

## DEVELOPMENT OF A COMPOSITE WRAPPED PROPELLANT TANK

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### ABSTRACT

In order to provide a lighter weight, less complicated, more easily manufactured, highly reliable, and more capable hydrazine fuel tank for an advanced high capacity communications satellite, a new design was conceived from three previous very successful communications satellite programs. This approach allows the new design to rely on significant heritage from the earlier programs since there are many successfully operating satellites in orbit with hundreds of years of operating experience.

A lightweight tank shell coupled with a redesigned propellant management device (PMD) fulfilled this requirement. The resultant tank is fabricated in an all-welded, graphite composite wrapped titanium configuration with a sponge, vane and trap 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. The PMD has additional capability to allow horizontal handling with a low propellant fill fraction and multiple erection and de-erection cycles. This advanced PMD is derived from an ongoing program while the tank shell is derived from two ongoing programs which employ two shorter composite wrapped shells with the same tank diameter. All heritage hardware was previously qualified for the other programs.

Each spacecraft contains three tanks - two for nitrogen tetroxide ( $N_2O_4$ ) oxidizer and the other for hydrazine ( $N_2H_4$ ) fuel. The tanks are mounted side by side in the spacecraft with the two oxidizer tanks flanking the middle fuel tank. The fuel tank, which is the subject of this paper, is mounted to the spacecraft with four mount plates which are bonded to the propellant outlet side of the tank cylinder at 90 degree intervals. Each mount plate contains four nutplates. The fuel tank is stabilized with struts mounted at the

top pressurant port and the bottom propellant outlet port.

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 tests on one flight-type unit empirically validated the analysis and design of the tank assembly. One flight unit has been delivered on time.

### INTRODUCTION

Pressure Systems, Inc. (PSI) was contracted to analyze, design, fabricate, assemble, test, qualify and deliver propellant tanks to support an initiative to build a cost competitive, high capacity, advanced communications satellite. This satellite features broadband transponders. The program provided for one qualification unit and four flight units. One flight unit has been delivered, and the qualification tank is ready for qualification testing.

Each of the satellites includes three propellant tanks - two for the nitrogen tetroxide oxidizer and one for the hydrazine fuel. They are mechanically mounted side by side inside the satellite's structure with the oxidizer tanks flanking the central fuel tank. The fuel tank is installed with four mount plates containing four nutplates each and stabilizing struts at the two dome ports. The tank is tungsten inert gas (TIG) welded into the propulsion fluid system. The tanks are of an all-welded titanium construction with a graphite composite wrapped central cylinder. The tank shell is designed to hold the

fluids while the composite wrap takes the loading. The fuel tank incorporates a passive propellant management device for propellant acquisition and to supply gas-free propellant 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, Proton, Sea Launch, Titan, and H-2A 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 Table 1.

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

Tank Outside Diameter (in.)	35.3
Tank Length (in.)	132
Tank Fluid Capacity, Minimum Liters in <sup>3</sup>	1,920 117,154
Maximum Initial Propellant Load	97% of tank volume 1,856.5 kg Hydrazine
Fluids	Hydrazine, IPA Distilled Water, Ar, He, GN2
Temperature Range	36-160°F
Pressures (Psia) MEOP * Collapse Proof Burst	300 2.0 375 450
Minimum Expulsion Efficiency, %	99.7 minimum
Leakage	Zero liquid leakage $\leq 1 \times 10^{-6}$ scc/sec He at MEOP * Pressurant Leakage
Maximum Weight , lb.	207.2
Minimum Design Life On Orbit, Years	15
Stiffness Tank Propellant Fill Fraction (Worst Case)	> 31.5 Hz (Lateral), > 35 Hz (Axial)
Launch Vehicle Compatibility	Atlas-Centaur, Ariane, Long March, Proton, Sea Launch, Titan, and H-2A

\* Maximum expected operating pressure.

Table 2 outlines the vibration requirements for the hydrazine tank.

**TABLE 2: VIBRATION REQUIREMENTS**

Test (Sine)	Axis	Frequency (Hz)	Acceleration (g, 0-Peak)	Limit Acceleration (g)
Qualification 2 Octaves/Min (Wet & Dry Tests)	Lateral (Y & Z)	5 - 10	0.59 in. D.A.*	5.0
		10 - 75	3.0	5.0
		75 - 100	2.0	5.0
	Axial (X)	5 - 15	0.44 in. D.A.*	10.0
		15 - 20	5.0	10.0
		20 - 65	6.0	10.0
		65 - 100	3.0	10.0

Frequency (Hz) (Wet)	Qualification (Wet Random)	Frequency (Hz) (Dry)	Qualification (Dry Random)
Time per axis (X, Y, & Z)	2 minutes	Time per axis (X, Y, & Z)	2 minutes
Fluid & pressure	97% fill fraction with water at 150 psig	Fluid & pressure	Empty tank at 150 psig
20 to 100	+6 dB/OCT	20 to 1000	0.1 g <sup>2</sup> /Hz
100 to 1000	0.04 g <sup>2</sup> /Hz	1000 to 2000	-6 dB/OCT
1000 to 2000	-9 dB/OCT		
OVERALL grms	7.24	OVERALL grms	12.18

\* Double amplitude.

The acceleration load limit for all axes of the random vibration test is 4.0 G<sup>2</sup>/Hz.

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

The tank propellant and pressurant hemispherical domes are machined from annealed titanium alloy Ti-6Al-4V hemispherical forgings. During processing the hemispheres are rough machined, solution heat treated and partial aged, skim machined, final aged and then final machined. The tank's cylinder section is made up of three rolled and longitudinally welded Ti-6Al-4V 0.032 inch nominal sheet thickness material. After fabrication the three cylinder sections are TIG welded together.

The final tank shell assembly with the enclosed PMD is hydrostatically autofrettaged (ambient

proof pressure tested) at 180 psig. The tank shell is then shipped to Aerojet – Sacramento for the central cylinder composite wrap and the bonding of the mount plates to the tank shell.

There are seven layers of T800 carbon fiber oriented in various directions to account for the loading on the tank shell applied. The epoxy resin is Epon 862. The plies include full circumferential hoop plies, 45 degree cross plies, axial stiffening plies, hoop compaction wrap, and hand laid up pre-preg wraps. These materials were characterized through an extensive series of tests before use on the flight hardware.

The tank is mounted into the spacecraft structure by bonded-on Ti-6Al-4V mount plates with

integral nut plates located on the cylinder section closest to the propellant (outlet) hemisphere near one of the four girth welds. Both ports are 3/8 inch diameter titanium alloy compatible with the spacecraft's Ti-3Al-2.5V tubing.

Figures 1 and 2 depict an outline of the propellant tank assembly.

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 Tables 1, 2, and 3 dictated the structural and stress analysis parameters and boundary conditions. Extensive finite element analyses using the COSMOS/M program were conducted. These analyses were also used to determine the carbon wrap configuration.

The all-titanium propellant management device is a combination of a center posted vane device, a sponge, a trap, a tortuous trap entrance, a geyser limiting baffle, and a trap pickup assembly. The center post and upper vanes are welded into the pressurant hemisphere. The trap, sponge, lower vanes, and trap pickup assembly are welded into the propellant hemisphere. A slide, to allow for tank growth, is located immediately above the sponge.

This surface tension PMD has been designed to provide gas-free propellant delivery throughout mission including, but not exclusively, LAE firings and 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 all required porous material bubble points. 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 17.63 inch radius tank with hemispherical heads and a 97 inch long

cylindrical section. 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, to accommodate fluid transient motion (which could cause premature ingestion of gas), to allow horizontal handling with a low propellant fill fraction, and to allow multiple erection and de-erection cycles without ingesting gas in the PMD. These additional design considerations have led to a reliable and efficient PMD design.

Figures 3, 4, and 5 depict the propellant management device components.

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 is EB drilled Ti-6Al-4V titanium sheet while the screen is 30X160 plain Dutch weave made from CP titanium.

