DESIGN AND MANUFACTURE OF A COMPOSITE OVERWRAPPED PRESSURANT TANK ASSEMBLY

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ABSTRACT

A titanium-lined, composite overwrapped pressure vessel (COPV) for helium pressurant storage was designed for a commercial spacecraft. This tank has a nominal propellant volume of 81.4 liters (4,967 cubic inches) and a nominal weight of 11.7 kg (25.8 pounds). The maximum expected operating pressure is 331 bar (4,800 psi). Proof pressure requirement is 414 bar (6,000 psi), and the minimum burst pressure is 497 bar (7,200 psi).

The pressurant tank design is based on a flight-qualified pressurant tank to take advantage of its design and flight heritage. To minimize risk, the pressurant tank is designed to use only existing manufacturing technology, processes, and procedures. Manufacturing cost is minimized by using existing tooling to the fullest extent.

Nonlinear material and geometric modeling techniques were used to analyze this tank. Stress analysis showed positive margins of safety for pressure cycle fatigue, vibration fatigue and minimum burst pressure over the design requirements. Qualification testing verified the design margins and showed the design analyses to be conservative.

The liner is constructed from commercially pure titanium. This material was chosen due to heritage and for its superb manufacturability, relative high strength, excellent corrosion and oxidation resistance characteristics, good low and high cycle fatigue characteristics, and competitive manufacturing cost.

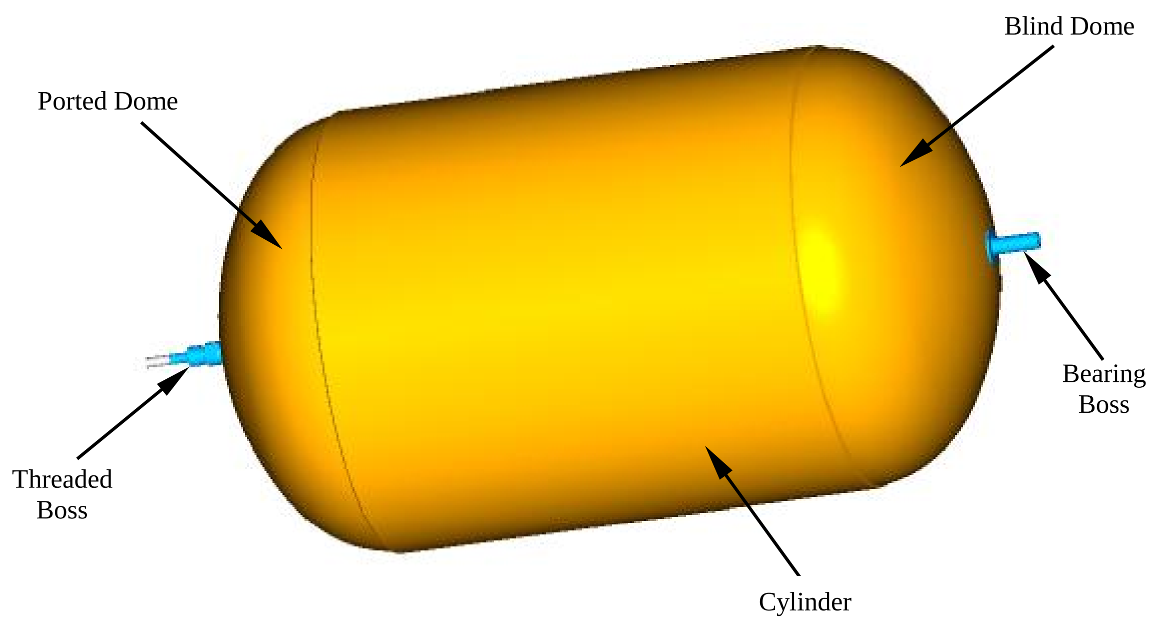
The overwrap consists of high strength Torayca T1000G carbon fiber and Epon 826 cured resin system. Several composite layers are applied, including helical and hoop wraps.

