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Propellant Tank
For an Advanced
Communications Satellite

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PROPELLANT TANK FOR AN ADVANCED COMMUNICATIONS SATELLITE

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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 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 operating satellites in orbit with over 800 years of total operational time.

A lightweight tank shell coupled with re-oriented pressurant and propellant ports and 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 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.

Each spacecraft contains two tanks - one for nitrogen tetroxide ($N_2O_4$) oxidizer and the other for monomethylhydrazine (MMH) fuel. The tanks are mounted in tandem in the spacecraft at 32 tabs with nutplates located near one of the tank girth welds.

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. Two flight units and four thermal and structural models have been delivered on time. The first launch of this propellant tank design is tentatively scheduled for the 2002-2003 timeframe.

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 S-Band transponders and will demonstrate mobile phone communications. The program provided for one qualification unit, two flight units, and four test models. Presently, two additional tanks are in production at PSI.

Each of the satellites includes two propellant tanks -- one for the nitrogen tetroxide ($N_2O_4$) oxidizer and one for the monomethylhydrazine (MMH) fuel. They are mechanically mounted in tandem inside the satellite’s central cylinder with 32 equally spaced tabs and 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 the Atlas-Centaur, Ariane, Long March, Proton, and H-2A boosters.

DESIGN, DEVELOPMENT, AND ASSEMBLY

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

FIGURE 1: SPACECRAFT PROPELLANT TANK SUMMARY OF CAPABILITIES

<table>
<thead>
<tr>
<th>Test (Size)</th>
<th>Axis</th>
<th>Frequency (Hz)</th>
<th>Acceleration (g, 0-Peak)</th>
<th>Limit Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>Lateral</td>
<td>5 - 13</td>
<td>0.20 in. S.A. *</td>
<td>4.0</td>
</tr>
<tr>
<td>(3,038 lbs. of water at 250 psi)</td>
<td>(X &amp; Y)</td>
<td>13 - 17</td>
<td>3.4</td>
<td>4.0</td>
</tr>
<tr>
<td>4 Octaves/Min</td>
<td>45 - 100</td>
<td>2.4</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Axial</td>
<td>5 - 20</td>
<td>0.20 in. S.A.</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>(Z)</td>
<td>20 - 24</td>
<td>8.2</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>24 - 50</td>
<td>2.1</td>
<td>7.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 - 100</td>
<td>1.04</td>
<td>7.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fluids

MMH, N2O4, IPA
Distilled Water, Ar, He, N2

Temperature Range

40-131°F

Pressures (Psi at 131°F)

MEOP *

250

Collapse

3.0

Proof

312.5

Burst

375

Minimum Expulsion Efficiency, %

99.5 target, 99.8 goal

Leakage

Zero liquid leakage

≤ 1 x 10^-6 scf/sec He at MEOP *

Pressure Leakage

Maximum Weight, lb.

99.2

Minimum Design Life, Years

15

Stiffness

Tank Propellant Fill Fraction (Worst Case) > 50 Hz Natural Frequency

Launch Vehicle Compatibility

Atlas-Centaur, Ariane, Long March, Proton, and H-2A

* Maximum expected operating pressure.
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 PDM 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.

The all-titanium propellant management device is a combination arrangement. This lightweight, round, and vane design with a feature allowing horizontal handling with a low fill fraction.

This surface tension PDM has been designed to provide gas-free propellant delivery throughout mission including, but not exclusively, stoppage 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 PDM design, which easily meets the mission requirements and, in addition, provides for some off-design capability.

The PDM is for use in a 49.1 inch diameter tank with hemispherical heads and a 14.2 inch long cylindrical section. The same design can be used in the NTO and the MMH propellant tanks. Additional features were incorporated into the design to provide optimal service. First, because the PDM is a passive device with no moving parts, the design is inherently reliable. Second, the design is constructed entirely of titanium. The PDM is lightweight and offers exceptional compatibility, long life, and reliability. Finally, the PDM is designed not only to provide propellant during steady flow conditions but also to ensure gas-free delivery throughout the mission. The PDM is designed to suppress vortexing, to suppress surface dip, to accommodate fluid transient motion (which could cause premature ingestion of gas), and to allow horizontal handling with a low propellant fill fraction. These additional design considerations have led to a reliable and efficient PDM design.

