AIAA 2008-4942
PROPELLANT TANK WITH SURFACE TENSION PMD FOR TIGHT CENTER-OF-MASS PROPELLANT CONTROL

Walter Tam and Ian Ballinger
ATK Space - Commerce

and

Don E. Jaekle, Jr.
PMD Technology

ABSTRACT

A propellant tank containing a surface tension Propellant Management Device (PMD) was designed and manufactured to store and supply propellant in support of a space scientific mission. Two identical tanks are utilized for the spacecraft propulsion system, one contains Monomethylhydrazine (MMH) fuel, and the other Nitrogen Tetroxide (MON 3) oxidizer. A flight qualified tank shell made from solution treated and aged (STA) 6Al-4V titanium was adapted for the application to reduce program cost. A vibration test program was conducted to acquire the structural loads exerted on the tank shell by a simulated PMD. These realistic loads were used as inputs to the stress analysis which enabled tank shell qualification by analysis and protoflight testing only, and eliminated the need for a dedicated tank shell qualification program.

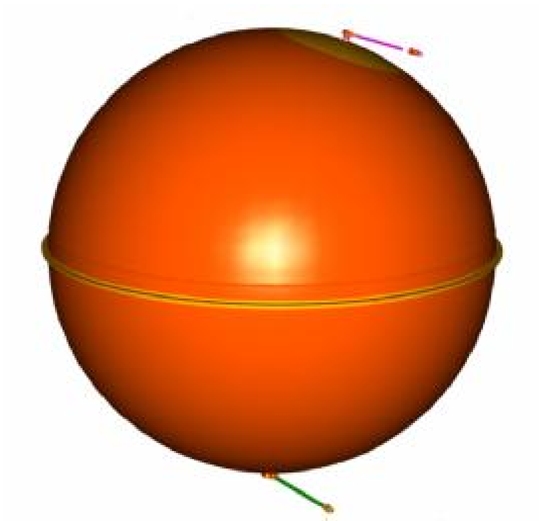
A surface tension PMD capable of providing relatively tight control over propellant center-of-mass was custom-designed for the mission. Similar to all previous PMD designs, the functional validation was supported by analysis only. The PMD performance analysis utilized the same design methodology and conservative approaches as all previous PMD design efforts. A PMD structural analysis was conducted to validate all mechanical elements. The passive, all-titanium PMD design was robust, efficient, and highly reliable.

Two flight tanks were manufactured. One tank was protoflight tested, and the other acceptance tested. Both tanks were delivered to the customer in 2006.

INTRODUCTION

In 2004 ATK Space – Commerce (ATK Commerce, formerly PSI) was contracted to develop a bi-propellant tank capable of relatively tight propellant Center-of-Mass control for a scientific mission. An off-the-shelf, flight-qualified 42” diameter spherical tank shell was baselined. The tank shell was specifically selected to avoid a qualification test program in order to minimize program cost. A model of this bi-propellant tank is presented in Figure 1.

Figure 1, The Bi-Propellant Tank Assembly



The propellant tank must meet the specification requirements listed in Table 1:

Table 1: P/N 80484 Propellant Tank Specification Requirements

Parameters	Requirements
Operating Pressure	2.07 MPa @ 40 °C (300 psia @ 104 °F)
Proof Pressure	1.25 x MEOP, 2.59 MPa (375 psia)
Burst Pressure	1.50 x MEOP, 3.10 MPa (450 psia)
Material of Construction	Tank Shell: Solution Treated and Aged (STA) 6AL-4V Titanium Inlet and Outlet Ports: 3Al-2.5V titanium tubes PMD: all-Titanium
Membrane Thickness	0.914 mm (0.036 inch) minimum
Tank Mount	Continuous Flange
Expulsion Efficiency	> 99%
Propellant Load	548 kg (1,206 lbm) MMH 884 kg (1,945 lbm) MON-3
Design Fill Fraction	98% maximum
Tank Capacity	640,000 cm^3 (39,000 in^3) minimum
Internal Dimensions	107.2 cm (42.210 inch) ID Sphere
Tank Weight	28.2 kg (62 lbm) maximum design weight
Propellant	MMH and MON3
Fluid Compatibility	MMH, MON3, GAr, GHe, GN_2, D.I. water, Isopropyl alcohol
Shell Leakage	$<1x10^{-6}$ std cc/sec He @ 2.07 MPa (300 psia)
Natural Frequency	>30 Hz lateral, >50 Hz axial
Failure Mode	Leak Before Burst / Fracture Mechanics Safe-Life
Temperature Environment	0°C to 40°C (32°F to 104°F)
Mission Life	5 years maximum

TANK SHELL HERITAGE

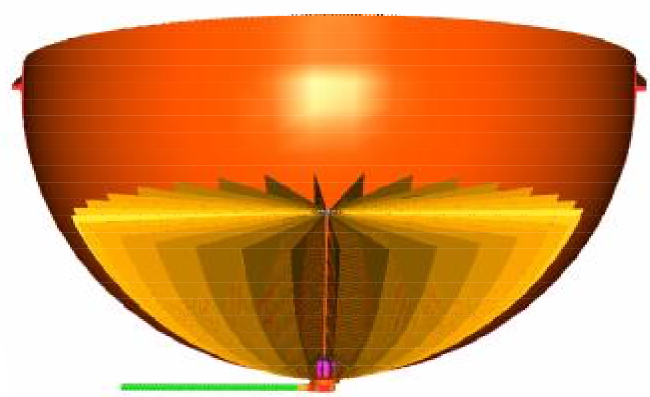
The propellant tank shell was originally developed in 1988 for a Mars exploration program oxidizer tank. The same tank, including its original PMD, was later used on a series of geosynchronous commercial satellite missions. Over a dozen tanks had flown. However, this heritage tank shell presented several challenges for the new tank development program:

1) The tank shell was tested to 50 MEOP cycles, but only one proof pressure cycle, in the original qualification program. It does not meet the current equipment specification pressure cycle requirements.

2) The tank shell was not shock tested in the original qualification program, but the new equipment specification has a specific shock environment.

3) The original PMD had multiple attachment points – at the outlet boss and on the tank shell interior near the girth weld. The new PMD is bigger and heavier than the original PMD, and is mounted canterliver at the outlet boss only. See Figure 2. This new PMD attachment may not provide sufficient margin of safety.

