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DESIGN AND DEVELOPMENT OF THE AXAF-IPS PMD & PMD INTEGRATION

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ABSTRACT

A new propellant tank approach was conceived by TRW Space and Electronics Group for use in a dual-mode bipropellant propulsion system. The resultant final assembly consists of an easily manufactured surface-tension propellant management device (PMD) within a composite overwrapped aluminum liner.

This new technology was the result of the combined efforts of TRW and a number of subcontractors. The PMD assembly was successfully qualified for NASA's Advanced X-Ray Astrophysics Facility (AXAF) Program and used in the largest aluminum-lined, completely overwrapped bipropellant tanks qualified to date.

The tank assembly stores and provides pressurized gas-free propellants to the main satellite bipropellant liquid apogee engines and the reaction control system monopropellant thrusters in a Zero G environment. This integral propulsion system (IPS) is used only for orbit insertion. An auxiliary monopropellant system is used on orbit for momentum wheel unloading.

The attendant PMD is lightweight, straightforward, and offers excellent propellant compatibility, long life, and reliability. The PMD design incorporates a centerpost, baffle, vane, and trap. It is fabricated from titanium, aluminum, and stainless steel.

The NASA Advanced X-Ray Astrophysics Facility (AXAF) integral propulsion system contains two identical propellant tanks - one for nitrogen tetroxide (N_2O_4) oxidizer and one for

hydrazine (N_2H_4) fuel. The tanks are polar mounted in the core of the observatory satellite with the propellant outlet down.

Successful acceptance and qualification tests on one flight-type unit empirically validated the analysis and design of the tank assembly. Three other flight units, which have been acceptance tested, have been delivered - two are installed on the spacecraft while the third is waiting for qualification testing. The launch of the AXAF satellite is scheduled for August 1998 aboard the Space Shuttle using an IUS upper stage, a two-stage solid propellant vehicle.

From its highly elliptical earth orbit (6,200 miles by 87,000 miles) this satellite will afford astronomers a new, unprecedented view of the universe. It will allow an unobstructed study of X-Ray radiation from deep space. Study details will include black holes, quasars, neutron stars, globular clusters, galaxies, supernovas, stellar coronas, and dark matter.

The hard mount at the propellant outlet side of the tank incorporates a monoball to provide moment relief. The flexible mounting struts on the pressurant side of the tank also provide moment relief and allow tank axial movement due to pressure and temperature changes while providing lateral stiffness.

A stress analysis was used to analyze the PMD details, subassemblies, and assemblies including its installation into the tank. The imposed environmental conditions, operational

requirements, and spacecraft interface loads dictated the structural and stress analyses parameters and boundary conditions.

PMD Technology provided the analysis and design concepts for the PMD; and Pressure Systems, Inc. (PSI) designed and provided the PMD hardware, assembled the PMD into the tank shell, welded on the end caps, and tested the integrated tank assembly. All work was accomplished on subcontract to TRW Space & Electronics Group. NASA Marshall Space Flight Center, Huntsville, AL is the cognizant government agency.

INTRODUCTION

TRW Space & Electronics Group (TRW) subcontracted with Pressure Systems, Inc. (PSI) to analyze, design, fabricate, assemble, test and deliver PMD kits, which included a PMD centerpost assembly, trap assembly, transition tubes, end caps, and tank assembly hardware. TRW separately subcontracted the analysis, design, fabrication, testing, and delivery of overwrapped shell and integrated tank assemblies. PSI was on subcontract to assemble the PMD kits into the shell assemblies and to test the PMD(s) and the tank assemblies. PSI's tasks included the mechanical installation of the trap and centerpost assemblies into the shell, the electron beam welding of the transition tubes and end caps to the tank shell, and the radiographic and dye penetrant inspection of the weld joints. The completed assembly was acceptance tested, cleaned, and delivered.

The AXAF program provided for two flight units and two qualification units. One additional design verification unit (DVT) was assembled as a forerunner to the production units to refine and substantiate cleaning and assembly techniques, weld schedules, and X-Ray inspection parameters.

The spacecraft includes two Integral Propulsion System propellant tanks - one for nitrogen tetroxide (N_2O_4) and one for hydrazine (N_2H_4). The pressurized propellants are used in a

bipropellant mode by TRW's 105 pound thrust advanced liquid apogee engines (LAE) and in a monopropellant mode by the 20 pound thrust reaction control thrusters. This system is used for satellite orbit insertion as well as vehicle attitude control during orbit transfer. These tanks incorporate a passive surface-tension type propellant management device to supply gas-free propellant to the system thrusters throughout the required mission life. Figure 1 illustrates the AXAF propulsion subsystem.

The PMD is fabricated from aluminum, titanium, and stainless steel. The PMD was specifically analyzed and designed to meet the defined mission profile and requirements. With no moving parts, a minimum of surface tension elements, and a majority of aluminum and titanium components, this newly analyzed and designed PMD minimizes weight and complexity.

The tanks are mechanically mounted in the core of the spacecraft with the propellant outlet down as shown in Figure 1. Friction-welded transition tubes provide the interface between the aluminum tank and the all-welded stainless steel fluid system with the exception of the LAE(s) which use B-nuts.

