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Design and Manufacture of a Composite Overwrapped Xenon Conical Pressure Vessel

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DESIGN AND MANUFACTURE OF A COMPOSITE OVERWRAPPED XENON CONICAL PRESSURE VESSEL

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ABSTRACT

A unique titanium-lined, carbon fiber overwrapped Xenon storage pressure vessel was designed for an aerospace application. This tank has a nominal propellant volume of 1980 cubic inches and a nominal weight of 13.5 pounds. The operating pressure is 2500 psi, and the minimum burst pressure is 3750 psi.

Due to limited space aboard the spacecraft, the tank was designed to fit within a conical envelope. This conical shape presented several major challenges for analysis, design and manufacture.

Nonlinear material and geometric modeling techniques were used to analyze this tank. Stress analysis shows positive margins of safety for pressure cycle fatigue, vibration fatigue and minimum burst pressure over the design requirements.

The liner was constructed from commercially pure (CP) titanium. CP titanium was chosen due to its relative high strength, excellent corrosion and oxidation resistance characteristics, superb weldability, good low and high cycle fatigue characteristics, and competitive manufacturing cost.

The overwrap consists of high strength Torayca T1000GB carbon fiber and Shell Epon 826 cured resin system. Four composite layers were applied, two helical and two hoop wraps.

A complete qualification program was conducted to verify the tank design, including two destructive burst pressure tests. A leak-before-burst demonstration was also performed. The tank qualification program was successfully completed on 28 March 1996.

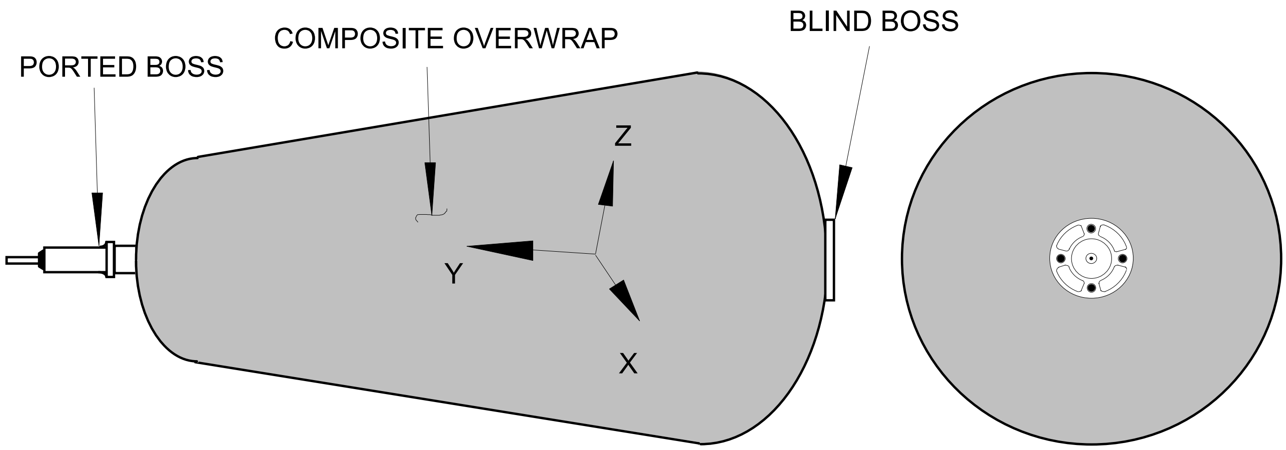
INTRODUCTION

A Xenon storage pressure vessel with unique characteristics is needed for a Xenon propulsion system. This tank must be high performance, light weight, and designed to withstand severe launch and operational loads. Additionally, it requires an unusual conical shape to allow it to be mounted without interference from nearby components. 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.

The tank is mounted to the spacecraft by polar bosses located on the tank centerline axis. The blind boss is attached to the spacecraft by four 1/4” bolts. The ported stinger boss mounts on a slip joint bearing. This slip joint bearing is designed to accommodate the tank’s axial growth during pressurization.

Two tanks are required per spacecraft.

