AIAA 2008-5105
SURFACE TENSION PMD TANK FOR ON ORBIT FLUID TRANSFER

Walter Tam and Ian Ballinger
ATK Space Sysems - Commerce

and

Don E. Jaekle, Jr.
PMD Technology

ABSTRACT

A hydrazine propellant tank was designed and manufactured to support a mission to demonstrate on-orbit propellant transfer capabilities. To reduce program cost, a flight qualified tank shell made from Solution Treated and Aged 6Al-4V titanium was baselined. This tank shell was selected based on its qualified capabilities as well as its ability to adapt a new cantilever-mounted Propellant Management Device (PMD). Stress and fracture mechanics analyses were conducted to validate the tank shell for the new mission. The tank shell qualification was by analysis only, without protoflight testing, due to large analytical margins of safety.

A surface tension PMD was custom-designed for the mission. This PMD must be capable of transferring both gas-free propellant and liquid-free pressurant upon demand. 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 the mechanical elements. The passive, all-titanium PMD design was robust, efficient, and highly reliable.

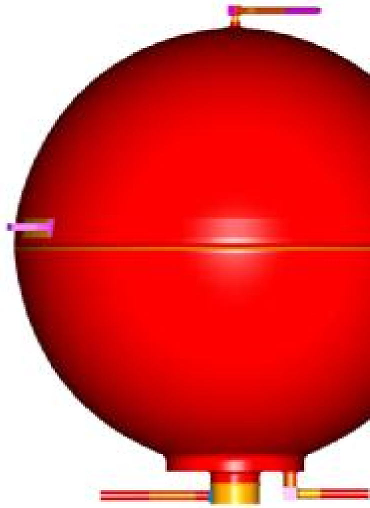
The flight tanks successfully supported all the intended mission maneuvers and completed the on-orbit mission in 2007.

INTRODUCTION

ATK Space Systems – Commerce (ATK Commerce) was contracted to develop a hydrazine tank for an in-flight fluid transfer demonstration. To minimize program cost, a heritage tank shell made from Solution Treated and Aged (STA) 6Al-4V titanium was baselined. This flight qualified tank shell was selected due to its qualified capabilities as well as its ability to adopt a new cantilever-mounted Propellant Management Device (PMD) without affecting its qualification status. A surface tension PMD capable of transferring both gas-free propellant and liquid-free pressurant was custom-designed for the mission. A picture of this hydrazine tank is presented in Figure 1.

**Copyright ã 2008 by ATK Space Systems - Commerce.
Published by American Institute of Aeronautics & Astronautics with permission.**

Figure 1: The Hydrazine Tank Assembly



The hydrazine tank must meet the following specification requirements in Table 1:

Table 1: P/N 80454 Hydrazine Propellant Tank Specification Requirements

Parameters	Requirements
Operating Pressure	400 psid @ 120°F
Proof Pressure	500 psid @ 120°F
Burst Pressure	600 psid @ 120°F, minimum
Reverse Pressure	15 psid pressure differential
Material of Construction	Shell: Solution Treated and Aged (STA) 6AL-4V Titanium Heads Inlet/outlet Ports: 3Al-2.5V titanium to 304L stainless transition tubes PMD: 6AL-4V and CP Titanium
Membrane Thickness	0.031 inch minimum at tank shell membrane
Tank Mount(s)	Machined mounting lugs adjacent to girth weld
Expulsion Efficiency	98.5% minimum
Design Fill Fraction	88% minimum
Tank Capacity	2,325 in^3 ± 1% at 70°F
Internal Dimensions	16.5" ID Spherical
Tank Weight	13.5 lbm (6.1 kg) maximum design weight Actual weight 11.4 lbm
Propellant Capacity	73 lbm (33.2 kg) Hydrazine
Shell Leakage	$<1 \times 10^{-6}$ std cc/sec He @ 400 psid
Failure Mode	Leak Before Burst
Natural Frequency	> 150Hz, both lateral and axial
Temperature Environment	40°F to 120 °F (4 °C to 49 °C)
On Orbit Life	5 years minimum