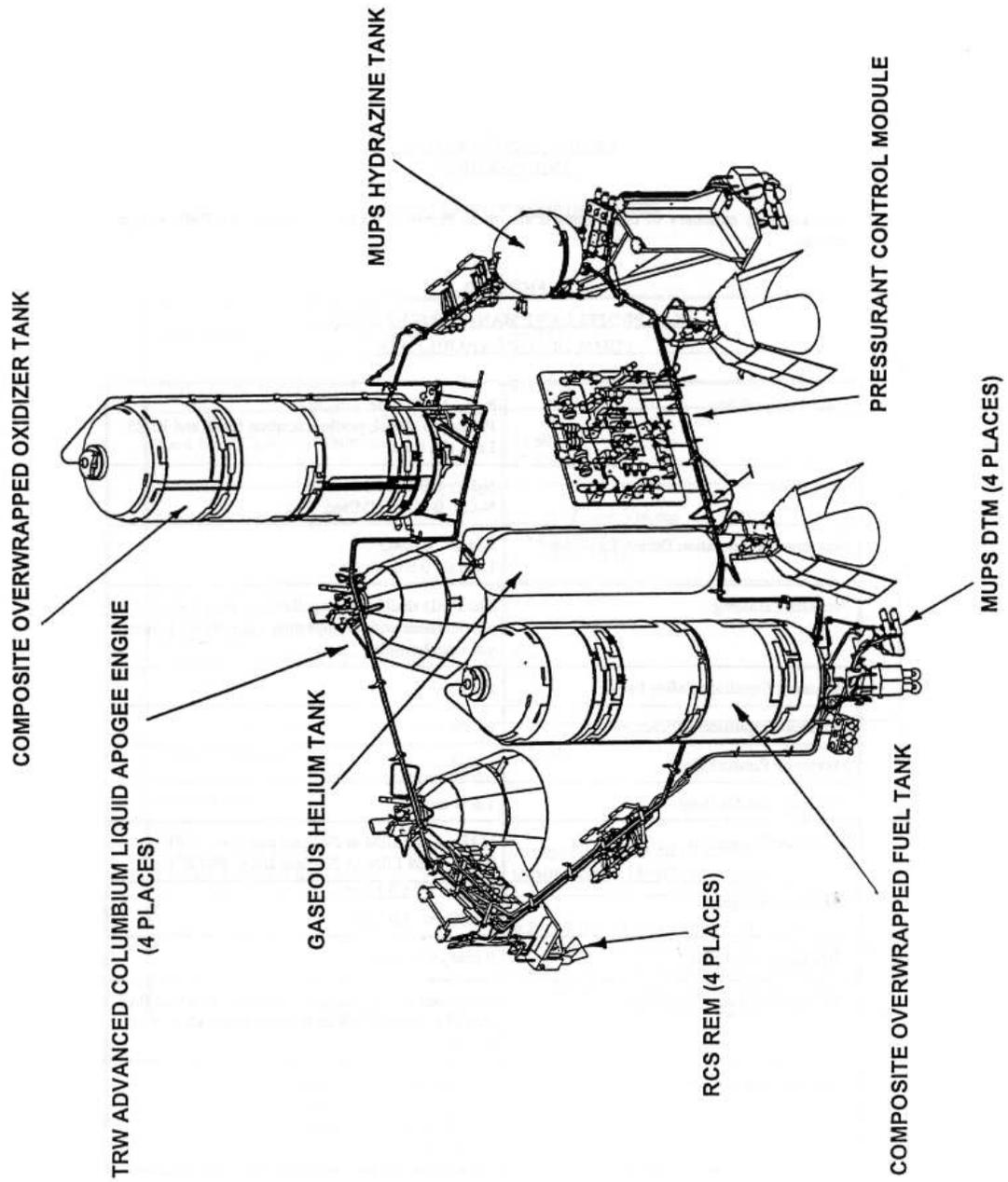


Figure 1: AXAF-IPS Propulsion Subsystem

**DESIGN, DEVELOPMENT,
AND ASSEMBLY**

The PMD assembly summary of capabilities is shown in Figure 2. Figure 3 contains the PMD design requirements.

**FIGURE 2
AXAF PROPELLANT MANAGEMENT DEVICE
SUMMARY OF CAPABILITIES**

Fluid Compatibility	N ₂ H ₄ , N ₂ O ₄ , GHe, GN ₂ , IPA, Propylene glycol, perfluorocarbon fluid, and Kr 85 Leak test fluid
Flow Rates	N ₂ H ₄ : 0-0.59 LBM/sec N ₂ O ₄ : 0-0.33 LBM/sec
Maximum Acceleration During Expulsion	Axial: 0.024G Lateral: 0.0027G
Propellant Holding	The PMD shall hold propellant against all adverse accelerations without ingesting more than 0.1 ml of gas into the outlet.
Minimum Expulsion Safety Factor	2.0
Minimum Expulsion Efficiency	99.5%
Maximum Pressure Drop	5 psid
Minimum Bubble Point	1.6 G-inch
Propellant Throughput	N ₂ H ₄ : 1125 LBM at 290 psia and + 40-120°F N ₂ O ₄ : 1008 LBM at 290 psia and + 40-120°F
Maximum Weights	PMD: 5.0 LBM End Caps: 3.0 LBM
Minimum Useful Life	9 years & 5 months
Priming Flow Rates & Pressures	Withstand priming pressure of 68 psi for a fuel flow rate of 4.40 lbs/sec or an oxidizer flow rate of 5.28 lbs/sec.
Random Vibration Levels	20 - 60 Hz + 6 dB/octave 60-400 Hz 0.4 G ² /Hz 400-2000 Hz - 9 dB/octave Overall G _{rms} = 14.86

FIGURE 3

AXAF PMD DESIGN REQUIREMENTS

Tank Outside Diameter, Unpressurized	24.00 in.
Tank Length, Unpressurized	81.55 in.
Tank Fluid Capacity, Minimum	31,600 in ³ 517.8 liters
Maximum Initial Propellant Load	98.7% of Tank Volume 1008 LBM N ₂ O ₄ 1125 LBM N ₂ H ₄
Pressures (Psid at 120°F) Maximum Design Pressure (MDP) Proof Burst	300 375 450
Natural Frequency When loaded with propellants and pressurized to 35-85 psig	≥ 20 Hz
Acoustic Vibration, Overall Sound Pressure Level	Acceptance = 133 dB (1 minute) Qualification = 139 dB (1.5 minutes)
Slosh	0.2 - 2.0 Hz at 2.0 inch double amplitude for 3 hours in an axial direction and one lateral direction. Sweep rate = 2.0 octaves/minute. Loaded with 1008 LBM of perfluorocarbon fluid at 85 psig.

Figure 4. reflects the vibration requirements for the AXAF Propellant Tank Assembly.