Figure 1: Titanium-Lined, Composite Overwrapped Xenon Conical Pressure Vessel



The Xenon tank was designed to the following requirements:

Table 1: Xenon Tank Design Requirements

PARAMETERS	REQUIREMENTS
Operating Pressure	2500 psi, 50 cycles
Proof Pressure	3125 psi, 4 cycles
Burst Pressure	3750 psi minimum
External Pressure	0 to 14.7 psi, 24 cycles
Propellant Weight	116 lbm Xenon
Size	13.24" max. dia. x 29.625" long
Tank Weight	14 lbm maximum
Tank Capacity	1960 in^3 minimum
Overall Length	29.625 inches nominal
Fluid	Xenon gas
Shell Leakage	<1x10^{-6} std cc/sec He @ MEOP
Failure Mode	Leak-before-burst
Operating Temperatures	19 °F to 122 °F

This tank is also designed to withstand vibration loads of 15g's in the X and Z axes and 17g's in the Y axis at 70°F when fully loaded and pressurized to 1100 psi. All design requirements were verified by qualification testing.

DESIGN HERITAGE

A titanium-lined composite overwrapped tank is unique in the Aerospace Industry since aluminum is typically the material of choice for liners. However, a CP titanium lined helium pressurant tank similar in design and construction had been built and qualified[1] for another customer prior to the fabrication of the Xenon tank. This Xenon tank draws its heritage from the helium tank and utilizes the same basic design and manufacturing techniques. The liner material used on both programs is identical, although the Xenon tank liner is slightly thicker. The filament/epoxy resin system is basically the same. The only difference between the two resin systems is the curing agent, whose use is driven by thermal requirements of the specification.

Prior to the design and fabrication of the helium pressurant tank, a material trade study was conducted to compare material properties of titanium versus aluminum for use as the liner material. It was found that a titanium liner exhibits the following favorable characteristics compared to an aluminum liner:

- Better corrosion and oxidation resistance;
- Less susceptible to pitting and stress corrosion;
- Higher strength-to-weight ratio;
- Better galvanic compatibility with carbon fiber;
- Better low cycle fatigue performance;
- Better high cycle fatigue performance.

Other properties also favor titanium liners:

- Good machinability and weldability;
- Excellent weld properties;
- Competitive manufacturing cost;
- Good performance characteristics.

DESIGN APPROACH

The design of the Xenon tank presented several major challenges due to its odd shape: the analytical approaches, the manufacturing of the domes and the center section, the assembly and welding of the thin liner, and the wrapping of the tank.

The original design approach for this tank was to achieve a wrap pattern for a fixed liner design. It was found that this approach failed to optimize the properties of both the liner material and the filament wrap, and the resultant design was deemed inefficient. This method was abandoned in favor of a better approach that maximizes the material properties of both the liner and the composite.

The preliminary design revealed that because of the filament winding constraints associated with a conical tank, performance of the conical tank will be lower than a cylindrical tank of the same capacity. This inherent inefficiency makes weight minimization a time-consuming task requiring multiple design iterations. Due to schedule constraints, weight optimization was not rigorously pursued. The results of qualification testing indicate that the tank is slightly overdesigned and additional analytical iterations would indeed further reduce the tank weight.

TANK DESIGN AND ANALYSIS

Several analytical models were used to design and analyze the Xenon tank, as follow:

- A Shell Finite Element Model was used to analyze buckling, uniform acceleration, racking, and stress stiffened vibration modes.
- A Nonlinear Axisymmetric Finite Element Model was utilized to analyze deflections, strains, and plastic strains. This model also considered detailed geometry and material distribution and analyzed geometric and material nonlinear behavior.
- The Coffin Manson Predictions were used to perform the linear low cycle fatigue analysis associated with pressure cycling.
- The Goodman Diagram was used to calculate high cycle fatigue associated with external/vibration loads on the end fittings.

The design analysis predictions correlated well with qualification test results.

MARGIN SUMMARY

The stress analysis shows large positive margins of safety for pressure cycle fatigue, vibration fatigue and minimum burst pressure, as summarized in Table 2.