After assembly, the PMD subassemblies are mounted and welded into the inlet and outlet hemispheres while the vane-to-tank wall gaps are maintained. The expulsion assembly is bubble point tested and accepted before the tank assembly is closed. For the final tank assembly there is one automatic TIG girth weld that joins the expulsion assembly to the center section-to-hemisphere assembly.

All girth welds are radiographic and dye penetrant inspected. The last girth weld can only be radiographic inspected since the interior of the tank is not available for a dye penetrant inspection. The nut plates are then installed with a two-part epoxy on the sidemount plates. 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 ( $N_2H_4$ ) during all mission accelerations with a minimum expulsion efficiency of 99.7% 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 multiple LAE burns with three axis stabilization to achieve orbit, and reaction control system thruster firings of varying duration to maintain orbit. In addition, horizontal handling with low propellant fill fractions has been added to increase the capability of the PMD. The mission requirements are summarized in Table 4.

### **II. PMD General Design Description**

The PMD design incorporates a trap, a large radial sponge, and four vanes as illustrated in Figures 3, 4, and 5.

The sponge is designed to maintain a minimum of 652 cubic inches of hydrazine to satisfy all mission requirements. The sponge panels contain holes to allow crossflow of the propellant. A baffle is incorporated on the top of the sponge to prevent propellant geysering.

Four vanes are employed. They are positioned on the +/- Y and +/- Z axes of the spacecraft at a 90 degree circumferential spacing. The vanes incorporate notches at the interfaces to the sponge assembly to prevent leakage from the sponge during lateral accelerations.

**TABLE 3: FACTORS OF SAFETY FOR  
STRUCTURAL ANALYSES**

REQUIREMENT	COMMENTS
Yield Load X Factor of Safety (FS)	1.15 X Limit Load (by test); 1.6 X Limit Load (by analysis). Tank is to withstand combined yield load & MEOP under all specified environmental conditions.
Ultimate Load X Factor of Safety (FS)	1.25 X Limit Load (by test); 2.0 X Limit Load (by analysis). Tank is to withstand combined ultimate load & MEOP under all specified environmental conditions.
Safety Factor (FS)	For buckling = 1.6.
Safety Margin (MS)	$MS = [\text{Allowable Stress (or load)} / FS \times \text{Applied Stress (or load)}] - 1$

**TABLE 4  
PROPELLANT MANAGEMENT DEVICE  
PERFORMANCE REQUIREMENTS SUMMARY**

General Requirements

- The minimum tank internal volumetric capacity is 117,154 cubic inches. The tank radius is 17.63 inches, and the tank length is approximately 132 inches. The tank is cylindrical with hemispherical heads.
- The propellant used in the tank is hydrazine, and the pressurant is helium.
- Each unit shall be capable of operating with propellant and pressurant between + 36 and + 160 degrees F.
- The PMD safety factor will be a minimum of two. All porous elements will have a safety factor of three minimum on test samples and a safety factor of two minimum on tank assembly level test levels.
- The propellant outlet is located at the +X pole. The tank is mounted in the spacecraft with the hydrazine tank centerline on the X axis. The hydrazine tank bottom is 13.24 inches above the separation plane. The spacecraft center of gravity is on the hydrazine tank centerline 1.5 to 22.2 inches above the hydrazine tank mid-plane.
- During horizontal handling, the spacecraft is rotated so that the + Z axis is up.

Ground Operations

- The tank is filled with hydrazine to a fill fraction between 45 and 97 % full. The tank orientation during filling and draining is outlet down with the tank axis within +/- 2 degrees from vertical.
- Fill and drain flow rates will be limited to 2.6 gpm or 10 cubic inches per second. The initial flow rate and/or tank pressure may be limited by the PMD, as required.
- The tank is pressurized to 150 +/- 5 psia after propellant loading.
- The tank will be handled in the upright or horizontal position. While upright, the PMD must subsequently operate and survive slosh loads induced by a 6 inch amplitude motion at the first slosh mode frequency. While horizontal, the spacecraft and tank + Z axis is up. During horizontal handling, the PMD must subsequently operate and survive slosh loads induced by a 1.5 inch longitudinal and/or lateral amplitude motion at the first slosh mode frequency.

## Boost Operations

- Three axis stabilized launch occurs with the tank in the upright, outlet down position. No fuel is required.
- Following launch, separation occurs. The separation event is assumed to be a settling, short duration event that has a negligible impact on the PMD design. Following separation, an 8 degree/second rotation about any axis passing through the CG is possible. System priming occurs post separation and occurs with the tank pressure at 150 +/- 5 psia. A maximum of 162 cubic inches of fuel is required from the tank. The maximum flow rate shall be limited by the propellant tank design to preclude any PMD damage.
- Following system priming, capture is accomplished with hydrazine. A maximum of 272 cubic inches (4.5 kg) is required producing up to 0.033 radians/second (high angular acceleration from aft facing 5 lbf thrusters coupled with up to 0.0016 G settling and/or 0.00061 G laterally. The NTO PMD will require a 5.5 second minimum 5 lbf thruster pulse, assuming a settling acceleration of 0.00091 G minimum, after spinning at rates above 1.5 degrees/second.
- Following separation recovery, the spacecraft is spinning at up to 0.1 rpm (0.06 degree/second) maximum about the X axis. This thermal roll may be present throughout transfer orbit.
- Pressurization to 300 psia maximum follows separation capture. The tank pressure is regulated to 300 psia throughout transfer orbit (185 psia minimum during orbital operations).
- The primary use of hydrazine during the transfer orbit is during the LAE firings.
- Prior to each LAE ignition, a hydrazine settling burn may occur (for worst case it is assumed that a settling burn may not always occur). The PMD is designed to allow LAE ignition with propellant in its zero G coast configuration. A hydrazine settling burn produces between 0.00091 and 0.00335 G. The hydrazine flow rate is between 0.0554 and 0.1108 lbm per second (1.52 and 3.04 cubic inches/second, respectively). Burn duration is not specified. Prior to each settling burn or LAE firing is a 30 minute minimum coast period.
- The tank fill fraction during each LAE firing is between 25 and 97%. Each LAE firing produces a settling, -X axis acceleration between 0.0091 and 0.0235 G. The maximum flow rate is 0.24 lbm/second of hydrazine (6.59 cubic inches/second). The minimum flow rate is 0.156 lbm/second (4.28 cubic inches/second). Burn duration is unlimited, and the tank flow loss shall not exceed 5 psid at a flow rate of 0.167 lbm/second (4.58 cubic inches/second).
- Between LAE firings, several maneuvers may occur including nominal operations and failure recovery. Fuel is required during these maneuvers, and a 30 minute minimum zero G coast will precede each LAE ignition.
- Nominal operations: During nominal operations, lateral thruster firings and slew maneuvers may occur. The maximum angular rate throughout nominal operations is 1.2 degrees/second.
- Lateral thruster firings: The maximum acceleration is 0.00015 G and the maximum flow rate is 0.00066 lbm/second (0.018 cubic inches/second). The burn duration is unlimited.
- Slews: Slews are produced by pulsing the 5 lbf aft facing thrusters. The maximum angular acceleration is 0.004 radians/second coupled with 0.0017 G settling acceleration. This angular acceleration's duration is limited to 5.5 seconds to insure that the maximum rate of 1.2 degrees/second is not exceeded. The flow rate is 0.00517 lbm/second (0.14 cubic inches/second) maximum.
- Failure recovery: Failure is characterized by an 8 degrees/second rotation about any axis. For recovery, a maximum of 272 cubic inches (4.5 kg) is required producing up to 0.033 radians/second (high angular acceleration from aft facing 5 lbf thrusters) coupled with up to 0.0016 G settling and /or 0.00061 G laterally.