A tank structural analysis and fracture mechanics analysis, utilizing ANSYS and the NASA Flagro Program, were used to design the PMD and the tank end caps to which the PMD was attached. A stress analysis was used to analyze the PMD details, subassemblies, and assemblies including its installation into the tank. A fracture mechanics plan governed the described analyses while the imposed design and environmental test conditions, as listed in Figures 2 - 5, dictated the structural and stress analysis parameters, boundary conditions, and structural factors of safety.

The tank is polar boss mounted into the spacecraft at the propellant outlet by an eight bolt configuration built into the end cap and at the pressurant inlet by a four bolt configuration machined into the mounting flange of the end cap. At the outlet the end cap connects to a monoball to provide moment relief. The "Bipod" struts at the pressurant side also incorporate monoballs to allow tank axial movement and provide moment relief.

The propellant port is a 0.500 inch diameter 6061-T6 aluminum-to-304L CRES transition joint while the pressurant port is a 0.250 inch diameter 6061-T6 aluminum-to-304L CRES transition joint. These transition joints are tubes which are formed by the inertial welding process as solid bars and then machined to the final configuration.

The propellant and pressurant end caps are machined from 6061-T6/T651 aluminum bars. After machining they are dimension inspected, etched, and dye penetrant inspected. The ends are machined to interface with the tank shell, transition tubes, and "T" shaped metal weld filler rings.

The propellant management device is a centerpost, vane, baffle, and trap design. The trap is conical shaped with an upper and lower piece of perforated sheet and provisions for internal and external O-rings to seal after assembly into the tank shell. The perforated sheet has 0.008 inch diameter electron beam

drilled holes and prevents gas from entering the propellant at the tank outlet during adverse acceleration conditions. The trap ring and two perforated sheets, which are made from 6AL-4V titanium alloy, are TIG welded into the assembly.

The centerpost is made from a 6063-T6 aluminum extrusion trimmed to length and dye penetrant inspected.

The PMD contains four baffles, located at the propellant outlet side, and spaced at 90 degrees to each other. The baffles follow the inside contour of the tank near the bottom and interface above the trap at the bottom of the tank. Four vanes are located equidistant between the baffles and also interface above the trap at the bottom of the tank. They are fabricated from 6AL-4V titanium sheet and are attached to the centerpost with stainless steel (304L and A286) rivets and screws/nuts. The remaining parts of the PMD assembly kit, such as the mounting ring, adapter, bands, retaining nut, and retaining wire are also made from 6061-T6/T651 aluminum or 6AL-4V titanium alloys. All parts were dye penetrant inspected for defects. No subassembly of the PMD was welded; fasteners were used throughout.

For assembly of the PMD kit into the tank shell, first, the 4.00 inch diameter end cap was electron beam (EB) welded to the shell, and the weld was dye penetrant and radiographic inspected to fracture critical requirements. The baffles on the centerpost are furled into a six inch diameter, maintained in position by a special tool, and the centerpost assembly is inserted into the tank shell through the 6.5 inch diameter pressurant inlet side opening. After installation the baffles are allowed to unfurl. The PMD is then positioned with the retaining wires in locking grooves on the pressurant side. It is attached to the propellant side of the tank shell assembly by a retaining nut, torqued to a predetermined value, while the baffle-to-tank wall gaps are maintained.

The 7.00 inch diameter end cap was EB welded onto the tank shell. The weld was accepted with fracture critical dye penetrant and radiographic inspections. Previously, the small diameter

transition tube had been EB welded in place on this end cap, inspected, and accepted. Finally, the tank assembly was bubble point tested with isopropyl alcohol and accepted before proceeding. The bubble point results were typically comparable with all previous detail and subassembly test results. As a final tank close-out the propellant transition tube was EB welded onto the 4.00 inch diameter end cap.

The four EB welds, which assembled the tank assembly with the PMD assembly, used 4043 aluminum alloy “T” shaped weld filler rings. All welds were fracture critical dye penetrant and radiographic inspected and accepted before proceeding to the next step.

It should be noted that a significant EB weld development program was conducted with TRW, PSI, and Advanced Technology Company as participants before welding the actual flight hardware. This program included weld samples which simulated flight components and actual flight hardware. Components and samples were cleaned, welds were made, dye penetrant and radiographic inspected, samples sectioned, tensile tests performed and evaluated, and mounted sections examined microscopically. Weld schedules were developed from this work. A DVT unit was welded and accepted before the four flight tanks were welded.

After completion the four flight units were subjected to acceptance tests, cleaned, and

delivered for installation into the AXAF Spacecraft and for use as qualification units.

PMD ANALYSIS & DESIGN

I. PMD Introduction and Requirements

The AXAF Propellant Management Device (PMD) is a passive surface tension device designed to provide gas-free nitrogen tetroxide (NTO) and hydrazine (N₂H₄) during all mission accelerations with a minimum safety factor of two. The PMD is designed for use in a 24 inch diameter by 80 inch long cylindrical, aluminum, overwrapped tank with near 2:1 spheroidal heads.

As with most PMDs, the AXAF PMD is designed specifically for the AXAF mission. The mission requirements include upright ground operations and launch followed by three axis stabilized ascent operation. Ascent operation includes spacecraft rotations and long duration settling ascent maneuvers. The mission requirements are summarized in Table 1.

The PMD was designed to be installed into a fabricated tank shell through a 6.5 inch diameter opening in the pressurant head. This challenge was easily met by designing nearly all the components to this maximum diameter and by furling those components larger than the 6.5 inch diameter opening.