The trap is cylindrically shaped with internal fins and a closed, flat top. The trap allows gas-free propellant during off design operation, provides a flow path to the bulk space propellant during all phases of demand, and minimizes propellant residuals. In the bottom of the trap is a pick up assembly, which incorporates four perforated sheet windows. The trap's bottom platform is machined from a ring forging and incorporates four screened window assemblies.

These trap inlet window assemblies, consisting of 80 x 700 mesh CP titanium screen and a support plate, are EB welded to the bottom platform and are located at 90° intervals around the platform. This platform also supports the spong panels at the bottom. The sponge panel support plate is machined from a ring forging and provides the supports for the sponge panels and some panels near the middle of the trap. Finally, the trap is closed at the bottom by a trap base plate, which is also machined from a ring forging.

The trap inlet tube, which is a 0.8 inch ID titanium tube, connects the X-Y side of the trap inlet manifold to the +X-Y side of the top of the trap. This tube is composed of three sections: a vertical section up the side of the trap, a horizontal section across the top of the trap, and then into the top of the trap.

The trap inlet manifold and trap inlet tube are oriented and configured to allow for horizontal handling of the tank assembly. The vertical direction of the horizontal and loaded tank assembly must be maintained at 45° to the +X and -Y axes. The perforated sheet windows are positioned so that propellant access during launch and setting maneuvers is assured throughout mission. The trap has been sized to contain propellant for contingency maneuvers during which time the trap inlet windows will not have access to propellant. No such maneuvers are currently planned. In addition to the trap, a sponge comprised of titanium sheet separated by a tapered gap, has been incorporated into the design. The sponge has been designed to provide liquid to the trap during the repetitive nonsettling maneuvers. These include acquisitions, deployments, station keeping, synchronous orbit maneuvers, housekeeping, and droph. The sponge also will provide propellant during transient fluid orientation at apogee ignition.

The sponge and trap are connected by four titanium-screened windows located on the four thrust axes. These windows allow propellant into the trap while preventing gas penetration. Four large major vanes, which are laser cut from thin titanium sheets, are spaced 90° apart and follow the inside contour of the tank. They interface into the trap at the bottom of the tank. They re-supply the sponge during the coast between burns. The major vanes and window assemblies are oriented on the major spacecraft axes. Figures 5A and 5B present schematic views of the PDM.

The PDM is fabricated from 6AL-4V, 3AI-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 metal sheets are EB drilled while the sponge panels are chemically etched to provide the hole pattern.

After assembly, the PDM is mounted and welded into the outlet hemisphere while the vane-to-tank wall gaps are maintained. The expulsion assembly is bolide point tested and accepted before the tank assembly is closed. Previously, the cylindrical section was automatic TIG welded to the mounting hemisphere and the mounting tabs were finished machined. For the final tank assembly there is one automatic TIG girth weld that joins the expulsion assembly to the center section-to-hemisphere assembly.

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

PDM ANALYSIS AND DESIGN

1. PMD Introduction & Requirements
The PMD is a passive, all titanium, surface tension device designed to provide gas-free nitrogen tetroxide (NTO) and monomethylhydrazine (MMH) 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 multiple space 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 1.

II. PMD General Design Description

The PMD design incorporates a small trap, a large radial sponge, and four vanes as illustrated in Figures 5A and 5B.

The device consists of a cylindrical trap housing attached to the tank with bolts. The PMD attachment was designed to allow the PMD to be installed in an existing tank shell. One of the existing bolt holes is used as the propellant outlet. The trap housing incorporates a pick up assembly with four electron beam drilled perforated sheet windows and overlying fins, which feed propellant to the windows during lateral firings and spinning operations. The entrance to the trap consists of an annular manifold located outboard from the trap and below the sponge. Four screened windows are located in this manifold on the X and Y axes. Propellant flows from the bulk space, through the manifold windows into the trap inlet manifold, up and across the trap inlet tube, down into the trap housing, and then into the propellant outlet through the pick up assembly. The tortuous path provided by the trap inlet tubing minimizes gas entering the trap during horizontal handling operations with low propellant fill fractions. Also attached to the bottom side of the trap housing at 90 degree intervals are four vanes, which extend from the trap to the tank center section. This trap, sponge and vane PMD concept easily meets the mission requirements.

