

DEVELOPMENT OF A TITANIUM PROPELLANT TANK

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ABSTRACT

In order to provide a lighter weight, less complicated, more easily manufactured, highly reliable, and more capable propellant tank for a typical advanced satellite, a new design was conceived from a previous, very successful environmental satellite program. This approach allows the new design to rely on significant heritage from the earlier program since there are a number of operating satellites in orbit with over 60 years of total operational time.

A lightweight tank shell coupled with a redesigned propellant management device (PMD) fulfilled this requirement. The resultant tank is fabricated in an all-welded titanium configuration with a sponge, vane and baffle PMD to store and to provide pressurized gas-free propellants to the main satellite thrusters and reaction control system thrusters in a zero g environment.

A typical spacecraft contains one hydrazine tank. The tank would be mounted in a spacecraft at 24 tabs with nutplates located near the tank girth weld.

The newly analyzed and designed PMD, with no moving parts, a minimum of surface tension elements, and titanium alloy components, minimizes weight and complexity. A stress and fracture mechanics analysis on the tank assembly, using imposed environmental conditions, operational requirements, and spacecraft interface loads, verified the structural adequacy of the PMD and tank assembly.

Successful acceptance and qualification tests on one flight-type unit empirically validated the analysis and design of the tank assembly.

INTRODUCTION

Pressure Systems, Inc. (PSI) was contracted to analyze, design, fabricate, assemble, test, qualify and deliver propellant tanks for a typical advanced spacecraft program.

Each of the satellites includes one hydrazine fuel tank. It is mechanically mounted inside the satellite's central core with 24 equally spaced tabs and welded into the propulsion fluid system. The propellant tanks are of an all-welded titanium construction. They incorporate a passive propellant management device for propellant acquisition and to supply gas-free propellants to the system thrusters throughout the required mission life.

This tank assembly reflects the latest in design innovation and state-of-the art technology for improved manufacturability, performance, reliability and testing.

The PMD was specifically analyzed and designed to meet the defined mission profile and requirements. This tank assembly is compatible with launches on the Atlas-Centaur, Ariane, Long March, and Delta boosters.

The tank and PMD assemblies were also designed for producibility since additional tanks are required to support options for follow-on units.

**DESIGN, DEVELOPMENT,
AND ASSEMBLY**

The propellant tank assembly summary of capabilities is shown in Figure 1.

**FIGURE 1: SPACECRAFT PROPELLANT TANK
SUMMARY OF CAPABILITIES**

Tank Outside Diameter (in.)	40.5
Tank Length (in.)	40.965
Tank Fluid Capacity, Minimum Liters in ³	565 34,481
Maximum Initial Propellant Load	70.1% of tank volume 400 kg Hydrazine
Fluids	Hydrazine, IPA Distilled Water, Ar, He, GN2
Temperature Range	41-140°F
Pressures (Psia at 131°F) MEOP * Collapse Proof Burst	330 3.5 412.5 495
Minimum Expulsion Efficiency, %	99.5 minimum, 99.9 goal
Leakage	Zero liquid leakage $\leq 1 \times 10^{-6}$ scc/sec He at MEOP * Pressurant Leakage
Maximum Weight , lb.	48.0
Minimum Design Life, Years	10
Stiffness Tank Propellant Fill Fraction (Worst Case)	> 50 Hz Natural Frequency
Launch Vehicle Compatibility	Atlas-Centaur, Ariane, Long March, & Delta

* Maximum expected operating pressure.

Figure 2 outlines the vibration and shock requirements for the propellant tank.

FIGURE 2: VIBRATION & SHOCK REQUIREMENTS

Test (Sine)	Axis	Frequency (Hz)	Acceleration (g, 0-Peak)	Limit Acceleration (g)
Acceptance (882 lbs. of water at 330 psig) 4 Octaves/Min	Lateral (Z & Y)	5 - 14	0.5 in. D.A. *	5.0
		14 - 60	5.0	5.0
		60 - 100	3.0	5.0
	Axial (X)	5 - 18	0.5 in. D.A.	8.0
		18 - 30	8.0	8.0
		30 - 100	3.0	8.0

Test (Sine)	Axis	Frequency (Hz)	Acceleration (g, 0-Peak)	Limit Acceleration (g)
Qualification (882 lbs. of water at 330 psig or dry at 0 psig) 2 Octaves/Min	Lateral (Z & Y)	5 - 15.7	0.50 in. D.A.	6.25
		15.7 - 60	6.3	6.25
		60 - 100	3.8	6.25
	Axial (X)	5 - 19.8	0.50 in. D.A.	10.0
		19.8 - 30	10.0	10.0
		30 - 100	3.8	10.0

Frequency (Hz)	Qualification (Random)	Acceptance (Random)
Time per axis (X, Y, & Z) Fluid & pressure	3 minutes Dry at 0 psig or 882 lbs. of water at 330 psig	60 seconds 882 lbs. of water at 330 psig
20 to 150 150 to 700 700 to 2000	+6 dB/OCT 0.1 g ² /Hz -3 dB/OCT	+6 dB/OCT 0.04 g ² /Hz -3 dB/OCT
OVERALL grms	11.6	7.73

* Double amplitude.

The acceleration load limits are the same for the random vibration test as for the sine vibration test.

QUALIFICATION TEST (SHOCK)	AXIS	FREQUENCY (HZ)	SHOCK RESPONSE SPECTRUM
		100-800	+8 dB/OCT
(Dry at 0 psig)	(X, Y, & Z)	800-3,000	1,500 G

**DESIGN, DEVELOPMENT
& ASSEMBLY** (cont'd)

The tank shells are machined from annealed titanium alloy Ti-6AL-4V hemispherical and ring forgings. During processing the hemispheres and cylinders are rough machined, solution heat treated and partial aged, skim machined, final aged and then final machined.

The tank is mounted into the spacecraft structure by circumferential tabs with nut plates located on one of the hemispheres near the girth weld. The mounting tabs are machined from a ring forging that is electron beam (EB) welded to one of the hemispheres in the partial machined state. Individual tabs are finish machined from the ring when the hemisphere is completed. The propellant port is a 1/4 inch diameter 6AL-4V titanium-to-304L CRES transition tube while the pressurant port is also a 1/4 inch diameter 6AL-4V titanium-to-304L CRES transition tube.

Figure 3 depicts the powder blasted propellant tank assembly ready for final cleaning and packaging for delivery.

A shell structural analysis and fracture mechanics analysis, utilizing the NASA FLAGRO program, were used to design the tank shell thicknesses and reinforcements while a stress analysis was used to analyze the PMD details, subassemblies, and assemblies including its installation into the tank. An initial fracture mechanics plan with the tank's histogram governed the former analysis while the imposed design and environmental test conditions, as listed in Figures 1, 2, and 4 dictated the structural and stress analysis parameters and boundary conditions.

FIGURE 3: COMPLETED PROPELLANT TANK ASSEMBLY



The all-titanium propellant management device is a combination radial sponge with integral propellant motion baffles, perforated sheet pickup assembly, and vanes.

This surface tension PMD has been designed to provide gas-free propellant delivery throughout mission including all on-orbit maneuvers. The design utilizes a safety factor of approximately two (2) on all required volumes and a safety factor of three (3) on the required porous material bubble point. These

design margins coupled with conservative analyses have yielded a PMD design, which easily meets the mission requirements and, in addition, provides for some off-design capability.