FIGURE 4
TANK ASSEMBLY
VIBRATION REQUIREMENTS

<u>Test</u>	<u>Axis</u>	<u>Frequency (Hz)</u>	<u>Acceleration</u>
Sine (1135 lbm of propylene glycol at 85-95 psig) 2 octaves/minute	All (X, Y, Z)	5-2000	0.25 G
Random (Dry & Pressurized to 85-95 psig) 90 second run Overall level = 3.98 Grms	All (X, Y, Z)	20-70 70-300 300-200 2000	+ 9.0 dB/octave 0.04 g ² /Hz -9.0 dB/octave 0.00013 g ² /Hz

FIGURE 5
A. PMD STRUCTURAL FACTORS OF SAFETY

<u>Load Condition</u>	<u>Factor of Safety</u>
PMD Static Pressure Stress	1.5 on Ultimate Strength 1.25 on Yield Strength
PMD Dynamic Pressure & Acceleration	2.0 on Ultimate Strength 1.25 on Yield Strength
End Cap Static Pressure	1.5 on Ultimate Strength at 300 psig 1.25 on Yield Strength at 300 psig

B. TANK STRUCTURAL FACTORS OF SAFETY

<u>Load Condition</u>	<u>Factor of Safety</u>
Launch Stress on Overwrapped Membrane (Launch pressure stress added to the limit level of all other simultaneous stresses)	1.5 on Ultimate Strength
Launch stress on non-overwrapped membrane	1.5 on Ultimate Strength 1.25 on Yield Strength
Static pressure stress on overwrapped membrane	1.5 MDP
Static pressure stress on non-overwrapped membrane	1.5 on Ultimate Strength 1.25 on Yield Strength
Autofrettage	1.25 MDP

II. PMD General Design Description

The PMD design incorporates a very simple and lightweight centerpost and baffle type device as illustrated in Figure 6.

The device is bolted into the propellant head and attached with a novel flex joint to the pressurant head. The PMD attachment was designed to allow tank growth in response to pressurization with no impact on PMD performance.

Another unique feature of the PMD is that it was designed to be installed into the tank after tank fabrication via a 6.5 inch diameter hole located in the pressurant head. A 4 inch diameter hole in the propellant head accepts the PMD outlet.

The key components of the PMD include:

- 1) The Centerpost,
- 2) The PMD Core,
- 3) The Baffles,
- 4) The Outlet, and
- 5) The Pressurant Head Attachment

The Centerpost and PMD Core. The centerpost runs from the propellant head to the pressurant head. The upper portion of the centerpost is a simple cross. The lower 14 inches of the centerpost, described as the PMD core, is 6 inches in diameter and consists of eight equidistant radial panels; four triangular and four rectangular.

The PMD core is designed to provide propellant during main engine ignition and all rotation maneuvers. Four panels are triangular to ensure gas ejection from the PMD core with the tangential placement of the baffles (see below). The centerpost is designed to refill the PMD core during zero G coast if a maneuver dislodges propellant from the bottom of the tank. The analysis shows that this should not occur given the current maneuver acceleration profiles. Therefore, the centerpost is incorporated for design robustness -- to allow some off design operation and/or allow for future maneuver definition changes.

The Baffles. Integrated with the rectangular panels in the PMD core are the four baffles. The

baffles extend tangentially from the edge of the rectangular PMD core panels and are designed so that if extended radially they cannot contact the tank wall. This ensures that the PMD cannot damage the thin aluminum liner.

The baffles serve two purposes: a) they damp propellant motion during main engine ignition and b) they aid the PMD core's capillary retention by creating the square PMD core 6 inches across (see Figure 5). The baffles are not radial to accommodate b) above and to ease installation - during which the baffles must roll to fit through a 6.5 inch opening. The furling requirement was one of the many challenges addressed by the PMD design.

The Outlet. Beneath the PMD core is the trap assembly. The upper sheet is 0.1 inches above the tank shell inner mold line and prevents any gas near the outlet from exiting the tank prior to depletion. The lower sheet is designed to eliminate velocity spikes which could overload the upper sheet locally and compromise its capillary capability.

The Pressurant Head Attachment. The PMD is attached at the pressurant head with a flexure. This flexure was implemented for tank growth and structural reasons and is designed to have little impact on PMD operation. The flexure is designed to ensure that if propellant resides in the pressurant head, the centerpost can access and deliver it to the PMD core.

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 contains no screen and a minimal quantity of perforated sheet; providing increased strength and reliability. Eliminating screen dramatically increases reliability.