Figure 2: The Canterliver-Mounted PMD

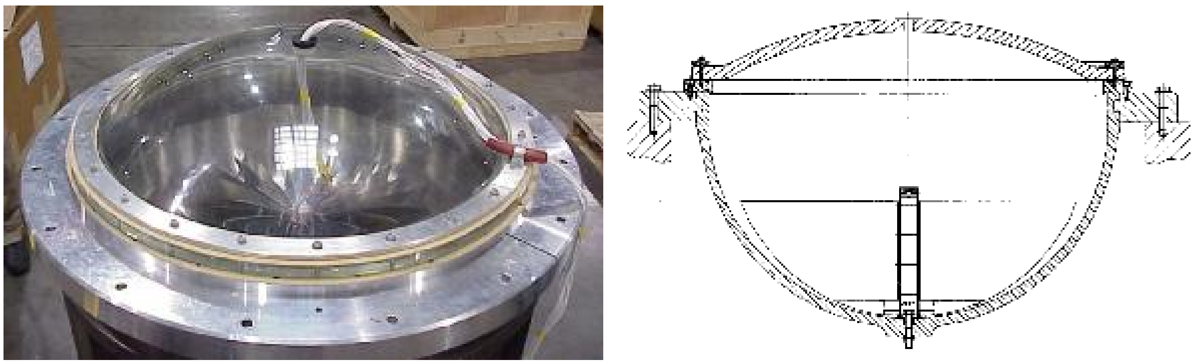


Stress and fracture mechanics analyses were conducted to address items 1 and 2. However, item 3 caused a major concern at the start of the program. A preliminary assessment, using traditional and conservative analytical approaches, revealed that the tank shell as designed would not meet the new mission requirements. However, it was also understood that the assumptions made were conservative. To properly assess PMD attachment loads and their effect on the propellant tank shell, more representative input loads for the stress analysis were needed. A test program was devised to acquire more realistic dynamic loads for this tank shell assessment.

PMD ATTACHMENT LOADS TEST PROGRAM

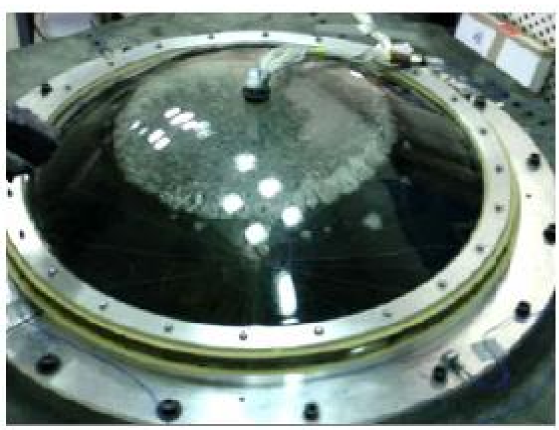
A vibration test program was performed on a simulator to obtain the interface loads between the PMD and the tank shell. The simulator consists of a hemispherical shell and a full-scale simulated PMD. See Figure 3. A plexiglas dome covers the simulated shell to contain the test fluid during the vibration testing. Accelerometers and strain gauges were installed at various locations to record responses to the test inputs.

Figure 3: Test Simulator Setup



A photograph of the simulator vibration testing is shown in Figure 4. The test program yielded actual PMD attachment loads which were used as input loads for tank shell stress analysis. Analysis using this test data confirmed that the new PMD could be mounted in the existing shell and meet mission requirements. The analysis yielded "No Test" Safety Factor for all except lateral dry sinusoidal vibration where a "Test" Safety Factor has resulted. This highlighted an additional validation requirement that must be satisfied by protoflight vibration testing on the flight tank.

Figure 4: Simulator Vibration Testing



TANK SHELL VERIFICATION ANALYSES

Tank shell verification analyses were conducted to validate the qualified tank shell against the new requirements in Tables 2 through 7.

Table 2: Load Requirement (Full Tank)

Axis	Fuel Tank		Oxidizer Tank	
	Limit Level (g)	Qualification Level (g)	Limit Level (g)	Qualification Level (g)
Axial (X)	+ 6.132 / -1.323	+ 7.665 / -1.654	+ 6.119 / -1.144	+ 7.649 / -1.430
Lateral (Y)	+ 1.438 / -1.442	+ 1.798 / -1.803	+ 1.183 / -1.239	+ 1.479 / -1.549
Lateral (Z)	+ 1.864 / -1.839	+ 2.330 / -2.299	+ 1.314 / -1.298	+ 1.643 / -1.623

Table 3: Load Requirement (Empty Tank)

Axis	Limit Level (g)	Qualification Level (g)
Axial	± 1.0	± 1.250
Lateral	± 3.5	± 4.375

Table 4: Random Vibration Environment (Full Tank)

Frequency (Hz)	Limit Level (g^2/Hz)	Qualification Level (g^2/Hz)
20	0.010	0.010
2000	0.010	0.010
Overall	4.45 g_{rms}	4.45 g_{rms}

Table 5: Random Vibration Environment (Empty Tank)

Frequency (Hz)	Limit Level (g^2/Hz)	Frequency (Hz)	Qualification Level (g^2/Hz)
20	0.01	20	0.01
80	0.04	80	0.04
500	0.04	350	0.04
800	0.05	600	0.1
1250	0.035	850	0.1
1350	0.015	1250	0.07
2000	0.01	1500	0.013
		2000	0.01
Overall	7.77 g_{rms}	Overall	10.06 g_{rms}

Table 6: Sine Vibration Environment (Full Tank)

Test Axis	Frequency (Hz)	Limit Level (g)	Qualification Level (g)
All	5 – 50	2.0	2.5

(4 oct/min for flight)

Table 7: Sine Vibration Environment (Empty Tank)

Test Axis	Frequency (Hz)	Limit Level (g)	Qualification Level (g)
Axial	5 – 30 30 - 50	1.0 0.3	1.25 0.38
Lateral	5 – 15 15 – 30 30 - 50	1.0 3.0 0.5	1.25 3.75 0.63

(4 oct/min for flight)

The tank shell analyses included stress analysis, fracture mechanic analysis, and dynamic analysis. All analyses used the same approaches, assumptions, published material properties, test data, and experimental data utilized on a majority of the ATK Commerce pressure vessel designs. Conservatism was used throughout the analysis process, and the worst case scenarios were analyzed. The analyses concluded with positive margins of safety for all design parameters. Some of the analytical safety margins are summarized in Table 8.