The PMD is for use in a 40.44 inch diameter tank. The PMD has been specifically designed for use in hydrazine propellant. Additional features were incorporated into the design to provide optimal service. First, because the PMD is a passive device with no moving parts, the design is inherently reliable. Second, the design is constructed entirely of titanium. 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 ensure gas-free delivery throughout the mission. The PMD is designed to suppress vortexing, to suppress surface dip, and to accommodate fluid transient motion (which could cause premature ingestion of gas). These additional design considerations have led to a reliable and efficient PMD design.

The radial sponge is comprised of titanium sheets separated by a tapered gap. The sponge has been designed to provide hydrazine to the pickup assembly during contingency recovery maneuvers where a spin rate of 10 degrees/second prevents the vanes from operating. Integral to the sponge are two propellant motion baffles. There is a radial baffle at the outboard edge of the sponge and an axial baffle on top of the sponge.

Four large major vanes, which are laser cut from thin titanium sheet, are spaced 90° apart and follow the inside contour of the tank. They interface into the sponge at the bottom of the tank. The vanes provide a flow path from the side of the tank to the sponge. The vanes are designed to provide propellant during on orbit 2 degree/second rotations and 1N thruster firings. The major vanes are oriented on the major spacecraft axes. Figures 5A and 5B present schematic views of the PMD.

Below the sponge is a perforated sheet pickup assembly. The perforated sheet is an annulus with a portion of the perforated sheet blocked near the outlet tube. The perforated sheet provides propellant to an annular outlet region, which, in turn, provides propellant to the outlet tube. The perforated sheet is the only capillary barrier to gas and insures gas-free propellant withdrawal from the tank throughout the mission.

The PMD is fabricated from 6AL-4V, 3AL-2.5V, and commercially pure (CP) titanium sheet, tube, and bar stock. All details are resistance welded, tungsten inert gas (TIG), or EB welded into subsequent assemblies. The perforated sheet disks are EB drilled while the sponge panels are chemically etched to provide the hole pattern.

After assembly, the PMD is mounted and welded into the outlet hemisphere while the vane-to-tank wall gaps are maintained. The expulsion assembly is bubble point tested and accepted before the tank assembly is closed. Previously, the pressurant hemisphere was finish machined. For the final tank assembly there is one automatic TIG girth weld that joins the expulsion assembly with the mounting tabs to the pressurant or inlet hemisphere.

The girth weld is radiographic and dye penetrant inspected and the final assembly is stress relieved in a vacuum heat treat furnace. The nut plates are then installed in the mounting tabs. The tank is ready for final inspection, acceptance testing, cleaning, and delivery.

PMD ANALYSIS AND DESIGN

I. PMD Introduction & Requirements

The PMD is a passive, all titanium, surface tension device designed to provide gas-free hydrazine (N₂H₄) during all mission accelerations with a minimum expulsion efficiency of 99.5% and a safety factor of two.

As with most PMDs, this PMD is designed specifically for the defined mission. The mission requirements include ground operations and launch, followed by separation, 20N thruster firings, rotations, contingency recovery, and three-axis stabilization.

The mission requirements are summarized in Table 1.

II. PMD General Design Description

The PMD design incorporates a radial sponge, propellant motion baffles, an outlet pickup assembly, and four vanes as illustrated in Figures 5A and 5B. Figure 5C shows the propellant flow through the tank assembly.

FIGURE 4: FACTORS OF SAFETY FOR STRUCTURAL ANALYSES

STRENGTH REQUIREMENT	COMMENTS
Yield Load	1.25 X Limit Load. Tank is to withstand combined yield load & MEOP under all specified environmental conditions.
Ultimate Load	1.5 X Limit Load. Tank is to withstand combined ultimate load & MEOP under all specified environmental conditions.
Safety Factor	Proof Factor: > 1.25 Burst Factor > 1.5 Multiply MEOP by these factors to design the tank.
Safety Margin	Safety Margin (yield load) = (Yield Stress - material)/(Stress - yield load) - 1 Safety Margin (ultimate load) = (Fracture Stress - material or Buckling Stress - material)/(Stress - ultimate load) - 1

**FIGURE 5A: SCHEMATIC SHOWING THE PROPELLANT
MANAGEMENT
DEVICE COMPONENTS (TOP VIEW)**

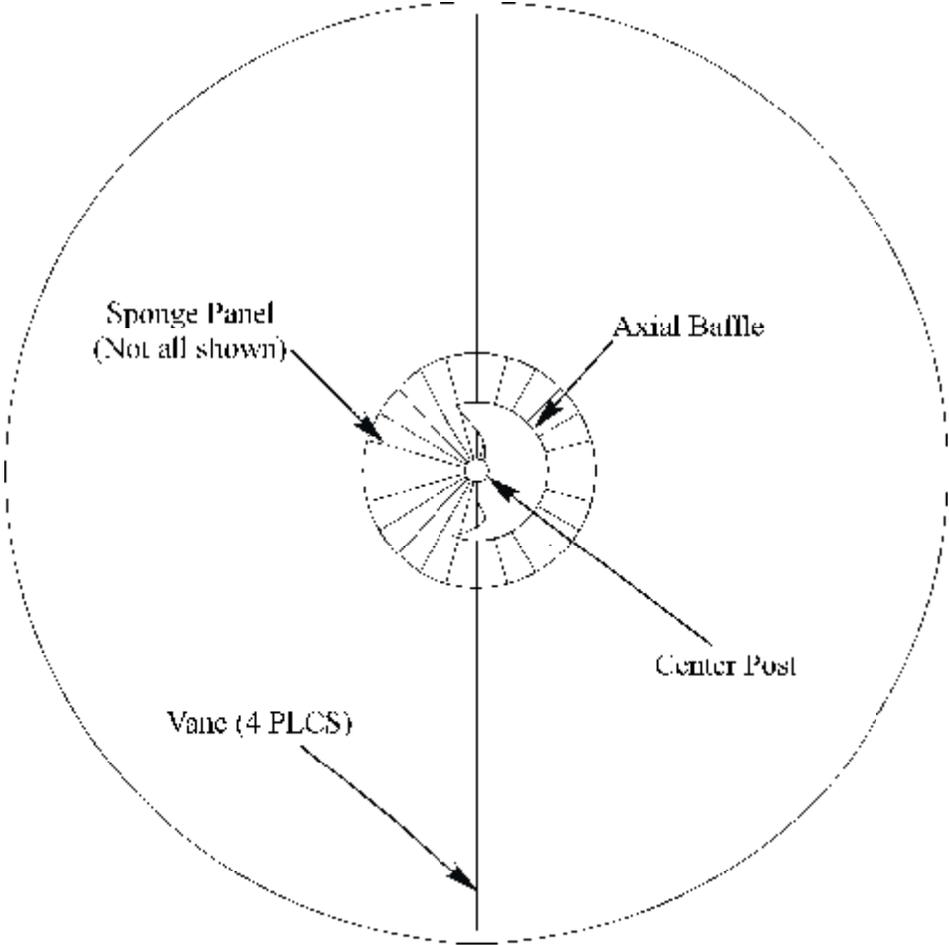


FIGURE 5B: SCHEMATIC SHOWING THE PROPELLANT MANAGEMENT DEVICE COMPONENTS (SIDE VIEW)

