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DESIGN MODIFICATION OF A DIAPHRAGM PROPELLANT TANK FOR A PRESSURANT TANK APPLICATION

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ABSTRACT

Pressure Systems, Inc. (PSI) has modified the design and completely re-qualified the existing design of a 15.4" diameter thin wall titanium propellant tank for a pressurant tank application. The 15.4" diameter thin wall titanium pressure vessel has been manufactured since 1975. The tank was originally designed, qualified, subsequently manufactured and utilized on several programs with an internal elastomeric rubber diaphragm acting as a positive expulsion device for the hydrazine fuel.

In the current application as a pressurant tank, the design is incorporated on a bootstrap ullage tank system used to store pressurant for the spacecraft's reaction control system. The pressurant tank incorporates the previously qualified 15.4" diameter tank shell design with integral pedestal mounting flange and eliminates the elastomeric rubber diaphragm and retaining ring, which reduced cost and weight. Stress and fracture mechanics analyses were conducted to verify the modification to the design.

The tank fabrication utilized existing, reliable, and proven manufacturing technologies and inspection techniques. The tank program was also developed to minimize overall program cost. Existing tooling was used to the fullest extent, including machining, weld, and test tooling. A qualification test program validated the tank design. The qualification program included pressure cycles, vibration testing and a final burst pressure test. The tank, as delivered to the customer, incorporates thermal blankets, heaters, pressure lines and electrical connectors reducing the time and scope of the customer's integration effort.

INTRODUCTION

In order to reduce overall cost to the program, an existing tank shell design was proposed and baselined. This approach reduced the non-recurring expenditures such as engineering, documentation and tooling. It also eliminated the need for weld qualification and development. The use of an existing tank shell provides established flight heritage, which is an added advantage.

Figure 1: Evolution of design from Propellant Tank to Pressurant Tank



The existing propellant tank was originally qualified over twenty years ago and fourteen tanks have been manufactured, delivered and flown. A comparison of the requirements for the existing propellant tank and the new pressurant tank is shown below in Figure 2.

MANUFACTURING

The propellant tank membrane was not changed. Modification to the tank shell is limited to the elimination of one port which is no longer necessary and reduces weight. The tank is pedestal mounted to the spacecraft structure. The number of mounting holes was changed from twelve to six.

The heritage propellant tank and the modified pressurant tanks both consist of two hemispherical heads and a base ring. Both the hemispheres and the base ring are machined from 6AL-4V titanium forgings. Each forging is machined to the tank shell thickness as required by the stress analysis. The as-delivered hemispherical forgings have a nominal thickness of 0.44 inch, and the

finished tank shell membrane has a nominal thickness of 0.022 inch. The entire machining process removes over 95% of the forging material.

The tank shells similar to most tank shells fabricated at PSI have solution treated and aged (STA) properties resulting in optimal tank weight. The modified design has eliminated the elastomeric diaphragm and the diaphragm retaining ring, combined with the elimination of the one port discussed above, resulting in a nominal weight reduction of 2.7 lbm or almost a third of the tank assembly's weight.

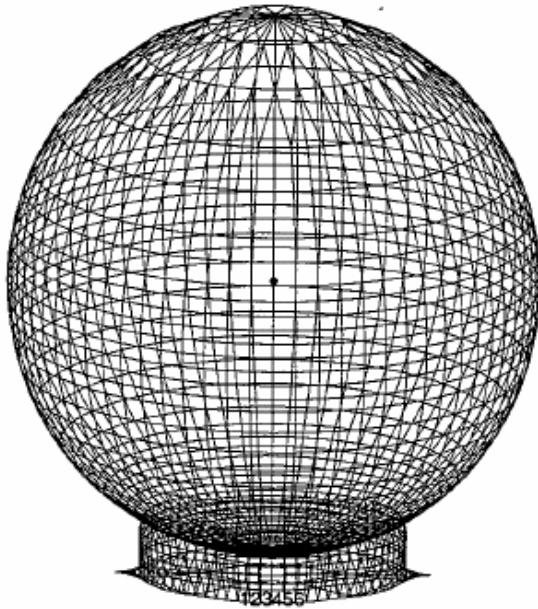
Elimination of the elastomeric diaphragm and retaining ring simplifies the single girth weld and allows the tank to be stress relieved after completion of the tank close out weld enhancing tank properties.

