# DESIGN AND MANUFACTURE OF THE MESSENGER PROPELLANT TANK ASSEMBLY

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## ABSTRACT

An ultra-lightweight propellant tank was required for the MESSENGER spacecraft, and a new tank development program was conducted to design, fabricate, and test this tank. The development program was conducted in three phases: trade study, analysis and design, and hardware fabrication and test.

Phase 1 trade study was conducted to determine the most weight efficient tank design. This phase was done primarily by analysis with multiple iterations. Over 50 tank configurations were considered before a final selection was made.

Phase 2 design and analysis included efforts to design and analyze a vortex suppressor, anti-slosh baffle for nutation control during launch, and tank shell. The effort included subscale drop tower simulations to determine the number, size and location of anti-slosh baffle, analytical determination of the loads on the vortex suppressor and baffle, baffle structural analysis, and tank shell stress and fracture mechanics analyses.

Phase 3 fabricated a qualification tank and four flight tanks (3 flight and a spare). The tank shell components were fabricated from solution treated and aged (STA) 6AL-4V titanium alloy. The anti-slosh baffles were machined from annealed 6AL-4V titanium ring forgings, and the vortex suppressors were fabricated from 6AL-4V titanium sheets. The tank shell was assembled with 4 girth welds-two of which were made to have STA properties, and the remaining two were annealed closure welds that were also baffle installation welds. All 5 tanks were fabricated using identical processes and procedures.

The qualification tank must undergo a qualification test program that includes loaded sine and random vibration testing. The qualification test program is to conclude with a destructive burst pressure test. All flight tanks are protoflight tested prior to precision clean and delivery.

The completed flight tank has a mass of less than 20 pounds, including attachment hardware. This ultra-lightweight tank will play a critical role toward the success of the MESSENGER Program.

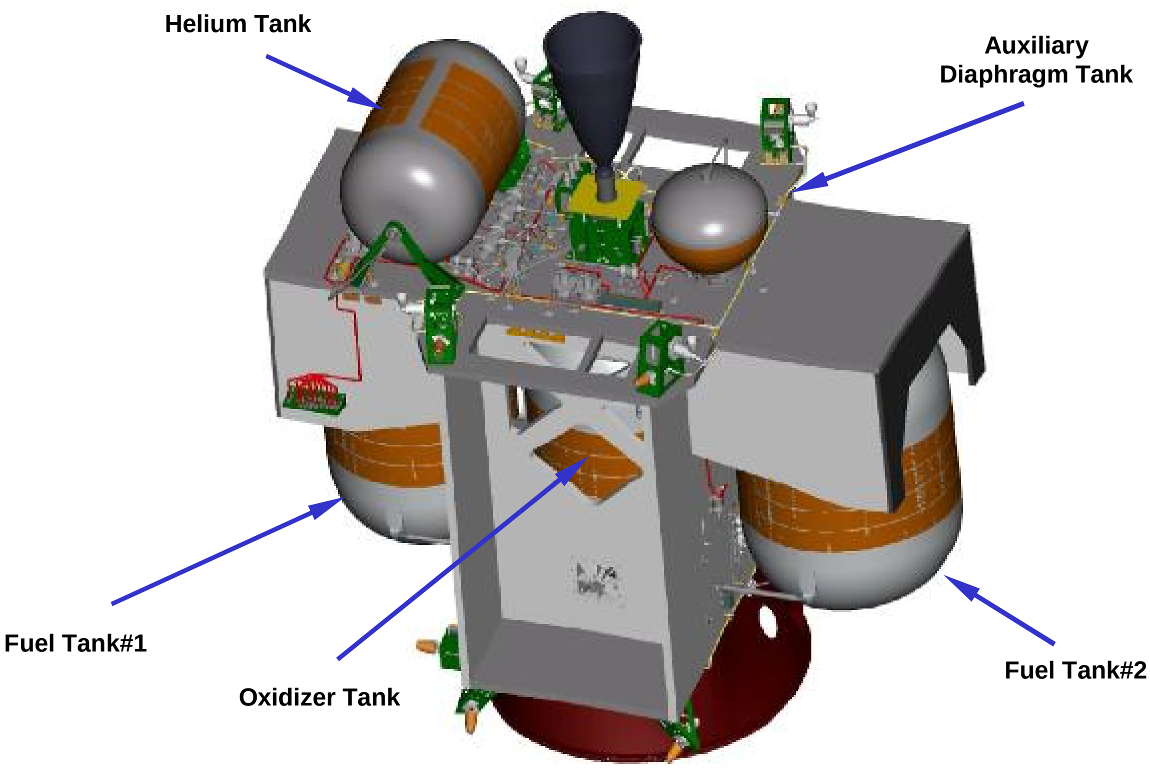
## INTRODUCTION

In 2000 Pressure Systems, Inc. (PSI) was contracted to provide a full complement of propulsion system tanks for the MESSENGER spacecraft. These tanks include a 12-inch diameter elastomeric diaphragm tank, a 16-inch diameter by 30-inch long COPV helium presurrant tank, and three 24-inch diameter main propellant tanks-two fuel and one oxidizer-of the same configuration. See Figure 1. Both the diaphragm and pressurant tanks are derivatives of existing PSI tank designs which required no development. However, the main propellant tank required significant effort for development and qualification.