Table 8: Propellant Tank Safety Margins

Characteristics	**M.S.**
Membrane, proof	+0.35
Membrane, burst	+0.23
Weld, proof	+0.07
Weld, burst	+0.12
Near flange, proof	+1.57
Near flange, burst	+1.34
Shell external load, environmental test, near tab, test	+1.05
Shell external load, environmental test, near tab, no test	+0.91
Shell external load, protoflight, near tab, test	+1.82
Shell external load, protoflight, near tab, no test	+1.67

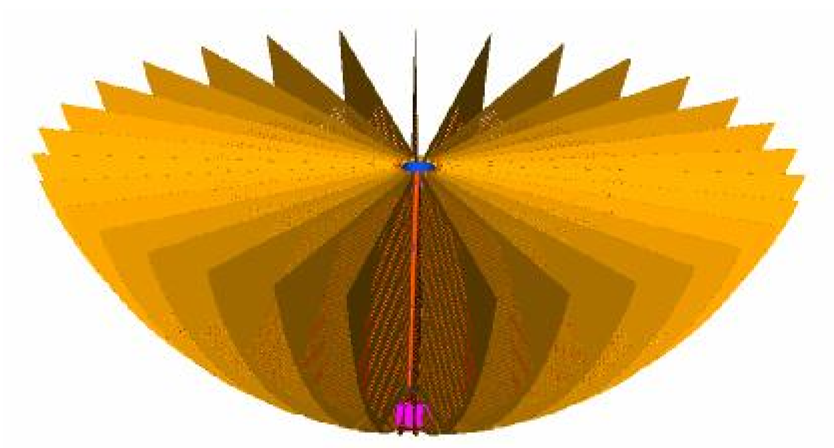
PMD STRUCTURAL ANALYSIS

Because the PMD is completely enclosed within the tank shell, by definition, a fracture mechanics analysis is not required for the PMD. A PMD stress analysis was conducted to validate the structural integrity of the PMD components, subassemblies, and assembly. This 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.

PMD DESIGN AND PERFORMANCE ANALYSES

The propellant tank PMD is a passive surface tension device designed to provide gas free propellant upon demand. As with most PMDs, this PMD was designed specifically for the intended mission, and for use with either MMH and NTO. The PMD concept is shown in Figure 5.

Figure 5: The PMD Concept



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

- Survive launch and other non-operational phases of the mission;
- Provide gas-free propellant delivery throughout mission, including system priming, main engine thruster firing, rotations, and de-orbit;
- Provide propellant center-of-mass control within 5 minutes after wheel operations and 20 minutes after thruster operations.

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. These are the same safety factor as all previous PMD design efforts.

Additional features were incorporated into the PMD design to provide optimal service, including:

(1) A passive design with no moving parts, which is inherently reliable;

(2) All-titanium construction that is lightweight, compatible with both propellants, long life, and highly reliable;

(3) Large safety factors that provide a robust PMD solution.

The key features of this PMD include:

- Large Upper Sponge: The large sponge consists of 32 panels. This large sponge was designed to provide center-of-mass control at fill fractions below 18%.

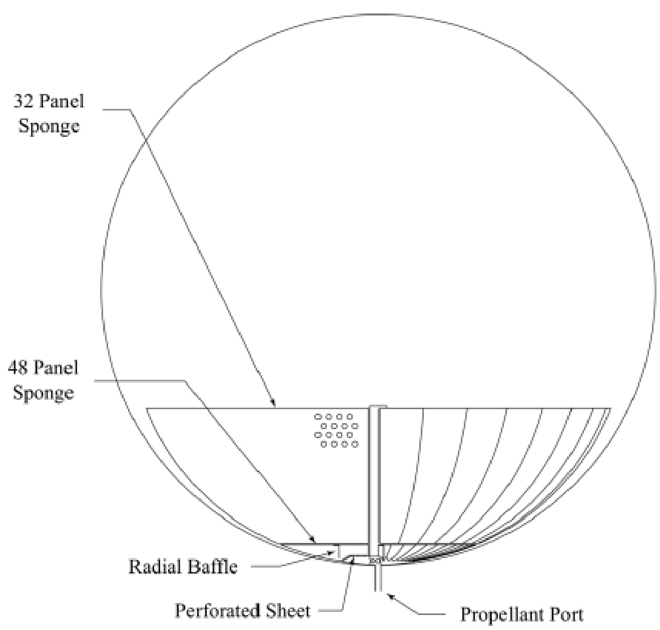
- Small Lower Sponge: The small sponge is located below the large sponge. It consists of 48 panels.

- Propellant Motion Baffle: The propellant motion baffle is integral to the small sponge.

- Pickup Assembly: The pickup assembly has a perforated sheet that provides propellant to the tank outlet.

A sketch of the PMD with its key features is provided in Figure 6.

Figure 6: The Propellant Tank PMD

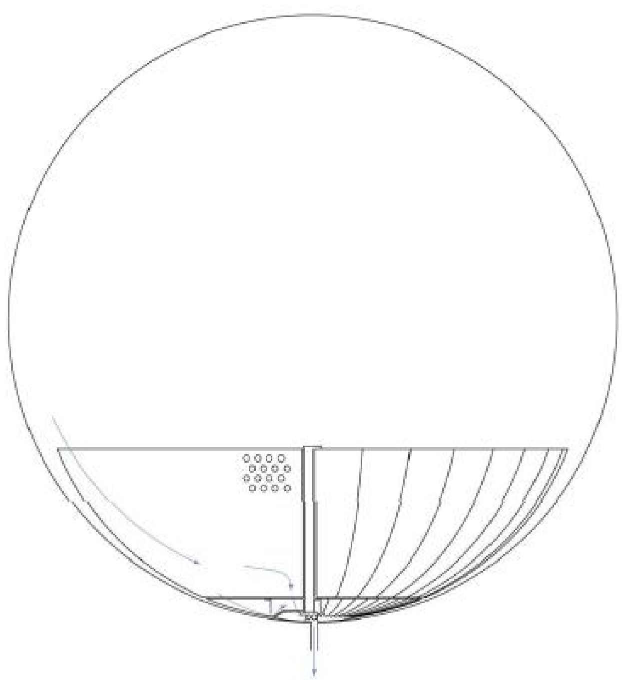


PMD OPERATIONS

The Propellant Tank PMD is designed to provide gas free propellant to the tank outlet throughout the mission. During ground operations, the PMD is designed to enable tank filling, tank handling (upright), and tank draining. During launch, the PMD does not function and is designed to maintain propellant over the outlet and not be adversely affected by the launch conditions encountered. Once in orbit, separation from the booster occurs and the propulsion system is activated. The primary use of the PMD is to provide gas free propellant during axial thruster firings and rotations.