Table 2: Xenon Tank Safety Margins

Characteristics	M.S.
Minimum burst pressure	+0.07
External pressure	+13.20
Peak strain due to pressure cycling	+0.07
Operating/proof pressure cycles	+3.80
G-load on composite, helical	+4.40
G-load on composite, hoop	+4.20
G-load on blind end fitting	+9.50
G-load on ported end fitting	+0.40

LINER DESIGN AND FABRICATION

Typically, a liner is a low load bearing member of a high performance, filament wrapped pressurant tank. It serves as a container for the pressurant and provides a defined shape to apply the filament overwrap. The composite wrap furnishes most of the strength for the pressurant tank, and the liner wall is kept as thin as practical to minimize tank weight. However, two additional factors must also be considered when designing this Xenon tank liner:

(1) The mass property of Xenon is closer to liquid than gas. The density of Xenon gas at the operating temperature is in fact greater than liquid water; and

(2) The long trunnion at the ported stinger fitting coupled with the large mass carried by the tank creates a large moment arm during vibration.

The boss loads on the Xenon tank are therefore significantly higher than a typical pressurant tank. A thin liner design would be susceptible to failure due to bending induced metal stress during vibration. The problem is resolved by:

- Building a liner with high-strength material such as titanium, and
- Fabricating stiffened fittings to sustain the bending induced loads.

Commercially pure titanium sheet was selected over other potential titanium alloys because CP titanium demonstrates excellent formability at room temperature and is readily available. However, the selection of liner thickness presented a different challenge. PSI has welded CP titanium liners as thin as 0.020 inch[1]. The 0.020 inch material produced a small weight saving as compared to the 0.032 inch material. However, the 0.032 inch thick material greatly enhanced manufacturability and repeatability, and in this schedule critical application, was chosen as the liner material.

The tank liner is constructed of five basic elements, as shown in Figure 2:

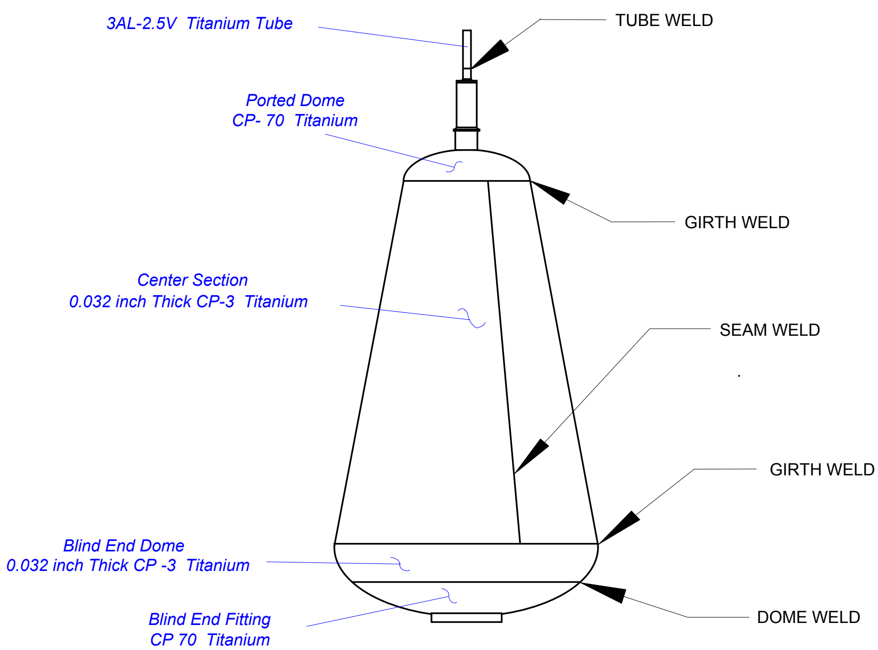
- a 3AL-2.5V titanium tube;
- a CP-70 titanium ported dome/stinger fitting;
- a CP-3 titanium conical center section;
- a CP-3 titanium blind end dome;
- a CP-70 Titanium blind end fitting.

