom, priming pressure, stress, ultimate	Large
Centerpost, lateral, yield	+0.38
Centerpost, lateral, ultimate	+0.39
Centerpost, axial, yield	Large
Slosh control device, yield	+5.40
Return tube, yield	+1.30
Return tube, ultimate	+1.32
Return tube base, yield	+0.58
Top plate trap, dynamic loads, yield	+3.87

# PMD PERFORMANCE ANALYSES AND PMD DESIGN

The Oxidizer Tank PMD is a passive surface tension device designed to provide gas free nitrogen tetroxide (NTO) during all mission accelerations. As with most PMDs, the Oxidizer Tank PMD was designed specifically for the intended mission. To minimize mass and optimize service, this PMD is custom designed for use with NTO.

A comprehensive PMD performance analysis was performed to design, analyze, and validate the PMD. Specifically, the PMD has been designed to:

- Allow low fill fraction horizontal handling;
- Accommodate slews, lateral firings, failure recovery, and zero g propellant transfer;
- Provide gas free propellant delivery throughout mission including system priming, LAE ignition, and LAE steady state firing,
- Retain residual propellant in the AFT end of the tank to prevent on orbit slosh and CG migration, and
- Be interchangeable between each side of the spacecraft.

The design utilizes a minimum safety factor of three (3) on sample bubble points and a minimum safety factor of two (2) on flight unit bubble point testing and on all PMD loads. Additional features are incorporated to provide an optimal design:

- (1) Because the PMD is a passive device with no moving parts, the design is inherently reliable;
- (2) The design is constructed entirely of titanium, thus the PMD is lightweight and offers exceptional compatibility, long life, and reliability;
- (3) The PMD is 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 margin.

The key components of this PMD are:

- Sponge;
- Geyser Limiting Baffle;
- Slosh Control Device; and
- Trap Pick Up Assembly.

All PMD components are located over the tank outlet. A sketch of the PMD is provided in Figure 6.

#### The Sponge:

The sponge consists of 24 radial titanium sheet metal panels extending from the center support cylinder. The panels are attached to the center post as well as the geyser limiting baffle. Each panel is 6 inches high and is positioned directly above the trap housing and trap entrance window.

#### The Geyser Limiting Baffle:

On top of the sponge is a geyser limiting baffle that consists of a 7-inch diameter plate designed to limit geysering near the sponge. The plate is designed to support the sponge panels as well. The baffle is partially perforated with large holes for the purpose of weight reduction, but still offers sufficient solid area to limit geysering.

The thickness of the baffle is determined by structural analysis and does not affect the PMD functional properties.

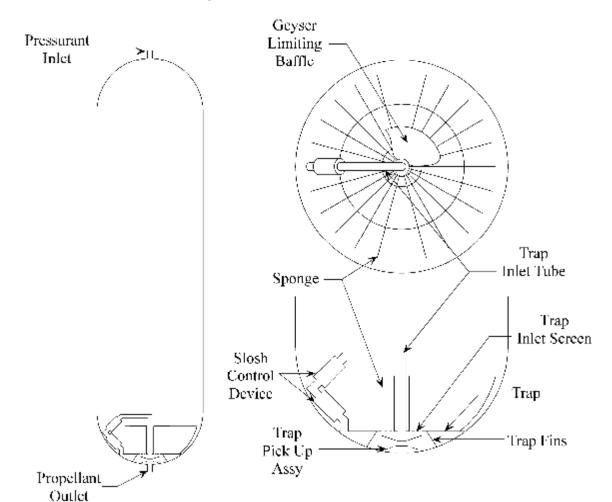


Figure 6: The Oxidizer Tank PMD

# The Trap Housing and Slosh Control Device:

Below the sponge is a trap, which connects the tank bulk space to the outlet. This trap is shaped to reside as low in the tank as possible. The upper trap housing resides in a horizontal plane, and the lower trap housing is contoured to follow the tank shell. The trap housing is attached to the tank wall at the outlet.