The propellant flow path through the PMD is shown in Figure 7. The PMD was designed to minimize flow losses. Nearly all the tank's flow loss is in the entrance to and within the outlet tube.

Figure 7: PMD Flow Diagram



Highlights of the Hydrazine Tank operational sequence is described below and shown in Figure 8.

Ground Operations

- Tanks are filled in the upright, outlet down position.
- Handling occurs with the tank in the upright, outlet down position. This PMD was not designed for horizontal handling.
- Tanks are drained in the upright, outlet down position.

Figure 8, operational sequence

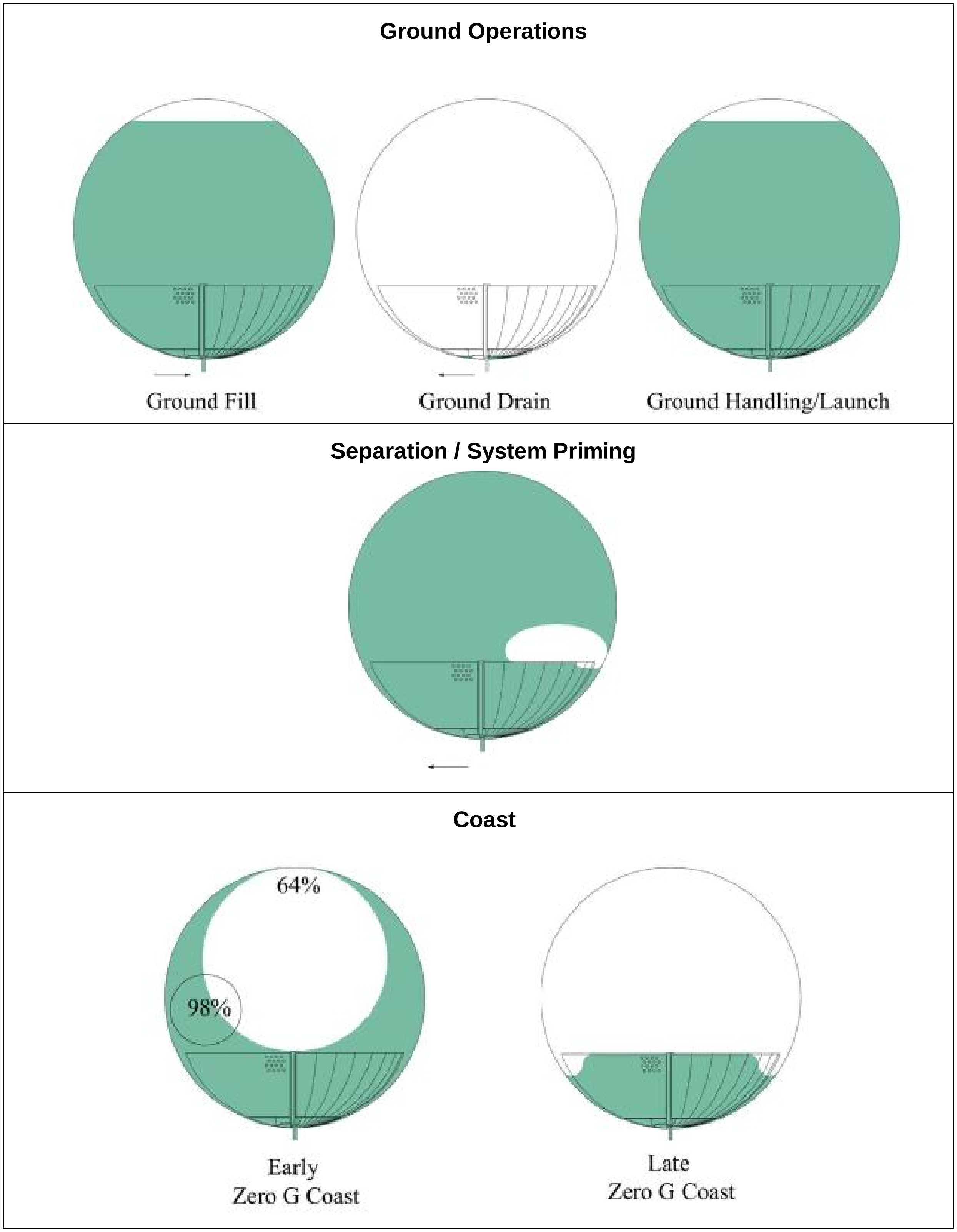
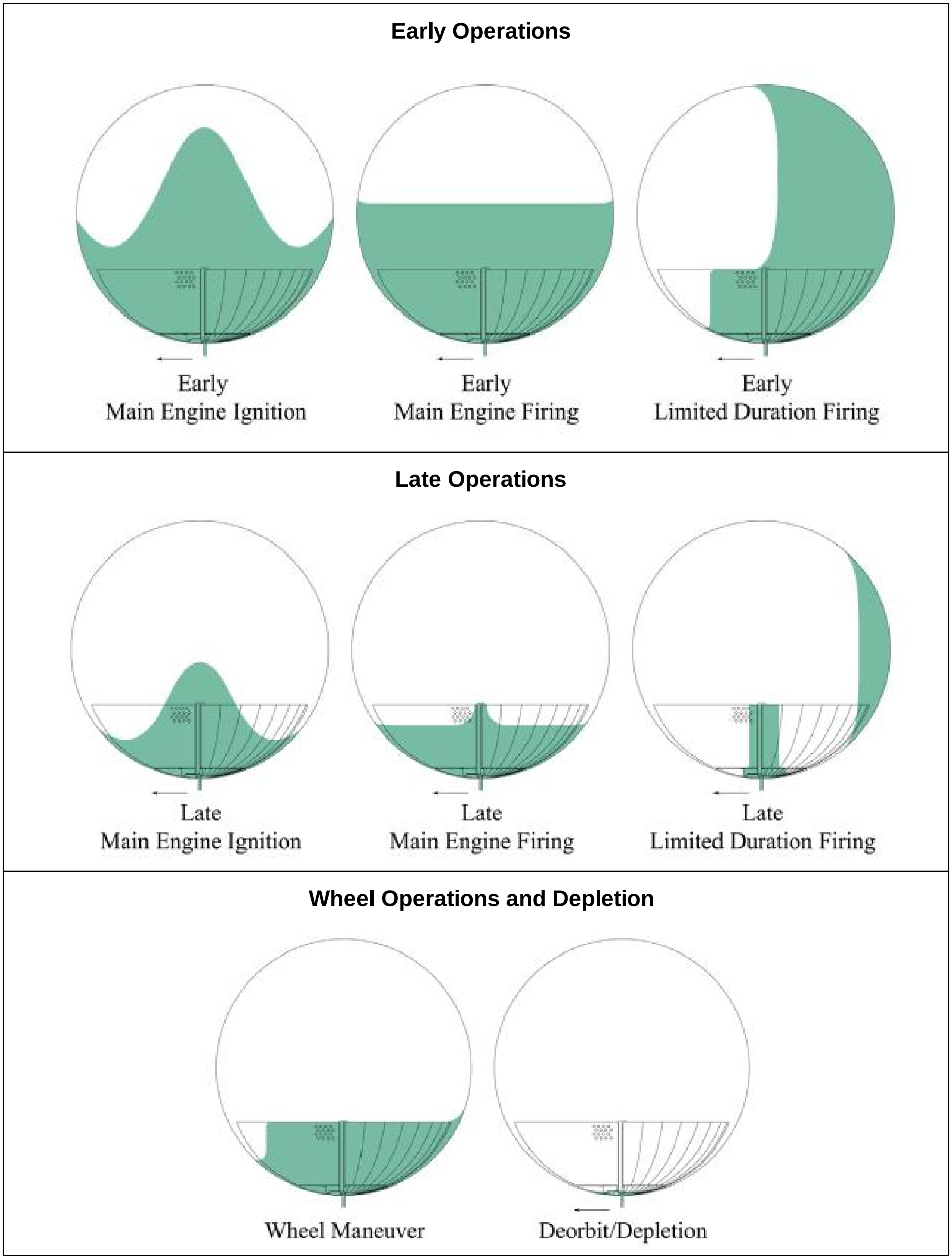