A complete qualification program was conducted to verify the tank design, including a destructive burst pressure test. The tank successfully completed qualification testing on 03 April, 2002. The production program is in progress. Over 10 flight tanks have been manufactured to date.

INTRODUCTION

A Helium pressurant storage pressure vessel with unique characteristics is needed for a commercial spacecraft. This tank must be high performance, light-weight, and designed to withstand severe operational loads. Additionally, this tank must be built with existing technology to minimize manufacturing cost and program risk. A titanium-lined, carbon fiber overwrapped tank was designed and manufactured to meet such a need. A sketch of this tank is shown in Figure 1.

Figure 1: COPV Pressurant Tank



The tank is mounted to the spacecraft by polar bosses located on the tank centerline axis. The ported end is the fixed end with a threaded attachment to mount onto the spacecraft structure. The blind end stinger boss, mounted on a slip joint bearing, is designed to accommodate the tank's axial growth during pressurization. Two pressurant tanks are required for the spacecraft.

This pressurant tank was designed to the requirements listed in Table 1 below:

Table 1: Pressurant Tank Design Requirements

PARAMETERS	REQUIREMENTS
Maximum Expected Operating Pressure (MEOP)	331 bar (4,800 psi), 50 cycles minimum
Proof Pressure	414 bar (6,000 psi), 8 cycles minimum
Burst Pressure	497 bar (7,200 psi) minimum
Size	424 mm dia. OD x 737 mm long, (16.7" dia. OD x 29" long), boss to boss
Overall Length	841.8 mm (33.14") nominal
Tank Weight	11.7 kg (25.8 lbm) maximum
Tank Capacity	81.4 liters (4,967 in^3) minimum, @ MEOP
Compatibility	Argon, IPA, Helium, Nitrogen, and DI water
Shell Leakage	<$1x10^{-6}$ std cc/sec He @ MEOP
Failure Mode	Leak-before-burst
Operating Temperatures	-95°C to 60°C (-140°F to 140°F)

This tank was also designed to withstand shock and vibration loads. All design requirements were verified by either analysis or qualification testing.

DESIGN HERITAGE

PSI has designed three titanium lined COPV's that were similar in design and construction – one a high-pressure helium tank[1], the second a high-pressure conical Xenon tank[2], and the third a high-pressure cylindrical Xenon tank[3]. All three tanks are titanium lined and T1000 carbon fiber overwrapped. Additionally, the helium tank of reference 1 was redesigned to eliminate the two end fitting-to-dome welds. To date dozens of these COPV's have been delivered. The new pressurant tank draws its heritage from all these programs. The manufacturing technology established by these programs has matured and this new pressurant tank program did not attempt to establish any new technology. The focus of the tank design was mainly to minimize cost and risk.

To maximize design and flight heritage, the design of the new pressurant tank blind and ported heads are nearly identical to the previous blind and ported heads of the helium pressurant tank, including the mounting features. See Figure 2. Additionally, both liner center sections have the same wall thickness and have identical method of construction. A comparison of the two tanks is provided in Table 2.

The liner material is CP titanium, identical to the previous COPV helium pressurant tank. The selection of CP titanium was made to maintain heritage. The filament wrap remains the same T1000 carbon fiber.

DESIGN ANALYSES

The basic approach in designing the pressurant tank was to maximize heritage by maintaining as many design features from the previous pressurant tank as possible while enhancing the manufacturability of the liner and overwrap. To minimize risk only existing manufacturing technology was used.