The MESSENGER propellant tank development program drew heritage from the NEAR program propulsion system tank development[1]. There were many similarities between the two programs, such as the initial trade study, the development of a vortex suppressor, and the propellant management philosophy of using a diaphragm tank to allow settling burns to settle propellant at the tank outlet prior to the start of main engine burns. However, there were also new challenges, such as the analysis and development of anti-slosh baffles, and the design, analysis, and test of a tank that's launched in an upside down orientation (outlet side on top).

The main propellant tank development program was separated into three phases: (1) trade study, (2) analysis and design, and (3) fabrication and test.

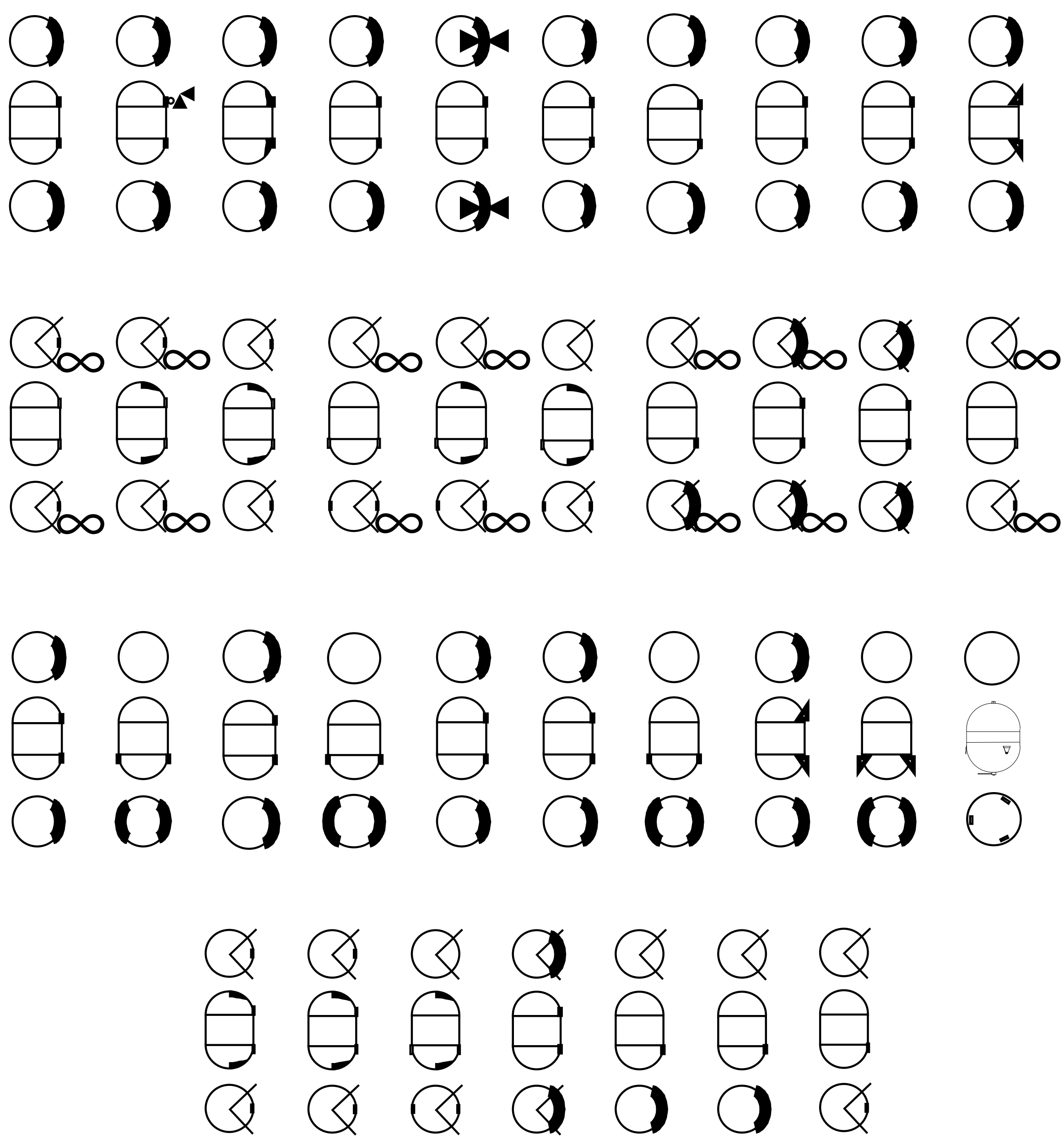
**Figure 1, MESSENGER Propulsion System Tanks**



## PHASE 1, TRADE STUDY

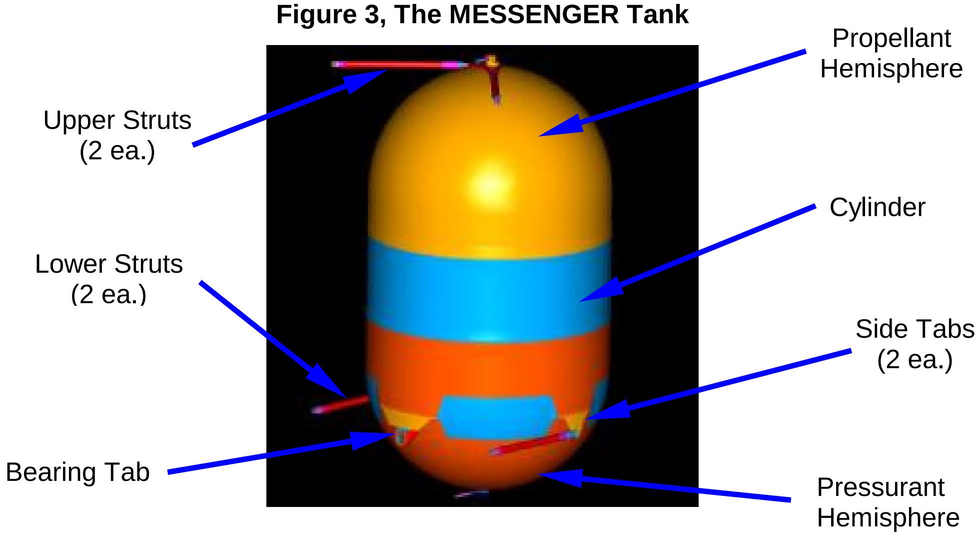
The goal of the phase 1 trade study was to determine a tank configuration that offers the lowest tank mass. This was a 3-month long effort involving several analytical iteration and repeated reviews. Factors considered in the trade study included tank diameter, resonant frequency, tank shell thickness, tank shell transition, types of tank mounts (flange, tabs, struts), location of tank mounts, size (length, width and thickness) of mounting tabs, risk, and cost. Over 50 tank configurations were considered. Figure 2 below provide a sample of tank configurations considered in the trade study.