After completion of all manufacturing operations the tank was fully acceptance and qualification tested

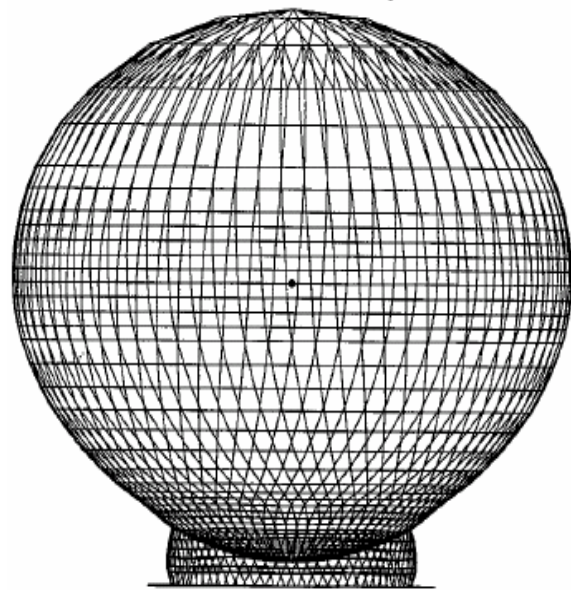
**Figure 2:
Comparison of the Existing Propellant Tank Design vs. "Modified" Pressurant Tank Requirements**

REQUIREMENT	Existing Propellant Tank Design Requirements	"Modified" Pressurant Tank Design Requirements
Propellant	N2H4	Not Applicable
Pressurant	GN2	GN2
Tank Volume	1865 in3	1865 in3
Propellant Management	Elastomeric Diaphragm	Not Applicable
Operating Pressure	320 psi	400 psi
Proof Pressure	510 psi	500 psi
Burst Pressure	640 psi	600 psi
Shell Leakage	< 1 x 10 ⁻⁶ std cc/sec He	< 1 x 10 ⁻⁶ std cc/sec He
Operating Temperature Range	41 to 122 °F	-22 to 158 °F
Weight	8.2 lbm	5.5 lbm*
Size	15.38 in ID	15.38 in ID
Expulsion Efficiency	≥ 98%	Not Applicable
Material of Construction	Ti-6AL-4V	Ti-6AL-4V
Shell Wall Thickness	0.022 in	0.022 in

*** Weight of Tank Assy excluding weight of heaters and thermal blankets.**



MODE 1



MODE 2

Figure 3: Some Vibration Modes

ANALYSIS

The tank design analyses included stress and fracture analysis for the tank shell. Upgraded stress and fracture analyses were performed based on the previous analysis completed for the heritage propellant tank, taking into account the new requirements for the pressurant tank.

The tank design analysis approach 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 four decades at PSI. Conservatism was used throughout the analyses.

The stress analysis performed on the tank shell took into consideration such factors as:

- Temperature environment
- Material properties
- Volumetric properties
- Mass properties of the tank shell material

- Mass properties of fluid
- Fluids used by the tank
- Tank pressurization history
- External loads
- Girth weld offset and suck-in
- Size of girth weld
- Resonant frequency
- Tank boundary conditions
- Residual stress in girth weld
- Load reaction points and
- Design safety factors

The stress analysis validated the use of the existing tank shell design and the modifications including the elimination of the diaphragm, retaining ring, one port and the number of mounting holes in the pedestal base for the new mission. The analysis also provided predictions on resonant frequencies. Figure 3 shows some of the vibration modes determined from the analysis.

The stress analysis showed positive margins of safety as shown in Figure 4

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

- Girth weld and weld heat affected zones
- Maximum pressure stress location in the hemisphere
- Intersection between the hemisphere and the pressurant port
- Maximum external load stress in the hemisphere near the pressurant port

The fracture mechanics analysis established the leak-before-burst (LBB) characteristics of the pressurant tank. The results show that this design satisfies all fracture mechanics requirements. Figure 5 shows the completed tank assembly.

Figure 4: Summary of Margins of Safety

Area	M.S.
Membrane, proof	+0.46
Membrane, burst	+0.30
Membrane, collapse	+0.12
Outlet Tube, ti, yield	+8.85
Outlet Tube, ti, ult	+3.75
Outlet Tube, 304L, yield	+5.60
Outlet Tube, 304L, ult	+6.20
Outlet Boss Taper, yield	+0.28
Outlet Boss Taper, ult	+0.14
Weld, yield	+0.22
Weld, ult	+0.12
Shell/Support Cyl, External Load, yield	+0.56
Shell/Support Cyl, External Load, ult	+0.65
Support Cyl, External Load, yield	+0.48
Support Cyl, External Load, ult	+4.48
Isolator, yield	+0.69
Isolator, ult	+2.00
Bolt, yield	+0.78
Bolt, ult	+1.31



Figure 5: Pressurant Tank Assembly shown with heaters, sensors, cables and flight bracket installed.