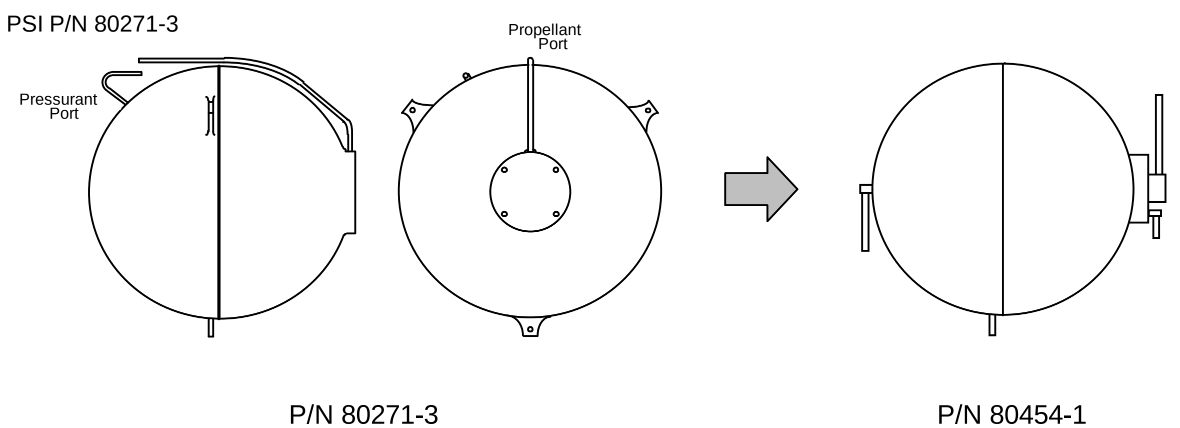
TANK SHELL HERITAGE

The hydrazine tank is a derivative of a flight-qualified diaphragm tank, ATK P/N 80271. The tank shell was selected primarily due to its large outlet boss upon which a cantilevered PMD can be mounted with sufficient structural margin for the intended mission.

Converting a diaphragm tank into a PMD tank had been done previously in 1995, when a 19" diaphragm tank was converted into an oxidizer tank for the NEAR mission [1]. A similar approach was adopted on this program to convert the tank shell as noted in Figure 2. The modifications to the 80271 shell included:

- Elimination of the elastomeric diaphragm;
- Removal of the machined-in diaphragm retaining features on both the diaphragm support ring and the tank shell;
- Relocation of the pressurant port;
- Modification of the propellant outlet tube;
- Addition of a drain tube at the outlet boss; and
- Modification of the outlet boss for a PMD mount.

Figure 2: Hydrazine Tank Heritage



TANK SHELL VERIFICATION ANALYSES

Tank shell verification analyses were conducted to validate the qualified tank shell against the new requirements in Table 1 and the flight environments of Tables 2, 3 and 4. A second objective of the analysis was to determine whether the tests conducted on P/N 80271 exceeds these new mission requirements.

Table 2: Launch Acceleration Loads

Limit Axial Acceleration (g)	+12
Limit Lateral Acceleration (g)	± 6

Table 3: Random Vibration Environment for Full Tank

Frequency (Hz)	Axial		Lateral	
	Limit PSD Level (g^2/Hz)	Qualification PSD Level (g^2/Hz)	Limit PSD Level (g^2/Hz)	Qualification PSD Level (g^2/Hz)
20	0.004	0.016	0.008	0.033
20 – 50	+6 dB/oct	+6 dB/oct	+6 dB/oct	+6 dB/oct
50 – 800	0.05	0.20	0.10	0.40
800 – 2000	-3 dB/oct	-3 dB/oct	-3 dB/oct	-3 dB/oct
2000	0.015	0.060	0.030	0.12
Overall	8.0 g_{RMS}	16.0 g_{RMS}	11.3 g_{RMS}	22.6 g_{RMS}
Duration/Axis	1 minute	3 minute	1 minute	3 minute

Table 4: Random Vibration Environment for Empty Tank

Frequency (Hz)	Axial		Lateral	
	Limit PSD Level (g^2/Hz)	Qualification PSD Level (g^2/Hz)	Limit PSD Level (g^2/Hz)	Qualification PSD Level (g^2/Hz)
20	0.005	0.02	0.01	0.04
20 – 90	+6 dB/oct	+6 dB/oct	+6 dB/oct	+6 dB/oct
90 – 400	0.10	0.40	0.20	0.80
400 – 2000	-3 dB/oct	-3 dB/oct	-3 dB/oct	-3 dB/oct
2000	0.02	0.08	0.04	0.16
Overall	9.9 g_{RMS}	19.8 g_{RMS}	14.03 g_{RMS}	28.1 g_{RMS}
Duration/Axis	1 minute	3 minute	1 minute	3 minute

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 pressure vessel designs. Conservatism was used throughout the analysis process, and the worst case scenarios were analyzed. The stress analysis showed the following:

- The tank's demonstrated burst capability exceeds the new program requirement by 136% based on actual test data on P/N 80271; and
- The tested acceleration load greatly exceeds the combined 12 g axial and 6 g lateral load of the new program requirement.

These conclusions precluded the need for qualification burst test and protoflight vibration or acceleration tests for the tank shell. The fracture mechanics analysis also showed that the tank meets all the fracture requirements. The analyses concluded with very high positive margins of safety for all design parameters, including collapse pressure. Some of the analytical safety margins are summarized in Table 5.

Table 5: Hydrazine Tank Safety Margins

Characteristics	Margin of Safety
Weld, burst, ultimate	+1.11
Weld, proof, yield	+1.05
Tank burst pressure, ultimate	+1.00
Tank burst pressure, based on qualification burst result	+1.36
Tank membrane, burst, ultimate	+0.81
Propellant boss, burst, ultimate	+1.03
Pressurant boss, proof, yield	+0.82
External pressure load	+0.73
Bolt, launch load, ultimate	+0.560
Tab, launch load, ultimate	+1.14

The large safety factors indicate that the tank shell as designed greatly exceeds the new program requirements. This provides the justification for qualification by analysis without supporting protoflight testing. The elimination of protoflight testing also generated additional program savings. However, the extra margin also points to an overdesigned tank shell due to the absence of iterative design efforts, and the program must pay a penalty to deliver the extra mass on orbit.