**Figure 2, Some Tank Configurations Considered in the Trade Study**



At the conclusion of the trade study, a tank configuration as shown in Figure 3 was selected for analysis and detail design.

**Figure 3, The MESSENGER Tank**




The propellant tank specification requirements are listed below in Table 1:

**Table 1: Propellant Tank Assembly Design Requirements**

| Parameters | Requirements |
|---|---|
| Operating Pressure | MEOP is 325 psia @ 50°C (122°F), 100 cycles |
| Proof Pressure | 406 psia @ 50°C (122°F), 16 cycles |
| Burst Pressure | 488 psia minimum @ 50°C (122°F), |
| Material of Construction | Membrane: 6Al-4V titanium, solution treated and aged<br>Inlet/outlet ports: 3Al-2.5V titanium<br>Vortex suppressor: 6AL-4V titanium<br>Baffles: 6AL-4V titanium |
| Expulsion Efficiency | 99.75% minimum |
| Propellant Weight | 611 lbm (277 kg) maximum nitrogen tetroxide |
| Propellant Fill Fraction | 85% minimum, 95% maximum |
| Tank Capacity | 12,150 $in^3$ (199.1 liters) minimum |
| Internal Dimension | 22.14" ID x 39.175" long |
| Propellant Flow Rate | 8.7 gpm minimum |
| Overall Length | 40.95", boss to boss |
| Tank Weight | 20.9 lbm (9.5 kg) maximum |
| Propellant | Hydrazine and Nitrogen tetroxide |
| Fluid Compatibility | $N_2H_4$, $N_2O_4$, GAr, GHe, $GN_2$, D.I. water, Isopropyl alcohol |
| Shell Leakage | $<1x10^{-6}$ std cc/sec He @ 325 psia |
| Natural Frequency | > 30 Hz in lateral direction, > 35 Hz in thrust direction |
| Failure Mode | Leak Before Burst |
| On-Orbit Temperatures | 50 to 122 °F (10 to 50 °C) |
| Shelf Life | 5 years minimum |
| Operating Life | 8 years minimum |
| Range Safety | Per EWR 127-1 October 1997 |

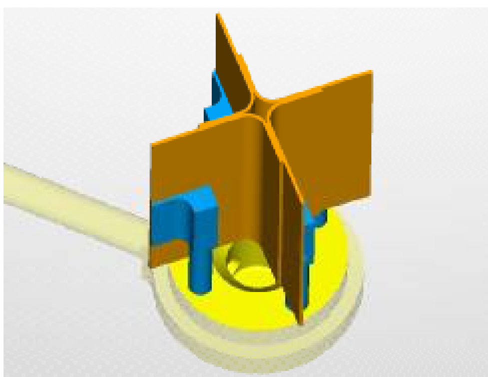
## PHASE 2, ANALYSIS AND DESIGN

Several design analyses were performed to design the MESSENGER Propellant Tank. These analyses include vortex suppressor structural verification, baffle design and structural load analyses, and stress and fracture mechanics analyses for the tank shell.

## VORTEX SUPPRESSOR AND VORTEX SUPPRESSOR LOAD ANALYSIS

The MESSENGER vortex suppressor is based on the NEAR vortex suppressor design and configured as a four-vane cruciform. It is positioned directly above the propellant outlet, as shown in Figure 4.

**Figure 4, The MESSENGER Tank Vortex Suppressor**



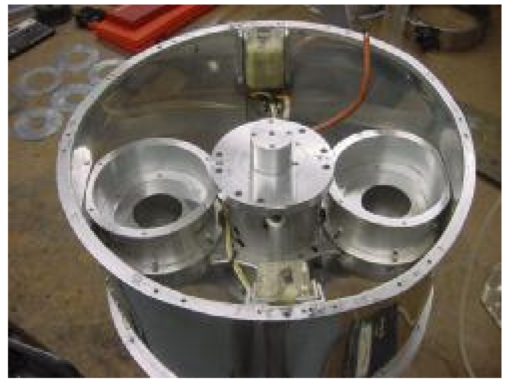
A structural analysis was performed to validate the vortex suppressor design. As noted before, the MESSENGER propellant tank is oriented upside down during the launch sequence, thus the vortex suppressor is always dry during launch. The only factors considered during vortex suppressor analysis were pad slosh and vibration. It was found that pad slosh exerts the highest load on the vortex suppressor, but the vortex suppressor design still provides a positive margin of safety.