The ported dome and the blind end fitting are machined from CP-70 titanium bar stock. This material has a yield strength of 70 ksi, an ultimate tensile strength of 80 ksi, and a typical elongation of 15%[2].

The conical center section and the blind end dome are fabricated from 0.032 inch thick CP-3 titanium sheet. This titanium material has good strength, high elongation, and good formability. The CP-3 titanium has a yield strength of 40 ksi, an ultimate tensile strength of 50 ksi, and a typical elongation of 20%[2]. The conical center section is rolled and formed with one longitudinal seam weld. The blind end dome is cold hydroformed to the correct dome contour.

A test fitting is welded to the titanium tube to form the fitting assembly. This fitting assembly is welded to the ported dome to form the ported dome assembly. The fitting is used only for acceptance testing and is removed from the tank after completion of acceptance tests and prior to final tank cleaning and delivery. The blind dome is match machined and welded to the blind end fitting to form the blind dome assembly. Both the ported dome and the blind dome assemblies are then girth welded to the center section to complete the liner assembly. The finished liner is stress relieved and leak tested prior to the filament winding operation.

Figure 2: Components of the Xenon Tank Liner



COMPOSITE OVERWRAP DESIGN AND FABRICATION

The shape of the Xenon tank presented a number of analytical and producibility challenges. The conical section of the tank creates a unique problem in that the radius of the structure, and the resultant stresses due to internal pressure, vary along the tank length. Vessel laminates are usually designed using uniform and continuous plies or fiber interspersions at a given angle. Fiber applied in a stable pattern on a conical section changes its angle of orientation continuously with the changing radius. The result is that the loads, fiber orientation, and ply thickness are unique for every point along the tank length. This greatly complicates the analytical effort required to design a workable laminate.

Another related challenge is that critically efficient hoop fiber wrapped under tension in a 90° orientation is unstable and tends to slump off the smaller end. Either a variety of stable helical patterns would have to be selected to provide the laminate's hoop strength (with a weight penalty), or some means would have to be devised to make true hoop-oriented plies feasible.

The process chosen to apply the vessel's structural composite overwrap was wet filament winding, using dry fiber roving that is in-process impregnated with a low-viscosity resin. The materials used in the composite overwrap of the Xenon tank include Torayca T1000GB high performance carbon fiber, and an epoxy/amine type filament winding resin system. The basic resin system selected has years of industry heritage and offers the following characteristics:

- Low viscosity;
- Reasonable pot life;
- High strain-to-failure capability;
- Good chemical and moisture resistance;
- Low toxicity; and
- Low outgassing.

The resin system has a 250°F cure temperature. The glass transition temperature (Tg) of the cured system is 175°F, providing a comfortable margin over the tank's maximum operating temperature of 122°F.

A number of innovative steps were taken to allow hoop oriented fiber to be wet-filament wound along the vessel's conical section. A vessel laminate consisting of hoop, polar, and helical fiber interspersions was developed and analyzed. The design included a layer of film adhesive between the liner and composite laminate. The adhesive ensures adhesion between the metallic liner and the composite overwrap and provides a measure of galvanic isolation between the metal liner and the carbon fiber.

A four-axis, computer-controlled filament winding machine is used in the precise placement of the composite overwrap on the liner. The computer code was generated to control the machine's movements during the wrap process. The entire wrap process was automated as much as possible to maximize the assembly's quality and repeatability. Prior to filament winding, a layer of film adhesive is applied to the liner's surface. After completing the laminate, the vessel assembly is gelled and cured.

TANK SIZING

The Xenon tank is subjected to a sizing operation (autofrettage) after the tank is wrapped and the resin system is cured. This operation is performed prior to acceptance testing, at a pressure slightly above the proof pressure.

This sizing operation produces a permanent deformation of the wrapped liner. The stress analysis predicted axial growth of 0.033 inch after autofrettage. The actual growth of the Qualification Tank was 0.033 inch, exactly as predicted. It is worth noting that immediately after the autofrettage, the tank had a measured growth of 0.052 inch. A short settling period must elapse to allow the tank to stabilize before measuring the permanent tank growth.