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 Hydrazine Tank PMD is a passive surface tension device designed to provide gas free propellant and liquid free pressurant upon demand. As with most PMDs, this PMD was designed specifically for the intended mission, and for use with hydrazine (N_2H_4) propellant.

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

- Survive launch & other non-operational phases of the mission;
- Provide gas-free propellant delivery throughout mission, including system priming, pump fed transfer, and pressure fed transfer;
- Provide liquid-free gas delivery during pump fed propellant transfer.

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 incorporated during the design effort to provide optimal service include the following:

(1) Because the PMD is a passive device with no moving parts, the design is inherently reliable;

(2) The PMD 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 operation in some off-nominal conditions, thus providing additional operational safety margin.

The key features of this PMD include:

- Sponge: The sponge is cantilevered from a central support tube that contains a perforated pickup assembly. The sponge consists of 16 panels of titanium sheet. The sponge was designed to maintain the ullage bubble and provide hydrazine to pickup assembly during transfer operations. The sponge is designed to orient all the gas in the tank to the top of the tank.

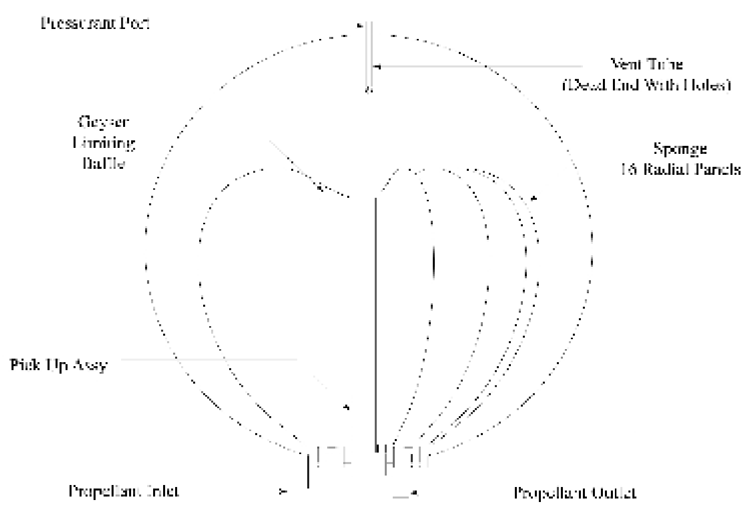
- Pickup Assembly: The pickup assembly is integrated into the central support tube. The propellant must pass through the perforated pickup assembly to enter into the outlet tube.

- Geyser Limiting Baffle: A small annular baffle is included at the top of sponge to prevent axial jets during propellant slosh. This geyser limiting baffle is not required to perform the mission, but its inclusion reduces risk and provides excellent benefit with little cost.

- Pressurant Port Vent Tube: A 2-inch long vent tube is integrated into the pressurant port to allow access of the pressurant gas near the outlet tube.

A sketch of the PMD with its key features is shown in Figure 3.

Figure 3: The Hydrazine Tank PMD



PMD OPERATIONS

The Hydrazine 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 horizontal), 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 transfer system is activated. The primary use of the PMD is to provide gas free hydrazine while receiving gas or to provide liquid free gas while receiving hydrazine.

Highlights of the Hydrazine 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 not designed to prevent gas ingestion during horizontal handling or transport. At high (95%) propellant fill fraction, gas ingestion is not likely to occur. At lower (<75%) fill fraction, horizontal handling is likely to ingest gas into the outlet line. Due to the nature of the mission, gas ingestion into the outlet line due to horizontal handling has no effect on the in-flight demonstration.