## BAFFLE DESIGN ANALYSIS

It was anticipated that an unbaffled MESSENGER propellant tank would experience severe propellant sloshing during launch, resulting in unacceptable nutation growth of the launch vehicle spin stabilized 3$^{rd}$ stage. During the course of tank design, it was decided that baffle (or baffles) must be installed to provide nutation control.

Prior to detail baffle design, subscale drop tests were conducted to determine the number and the location of the baffle(s) for the MESSENGER propellant tank. Several subscale models were constructed for this test, including spacecraft centerline oxidizer tank and off-axis fuel tanks, as seen in Figure 5.

**Figure 5, Off Axis Fuel Tank Model**



Additionally, several sizes of baffle rings were manufactured and tested, as shown below in Figure 6.

**Figure 6, Simulated Baffle rings**

The data collected from the drop tower test supported a tank design with two annular ring baffles. The baffles are located on the tank cylindrical section approximately 8 inches apart and equal distance from the tank mid-plane. Both baffles are identical in size - approximately 8 inches wide with a 7-inch "hole" in the center of the baffle.

## BAFFLE LOAD DETERMINATION

Prior to the structural analysis of the baffles, a fluid dynamics analysis was conducted to determine the loads exerted on the baffles. Factors considered were pad slosh, test and launch vibration, and ignition of the launch vehicle 3rd stage (AKM ignition). Both the oxidizer tank baffles (centerline on spin axis) and fuel tank baffles (off axis) were examined. Some of the 3-D models produced are shown below in Figure 7:

**Figure 7a, Propellant Movement Due to Pad Slosh**

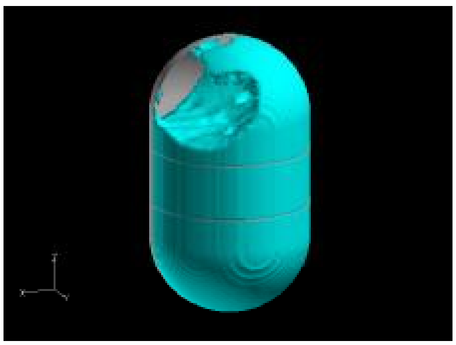


**Figure 7b, Propellant Movement Due to AKM Ignition, Fuel Tank**

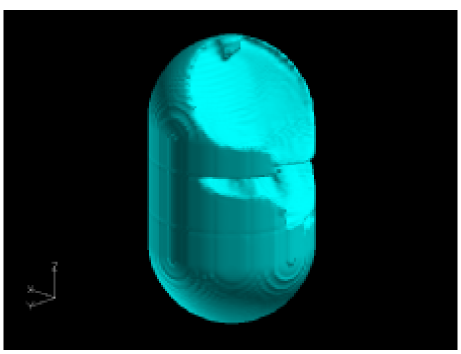
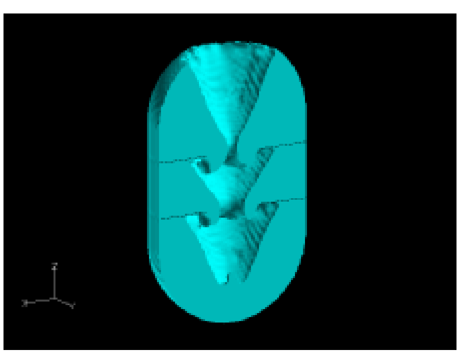


**Figure 7c, Propellant Movement Due to AKM Ignition, Oxidizer Tank**



The pressure distribution on the baffles was plotted and the loads quantified. Some of the pressure load plots are presented below:

**Figure 8a, Pressure Distribution due to Pad Slosh, Upper Baffle**

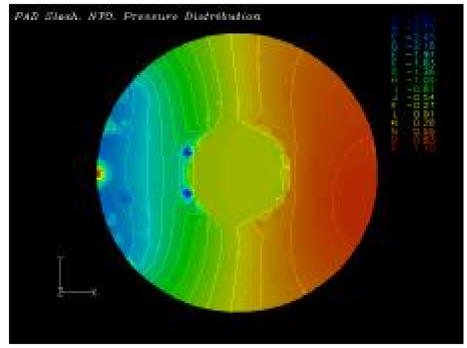


**Figure 8b, Pressure Distribution due to AKM Ignition, Fuel Tank**

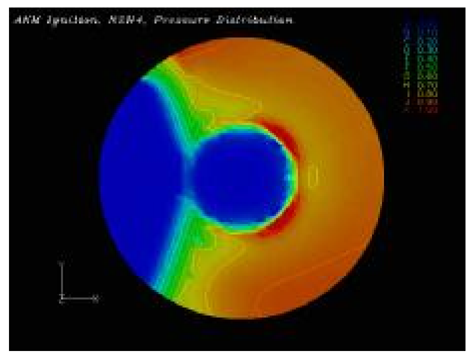
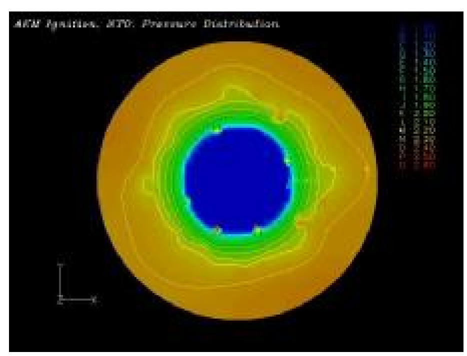


**Figure 8c, Pressure Distribution due to AKM Ignition, Oxidizer Tank**



The baffle loads analysis showed that baffle loads are low, since the fluid supports the baffle during launch. The analysis concluded that the loads on the oxidizer tank during NTO AKM ignition are worst case, and a design load was quantified for subsequent structural analysis.

