

## **DESIGN, DEVELOPMENT, QUALIFICATION, AND MANUFACTURE OF THE HS 601 PROPELLANT TANK**

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### **ABSTRACT**

The HS 601 communications satellite was introduced by Hughes Space and Communications in 1987. It is the company's first body-stabilized spacecraft model, and also the world's best selling spacecraft.

The spacecraft's propellant needs are provided by four tanks that are identical in material and construction. Each spherical tank assembly is fabricated from two 6AL-4V titanium alloy hemispherical forgings that are joined with a single girth weld. A passive Propellant Management Device (PMD) is installed into the propellant hemisphere prior to the tank closure weld. The PMD provides continuous gas-free propellant delivery to the satellite thrusters.

The tank shell is constructed of solution heat treated and aged 6AL-4V titanium alloy. The PMD is constructed of various components including vanes, trap, sponge, manifold, and pickup arms, all of which are made from titanium. Stress and fracture mechanics analyses were performed to design and analyze the tank shell, and stress and PMD performance analyses were conducted to analyze the PMD. Acceptance and qualification testing include testing the tank shell integrity as well as the PMD functionality.

The tank Qualification program was conducted and completed in 1990. A total of 157 tanks have been fabricated to date, and 28 are in work.

Although the HS 601 PMD was designed for upright handling, it is also flexible enough to accommodate horizontal handling required by the Russian Proton launch vehicle. The PMD design has been verified in numerous missions, including an end-of-life maneuver which depleted the tanks. After the maneuver the remaining propellant on the spacecraft was estimated at less than one pound.

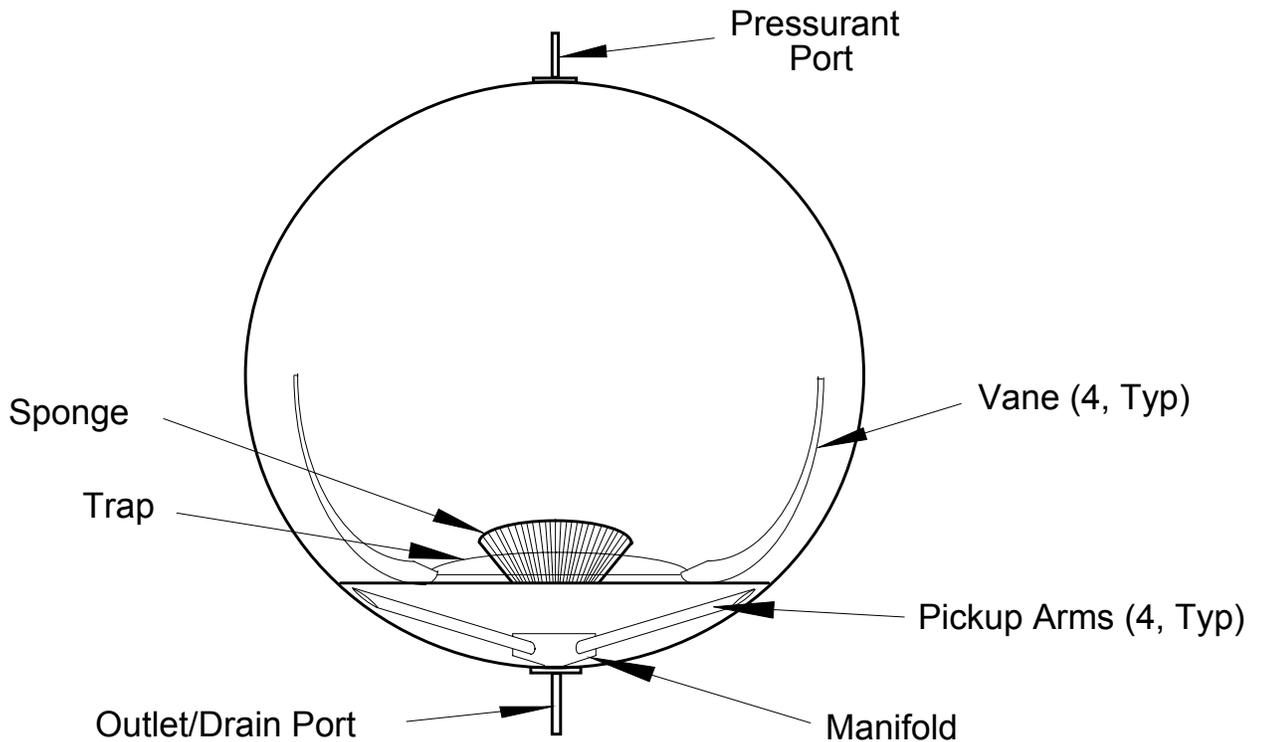
### **INTRODUCTION**

The HS 601 satellite model was introduced by Hughes Space and Communications (HSC) in 1987. It is the company's first 3-axis body-stabilized communication satellite. All previous Hughes satellites have been cylindrical spacecrafts that were spin-stabilized. With 57 versions ordered by the end of 1995, the HS 601 has become the world's most popular spacecraft. Customized variations of this spacecraft have been order by customers from U.S., Canada, Mexico, Europe, Asia, and Australia for programs such as Optus B, UHF Follow-On, Astra, Solidaridad, PanAmSat, APStar 2, ASC, Galaxy, MSAT, DBS, Palapa C, Superbird, and TDRS.

Each HS 601 spacecraft requires four (4) tanks; two for the monomethylhydrazine (MMH) fuel and two for the nitrogen tetroxide (NTO) oxidizer. These four tanks of propellants enable the spacecraft to perform a series of maneuvers starting with separation from the booster to deployment in geosynchronous orbit to station keeping once the spacecraft is on orbit, and ending with a final ascent to a graveyard orbit.

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Figure 1: The HS 601 Propellant Tank



Each propellant tank is a 35 inch diameter sphere with two polar mounting bosses. The top boss contains a pressurant port, and the bottom boss contains an outlet/drain port. The tanks are mechanically mounted into the spacecraft structure at these two polar bosses and welded into the propulsion system at the pressurant and the outlet/drain ports. The tank was designed to the requirements shown in Table 1.

A passive Propellant Management Device is installed in each tank to provide gas-free propellant delivery to the spacecraft thrusters. The PMD is welded to the inside of the propellant hemisphere prior to the tank closure weld. A sketch of this PMD in the tank is shown in Figure 1.

**PMD INTRODUCTION**

The HS 601 PMD is designed to provide gas free NTO and MMH during all mission accelerations with a minimum expulsion efficiency of 99.5% and a safety factor of 2.

Table 1: HS 601 Propellant Tank Design Requirements

PARAMETERS	REQUIREMENTS
Operating Pressure	260 psig
Proof Pressure	325 psig
Burst Pressure	390 psig
Tank Capacity	22,450 in <sup>3</sup> minimum
Size	35 inch diameter sphere
Expulsion efficiency	99.5%
Flow Rate	2.9 in <sup>3</sup> maximum
Tank Weight	28.9 lbm maximum, 26.6 typ.
Shell Leakage	< 1 x 10 <sup>-6</sup> std cc/sec He
Mission Life	15 years
Operating Temperature	19 °F to 105 °F

As with most PMD's, the HS 601 PMD is designed specifically for the HS 601 mission. The mission requirements include upright ground operations and launch, followed by spinning perigee and apogee burns to achieve orbit, and lateral thruster firings of varying duration to maintain orbit. In addition, the mission requires a de-orbit maneuver at the end of life.

The HS-601 mission profile requires that the PMD allow operation of the tank during spinning operations and subsequent three axis stabilized operation. The maneuver duration is extremely long during spinning operations and of limited duration during three axis operations.

### **PMD DESIGN**

There are two classic categories of PMDs: control devices and communication devices<sup>1</sup>. Control devices are able to deliver a fixed quantity of propellant while communication devices offer unlimited duration operation. Because the HS-601 mission required 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 Hughes mission is the most robust, reliable and lightweight design available.

The spacecraft spinning phase is most easily accommodated with a pickup assembly positioned in the propellant pool. This is accomplished by using the trap and trap inlet window as a pick up assembly; the trap inlet window is positioned outboard in the propellant pool. All of the spinning maneuvers are accommodated by the placement of the trap inlet window.

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 the HS-601 PMD: the sponge and the trap.

The sponge can provide the propellant required for each of repetitive maneuvers such as stationkeeping. The size of the sponge and the number of sponge panels were determined based upon the North-South stationkeeping requirement. The sponge is a refillable control

device and the vanes were implemented to refill the sponge between each maneuver.

The trap is not refillable and is designed to accommodate once-in-a-lifetime maneuvers which the sponge cannot accommodate. Examples include the long duration station change maneuver and the low fill fraction despin. The trap is sized to provide propellant for all of these maneuvers as well as to allow the gas ingested into the trap to expand upon blowdown. Inside the trap is a communication device to allow unlimited burn duration for the propellant in the trap.

### **PMD DESCRIPTION**

The PMD design incorporates the following components:

- Trap;
- Sponge assembly;
- Vanes;
- Pick up assembly.

**Trap:** A trap is formed by welding an upper trap housing to the propellant hemisphere to create a compartment in which to trap propellant. The trap housing consists of a domed region, a cylindrical region, and a planar region. The planar region is used as installation base for sponge and vanes. The cylindrical region provides a fluid fillet area for circumferential propellant flow in zero gravity. The domed portion provides stability and extra trap volume. This trap housing has a nominal thickness of 0.060 inch and is fabricated from 6AL-4V titanium forging.

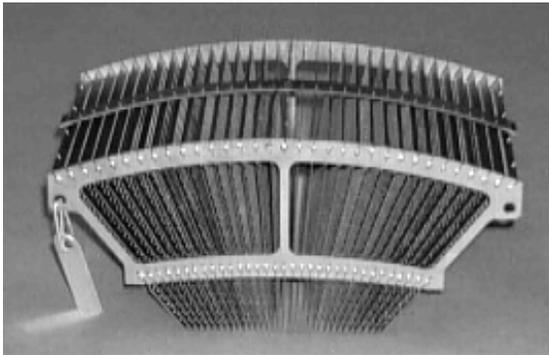
A single screen covered window with a surface area no larger than 2.5 square inches is used for propellant acquisition for the trap. There is no other access to the trap from the rest of the tank. This trap inlet window is located outboard on the spacecraft to allow propellant access during spinning operation. The screen is constructed from commercially pure titanium and is supported by a window pane grid.

**Sponge:** Located directly above the trap inlet window on the trap housing is a sponge. The sponge consists of thin sheet metal panels positioned in proximity to one another and forming a tapered gap between each panel pair. The taper ensures that the sponge is full in zero g and that sponge draining is efficient. Each sponge assembly has 33 each 3.75" x

4.5" sponge panels. 0.062 inch diameter through holes are chemically etched into each panel. The panels are made from 0.010 inch and 0.020 thick commercially (CP) titanium sheets.

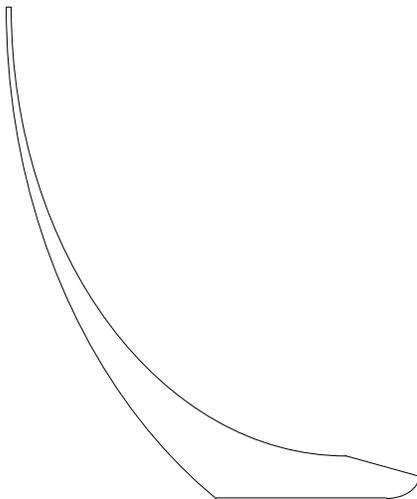
Slotted retaining plates are utilized to locate and retain the panels. Each panel is welded to the retaining plates. The completed sponge assembly is stress relieved prior to installation into the PMD assembly. Figure 2 presents a completed sponge assembly.

**Figure 2: HS 601 Sponge Assembly**



**Vanes:** Also attached to the trap housing are vanes which extend from the trap to the tank girth. The vanes are fabricated from 0.016 inch thick 6AL-4V titanium sheet. Figure 3 shows a sketch of this vane.

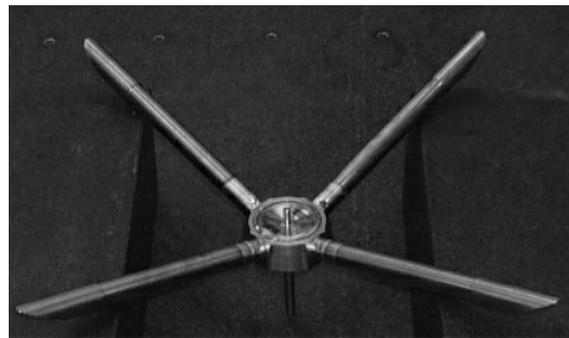
**Figure 3: HS 601 PMD Vane**



Four vanes are required for each tank assembly. The vanes are positioned on the east, west, north, and south axes and follow the tank contour from the trap housing to the tank girth. The vanes provide a flow path to the trap and the sponge from the propellant pool settled by the lateral operational accelerations. These vanes are designed to refill the sponge during period of zero g coast.

**Pickup assembly:** Within the trap is a pickup assembly consists of four tubes attached to a central manifold, as shown in Figure 4.

**Figure 4: HS 601 Pickup Assembly**



The scarfed end of each pickup arm is covered with a laser drilled perforated titanium window to allow gas free propellant acquisition within the trap. The manifold body adjacent to the tank wall is also covered with the same perforated material. The tubes are aligned with the spacecraft axes to provide gas free propellant during long duration burns.

All PMD components, including the porous elements, are fabricated from titanium. The porous elements 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 less than 2.5 square inches of screen.

### **PMD CHARACTERISTICS**

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, which enhances strength and reliability. As a design rule, reducing the area of the screen would increase the reliability of the PMD.

Finally, the design is implemented to minimally rely on porous elements within the PMD. As an example, during a nominal mission the trap inlet screen is not exposed to gas until bulk space depletion. The result is a PMD design which would meet the mission requirements of a nominal mission even with a screen failure. This detail to design robustness is a key feature of this PMD.

**TANK ASSEMBLY FABRICATION**

The HS 601 tank shell is machined from 6AL-4V Titanium alloy hemispherical forgings. Each hemisphere is rough machined, solution heat treated, quenched, partial aged, skim machined and finish machined. The finished membrane has a nominal thickness of 0.026 inch.

The PMD installation starts with welding the pickup assembly to the completed propellant hemisphere to form the hemisphere/pickup assembly. The trap housing is then welded over the pickup assembly to create the trap assembly. The sponge and the four vanes are installed on top of the trap housing to complete the expulsion assembly.

The expulsion assembly and the pressurant hemisphere are then automatic Tungsten Inert Gas (TIG) welded into the tank weldment. The girth weld is radiographic and dye penetrant inspected for weld defects followed by a final vacuum stress relief cycle that completes the shell aging. Following stress relief, the tank mounting bosses are final machined to complete the tank assembly.

**DESIGN ANALYSES**

The following analyses were conducted to support the design of the HS 601 propellant tank:

**Stress Analyses:** Stress analyses include:

- Tank shell, membrane;
- Tank shell, boss regions;
- Tank shell, weld region;
- PMD to outlet port weld;
- PMD, trap housing.

The stress analysis shows positive margins of safety for all components, as summarized in Table 2.

**Table 2: Summary, Margins of Safety**

Area	M.S.
Membrane, burst	+.095
Membrane, proof	+.289
Membrane transition, proof	+.140
Membrane, launch	+1.670
Membrane transition, launch	+1.360
Bulkhead, burst	+1.050
Bulkhead, operating pressure	+1.000
Bulkhead, ext. pressure, buckling	+50.000
Tank @ bulkhead, burst	+.060
Tank @ bulkhead, operating	+.140
Weld, burst pressure	+.020
Weld, proof pressure	+.170
Bottom boss, axial load, yield	+.200
Bottom boss, axial load, ultimate	+.030
Bottom boss, pressure, burst	+.010
Bottom boss, lateral load, yield	>.250
Bottom boss, lateral load, ultimate	>.070
Top boss, lateral load, yield	+.680
Top boss, lateral load, ultimate	+.430
Top boss, pressure, burst	+.030
Bottom boss, axial compression	+.290
Bottom boss, axial tension	+.310
Top boss, axial tension	>0
Top boss, lateral load	+.550
Bottom boss, lateral load	>.290

**Fracture Mechanics Analysis:** The fracture mechanics analysis was performed using

NASA/FLAGRO with minimum thickness as parameters. The analysis include:

- Tank shell, membrane;
- Tank shell, bosses;
- Tank shell, weld.

The result shows that this design satisfies all fracture mechanics requirements.

**PMD Performance Analyses:** The PMD performance analyses examined, in detail, the fluid’s reaction to all phases of the mission. Propellant location, reorientation, and flow characteristics were determined and evaluated to ensure adequate control and delivery of propellant. The porous elements were shown to demonstrate the required margins. In addition, flow losses and flight depletion residual propellant quantities were analytically determined.

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

Because each spacecraft maneuver in a mission can directly affect the PMD, each performance analysis addressed a phase of mission. First, the impact of Ground Operations on the PMD was examined. Second, the impact of the operation during Ascent Operations was examined. And finally, the functionality of the PMD during all Orbital Operations was analyzed.

The following PMD analyses were conducted for the HS 601 PMD:

- PMD General Design Analyses, including:
  - Trap sizing;
  - Trap inlet window sizing;
  - Sponge sizing;
  - Pick-up assembly sizing;
  - Thermal effects on PMD.
- PMD Performance Analyses, Ground Operations:
  - Fill;
  - Drain;
  - Handling and pad slosh.
- PMD Performance Analyses, Ascent Operations:
  - Boost;

- Separation;
- System priming start transient;
- Spin up;
- Perigee;
- Spin down;
- Spinning LAM;
- Three axis stabilized LAM;
- Spin down and station acquisition.

- PMD Performance Analyses, Orbital Operations:

- Sponge usage;
- Sponge refill;
- Trap usage;
- Station change;
- Depletion.

Due to the summary nature of this paper, no results are presented. The detailed process of vane, sponge and trap design and analysis can be found in the series of papers titled Propellant Management Device Conceptual Design and Analysis: Vanes (Sponges or Traps and Troughs) by D.E. Jaekle, Jr.<sup>2,3,4</sup>

The analyses conducted verify that the PMD meets all the requirements by providing gas free propellant upon demand.

### **WEIGHT SUMMARY**

The tank component weights are summarized below in Table 3.

**Table 3: Weight Summary**

<b>Component</b>	<b>Weight (lbm).</b>
Pressurant hemisphere	11.11
Propellant hemisphere	12.44
Vanes	.54
Sponge assembly	.89
Bulkhead assembly	2.18
Trap housing	.55
Manifold assembly	1.17
<b>TOTAL WEIGHT</b>	<b>28.88</b>

### **ACCEPTANCE TESTS**

Acceptance tests are performed at component, subassembly, and assembly levels.

**Component Level Acceptance Tests:** Three PMD components, the trap inlet screen, the pickup arm window and the manifold window, require special testing prior to assembly. The trap inlet screen, the pickup arm window and the manifold window are checked for bubble point and the pickup arm window and the manifold window are checked for flow rate. The intent of the acceptance tests is to identify and eliminate inferior PMD components.

**Subassembly Tests:** Subassembly level acceptance tests are verification tests intended to identify the bubble point of each PMD subassembly. The bubble point tests on the following subassemblies are performed:

- (1) Trap housing inlet screen assembly;
- (2) Pickup arm assembly;
- (3) Hemisphere/manifold assembly;
- (4) Expulsion assembly.

The bubble point requirements at each PMD subassemblies are chosen to minimize the risk of using inferior components in the final assembly. Thus the bubble point requirement is lowered at each subsequent PMD assembly to minimize the possibility of failure at a more expensive next level assembly.

**Assembly Level Tests:** Each flight tank assembly undergoes a sequence of acceptance tests prior to tank delivery. The tests are performed per the sequence listed:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure
- Post-proof volumetric capacity
- Dry sinusoidal vibration
- PMD functional test
- External leakage
- Penetrant inspection

- Radiographic inspection of tank shell
- Radiographic inspection of PMD
- Final examination
- Cleanliness

**Volumetric Capacity Examination:** The volumetric capacity of the HS 601 propellant tank is measured using weight of the water method. Deionized (DI) water is used to conduct this test. Each tank must have a minimum capacity of 22,450 in<sup>3</sup>.

**Proof Pressure Test:** The propellant tank is pressurized to 325 psig for a minimum of 5 minutes for the proof pressure test. The test is conducted hydrostatically using DI water.

**Sinusoidal Vibration:** The drained and dried propellant tank is subjected to acceptance level sinusoidal vibration in each of the three principal axes. The vibration spectrum is listed below in Table 4. Sweep rate is 4 octaves per minutes. The sine input is not notched during acceptance testing. The purpose of this test is to verify the PMD workmanship.

The vibration test fixture is designed to simulate the tank-to-spacecraft installation interface. The fix end propellant boss is restrained in all directions during all vibration testing. The free-end pressurant boss is free to move in the tank longitudinal axis but is restrained in all other directions during test. The fixture is also sufficiently stiff to be considered rigid for the test frequencies.

Control accelerometers are placed on the vibration test fixture near each attachment boss to control energy input. Response accelerometers (X,Y and Z) are placed near the tank girth plane to monitor the tank responses.

**Table 4: Acceptance Level Sinusoidal Vibration Test Environment**

Axes	Frequency (Hz)	Acceleration (g 0-PEAK)	Displacement (DA)
X,Y, Z	5 - 8	-	13 mm (0.5 in)
	8 - 100	1.9	

**PMD Functional Tests:** The tank assembly level PMD functional tests are bubble point

tests intended to verify the capillary integrity of each screened PMD element. Three PMD elements are tested: the trap inlet screen, the

pick-up arm perforated windows, and the manifold assembly perforated window.

**External Leak Test:** The external leak test verifies the integrity of the tank shell. The tank is placed in a vacuum chamber, which is evacuated to under 0.2 microns of mercury, and helium pressurized to 255 psig for 30 minutes. The helium leak rate cannot exceed  $1 \times 10^{-6}$  std cc per second throughout the 30-minute test period.

Successful completion of these tests validate previous acceptance tests.

**Non Destructive Examination:** Fracture critical dye penetrant inspection of the tank shell, fracture critical radiographic examination of the tank girth weld, and radiographic examination of PMD components are conducted to insure that the tank shell integrity and the PMD structure integrity have not been compromised after each pressure or vibration test.

**Final Examination:** A final visual inspection is conducted to verify that no damages are done to the tank as a result of the acceptance testing. The weight of the tank is also recorded. The maximum weight limit is 28.9 pounds. A typical HS 601 tank weighs 26.6 lbs.

**Cleanliness Verification:** The HS 601 flight tank is final cleaned to the cleanliness level specified in Table 5:

**Table 5: HS 601 Tank Final Cleanliness Level**

Particle Size Range (Microns)	Maximum Allowed per 5000 ml
Less than 5	No silting of particles
6 to 10	60,000
11 to 25	10,000
26 to 50	2,500
51 to 100	250
Over 100	None

**QUALIFICATION TESTING**

The Qualification Test Program for the HS 601 propellant tank included acceptance tests followed by a sequence of qualification tests. PMD functional tests and radiographic

inspections were performed at intervals throughout the test program to verify the PMD integrity and performances. External leak tests and radiographic inspections were also performed at intervals to verify shell integrity. The qualification tests are listed below:

- Acceptance tests
- Dry sinusoidal vibration, qualification level
- PMD bubble point test
- Radiographic inspection of tank shell
- Radiographic inspection of PMD
- Wet random vibration
- PMD bubble point test
- External leakage
- Radiographic inspection of tank shell
- Radiographic inspection of PMD
- Pressure cycle
- External leakage
- Acoustic test
- PMD bubble point test
- Radiographic inspection of tank shell
- Radiographic inspection of PMD
- Collapse pressure
- External leakage
- Dry sinusoidal vibration
- PMD bubble point test
- External leakage
- Penetrant inspection of tank shell
- Radiographic inspection of tank shell
- Radiographic inspection of PMD
- Final examination
- Burst pressure test

**Dry Sinusoidal Vibration, Qualification Level:** The qualification level sinusoidal vibration test setup is identical to the acceptance sinusoidal vibration test setup, except that strain gauges are installed on the qualification tank near each support to measure axial and bending strains during vibration testing. The test requirements are listed in Table 6. The sweep rate is 2 oct/minute.

**Random Vibration:** The qualification random vibration test setup is identical to the qualification level sinusoidal vibration test setup, including strain gauge installation. The random vibration test requirements are listed in Table 7. The test duration is 3 minutes per axis. Peak responses of the random vibration runs are limited to 10 g for X and Y axes and 12 g for Z axis.

**Pressure Cycles:** A total of 2 proof pressure cycles (0 to 325 to 0 psig) and 75 operating

pressure cycles (0 to 260 to 0 psig) were conducted on the Qualification Tank.

**Acoustic Test:** The test was conducted with the Qualification Tank suspended vertically by an elastic cord from a mounting assembly that is bolted to the propellant boss. The tank was subjected to the acoustic environment defined in Table 8.

**Collapse Pressure Test:** The collapse test was conducted by keeping the tank external pressure at ambient (14.7 psig) while evacuating the internal pressure to 10.7 psig. The pressure differential across the tank shell was held for a period of 15 minutes.

**Table 6: Qualification Level Sinusoidal Vibration Test Environment**

Axes	Frequency (Hz)	Acceleration (g 0-PEAK)	Displacement (DA)
X,Y, Z	5 - 10	-	13 mm (0.5 in)
	10 - 100	2.5	

**Table 7. Qualification Level Random Vibration Test Environment**

Axes	Frequency (Hz)	PSD		Grms
		(G <sup>2</sup> /Hz)	(dB/OCT)	
X,Y,Z	20 - 50	0.076	+6	6.14
	50 - 200		-6	
	200 - 390	0.020	-6	
	390 - 800		-6	
	800 - 2000		-6	

**Table 8. Acoustic Requirements**

Octave (Hz)	Envelope (dB)	Tolerance (dB)	Overall (dB)	Duration (Minutes)
31.5	129.1	±3	148.3 ± 1.5	3
63.0	134.7	±3		
125.0	140.0	±3		
250.0	144.1	±3		
500.0	142.9	±3		
1000.0	138.0	±3		
2000.0	132.0	±3		
4000.0	126.8	±3		
8000.0	124.0	±3		

**Destructive Burst:** After the completion of all the qualification tests, the Qualification Tank was subjected to a final destructive burst pressure test. The Qualification Tank burst at

555 psig, 165 psi (42%) over the design burst pressure of 390 psi.

**PMD VERIFICATION**

PMDs are generally not ground testable because they are designed to operate in or near “0 g” environment. The industry has to rely on analyses to verify PMD capability. Additionally, since the most challenging task for the PMD is near the end of a mission when the tanks are nearly depleted, the actual proof of the PMD functionality cannot be verified usually until 10 to 15 years after launch. However, a recent event accelerated the HS 601 PMD verification.

On March 25, 1993 the UHF Follow-on F-1 satellite, a 6,319 lb. HS-601, was stranded in the wrong orbit. The 136 mile perigee was as planned, but the apogee was 3,500 miles short of the 9,000 mile target. The satellite checked out as healthy but would use up all its on-board fuel getting to its intended orbit and therefore was declared a total mission failure by the Navy.<sup>5,6</sup>

Hughes engineers took advantage of this situation to verify that the PMD was able to operate down to very low fill fractions and perform the end of life maneuver. The PMD worked flawlessly. When the propulsion was terminated, it was estimated that of over three thousand pounds of hydrazine and nitrogen tetroxide, there was less than one pound of usable fuel left. This successful maneuver demonstrated that this PMD functioned as designed.

### **PROTON LAUNCH AND GROUND HANDLING**

The PMD was designed for handling in the upright outlet down orientation of Figure 1. Launching the HS 601 satellite on the Russian Proton launch vehicle raises two issues:

- (1) For Proton launch, the satellite is rotated 90° into a sideways orientation after the tanks are loaded with propellant and pressurized to PAD pressure. The satellite is then transported on railroad tracks for several kilometers before the booster and the satellite are tipped upright for launch. Situating the tanks at 90 degrees when filled and the slosh environment during the railroad transport were not analyzed prior to qualification.
- (2) The PMD was originally analyzed for a minimum of 70% fill fraction. However, at

70% fill fraction, the Proton booster cannot insert the satellite mass into orbit. Fortunately, the Proton booster can inject the satellite directly into geosynchronous orbit, thus allowing a significant amount of propellant to be off loaded. The off loading of the tanks below 70% fill fraction was not analyzed prior to qualification.

The fundamental problem of the Proton launch for the HS 601 propellant tank is simply the minimization of gas ingestion into the PMD trap. Several operations can be taken to allow a Proton launch:

- Tip the tank during tank fill to minimize trapped gas volume;
- Maintain a fill fraction high enough to ensure no propellant leaves the trap;
- Maximize the tank pressure during Proton handling to minimize trapped gas volume.

The recent successful launch of the HS 601 ASTRA 1F spacecraft indicated that the HS 601 propellant tanks can indeed be launched from the Russian Proton launch vehicle.

### **CONCLUSION**

The HS 601 propellant tank has a robust design which allows simple ground handling and superb operations both during ascent and while on orbit. The tank’s PMD has been proven effective for all phases of a mission, including the final end-of-life maneuver.

The HS 601 PMD is functionally one of the most complex PMD ever built. It relies on a combination of several PMD components to achieve the mission objective. However, its modular design allows easy fabrication, assembly, and installation. A HS 601 tank can be fabricated, tested, and delivered within ten months.

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