ACCEPTANCE TESTING

The modified pressurant tank is subjected to the following sequence of acceptance tests prior to delivery:

- Preliminary visual examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- External leakage test
- Penetrant inspection
- Radiographic inspection
- Mass measurement
- Final examination
- Cleanliness verification

The ambient hydrostatic proof pressure test is conducted at 521 +20/-0 psig for a pressure hold period of 300 seconds. Post proof test volume cannot exceed .33% from the pre-proof test value.

The external leak test is conducted to verify the integrity of the tank shell. The test specimen is placed in a chamber, as shown in Figure 6, which is evacuated to 0.2 microns of mercury or less and the helium pressurized to 400 psig for 5 minutes. The leakage cannot exceed 1×10^{-6} std cc/sec.



Figure 6: External Leak Testing Set-Up

Post acceptance test radiographic inspection of the girth weld and penetrant inspection of the entire external surface are conducted to verify that the tank is not damaged during acceptance testing.

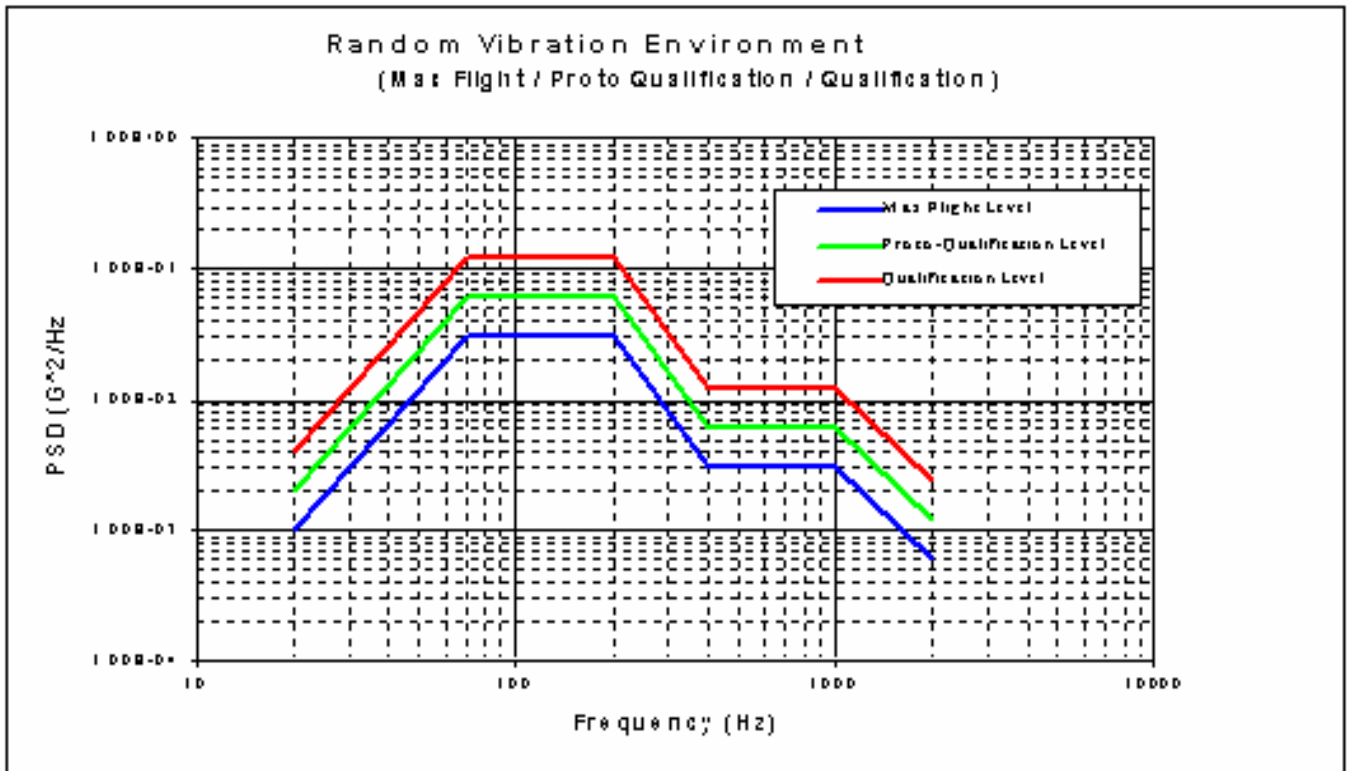
All units successfully passed acceptance testing.