## BAFFLE STRUCTURAL ANALYSES

A baffle structural analyses was performed to validate the structural integrity of the ring baffle design. The analysis took into consideration design requirements such as material properties, fluid properties, baffle loads as determined in the previous study, vibration environment, and design safety factors. Both axi-symmetric and asymmetric models were constructed to facilitate the analytical evaluation. Cases analyzed include pad slosh, vibration, and AKM ignition. Finite Elements Models were constructed to examine elements such as pressure loading and displacement, as shown in Figure 9 below:

**Figure 9a, FEM, Pressure Loading**

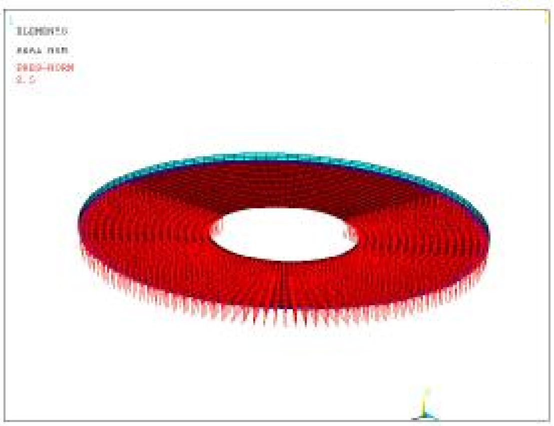
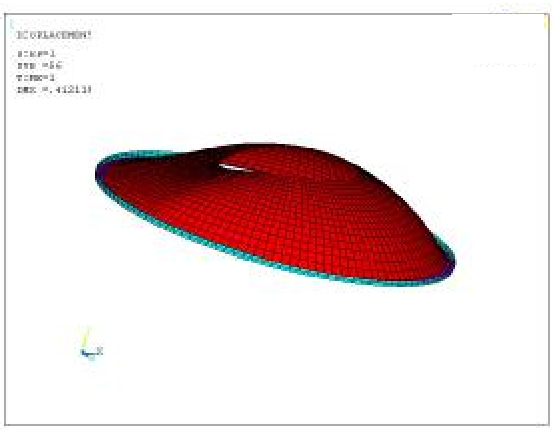
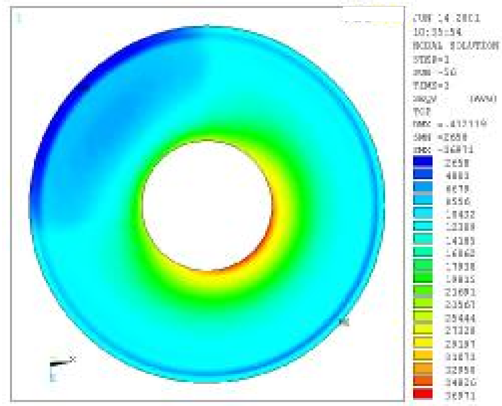


**Figure 9b, FEM, Displacement**



Stress contour plots were also used to examine surface stress/strain. As shown in Figure 10.

**Figure 10, von Mises Stress Contour Plot**



The baffle structural analysis concluded with large positive margins of safety for the nominally 0.010 inch thick baffle.

## TANK SHELL ANALYSES

The tank shell analyses included stress analysis and fracture mechanic analysis. All analyses used assumptions, computer tools, test data and experimental data utilized on a majority of the pressure vessels successfully designed, fabricated, tested and qualified during the past three decades. Conservatism was used throughout the analysis process, and the worst case scenarios were analyzed.

## TANK SHELL STRESS ANALYSIS

A stress analysis was performed to establish that the tank meets the specification requirements. The analysis took into consideration the requirements such as:

- Temperature environment;
- Material properties, STA titanium;
- Material properties, annealed titanium;
- Volumetric requirements;
- Mass properties of tank shell material;
- Mass properties of fluid;
- Fluids used by the tank;
- Tank pressurization history;
- External loads;
- Girth weld offset and weld suck-in;
- Size of girth weld bead;
- Resonant frequency;
- Tank boundary conditions;
- Residual stress in girth weld;
- Load reaction points; and
- Design safety factors.

This stress analysis established the tank shell design and mounting features for the MESSENGER propellant tank. The analysis dynamic model provided resonant frequency predictions. The first through third modes are shown below:

**Figure 11a, Oxidizer Tank 1st Mode**

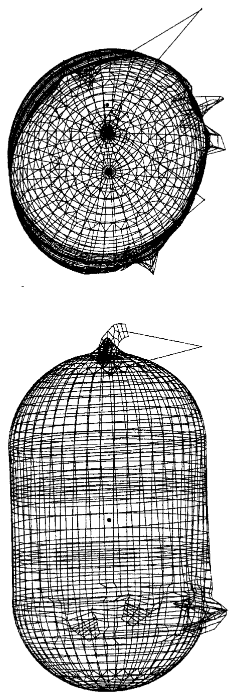


**Figure 11b, Oxidizer Tank 2nd Mode**

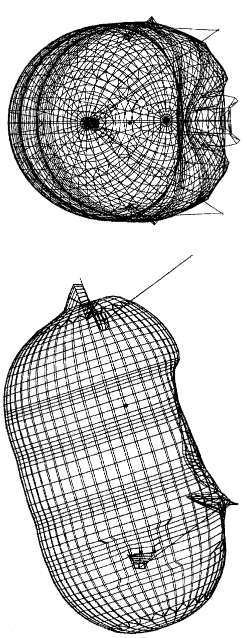
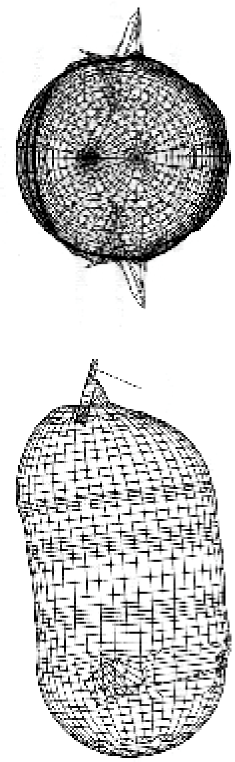
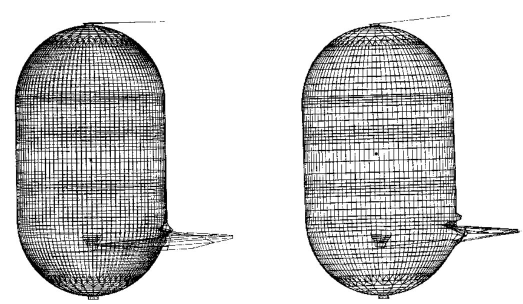


**Figure 11c, Oxidizer Tank 3rd Mode**



Buckling analysis was also conducted as part of the tank analysis. Select buckling shapes are shown below in Figure 12:

**Figure 12, 1st and 2nd Buckling Modes**



## STRUT DESIGN ANALYSIS

An analysis for all-titanium struts was also conducted as part of the overall tank design. As part of the acceptance and qualification philosophy, each set of four lightweight struts accompanied the flight and qualification tanks throughout acceptance and qualification testing.

The stress analyses concluded with positive margins of safety for all design parameters, as summarized in Table 2.

**Table 2: Propellant Tank Safety Margins**

| Characteristics | M.S. |
|---|---|
| Pressure, proof, sphere, yield | +0.06 |
| Pressure, proof, cylinder, yield | +0.05 |
| Pressure, burst, sphere, ultimate | +0.02 |
| Pressure, burst, cylinder, ultimate | +0.09 |
| Girth weld, yield | +0.01 |
| Girth weld, ultimate | +0.14 |
| Inlet tube, yield | +3.60 |
| Inlet tube, ultimate | +6.30 |
| Outlet tube, yield | +4.14 |
| Outlet tube, ultimate | +7.00 |
| EB weld, yield | +0.07 |
| EB weld, ultimate | +0.18 |
| Baffle, yield | +0.17 |
| Baffle, ultimate | +0.19 |
| Strut, yoke, yield | +1.80 |
| Strut, yoke, ultimate | +2.30 |
| Strut, yoke, global buckling | +1.01 |
| Strut, yoke, local crippling | large |
| Strut, yoke, bolt, ultimate | +2.74 |
| Strut, yoke, weld, ultimate | large |
| Strut, side, yield | +1.60 |
| Strut, side, ultimate | +2.10 |
| Strut, side, global buckling | +1.52 |
| Strut, side, crippling | large |
| Strut, side, bolt | +3.90 |
| Vortex suppressor, screws, yield | +3.43 |
| Vortex suppressor, screws, ultimate | +3.48 |
| Vortex suppressor, legs, yield | +1.01 |
| Vortex suppressor, legs, ultimate | +1.05 |
| Axial tab (+X side), external load, yield | +0.50 |
| Axial tab (+X side), external load, ult. | +0.53 |
| Shell, axial tab, external load, yield | +0.97 |
| Shell, lateral tab, external load, yield | +1.09 |

## TANK SHELL FRACTURE MECHANICS ANALYSIS

A fracture mechanics analysis was performed to establish whether the growth of an initial flaw in the anticipated cyclic and sustained pressure environment may cause a failure in the tank shell. The analysis was performed using external and internal stresses from the stress analysis, and using NASA/FLAGRO with minimum thicknesses as parameters. Special fracture critical dye-penetrant and radiographic inspections are required to detect flaws. The minimum flaw size that can be detected by such special fracture critical inspections was used as initial flaw size for this fracture mechanics crack propagation analysis. The analysis was performed at:

- Girth welds and heat affected zones;
- Maximum pressure stress location in the hemisphere;
- Maximum stress location in the cylinder;
- Maximum stress location in the cylinder side boss;
- Maximum stress location in the hemisphere/cylinder transition;
- Intersection between the hemisphere and the pressurant boss;
- Intersection between the hemisphere and the propellant boss; and
- Maximum external load stress in the hemisphere near the pressurant and the propellant bosses.

The fracture mechanics analysis established the leak-before-burst (LBB) characteristics of the propellant tank. This analysis concluded that the MESSENGER tank shell meets all the fracture mechanics requirements. The special fracture critical NDE flaw screening required by this fracture mechanics analysis include:

- Fracture critical dye-penetrant inspection; and
- Fracture critical radiographic inspection.

These requirements were instituted as part of the tank fabrication requirements.

## TANK FABRICATION

The MESSENGER propellant tank shell consists of two hemispherical heads, two cylinder extensions, and a cylindrical center section. All 5 shell component pieces were machined from 6AL-4V titanium alloy forgings, as shown in Figure 13. All raw forgings have annealed properties at the time of receipt.