A trap window is designed to access NTO in the sponge. The screen area is approximately 4 in<sup>2</sup> and the screen is positioned under the sponge. The trap inlet tube consists of a vertical tube and two slosh control devices oriented at 90 degrees apart.

#### The Trap Pick Up Assembly:

Within the trap resides a pick up assembly designed to prevent gas in the trap from exiting the tank using 24 radial fins that are positioned above a perforated sheet.

#### **PMD OPERATIONS**

The Oxidizer Tank PMD is designed to provide gas free propellant to the tank outlet throughout the mission. ground operations, the PMD is designed to enable tank filling, tank handling (upright and horizontal), and tank draining. During launch, the PMD does not function and is designed to maintain propellant over the trap and not be adversely affected by the launch conditions encountered. The PMD is designed to provide gas free propellant to the tank outlet subsequent to the separation and separation recovery event. The primary use of the PMD is to provide gas free NTO during the three axis stabilized ascent following launch. addition, the PMD is designed to retain residual propellant in the AFT end of the tank while on orbit - thus preventing any significant CG shift due to NTO movement.

The flow path through the PMD is illustrated in Figure 7.

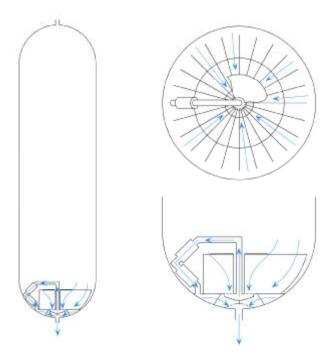


Figure 7: The Oxidizer Tank PMD Flow Path

Highlights of the Oxidizer Tank operational sequence is described below:

#### **Ground Operations**

- Tanks are filled in the upright, outlet down position.
- ◆ Tanks are drained in the upright, outlet down position.
- Handling may occur with the tank upright or with the spacecraft rotated horizontal. The PMD is designed to prevent gas ingestion during upright-to-horizontal handling. There are two possible orientations during ground handling – the "left" and the "right" tank, as shown in Figure 8. The PMD prevents any gas from reaching the outlet during low fill fraction horizontal handling. Horizontal handling has no effect of future PMD performance.

Figure 8 shows the various ground operations.

# **Ascent Operations**

- Ascent operations can be divided into five stages: launch, separation, failure recover, slew, and liquid apogee engine (LAE) firing. The PMD is designed to withstand the structural loads during these stages of ascent, prevent gas from penetrating into the propellant outlet, and provide gas free propellant as required.
- PMD is launched in the outlet down position.
- After launch, the spacecraft is separated from the launch vehicle. Separation consists of a short duration axial acceleration, which tends to settle propellant over the PMD. Separation recovery is accomplished with hydrazine only. No NTO is required.
- ◆ After separation recovery, it is possible that the bulk space propellant will reside at the top of the tank. A settling burn will then refill the sponge. This burn is required only if the separation spin rate exceeds 1.5 °/s.

- Following separation, the propellant will be in its coast orientation. Coast could be at either zero g or with the spacecraft spinning about its X-axis.
- System priming of the oxidizer tank occurs during coast. This is the first demand from the oxidizer tank.
- During ascent, a failure could cause the spacecraft to spin about any axis at up to 8 °/s. NTO is not required during failure recovery. After failure recovery, a settling burn will refill the sponge.
- During a slew maneuver, the propellant moves in response to short duration thruster pulses. NTO is not required during slews.
- Liquid apogee engine ignition and steady firing are the main uses of the oxidizer during spacecraft mission, during which the oxidizer is re-oriented to the tank bottom by settling acceleration. Upon reaching the bottom of the tank, the propellant continues its motion and forms a geyser in the middle of the tank. The geyser limiting baffle is designed to prevent the geyser from stripping the sponge of its propellant.
- During the last LAE firing, depletion can occur. The PMD is designed to provide gas free propellant until fill fraction falls below 0.25%.

Figure 9 shows various stages of ascent operations.

#### **Orbital Operations**

 At the end of the final LAE firing, some amount of oxidizer could reside in either tank. The PMD is designed to prevent this propellant from migrating within the tank during the on orbit lateral thruster firings.