Figure 2: Design Heritage of the Pressurant Tank

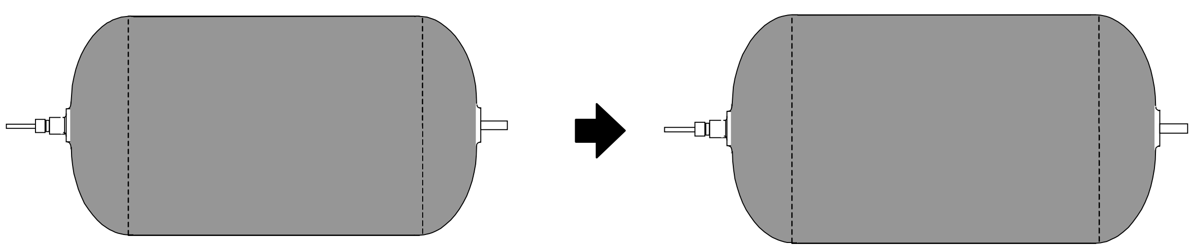


Table 2: Comparison of the Two Cylindrical Pressurant Tanks

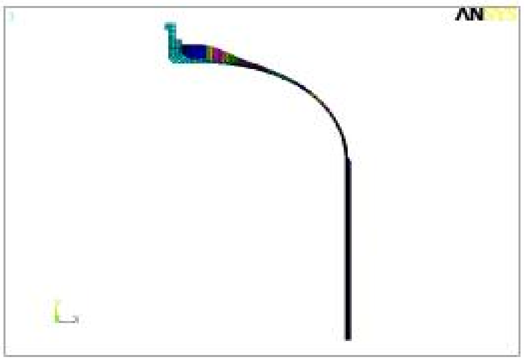
	Previous He Tank	New He Tank
Dimension	41 cm dia. x 66 cm long	42 cm dia. x 74 cm long
MEOP	310 bar (4500 psi)	331 bar (4800 psi)
Volume @ MEOP	67.3 liter (4105 in^3)	81.4 liter (4967 in^3)
Actual burst	546 bar (7919 psig)	572 bar (8297 psig)
Weight of qual tank	10.1 kg (22.32 lb)	11.7 kg (25.73 lb)

Several analyses were conducted to design and analyze the pressurant tank, including:

- Finite element analysis to conduct the liner material study.

- Nonlinear axisymmetric analysis to design the pressurant tank ported and blind heads. Figure 3 shows the ported head as modeled by the analysis. The blind head is similarly analyzed.

Figure 3: Nonlinear Axisymmetric Finite Element Models



- Three-dimensional finite element model for the modal analysis. The analysis is conducted to predict the natural frequencies of the pressurant tank. The actual frequency of the tank is determined at vibration test. Figure 4a shows the first axial mode, and Figure 4b shows the first lateral mode.

Figure 4a: First Axial Mode

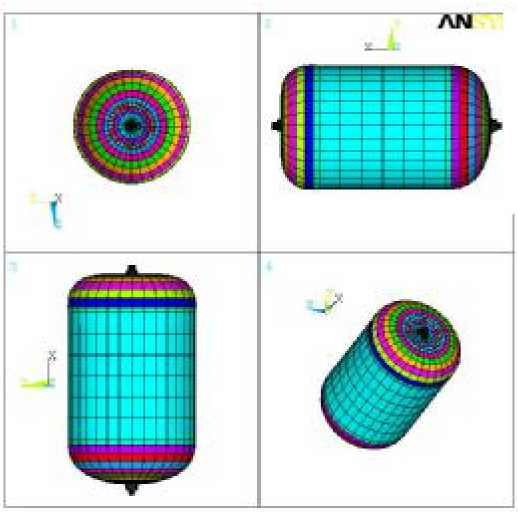
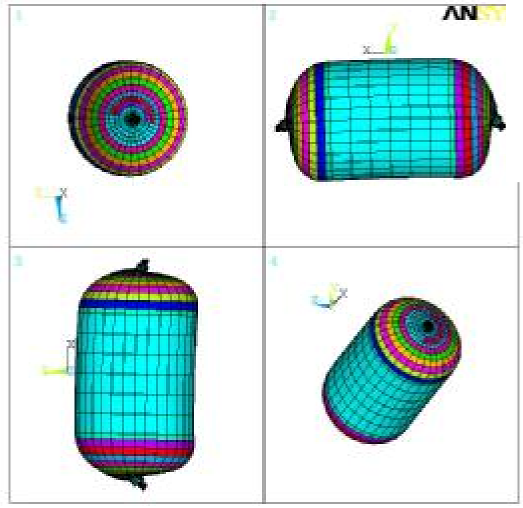


Figure 4b: First Lateral Mode



- Random vibration analysis to determine stress and fatigue effects of random vibration on the vessel. See Figure 5a and 5b. For conservatism, only the qualification level power spectral density was analyzed.

