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DESIGN AND DEVELOPMENT OF A PMD-TYPE BIPROPELLANT TANK

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ABSTRACT

In order to provide a lightweight, straightforward, easily manufactured, and highly reliable bipropellant tank for a new dual-mode spacecraft, a new design was conceived to meet or exceed mission requirements & to provide gas-free propellants from the tank throughout the mission.

A lightweight tank shell coupled with a new, robust propellant management device (PMD) fulfilled this requirement. The resultant tank is fabricated in an all-welded titanium configuration with a PMD, which incorporates a manifold, pick-up window & tube assemblies, vanes, & a perforated sheet outlet, to store and to provide pressurized gas-free propellants to the reaction control system thrusters in a zero g environment.

Each spacecraft contains three tanks - one for nitrogen tetroxide (N_2O_4) oxidizer and the other two for hydrazine (N_2H_4) fuel. The tanks are mounted in a plane in the spacecraft at both polar locations. Pressurant & propellant tubes are incorporated in the mounting bosses.

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 to date on one flight-type unit empirically validated the analysis and design of the tank assembly. Three flight units & one spare unit have been delivered on time.

INTRODUCTION

Pressure Systems, Inc. (PSI) was contracted to analyze, design, fabricate, assemble, test, qualify and deliver bipropellant tanks to support a reliable dual-mode spacecraft. The program provided for one qualification unit, six flight units, & one spare unit. Three flight tanks & the spare unit have been delivered. Presently, additional tanks are in production at PSI.

Each of the satellites includes three propellant tanks -- one for the nitrogen tetroxide (N_2O_4) oxidizer and two for the hydrazine (N_2H_4) fuel. They are mechanically mounted at the two polar bosses in a single plane in the spacecraft and are welded into the propulsion fluid system. The 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 Atlas-Centaur, Ariane, Long March, & Titan launch vehicles. It was not designed for horizontal transport & handling.

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

DESIGN, DEVELOPMENT, AND ASSEMBLY

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

FIGURE 1: SPACECRAFT BIPROPELLANT TANK SUMMARY OF CAPABILITIES

Tank Outside Diameter, Pressurized (in.)	28.600
Tank Length, Pressurized (in.)	54.990
Tank Fluid Capacity, Minimum	
Liters	438
in^3	26,750
Minimum Initial Propellant Load	50% of tank volume 921 lbs N_2O_4 641 lbs N_2H_4
Fluids	N_2H_4, N_2O_4 (MON-3), IPA, Distilled Water, Ar, He, N_2
Temperature Range	40-103°F
Pressures (Psia at 122°F)	
MOP *	350
Proof	468
Burst	525
Minimum Expulsion Efficiency, %	99.0
Leakage	Zero liquid leakage $\leq 1 \times 10^{-6}$ scc/sec He at MOP * Pressurant Leakage
Maximum Weight, lb.	50.0
Minimum Design Life, Years	17
Stiffness Tank (50% Propellant Fill Fraction)	> 40 Hz Natural Frequency (All Axes)
Launch Vehicle Compatibility	Atlas-Centaur, Ariane, Long March, & Titan

* Maximum Operating Pressure.

Figure 2 outlines the vibration requirements for the bipropellant tank.

FIGURE 2: VIBRATION REQUIREMENTS

Flight (Liftoff & Ascent) (Sine) (Loaded with propellant & pressurized to 270-350 psig)	Axis	Frequency (Hz)	Acceleration (g, 0-Peak)
	Lateral (X or Y)	3.9-300	+/- 3.7
	Axial (Z)	3.9-300	+/-4.6

Frequency (Hz)	Acceptance Level	Qualification Level	Units
Random (System acoustic test) (Dry & unpressurized; all axes)	1	3	minutes
20	0.005	0.02	g^2/Hz
20-50	9	9	dB/octave
50-1000	0.075	0.30	g^2/Hz
1000-2000	-6	-6	dB/octave
2000	0.019	0.075	g^2/Hz
Overall	10.5	20.9	g rms

DESIGN, DEVELOPMENT & ASSEMBLY (cont'd)

The tank shells 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 cylinder section is machined from an annealed titanium alloy Ti-6Al-4V ring forging. It is processed like the hemisphere forgings.

The tank is mounted into the spacecraft structure by six equally spaced threaded boltholes in the end of each polar boss. The propellant and pressurant ports are 0.250-inch diameter 6Al-4V titanium tubes with a flow control orifice in the propellant line. This device limits the loads on the PMD due to system priming flow. The tubes extend from the sides of the bosses. The tubes are threaded into the individual hemispheres & are then electron beam (EB) welded into position. Weld samples before & after the welding of the flight hardware verify the acceptability of the EB weld process.

Figure 3 depicts an outline of the bipropellant tank assembly.

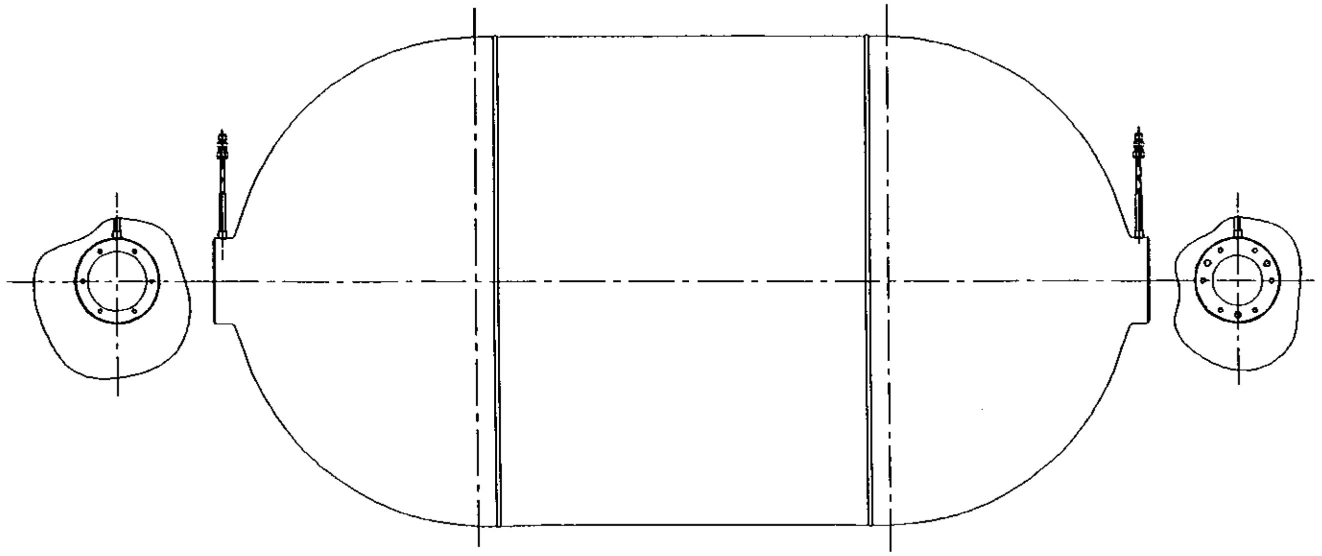


FIGURE 3: OUTLINE OF BIPROPELLANT TANK ASSEMBLY

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 Figures 1, 2, 4A, & 4B dictated the structural and stress analysis parameters and boundary conditions.