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

FIGURE 4: FACTORS OF SAFETY FOR STRUCTURAL ANALYSES

<table>
<thead>
<tr>
<th>STRENGTH REQUIREMENT</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Load 1.25 x Limit Load.</td>
<td>Tank is to withstand combined yield load &amp; MEOP under all specified environmental conditions.</td>
</tr>
<tr>
<td>Ultimate Load 1.5 x Limit Load.</td>
<td>Tank is to withstand combined ultimate load &amp; MEOP under all specified environmental conditions.</td>
</tr>
<tr>
<td>Safety Factor Proof Factor &gt; 1.25</td>
<td>Burst Factor &gt; 1.5</td>
</tr>
<tr>
<td>Safety Margin Safety Margin (yield load) = (Yield Stress - material)(Stress - yield load) - 1</td>
<td>Safety Margin (ultimate load) = (Fracture Stress - material or Buckling Stress - material)(Stress - ultimate load) - 1</td>
</tr>
</tbody>
</table>
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 70% and 96%.
- Tanks are upright or horizontal during handling. The tank pressure will be 135 psia minimum 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.
- System line priming occurs during coast and after separation.
  - The maximum priming demand is 119 in².
  - The maximum tank pressure is 230 psia.
  - Spacecraft rotation is 2 degrees/second maximum about the X axis.
- Initial Maneuvers (Thrust Check, Adjust Deployment, Acquisition, Gyro Calibration, and Attitude Change).
  - 4 kg total propellant use; 3 kg maximum propellant use in any one hour period.
    - 0.0015 g maximum acceleration.
    - 0.85 in²/second maximum flow rate.
    - Maximum spin of 0.5 degrees/second in X axis.
- AKE Check:
  - 1 kg total propellant use.
    - 0.009 g maximum settling acceleration.

AEF Maneuvers.

- 1 kg total propellant use.
- 0.0015 g maximum settling acceleration.
- 0.85 in²/second maximum flow rate.
- Settling burn prior to each burn.
- Four engine starts; continuous long duration burn.
- 0.019 g maximum settling acceleration.
- 5.1 in²/second maximum flow rate.
- Three axis stabilized (no spinning).
- Between AEF Maneuvers.
  - 4.55 kg total propellant use (over +19 hours); 3 kg maximum use in any one hour period.
  - 0.0029 g maximum acceleration.
  - 0.85 in²/second maximum flow rate.
  - Maximum spin of 0.25 degrees/second in X axis.
- After AEF Maneuver #4 and Before Synchronous Orbit.
  - 6.42 kg total propellant use (over 10 hours); 3 kg maximum use in any one hour period.
  - 0.005 g maximum acceleration.
  - 0.85 in²/second maximum flow rate.
  - Maximum spin of 0.75 degrees/second in X or Y axis.
Synchronous Orbit Maneuvers.
- 18.2 kg total propellant use; 3 kg maximum use in any one hour period.
- 0.0015 g maximum acceleration in +/- X directions.
- 0.43 in^2/second maximum flow rate.
- Minimum of 11 hours 50 minutes of coast separates burns.

Orbital Operations
- During orbital operations, all stationkeeping maneuvers are in one of four lateral directions: east, west, north, and south. Stationkeeping maneuvers will occur repeatedly.
- The tanks are in blow down mode with a minimum pressure of 200 psia.
- 3 kg maximum propellant use in any one hour period.
- Pulsed thruster operation occurs throughout mission.
- 0.43 in^2/second maximum flow rate.
- 0.0015 g maximum acceleration in any direction except -Z; principal lateral directions are +/- X & +/- Y.

Contingency
- 3 kg total propellant used in mission life (1 kg per maneuver).
- Can occur at any time.
- 0.85 m^3/second maximum flow rate.
- 0.0031 g maximum acceleration in any direction except -Z.
- X, Y, or Z axis spin of up to 0.25 degrees/second may occur; 360 degree rotations at 1 degree/second may occur.

Description
- 6 kg total propellant used.
- 0.0032 g maximum settling acceleration.
- 0.85 in^2/second maximum flow rate.
- 11 hours of coast between first perigee maneuver and second apogee maneuver.

The trap housing consists of a centrally located cylindrical region and an annular region below the sponge. The trap housing encloses a volume of propellant, which is available for contingency maneuvers.

The screened trap inlet windows are located along the thrust axes below the sponge and near the cylindrical region of the trap. All of the screens in the PMD lies in a single plane simplifying bubble point testing. The screen is constructed from commercially pure titanium and is supported by a doubler with circular bolts.

The sponge consists of thin sheet metal panels positioned in proximity to one another and forming a taper 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 trap inlet windows and provides a refillable reservoir of propellant available for stationkeeping maneuvers.