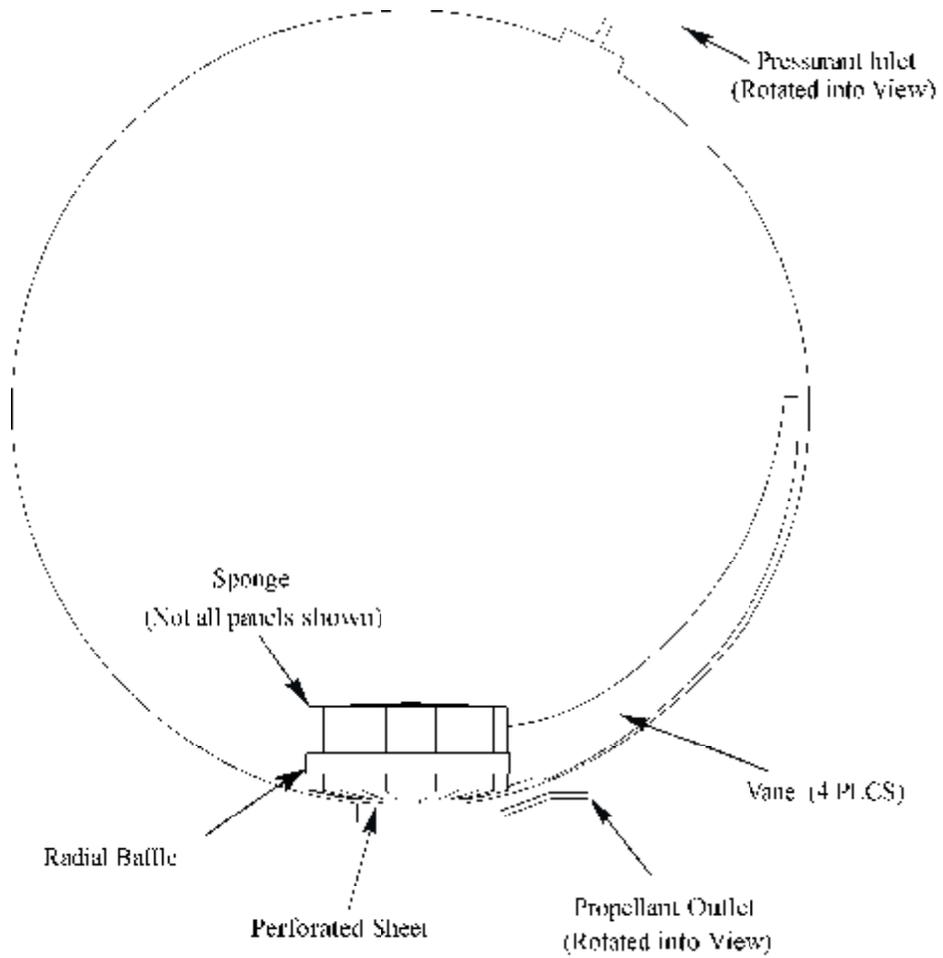


FIGURE 5C: SCHEMATIC SHOWING THE PROPELLANT FLOW THROUGH THE TANK ASSEMBLY

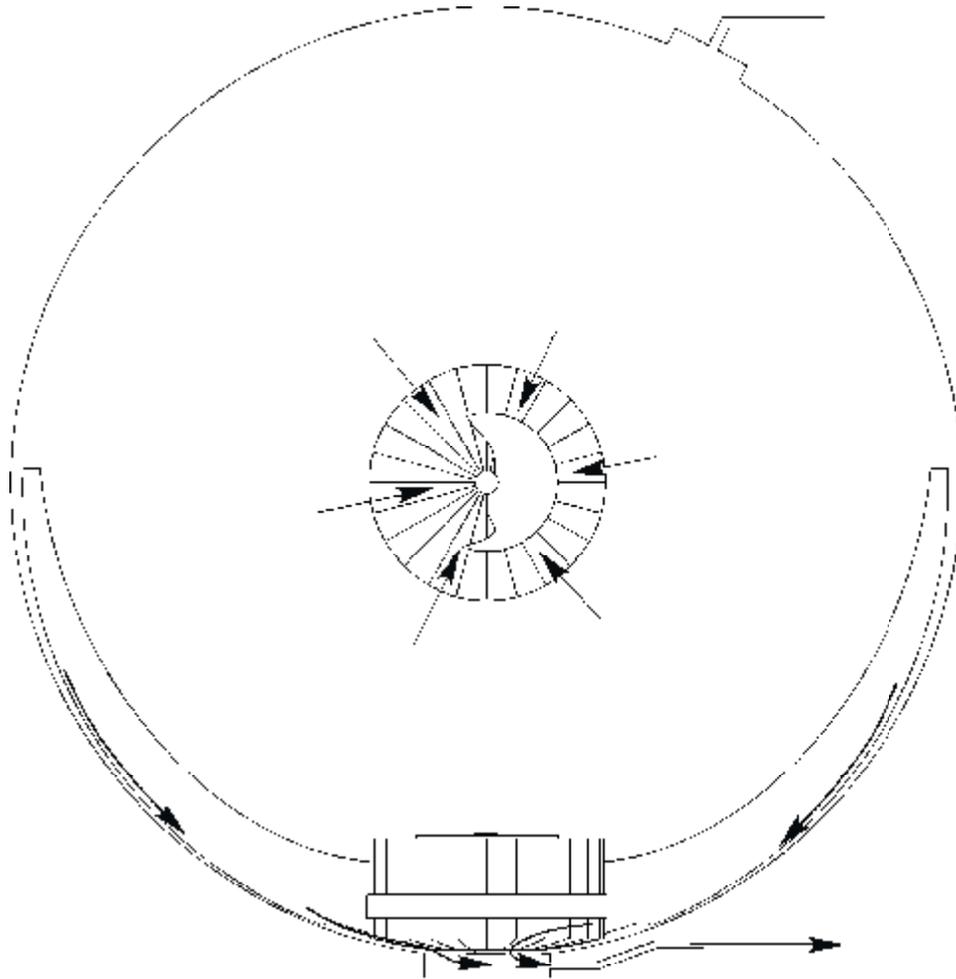


TABLE 1
PROPELLANT MANAGEMENT DEVICE
PERFORMANCE REQUIREMENTS SUMMARY

Ground Operations and Launch

- Tanks are filled, drained, and launched outlet down .
- Tank fill fraction is between 26% and 70%.
- Tanks are upright or horizontal during handling. The tank pressure will be 275 psia maximum after loading.
- During launch, the settling acceleration is greater than 1g. No propellant is required. Propellant is positioned over the outlet.

Ascent Operations

- Separation from the booster produces a negligible acceleration; however, it is settling.
- A 2 degrees/second maximum spacecraft rotation about any axis can occur.
- A system priming event is not required.
- During separation, no propellant is required.
- Following separation, the hydrazine propulsion system becomes active.