Figure 10 shows the lateral steady state firing while on orbit. The sponge remains filled with propellant.

**Figure 8a: Ground Operations** 

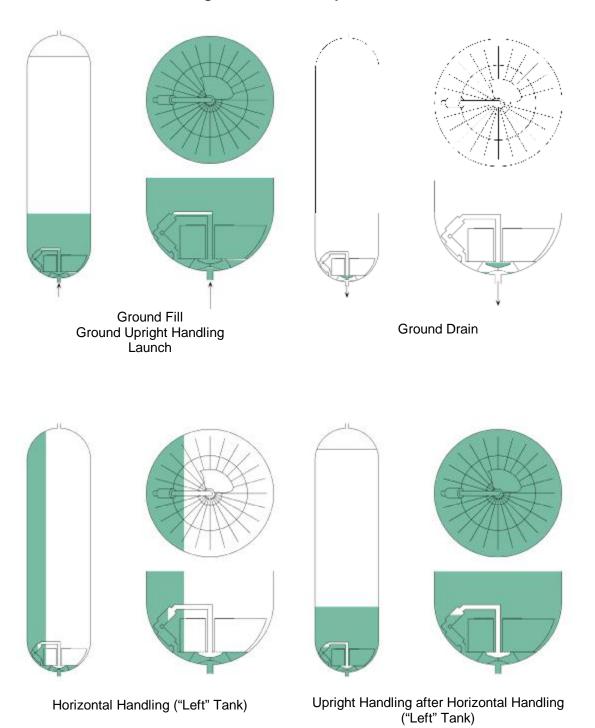


Figure 8b: Ground Operations (cont'd)

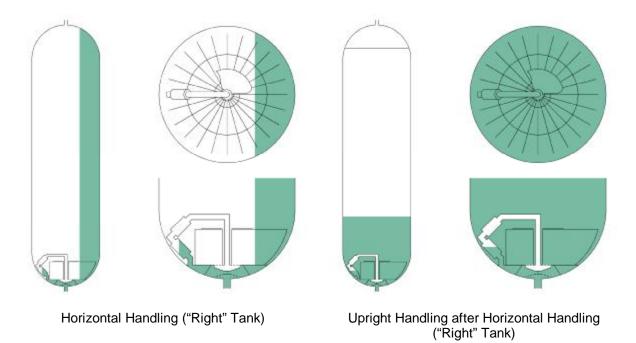


Figure 9a: Ascent Operations

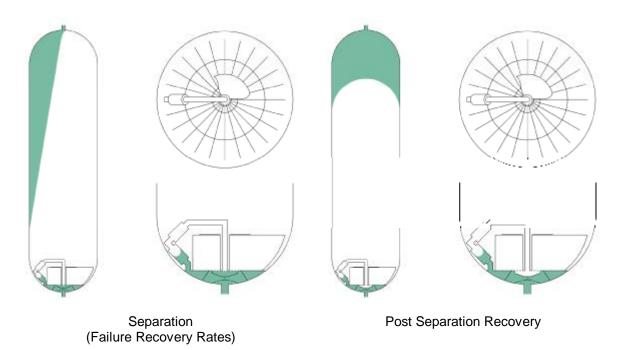
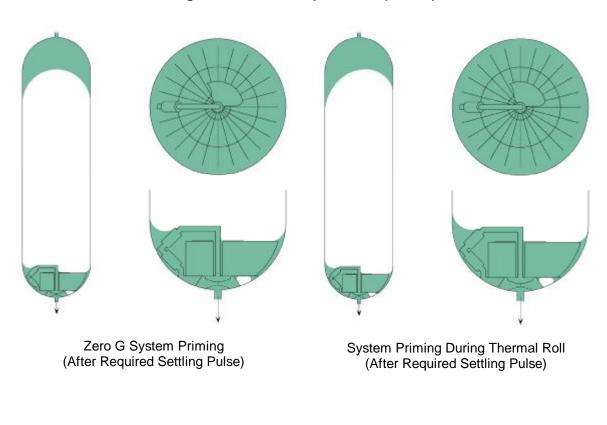