**Figure 13, Hemisphere & Ring Forgings**

The outlet hemisphere and its cylinder extension forgings were rough machined and electron beam (eb) welded together, as shown in Figure 14.

**Figure 14, EB welded Outlet Hemisphere and Cylinder Extension**


This assembly was solution treated, aged, and finish machined to the tank shell thickness as required by the stress analysis. This process allowed the eb weld joint to have STA properties. At final machine, the eb weld joint was machined as part of the shell membrane and became indistinguishable from the rest of the membrane material. After final machine, the eb weld joint has the same membrane thickness (0.020 $\pm$ .003) as the rest of the membrane material. There is no weld reinforcement at or near the eb weld joint. A finish machined outlet hemisphere/cylinder extension is shown in Figure 15.

**Figure 15, Finished Machined Outlet Hemisphere and Cylinder Extension**

The mounting hemisphere was also eb welded to a cylinder extension, solution treated and aged, and finish machined. However, part of the finish machine process also included eb welding three tabs to the mounting hemisphere and final machine these mounting tabs. A finish machined mounting hemisphere is shown below in Figure 16.

**Figure 16, Finished Machined Mounting Hemisphere and Cylinder Extension**

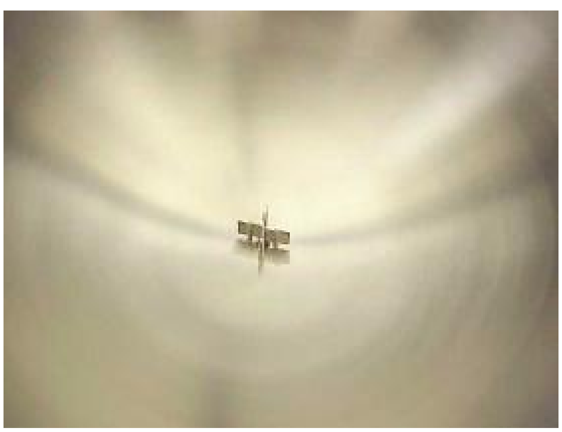
The fifth tank shell component, the center cylinder, also underwent the rough machine-solution treat-finish machine manufacturing process. The solution heat treat process increases the strength of the titanium alloy, thus minimizing the weight of the tank shell. The excellent strength to weight property, coupled with its manufacturability, make this titanium alloy the material of choice for aerospace application.

In addition to the tank shell components, two baffles were machined from titanium ring forgings. These baffles have a nominal thickness of 0.010 inch. A picture of a machined baffle is shown in Figure 17.

**Figure 17, A Machined Baffle**

Prior to the start of girth weld, the vortex suppressor was installed above the outlet port. This four-vane cruciform vortex suppressor was constructed of titanium sheets and supported with four support posts. The four support posts were welded to the tank shell, as shown in Figure 18.

**Figure 18, An Installed Vortex Suppressor**



The MESSENGER propellant tank was assembled with two girth welds. Both girth welds have the same weld joint design. This weld joint is nearly identical to weld joints on all PSI's diaphragm tanks, thus provided with flight heritage of almost 900 tanks. Nevertheless, a Weld Development Program was conducted to develop a customized weld schedule for the MESSENGER Propellant Tank. Each girth weld was designed to join together three components: a hemisphere/cylinder extension assembly, the center cylinder, and a machined baffle. Figure 19 shows a tank assembly with the first girth weld complete, which includes the welded-in baffle .

**Figure 19, The Welded Baffle**

After both welds are complete, the girth welds were subjected to fracture critical radiography and dye penetrant inspection as required by fracture analysis. Figure 20 shows the tank being radiographically inspected after closure weld.

**Figure 20, Radiographic Inspection, Propellant Tank Assembly Girth Weld**

After closure the tank assembly is stress relieved in a vacuum furnace to remove residual stress from the weld operations. See Figure 21.

**Figure 21, Vacuum Heat Treat**

Following closure weld, a boomerang was installed to the propellant hemisphere as shown in Figure 22. The boomerang is used for strut connection.

**Figure 22, Installed Boomerang Assembly**

## TANK WEIGHT

The propellant tank weight per the specification is not to exceed 20.9 lbs. The actual weight of the qualification tank is less than 19.00 lbs. With the addition of 1.01 lbm for the four struts and mounting hardware, the as-delivered tank weight is less than 20.0 lbs.

## QUALIFICATION TEST PROGRAM

The propellant tank is qualified by test. A qualification tank was fabrication for the qualification test program. The qualification test sequence is listed below:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- MEOP pressure cycle
- Proof pressure cycle
- Expulsion efficiency
- Flow rate determination
- External leak test
- Qualification vibration test
- External leakage test
- Penetrant inspection of girth welds
- Radiographic inspection of girth welds
- Final visual examination
- Burst pressure test

Conservatism was exercised throughout the qualification test program, and all pressure tests were temperature adjusted for the worst case operating temperature. Pass/Fail criteria consisted of acceptance type external leak tests and non-destructive evaluations conducted at intervals throughout the test program.

The MESSENGER Program qualification testing philosophy was to test associated flight items along with the tank, including mounting struts, thermal switches, a Click Bond, and a heater installed around the perimeter of the tank's cylindrical section. These items were installed onto the qualification tank prior to the start of qualification testing.

**Volumetric Capacity Examination**: The capacity of the propellant tank was measured utilizing the weight of water method, using clean, filtered deionized water as the test medium. This test was conducted before and after the proof pressure test to verify that the proof pressure test did not significantly alter the tank capacity.