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 and are designed to refill the sponge during periods of zero g coast.

The trap pick up assembly consists of an annular channel positioned within the trap. Four electron beam drilled perforated sheet windows are positioned in the upper portion of the pick up channel. The windows are 90° apart and are located on the thrust axes. This position reduces residuals while allowing horizontal handling with no risk of gas ingestion.

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 6 square inches of screen and 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 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. Typical PMD safety factors are listed in Table 2.

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 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 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 trap inlet windows and fill the manifold 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

Boost operations can be divided into many stages: launch, system priming, coast, spogue pitch over, settling, and spogue engine firing. In addition, the spacecraft will encounter lateral firings for station acquisition and may encounter 0.75 degrees/second rotations about the X or Y axis.

The PMD is designed to be launched in the outlet down position. Launch is illustrated in the operational sequence and the propellant position is identical to upright ground handling.

TABLE 2

<table>
<thead>
<tr>
<th>TYPICAL CALCULATED PMD SAFETY FACTORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trap Usage: Allocation of Volume</td>
</tr>
<tr>
<td>Mission Stage</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>Contingency</td>
</tr>
<tr>
<td>Gas Trapped</td>
</tr>
<tr>
<td>During Fill</td>
</tr>
<tr>
<td>Ingested During</td>
</tr>
<tr>
<td>Handling</td>
</tr>
<tr>
<td>Total Trap Use</td>
</tr>
<tr>
<td>Total Trap Volume</td>
</tr>
<tr>
<td>Trap Residual Vol.</td>
</tr>
<tr>
<td>Available Volume</td>
</tr>
<tr>
<td>Safety Factor (SF)</td>
</tr>
</tbody>
</table>

- Perforated Sheet Loads

<table>
<thead>
<tr>
<th>Event</th>
<th>SF* (NTO)</th>
<th>SF (MMH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apogee - 4 windows</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>Apogee - 7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>2 windows</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>Nonsettling - 1 window</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Nonsettling - ½ window</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Sponge Volume (Worst Case) - 104°F NTO

<table>
<thead>
<tr>
<th>Acceleration (g)</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>.0031</td>
<td>2.19</td>
</tr>
</tbody>
</table>

*Safety Factor

**Figure 6: The PMD Operational Sequence**
After launch, the spacecraft is separated from its booster. Separation produces a negligible acceleration but the spacecraft will be spinning at up to 2 degrees/second about the X axis. The propellant will settle in the NTO tank and unseat in the MMH tank as illustrated in the operational sequence. However, the acceleration at the MMH trap and sponge is sufficiently low to ensure that they are filled with propellant.

The system is primed during this 2 degrees/second maximum X axis spin. 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. The fins inside the trap and the sponge outside of the trap maintain the gas away from the PMD's 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 priming, the spacecraft is three-axis stabilized in zero g coast. The gas in the tank bulk space and in the trap occupies a spherical bubble. The bubble in the tank bulk space is free floating and can reside anywhere in the tank. Zero g early coast and mid-coast are illustrated in the operational sequence. In the early coast illustration, the spherical bubble is shown at a 70%, 85%, and 96% fill fraction. In the mid-mission picture, the gas is no longer spherical, and the propellant resides primarily in the lower hemisphere as dictated by the PMD.

During boost operations, a series of maneuvers are repeated. A settling burn is not required and may, or may not, occur. During pitch overs, the propellant will begin to retract from its zero g position in the bottom of the tank to the tank side wall. The maneuver will be over before equilibrium is obtained, and the propellant will continue to move toward the top of the tank. The sponge will retain sufficient propellant to complete the settling burn prior to apogee engine firing or will provide gas-free propellant during apogee engine ignition if a settling burn does not occur.

Once the propellant is settled over the PMD, propellant access during apogee engine firing is very straightforward. Apogee uses the majority of the tasks' propellants. Apogee engine 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.

Acquisition can produce accelerations in any direction except X with the worst case for the PMD being lateral accelerations. During a long duration lateral firing, the propellant will settle on the tank side wall. The sponge will hold sufficient propellant to meet the demand during these maneuvers. Once the maneuver is finished and zero g coast is encountered, the vanes will refill the sponge preparing it for another maneuver. The sponge is sized to provide up to 3 kg of total propellant for each nonsettling maneuver.