Figure 8, operational sequence (continued)



Ascent Operations

- The PMD is launched in the outlet down position.
- During launch, vibration will induce large loads on the cantilevered PMD. These loads were examined during the test program and the PMD was designed to withstand the structural loads during launch.
- After launch, the spacecraft is separated from the launch vehicle. After separation, the spacecraft may spin at about any axis. During separation, the gas bubble will not enter the sponge due to the presence of surface tension forces.
- After separation, system priming begins. The PMD will maintain the gas bubble sufficiently far away from the outlet to prevent gas ingestion.

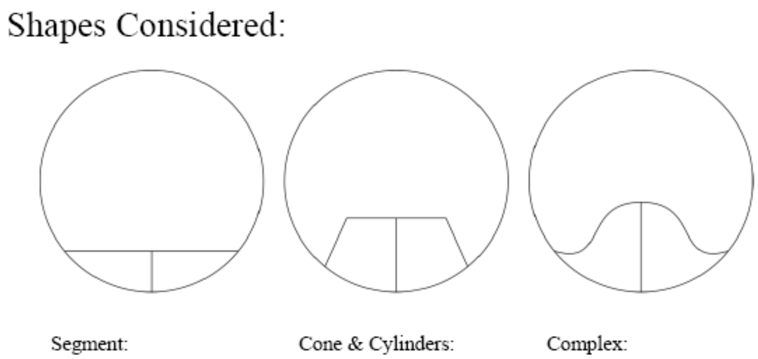
Orbital Operations

- During most of the spacecraft's time in orbit, zero g coats will be the norm.
- At high initial fill fractions (98% illustrated), the gas bubble in the tank is spherical and free-floating.
- At 64% fill fraction, the gas bubble becomes trapped between the PMD and the upper hemisphere.
- At fill fraction below 64%, the gas is no longer spherical and is squeezed by the PMD.
- At all fill fractions in zero g, the sponge is filled with propellant and maintains the gas bubble away from the outlet.
- The PMD is designed to provide gas free propellant during two types of maneuvers: 1) axial settling ignitions and steady state firing, and 2) limited duration rotations.
- During thruster ignition, the propellant reorients from zero g configuration into settled configuration. During this transient, a geyser may form. The PMD sponges and propellant motion baffle are designed to ensure that sufficient propellant remains over the outlet.
- During small thruster firings, vehicle may rotate and liquid may be pushed laterally away from the outlet. The sponge is designed to retain sufficient propellant for the RCS maneuvers.
- During wheel operations, the sponge retains all the propellant. The propellant center of mass will shift laterally and somewhat axially during the maneuver, but within 5 minutes of zero g coast following the wheel maneuver, the sponge will pull the propellant back to the equilibrium position.
- Depletion occurs during a steady state axial firing. As the settled propellant is consumed, the outlet will become exposed to gas. When the gas enters the outlet tube, depletion occurs. The total liquid propellant residual volume will be less than 1% of the tank volume.

PMD Trade Study

Several trades were conducted during the PMD detail design. For example, Thirteen (13) large sponge shapes were considered, some of which are shown in Figure 9. Other trades include the number of panels and the dimensions of the panels, location of the entrance to pick up assembly, type of porous element and the flow area of the porous element. As always, these types of trade studies were not conducted to maximize a particular aspect of the PMD, but were done to optimize the overall PMD functionality. Items such as mass, performance, manufacturability, testability, reliability, contamination concerns, and cost are always part of the trade space.