Figure 9b: Ascent Operations (cont'd)



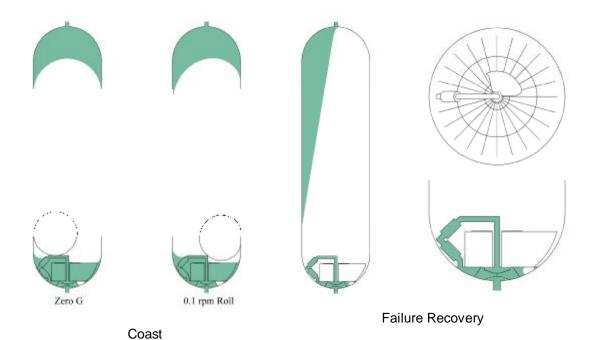
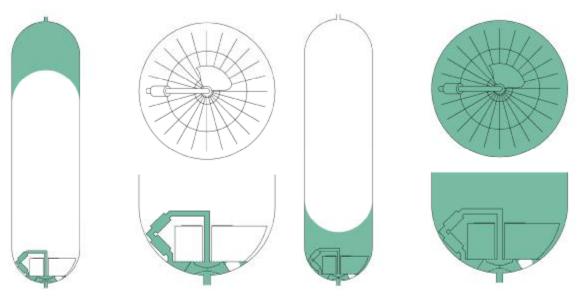


Figure 9c: Ascent Operations (cont'd)



Coast Following Failure Recovery

Coast Following Failure Recovery & Settling Pulse

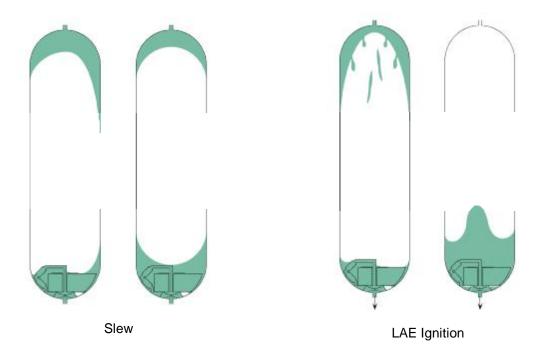
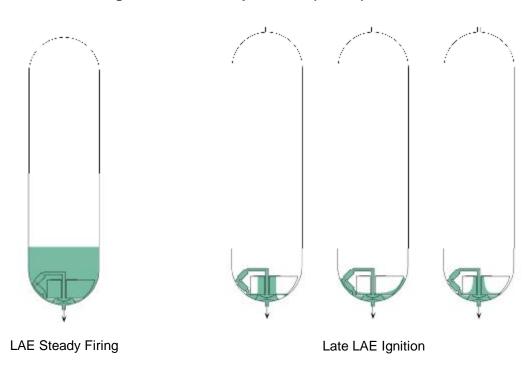


Figure 9d: Ascent Operations (cont'd)



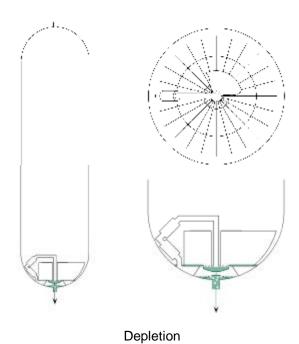
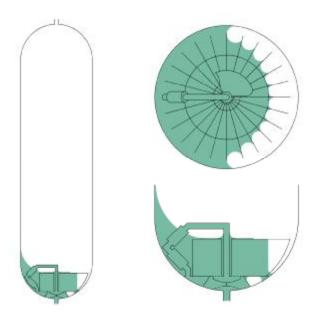


Figure 10: Orbital Operations



Lateral Steady Firing

#### TANK CONSTRUCTION

The propellant and pressurant hemispherical domes are rough machined from annealed 6Al-4V titanium forgings, solution treated and aged, and finish machined to the final thickness specified by the stress and fracture mechanics analyses. The propellant and pressurant interface tubes, fabricated from Ti-3Al-2.5V tubing, are orbital welded to the domes to complete the dome assemblies.