- Shock analysis to determine stress responses due to shock. See Figure 6. The same finite element model for the modal analysis is used on the shock analysis.

- Fatigue analysis to determine the cumulative damage factor due to fatigue. The fatigue life requirements for the pressurant tank liner consists of 1 sizing (autofrettage) cycle and 4 design service lifetimes, including proof pressure cycles and operating pressure cycles.

LINER DESIGN AND FABRICATION

To maintain heritage, this pressurant tank was designed to have the same CP titanium liner as the previous pressurant tank. Typical of most COPV's, the composite overwrap for the pressure vessel is designed to provide most of the strength for the tank. The liner is a low load-bearing part of the tank shell that serves as a container to carry the helium pressurant and provides a defined shape to apply the filament overwrap. To minimize weight the liner wall is kept as thin as practical while maintaining manufacturability. However, the design of the liner also takes into account the high vibration and shock loads during launch. The high strength, low weight CP titanium is ideal for this application.

Figure 5a: Vibration Analysis, Lateral Random Stress Response of Liner

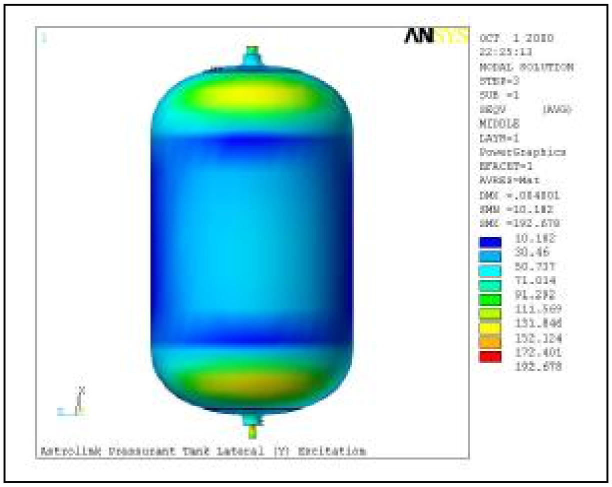


Figure 5b: Vibration Analysis, Axial Random Stress Response of Liner

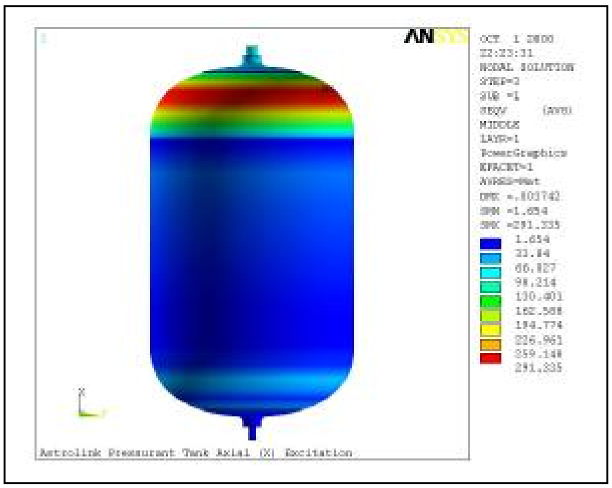
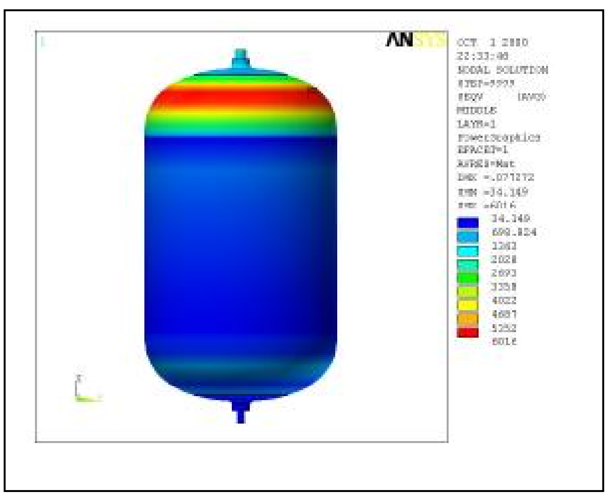
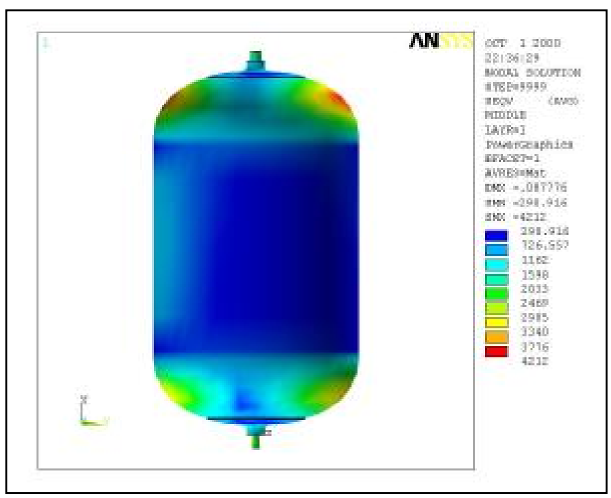