Figure 4: Operational Sequence

Ground Fill

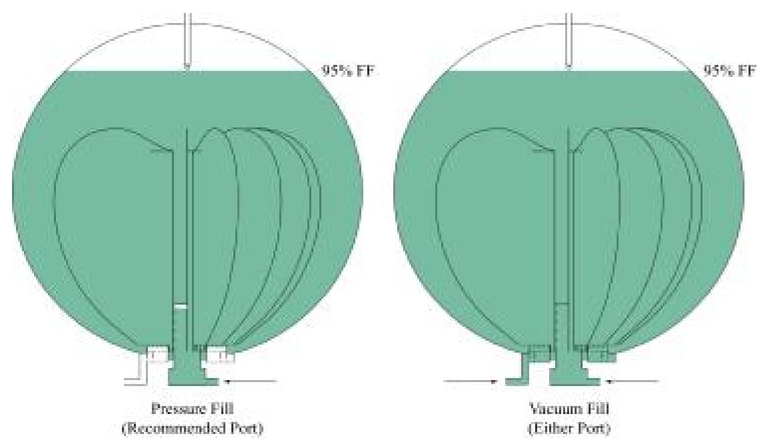
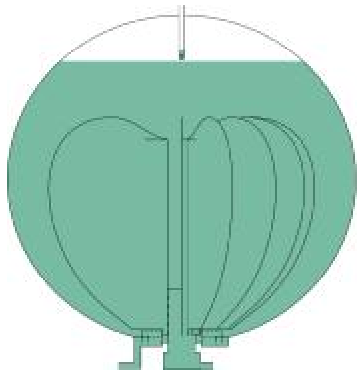
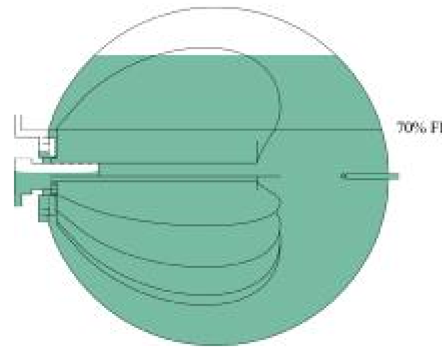


Figure 4: Operational Sequence (continued)

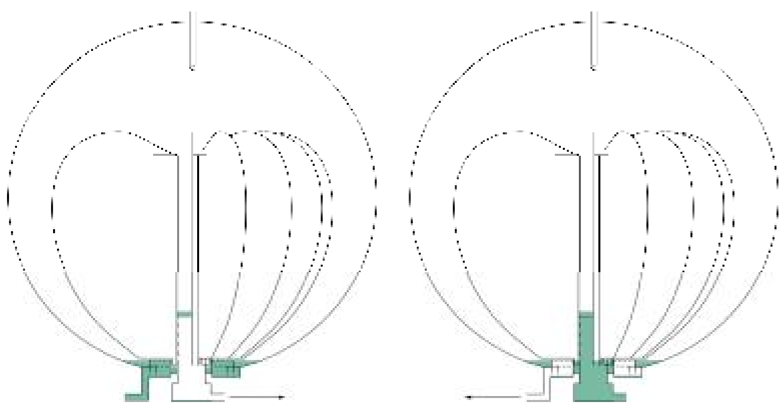
Upright Ground Handling



Horizontal Handling



Ground Drain



Launch

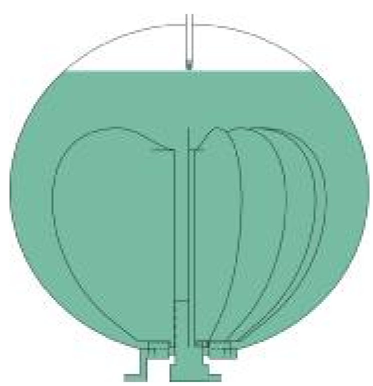


Figure 4: Operational Sequence (continued)