## Orbital Operations

- On orbit operations include +/- Y and +/- Z axis thrust using the hydrazine thrusters. The maximum lateral acceleration is 0.00018 G. The maximum flow rate is 0.0038 lbm/second (0.10 cubic inches/second). The burn duration, and therefore the demand quantity, is unlimited.
- Failure recovery is required. During failure recovery, an 8 degrees/second rotation about any axis is possible. Hydrazine is used to produce up to 0.038 radian/second coupled with a 0.00234 G settling acceleration (5 lbf thruster firing). 4.5 kg (272 cubic inches) of hydrazine are required at a maximum flow rate of 0.093 lbm/second (2.55 cubic inches/second).
- The requirement of 99.9% expulsion efficiency is accepted only as a goal. Depletion will occur during a lateral on orbit hydrazine thruster firing as described above. An expulsion efficiency of 99.7% can be guaranteed.

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All of the porous elements in the design are titanium and prevent gas from penetrating into the trap and into the outlet lines prior to depletion. The minimal area of porous element greatly increases reliability. The entire design uses 13 square inches of screen and 13 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 screen and perforated sheet; providing increased strength and reliability. Reducing screen 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.

Figure 6 depicts additional views of the tank assembly while Figure 7 shows the flow path of fluids through the tank assembly.

## **III. PMD Operational Description**

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

The various phases of the mission that the PMD will encounter and how the PMD will affect the propellants are illustrated in Figure 8, 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 or near atmospheric pressure to reduce the amount of gas retained in the trap above the trap inlet windows. The trapped gas will be compressed upon pressurization. The filling process is straightforward and should introduce no difficulties either to the technician or to the PMD.

The PMD was designed for handling with the tank in the outlet down or horizontal orientation. Gas may penetrate the area below the perforated



sheet, the top of the trap, the trap inlet tube, and the slosh control device during handling at low fill fractions or due to slosh during transport but gas will not enter the trap. Both upright and horizontal handling are illustrated in the operational sequence.

Ground draining may have to be accomplished with propellants and certainly will occur with test fluids. The liquid remaining in the tank at the end of ground draining will have to be evaporated from the tank. The tank will be drained in the outlet down position as shown in the operational sequence.

### Boost Operations

After launch, the spacecraft is separated from its booster.

The PMD is designed to be launched in the outlet down position. Launch is illustrated in the operational sequence operational sequence.

The propulsion system is then primed. High flow rate propellant demand occurs during system priming. Both within the trap and in the bulk space, the gas is far from the porous elements. System priming will dynamically load the trap housing. The trap housing has been designed to accommodate the system priming transient structural loads.

Following separation, the vehicle may be spinning at up to 8 degrees/second about any axis. Hydrazine is used to recover the vehicle. Recovery requires a maximum of 4.5 kg or 272 cubic inches of hydrazine. Throughout the mission a failure may occur, which would cause a similar rotation, and this amount of fuel would be used again to recover the spacecraft.

Once the propellant is settled over the PMD with a settling burn, propellant access during LAE firing is very straightforward. Attainment of orbit uses the majority of the tank's propellant. LAE firing produces relatively high settling accelerations, and the propellant surface in the tank is planar and negligibly affected by surface tension. These operations are illustrated in the operational sequence.

Boost operations can be divided into the following stages: launch, system priming, separation and failure recovery, and LAE firing.

Throughout boost and the geosynchronous transfer orbit, the propellant tank operates in a pressure regulated mode. After reaching orbit, the system will be sealed, and the tank will blowdown for the remainder of the spacecraft's life.

### Orbital Operations

Once on-orbit, the PMD has been designed to provide gas-free propellant delivery during three types of maneuvers: 1) slews, 2) on orbit lateral firings, and 3) depletion.

Between these maneuvers, a zero g coast is encountered, and the propellant will occupy a position minimizing its surface area (and thus surface energy) as illustrated in the operational sequence. The sponge is filled with propellant and the propellant resides primarily in the outlet hemisphere.

The low consumption maneuvers are of sufficiently short duration to ensure that the propellant will not displace far from its zero g equilibrium condition. Sponge propellant is easily consumed without any risk of gas ingestion into the trap. Likewise, the trap pick-up assembly will always be in contact with propellant making gas ingestion impossible. The operational sequence shows the zero g propellant position with all porous elements submerged.

During a lateral maneuver, the propellant in the sponge is consumed. The burn may be sufficiently long to reorient most of the propellant into a pool on the tank wall where it is inaccessible. The sponge will retain propellant between sponge panels during the lateral acceleration. Subsequent to a lateral maneuver, the propellant in the bulk space will reorient into its coast configuration refilling the sponge thus readying it for the next maneuver. Refilling will require less than one hour at the lowest fill fractions. Thus, the sponge and vane system can supply the propellant for all nonsettling maneuvers.

Depletion, by definition, occurs when gas is ingested into the outlet of the tank. Depletion is a multistage process in this PMD design. First, the vanes are unable to supply propellant to the center post at the demand rate. Second, the center post is unable to supply propellant to the sponge at the demand rate. Third, the sponge propellant will be consumed, and gas will be ingested into the trap as the trap supplements the vane/center post/sponge flow. Finally, the trap empties, and gas is ingested into the perforated sheet. Depletion is marked when gas first penetrates the outlet perforated sheet since there are no further barriers to gas ingestion.

#### **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. Upright and horizontal ground handling are accommodated. During launch, the PMD does not function and has been designed to maintain a nearly full trap and not be adversely affected by any of the encountered launch conditions. Once in low earth orbit, separation from the booster occurs, and the propulsion system is primed. The PMD has been designed to provide for failure recovery as required. The LAE firing portion of boost occurs next. The PMD has been designed to accommodate multiple LAE firings and will provide gas-free propellant as needed between LAE firings. After the LAE firings, the tanks are

used to acquire station. Finally, 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.<sup>1</sup> Control devices are able to deliver a fixed quantity of propellant while communication devices offer unlimited duration operation. Because this mission requires fixed quantity propellant delivery for most maneuvers, a control PMD is feasible. A communication PMD could meet the mission requirements but the PMD chosen for this mission is the most robust, reliable and lightweight design available.

The apogee phase is most easily accommodated with a pickup assembly positioned in the propellant pool. This is accomplished by using the trap inlet windows as the pickup assembly. The sponge acts as a reservoir to accommodate transients and as a vortex suppressor.

The limited duration of the on-orbit maneuvers, allows the use of control devices which are more reliable, smaller, and simpler than communication devices. Two control devices were incorporated into this PMD: the sponge and the trap.

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

The trap is sized to a) house the gas ingested into the manifold during horizontal handling and b) provide gas-free propellant for those stages of the mission where the trap inlet windows are not in contact with propellant. Nominally, no such maneuvers are scheduled; and therefore, this is the contingency requirement.

##### 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 Boost Operations are examined. And finally, the operation of the PMD during all On-Orbit Operations is analyzed.

The specific analyses are listed in Table 5. 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.<sup>2,3,4,5</sup>

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

**TABLE 5**  
**PMD PERFORMANCE ANALYSES**

- I. General Design Analyses
  - A. Center Post and Vanes
  - B. Pickup Assy Sizing
  - C. Trap Baffle
  - D. Sponge Sizing
  - E. Flow  $\Delta P$
  - F. Thermal Effects

- G. Trap Housing and Tortuous Entrance
- H. Bulk Temperature Extremes
- I. Temperature Differentials

- II. Ground Operations
  - A. Filling
  - B. Draining
  - C. Handling and Pad Slosh

- III. Ascent Operations
  - A. System Priming
  - B. Separation and Failure Recovery
  - C. LAE Firing

- IV. Orbital Operations
  - A. Slews
  - B. On Orbit Lateral Firings
  - C. Depletion

**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 9.

**FIGURE 9: QUALIFICATION TESTS FOR THE PROPELLANT TANK**

- Preliminary Inspection of Product
- Pre-Proof Volumetric Capacity
- Ambient Proof Pressure Test
- Visual Inspection
- Post-Proof Volumetric Capacity
- MEOP & Proof Cycle Life Test
- External Leakage Test
- Wet & Dry Sine & Random Vibration Tests
- Volumetric Capacity Test
- Pressure Drop & Expulsion Efficiency Tests
- External Leakage Test
- Visual Inspection
- Dimensional Inspection & Workmanship Verification
- Weight Determination
- Data Review
- Burst Pressure Test and Visual Inspection
- Final Data Review

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

The tank is subjected to an ambient hydrostatic proof pressure of 375 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 are allowed. Tank radial and linear growth measurements are recorded during this test and during the subsequent pressure drop test.