Figure 6: Liner Shock Response, Axial and lateral





Other factors that contribute to the selection of titanium include:

- Good corrosion and oxidation resistance,
- Not susceptible to pitting and stress corrosion,
- High strength-to-weight ratio,
- Good galvanic compatibility with carbon fiber,
- Good low cycle fatigue performance,
- Good high cycle fatigue performance,
- Good manufacturability,
- Good weld properties,
- Good performance characteristics.

The pressurant tank liner is a four-piece construction that consists of two heads, a cylinder, and an outlet tube. The three components of the liner body are shown in Figure 7. This simplified approach minimized the number of components to handle and assemble.

Figure 7: Components of the Pressurant Tank Liner

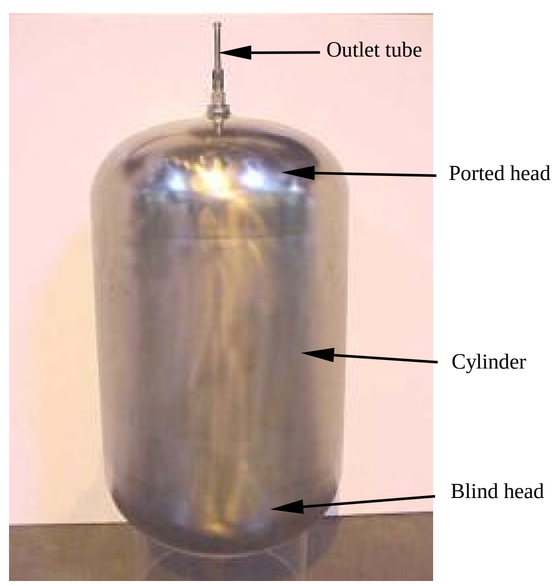
The pressurant tank liner was designed to mirror the construction of the previous pressurant tank liner. Although it has a slightly larger diameter, a forging was designed such that all four heads from these two tanks can be machined from the same forging configuration. The forging is made from CP 70 titanium bar. Figure 8 below shows a liner head being machined.

Figure 8: Machining of a Liner Head

The outlet tube is made from 9.53 mm (0.375 inch) outside diameter tubing. The center section is fabricated from 0.5 mm (0.020 inch) thick CP-3 titanium sheet, rolled, formed, and welded into a cylinder with one longitudinal seam weld. This cylinder is manufactured using the same manufacturing technique as the previous helium pressurant tank center section.

The liner is assembled with two girth welds and a tube assembly weld using the same weld technique and weld schedule as the previous helium pressurant tank. Each weld is radiographic and penetrant inspected for acceptance. The completed liner is leak tested prior to the filament wrap operation. A completed liner is shown in Figure 9.