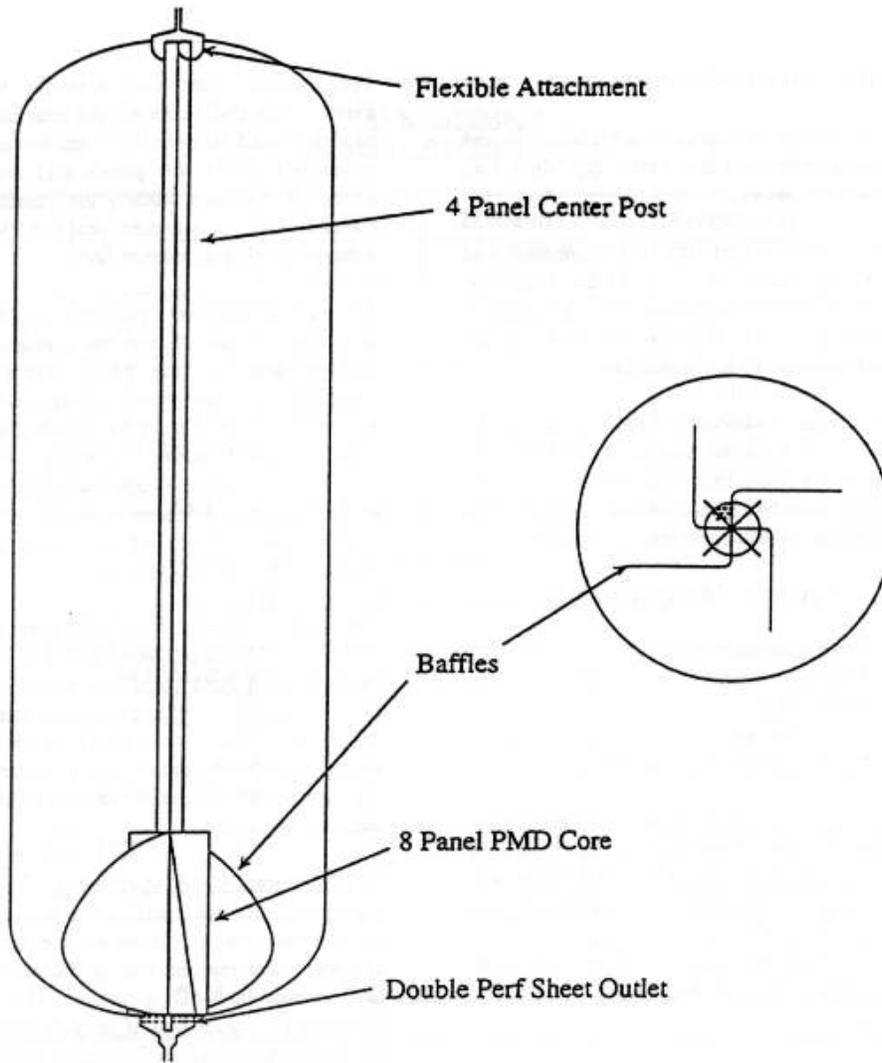


Figure 6. PMD Design Configuration

Finally, the design is implemented to rely minimally on the porous elements within it. During nearly all 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.

Table 1
AXAF Propellant Management Device
Performance Requirements Summary

Ground Operations and Launch

- Tanks are filled, handled, and drained in the upright down position.
- Fill flow rates may be controlled to prevent gas entrapment in the PMD and structural loading.
- Tank fill fraction is >61% in the NTO tank and >96% in the N₂H₄ tank.

Boost Operations

- Tanks are launched in the upright outlet down position.
- System line priming is the first demand of propellant from the tanks:
 - The priming flow rate is 121 in³/sec maximum.
 - Priming occurs during either the settling launch acceleration or the subsequent zero G coast.
- IUS tip off produces up to 1°/sec roll and up to 0.4°/sec pitch and yaw. Recovery requires 1.5 lbm of N₂H₄ at a flow rate of 0.17 lbm/sec maximum. Thruster accelerations are up to 0.0027 G settling and 0.0027 G lateral.

Ascent Operations

- The AXAF propellant is used for ascent. All maneuvers are one of two types:
 - long duration settling burns
 - vehicle rotations involving short duration pulsing
- Main engine firing settles propellant over the outlet:
 - minimum settling acceleration of 0.024 G.
 - maximum short duration lateral accelerations of 0.0027 G.
 - maximum flow rate of 0.33 lbm/sec NTO and 0.59 lbm/sec N₂H₄.
 - can occur immediately following rotation maneuver (desired).

- NTO and N₂H₄ depletion occurs during a final main engine firing. The last burn begins with a 30% fill fraction in the NTO tank and a 46% fill fraction in the N₂H₄ tank.
- Rotation maneuvers occur between main engine firings:
 - instantaneous acceleration of 0.0027 G settling and 0.0027 G lateral.
 - rotation rate is 0.5°/sec maximum (0.2°/sec maximum in yaw)
 - time averaged acceleration over 1.024 seconds of 3.6×10^{-4} G maximum settling and 3.8×10^{-4} G maximum laterally. These numbers account for the rotational accelerations as well as linear accelerations.
 - 4.5 lbm maximum of N₂H₄ is required between main engine firings at a maximum flow rate of 0.17 lbm/sec.
 - 1.024°/sec² maximum angular acceleration with a center of mass at (+/-47, -/-46, 65) relative to each tank center. Thruster on time limited to 0.5 second in any single direction without opposing thruster activity.
 - Simplified pitch model consists of 25 0.020 sec pulses, each every 1.024 seconds to start the 0.5°/sec rotation followed by a coast period and then 25 0.020 sec pulses, each every 1.024 seconds to stop the 0.5°/sec rotation.
 - Actual rotation maneuver accelerations as a function of time were provided electronically.
- The tank flow losses shall be limited to 5 psi at the maximum operating flow rate.

Miscellaneous

- Gas-free propellant delivery is required throughout mission.
- The PMD safety factor will be two minimum.
- Residuals shall be limited to 0.1% of the tank volume as a goal.

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 Ascent Operations.

The various phases of mission that the PMD will encounter and how the PMD will affect the propellant are illustrated in Figure 7, The 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 ground operations.

Filling occurs with the tank upright in the outlet down position. The tank pressure is atmospheric initially to reduce/eliminate the amount of gas trapped beneath each perforated sheet. If any gas is trapped, it will be compressed upon pressurization and is likely to be dissolved into the low pressure saturated propellant. The filling process is straightforward and should introduce no difficulties either to the technician or to the PMD.

Handling occurs with the tank in the outlet down position. Gas will not enter the outlet during handling. Ground handling is identical to ground fill and 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.

Boost Operations

Boost operations can be divided into three stages: boost, system priming, and separation. The PMD has been designed to withstand the structural loads during these stages of boost and provide propellant as required.

The PMD is designed to be boosted in the outlet down position. Similar to ground handling, there is no perceived danger of ingesting gas into the outlet. Boost is illustrated in the operational sequence with the propellant position identical to ground filling and ground handling.

During zero G coast, system priming occurs. During system priming, a high flow rate is demanded from the tank to fill the evacuated lines downstream of the isolation valve. This high flow rate can structurally load the perforated sheet and if gas is near the outlet pull gas into the lines. The PMD is designed to maintain propellant over the outlet during zero G coast; thus gas ingestion is not possible. The structural loads are accommodated by the PMD.

After the initial ascent, the spacecraft is separated from its booster and the system becomes operational. Vehicle rotations may result from separation. Most rotations will deposit liquid over the outlet. Even if gas were pushed toward the outlet, the surface tension forces are significant in the PMD core and will maintain liquid over the outlet. During and after separation, propellant demand is easily met with the propellant positioned in the PMD core and over the outlet. Separation poses no operational difficulties for the PMD.