The maximum allowable volume change between the pre-proof test & post-proof test values is 0.2%. The minimum volume requirement is 115,855 in<sup>3</sup>. A visual inspection is then performed to verify there is no damage or deformation. The tank is not drained and dried since the following test requires a tank full of water.

For the pressure cycling test the tank is first subjected to 12 ambient hydrostatic proof pressure cycles at 375 psig. The tank is then subjected to 50 ambient hydrostatic MEOP pressure cycles at 300 psig. Each pressure cycle is held for 30 seconds minimum. There is no leakage or permanent damage or deformation allowed. During the first proof cycle the volumetric capacity & volume change are checked again before & after the pressure cycle. The test requirements are the same as for the initial proof pressure test sequence.

The external leakage test is conducted in a vacuum chamber with the tank pressurized to 300 psig with helium gas. The chamber is evacuated to less than 0.2 microns, and the test is run for 5 minutes. The maximum allowable leakage is  $1.0 \times 10^{-6}$  scc/sec. There is no leakage allowed from the test specimen.

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. Table 2 presents the vibration test parameters.

The dry sine and random vibration tests are performed with the tank empty, the ports sealed, and pressurized to 150 psig with gaseous nitrogen. The wet sine and random tests are performed with the tank loaded to the 97% fill fraction level with distilled, deionized water and pressurized at 150 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.

The tank is visually inspected during and after the vibration tests and no damage or deformation is allowed. The tank is returned to PSI for the remainder of the tests.

The volumetric capacity test is repeated with ambient distilled, deionized water. The volumetric capacity value is compared to the initial test to verify nothing happened to the tank during the environmental tests.

An expulsion and pressure drop test is then performed using the 97% filled tank from the previous test. The tank is pressurized to 150 psig. The tank is drained in the vertical attitude using the 150 psig ullage pressure and a flow rate of 1.2 gpm. Pressure drop and residual water volume are measured. The pressure drop requirement is 5.0 psid while the maximum allowed residual water weight is 12.55 pounds. A minimum resultant expulsion efficiency of 99.7% is required. An inspection after this test verifies that there is no leakage or damage.

The external leakage test is repeated and is conducted in a vacuum chamber with the tank pressurized to 300 psig with helium gas. The chamber is evacuated to less than 0.2 microns, and the test is run for 5 minutes. The maximum allowable leakage is  $1.0 \times 10^{-6}$  scc/sec. It is verified that there is no leakage from the test specimen.

Post-test inspections include visual, workmanship, dimensional, and weight determination. The visual inspection examines the test unit for damage or deformation. None is allowed.

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 tank is filled with ambient, deionized water, and the burst test is accomplished with a pressure value of 450 psig. The tank pressure is held for 15 seconds. There is to be no leakage or damage to the tank. The tank is then pressurized to rupture. The residual water is drained out of the tank, photographs are taken, and the failure site is identified and examined.

A final data review verifies that all data is correct and complete. All data sheets are signed and certified by the Quality Assurance Department.

The propellant tank is scheduled for qualification testing. It has not been completed. Because of schedule considerations, the first flight tank was delivered to the customer after successfully completing the acceptance tests as described below.

### **ACCEPTANCE TESTS**

The acceptance tests for the propellant tanks are listed in Figure 10.

#### **FIGURE 10: ACCEPTANCE TESTS FOR THE PROPELLANT TANK**

Preliminary Inspection of Product  
Pre-Proof Volumetric Capacity  
Ambient Proof Pressure Test

Visual Inspection  
Post-Proof Volumetric Capacity  
Static Load Test  
Pressure Drop Test  
External Leakage Test  
Examination of Product  
Weight Determination  
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, damage, material certifications, workmanship, and completed rework instructions.

The tank is subjected to an ambient hydrostatic proof pressure of 375 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 are allowed. Tank radial and linear growth measurements are recorded during this test and during the subsequent pressure drop test.

The maximum allowable volume change between the pre-proof test & post-proof test values is 0.2%. The minimum volume requirement is 115,855 in<sup>3</sup>. A visual inspection is then performed to verify there is no damage or deformation. The tank is drained and dried for the next test.

The static load test is performed with the tank installed in a fixture which simulates the spacecraft interfaces. Strain gages are applied to appropriate locations on the tank surface. The tank is empty and pressurized to 150 psig for this test. Using hydraulic cylinders, thrust loads in the +X and -X directions (8,600 pounds) and lateral loads in the +Y and -Y directions (6,400 pounds) are applied to the tank through the mounting interface. Strains are recorded and evaluated after the test. The tank pressure is vented, and it is inspected for damage and deformation. None is allowed. This test verifies that the four mounting plates bonded to the tank surface with composite materials do not experience any debonding, cracking, or unusual strains in the bonding material.

A pressure drop test is then performed using a 97% water-filled tank. The tank is pressurized to 150 psig. The tank is drained in the vertical attitude using the 150 psig ullage pressure and a flow rate of 1.2 gpm. The pressure drop is measured. The pressure drop requirement is 5.0 psid maximum. An inspection after this test verifies that there is no leakage or damage.

The external leakage test is conducted in a vacuum chamber with the tank pressurized to 300 psig with helium gas. The chamber is evacuated to less than 0.2 microns, and the test is run for 5 minutes. The maximum allowable leakage is  $1.0 \times 10^{-6}$  scc/sec. There is no leakage allowed from the test specimen.

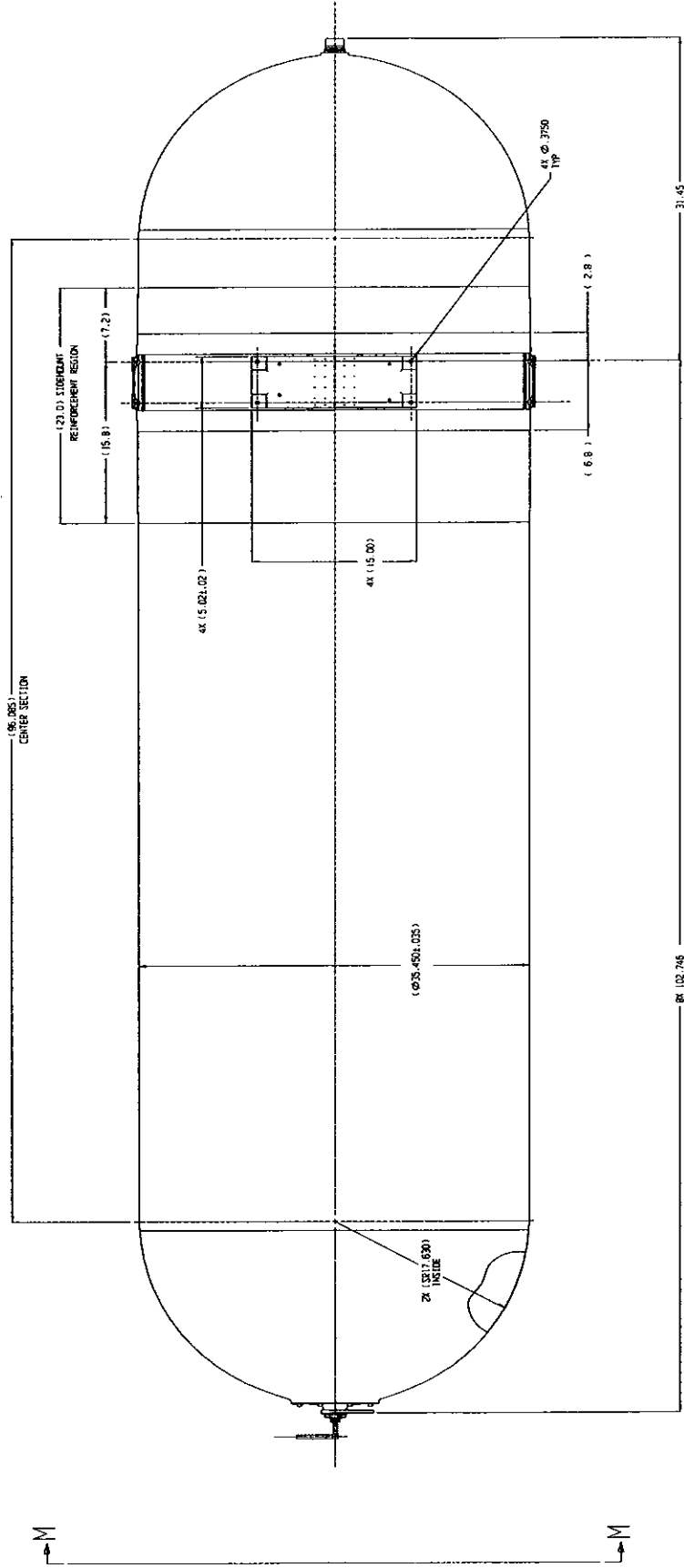
Post-test inspections include visual, workmanship, dimensional, and weight determination. The visual inspection examines

the test unit for damage or deformation. None is allowed.