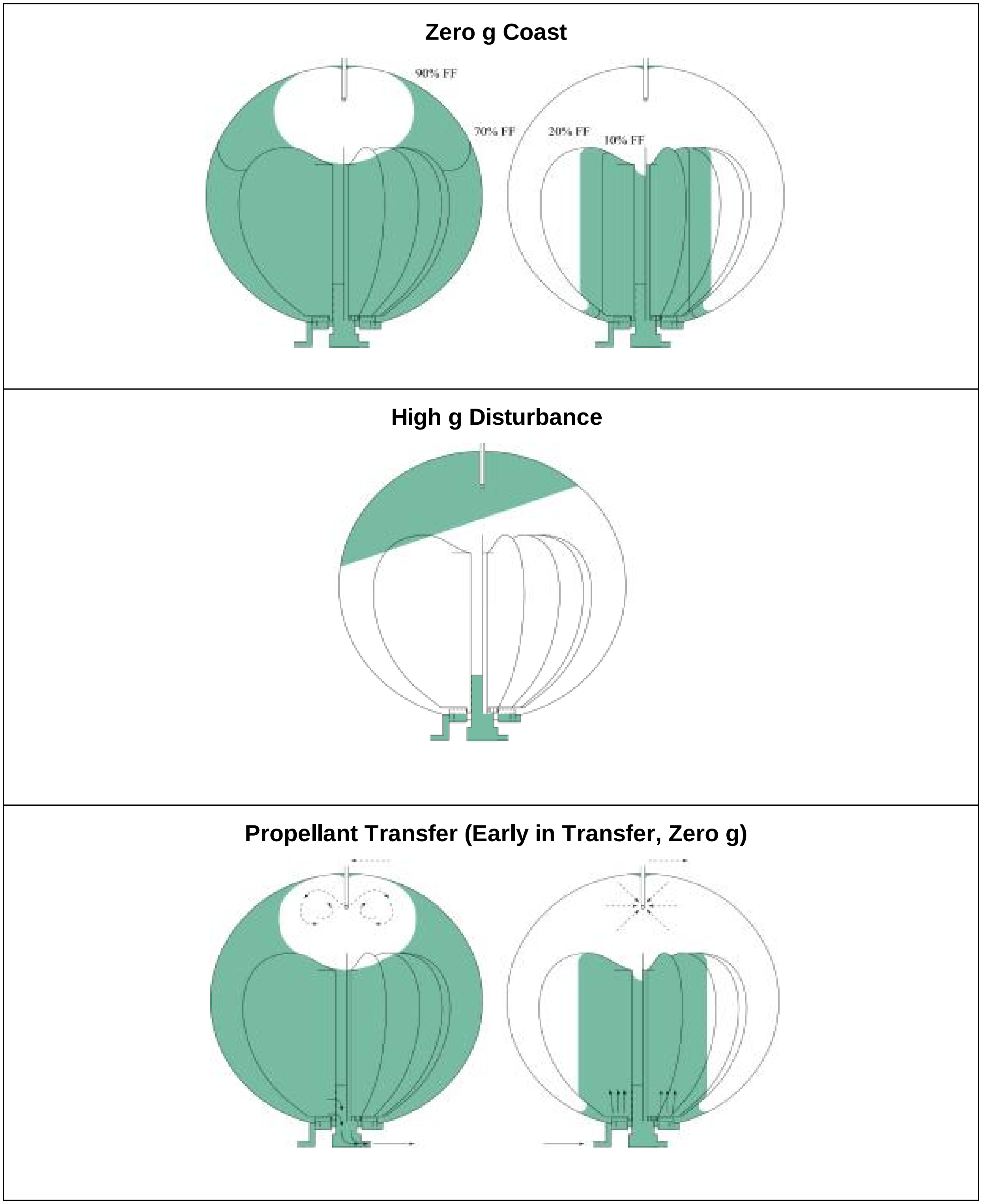
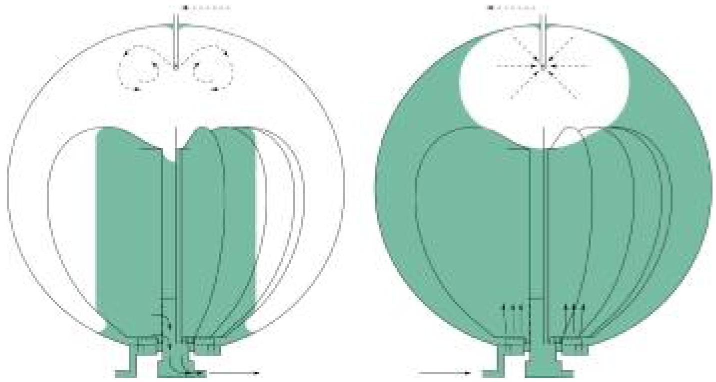
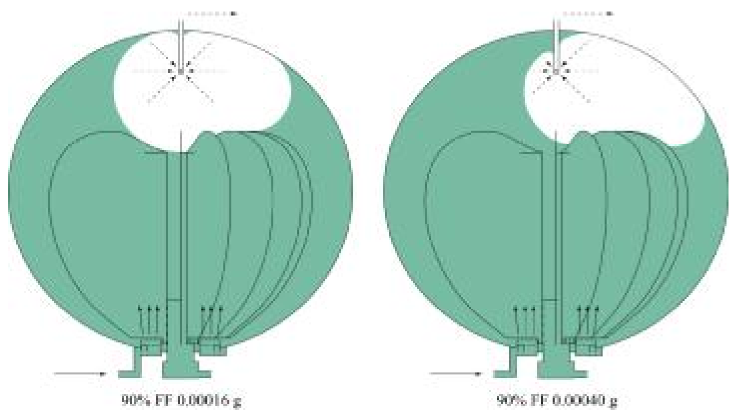


Figure 4: Operational Sequence (continued)

Propellant Transfer (Late in Transfer, Zero g)



Propellant Transfer (Gas Acquisition with Lateral Acceleration)



Propellant Transfer (Gas Acquisition with Lateral Acceleration)

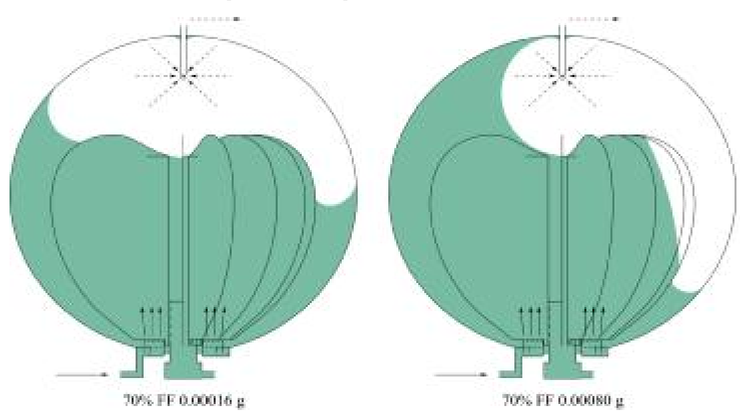
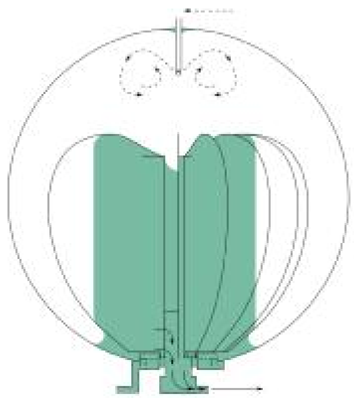
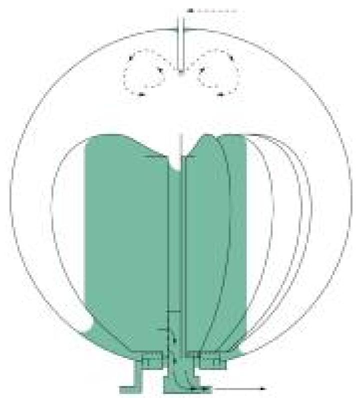