Orbital Operations

- During orbital operations, the fill fraction may be between 70% and 0.5%.
- The tanks are in blow down mode with a minimum pressure of 125 psia.
- For most of the mission, the spacecraft is in zero G coast with no spin. Propellant is consumed during three types of maneuvers: settling burns with four 20N thrusters firing or four 1N thrusters firing, rotations with multiple 1N thrusters firing, and contingency recovery.
- For 20N thruster settling burns, at the beginning of life, the thruster firing produces a settling +X axis acceleration of 0.0036 G maximum. In addition, a 0.0001 G acceleration in any direction except -X may be superimposed. The spacecraft is not spinning. The maximum flow rate is 2.1 cubic inches/second of hydrazine. At the end of life, the +X settling acceleration decreases to 0.0028 G maximum, and the flow rate decreases to 1.7 cubic inches/second maximum. The burn duration is unlimited. As a backup, four 1N thrusters may be used instead and will produce lower accelerations and lower flow rates. These are not a problem for the PMD.
- Rotations are conducted with multiple 1N thruster firings. The beginning-of-life (BOL) conditions are: 0.092 cubic inches/second maximum flow rate, 0.0001 G maximum in any direction not containing a -X component, and 2 degrees/second spin maximum about any axis. The end-of-life (EOL) conditions are: 0.067 cubic inches/second maximum flow rate, 0.0001 G maximum in any direction not containing a -X component, and 2 degrees/second spin maximum about any axis.

Contingency Recovery

- Gas-free propellant delivered in order to recover from a 10 degrees/second spin about any axis.

- Multiple 1N thruster firings are required to lower the spin rate to 2 degrees/second maximum.
- 1 kg of hydrazine is required above 2 degrees/second.
- A 15 minute coast, after despin to 2 degrees/second, is required before further demand.
- A 60 minute coast, with no demand and after despin to 2 degrees/second, is required to reset the sponge and provide capability for another contingency recovery.
- The beginning-of-life (BOL) conditions are: 0.092 cubic inches/second maximum flow rate, 0.0001 G maximum in any direction not containing a –X component, and 10 degrees/second spin maximum about any axis.
- The end-of-life (EOL) conditions are: 0.067 cubic inches/second maximum flow rate, 0.0001 G maximum in any direction not containing a –X component, and 10 degrees/second spin maximum about any axis.

Deorbit

- No deorbit is specified.
 - Depletion is assumed to occur during any of the preceding maneuvers.
 - Liquid residuals shall be 0.5% of the tank volume maximum with a 0.1% fill fraction target.
-

The radial sponge consists of thin sheet metal panels positioned in proximity to one another and forming a tapered gap between each panel pair. The taper ensures that the sponge is full in zero g and that sponge draining is efficient. The sponge is located over the pickup assembly porous element and provides a refillable reservoir of propellant available for on-orbit maneuvers. The sponge contains two other features. To enable sponge cross flow the sponge panels are perforated and the sponge panels over the pickup assembly where the perforated sheet is blocked contain a notch near the bottom of the sponge.

The perforations in the sponge panels are typical and are designed to allow cross flow during thruster firings and during zero G coast when the sponge refills.

The notches in the sponge panels are designed to allow cross flow during 20N thruster firings at low fill levels. During 20N thruster firing, liquid flows from outboard of the sponge into the sponge panel gaps to the perforated sheet. A 45 degree sector of the pickup assembly has no perforated sheet and propellant flowing into the sponge panel gaps over this region must flow across panels to reach the perforated sheet. To ease cross flow the sponge panels above the pickup assembly are notched.

Two propellant motion baffles are employed with the sponge – a radial baffle around the outside diameter of the sponge and an axial baffle on top of the sponge. The baffles are designed to limit propellant velocities within the sponge during 20N thruster firings, mitigate geysering, and prevent propellant from migrating radially out of the sponge.

The four sheet metal vanes are positioned on the east, west, north, and south axes and follow the tank contour from the sponge to the tank center section. The vanes provide a flow path to the sponge from the propellant pool settled by the lateral operational accelerations. The vanes are notched at the sponge to minimize sponge leakage during contingency recovery spin and are designed to refill the sponge during periods of zero g coast.

The pickup assembly, which is located just above the tank outlet, consists of an annular piece of perforated sheet 315 degrees around. There is no perforated sheet directly over the outlet tube to prevent exposure of the porous element to the high velocities near the outlet entrance. The window is positioned under the sponge, at the lowest point in the tank, to minimize residuals.

The annular outlet region below the perforated sheet provides a pathway to the outlet tube. It is sized to minimize flow velocities and mitigate transient pressure spikes.

The porous element in this design is titanium and prevents gas from penetrating into the pickup assembly and into the outlet line prior to depletion. The minimal area of porous element greatly increases reliability. The entire design uses 5 square inches of perforated sheet.

Several key characteristics make the PMD robust, reliable and able to provide optimal service.

First, because the PMD is a passive device with no moving parts, the design is inherently reliable.

Second, the design is constructed entirely of titanium. Thus, the PMD is lightweight and offers exceptional compatibility, long life, and reliability.

Third, the design contains a minimal quantity of perforated sheet; providing increased strength and reliability. Reducing porous element area dramatically increases reliability.

Finally, the design is implemented to rely minimally on the porous elements within it. During many nominal operations all porous elements are submerged. This detail to design robustness is a key feature of this PMD.

The extremely simple and robust PMD provides low cost, low mass, and high reliability. PMD performance will exceed all requirements.

III. PMD Operational Description

This section describes the PMD function during each phase of the spacecraft's life. The operation is separated into three logical phases: Ground Operations, Ascent Operations, and Orbital Operations.

The various phases of the mission that the PMD will encounter and how the PMD will affect the propellant are illustrated in Figure 6, the PMD Operational Sequence.

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 depicts these ground operations.

Filling occurs with the tank upright in the outlet down position. The tank pressure is initially at a maximum of 25 psia to reduce the amount of gas trapped below the perforated sheet. The trapped gas will be compressed upon pressurization. The filling process is straightforward and should introduce no difficulties either to the technician or the PMD.

Ground draining may have to be accomplished with the propellant 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. The tank will be drained in the outlet down position as shown in the operational sequence.

Ascent Operations

After launch, the spacecraft is separated from its booster. Separation produces a short duration, settling acceleration. The spacecraft may be rotating at up to 2 degrees/second about any axis following

separation. No system priming is required. The propellant outlet is submerged. Following separation, orbital operations will proceed.

Orbital Operations

Once on orbit, the PMD has been designed to provide gas-free propellant delivery during four types of maneuvers: 1) 20N thruster firing, 2) 2 degrees/second spin and 1N thruster firing, 3) 10 degrees/second contingency recovery, and 4) depletion.

Prior to 20N thruster ignition, the spacecraft will experience zero G coast. At thruster ignition, propellant will reorient, and a geyser will form. The geyser specifics will depend upon initial bubble position. The baffle will mitigate the effects of this geyser. In all cases of various fill fractions from 5% to 70%, the outlet is submerged and the sponge is full of propellant. The sponge retains more than enough propellant for ignition.

After ignition, the propellant is settled over the perforated sheet in the bottom of the tank. At all but the lowest fill fractions, there are no issues with steady demand for the 20N thrusters. The perforated sheet has been designed to minimize pressure losses, to prevent gas ingestion into the tank outlet during ignition and steady state flow, and to withstand the structural loads imparted by the high propellant flow rate for the 20N thrusters.