Finally, the units are cleaned to Table 6 levels, purged to a  $-65^{\circ}\text{F}$  dew point, the ports fitted with 5.0 micron filters open to the atmosphere to allow the tank to breathe during shipment, and packaged in two sealed plastic bags for shipment. The wrapped tank is finally installed in a plywood container with internal foam inserts for shipment to the customer.

Figures 1 and 2 depict an outline of the propellant tank showing the port orientations.

**FIGURE 1: PROPELLANT TANK OUTLINE**



**FIGURE 2: PROPELLANT TANK OUTLINE**

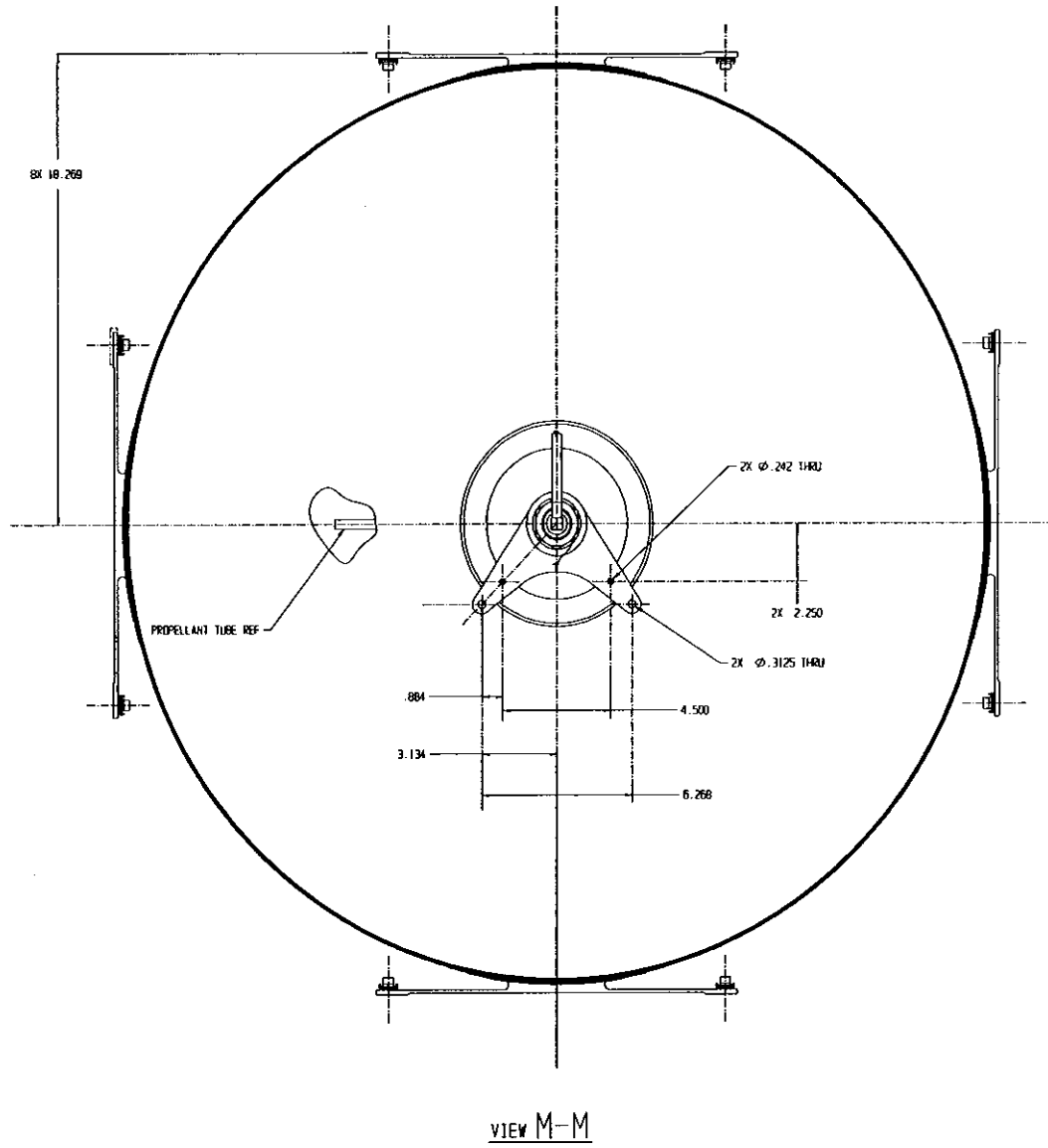




FIGURE 3: PMD ASSEMBLY

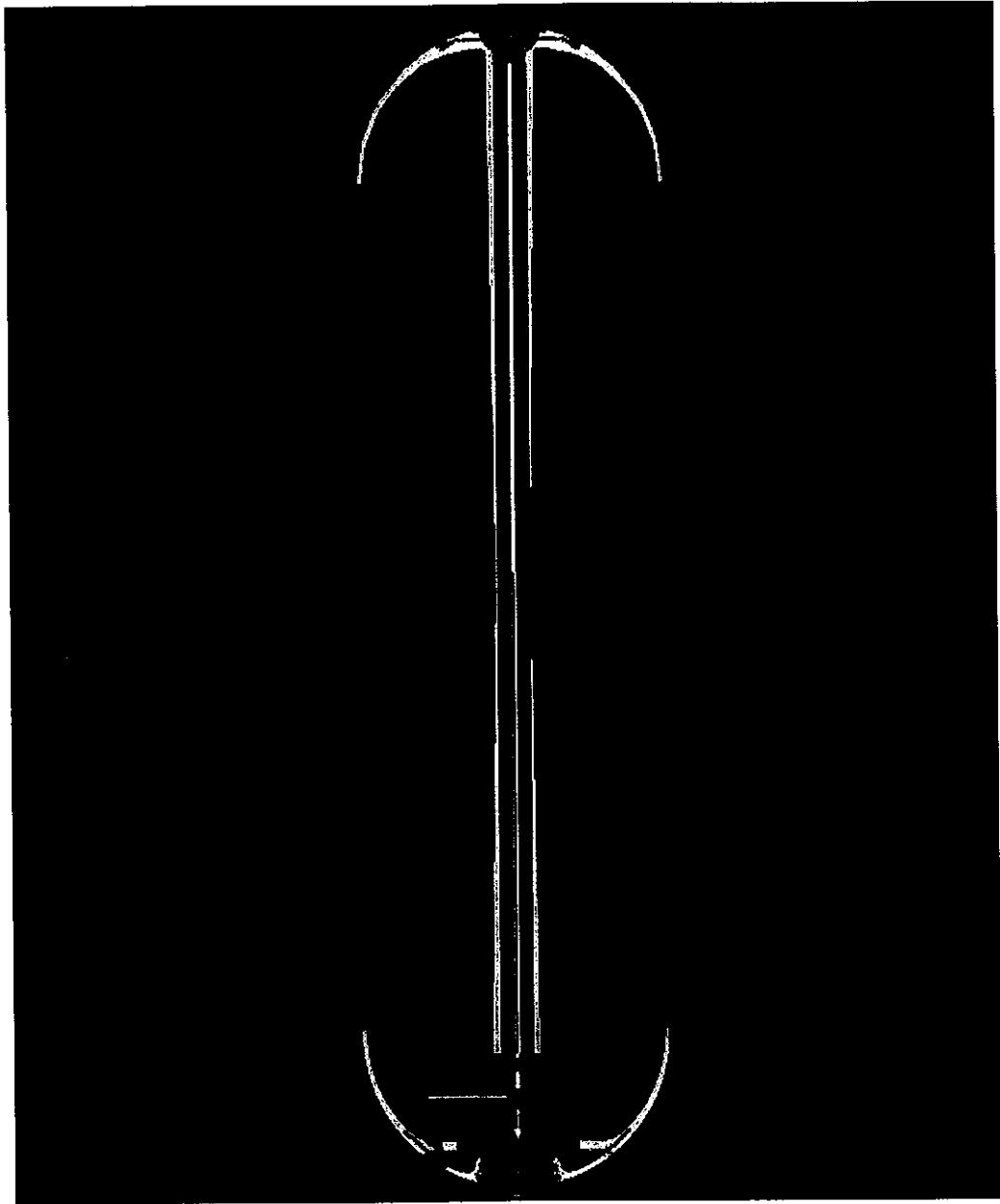


FIGURE 4: PMD DETAILS

LOWER PMD ASSY

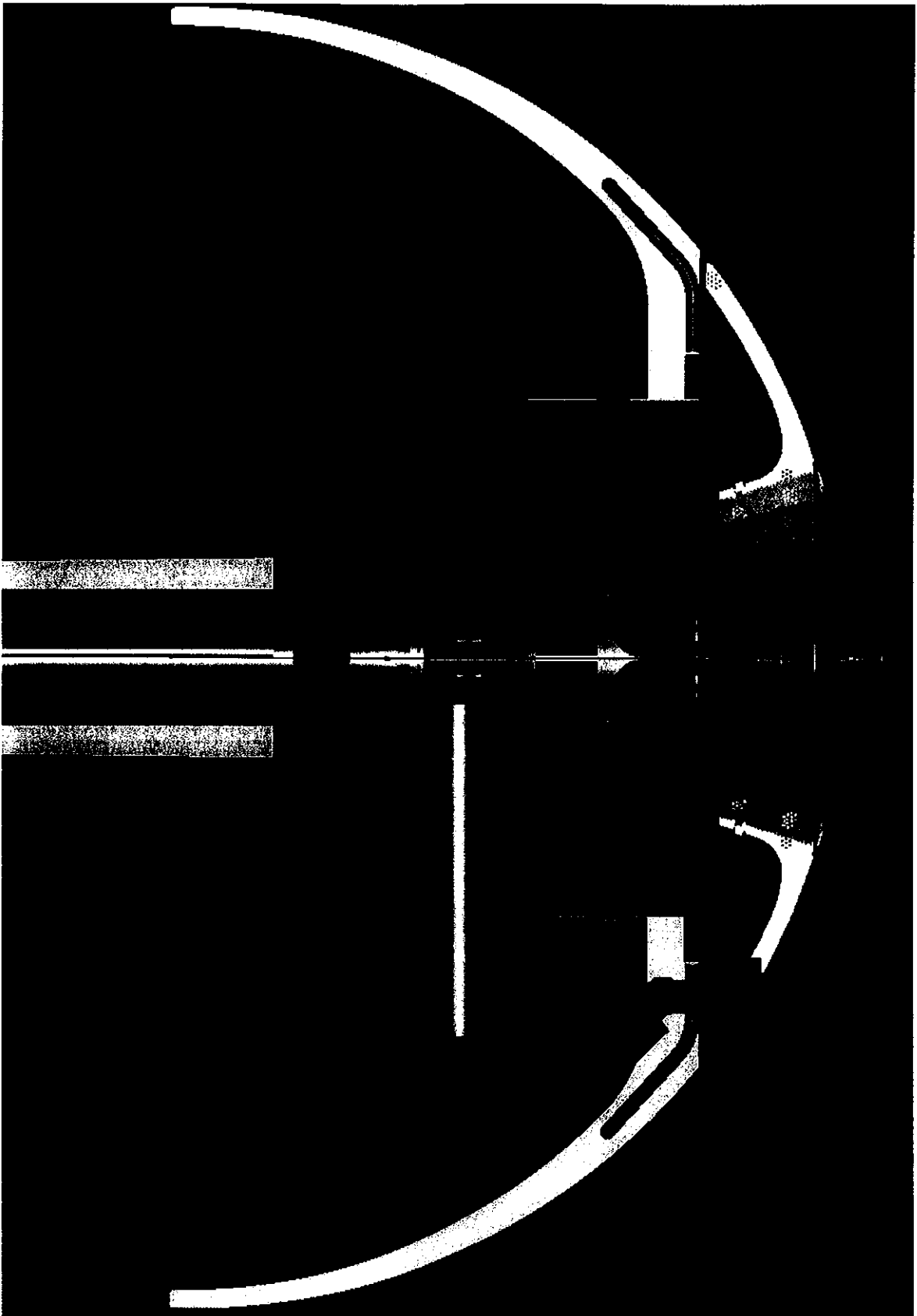
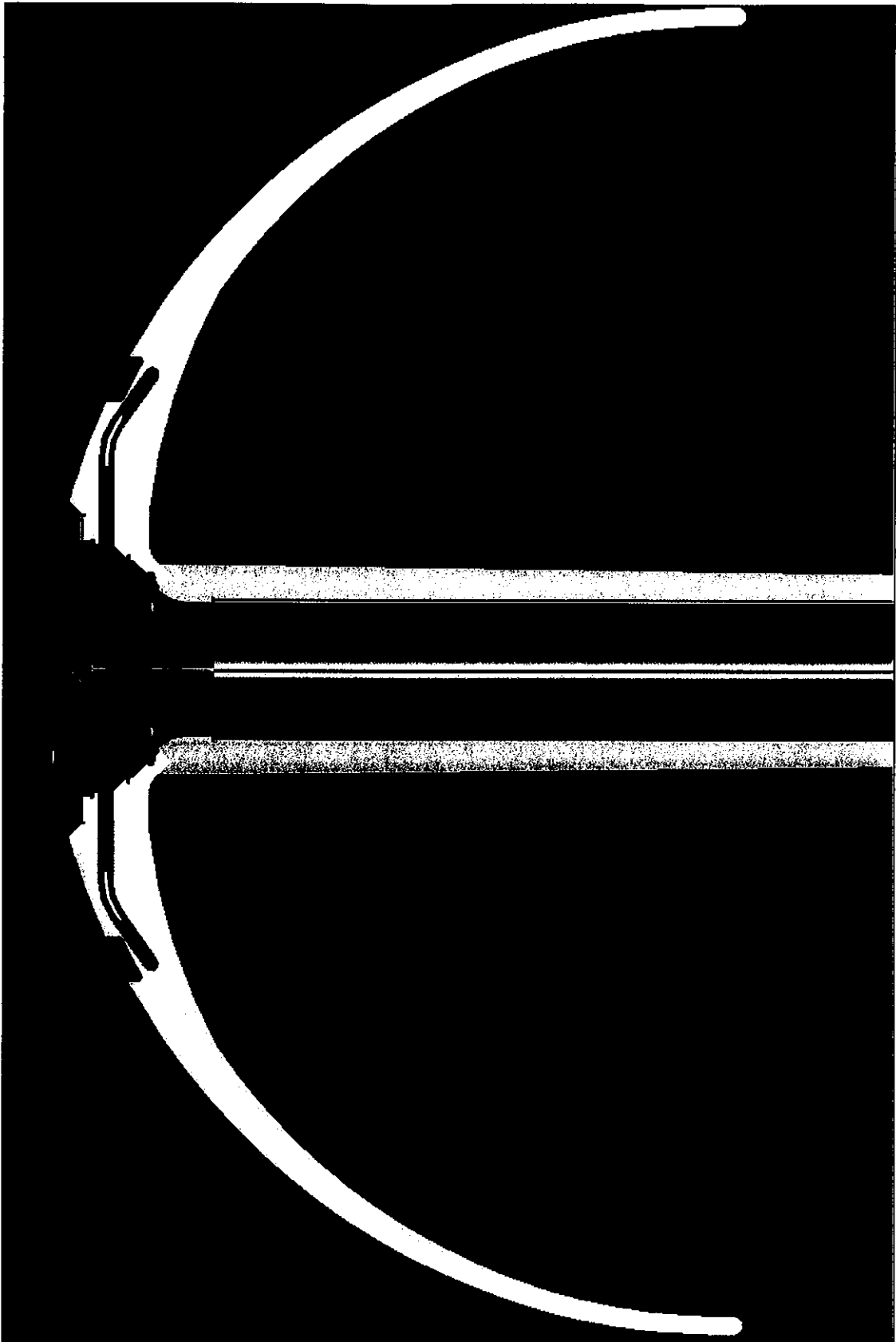
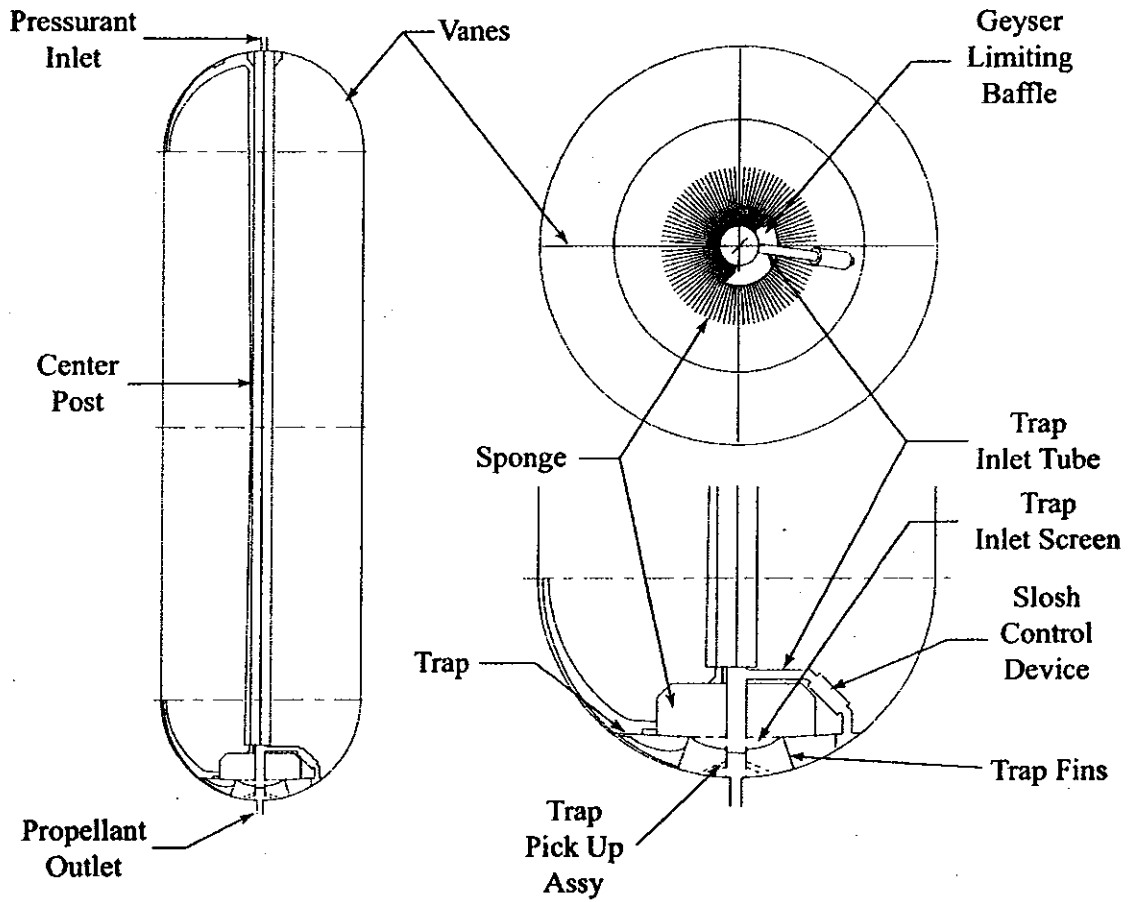