Figure 4: Operational Sequence (continued)

Propellant Transfer (Propellant Acquisition with Lateral Acceleration)

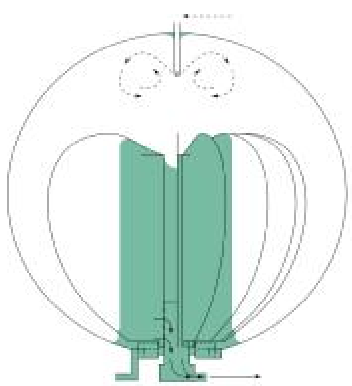


20% FF 0.00016 g

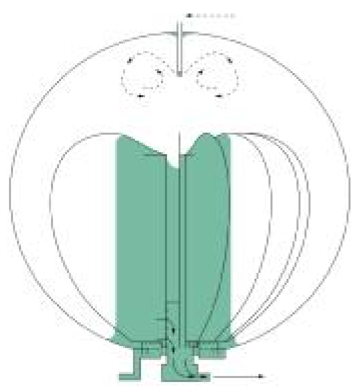


20% FF 0.0008 g

Propellant Transfer (Propellant Acquisition with Lateral Acceleration)

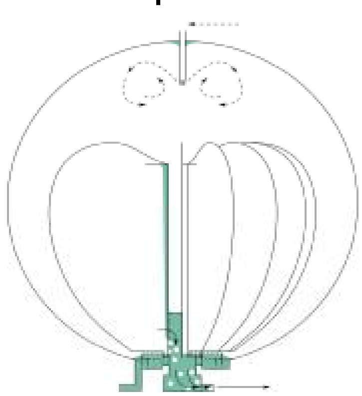


10% FF 0.00016 g



10% FF 0.0008 g

Depletion



Ascent Operations

- Ascent operations can be divided into two stages: launch and separation. The PMD is designed to withstand the structural loads during launch.
- The PMD is launched in the outlet down position.
- After launch, the spacecraft is separated from the launch vehicle. The separation produces small acceleration (up to 0.005 g axially and/or 0.003 g laterally) but hydrazine is not required for this event.