Figure 9: A Completed Pressurant Tank Liner



COMPOSITE OVERWRAP DESIGN AND FABRICATION

The pressurant tank composite overwrap contains several layers of high angle, helical and hoop wraps. The same wet filament winding technique used on the previous pressurant tank is applied to this pressurant tank. This process utilizes dry fiber roving that is in-process impregnated with a low-viscosity resin. The materials used in the composite overwrap include Torayca T-1000G high performance carbon fiber and EPON 826 epoxy resin system. The basic resin system has years of commercial heritage and offers excellent characteristics including: low viscosity; reasonable pot life; high strain-to-failure capability; good chemical and moisture resistance; and low toxicity. Thousands of COPV's have been wrapped using this resin system.

The resin system has a 107°C (225°F) cure temperature. The glass transition temperature (Tg) of the cured system is 99°C (210°F), providing a comfortable margin over the tank's maximum operating temperature of 60°C (140°F).

A computer-controlled filament winding machine is used to perform the composite overwrap operation. See Figure 10. A computer code was generated to wrap the pressurant tank. The entire wrap process was automated to insure quality and repeatability.

Figure 10: Automated Filament Winding

The filament wrap is bonded to the liner by a thin layer of adhesive. This adhesive is applied to the liner immediately prior to the filament wrap operation. After filament wrap, the vessel is placed in an oven and the resin is gelled and cured.

WEIGHT DISTRIBUTION

The pressurant tank weight distribution is summarized in Table 3 below:

Table 3: Pressurant Tank Weight Distribution

Item	Nominal Weight (kg)	Nominal Weight (lbm)
Liner	3.7	8.1
Composite	8.0	17.7
TOTAL	**11.7**	**25.8**

The qualification tank was slightly above the nominal weight. However, most flight tanks fabricated were slightly below nominal weight.

TANK GROWTH

The pressurant tank undergoes expansion as it is being pressurized. The tank expansion data for the Qualification tank is summarized in Table 4. The measured tank growth closely matches the predicted values.

TANK SIZING

The pressurant tank is subjected to a sizing operation (autofrettage) after the tank is wrapped and the resin system is cured. The autofrettage pressure is selected during tank analysis. This pressurization cycle is considered part of the manufacturing process and is not included in the pressure cycle history. Autofrettage is performed immediately prior to acceptance proof pressure testing.

Table 4: Pressurant Tank Growth Data

Pressure	Linear Growth	Radial Growth	Volume Growth
MEOP, (331 bar/4800 psi)	9.6 mm / 0.376 inch	2.0 mm / 0.078 inch	3.1 liters (191.4 in^3)
Proof Pressure, (414 bar/6000 psi)	10.8 mm / 0.427 inch	2.4 mm / 0.093 inch	4.0 liters (244.1 in^3)

QUALIFICATION TEST PROGRAM

A Qualification Tank was fabricated for the qualification test program. The qualification testing consists of a series of tests intended to verify the pressurant tank design in the following areas:

- Physical properties such as volume and weight
- Tank shell integrity
- Low cycle fatigue
- High cycle fatigue
- Shock fatigue
- Burst margin

Pass/Fail criteria consisted of acceptance type external leak tests conducted at intervals throughout the test program. After the tank passed the final external leak test, it underwent a destructive burst pressure test. The successful burst certified the tank for flight use.

The Qualification Tank was subjected to the following qualification tests:

- Volumetric capacity
- Proof pressure test
- Volumetric capacity at ambient
- Volumetric capacity at MEOP
- Pressure cycles
- External leakage
- Pressurized pyrotechnic shock
- External leakage
- Sinusoidal and random vibration
- External leakage
- Final examination
- Destructive burst pressure test

Volumetric Capacity Examination: The volumetric capacity of the pressurant tank was measured using the weight of water method at ambient condition. Deionized (DI) water was used to conduct this test. The tank volumes before and after the proof pressure test were measured to verify that the tank volume met the specification requirement and that the proof pressure test did not significantly change the tank volume. As an example, the internal volume of the Qualification Tank did not increase after the proof pressure test, signifying that the pressurant tank was manufactured successfully.