The PMD components, fabricated from either titanium sheets or titanium bars, are assembled into PMD subassemblies (such as sponge assembly, slosh control device assembly, trap pick up assembly) and finally built up into the PMD assembly. The PMD assembly is attached to the propellant hemisphere assembly to complete the expulsion assembly is shown in Figure 11.

Figure 11, The Expulsion Assembly



Due to the length of the oxidizer tank, the tank cylinder section must include 2 liner cylinders that are fabricated form rolled and seam welded 0.032 inch 6Al-4V The titanium sheets. pressurant hemisphere assembly, the expulsion assembly, and 2 cylinders are assembled using 3 identical girth welds. The liner methodology assembly and weld schedule are both based on heritage and no manufacturing development was required. A picture of the completed liner is shown in Figure 12.

Figure 12: Oxidizer Tank Liner



The welded liner is stress relieved in a vacuum furnace to reduce the stresses caused by the girth welds. Following stress relief, G40-800 fibers are applied over the tank cylinder section to complete the overwrap. See Figure 13.

Figure 13: Composite Overwrapped
Tank Shell



To complete the tank shell, a mounting plate is bonded to the tank cylinder section near the propellant end as shown in Figure 14.

Figure 14: Wrapped Tank with Bonded Mounting Plate



The oxidizer tank is stabilized with struts that are attached to flexplates on the upper pressurant port and the lower propellant port. The flexplates are added to the ports after final machine.

# **TANK WEIGHT**

The tank weight as analyzed is provided in Table 5 below:

**Table 5, Tank Weight Estimate** 

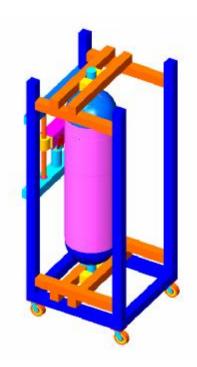
Components	Nominal (lbm)	Maximum (lbm)
Shell	30.0	32.0
Composite	16.0	17.5
PMD	7.5	8.0
Side Mount	2.5	2.75
Flexplate, Nuts & Washers	2.0	2.25
Total	58.0	62.5

The actual mass of the flight tank S/N 2 is 54.12 lbm, and for S/N 3 is 53.24 lbm.

# STATIC LOAD TESTING

A static load test is used to verify the integrity of the side mount. The static load test is conducted using a test fixture to apply axial loads. The fixture concept is shown in Figure 15.

Figure 15: Static Load Test Fixture
Concept



# **ACCEPTANCE TESTING**

Acceptance testing consists of the following tests:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- Static load test
- Pressure drop test
- PMD bubble point test
- External leakage test
- Final visual examination
- Cleanliness

Two tanks have successfully completed acceptance testing.

#### **QUALIFICATION TESTING**

Qualification testing consists of the following tests:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure test

- Post-proof volumetric capacity
- MEOP and proof pressure cycle life
- PMD bubble point test
- External leakage test
- Vibration test
- Volumetric capacity test
- Pressure drop & expulsion efficiency
- PMD bubble point test
- External leak test
- Final visual examination
- Burst pressure

At the time of publication, the qualification testing has not yet begun.

# **CONCLUSION**

The oxidizer tank PMD is custom designed to meet all mission requirements. This PMD has a simple, robust design that's easy to manufacture. It has been acceptance tested and shows excellent strength, durability, and reliability.

The oxidizer tank assembly is lightweight, hiah performance. and easv The tank assembly is manufacture. accomplished standard using manufacturing processes and procedures. Special materials and processes are not required.

Two flight tanks have successfully completed acceptance testing without failure.

#### <u>ACKNOWLEDGMENT</u>

This paper is dedicated to Mr. Mike Debreceni, who was the Program Manager responsible for the development of the Oxidizer tank.

# ABOUT THE AUTHORS

Mr. Walter Tam is the Director of Business Development at ATK PSI Operations, Commerce, California. Mr. Don Jaekle, Jr. is the President of PMD Technology, North Andover, Massachusetts.

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# **NOTES**