Ascent Operations

Once separated from the booster, the PMD is operational and has been designed to provide gas-free propellant delivery during all maneuvers. The PMD's two primary purposes are to deliver gas-free fuel during all rotation maneuvers and gas-free fuel and oxidizer during main engine ignition and firing. The device is designed to maintain both fuel and oxidizer over the outlet during all rotation maneuvers to accommodate main engine firing on demand.

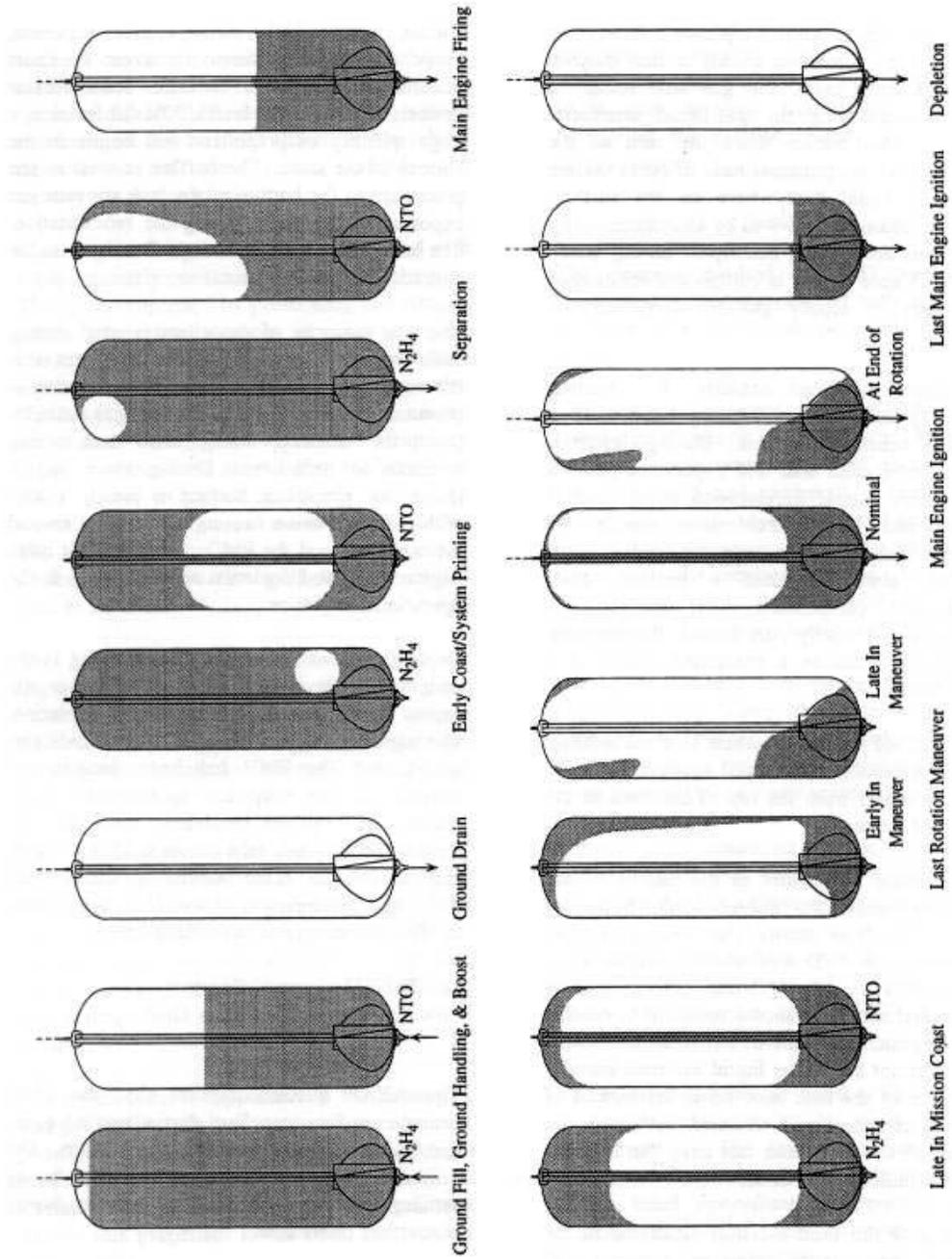


Figure 7. The PMD Operational Sequence

Next, the operational sequence shows the propellant configuration during a late mission coast. 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 are identically equal everywhere on the surface. Late in mission, the gas will be axisymmetrically distributed around the centerpost during coast. The PMD core region is completely submerged and ready to supply gas-free propellant on demand.

A rotation maneuver consists of a starting thruster pulse train, a rotating coast, and a stopping thruster pulse train. During a pitch or yaw rotation, each tank will experience either a nearly pure lateral acceleration or a coupled settling and lateral acceleration during the starting and stopping thruster burns (roll rotations always contain a settling, axial acceleration component). If the starting acceleration is nearly pure lateral, the stopping acceleration must be a combined settling and lateral burn.

The result of the combination is a net settling axial acceleration. This axial acceleration tends to move liquid from the top of the tank to the bottom of the tank.

The question is whether in the middle of the maneuver propellant moves away from the outlet. Analysis shows that during rotation maneuvers, the PMD core retains nearly all of its NTO and N_2H_4 , for gas-free delivery. The operational sequence shows the fluid in motion at the beginning and end of a rotation maneuver. Most, but not all, of the liquid assumed initially in the top of the tank ends up in the bottom of the tank and the liquid assumed initially in the bottom of the tank does not stray far from its zero G equilibrium position.

Please note the fluid location illustrated in the rotation maneuver is based upon actual 3-D modeling in which the centerpost was not modeled. Hence no propellant is illustrated in the centerpost while in reality some will remain - this is conservative assumption.

During a nominal main engine ignition, propellant reorients from its zero G coast position to the bottom of the tank. Since the last ignition begins with at least a 30% fill fraction, a

large quantity of propellant will begin in the bottom of the tank. The baffles as well as the propellant in the bottom of the tank prevent gas exposure to the outlet during the reorientation. The last main engine ignition is illustrated in the operation sequence.