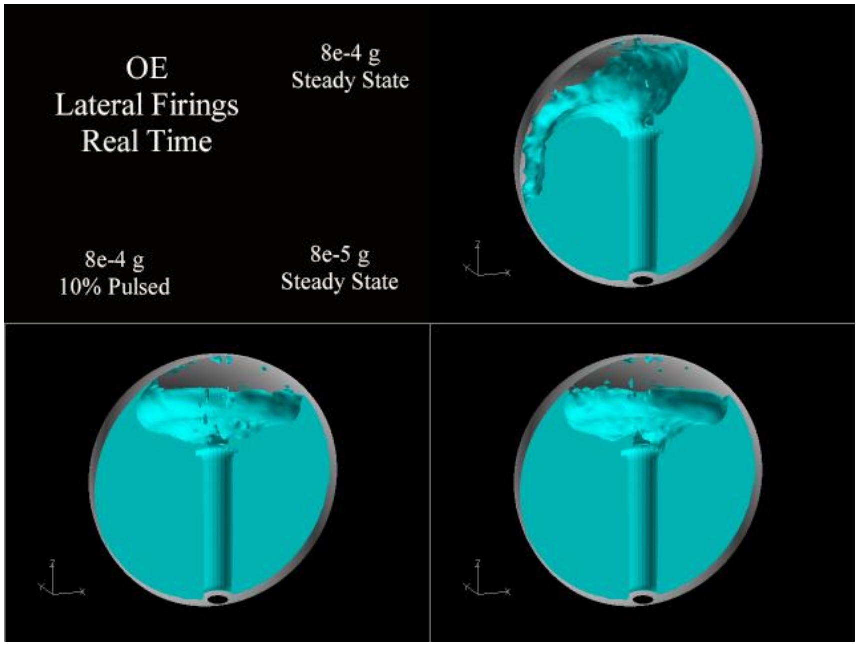
Orbital Operations

- After separation and during most of the time on orbit, the spacecraft is at zero g coast. At high initial fill fractions, the gas bubble in the tank is nearly spherical and located at the top of the tank.
- As the fill fraction falls during propellant transfer, the gas bubble is squeezed into the gap between the sponge panels. At very low fill fractions, the propellant occupies a cylindrical region in the sponge, covering the perforated pickup assembly. Thus at all fill fractions, the vent tube is in the gas and the perforated pickup assembly is in the propellant.
- Throughout the mission the PMD is exposed to accelerations during which it is not required to deliver propellant or pressurant. During these non-operational events, propellant can be moved away from the propellant pickup assembly. The PMD is designed to reestablish functionality within 600 seconds.
- During propellant transfer, the propellant is moved from a supply tank to a receiver tank, both with the same PMD. In the supply tank, gas free propellant is delivered to the outlet and pressurant is being introduced simultaneously via the vent tube. In the receiver tank, liquid free pressurant is delivered to the vent tube and the propellant is being introduced simultaneously via the propellant tube.
- The PMD is designed to transfer and receive propellant and pressurant at zero g as well as at various lateral acceleration as illustrated in Figure 5.

Design Tools

Several commercially available design tools were used to provide simulation and visual aid during design and analysis. These simulation tools have proven effective in converting analysis results into pictorial presentations, and have been an integral part of the analysis package for many years. Some design outputs are shown in Figures 5 and 6.

Figure 5: Fluid Dynamics Simulation



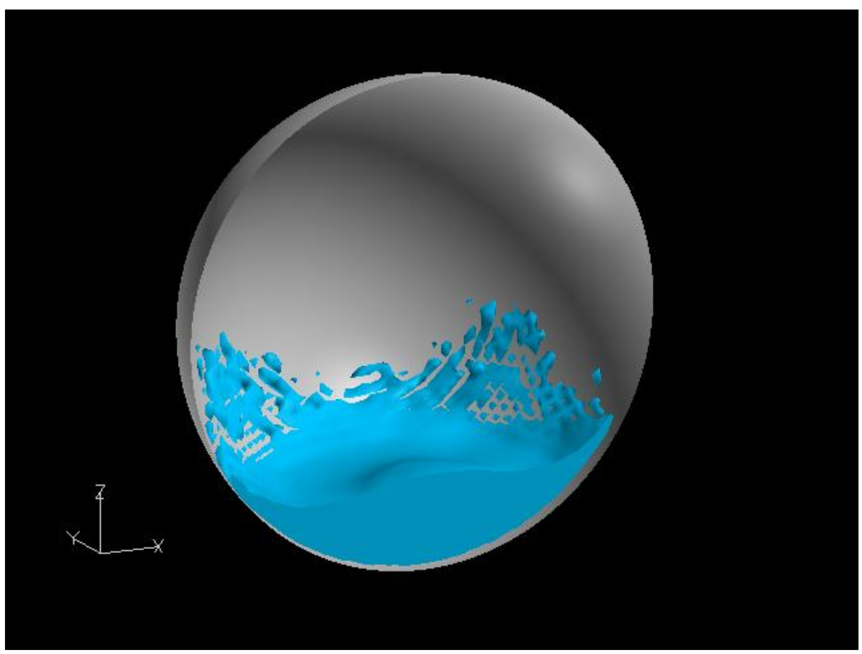
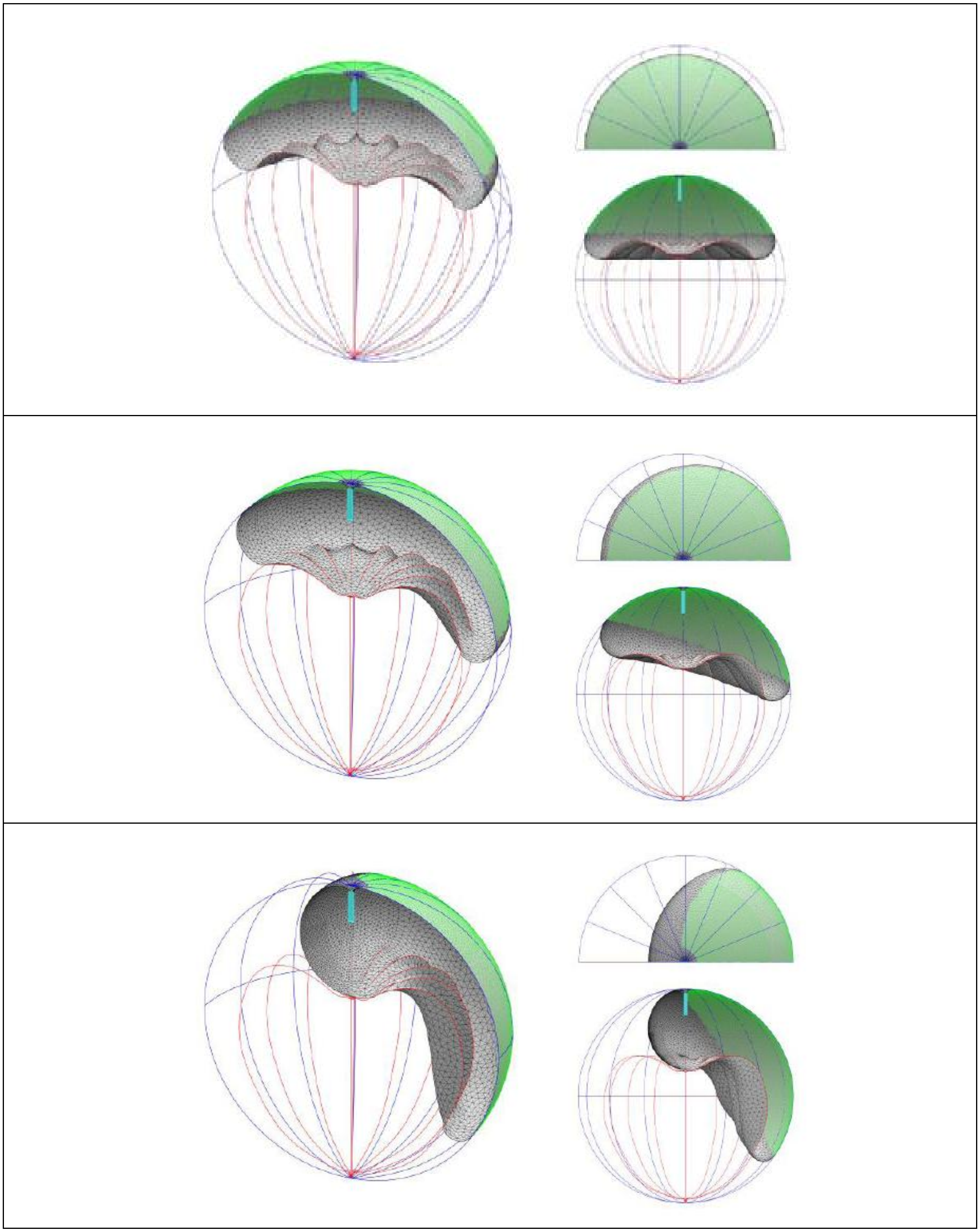