Figure 9: PMD Sponge Design Trade Studies



PMD Design Tools

Many commercially available design tools were used to provide simulation and visual aid during design and analysis. Some simulation outputs are shown in Figures 10 and 11.

Figure 10, Fluid Dynamics Simulation – Axial Firing and the Resulting Geyser

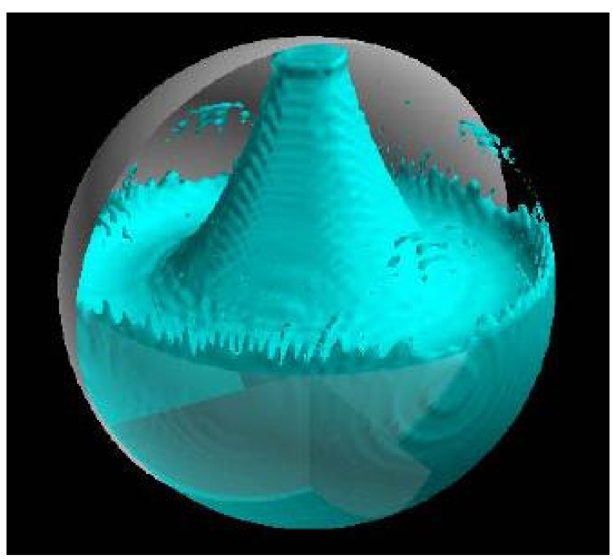
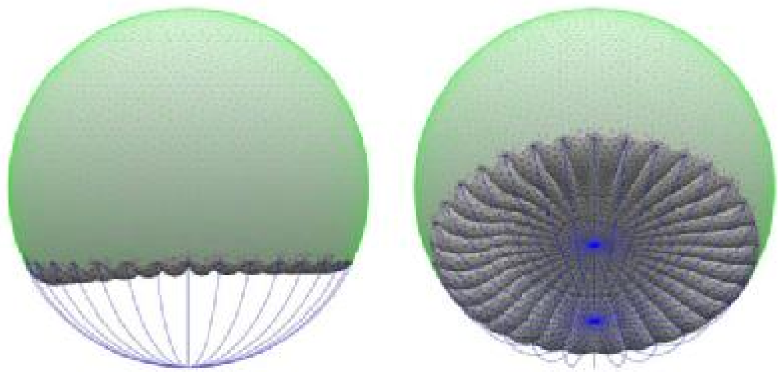
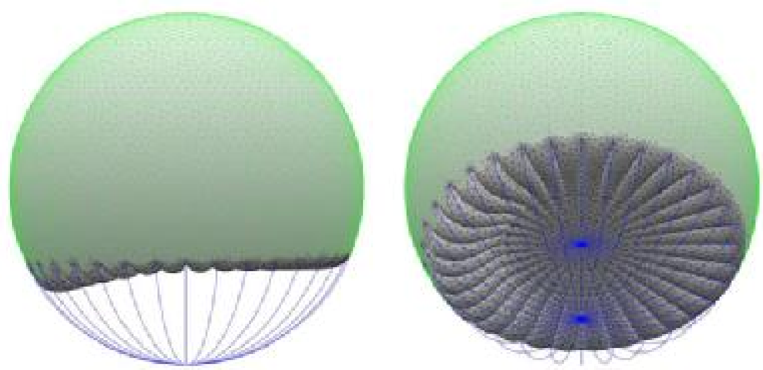


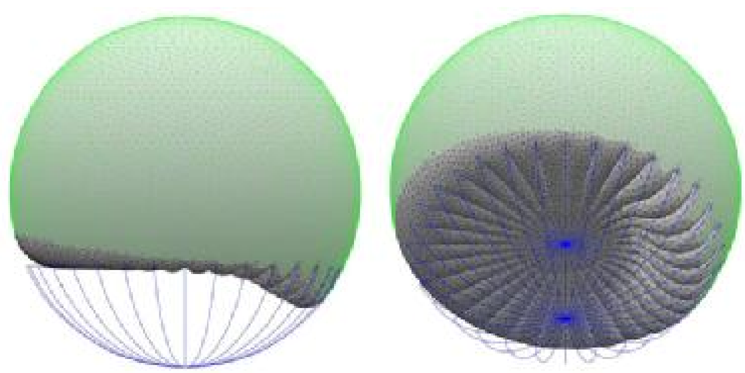
Figure 11, Fluid Dynamics Simulation



32 Panel Segment PMD with 18% FF At 0.85e-5 g



32 Panel Segment PMD with 18% FF At 2.8e-5 g



32 Panel Segment PMD with 18% FF 2°/s
Spin Axis 40 degrees Off Vertical (Worst Case)

Because the PMD was designed to control propellant Center-of-Mass, a detail study of the CoM characteristics was conducted. CoM shift as a function of acceleration and fill fraction are plotted in Figures 12a and 12b.

Figure 12a, Lateral Center of Mass vs. Fill Fraction at Relevant Lateral Linear Accelerations