The vane system is used for providing gas-free propellant during the 2 degrees/second and 1N thruster firing maneuvers. The vanes are designed to provide a flow path from the propellant pool on the side of the tank to the sponge. The vanes provide propellant during steady state operation and during transient operation from thruster ignition, thruster pulsing, and depletion. The PMD analysis has shown that the vane system easily provides gas-free propellant at all possible on-orbit fill fractions via steady flow from the pool on the tank side wall to the perforated sheet window. The vane system will actually perform successfully to a fill fraction of less than 0.5%.

The vane system also has the ability to refill the sponge within the required 60 minute coast period following a contingency recovery.

The sponge was designed to retain 232 cubic inches of hydrazine (minimum safety factor of 2) during 0.0001 G lateral accelerations for 20N thruster firings and to deliver 1 kg of hydrazine (minimum safety factor of 2) while spinning between 2 and 10 degrees/second about any axis. The total sponge volume is 375 cubic inches.

Finally, depletion, by definition, occurs when gas is first ingested into the outlet of the tank. This will occur if the propellant flow area at the perforated sheet decreases to a point where it creates flow losses in excess of the bubble point of the porous element (with a safety factor of 3 on the sample point bubble). At this point, gas will penetrate the perforated sheet.

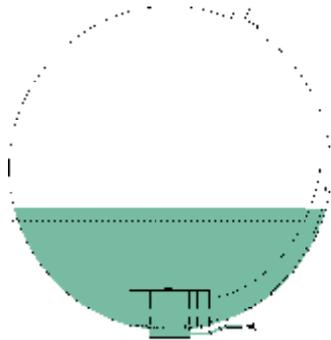
Depletion will occur during any one of three types of maneuvers: 1) 20N thruster firing, 2) 1N thruster firing, or 3) contingency recovery. In all instances, the analysis has shown that the maximum residual propellant is 0.13% fill fraction in the worst case. This PMD then easily meets the 0.5% fill fraction maximum residual requirement and is extremely close to the 0.1% fill fraction residual target.

IV. PMD Design and Analysis

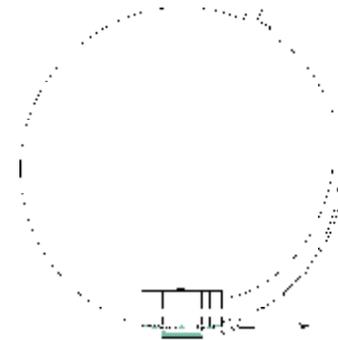
Design

This advanced spacecraft 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, handling, and draining. Only upright ground handling is accommodated. During launch, the PMD does not function and has been designed to maintain propellant over the tank outlet region and not be adversely affected by any of the encountered launch conditions. Once in earth orbit, separation from the booster occurs. On orbit

GROUND AND ASCENT OPERATIONS

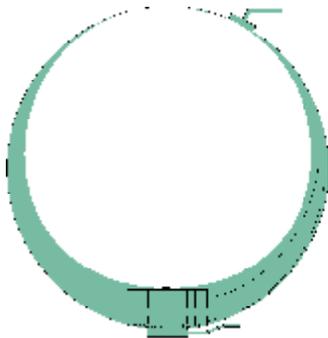


GROUND FILL

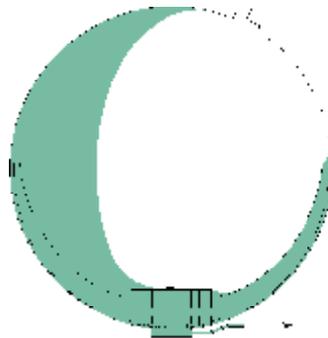


GROUND DRAIN

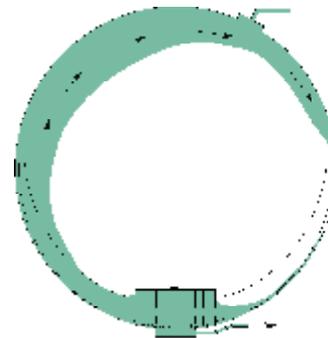
EARLY IN MISSION ORBITAL OPERATIONS



COAST



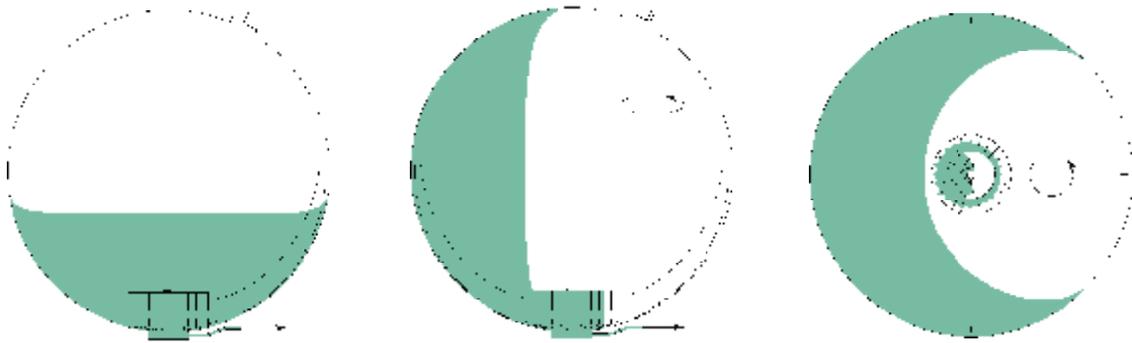
STEADY 0.0001 G LATERAL



PITCH OVER

FIGURE 6: THE PMD OPERATIONAL SEQUENCE

EARLY IN MISSION ORBITAL OPERATIONS (CONTINUED)

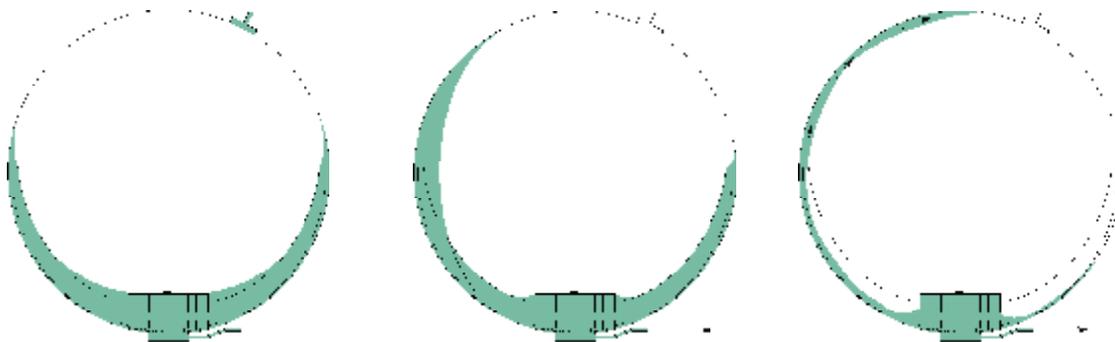


**20N THRUSTER FIRING
TOP**

10 DEG/SEC ROTATION, SIDE

**10 DEG/SEC ROTATION,
TOP**

LATE IN MISSION ORBITAL OPERATIONS



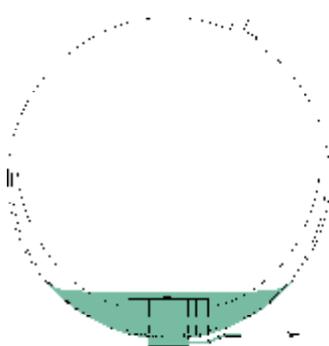
COAST

STEADY 0.0001 G LATERAL

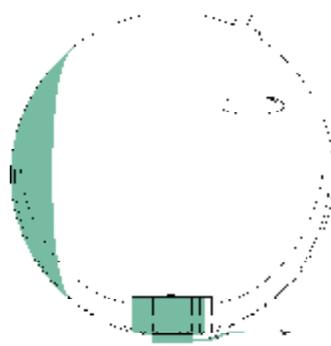
PITCH OVER

FIGURE 6: THE PMD OPERATIONAL SEQUENCE (CONTINUED)