Figure 6: Fluid Dynamics Simulation



TANK CONSTRUCTION

The hydrazine tank consists of two primary bodies: the tank shell and the PMD.

The tank shell is machined from two solution treated and aged (STA) 6Al-4V titanium forgings. Three mounting tabs made from the same 6Al-4V titanium alloy are electron beam welded to the pressurant hemisphere and machined to the final configuration. A third titanium ring, machined to the diaphragm retaining ring configuration but without the diaphragm retaining features, is also included in the tank shell body.

The PMD is manufactured independently in a parallel effort. The PMD components, fabricated from either titanium sheets or titanium bars, are assembled into PMD subassemblies (such as sponge assembly, slosh control baffle, and pick up assembly) and finally built up to the PMD assembly.

After PMD installation, the two heads and the titanium ring are automatic Tungsten Inert Gas (TIG) welded into a tank weldment. Although the titanium ring no longer serves any functional purposes, it must be used in this closure weld to maintain the qualification status of the tank shell. It serves to simulate the diaphragm retaining ring which is an integral part of the qualified weld design. Although a small mass penalty is paid for the inclusion of this non-functional ring, a significant cost savings is achieved by eliminating the need for a qualification program with a dedicated qualification tank.

The completed tank assembly is shown in Figures 7 and 8.

Figure 7: Hydrazine Tank - Top View

Figure 8: Hydrazine Tank - Bottom View

ACCEPTANCE TESTING

Because tank analysis resulted in very large margins of safety, protoflight environmental tests were not required. The flight tanks were acceptance tested to the following test sequence:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- Reverse pressure test
- External leakage test
- Dye penetrant Inspection
- Radiographic inspection
- Weight measurement
- Final dimensional and visual examination
- Precision clean

The actual mass of the flight tank S/N 1 is 11.51 lbm, and for S/N 2 is 11.44 lbm. Two tanks successfully completed acceptance testing prior to delivery to the customer.

CONCLUSION

The hydrazine tank development program took advantage of a qualified, off-the-shelf diaphragm tank and successfully converted this tank into a PMD tank assembly. Although the propellant tank shell was not the primary focus of the program, the effort nevertheless delivered a tank shell with excellent quality and reliability, as well as contributed to significant cost savings for the program.

The PMD development program successfully designed and developed a robust and highly reliable PMD for a never-before attempted technology demonstration. The PMD was qualified by analysis only, as no zero g PMD functional tests could be conducted on the ground under 1g conditions.

Two hydrazine flight tanks were successfully launched into orbit. The on-orbit propellant transfer demonstrations proceeded as planned, and the PMDs performed as designed. The knowledge acquired from the mission proved highly valuable, and the successful technology demonstration is expected to pave the way for future missions requiring in space re-fueling.

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

REFERENCE

1. W. Tam, M. Debreceni, W. Lay, D. Gallet, "Design and Development of the NEAR Oxidizer Tank", AIAA 95-2528.