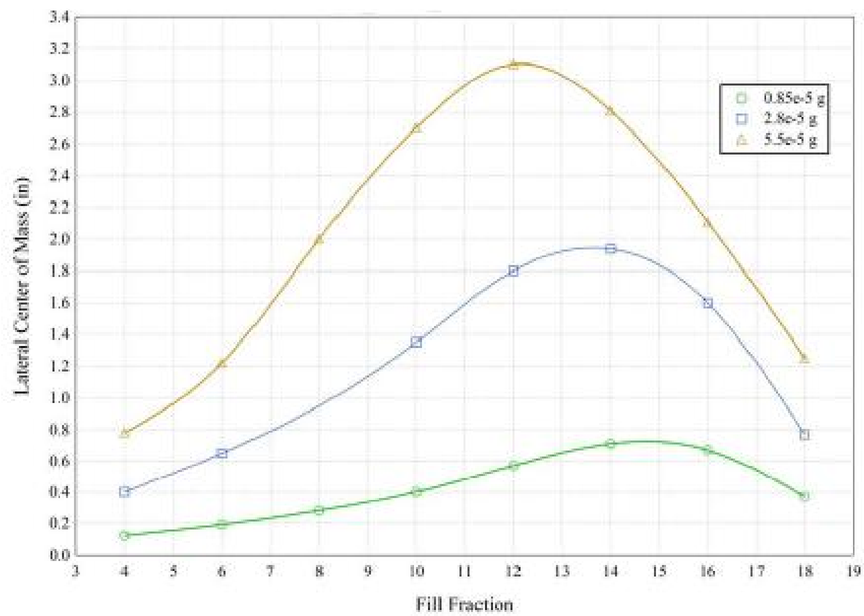
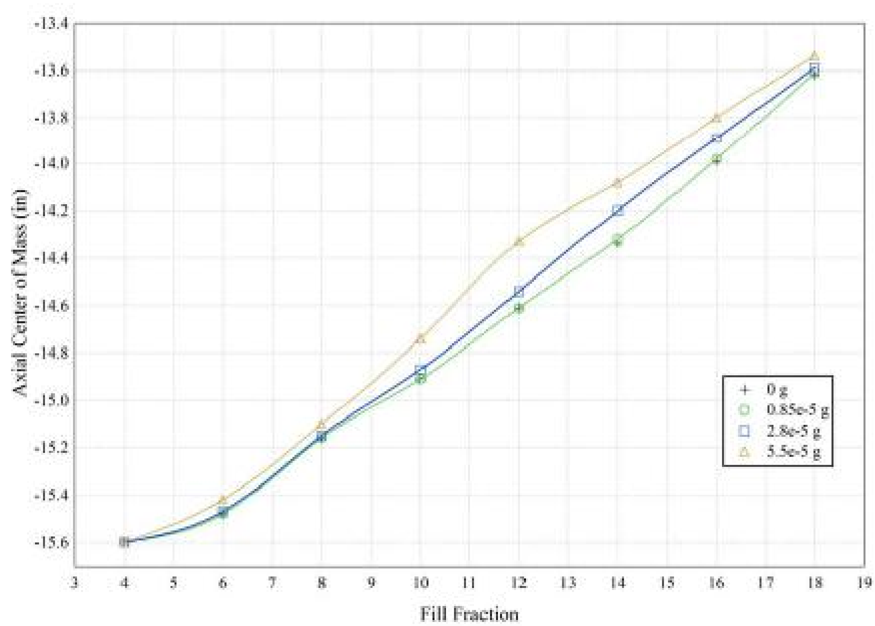


Figure 12b, Axial Center of Mass vs. Fill Fraction at Relevant Lateral Linear Accelerations



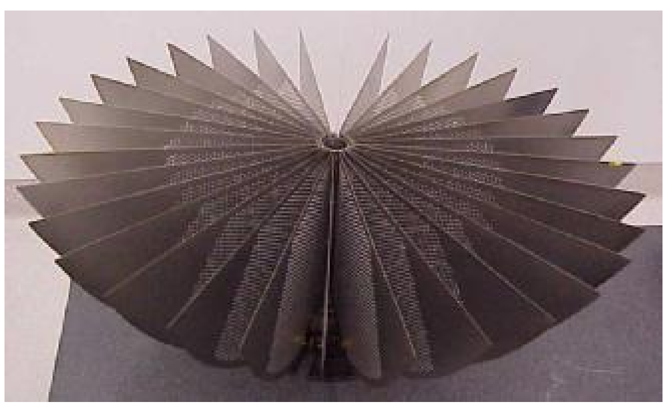
TANK CONSTRUCTION

The propellant tank shell consists of two STA 6Al-4V titanium domes machined from forgings. A continuous mounting flange is machined integral from the propellant hemisphere as shown in Figure 13, and an off-axis pressurant port is machined into the pressurant hemisphere.

Figure 13: The Propellant Tank Shell

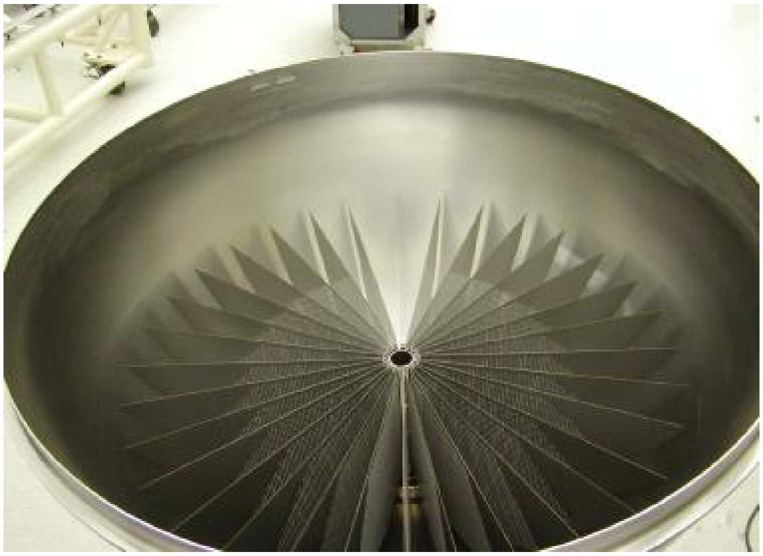
The PMD is manufactured separately in a parallel effort. The PMD components are fabricated from either titanium sheets or titanium bars, and welded into the PMD assembly as shown in Figure 14. This PMD assembly does not contain moving parts and, as noted earlier, is inherently reliable.

Figure 14: The PMD Assembly



The PMD assembly is installed onto the propellant hemisphere assembly to complete the expulsion assembly, as shown in Figure 15.