FIGURE 5: PMD DETAILS

UPPER PMD ASSY

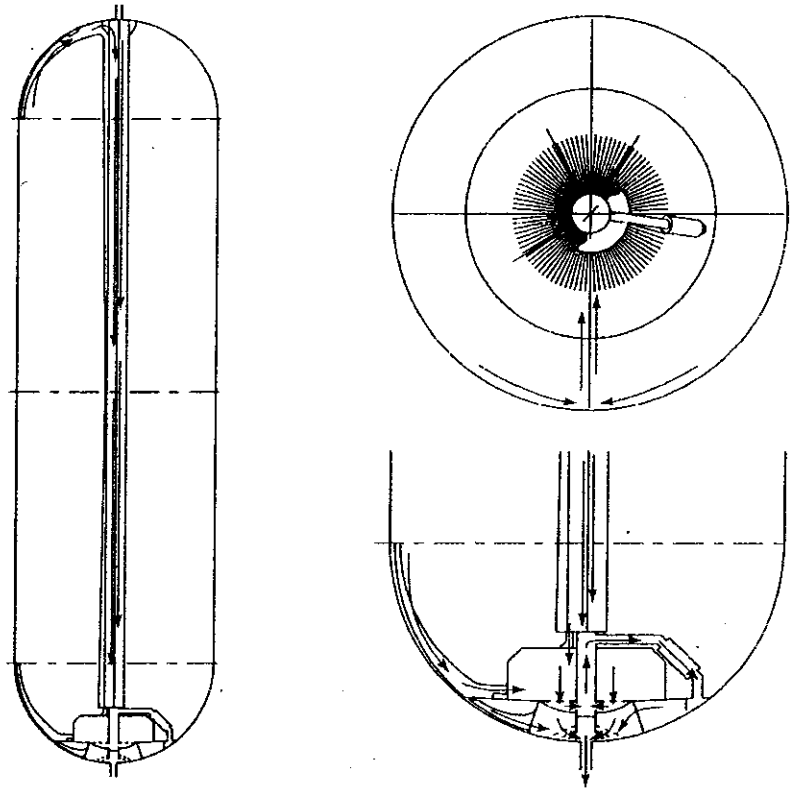


**FIGURE 6: TANK ASSEMBLY VIEWS**



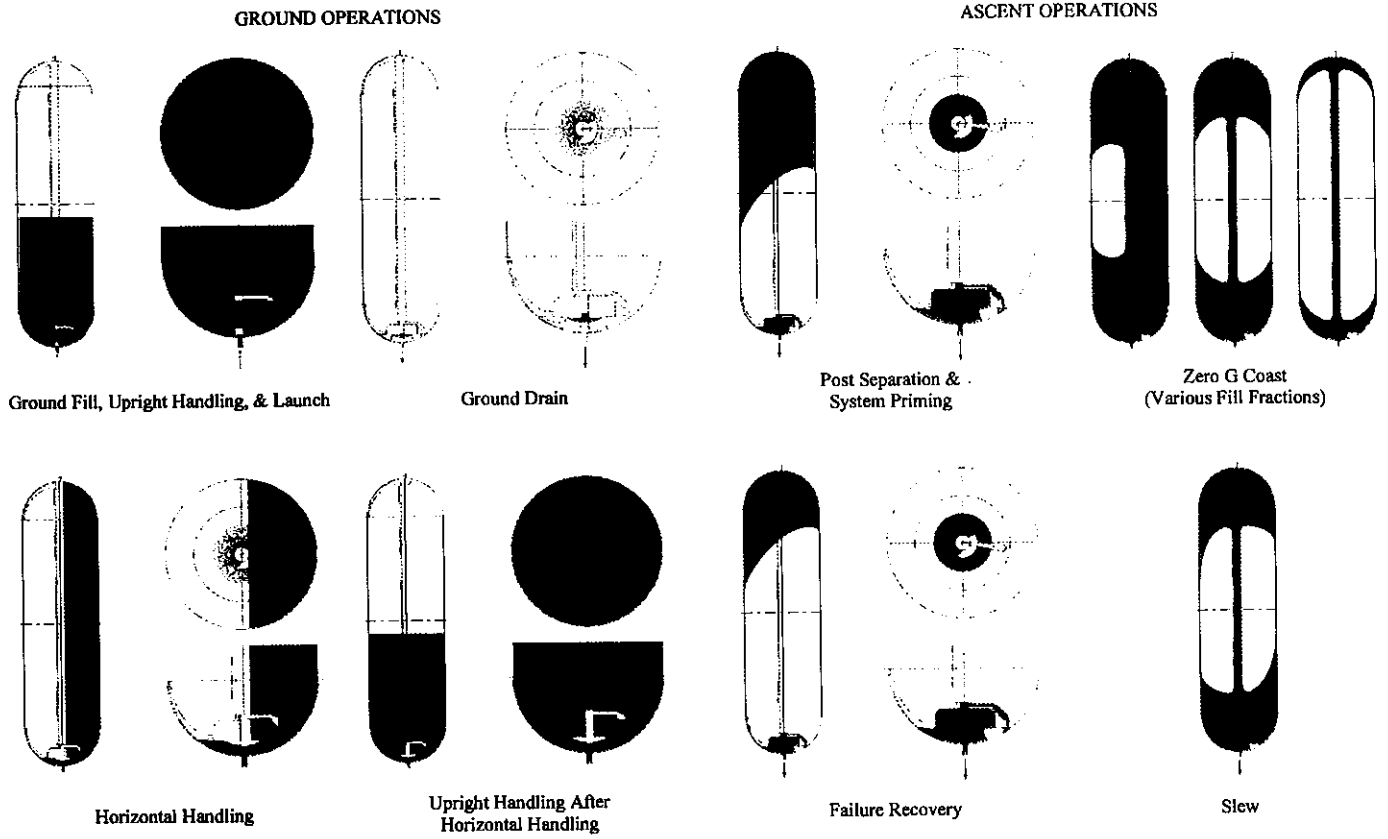
**PMD General Configuration**

**FIGURE 7: FLOW PATHS IN TANK ASSEMBLY**



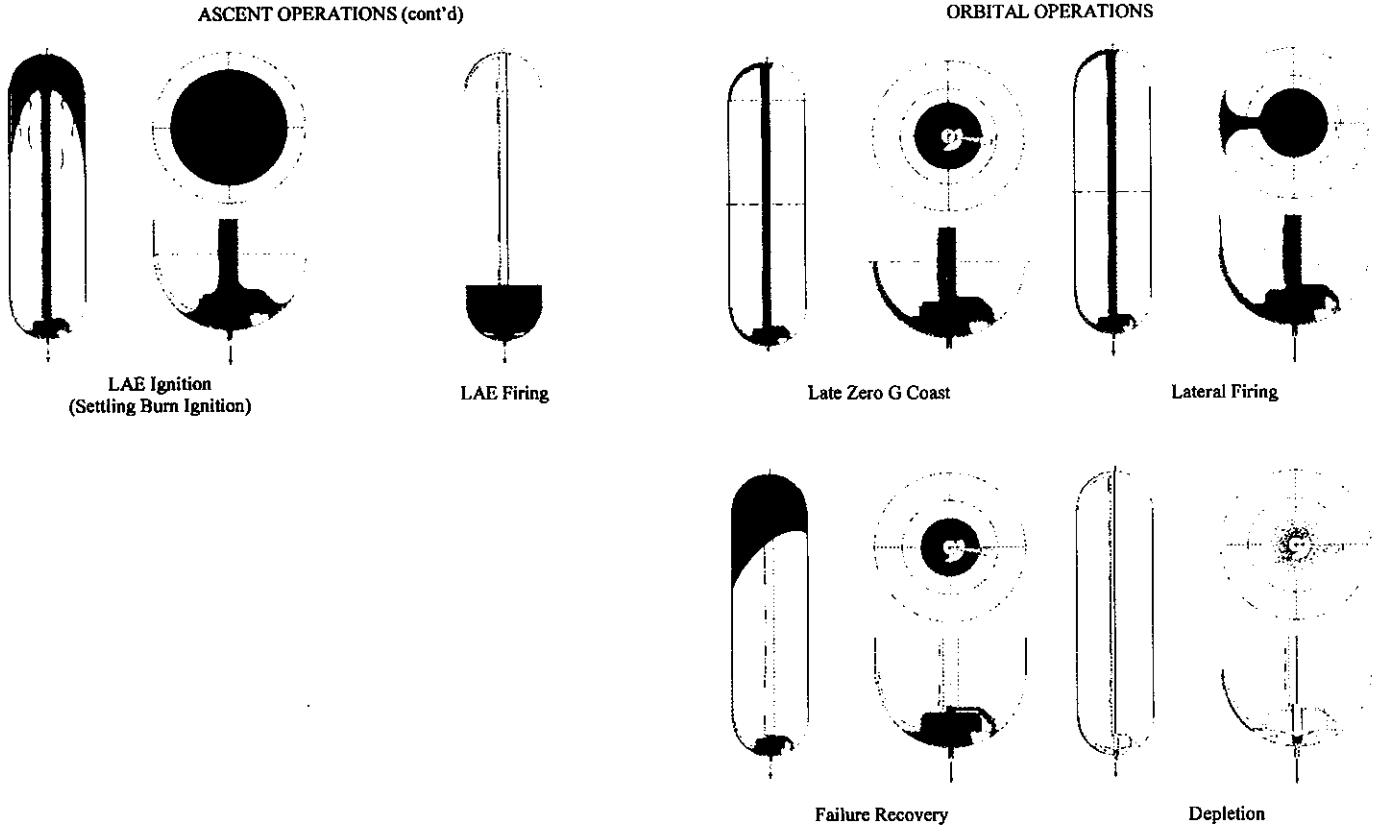
**PMD Flow Diagram**

**FIGURE 8: OPERATIONAL SEQUENCE**



Operational Sequence (Part 1 of 2)

**FIGURE 8: OPERATIONAL SEQUENCE (CONTINUED)**



Operational Sequence (Part 2 of 2)

**TABLE 6: TANK CLEANLINESS  
LEVEL**

<u>Particle Size (Microns)</u>	<u>Maximum Amount of Particles</u>
> 150 Microns	None
101-150 Microns	4
51-100 Microns	45
26-50 Microns	280
< 25 Microns	No Silting

**NOTES:**

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

**CONCLUSIONS**

This propellant tank has met all design objectives that can be verified by analysis. The qualification test specimen is scheduled for testing.

One flight-type propellant tank has been delivered on time. It successfully passed the acceptance tests listed in Figure 10 before delivery.

**ACKNOWLEDGMENTS**

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**REFERENCES**

- <sup>1</sup> 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.
- <sup>2</sup> Jaekle, D. E., Jr., "Propellant Management Device Conceptual Design and Analysis: Vanes", AIAA-91-2172, 1991.
- <sup>3</sup> Jaekle, D. E., Jr., "Propellant Management Device Conceptual Design and Analysis: Sponges", AIAA-93-1970, 1993.
- <sup>4</sup> Jaekle, D. E., Jr., "Propellant Management Device Conceptual Design and Analysis: Traps and Troughs", AIAA-95-2531, 1995.
- <sup>5</sup> Jaekle, D. E., Jr., "Propellant Management Device Conceptual Design and Analysis: Galleries", AIAA-97-2811, 1997.

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**NOTES**