The vast majority of propellant is used during main engine firing which settles propellant over the outlet. The PMD has very little function -- preventing vortexing, eliminating gas bubbles from the demand stream, and minimizing residuals at depletion. During main engine firing, the propellant surface is nearly planar with surface tension causing a meniscus around the tank wall and the PMD. Both the last main engine firing and depletion are illustrated in the operational sequence.

Depletion shows the propellant remaining in the tank when gas is first ingested. Surface dip causes an annular pool to remain at depletion. 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 0.42% in N_2H_4 and 0.18% in NTO assuming worst case conditions and below 0.19% in N_2H_4 and 0.10% in NTO assuming nominal conditions.

IV. PMD Design and Analysis

Design

The AXAF mission requires that the PMD provide gas-free propellant during settling burns and during rotations between settling burns. The maneuver duration is extremely long during settling operations and of limited duration during nonsettling operations.

PMDs can be classified into two basic categories: control devices and communication devices.¹ Control devices are able to deliver a fixed quantity of propellant while communication devices offer unlimited duration operation. Because the AXAF mission requires a 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 the AXAF mission is the most robust, reliable and lightweight design available.

Main engine firing is easily accommodated with a trap assembly positioned in the propellant pool. This is accomplished by positioning two circular pieces of perforated sheet in series over the outlet. The upper sheet prevents any gas which approaches the outlet from reaching the outlet. The lower sheet eliminates velocity spikes in the upper sheet ensuring the upper sheet's capillary integrity. The sheets are 4 inches in diameter to allow access to propellant during surface dip where a core of gas could reside over the outlet. The trap assembly acts as a communication device; providing a flow path from the settled pool to the outlet.

The PMD core, baffles, and centerpost are implemented to provide propellant during the rotations between burns and main engine ignition. They are positioned on the tank center line to ease installation through the 6.5 inch diameter opening.

The PMD core acts as a reservoir to accommodate all transients and to suppress vortexing during main engine firing. The PMD core controls sufficient propellant to meet the demand during rotations and bipropellant main engine ignition. The PMD core is the principal functioning PMD component and is a control device.

The PMD core is supported by the centerpost and the baffles. During rotation maneuvers it is possible, although very unlikely, to reorient propellant into the pressurant head. The fillets formed between the centerpost's panels can deliver this propellant to the PMD core during zero G coast.

During rotation maneuvers and during main engine ignition, propellant is in motion within the tank. If unchecked, this motion can 'sweep' propellant from the PMD core. The baffles are designed to severely restrict the propellant motion near the PMD core; ensuring that the PMD core remains filled with propellant throughout the rotation maneuvers and main engine ignition.

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 Ascent Operations is analyzed.

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

- I. General Design Analyses
 - A. Outlet Configuration and Sizing
 - B. PMD Core Configuration and Sizing
 - C. Centerpost Configuration and Sizing

- D. Baffle Configuration and Sizing
- E. PMD Design at the Pressurant Head
- F. Flow Losses
- G. Temperature Effects

II. Ground Operations

- A. Filling
- B. Draining
- C. Handling

III. Boost Operations

- A. Boost
- B. Separation
- C. System Priming

IV. Ascent Operations

- A. Propellant Location
- B. Rotation Maneuvers
- C. Main Engine Firing
- D. PMD Core Refilling
- E. Depletion

ACCEPTANCE TESTS

The acceptance tests for the propellant tanks are listed in Figure 8. In addition, tests were performed on various components prior to assembly into the final tank. The transition tubes were radiographic inspected and proof and external leak tested with a helium mass spectrometer at 1,000 psid for 3 minutes. A mechanical bend test to destruct was performed on the first and last tube in the production run. The surface tension elements of the trap assembly were bubble point tested at the raw sheet level, subassembly, and final assembly levels.

During the assembly of the PMD(s) into the tank shells, the two shell-to-end cap electron beam (EB) welds and two end cap-to-transition tube EB welds were dye penetrant inspected and radiographic inspected. Also, the bubble point of the trap assembly and its installation was checked at the expulsion assembly level and again at the tank assembly level using isopropyl alcohol (IPA). All components making up the PMD centerpost assembly, trap assembly, end caps, and tank assembly hardware were 100% dye penetrant inspected. Finally, the nut which

retains the PMD in the shell was initially torqued and then re-verified to insure a proper installation at the tank subassembly level.

FIGURE 8
ACCEPTANCE TESTS FOR THE TRW
AXAF PROPELLANT TANK

- Preliminary Inspection of Product
- Proof Pressure Test Including
 - Length Measurements
 - External Leakage Test
 - Bubble Point Test
 - Weight Measurement
- Final Dimensional Inspection
- Radiographic Inspection
- Dye Penetrant Inspection
- Cleanliness Check & Visual Inspection
- Data Review

The acceptance test started with an inspection for dimensions, verification of previous inspections and tests, identification, successful completion of all manufacturing planning, damage, and material certifications. The tanks were subjected to an ambient gaseous nitrogen proof pressure test of 375 psig for one minute. The gas was filtered through a 1-micron absolute filter. During the pressure increase to 375 psig and subsequent decrease to 0 psig, length measurements were taken at 0, 50, 175, 300, 330, and 375 psig. These readings were taken remotely using a dial indicator and a video camera. After the test it was verified that the axial growth didn't exceed 1%.

An external leakage test was performed using a helium mass spectrometer with the test specimen at 300 psig for 30 minutes. The vacuum chamber was evacuated to 5×10^{-4} Torr or less. Leakage was not to exceed 1×10^{-6} standard Scc/Sec of helium gas.

To verify the integrity of the PMD surface tension elements after the proof pressure test, a bubble point test with IPA as the test fluid was performed. The bubble point was held for a minimum of 60 seconds and then the capillary breakdown was measured. In the case of the AXAF tank the minimum bubble point is 1.8 inches of IPA. The tank was drained and dried,

and weighed on a precision scale to within 0.1 pound accuracy.