Proof Pressure Test: The hydrostatic proof pressure test was conducted at 414 bar (6,000 psig) for a pressure hold period of 5 minutes. Successful completion of the proof pressure test and the subsequent volumetric growth and leakage verification indicated that the tank was manufactured successfully.

Pressure Cycles: The pressurant tank is designed to accommodate a minimum of 8 proof pressure cycles and 50 operating pressure cycles. As a practice several operating pressure cycles were added for contingency. A total of 8 proof cycles and 52 MEOP cycles were conducted at this pressure cycle testing. Additionally, the Qualification Tank experienced another operating pressure cycle during shock test, 3 operating pressure cycles for the 3 external leakage tests and 5 more operating pressure cycles during vibration testing. The cumulative total of operating pressure cycles is 61, or 11 cycles over the minimum requirement. A picture of the pressure test setup is shown in Figure 11.

Figure 11: Pressure Test Setup

External Leak Test: The external leak test verifies the integrity of the tank shell and also serves to validate the previous series of pressure testing. The tank is placed in a vacuum chamber, which is evacuated to under 0.2 microns of mercury, and helium pressurized to MEOP for 30 minutes. The helium leak rate cannot exceed 1×10^{-6} std cc per second after a 30-minute stabilization period. For example, the leak rate of the Qualification Tank was 2.3×10^{-8} scc/sec.

During pressurization, the compressed gas heats up, thus heating up the tank. To prevent overheating, four thermocouples are attached to the tank shell to monitor and control the pressurization rate and the tank temperature during pressurization. The tank temperature cannot exceed 140°F throughout the duration of the test.

Pressurized Pyrotechnic Shock Test: Pyrotechnic shock testing was performed on the Qualification Tank. Prior to testing, a pathfinder tank was mounted to the test fixture for equalization of the shock system and to demonstrate the achievable level of input shock response spectrum. The Qualification Tank was then installed in the fixture and pressurized to 4,800 psig. The test consisted of subjecting the tank, loaded with 4,800 psig of gaseous helium, to two metal-to-metal impact shock impulses. The impulses had an input shock response spectrum of 7000g. Both the longitudinal axis (X axis) and the lateral axis (Z axis) were excited simultaneously by the two qualification level metal-to-metal impact shock impulses. The shock spectrum is presented in Table 5. A picture of the shock test setup is shown in Figure 12.

Figure 12: Shock Test Setup

Vibration Test, Sinusoidal and Random: Qualification level sinusoidal and random vibration tests were performed on the Qualification Tank in each of the three principal axes. The vibration test requirements are shown in Tables 6 and 7.

The vibration test fixture is designed to simulate the tank-to-spacecraft installation interfaces and orientation. It is also sufficiently stiff to be considered rigid for the test frequencies. A preliminary test fixture evaluation was conducted prior to Qualification Tank installation to insure the fixture meets the testing requirements.

Control accelerometers were placed on the vibration test fixture near each end fitting to control the vibration input. Response accelerometers were placed on the Qualification Tank to measure the tank responses. The placements of the response accelerometers were selected to record the tank responses at locations of maximum stress as predicted in the analytical model.

The vibration test included fixture survey, full level sinusoidal and full level random runs. The same tests were conducted in all three axes. All testing was conducted with the tank pressurized to 4,800 psi with helium. A photograph of the vibration test setup is shown in Figure 13.

Figure 13: Pressurant Tank Qualification Vibration Test Setup

Destructive Burst: After the completion of the pressure cycles, shock, and vibration testing, the Qualification Tank was subjected to a final destructive burst pressure test. The Qualification Tank burst at 572 bar (8,297 psi), providing a 15.2% margin on burst pressure. This data represents a burst factor of 1.73 to 1, and a performance efficiency rating (Pressure x Volume / Weight) of 1.57 x 10^6 inches. This high efficiency factor represents the most efficient pressure vessel ever designed by PSI. Figure 14 shows the Qualification Tank after burst.