The spacecraft can experience a 0.75 degrees/second maximum rotation about the X axis during some maneuvers. This spin settles the propellant in the NTO tank and unseats the propellant in the MMH tank. However, the acceleration is sufficiently low in the NTO tank trap and sponge to ensure that the sponge will be filled with propellant. Thus, the sponge easily provides the 3 kg of propellant required.

Throughout boost the propellant tanks operated in a pressure regulated mode. After the last apogee engine firing, the system will be sealed, and the tanks 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 four types of maneuvers: 1) short duration, low propellant consumption, repetitive maneuvers such as housekeeping operations. 2) intermediate duration, intermediate consumption, repetitive burns such as lateral thruster firings, 3) long X axis spin rate maneuvers, and 4) the deorbit burn in the settling direction.

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 discharge far from its zero g equilibrium condition. Housekeeping is a low consumption maneuver. 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. The sponge has been sized to hold more than 3 kg of total propellant at the maximum lateral acceleration encountered. 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 up to 3 kg total propellant per hour for all nonsettling maneuvers.

The last set of maneuvers is doocit. First an attitude change maneuver is completed using sponge propellant. Then, two settling burns occur during which propellant access is straightforward. Depletion is assumed to occur at the end of doocit.

As the remaining propellant in the bulk space and sponge is consumed, the area of trap inlet window covered with propellant decreases. This decrease in area causes an increase in the flow losses. Once the flow losses increase to the bubble point of the sponge, gas will be drawn into the manifold where it will be entrained in the flow into the trap. Due to the settling acceleration, the gas will buoy to the top of the trap. The consumption of the trap propellant will proceed similarly until gas penetrates the perforated sheet. Because there are no porous elements downstream of the perforated sheet, the gas will enter the outlet and the tank will be depleted. The propellant below the screen in the tank bulk space, in a portion of the manifold, and within the pickup assembly internal volume was considered residual. In addition, propellant can be found in the small corners in the main bulk space, within the sponge, and within the trap. The total liquid propellant volume will be less than 0.5% of the tank volume as required.

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 apogee engine firing portion of boost occurs next. The PMD has been designed to accommodate multiple apogee engine firings and will provide gas-free propellant as needed between apogee engine firings. After the apogee engine 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. Control devices are able to deliver a fixed quantity of propellant with 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 be used to 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 station keeping. 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 vane 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 too much 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 operation during Boost Operations is examined. Finally, the operation of the PMD during all On-Orbit 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 valve, sponge and trap design and analysis can be found in the series of papers titled Propellant Management Device Conception, Design and Analysis: Vanes, Sponges, Galleries, or Traps and Troughs by D.E. Jackle, Jr. 1,2,3,4

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

<table>
<thead>
<tr>
<th>I. General Design Analyses</th>
<th>A. Trap Sizing</th>
<th>B. Pickup Assy Sizing</th>
<th>C. Trap Inlet Window Sizing</th>
<th>D. Sponge Sizing</th>
<th>E. Flow DP</th>
<th>F. Thermal Effects</th>
<th>G. Manifold and Trap Inlet Tube Sizing</th>
</tr>
</thead>
<tbody>
<tr>
<td>II. Ground Operations</td>
<td>A. Launch</td>
<td>B. Draining</td>
<td>C. Handling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III. Boost Operations</td>
<td>A. Launch</td>
<td>B. Separation</td>
<td>C. System Priming</td>
<td>D. Apogee Engine Firing (AEP)</td>
<td>E. 3 Axis Attitude Control</td>
<td>F. Maneuvers Between AEPs</td>
<td></td>
</tr>
</tbody>
</table>
IV. Orbital Operations
A. Sponge Use
B. Sponge Refill
C. Trap Use
D. X-axis Spinning
E. Decoil & 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 7.

FIGURE 7: QUALIFICATION TESTS FOR THE PROPRIETARY TANK

Preliminary Inspection of Product
Mass Measurement
Pre-Proof Volumetric Capacity
Ambient Proof Pressure Test
Visual Inspection
Post-Proof Volumetric Capacity
Bubble Point Test
External Leakage Test
Pressure Cycling Test
Visual Inspection
Noise & 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 Penetration Test
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, damage, material certifications, and completed rework instructions.

The dry and random vibration tests are performed with the tank empty, the ports sealed, and pressurized to 100 psig with gaseous nitrogen. The wet random test is performed with the tank loaded with 3,038 pounds of distilled, deionized water and pressurized at 250 psig with gaseous nitrogen. The wet sine test is performed with the tank loaded with 4,363 pounds of PF-5060, an environmental friendly fluid that simulates the oxidizer, and pressurized to 250 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 notchings are automatically programmed into the vibration control system while random notchings are accomplished through hand calculations. For all test runs, low-level runs are performed to verify the test set-up, the instrumentation, and the notchings.