Figure 15, The Expulsion Assembly



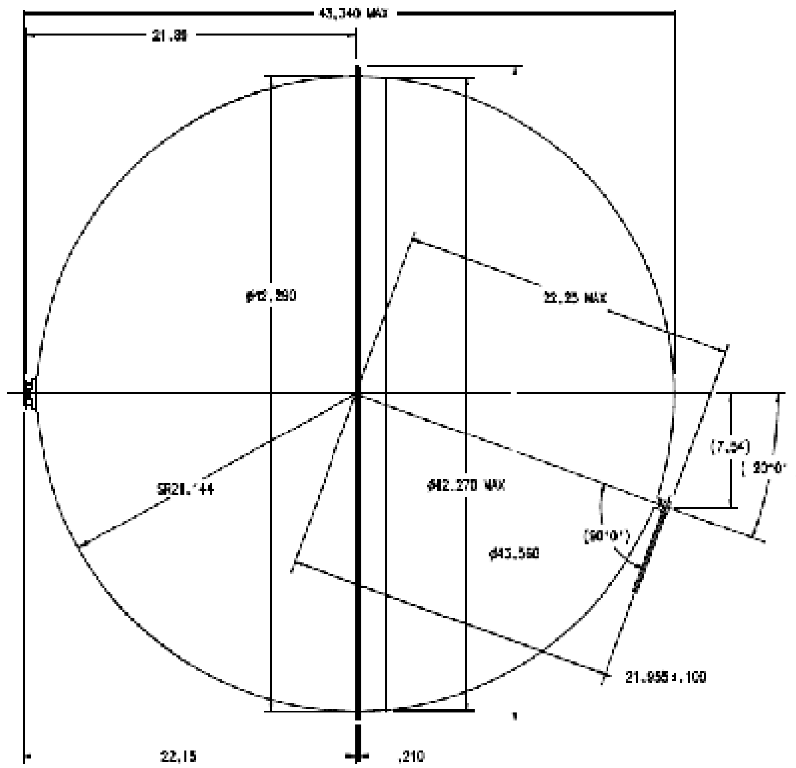
After PMD installation, the two heads are Tungsten Inert Gas (TIG) welded into a tank weldment. The completed tank assembly is shown in Figure 16.

Figure 16: The Welded Tank

INTERFACE DIMENTIONS

Some interface dimensions of the propellant tank are provided in Figure 17 :

Figure 17: Hydrazine Tank Interface Dimensions



PROTOFLIGHT TESTING

The tank analysis resulted in “test” margin of safety on lateral vibration, and protoflight tests were conducted to validate tank design against the new mission requirement. One of the two flight tanks was subject to the following protoflight test sequence:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- External leakage test
- Bubble point test
- Protoflight vibration: dry and wet sine, dry and wet random
- Bubble point test
- Protoflight acceleration test
- Bubble point test
- External leakage test
- Dye penetrant & radiographic Inspection
- Final dimensional and visual examination
- Precision clean

Protoflight vibration tests were conducted for one axial and two lateral axes. The vibration test setups are shown in Figure 18. Vibration testing included sine and random vibration conducted with the test specimen empty or loaded and pressurized.

Figure 18: Vibration Test Setup

Lateral Vibration Test Setup

Axial Vibration Test Setup

The Protoflight Dry Random Vibration was conducted per the input spectrum defined in Table 9:

Table 9: Protoflight Dry Random Vibration Input

AXIS	FREQUENCY (HZ)	PROTOFLIGHT LEVEL (g2/Hz)
3 AXIS	20	0.01
	80	0.04
	350	0.04
	600	0.1
	850	0.1
	1250	0.07
	1500	0.013
	2000	0.01
	Overall	**10.06 grms**

Test duration is 1 minute per axis.

The Protoflight Dry Sine Vibration test was conducted per the sinusoidal vibration test at the levels defined by Table 10:

Table 10: Protoflight Dry Sine Vibration Levels

TEST AXIS	FREQUENCY (HZ)	PROTOFLIGHT Level (g)
Axial	5-30	1.25
	30-50	0.38
Lateral	5-15	1.25
	15-30	3.75
	30-50	0.63

Note: Test level at 4 Oct/min.

The Protoflight Wet Random Vibration was conducted per the input spectrum defined in Table 11:

Table 11: Protoflight Wet Random Vibration

AXIS	FREQUENCY (HZ)	PROTOFLIGHT LEVEL (G2/Hz)
ALL	20	0.010
	2000	0.010
	Overall	4.45 grms

Test duration is 1 minute per axis.

The Protoflight Wet Sine Vibration was conducted per the levels defined in Table 12:

Table 12: Protoflight Wet Sine Vibration

TEST AXIS	FREQUENCY (HZ)	PROTOFLIGHT LEVEL (g)
All	5-50	3.48g

Limited to 0.5 inch maximum double amplitude

The Protoflight Tank underwent protoflight acceleration test as part of the tank shell validation. Two tank orientations were tested to the worst-case conditions. Typical test setups are shown in Figure 19a and 19b. The tests were conducted with 1385 lbm of water loaded in the test specimen, and tested to the g levels in Table 13:

Table 13: Acceleration Test g Loads

Axis	Qualification Level Case 1 (g)	Qualification Level Case 2 (g)
Axial (X)	+10.711	-2.073
Lateral (Y)	+2.156	-2.156
Lateral (Z)	+2.309	-2.309

Figure 19a: Acceleration Test Setup

Figure 19b: Acceleration Test Setup

ACCEPTANCE TESTING

The second flight tank was acceptance tested to the following test sequence:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- Differential pressure drop test
- External leakage test
- Bubble point test
- Dry random and dry sine vibration tests
- Bubble point test
- External leakage test
- Weld quality Inspection
- Radiographic inspection of PMD & expulsion assembly
- Final examination
- Precision clean

The actual mass of the flight tank S/N 1 is 56.7 lbm. Only one tank was subjected to acceptance testing prior to delivery.

CONCLUSION

The propellant tank shell development program successfully conducted analytical and test campaigns to allow the utilization of a qualified, off-the-shelf tank shell which provided significant cost savings to the customer. The PMD development program successfully designed and developed a robust and highly reliable PMD that provides excellent propellant center-of-mass control for the intended mission. The PMD was qualified by analysis only, as no zero g PMD functional tests could be conducted prior to flight.

Two flight tanks were delivered to the customer in 2006. The flight tanks were successfully integrated into the spacecraft propulsion system. The spacecraft is currently scheduled for launch in December 2008.

ABOUT THE AUTHORS

Mr. Walter Tam is the Director of Business Development at ATK Space, Commerce, CA.

Mr. Ian Ballinger is the Director of Engineering at ATK Space, Commerce, CA.

Mr. Don Jaekle, Jr. is the President of PMD Technology, North Andover, Massachusetts