The all-titanium propellant management device consists of three pick-up assemblies located on the cylinder near the lower hemisphere & three "V" shaped vanes running the length of the cylinder. A manifold over the tank outlet connects the three pick-up assemblies.

This surface tension PMD has been designed to provide gas-free propellant delivery throughout the mission which includes unlimited duration maneuvers in one of three lateral directions. The design utilizes a minimum safety factor of two (2) on all required volumes & a minimum safety factor of three (3) on all required porous element 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 28.226-inch internal diameter by 52.325 inch long tank assembly with hemispherical heads & a cylindrical section. The same design is used in the NTO and the hydrazine propellant tanks. 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 PMD is designed to meet the 1% maximum propellant residual requirement.

The outlet tube contains an integral sharp-edged orifice to limit system priming flow rates & prevent PMD structural damage. The outlet tube is connected to the cylindrical outlet boss.

The cylindrical manifold is machined from a Ti-6Al-4V titanium bar. It is located over the tank outlet to provide a junction for the three pick-up tubes as well as the ground drain window. The curved section of the manifold is covered with 30 x 160 mesh commercially pure (CP) titanium screen. The manifold window is designed to provide propellant during the engine ignition transient & thruster pulsing as well as access to the propellant during ground draining.

The ground drain window directly over the tank outlet & inside of the PMD is a circular piece of CP titanium perforated sheet. It ensures that the gas trapped in the PMD during fill is not ingested. It also helps to minimize liquid residuals & allows for some off-design operation by preventing small quantities of gas ingested into the PMD from exiting the tank.

Connected to the manifold are three pick-up tubes which follow the propellant's hemisphere contour to the cylinder section. The CP (40 ksi yield strength grade) titanium tubes were formed from thick-walled pipes, which were cut to an approximate length, bent to the proper radius, chemical machined to obtain the proper outside diameter & end fittings, machined to their final length & interface configuration, & then dye penetrant & dimensionally inspected. They are an elegant & simple solution to providing the flow paths from the pick-up windows to the manifold & tank outlet. The tubes are 0.742 inches minimum inside diameter to reduce flow losses. They are positioned 0.6 inch from the tank wall. The tubes are supported at both ends by a weld at the manifold body & a slip support on the tank wall near the cylinder.

Pick-up assemblies are attached to each of the arms & are positioned on the +X, -X, & +Y axes to provide a screen-covered window on these sides of the tank. These windows are 30 X 160 plain Dutch weave mesh CP titanium screen. Since all flight maneuvers are in either the +X, -X, or –Y lateral direction, only three pick-ups are required. There is no thrusting with resultant acceleration in the +Y direction. The pick-up screen is circular with a window pane support & is positioned outboard a fixed distance from the tank wall.

Attached to the pick-up assemblies are "V" shaped vanes which extend the full length of the cylinder. They are fabricated from laser-cut & preformed 6Al-4V titanium sheet. The "V" vanes provide a flow path from the pressurant hemisphere to the screen-covered pick-up assemblies. They are required to access propellant during lateral but slightly nonsettling accelerations. The "V" vanes are welded to the pick-up assembly & supported by a slide-type mechanism on the tank wall near the upper or pressurant hemisphere.

Figure 5 presents a schematic view of the PMD.

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 holes in the perforated sheet disks are EB drilled. Other details are laser cut & chemically machined to shape as required.

After assembly, the PMD is mounted and welded into the outlet hemisphere while the pick-up tube-to-tank wall gaps are maintained. The expulsion assembly is bubble point tested and accepted before the tank assembly is closed. The cylinder section is automatic TIG welded to the pressurant hemisphere, the weld is dye penetrant & radiographic inspected & accepted, & the assembly is trimmed to length & the final weld detail added. Another automatic TIG girth weld final assembles the expulsion assembly to the cylinder-to-hemisphere assembly.

This final girth weld is radiographic and dye penetrant inspected and the final tank assembly is stress relieved in a vacuum heat treat furnace. The polar mounting bosses are then final machined and the tank assembly is trimmed to length. The tank is then ready for final inspection, 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 nitrogen tetroxide (NTO) and hydrazine (N_2H_4) during all mission accelerations with a minimum expulsion efficiency of 99% and a safety factor of two.

As with most PMDs, this PMD is designed specifically for the defined mission. The mission requirements include upright ground operations and launch, followed by separation, system priming, & unlimited duration thruster firings in one of three lateral directions. The mission requirements are summarized in Table 1.

II. PMD General Design Description

The PMD design incorporates an outlet orifice, a circular perforated sheet gas arrestor, a screen covered manifold, three screen covered pick up assemblies, and three "V" shaped vanes as illustrated in Figure 5.

The manifold and circular perforated sheet are welded to the tank shell around their peripheries with a single continuous weld. Each PMD arm is supported in three places: at the manifold where pick up tube is welded to the manifold, near the pick up assembly where the pick up tube slides in a fitting attached to the tank shell, and at the tip of the "V" vane where a post slides into a fitting attached to the tank shell. The PMD attachment was designed to allow the PMD to be welded only at the outlet; simplifying assembly.

The outlet orifice is integral to the outlet tube and provides a small diameter hole through which all the propellant must flow.

The perforated sheet is 6Al-4V titanium sheet electron beamed drilled to approximately 22% open area.

The manifold consists of a machined cylindrical housing with an inverted conical top. The cylinder housing is penetrated by many small rectangular openings over which screen is welded as well as three inlet holes designed to accept the three pick up tubes.

The pick up tubes are bent to follow the tank wall contour maintaining a constant gap from the manifold to the screened pick up at the cylinder/lower hemisphere junction.

The screened pick ups are cylindrical housings with the screen welded to the end of the cylinder closest to the tank wall. The gap between the screen and the tank wall is maintained by connecting the tank wall and the pick up tube with sliding joint near the pick up.

Welded to the pick up is a tapered "V" shaped vane which runs the length of the cylinder. The "V" is formed and maintained by bending sheet titanium and welding a porous sheet over the top of the "V". The gap between the tank wall and the "V" vane is designed to provide a flow path from the top of the cylinder to the pick up screen where the PMD will acquire the propellant.

All of the porous elements in the design are titanium and prevent gas from penetrating into the PMD and into the outlet line prior to depletion. The minimal area of porous element greatly increases reliability. The entire design uses less than 10 square inches of screen and less than 3 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.

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

The extremely simple and robust PMD provides low cost, low mass, and high reliability. PMD performance will exceed all requirements. Typical PMD safety factors are listed in Table 2.

FIGURE 4A: <u>FACTORS OF SAFETY FOR STRUCTURAL ANALYSES</u>

Component	Load Condition	Factor of Safety
Pressure Vessel	1.32 X MOP + 1.32 X limit launch loads	Total less than material yield strength
	1.5 X MOP + 1.5 X limit launch loads	Total less than material ultimate strength
PMD & Other Components	All	2.00 on Ultimate 1.60 on Yield

FIGURE 4B: <u>DESIGN LIMIT ASCENT LOADS FOR UNTESTED FACTORS OF SAFETY</u>

Propellant	Interface Location	Pz (lb.)	Vr (lb.)	Mz (lb.)	Mr (lb.)
Oxidizer	A	5500	2000	6000	6000
	B	280	2000	6000	6000
Fuel	A	4000	1400	4500	5000
	B	185	1400	4500	5000

NOTES:

1. A = tank pressurant end
2. B = tank propellant end
3. Pz = lateral load
4. Vr = lateral load that can occur in any direction perpendicular to the Z axis & is the RSS value of both loads in the X & Y directions
5. Mz = moment around the Z axis
6. Mr = lateral moment that can occur in any direction perpendicular to the Z axis & is the RSS value of moments in the X & Y directions
7. Yield loads are 1.32 X design limit loads
8. Ultimate loads are 1.5 X design limit loads
9. Qualification loads are 1.2 X design limit loads

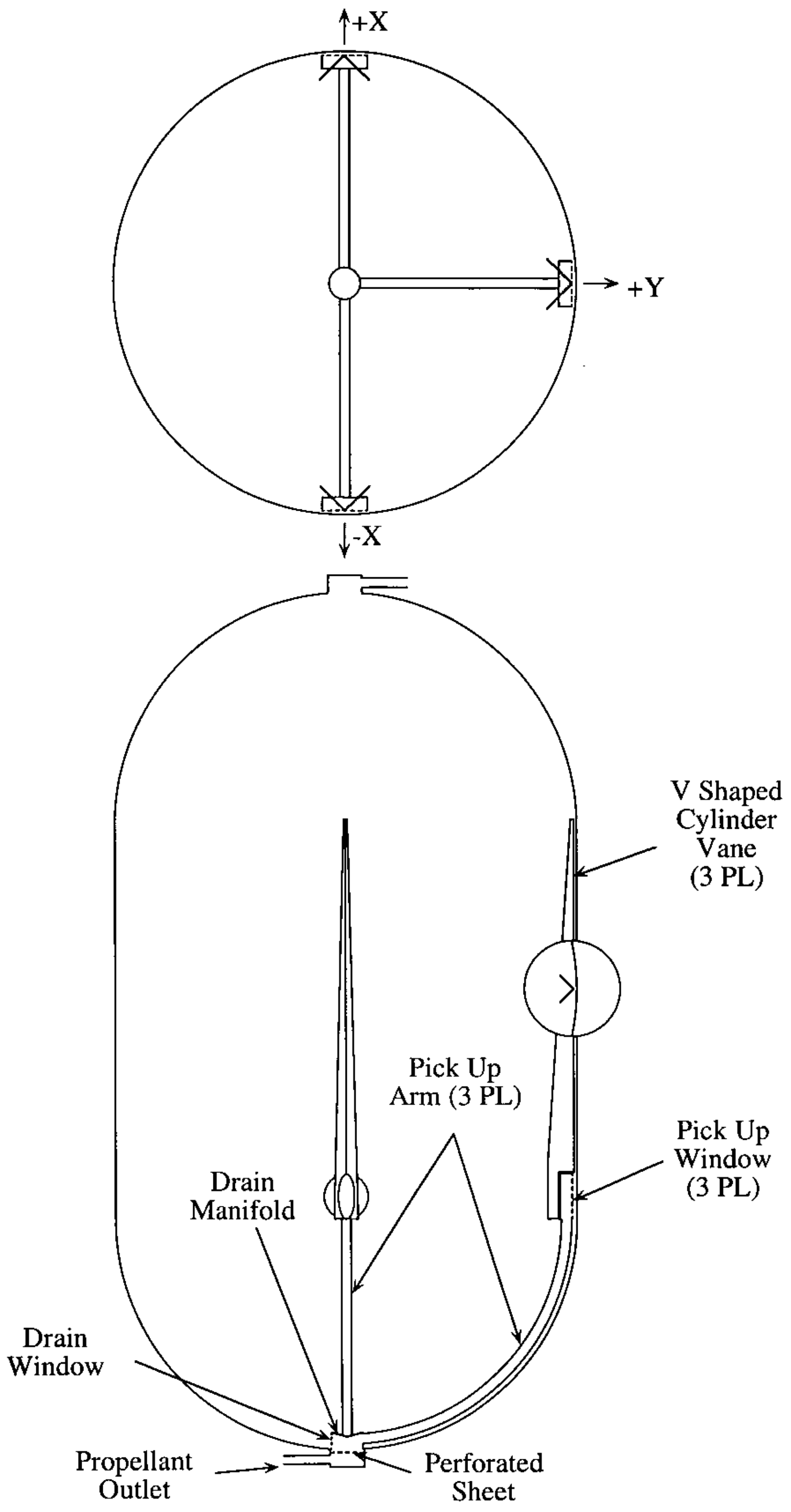


FIGURE 5: SCHEMATIC SHOWING THE PROPELLANT MANAGEMENT DEVICE COMPONENTS

TABLE 1
PROPELLANT MANAGEMENT DEVICE PERFORMANCE REQUIREMENTS SUMMARY

Ground Operations

- Tanks are filled, drained, and handled outlet down.
- Tank fill fraction is between 50% and 66%.
- After propellant loading, the tanks are pressurized to between 120 and 350 psia.
- Ground slosh is induced by 0.5 inch amplitude motion between 0.2 & 2 Hz for up to 3 hours.

Boost Operations

- Tanks are launched outlet down. No spinning occurs during launch.
- Launch slosh is induced by 3.7 g laterally with up to 4.6 g settling between 3.9 & 300 Hz.
- Separation was not specified and was assumed benign.
- System line priming occurs after separation.
  - The priming flow rate may be determined assuming 350 psia maximum pressure driving propellant into a 0.037 in^2 area line.
  - Priming occurs during coast.
  - 10 in^3 are demanded from each tank.

Orbital Operations

- All maneuvers are principally in one of three lateral directions: +X, -X, -Y. A small nonsettling Z component is possible
- Maneuvers are of any duration but a 15 minute coast will occur before each maneuver.
- The tanks are in blow down mode with a minimum pressure of 120 psia.
- At BOL (350 psia & 50-66% fill fraction), the lateral acceleration is 8.0e-4 g maximum with an 8.04e-5 g maximum nonsettling component and the maximum flow rate is 0.270 in^3/s NTO and 0.653 in^3/sec hydrazine.
- At EOL (120 psia & 1% fill fraction), the lateral acceleration is 5.2e-4 g maximum with a 6.09e-5 g maximum nonsettling component and the maximum flow rate is 0.178 in^3/s NTO and 0.313 in^3/sec hydrazine. The maximum nonsettling angle off lateral is 7.1°.

Miscellaneous

- Hydrazine and NTO are the propellants.
- Gas-free propellant delivery is required throughout mission.
- Residuals shall be limited to 1.0% of the tank volume maximum.
- Propellant temperature is between 40 and 85°F.
- Tank flow losses shall not exceed 10 psid at operational flow rates.

*

BOL = beginning of life

EOL = end of life

TABLE 2
TYPICAL CALCULATED PMD SAFETY FACTORS

- Pick-up Screen Loads

Event	SF* (NTO)	SF (N2H4)
Nominal		
Steady Operation	77	63
Ignition Transient	>3	3
Depletion**	3	3

- Manifold Screen Loads

Event	SF (NTO)	SF (N2H4)
Nominal		
Steady Operation	97	66
Ignition Transient	4.6	3
Depletion**	3	3

- Perforated Sheet Loads

Event	SF (NTO)	SF (N2H4)
Nominal		
Steady Operation	218	119
Ignition Transient	N/A	N/A
Depletion**	3	3

- Vane Capability

Event	SF (NTO)	SF (N2H4)
Nominal		
Steady Operation	>10***	>10
Ignition Transient	>10	>10
Depletion**	2	2

*Safety Factor

** By definition

*** Vane only functions with <4% fill fraction

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, Ascent 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 6, The Operational Sequence.

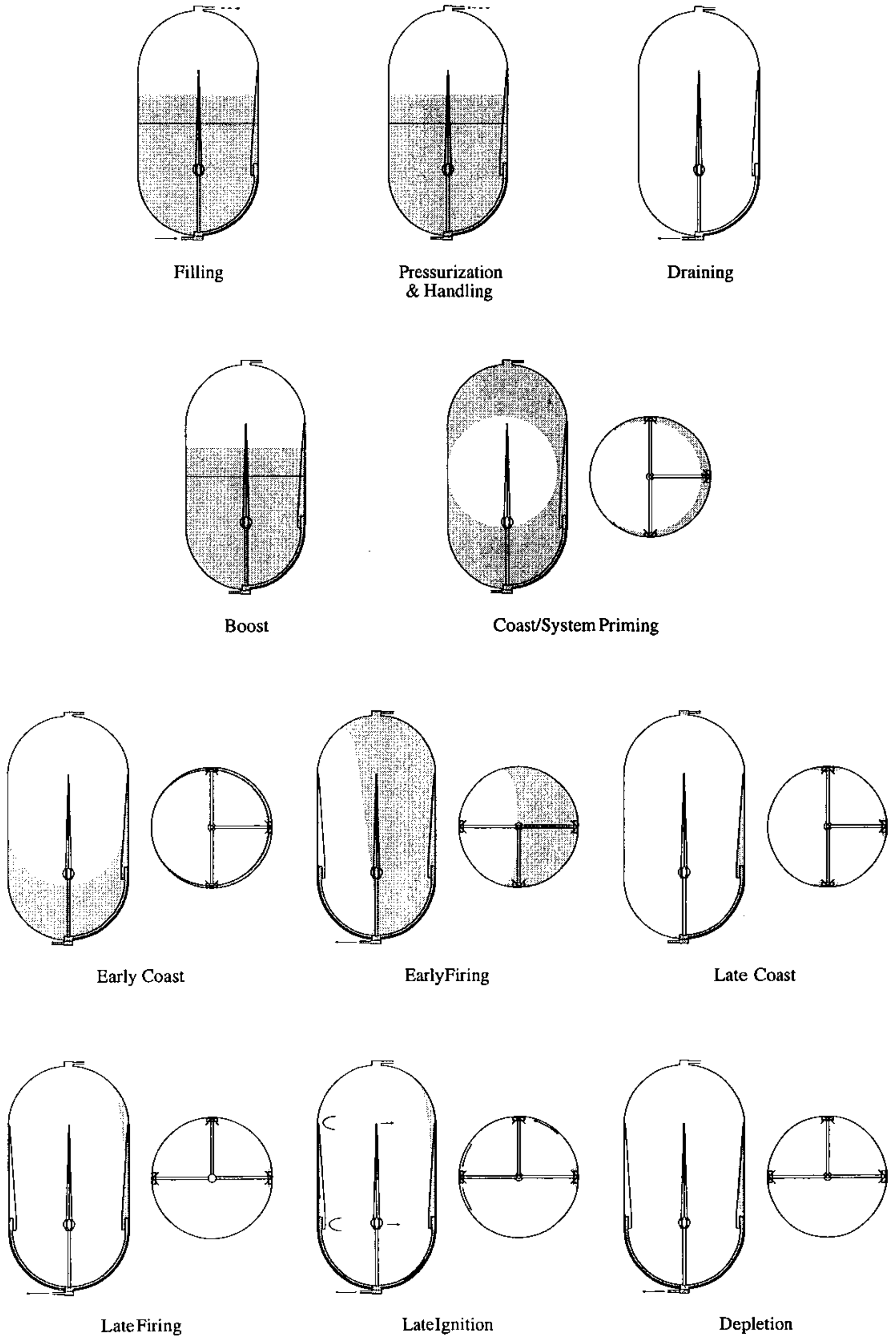


FIGURE 6: THE PMD OPERATIONAL SEQUENCE

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 is at atmospheric pressure when propellant is introduced into the tank through the propellant outlet line. During the filling process, a small quantity of gas may be trapped in the PMD. In the unlikely event that it does not go into solution, the perforated sheet will keep the gas from entering the outlet.

Typical handling occurs with the tank in the outlet down position. Gas will not enter the PMD during handling. Upright handling is 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.

Ascent Operations

Ascent operations include only boost and coast during which system priming occurs.

The PMD is designed to be launched in the outlet down position. Similar to upright ground handling, launch is illustrated in the operational sequence with the propellant position identical to ground handling.

After separation, the tank enters zero g coast. During zero g coast, propellant occupies its minimal energy state. At high fill fractions, the gas in the bulk space will be spherical. Zero g coast is illustrated in the operational sequence.

During zero g coast, the system is primed. High flow rate propellant demand occurs during system priming. The orifice designed into the outlet tube will limit the flow rate to structurally tolerable levels. Inside the tank the surface tension forces will maintain propellant over the porous elements. With all of the porous elements submerged in propellant, gas ingestion is not possible. System priming will dynamically load the manifold housing. The manifold has been designed to accommodate the system priming transient structural loads.

Orbital Operations

Once separated from the booster, the PMD becomes operational and has been designed to provide gas-free propellant delivery during all maneuvers. The PMD's primary purpose is to deliver gas-free propellant during long lateral accelerations in one of three directions. A small nonsettling component is possible. In addition, it is assumed that propellant may also be used in zero g coast for momentum dumping or attitude control.

The operational sequence shows the propellant configuration during an early in mission coast, an early in mission firing, a late in mission coast, a late in mission firing, a late in mission ignition, and depletion.

During coast, the gas will occupy a position minimizing the gas-liquid interfacial energy. This occurs when the sum of the reciprocals of the principal radii of curvature is identically equal everywhere on the surface. Without boundaries, this results in a spherical gas bubble. Only at BOL, when the tank is very full, will this occur. Once propellant is consumed, a spherical gas bubble cannot reside within the tank; it is distorted by the pick-up assembly, the "V" vanes and tank walls. Early in mission, the gas ullage bubble will be spherical and forced toward the top of the tank. Toward the end of mission, the propellant will adhere to the PMD and tank walls and will be distributed around the tank during coast. At intermediate fill fractions, the propellant will tend to reside in the bottom of the tank as the PMD reduces the effective tank diameter, moving propellant into the bottom of the tank. In all cases, the pick-up assemblies are completely submerged and ready to supply gas-free propellant upon thruster ignition.

During an early in mission lateral acceleration, the fluid will reorient into a pool on the tank wall opposite the direction of the acceleration. The pick-up assembly on that wall will be submerged in the propellant pool. The other arms may be exposed to gas but will prevent gas from entering the PMD by the screens. The gas will not enter as long as the pressure differential across the screen is less than the bubble point. The PMD is designed so that this is true with a minimum safety factor of three on sample bubble points. An early in mission lateral acceleration is illustrated in the operational sequence.

During a late in mission lateral acceleration, the fluid will likewise reorient into a pool on the tank wall opposite the direction of the acceleration. However, the pick-up assembly may not be submerged due to the nonsettling component of the acceleration. At the very least the tip of the "V" vane will reside in the pool. As depicted in the operational sequence, the propellant will cling to the vane. This is caused by the surface tension forces present, and provides a flow path for propellant to flow from the pool to the pick-up assembly, thereby allowing access to the propellant in the pool during slightly non settling lateral thrust.

Also illustrated in the operational sequence is a late in mission lateral ignition. All ignitions occur with the propellant beginning in its zero g configuration with all pick-up assembly screens submerged (a 15 minute minimum coast prescribed by the PMD will precede each ignition). The propellant, which has adhered to the vanes, pick-up tubes, and pick-up assemblies opposite the acceleration, will flow around the fillet system to the pool forming over one "V" vane. In no case are all three pick-up screens exposed to gas. Thus gas-free ignition is assured.

Finally, depletion is illustrated in the operational sequence. As propellant is consumed, the radii of curvature along the vane will decrease until the flow area on the "V" vane near the pick-up assembly can no longer supply the demand. At this point, the propellant near the pick-up assembly will be consumed. Eventually, as the screen flow area decreases, gas will be pulled through the screen and the PMD. The gas will bubble into the PMD and these bubbles will be entrained and drawn into the manifold where they will coalesce.

Eventually, the perforated sheet will be exposed to sufficient gas to lower its flow area to the point where flow losses exceed its bubble point and gas will be drawn through the perforated sheet and into the outlet. The ingestion of gas into the outlet line indicates depletion. The PMD has been designed to provide gas-free propellant to the tank outlet during the required conditions until the fill fraction of the tank falls below 1.1% in the worst case.

IV. PMD Design and Analysis

Design

The mission requires that the PMD provide gas-free propellant during long duration non-settling burns

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 unlimited maneuver duration, a control PMD is not feasible; a communication PMD is required.

The most conventional and most complex communication PMD utilizes screen covered galleries or channels, to provide a flow path from anywhere in the tank to the outlet. Fortunately, two requirements allow us to use a simpler and more reliable pick-up assembly device: a coast precedes each burn and the burns are limited to only three directions.

The coast period ensures that all of the pick-up assemblies screens are submerged prior to ignition – thus ensuring gas-free deliver during the ignition transient where propellant is reorienting within the tank.

With only three directions, only three pick-up assemblies are required. The principal complication is that the acceleration can be up to 7.1° off lateral; and in the nonsettling direction.

The "V" vanes solved this problem by delivering propellant settled in the pressurant hemisphere to the pick-up assembly at the base of the cylinder. NTO's low surface tension precluded the use of a simple vane and required the more complex "V" vane.

By using a novel combination of PMD components together, a simple lightweight PMD resulted.

Analysis

The principle method of PMD performance verification is analysis coupled with component and tank assembly bubble point and flow loss testing. Tank assembly bubble point testing was not feasible for this PMD design.

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 Ascent Operations is examined. And finally, the operation of the PMD during all Orbital Operations is analyzed.

The specific analyses are listed in Table 3. Due to the summary nature of this paper, no results are presented. The detailed process of vane and gallery design and analysis can be found in the series of papers titled *Propellant Management Device Conceptual Design and Analysis: Vanes, Sponges, Traps and Troughs, or Galleries* 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 3
PMD PERFORMANCE ANALYSES

I. General Design Analyses
    A. Pick-up Screen Configuration
    B. Pick-up Tube & Manifold Screen Area
    C. Perforated Sheet Configuration
    D. "V" Vane Configuration
    E. System Priming Orifice Size
    F. Thrust Vector Misalignment
    G. Flow ΔP
    H. Thermal Effects
II. Ground Operations
    A. Filling
    B. Draining
    C. Handling
III. Ascent Operations
    A. Boost
    B. System Priming
IV. Orbital Operations
    A. Propellant Location
    B. Steady Lateral Firing
    C. Transient Phenomena
    D. Depletion

QUALIFICATION TESTS

One test specimen will be subjected to a series of qualification tests. The qualification unit is a flight-type tank fabricated with the same processes, procedures, planning, & specifications used for the delivered flight articles. This test tank will be subjected to the tests listed in Figure 7. This tank had successfully completed all acceptance tests.

FIGURE 7: QUALIFICATION TESTS FOR THE BIPROPELLANT TANK

Flow Rate & Pressure Drop Test
Cyclic Pressurization Tests
Static Acceleration Test
Natural Frequency Test
Stiffness Test
External Leakage Test
Final Examination of Product
Burst Pressure Test

For the flow rate & pressure drop test, the test specimen was filled with 100 lbs. of distilled, deionized water & pressurized to 350 psig with nitrogen. A flow rate of 0.170 gpm (0.0238 lb./sec.) was established at the propellant outlet, & pressure drop readings were taken at the as loaded condition, 75 lbs. residual, 50 lbs. residual, & 25 lbs. residual. At no time did the pressure drop exceed the specification maximum of 10 psid. The pressure was reduced to 20 psig & the tank was drained.

The tank was then filled to capacity with distilled, deionized water. The cyclic pressurization test included two cycles from ambient to 437.5 psig (1.25 MOP) to ambient & 16 cycles from ambient to 350 psig (MOP) to ambient repeated four times. This sequence resulted in a total of eight 1.25 MOP cycles & 64 MOP cycles. The pressure was held for 10 seconds during each cycle & then vented rapidly to ambient. During the first MOP pressurization cycle the linear growth of the tank was measured for engineering information. It was well within the predicted value. There was no leakage or visible damage to the tank as a result of this test.

For the static acceleration test, the test specimen is installed in a fixture simulating the spacecraft interface & then mounted in a centrifuge. Loadcells are installed at the pressurant & propellant bosses to measure shear & axial loads. The tank is filled to capacity with distilled, deionized water, pressurized to 50 psig, & a compressive preload of 336 lbs. applied to the tank. The pressure is increased to 425 psig & the centrifuge speed is increased to impart an acceleration of 9 g's to the test specimen. The test is performed for 30 seconds. The imparted axial & shear forces will be verified to be within specification requirements. The tank is depressurized, the preload reduced to zero, & drained. The tank is inspected for leakage or damage.

The fixture used for the static acceleration test will be stiffened. The test unit is reinstalled to simulate the spacecraft installation. The first five natural frequencies of the tank are measured & recorded with the fill levels at 646 lbs. of distilled, deionized water (67%) & 926 lbs. of distilled, deionized water (96%) & pressurized to 355 psig. The vibration input is provided by a "stinger" rod attached to a shaker with a constant amplitude force input of 100 lbs. maximum & sine sweep of 5-200 Hz. Twenty-one accelerometers are used to measure the frequencies & five force input locations help to characterize the values & mode shapes. All values will be verified to exceed the specification requirement of 40 Hz. Figure 8 lists the calculated natural frequencies for specific conditions.

FIGURE 8: TANK NATURAL FREQUENCIES, 67% & 96% FILL FRACTIONS (HZ)

Axis	Calculated
Z	43
X or Y	72

The tank is visually inspected during and after the natural frequency test and to verify no damage or deformation occurred.

For the stiffness test, the test specimen is installed in a tensile testing machine with the propellant port down. The tank is filled with 646 lbs. of distilled, deionized water & pressurized to 355 psig. A tensile load is applied to the tank through boss end adapters from 0 to 1,000 lbs. in 100 lb. increments & then to 3,000 lbs. in 500 lb. increments. Axial deflections are measured through the use of three linear displacement transducers. The tank is depressurized, drained, & dried. No damage or deformation will be verified.

An external leakage test is then performed at 350 psig with helium gas for 30 minutes minimum in a vacuum chamber evacuated to 5 X 10^{-4} TORR. The leakage is verified not to exceed 1 X 10^{-6} std. cc/ sec. After these tests a final inspection of product is performed. No damage or permanent deformation is again verified.

As a final test the tank is filled to capacity with distilled, deionized water & pressurized to a burst pressure of 525 psig. This pressure is held for 10 seconds & no leakage or damage is verified. The pressure is then increased until rupture occurs. It is expected to be well in excess of the specification requirement.

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

ACCEPTANCE TESTS

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

FIGURE 9: ACCEPTANCE TESTS FOR THE BIPROPELLANT TANK

Preliminary Inspection of Product
Pre-Proof Volumetric Capacity
Ambient Proof Pressure Test
Visual Inspection
Post-Proof Volumetric Capacity
External Leakage Test
Bubble Point Test
Radiographic Inspection
Dye Penetrant Inspection
Mass Measurement
Final Dimensional 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, damage, and material certifications. The tank is subjected to an ambient hydrostatic proof pressure of 468 psig for a maximum of 45 seconds. 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%. The tank is then drained and dried. An external leakage test is run at 350 psig with helium gas for 30 minutes minimum in a vacuum chamber evacuated to 5 X 10^{-4} TORR or less. Leakage must not exceed 1 x 10^{-6} scc/sec of helium gas.

To verify the integrity of the PMD perforated sheet gas arrestor 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.

Fracture critical radiographic inspection of the girth welds and internal PMD views, fracture critical dye penetrant inspection of the entire external surface, overall dimensional inspection, and visual inspection are performed to verify the tank has no damage as a result of the preceding tests. After the tubes are trimmed the dry tank assembly is weighed on a precision scale.

Finally, the units are cleaned to Figure 10 levels, purged to a -65°F dew point, the ports capped, and the tank packaged in two sealed plastic bags for shipment.

Figure 11 depicts an outline of the bipropellant tank showing the port orientations.

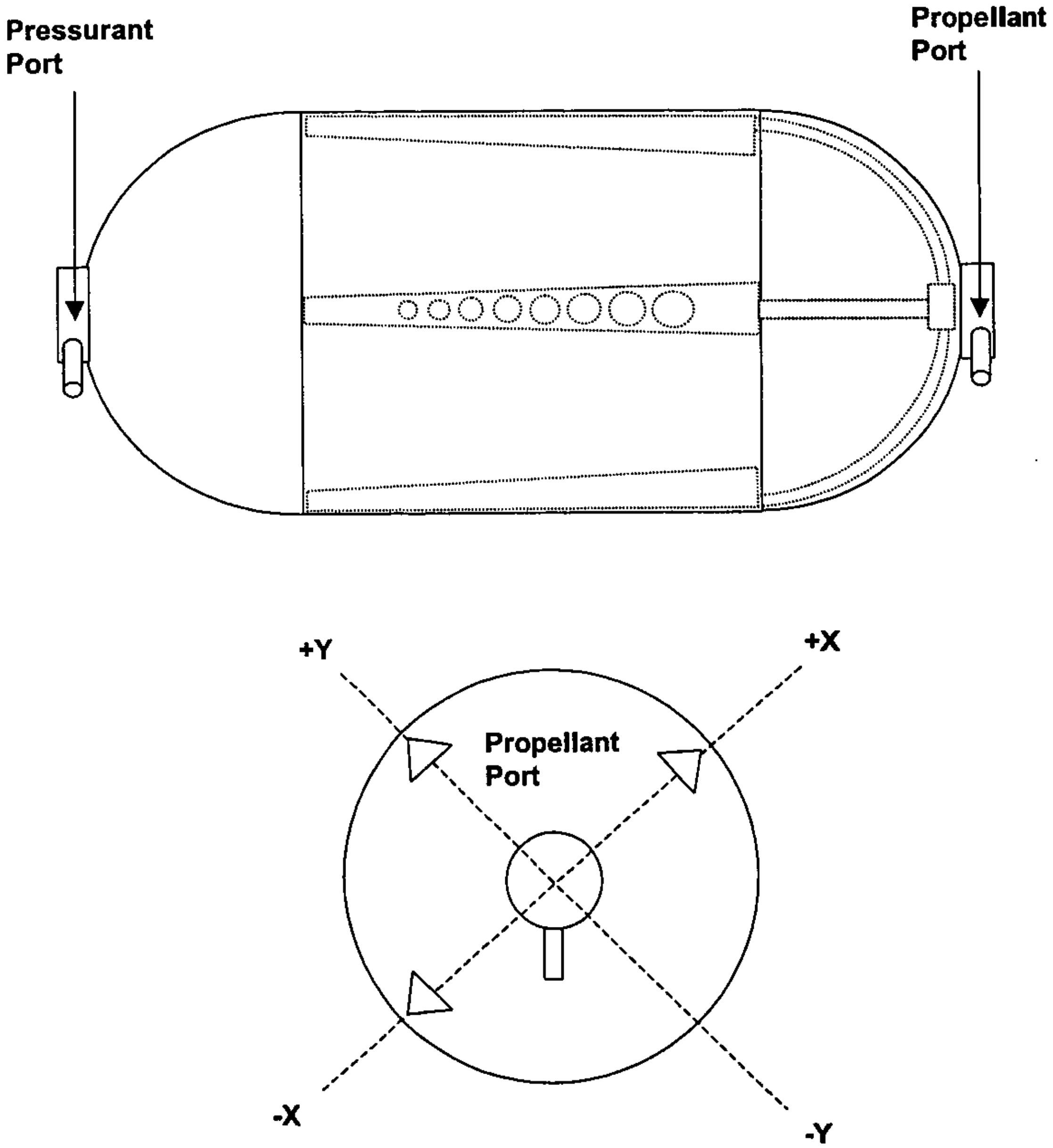


FIGURE 11: VIEWS OF THE BIPROPELLANT TANK SHOWING THE PORT LOCATIONS

FIGURE 12: PMD INSTALLED IN THE OUTLET HEMI

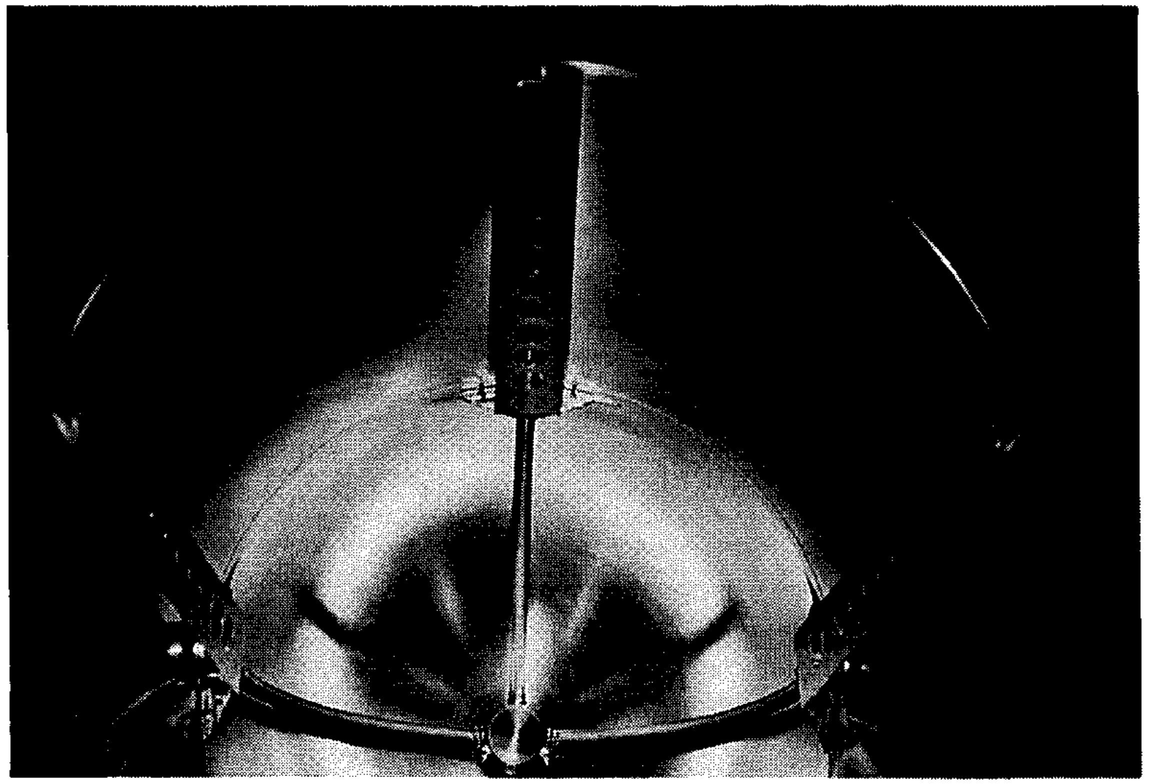


FIGURE 13: BIPROPELLANT TANK ASSEMBLY

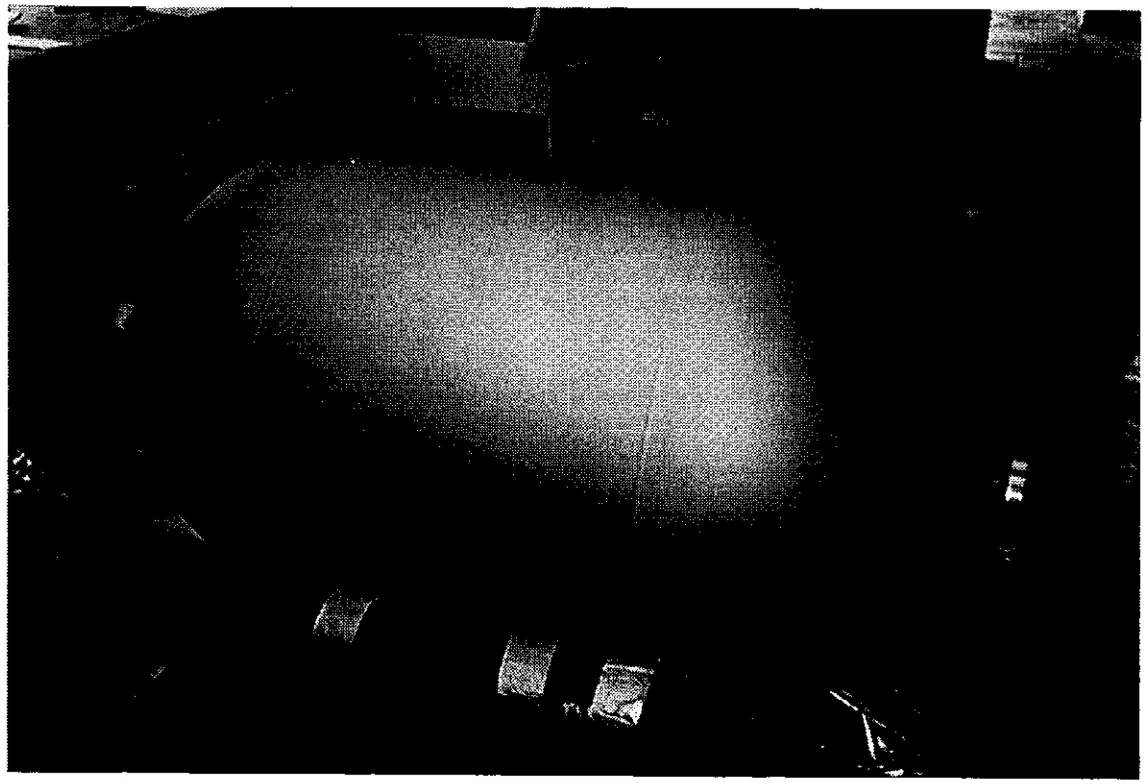


FIGURE 14: BIPROPELLANT TANK IN THE ACCELERATION TEST FIXTURE AT WYLE-NORCO

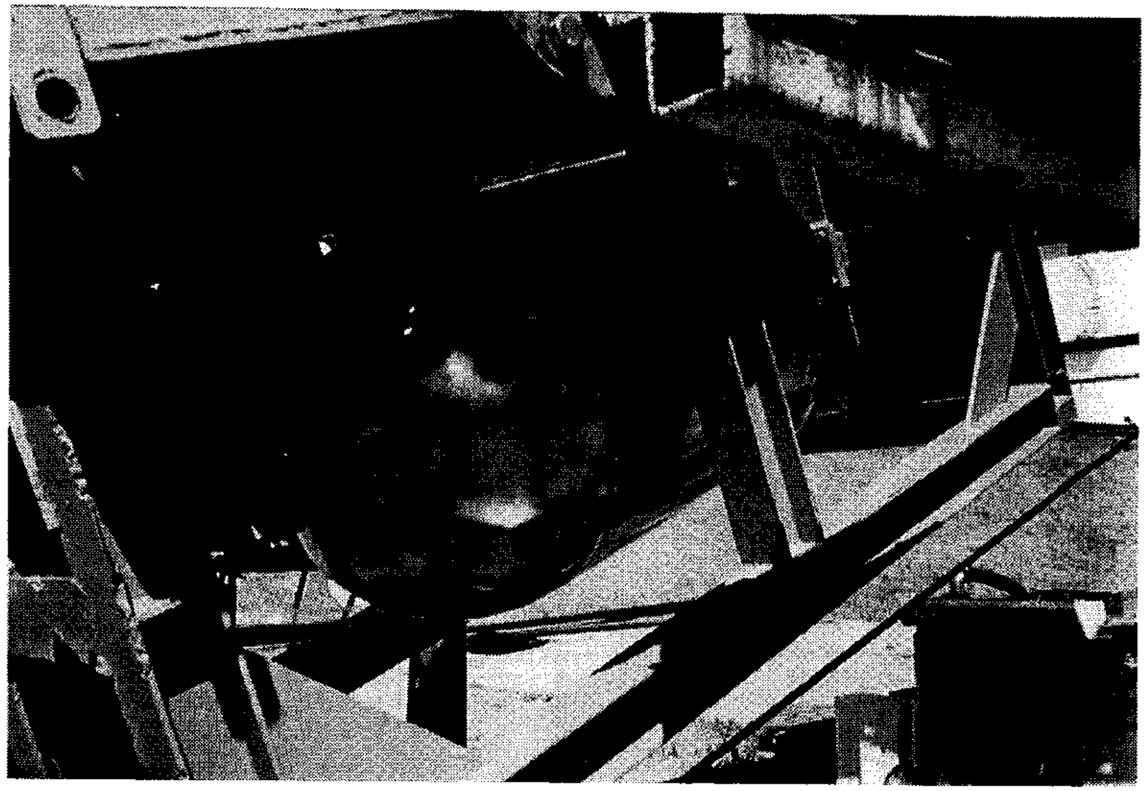
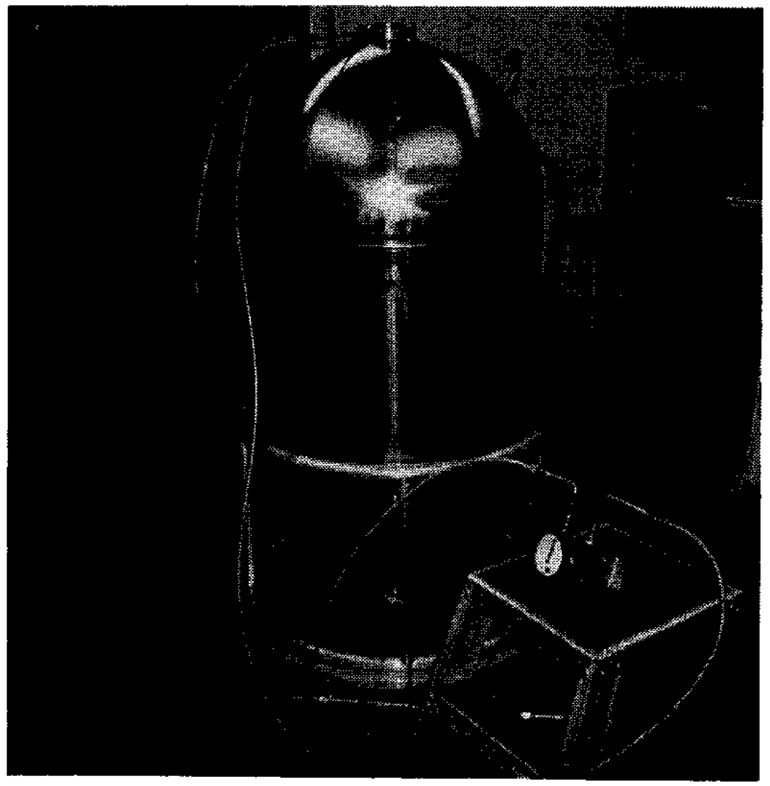


FIGURE 15: BIPROPELLANT TANK IN THE PROOF PRESSURE TEST FIXTURE AT PSI



Figures 12 through 15 show photographs of the PMD, the bipropellant tank, the qualification unit in the acceleration test fixture, and a tank installed in the proof pressure fixture, respectively.

FIGURE 10: TANK CLEANLINESS LEVEL

Particle Size (Microns)	Maximum Amount of Particles*
> 100 Microns	None
51-100 Microns	5
26-50 Microns	50
11-25 Microns	200
6-10 Microns	1200
< 6 Microns	No Silting

NOTES:

1. Non-volatile residue (NVR) = 5 ppm
2. * = Quantity/100 ml of fluid

CONCLUSIONS

This bipropellant tank has met all design objectives that can be verified by analyses and the qualification test specimen has successfully passed all tests to date.

Four bipropellant tanks have been delivered on time. Additional tanks are in work at Pressure Systems, Inc. (PSI). The qualification unit is in test at PSI.

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