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 ensure that the specification requirements are met. Natural frequency results are presented in Figures 8. They are consistent and meet the specification values of >50 Hz for all axes.

FIGURE 8: TANK NATURAL FREQUENCIES, HZ

<table>
<thead>
<tr>
<th>Axis</th>
<th>Calculated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>40.96</td>
<td>63</td>
</tr>
<tr>
<td>Y/Z</td>
<td>48.5</td>
<td>55</td>
</tr>
</tbody>
</table>

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 charged 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 87,816.9 in³ was measured versus a minimum requirement of 87,575 in³. This 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 250 psig. The water was initially discharged into an evacuated surge tank. This simulates the surge start operation and flow out of the propellant tank during system priming. The tank is drained in the vertical attitude using a 250 psig ullage pressure and a flow rate of 1.35 gpm. Pressure drop and residual water volume are measured. The empirical pressure drop of 4.4 psid compared favorably to the required 7-psid. The tank demonstrated residuals of 53.7 in³, which is well within the mission requirement of 175 in³. The resultant expulsion efficiency of 99.94% exceeded the minimum required of 99.8% 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 and screens. Bubble points are verified for 60 seconds minimum to verify PMD porous element integrity than the capillary breakdown values are measured. The screen bubble point was successfully tested to a level of 5.6 in. of head and the breakdown head was measured to be 7.6 in. 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. 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 252 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 x 10^-6 scie/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 375 psig from ambient temperature to the specification maximum allowable operating temperature of 131 degrees. The tank was hydraulically pressurized to 394.5 psig and held for five seconds. There was no leakage or damage to the tank. The tank was then pressurized to 483 psig where it ruptured. The crack developed in the parent metal of the mounting 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

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 dry tank assembly is weighed on a precision scale.

The tank is subjected to an ambient hydrostatic proof pressure of 312.5 psig for a maximum of 66 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%. A visual inspection verifies that the tank has not been damaged or deformed.

An external leakage test is run at 250 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 x 10^-7 scie/sec of helium gas.

To verify the integrity of the PMD screened 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 screen and perforated sheet are tested.

Wet size 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 response and control accelerometers are placed on the test fixture to insure compliance with the specification requirements. The size 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 1.35 gpm (worst case mission flow rate) with a 240-250 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 CN2, 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 top view illustrates the propellant port while the bottom view shows the pressurant and propellant outlet ports.

**FIGURE 10: VIEWS OF THE PROPELLANT TANK SHOWING THE PORT LOCATIONS**
Figures 11 through 14 show photographs of the PMD, the propellant tank, a unit in the lateral vibration fixture, and a tank installed in the proof pressure fixture, respectively.

**FIGURE 15: TANK CLEANLINESS LEVEL**

<table>
<thead>
<tr>
<th>Particle Size (Microns)</th>
<th>Maximum Amount of Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 100 Microns</td>
<td>None</td>
</tr>
<tr>
<td>51-100 Microns</td>
<td>5</td>
</tr>
<tr>
<td>26-50 Microns</td>
<td>25</td>
</tr>
<tr>
<td>11-25 Microns</td>
<td>100</td>
</tr>
<tr>
<td>5-10 Microns</td>
<td>600</td>
</tr>
<tr>
<td>&lt; 10 Microns</td>
<td>No Sifting</td>
</tr>
</tbody>
</table>

**NOTES:**
1. No metallics >50 microns
2. Non-volatile residue (NVR) less than 1mg/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.

Two flight-type propellant tanks have been delivered on time. Two thermal model tanks and two structural model tanks, all without PMDs, were also delivered as part of the purchase order. The thermal models include an external surface finish identical to the flight tanks.

The advanced communications satellite with this propellant tank is scheduled for launch in the 2002-2003 time frame.

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**REFERENCES**


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Michael J. Debrencsi is a Senior Program Manager at Pressure Systems, Inc. (PSI), Jerry Kao is a Senior Engineer at PSI, and Bill Lay, who is retired now, was the Engineering Manager at PSI.

Donald E. Jackle, Jr. is the owner of PMD Technology and PSI's PMD Analyst & Consultant.

Tokiaki Seki is the manager of the Space Engineering Department at MELCO.