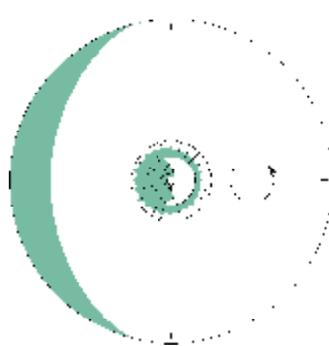
LATE IN MISSION ORBITAL OPERATIONS (CONTINUED)



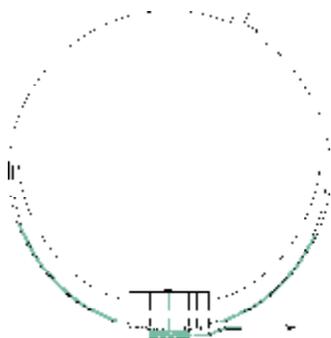
**20N THRUSTER FIRING
TOP**



10 DEG/SEC ROTATION, SIDE



**10 DEG/SEC ROTATION,
TOP**



DEPLETION

FIGURE 6: THE PMD OPERATIONAL SEQUENCE (CONTINUED)

IV. PMD Design and Analysis (continued)

Design (continued)

operation then follows. The PMD has been designed to accommodate and to provide gas-free propellant to the tank outlet during all on-orbit operations.

PMDs can be classified into two basic categories: control devices and communication devices.¹ Control devices are able to deliver a fixed quantity of propellant while communication devices offer unlimited duration operation. Because this mission requires transient or steady propellant delivery for most maneuvers, a communication type PMD is feasible. This communication PMD as chosen for this mission is the most robust, reliable and lightweight design available.

The sponge can provide the propellant required for each of the repetitive maneuvers such as 20N thruster firings. The size of the sponge and the number of sponge panels were determined based upon the volume and acceleration requirements. The sponge is a refillable control device and the vanes were incorporated to refill the sponge between maneuvers.

The vanes are designed to provide gas-free propellant during low G lateral thruster firings and to position the propellant in zero G. The multiple vanes are used to accommodate omni-directional thrust. The four vanes are aligned with the spacecraft axes because 1) the thrusters are located on the spacecraft axes and will produce accelerations aligned with the spacecraft axes, and 2) the size of the propellant pool potentially isolated from the vanes is very small and does not justify additional vanes.

Analysis

The principle method of PMD performance verification is analysis coupled with component and tank assembly bubble point and flow loss testing.

The analyses examine, in detail, the fluids' reaction to all phases of the mission. Propellant location, reorientation, and flow characteristics are determined and evaluated. The PMD is analyzed to ensure adequate control and delivery of propellant. The porous elements are shown to demonstrate the required margins. In addition, flow losses and flight depletion residual propellant quantities are analytically determined.

Because PMDs have been extensively proven in flight, and drop tower tests have verified the analytical techniques used to design them, no test verification program is required as such testing would yield no new information.

Because each maneuver in the mission can directly affect the PMD, each performance analysis addresses a phase of mission. First, the impact of Ground Operations on the PMD is examined. Second, the impact of and operation during Ascent Operations is examined. And finally, the operation of the PMD during all On- Orbit Operations is analyzed.

The specific analyses are listed in Table 2. Due to the summary nature of this paper, no results are presented. The detailed process of vane, sponge and trap design and analysis can be found in the series of papers titled *Propellant Management Device Conceptual Design and Analysis: Vanes, Sponges, Galleries, or Traps and Troughs* by D.E. Jaekle, Jr.^{2,3,4,5}

The analyses conducted verify that the PMD will meet all requirements of the specification by providing gas-free propellant upon demand.

TABLE 2
PMD PERFORMANCE ANALYSES

- I. General Design Analyses
 - A. Number of Vanes
 - B. Vane Positional Tolerances
 - C. Sponge Sizing
 - D. Propellant Motion Baffle Design
 - E. Porous Element Selection
 - F. Porous Element Window Area and Location
 - G. Outlet Area
 - H. Flow Losses
 - I. Thermal Effects
 - J. Steady Flow Requirements
 - K. Transient Flow Requirements
 - L. Geysering and Surface Dip
 - M. Bubble Point Requirements

- II. Ground Operations
 - A. Filling
 - B. Draining
 - C. Handling

- III. Ascent Operations
 - A. Launch
 - B. Separation

- IV. Orbital Operations
 - A. Sponge Use (10 degrees/second spin)
 - B. Sponge Refill
 - C. 20N Thruster Firing
 - D. Vane Operation (2 degrees/second spin and 1N thruster firing)
 - E. Depletion
 - F. Contingency Recovery

QUALIFICATION TESTS

One test specimen was subjected to a series of qualification tests. This flight-type test tank was subjected to the tests listed in Figure 7.

FIGURE 7: QUALIFICATION TESTS FOR THE PROPELLANT TANK

- Preliminary Inspection of Product
- Mass Measurement
- Pre-Proof Volumetric Capacity
- Ambient Proof Pressure Test
- Visual Inspection
- Post-Proof Volumetric Capacity

Pressure Cycling Test
Visual Inspection
External Leakage Test
Bubble Point Test
Sine & Random Vibration Tests
Visual Inspection
Cleanliness Check
Shock Test
Visual Inspection
Volumetric Capacity and Expulsion Test
Bubble Point Test
External Leakage Test
Radiographic Inspection
Dye Penetrant Inspection
Cleanliness Check
Burst Test and Visual Inspection
Data Review

The qualification test starts with an inspection for dimensions, verification of previous inspections and tests, identification, successful completion of all manufacturing planning, inspection for damage, material certifications, and completed rework instructions.

The dry tank assembly is weighed on a precision scale. The actual weight was 46.89 lbs. versus a maximum allowable of 48.0 lbs. The tank is subjected to an ambient hydrostatic proof pressure of 420 psig for 5 minutes, and the mass of water required to fill the tank is measured to determine the actual tank volume before and after the application of the proof pressure. No discrepancies were noted.

The pre-proof volumetric capacity was 34,509.4 in³ while the post-proof volumetric capacity was identical. This results in a zero volume increase. The maximum allowable volume change is 0.2%. The minimum volume requirement is 34,481 in³. A visual inspection revealed no damage or deformation. The tank was drained and dried.

For the pressure cycling test the tank is first subjected to seven ambient hydrostatic proof pressure cycles at 413-421 psig. The tank is then subjected to 50 ambient hydrostatic MEOP pressure cycles at 330-335 psig. Finally, the tank is subjected to five ambient external pressure cycles at 3.6 psid. There was no leakage or permanent damage or deformation.

The external leakage test is conducted in a vacuum chamber with the tank pressurized to 335 psig with helium gas. The chamber is evacuated to less than 0.2 microns, and the test is run for 15 minutes. The maximum allowable leakage is 1.0×10^{-6} scc/sec. There was no leakage from the test specimen.

A bubble point test with isopropyl alcohol (IPA) as the test medium is accomplished on the PMD perforated sheet. The bubble point is verified for 60 seconds minimum to verify PMD porous element integrity then the capillary breakdown value is measured. The perforated sheet bubble point was successfully tested to a level of 1.6 in. of head, and the breakdown head was measured to be 2.3 in.

Vibration tests are performed on the tank in three orthogonal axes (X, Y, and Z). The test fixture simulates the tank-to-spacecraft installation interface but is also sufficiently stiff to be considered a rigid mass and not introduce spurious inputs to or responses from the tank assembly. Figure 2 presents the vibration test parameters.

The dry sine and random vibration tests are performed with the tank empty, the ports sealed, and unpressurized. The wet sine and random tests are performed with the tank loaded with 882 pounds of distilled, deionized water and pressurized at 330 psig with gaseous nitrogen. The wet sine and random vibration spectrum inputs are notched to limit the tank responses and acceleration loads on the test specimen. Sine notching is automatically programmed into the vibration control system while random notching is accomplished through hand calculations. For all test runs, low-level runs are performed to verify the test set-up, the instrumentation, and the notching.

Up to 12 accelerometers are installed on the tank to measure the response levels and to characterize the response spectrum. Up to four control accelerometers are mounted on the test fixture to provide a closed loop control system with the vibration driver equipment to insure that the specification requirements are met. Natural frequency results are presented in Figure 8. They are consistent and meet the specification value of >50 Hz for all axes.

FIGURE 8: TANK NATURAL FREQUENCIES, HZ

<u>Axis</u>	<u>Calculated</u>	<u>Measured</u>
X (axial)	142	160
Y/Z (lateral)	128	150

The tank was visually inspected during and after the vibration tests and no damage or deformation was noted. The cleanliness level of the test unit was checked and found to easily meet the requirements noted in Figure 15.

A shock test is performed in the same three orthogonal axes as the vibration tests. The inputs are simultaneously applied to the test unit through the use of pyrotechnic shaped charges attached to the edges of the test plate that supports the tank. Input and response accelerometers record the shock levels. Two separate test runs are performed. An inspection after this test revealed no damage.

The volumetric capacity test is repeated with ambient distilled, deionized water. A value of 34,520.0 in³ was measured versus a minimum requirement of 34,481 in³. This test value very closely matches the previously measured volumetric capacities.

An expulsion and pressure drop test is then performed using the completely filled tank from the previous test. The tank was pressurized to 330 psig. The tank is drained in the vertical attitude using a 330 psig ullage pressure and a flow rate of 0.56 gpm. Pressure drop and residual water volume are measured. The empirical pressure drop of 1.1 psid compared favorably to the required maximum 2.0 psid. The tank demonstrated residuals of 8.3 in³, which is well within the mission requirement of 172 in³. The resultant expulsion efficiency of 99.97% exceeded the minimum required of 99.5% as far as ground residuals are concerned. An inspection after this test revealed no leakage or damage.

After the extensive environmental and pressure tests, a bubble point test with IPA as the test medium is again accomplished on the PMD perforated sheet. The bubble point is verified for 60 seconds minimum to verify PMD porous element integrity then the capillary breakdown values are measured. The perforated sheet bubble point was successfully tested to a level of 1.7 in. of head and the breakdown head was measured to be 2.3 in. These values are consistent with earlier tests.

The external leakage test is also repeated and is conducted in a vacuum chamber with the tank pressurized to 335 psig with helium gas. The chamber is evacuated to less than 0.2 microns, and the test is run for 15

minutes. The maximum allowable leakage is 1.0×10^{-6} scc/sec. There was no leakage from the test specimen.

Post-test inspections include visual, radiographic, dye penetrant, and cleanliness. The visual inspection revealed no damage or deformation. The X-ray inspection, including views from the pressurant port, propellant port, and from the side at 90-degree intervals, revealed no damage to the tank shell or PMD. A dye penetrant inspection of the complete external surface of the tank shell showed no damage. The final cleanliness level of the test unit was checked and found to easily meet the requirements noted in Figure 15.

A final data review verifies that all previous tests have been completed successfully, all data sheets are completed and correct, and the test specimen met all performance requirements.

The burst test is accomplished with a temperature-compensated pressure value. It adjusts the burst pressure test value of 495 psig from ambient temperature to the specification maximum allowable operating temperature of 140 degrees. The tank was hydrostatically pressurized to 532 psig and held for five seconds. There was no leakage or damage to the tank. The tank was then pressurized to 691 psig where it ruptured. The crack developed in the parent metal of the mounting (outlet) hemisphere near one of the tabs and progressed longitudinally in both directions.

Based upon the above tests and inspections, the propellant tank assembly was qualified for flight use.

ACCEPTANCE TESTS

The acceptance tests for the propellant tanks are listed in Figure 9.

FIGURE 9: ACCEPTANCE TESTS FOR THE PROPELLANT TANK

Preliminary Inspection of Product
Mass Measurement
Pre-Proof Volumetric Capacity
Ambient Proof Pressure Test
Visual Inspection
Post-Proof Volumetric Capacity
External Leakage Test
Bubble Point Test
Sine & Random Vibration Tests
Visual Inspection
Volumetric Capacity and Expulsion Test
Bubble Point Test
External Leakage Test
Radiographic Inspection
Dye Penetrant Inspection
Visual Inspection
Cleanliness Check
Data Review

The acceptance test starts with an inspection for dimensions, verification of previous inspections and tests, identification, successful completion of all manufacturing planning, inspection for damage, and material certifications. The dry tank assembly is weighed on a precision scale.

The tank is subjected to an ambient hydrostatic proof pressure of 412.5 psig, which is temperature compensated to 140 degrees F, for a maximum of 5 minutes. The mass of water required to fill the tank is measured to determine the actual tank volume before and after the application of the proof pressure. Permanent set must not exceed 0.2%. A visual inspection verifies that the tank has not been damaged or deformed.

An external leakage test is run at 330 psig with helium gas for 15 minutes minimum in a vacuum chamber evacuated to 0.2 microns of mercury or less. Leakage must not exceed 1×10^{-6} scc/sec of helium gas.

To verify the integrity of the PMD porous elements after the proof pressure test, a bubble point test with IPA as the test fluid is performed. The bubble point is held for a minimum of 60 seconds and then the capillary breakdown is measured. The perforated sheet is tested.

Wet sine and random vibration tests, configured as described in Figure 2, are performed on the tanks in three orthogonal axes (X, Y, and Z).

Sufficient response accelerometers are installed on the test specimen to characterize the tank responses and control accelerometers are placed on the test fixture to insure compliance with the specification requirements. The sine and random vibration spectrum inputs are notched to limit the acceleration loads on the tank.

Next, volumetric capacity and expulsion tests, using distilled, deionized water, are completed. Water is discharged at 0.56 gpm (worst case mission flow rate) with a 330 psig ullage pressure while the tank pressure drop is measured and compared to the specification requirements. The tank's volumetric capacity is re-verified, and the residuals are measured.

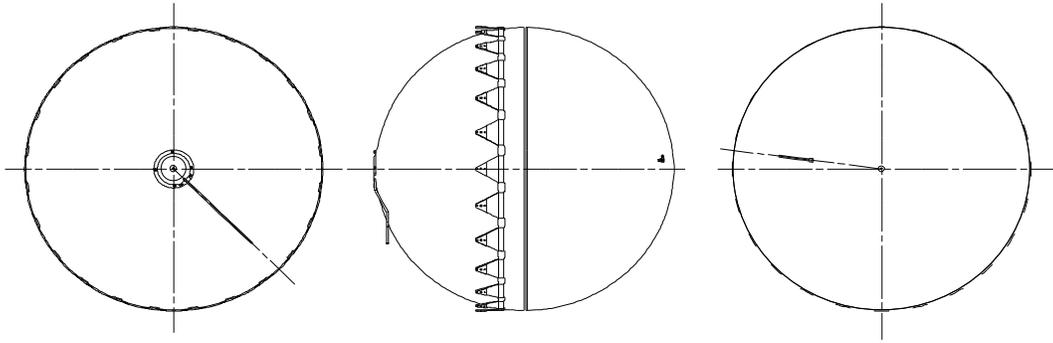
The bubble point test, external leakage test, fracture critical radiographic inspection of the girth weld and internal PMD views, fracture critical dye penetrant inspection of the external surface, and visual inspection are performed to verify the tank has no damage as a result of the environmental and pressure tests. These tests and inspections are identical to the ones performed during the qualification sequence.

Finally, the units are cleaned to Figure 15 levels, purged to a -65°F dew point, pressurized to 15 psig with dry GN₂, the ports capped, and packaged in two sealed plastic bags for shipment.

Figure 10 depicts an outline of the propellant tank showing the port orientations. The left view illustrates the propellant outlet port while the right view shows the pressurant inlet port.

**FIGURE 10: VIEWS OF THE PROPELLANT TANK
SHOWING THE PORT LOCATIONS**

+Y OUTLET PORT INLET PORT



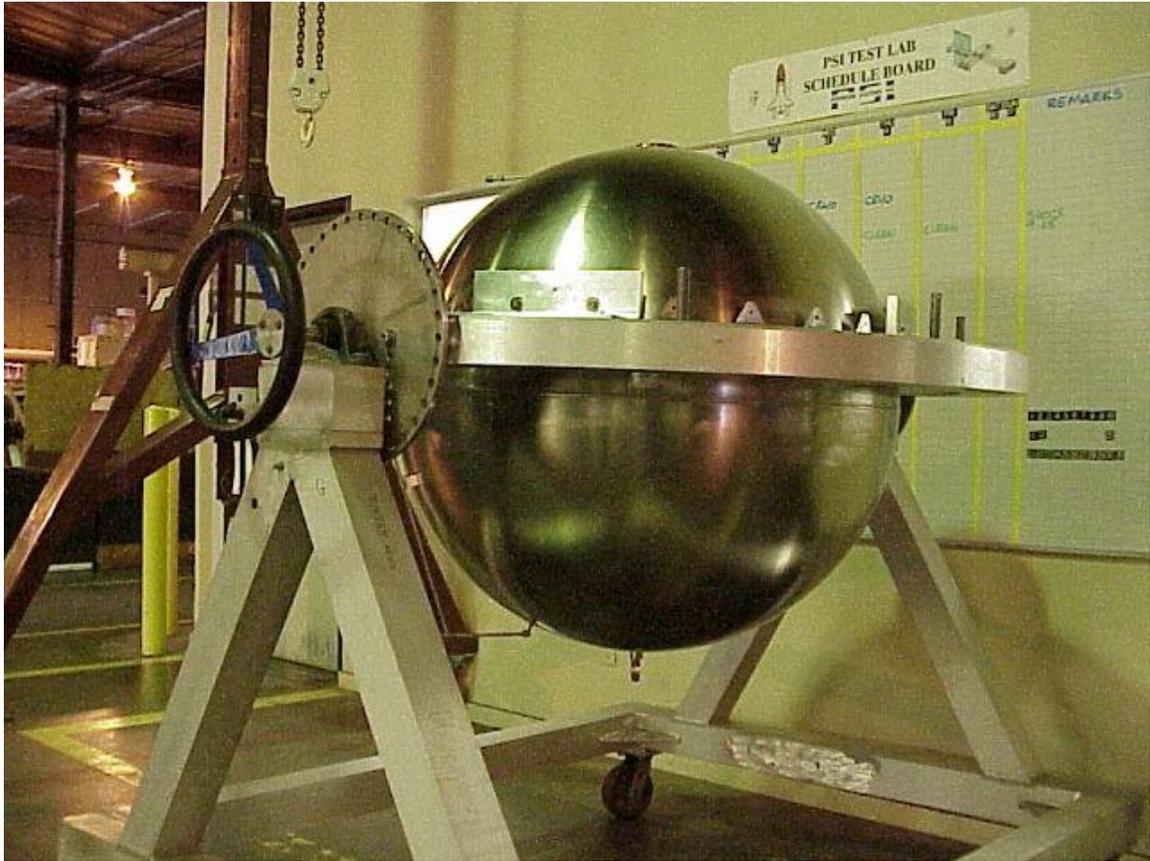
-Z **-Y** **+Z**

The X axis runs through the center of the tank and is coincident with the outlet port.

FIGURE 11: PMD INSTALLED IN THE OUTLET HEMI



FIGURE 12: PROPELLANT TANK ASSEMBLY



**FIGURE 13: PROPELLANT TANK IN THE VIBRATION
FIXTURE AT NTS**



FIGURE 14: PROPELLANT TANK IN THE PROOF PRESSURE TEST FIXTURE AT PSI



Figures 11 through 14 show photographs of the PMD, the propellant tank, a unit in the axial vibration fixture, and a tank installed in the proof pressure fixture, respectively.

FIGURE 15: TANK CLEANLINESS LEVEL

<u>Particle Size (Microns)</u>	<u>Maximum Amount of Particles</u>
> 100 Microns	None
51-100 Microns	3
26-50 Microns	25
11-25 Microns	100
5-10 Microns	600
< 10 Microns	No Silting

NOTES:

1. No metallics >50 microns
2. Non-volatile residue (NVR) less than 1 mg/100 ml.

CONCLUSIONS

This propellant tank has met all design objectives that can be verified by analysis, and the qualification test specimen has successfully passed all tests.

This titanium propellant tank assembly is acceptable for flight.

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REFERENCES

- ¹ Rollins, J. R., Grove, R. K., and Jaekle, D. E., Jr., "Twenty-Three Years of Surface Tension Propellant Management System Design, Development, Manufacture, Test, and Operation", AIAA-85-1199, 1985.
- ² Jaekle, D. E., Jr., "Propellant Management Device Conceptual Design and Analysis: Vanes", AIAA-91-2172, 1991.
- ³ Jaekle, D. E., Jr., "Propellant Management Device Conceptual Design and Analysis: Sponges", AIAA-93-1970, 1993.
- ⁴ Jaekle, D. E., Jr., "Propellant Management Device Conceptual Design and Analysis: Traps and Troughs", AIAA-95-2531, 1995.

⁵ Jaekle, D. E., Jr., "Propellant Management Device Conceptual Design and Analysis: Galleries", AIAA-97-2811, 1997.

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NOTES