**Proof Pressure Test**: The proof pressure test was the first pressurization cycle applied to the tank after fabrication. It was intended to validate the workmanship by verifying the strength and integrity of the tank shell. The test was conducted hydrostatically at proof pressure (406 psia, normalized for test temperature) for a pressure hold period of 5-minute minimum. Tank linear and radial growths were also recorded to validate the analytical predictions. Figure 23 below shows the pressure test setup for the MESSENGER propellant tank.

**Figure 23: The Pressure Test Setup**

**Pressure Cycles Tests:** The propellant tank was cycle tested with a total of 16 proof and 100 MEOP pressure cycles. Pressure testing was conducted hydrostatically. Both proof and MEOP test pressures were temperature adjusted to test the worst case conditions.

**Expulsion Efficiency:** The propellant tank was drained and the fluid expulsion efficiency determined. The MESSENGER propellant met the 99.75% expulsion efficiency requirement.

**Flow Test:** A flow test was conducted to determine flow rate through the propellant outlet. Figure 24 shows the flow test setup. Note that the flow test was conducted propellant side down. The tank easily met the required flow rate of 8.7 gallon per minute.

**Figure 24: The Flow Test Setup**

**Qualification Vibration Test:** The qualification vibration test is designed to verify workmanship of baffle and vortex suppressor, as well as the integrity of the tank shell. There are only two phases of the qualification vibration testing: wet random and wet sine. All three principal axes are tested. Deionized water was used as the test fluid and the required vibration levels were adjusted to account for the fluid density difference between deionized water and NTO. For both random and sine vibration testing, the Qualification Tank was loaded with 422 lbm of D.I. water and pressurized to 243 psig, adjusted for temperature. The tested vibration environment is shown below in Table 4.

Two test fixtures were fabricated for the vibration testing. The random vibration test fixture was designed to test the tank in the horizontal position, while the sine vibration test fixture was designed to test the tank in the vertical position. Both fixtures were designed to mount the propellant with flight struts. See Figure 25 for the test setup.

**Table 4a: Qualification Vibration Levels**

## Qualification Sine Vibration

| Axes | Frequency (Hz) | Acceleration | Sweep Rate |
|---|---|---|---|
| Thrust | 10 – 24<br>24 – 28<br>28 – 100 | 0.5 in DA<br>14.30 g<br>2.48 g | 2 oct/min |
| Lateral<br>(2 axes) | 10 – 20<br>20 – 25<br>25 – 100 | 0.34 in. DA<br>6.90 g<br>1.96 g | 2 oct/min |

## Qualification Random Vibration

| Axes | Frequency (Hz) | PSD Input Level | Overall Amplitude (Grms) | Duration (sec.) |
|---|---|---|---|---|
| Thrust | 20<br>80<br>800<br>2000 | 0.01<br>0.08<br>0.08<br>0.01 | 9.7 | 120 |
| Lateral<br>(2 axes) | 20<br>80<br>800<br>2000 | 0.01<br>0.04<br>0.04<br>0.01 | 7.3 | 120 |

**Figure 25: Vibration Test Setup**

**Random, X-axis**

**Random, Y-axis**

**Random, Z-axis,**

**Sine, X-axis**

**External Leak Test:** The external leak test verified the integrity of the tank shell and also serves to validate the above vibration testing. The tank is placed in a vacuum chamber, evacuated to under 0.2 microns of mercury, and helium pressurized to 325 psia for 30 minutes. The helium leak rate must the specification requirement of <1 x $10^{-6}$ std cc per second.

**Non-Destructive Examination:** Following the pressure tests, the tank shell was screened for flaws using fracture critical penetrant inspection and fracture critical radiographic inspection techniques. Tank acceptance after NDE marked the successful completion of tests prior to final burst pressure test.

**Burst Pressure Test:** Following NDE and a final visual examine, the Qualification Tank was burst pressure tested to determine the burst margin. The tank burst at 648 psig. This burst pressure is 142 psi above the minimum requirement and represents a burst margin of 28%.

## ACCEPTANCE TESTING

After the flight tank is assembled, it is subjected to the following acceptance tests prior to delivery:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- External leak test
- Protoflight vibration test
- External leakage test
- Penetrant inspection of girth welds
- Radiographic inspection of girth welds
- Final visual examination
- Cleanliness

**Protoflight Vibration Test:** Each flight tank is protoflight vibration tested. The protoflight sine vibration environment is identical to the qualification sine vibration environment, except sweep is 4 oct/minute. Protoflight vibration testing is conducted at 150 psig, adjusted for temperature.

**Cleanliness Verification:** After the non-destructive examination, the interior of each flight tank is cleaned to the cleanliness level specified below in Table 5:

**Table 5: Tank Cleanliness Level**

| Particle Size Range (Microns) | Maximum Allowed per 100 ml per $ft^2$ |
|---|---|
| 0 to 15 | 280 |
| 16 to 25 | 75 |
| 26 to 50 | 11 |
| 51 to 100 | 1 |
| 101 and over | 0 |

## CONCLUSION

The MESSENGER propellant tank assembly was custom designed to meet the MESSENGER mission requirements. The tank assembly was accomplished using standard manufacturing processes and procedures. Special materials and processes were not required. The simple, robust design allowed easy assembly. The tank is lightweight, and shows excellent strength, durability, and reliability.

The MESSENGER propellant tank assembly completed qualification testing without failure in July 2002. The successful development of this ultra lightweight propellant tank represented the completion of a critical milestone toward a successful Mercury Orbiter program.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## REFERENCE


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# NOTES