Figure 14: Qualification Tank After Qualification Burst Pressure Test

Table 5: Shock Test Spectrum

Axes	Frequency (Hz)	Shock response spectrum input (g)
Longitudinal and one lateral axis	100	80 ± 6 dB
	1500	7000 ± 6 dB
	3000	7000 ± 6 dB
	6000	7000 + 9 dB / -6 dB
	10000	7000 + 9 dB / -6 dB
Shock response spectrum based on Q=10		

Table 6: Qualification Level Sinusoidal Vibration Test Environment

Axes	Frequency (Hz)	Input Level (G)	Sweep Rate
X, Y, and Z	5 - 24	0.5 in. DA	2 oct/min
	24 - 65	15	
	65 - 100	7	

Table 7: Qualification Level Random Vibration Test Environment

Axes	Frequency (Hz)	PSD Input Level	Overall Level (Grms)	Duration (sec.)
X, Y, and Z	20 – 100	+3 dB/oct	18.1	120
	100 – 1000	0.2 g^2/Hz		
	1000 - 2000	-3 dB/oct		

Qualification Tank Pressure Log: In summary, the Qualification Tank has undergone the pressure cycles listed in Table 8. The successful completion of the qualification test program is an excellent demonstration of the tank's robust design.

ACCEPTANCE TESTING

The following acceptance tests are performed on a flight tank prior to delivery:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure
- Post-proof volumetric capacity
- Volumetric capacity at MEOP
- External leakage
- Weld quality inspection
- Final examination
- Cleanliness measurement

Cleanliness Verification: After the final external leak test, each flight tank is cleaned to the cleanliness level specified in Table 9.

Table 9: Pressurant Tank Cleanliness Level

Particle Size Range (Microns)	Maximum Allowed per 100 ml
5 to 10	140
11 to 25	20
26 to 50	5
51 to 100	1
Over 100	0

Photograph of a completed tank is shown in Figure 15.

Figure 15: A completed Pressurant Tank

Table 8: Summary of Qualification Tank Pressure Cycles

Pressure	Actual # of Cycles	Required Cycles	Description
331 bar (4,800 psig), Operating pressure	61	50	52 operating cycles 3 external leaks 1 shock test 5 pressurization cycles during vibration testing
414 bar (6,000 psig), Proof pressure	8	8	1 proof test, 7 proof cycles

CONCLUSION

The pressurant tank development program has successfully concluded qualification testing without failure. The qualification testing shows the pressurant tank having comfortable margins over all the operational requirements. The production program successfully fabricated several flight tanks.

The pressurant tank is high performance, light weight, and easy to manufacture. The composite overwrap and the liner components are made from commercially available materials. The liner assembly and filament winding are accomplished using standard manufacturing processes and procedures. Special material and processes are not required.

This tank is also lighter than a typical all-metal tank of the same capacity and capability. The manufacturing cycle is several months shorter than a comparable all-metal tank. Acceptance testing is simpler or equivalent to an all-metal pressurant tank.

The pressurant tank maintains excellent design and flight heritage. Its overall design and method of manufacturing are derived from several prior COPV programs. The design of this pressurant tank is extremely conservative and all manufacturing methods are based upon existing technology.

Most importantly, the successful qualification of this tank marks the milestone in which a derivative COPV pressurant tank is designed and manufactured efficiently and inexpensively using existing technology.

ACKNOWLEDGMENT

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REFERENCE

1. G. Kawahara, S. McCleskey, “Titanium-Lined, Carbon Composite Overwrapped Pressure Vessel”, AIAA 96-2751.

2. W. H. Tam, I. Ballinger, J. Kuo, W. Lay, S. McCleskey, P. Morales, Z. Taylor, S. Epstein, "Design and Manufacture of a Composite Overwrapped Xenon Conical Pressure Vessel", AIAA 96-2752.

3. W. H. Tam, A. C. Jackson, E. Nishida, Y. Kasai, A. Tsujihata, K. Kajiwara, “Design and Manufacture of the ETS VIII Xenon Tank”, AIAA 2000-3677.

NOTES: