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ABSTRACT

The HS 601 line of communication satellites was introduced by Hughes Space and Communications Company (HSC) in 1987. It was the company's first body-stabilized spacecraft model, and also has become the world's best selling spacecraft. An enhanced version, called the HS 601HP, has been developed to provide increased power capabilities.

The HS 601HP spacecraft's propellant needs are provided by four tanks that are identical in material and construction. Each tank assembly is fabricated from two 6AL-4V Titanium alloy hemispherical heads that are joined to a central cylindrical section. A passive Propellant Management Device (PMD) is installed into the propellant hemisphere prior to tank closure. The PMD provides continuous gas-free propellant delivery to the satellite thrusters.

The HS 601HP (Block II) propellant tank is essentially a modification of the original HS 601 (Block I) propellant tank. These Block II tanks operate under similar conditions as the Block I tanks and are installed within a similar spacecraft structure. The development of the Block II tank maximized the Block I tank shell and PMD design heritage, manufacturing technology and tooling to minimize the non-recurring cost and the long lead time of developing a new tank. The Block II tank shell is nearly identical to the Block I tank shell

except for the addition of the cylindrical center section. The Block II PMD is a modification of the Block I PMD. The PMD modifications include lengthening the four vanes to accommodate the propellant flow over the cylindrical center section, enlarging the sponge capacity to hold more propellant, and enlarging the trap inlet window to accommodate increased propellant flow rate. An additional modification was made to the trap to enhance manufacturability.

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. These analyses fully utilized the existing analyses already perform on the Block I tank.

Acceptance and qualification testing include testing the tank shell integrity as well as the PMD functionality. Forging qualification was not needed since the same forging is used to make the Block I tanks. A full qualification program was conducted to validate the new tank shell and PMD designs, including pressure cycle test, vibration test, PMD bubble point test, and a final destructive burst pressure test. The tank qualification program was completed in 1997.

A total of 14 tanks have been fabricated as of June 1998, and 8 more are on order.

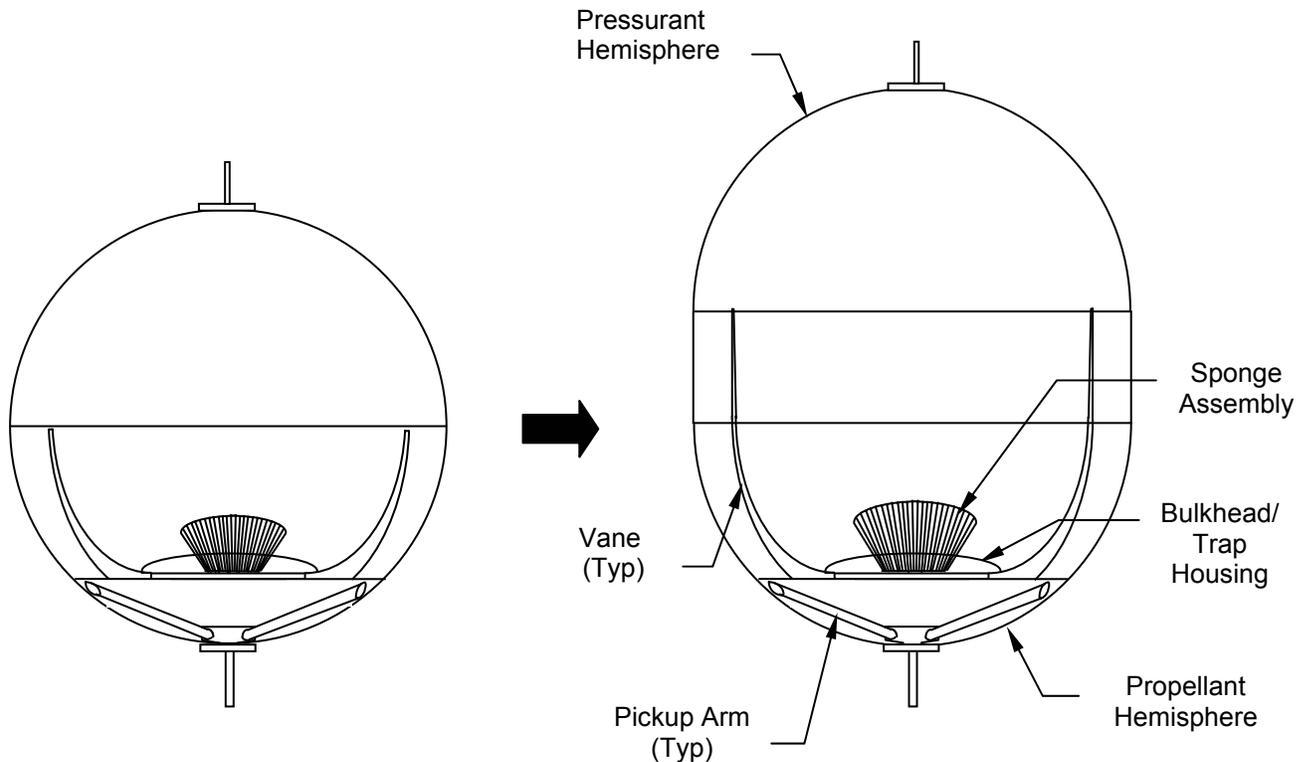
INTRODUCTION

The HS 601 model spacecraft was introduced in 1987. It enjoys the distinction as the world's most popular and best-selling spacecraft. Each spacecraft carries four (4) identical propellant tanks, two for the monomethylhydrazine (MMH) fuel and two for the nitrogen tetroxide (NTO) oxidizer. This original HS 601 (Block I) propellant tank was developed in 1987/88¹. It is a 35-inch diameter spherical tank 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. Each tank has a minimum capacity of 22,450 in³ and operates at 260 psig. 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. After this end-of-life maneuver, the remaining propellant on the spacecraft is estimated at less than one pound. Over 200 of these Block I tanks have been produced to date.

An enhanced version of the HS 601 spacecraft, called the HS 601HP (High Power), has been developed by HSC to provide increased power capabilities. The propellant requirement onboard the HP spacecraft exceeds the Block I tanks' capacity. Development effort started in 1996 to construct a Block II propellant tank that installs in a similar spacecraft structure and operates in a similar environment as the Block I tank, but with an additional 10,160 in³ of internal volume. To maximize design and manufacturing heritage and minimize non-recurring costs and the long lead time, the Block II tank utilizes the same hemispherical heads as the Block I tank. The additional internal volume comes from adding a cylindrical center section between the two hemispheres, as illustrated in Figure 1.

Figure 1: The HS 601 Block II Propellant Tank, Design Heritage



A passive Propellant Management Device is installed in the Block II tank to provide gas-free propellant delivery to the spacecraft thrusters. This PMD is also similar to the Block I PMD as shown in Figure 1, except several modifications were made to customize the PMD to the new tank configuration. The PMD is installed within the propellant hemisphere prior to the tank closure weld.

The Block II propellant tank was designed to the requirements listed below in Table 1:

Table 1: HS 601 Block II Propellant Tank Design Requirements

PARAMETERS	REQUIREMENTS
Operating Pressure	260 psid
Proof Pressure	325 psid
Burst Pressure	390 psid
Tank Capacity	32,610 in ³ minimum
Propellant Load	1,660 lbm
Size	35 in diameter x 46.4 in long
Expulsion Efficiency	99.5% minimum
Tank Weight	41.0 lbm maximum
Shell Leakage	< 1 x 10 ⁻⁶ std cc/sec Helium
Service Life	20 years
Operating Temperature	28 °F to 122 °F

PMD INTRODUCTION

The HS 601 Block II propellant tank 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.

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

Since the Block I PMD design concept is valid for the Block II PMD, the Block I PMD was

modified to accommodate the requirement changes and the impact of the new tank shape.

PMD DESIGN

There are two classic categories of PMD's: control devices and communication devices². Control devices are able to deliver a fixed quantity of propellant while communication devices offer unlimited duration operation. Because the HS 601HP mission, like the original HS 601 mission, requires fixed quantity propellant delivery for most maneuvers, a control PMD is feasible. A communication PMD could meet the mission requirements but the PMD chosen for this mission is the most robust, reliable and lightweight design available.

The 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 Block II PMD: the sponge and the trap.

The five requirement differences between HS 601 Block I and HS 601 Block II tanks are:

- (1) The Block I tank is a spherical tank made from two hemispherical heads, while the Block II tank uses the same hemispherical heads but is extended with a center cylinder.
- (2) The maximum system priming flow rate on Block II increased by 10% over Block I.
- (3) The apogee acceleration decreases as the vehicle mass increases.
- (4) The on-orbit stationkeeping propellant use per maneuver on Block II increased by 50% over Block I.
- (5) The operational temperature range is extended on Block II.

The changes in tank shape, system priming flow rate, and stationkeeping demand resulted in changes to the original HS 601 PMD. The other requirement changes were addressed analytically. The HS 601 Block II PMD concept and configuration is unaltered from the original HS 601 PMD.

Both PMD designs use a trap with an outboard trap inlet window to access propellant during the spinning phases of mission and a sponge, positioned over the trap inlet window, to provide the propellant required for each of the repetitive maneuvers such as stationkeeping.

A pickup assembly is used within the trap to access propellant, and vanes are used to refill the sponge during the coast periods between stationkeeping maneuvers.

Since the HS 601HP mission is nearly identical to the original HS 601 mission, the PMD designs are nearly identical.

PMD DESCRIPTION

The HS 601 Block I and Block II PMD designs incorporate the following components:

- Trap
- Sponge assembly
- Vanes
- Pickup assembly

Three changes to the HS 601 Block I PMD design were required for the HS 601 Block II PMD:

- (1) The vanes were extended into the upper hemisphere to ensure sponge refilling.
- (2) The sponge capacity was increased by 50% to allow for longer duration stationkeeping firings.
- (3) The trap inlet window flow area was increased by 10% to accommodate the system priming flow rate increase.

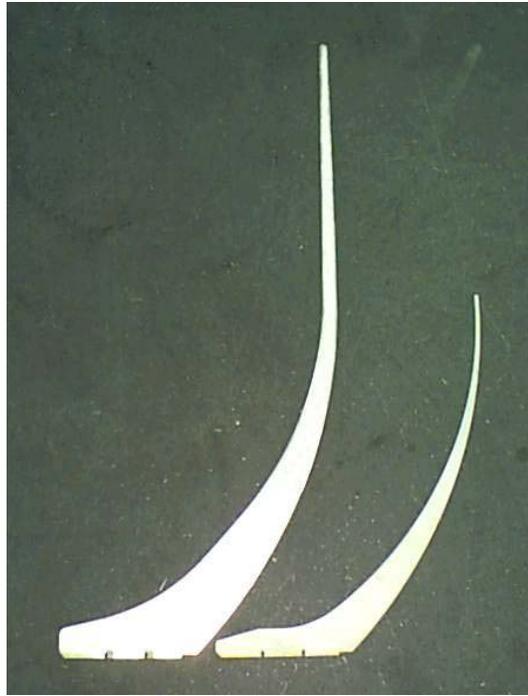
All other PMD components are identical to the original Block I PMD design.

Vane Changes: The vanes were extended to the cylinder/upper hemisphere junction to ensure access to any propellant in the upper hemisphere. This is the only change to the PMD required by the addition of the cylindrical section, although much of the PMD analysis had to be revisited. Figure 2 shows the original Block I vane and the new, longer Block II vane.

Without the vane extension, any propellant in the upper hemisphere would become isolated and inaccessible to the PMD during zero-g

coast. This would hamper sponge refilling and result in premature gas ingestion.

Figure 2: The HS 601 Block II and Block I PMD Vanes



Sponge Changes: The sponge capacity was increased to provide 50% more propellant. This was accomplished using the same sponge form and footprint. The sponge height was increased from 3.75 to 4.25 inches and the number of sponge panels was increased from 33 to 41 (thereby reducing the gaps between panels). The sponge panel thickness, width and support structure were unchanged.

By changing both the sponge volume and the number of panels, the sponge deliverable propellant volume was increased with a minimal weight increase.

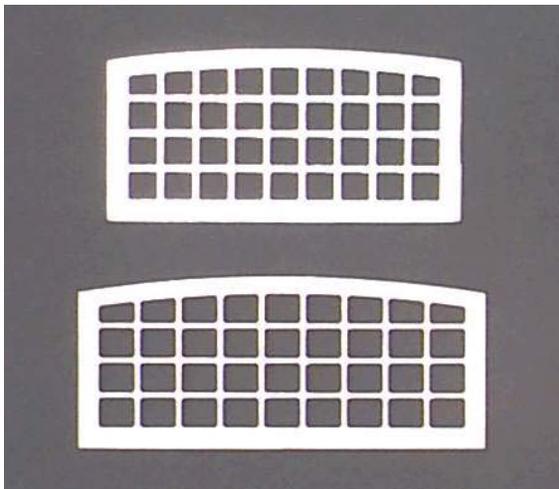
A comparison of the two sponges is shown below in Figure 3.

Figure 3: The HS 601 Block II and Block I Sponge Assemblies



Trap Inlet Window Changes: The trap inlet window size was increased to accommodate 10% higher system priming flow rates. This was accomplished by "stretching" the window panes lengthwise and maintaining the same window depth. By maintaining the same window depth, the access to propellant during low fill fraction spin operations would not change. If the depth had been increased, the window would be positioned further inboard and propellant access during spin restricted. The trap inlet window is shown in Figure 4.

Figure 4: The HS 601 Block I and Block II Trap Windows



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 3 square inches of screen.

Trap Changes: The original Block I PMD trap meets the Block II mission requirements and a design change was not needed. However, PSI took advantage of the trap inlet window size adjustment and incorporated several new features to the trap. The design improvement

enhanced the manufacturability of the Block II PMD.

PMD CHARACTERISTICS

Several key characteristics make the Block II 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.

Secondly, the design is constructed entirely of titanium. Thus the PMD is lightweight and offers exceptional compatibility, long life, and reliability.

Thirdly, 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.

Fourthly, 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.

Finally, the HS 601 Block II PMD uses the heritage of the HS 601 Block I PMD to ensure success. The HS 601 Block I PMD has flown more than 40 missions with no flight failures.

DESIGN ANALYSES

The HS 601 Block II tank design analysis approach used assumptions, computer tools, and experimental data utilized on a majority of the pressure vessels successfully designed, fabricated, tested and qualified during the past three decades. An added advantage of this task over other design efforts is its similarity to the Block I tank which was analyzed, designed, fabricated and tested by the same team of engineers assigned to this task. The approaches and tools used were very similar to this successful Block I tank. The additional data available from the Block I tank, especially the vibration test data, validated and

established the degree of analytical accuracy in select areas.

The tank design analyses included stress analysis and fracture mechanics analysis for the tank shell, stress analysis for the PMD, and the PMD performance analysis. Since the PMD is completely enclosed within the tank shell, by definition a fracture mechanics analysis is not required for the PMD.

Tank Shell Stress Analyses: The stress analysis establishes the design that meets the requirements specified in Table 1. The procedure and assumptions were almost identical to those used in the Block I tank analysis. This analysis took into consideration the design parameters such as:

- Temperature environment
- Material properties of tank shell
- Material properties of weld
- Mass properties of tank shell material
- Fluids used by the tank
- Mass properties of fluid
- Tank pressurization history
- Tank mounting
- Tank orientation
- Tank boundary conditions
- Stiffness
- External loads
- Girth weld offset
- Weld suck-in
- Residual stress in girth weld
- Size of girth weld bead
- Design safety factors
- Resonant frequencies
- Load reaction points

The computer analysis is similar to the computer analysis used to design the HS 601 Block I tank. A finite difference program was used to calculate the pressure and external load stresses in the shell. Sufficiently small elements were used to provide local stress distribution in the shell due to anticipated weld mismatch and other discontinuities at shell or thickness transitions. This approach has proven to provide very accurate stress variations at transition locations in the shell. Wherever possible, the test data from the Block I tank were used because test data were considered more accurate than computer predictions. The stress analyses include:

- Tank shell, membrane

- Tank shell, boss regions
- Tank shell, weld regions
- PMD to outlet port weld
- PMD, trap housing

The stress analysis concluded with positive margins of safety for all design parameters. Table 2 below summarizes the safety margins on all critical areas.

Table 2: Block II Propellant Tank Safety Margins

Area	M.S.
Membrane, burst	+0.07
Sphere, membrane, proof	+0.04
Sphere, membrane, launch	+0.31
Cylinder, membrane, burst	+0.07
Cylinder, membrane, proof	+0.05
Cylinder, membrane, launch	+0.35
Girth weld, burst	>0.00
Girth weld, proof	+0.08
Bulkhead interface, burst	+0.02
Bulkhead interface, proof	+0.09
Bulkhead interface, operating	+0.30
Pressurant boss, yield	+0.36
Pressurant boss, ultimate	+0.47
Propellant boss, yield	+0.02
Propellant boss, ultimate	+0.11
Buckling axial load, propellant boss	+0.00
Tensile buckling, propellant boss	+1.15
Buckling, pressurant boss	+0.01

Fracture Mechanics Analysis: A fracture mechanics analysis was performed to establish whether a final crack, resulting from a maximum initial crack and its growth due to cyclic and sustained loading in the anticipated environment, is sufficiently small to meet the requirements placed on the pressure vessel. The fracture control analysis and design techniques were applied to the flight tanks to preclude service failures caused by the propagation of surface flaws. The design

The fracture mechanics analysis was performed using NASA/FLAGRO, and conservative assumptions and parameters were used to show that the design satisfied the fracture mechanics requirements. The minimum thicknesses were used in performing the fracture mechanics analysis. A special fracture critical radiographic inspection method was used to detect imbedded or part-through flaws. A special dye-penetrant method was also used to detect flaws on interior and exterior surfaces. The analysis was performed in the following regions:

- Tank shell, spherical membrane
- Tank shell, cylindrical membrane
- Tank shell, bulkhead region
- Tank shell, bosses
- Tank shell, welds

The analysis result shows that the tank 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 PMD's 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 specific phase of the mission. First, the impact of Ground Operations on the PMD was examined. Secondly, the impact of the operation during Ascent Operations was examined. And finally, the functionality of the PMD during all Orbital Operations was analyzed.

All of the analyses were reviewed and revised to incorporate the PMD design changes as well as the mission requirement changes.

The following PMD analyses were reviewed and revised for the HS 601 Block II PMD:

- PMD General Design Analyses, including:
 - Trap inlet window sizing
 - Sponge 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, trap, and pickup design and analysis can be found in the series of papers entitled "Propellant Management Device Conceptual Design and Analysis: Vanes (Sponges or Traps and Troughs or Galleries)" by D.E. Jaekle, Jr.^{3,4,5,6}

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

PMD Stress Analyses: A PMD stress analysis was conducted to verify that the Block II PMD met all the program requirements. The analysis approach was simplified since the Block I PMD has been successfully operated, and only the design changes and the hardware affected by the changes were included in the analysis. The stress analysis procedures and assumptions were identical to those used in the

Block I PMD analysis. The stress analysis concluded with positive margins of safety for all design parameters.

TANK FABRICATION AND ASSEMBLY

The Block II propellant tank shell is machined from two 6AL-4V Titanium alloy hemispherical forgings and a 6AL-4V Titanium alloy cylindrical ring forging. Each forging 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. All finished tank shell components are radiographic and penetrant inspected prior to assembly weldment.

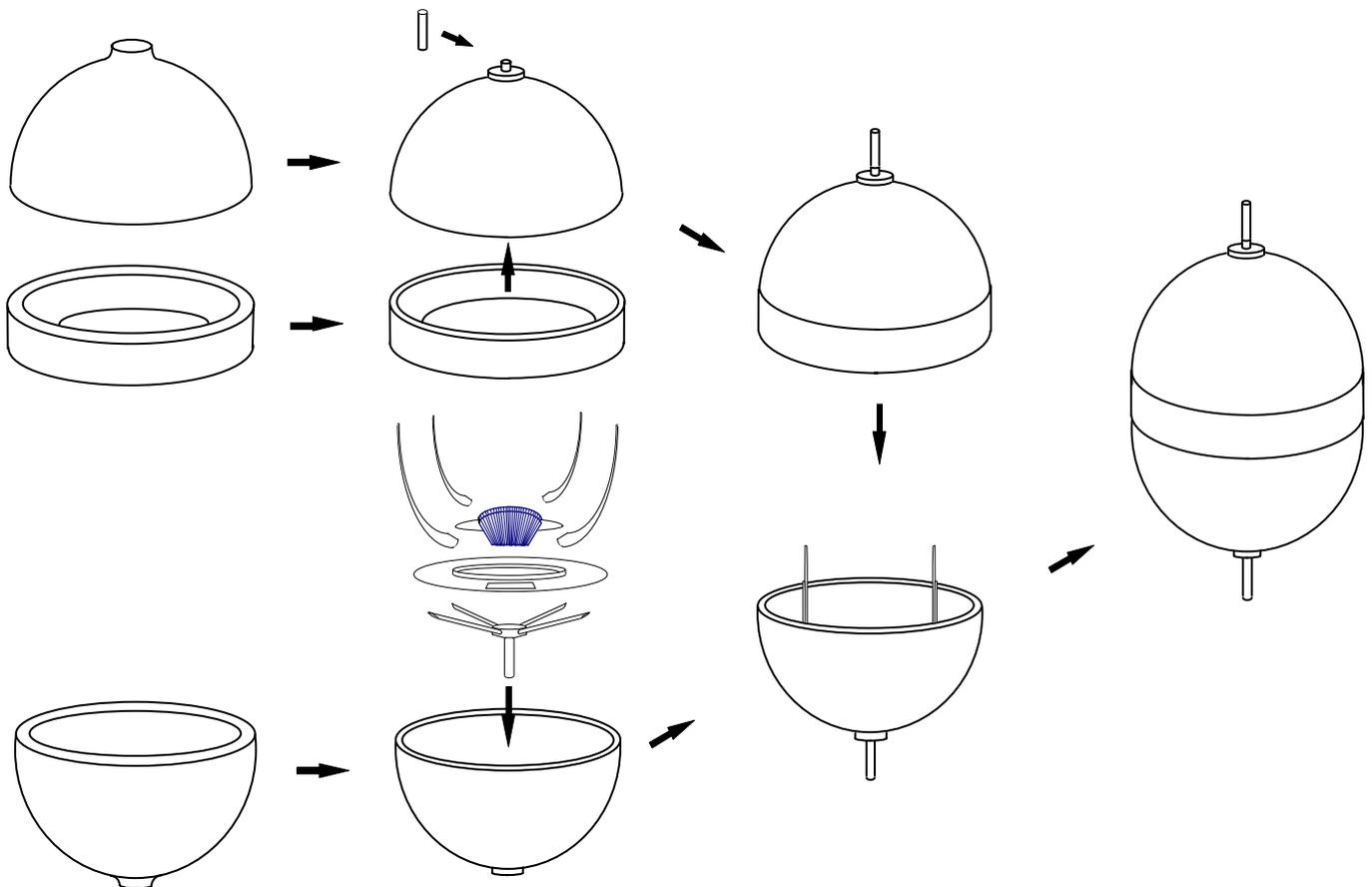
The PMD is installed in the propellant hemisphere prior to the tank closure weld. This PMD is assembled in several operations. First, the pickup assembly¹ is welded to the propellant hemisphere to make the hemisphere/pickup assembly. The trap housing is then welded over the pickup assembly to complete the trap assembly. This trap assembly must complete an in-process

PMD functional test and meet a minimum bubble point requirement prior to next assembly. The sponge assembly and the four vanes are installed above the trap housing to complete the expulsion assembly.

On the pressurant side, the cylindrical center section is automatic Tungsten Inert Gas (TIG) welded to the pressurant hemisphere to form the pressurant hemisphere assembly. This pressurant hemisphere assembly and the expulsion assembly are then TIG welded together to complete the tank weldment. Both girth welds are radiographic and dye penetrant inspected for weld defects. After the last girth weld, the propellant tank is stress relieved prior to acceptance testing. Following acceptance proof pressure test, the tank mounting bosses are faced to the final tank configuration.

A pictorial presentation of the Block II tank fabrication and assembly process is shown below in Figure 5.

Figure 5: HS 601 Block II Tank Manufacturing Flow



WEIGHT SUMMARY

The tank component weights are summarized below in Table 3.

Table 3: Weight Summary

Component	Weight (lbm).
Pressurant hemisphere	12.10
Propellant hemisphere	13.46
Center Section	6.95
Vanes	.76
Sponge assembly	1.33
Bulkhead assembly	2.18
Trap housing	.55
Manifold assembly	1.17
TOTAL WEIGHT	38.50

Each flight tank has a nominal weight of 38.5 pounds. This weight is 2.5 pounds below the specification requirement of 41.0 pounds.

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. The pickup arm window and the manifold window are also 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:

- Trap housing inlet screen assembly
- Pickup arm assembly
- Hemisphere/manifold assembly
- 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 series of acceptance tests prior to tank delivery. The tests are performed per the sequence listed:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- Dry sinusoidal vibration
- PMD functional test
- External leakage
- Penetrant inspection
- Radiographic inspection, tank shell & PMD
- Final examination and weight determination
- Cleanliness

Volumetric Capacity Examination: The volumetric capacity of the Block II propellant tank is measured using weight of the water method, using clean, filtered deionized (DI) water as the test medium. This test is conducted before and after the proof pressure test to verify that the proof pressure test does not significantly alter the tank capacity. A successful validation indicates that the tank shell is manufactured properly and that the tank can operate in the pressure environment for which it was designed. Typically, the volumetric growth after proof pressure test is zero.

The post-proof test capacity examination also serves to verify that the tank meets the designed volume requirement. Each tank must meet the minimum capacity of 32,610 in³.

Proof Pressure Test: The proof pressure test is typically the first pressurization cycle applied to the tank after fabrication. It is intended to provide evidence of satisfactory workmanship and material quality, as well as to establish the initial flaw size as analyzed in the fracture mechanics analysis. The test must be performed in a "safe" environment to minimize hazards to test technicians. This test is conducted hydrostatically at proof pressure (325 psi) for a pressure hold period of 5 minutes minimum.

Sinusoidal Vibration: The sinusoidal vibration test is designed to verify the PMD workmanship. The test is performed on an empty and vented tank. The 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. The sweep rate is 4 octaves per minute, and test duration is 1 minute per axis.

The vibration test fixture is designed to simulate the tank-to-spacecraft installation interface. The fixed-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.

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 pickup arm perforated windows, and the manifold assembly perforated window. Successful completion of the PMD functional

tests after the sinusoidal vibration test validates the PMD workmanship.

External Leak Test: The external leak test verifies the integrity of the tank shell and also serves to validate the prior pressure test. The tank is placed in a vacuum chamber, which is evacuated to under 0.2 microns of mercury, and helium pressurized to 270 psig for 30 minutes. The helium leak rate cannot exceed 1×10^{-6} std cc per second throughout the 30-minute test period.

Non-Destructive Examination (NDE): Fracture critical dye penetrant inspection of the tank shell, fracture critical radiographic examination of the tank girth welds, 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. Tank acceptance after NDE marks the successful completion of acceptance testing.

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 at this time. The maximum weight limit is 41.0 pounds. The HS 601 Block II tank has a nominal weight of 38.5 pounds.

Table 4: Acceptance Level Sinusoidal Vibration Test Environment

Axes	Frequency (Hz)	Acceleration (0-PEAK)	Displacement (in. D.A.)
Longitudinal (Z)	5.0 – 6.2	—	0.5 inch
	6.2 – 16.0	1.0 g	
	16.0 – 23.0	1.8 g	
	23.0 – 100.0	1.0 g	
Lateral (X,Y)	5.0 – 100.0	1.0 g	

Cleanliness Verification: After the non-destructive examination, the interior of each flight tank is cleaned to a cleanliness level specified by HSC.

QUALIFICATION TESTING

Since the Block II tank is a new design, a tank qualification program is required. A designated qualification tank was fabricated for the Qualification Test Program. The qualification tank was constructed the same as the flight tanks, using the same processes, procedure, and tooling.

The Qualification Test Program included acceptance tests followed by a series of qualification tests. Pass/fail criteria consist of acceptance type PMD functional tests, external leak test and non-destructive evaluation conducted at intervals throughout the test program to verify the PMD performance and tank shell integrity. A final burst pressure test was performed to verify minimum burst pressure and burst margin. A successful burst certifies the tank for flight use. The qualification tests are listed below:

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

Pressure Cycles: The pressure cycle test verified the pressure cycle requirements of the tank. A total of 50 operating pressure cycles from 0 to 260 to 0 psid and 12 proof pressure cycles from 0 to 324 to 0 psid were conducted. Pressure hold period was 5 seconds minimum at each peak pressure.

Acoustic Test: This test was conducted with the qualification tank suspended with a nylon net. The tank was subjected to the acoustic environment defined in Table 5 for a test duration of 120 seconds.

Qualification Level Sinusoidal Vibration, Dry: The qualification level sinusoidal vibration test setup is identical to the acceptance sinusoidal vibration test setup, except that strain gauges were 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 was 2 octaves per minute and the test duration was 3 minutes per axis.

Qualification Level Sinusoidal Vibration, Loaded and Pressurized: This qualification level sinusoidal vibration test setup is identical to the dry sinusoidal vibration test setup, including strain gauge installation. The qualification tank is loaded with 1,660 pounds of test fluid and pressurized to 50 psig. The test requirements are listed in Table 7. The sweep rate is 2 octaves per minute and the test duration was 3 minutes per axis.

Qualification Level Random Vibration, Loaded and Pressurized: This test was conducted immediately after the sinusoidal vibration test. The vibration test requirements are listed in Table 8. The test duration was 3 minutes per axis. Peak responses of the random vibration runs were limited to 7.1 g for X and Y axes and 12 g for the Z axis.

Collapse Pressure Test: The collapse pressure test was conducted by keeping the tank external pressure at ambient while evacuating the tank to achieve a pressure differential of 3.7 psid across the tank membrane. The pressure differential was held for a period of 15 minutes.

Destructive Burst: After the completion of all the qualification tests, the qualification tank was subjected to a final destructive burst pressure test. Prior to burst, the qualification tank was gridded and the tank thicknesses at the grid line intersections were recorded. The qualification tank burst at 581 psig, and the wall thickness at the point of rupture measured 0.027 inch. Based on the above, the burst pressure was normalized to 454 psi, or 16% above the design burst pressure of 390 psi.

Table 5: Acoustic Requirements

1/3 Octave Band Center Frequency (Hz)	Qualification Envelope SPL (dB)	Test Tolerance (dB)
25.0	126.0	-6 + 0
31.5	123.3	-2.4 + 3.6
40.0	126.6	-3 + 3
50.0	128.2	-2.2 + 1.8
63.0	129.9	-1.9 + 2.1
80.0	131.0	-1.2 + 2.8
100.0	133.0	-1.5 + 2.5
125.0	135.9	-2.9 + 1.1
160.0	136.4	-1.4 + 2.6
200.0	137.8	-1 + 3
250.0	139.0	-1 + 3
315.0	137.7	-1 + 3
400.0	135.0	-1 + 3
500.0	133.0	-1 + 3
630.0	131.3	-1.7 + 2.3
800.0	129.9	-2.3 + 1.7
1000.0	127.0	-1 + 3
1250.0	125.6	-1 + 3
1600.0	124.4	-1 + 3
2000.0	123.9	-1.8 + 2.2
2500.0	121.8	-1 + 3
3150.0	120.4	-3.2 + 2.8
4000.0	119.1	-3.6 + 2.4
5000.0	117.8	-3.3 + 2.7
6300.0	116.7	-3 + 3
8000.0	116.9	-3 + 3
10000.0	117.8	-3 + 3
Overall SPL	146.4	-1.4 + 2.6
Duration	120 seconds	± 5%

Table 6: Qualification Level Sinusoidal Vibration Test Environment, Dry

Axes	Frequency (Hz)	Acceleration (0-PEAK)	Displacement (in. D.A.)
Longitudinal (Z)	5.0 – 7.0	—	0.5 inch
	7.0 – 16.0	1.25 g	
	16.0 – 23.0	2.25 g	
	23.0 – 100.0	1.25 g	
Lateral (X,Y)	5.0 – 100.0	1.25 g	

Table 7: Qualification Level Sinusoidal Vibration Test Environment, Loaded and Pressurized

Axes	Frequency (Hz)	Acceleration (0-PEAK)	Displacement (in. D.A.)
Lateral (X,Y)	5 – 9.9 9.9 – 100	2.5 g	0.5 inch
Longitudinal (Z)	5 – 11.9 11.9 - 100	3.6 g	0.5 inch

Table 8: Qualification Level Random Vibration Test Environment, Loaded and Pressurized

Axes	Frequency (Hz)	PSD		Grms
		(G²/Hz)	(dB/OCT)	
X,Y,Z	20	0.0029		9.42
	20 – 118		+6	
	118 – 560	0.1		
	560 – 2000		-6	
	2000	0.008		

CONCLUSION

The development of the HS 601 Block II propellant tank optimized the Block I tank design heritage and the use of tooling, manufacturing technology and documentation. This process produced a highly reliable and easily manufacturable product, minimized the cost of designing a new tank, and significantly reduced the development cycle.

The HS 601 Block II propellant tank is a well designed, high quality spacecraft component that meets or exceeds all the design requirements. Its PMD is capable of 99.6% expulsion efficiency, which is 0.1% over the design requirement. This higher expulsion efficiency will provide each spacecraft with an extra 6.6 pounds of propellant. Additionally, each Block II tank has a nominal weight of 38.5 pounds, which is 2.5 pounds under the design requirement. This translates into a 10-pound weight savings for each spacecraft.

The HS 601 Block II propellant tank has a robust design which allows simple ground handling and superb operations both during ascent and while on orbit. Its PMD design has

been proven effective for all phases of a mission, including the final end-of-life maneuver.

The HS 601 Block II 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 for easy fabrication, assembly, and installation. A HS 601 Block II tank can be fabricated, tested, and delivered within eight months.

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