There was a final dimensional inspection, visual inspection for damage, fracture critical dye penetrant and radiographic inspections of the electron beam welds, and radiographic inspection of the PMD to verify that there was no internal damage. Finally, the units were cleaned to the Figure 10 cleanliness levels and packaged in two sealed plastic bags for shipment. Prior to packaging, the pressurant port, which had a Swagelok fitting installed, was sealed with a clean copper gasket and pressure cap. The propellant port, which also incorporated a Swagelok fitting, was assembled with an in-line 1-micron filter, pressure gage, valve, and desiccant container. The tank was pressurized to 10-25 psig with dry (-65 degrees dew point) nitrogen gas and the port sealed with a clean copper gasket and pressure cap.

QUALIFICATION TESTS

After successful completion of acceptance testing one unit was subjected to a series of qualification tests. They are listed in Figure 9. On a detail component level the inertial welded transition tubes were also qualification tested. Three test samples were subjected to a mechanical bend test to destruction and two of these were sectioned for macroscopic inspection of the weld zone to verify that the failure occurred in the aluminum section. A sample of each configuration was radiographic inspected, proof and leak checked at 1,000 psid with helium, and then burst pressure tested to 1,500 psid. It was confirmed that no failure occurred in the weld interface zone.

FIGURE 9 **QUALIFICATION TESTS FOR THE TRW** **AXAF PROPELLANT TANK**

Slosh
Radiographic Inspection
Bubble Point Test
Acceleration
External Leakage Test
Sine & Random Vibration
Bubble Point Test

External Leakage Test
Cyclic Pressurization Test
External Leakage Test
Burst Test

For slosh testing the test specimen was filled with 1,008 pounds of perfluorocarbon fluid, pressurized to 85 psig with helium, installed in a fixture to simulate the spacecraft installation, and subjected to a sinusoidal input of 2.0 inch double amplitude, from 0.2 to 2.0 Hz at a sweep rate of 2.0 octaves per minute. It was tested in one lateral axis and one axial axis for three hours each. After draining and drying, the unit was radiographic inspected at various angles and positions to verify no damage to the PMD. A bubble point test with IPA as the test medium was accomplished on the trap assembly. It was performed for 60 seconds and verified the required 1.8 inches of IPA minimum bubble point. The breakdown head was measured to be 2.1 inches. These values were consistent with all previous tests.

For the acceleration test, strain gages and accelerometers were installed on the test specimen, the tank was filled with 1,135 pounds of propylene glycol, pressurized to 85 psig, mounted on a centrifuge, oriented at 45° to the horizontal to impart the most critical acceleration load, and tested for 90 seconds. The orientation was then changed 180 degrees and the test was repeated. An acceleration level of 7.27 G(s) simulated the tension and compression loads imparted to the tank during launch. Strain and acceleration levels were continuously recorded during the runs. After draining and drying, the test specimen was leak tested using a helium mass spectrometer. The internal pressure was 300 psid while the leak test chamber pressure was reduced to 5×10^{-4} Torr. The pressure was held for 30 minutes. The test verified that the leakage was below the required 1×10^{-6} Scc/Sec of helium gas.

For vibration fixture evaluation a mass simulator was installed on the shaker and run through the same vibration spectra as the test unit. The fixture transmissibility between the two tank mounting points was verified not to exceed 3 dB from 20 to 2,000 Hz, and the crosstalk was verified not to exceed 0 dB from 20 to 2,000 Hz.

After fixture evaluation, vibration tests were performed on the test tank. Control and response accelerometers were installed on the fixture and tank assembly, respectively. It was first filled with 1,135 pounds of propylene glycol, pressurized to 85 psig helium, and subjected to a sinusoidal input of 0.25 G, from 5 to 2,000 Hz at a sweep rate of 2.0 octaves per minute. This test was run in each of three orthogonal axes. It was used to determine the natural frequency of the tank assembly. The tank was then drained, re-pressurized to 35 psig, and random vibration tested in the same three axes. The specimen was subjected to the following random spectrum in increments of 3 dB, starting at -12 dB and ending at 0 dB, for 60 seconds at each increment up to and including -3 dB and 90 seconds at full level. Acceleration data was recorded continuously during the runs. Plots of acceleration versus frequency and power spectral density versus frequency were prepared.

20 to 70 Hz at + 9.0 dB/Octave
 70 to 300 Hz at 0.04 G²/Hz
 300 to 2,000 Hz at -9.0 dB/Octave
 2,000 Hz at 0.00013 G²/Hz
OVERALL LEVEL = 3.98 G_{RMS}

FIGURE 10
TANK CLEANLINESS LEVEL

<u>Particle Size (Microns)</u>	<u>Maximum Amount of Particles</u>
> 100	None
51 - 100	5
26 - 50	50
11 - 25	200
6 - 10	1200
0 - 5	No Silting

Notes:

1. Particles counted per 100 ml of rinse fluid.
2. No metallics >50 microns.
3. Non-volatile residue (NVR) less than 5 ppm/

100 ml.

The bubble point test was repeated to verify that no damage to the surface tension elements had occurred during the vibration testing. The test was successful with comparable values to other earlier tests. The external leakage test was also performed again with no problems.

CONCLUSIONS

The propellant tank assembly has met all design objectives for the AXAF mission. Successful PMD bubble point tests were performed prior to and at the conclusion of all major qualification tests, i.e., slosh, acceleration, and vibration. The qualification tank assembly completed the cyclic pressure test and the final burst pressure was greater than 1.5 times the requirement.

PSI has integrated PMD(s) into the four propellant tanks that have been delivered to TRW. Two are installed in the AXAF spacecraft, which represents a one-of-a-kind mission. The third unit was used for qualification testing, and the fourth unit is in storage..

The AXAF satellite is scheduled for launch in August 1998 on the Space Shuttle from Kennedy Space Center, Florida. It will use an inertial upper stage (IUS) to boost it into a higher earth orbit.

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