QUALIFICATION TESTING

After the conclusion of acceptance testing one modified pressurant tank was subjected to the following sequence of qualification tests prior to delivery:

- Random vibration
- Proof pressure cycling test
- MEOP pressure cycling test
- External Leakage test
- Radiographic inspection
- Penetrant inspection
- Burst pressure test
- Visual inspection
- Data review

The qualification vibration tests are designed to verify the workmanship and integrity of the tank shell. All three principle axes are tested at the random vibration qualification levels as shown in Figure 7.



Max Flight Level			Proto-Qualification Level			Qualification Level		
Freq Hz	Envelope PSD g ² /Hz	Slope dB/Octave	Freq Hz	Envelope PSD g ² /Hz	Slope dB/Octave	Freq Hz	Envelope PSD g ² /Hz	Slope dB/Octave
20	1.00E-04	4.17	20	2.00E-04	4.17	20	4.00E-04	4.17
70	0.01	0.00	70	0.01	0.00	70	0.01	0.00
200	0.01	-10.00	200	0.01	-10.00	200	0.01	-10.00
1000	0.0001	0.00	1000	0.0001	0.00	1000	0.0001	0.00
2000	0.00001	-4.30	2000	0.00001	-4.30	2000	0.00001	-4.30
R ₁₀₀₀	1.11		R ₁₀₀₀	1.11		R ₁₀₀₀	1.11	

Figure 7: Vibration environment

The vibration test fixture is designed to simulate the tank to spacecraft installation interface. The fixed end pressurant boss is restrained in all directions during the vibration testing. The blank end is free to move in all directions during test. The fixture is sufficiently stiff to be considered rigid for the test frequencies.



Figure 8: Vibration test Set-Up

Control accelerometers are placed on the vibration test fixture near each attachment point to control energy input. Three tri-axial response accelerometers are used to monitor the tank responses: two on the tank center and one near the blank end. The vibration test set-up is shown in Figure 8.

The tank is required to meet the requirement of

being pressurized to a proof pressure of 521 +20, -0 psig at a ambient temperature for 8 cycles with a hold of 5 seconds maximum for each cycle. There is also a requirement to pressurize the tank to a MEOP pressure of 400 +20, -0 psig at ambient temperature for 50 cycles with a maximum hold of 5 seconds between each cycle. The test set-up is shown in Figure 9.

The external leak test verifies the integrity of the tank shell and also serves to validate the above vibration testing. The tank is placed in a vacuum chamber which is evacuated to under 0.2 microns of mercury and helium pressurized to 400 psig. The helium leakage rate cannot exceed 1×10^{-6} std cc/sec.

Following the pressure tests, the tank is screened for flaws using fracture critical penetrant inspection and fracture critical radiographic inspection techniques. Tank acceptance after NDE marks the successful completion of qualification testing subject to the successful completion of meeting the burst pressure requirements.

Prior to performing the burst pressure test, all test data sheets are reviewed to verify that all requirements have been met and that all data have been recorded correctly.

The test specimen was installed in the test set-up as shown in Figure 8. The tank was filled with de-ionized water and all air vented. The tank was pressurized to 600 +10,-0 psig at a uniform rate within 360 seconds. Burst pressure was held for 5 seconds maximum with no evidence of leakage or rupture. The pressure was then slowly increased until the tank ruptured at a pressure of 1048 psig. The tank grew approximately one inch when pressurized through failure. See figure 10.



Figure 9: Pressure Testing Set-Up

CONCLUSION

The pressurant tank assembly has successfully completed all acceptance and qualification level testing and the flight units have been delivered.

The tank meets or exceeds all requirements and provides the customer a robust, low cost solution for providing additional pressurization to the spacecraft.



Figure 10: Qualified Burst Tank

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Joe Benton is a Program Manager and Mike Debrececi is a Senior Program Manager at PSI