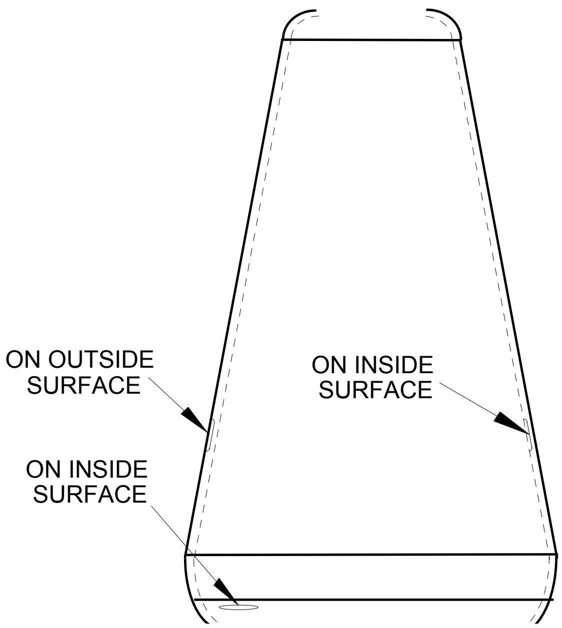
LEAK-BEFORE-BURST DEMONSTRATION

The Xenon tank was designed to a Leak-Before-Burst (LBB) failure mode, per MIL-STD-1522A.

A dedicated LBB tank was fabricated for a LBB demonstration. This LBB tank has three pre-fabricated flaws on the liner. Two of the flaws are located on the conical center section, and the third flaw is located on the blind end fitting near the end fitting-to-dome weld, as shown in

Figure 3. Each flaw has a depth that is at least half the thickness of the liner wall. All flaws are located at the high stress concentration points where the liner is most likely to fail.

Figure 3: LBB Tank Flow Locations



The LBB tank was fabricated along with the production units, using the same manufacturing processes and procedures. The LBB tank successfully completed autofrettage and developed a leak 30 seconds into proof pressure testing.

WEIGHT DISTRIBUTION

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

Table 3: Xenon Tank Weight Distribution

Item	Nominal Weight (lbm)
Liner	7.13
Adhesive	0.40
Composite	5.97
TOTAL	**13.50**

The Qualification tank weighed 13.44 pounds.

ACCEPTANCE TESTING

The following sequence of acceptance tests is performed on a flight tank prior to delivery:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure
- Post-proof volumetric capacity
- Ambient operating pressure tank capacity
- External leakage
- Final examination
- Cleanliness

Volumetric Capacity Examination: The volumetric capacity of the Xenon tank is measured using the weight of water method. Deionized (DI) water is used to conduct this test. The tank volumes before and after the proof pressure test are measured to verify that the proof pressure test does not significantly change the tank volume. As an example, the internal volume of the Qualification Tank increased by only 0.56 in^3 after the proof pressure test. This represents a 0.02% volume increase, which is insignificant.

Proof Pressure Test: The hydrostatic proof pressure test is conducted at 3125 (+50, -0) psig for a pressure hold period of 5 minutes. The stress analysis predicted an axial growth of 0.205 inch at proof pressure. Actual growth of the Qualification Tank was 0.197 inch.

Operating Pressure Tank Capacity: This test measures the volumetric capacity of the Xenon tank at operating pressure using the weight of the water method. DI water is used to conduct this test. The actual tank volume of the Qualification Tank at operating pressure is 2041 in^3, or 81 in^3 greater than the design requirement. The axial growth of the tank is also measured during the tank capacity test. The stress analysis predicted an axial growth of 0.154 inch. The actual axial growth of the Qualification Tank was 0.155 inch.

External Leak Test: The external leak test verifies the integrity of the tank shell and also serves to validate the above pressure tests. The tank is placed in a vacuum chamber, which is evacuated to under 0.2 microns of mercury, and helium pressurized to 2500 psig for 30 minutes. The helium leak rate cannot exceed 1×10^{-6} std cc per second after the 30-minute stabilization period.

The leak rate of the Qualification Tank was 1.6 x 10^{-8} scc/sec for this test.

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. The temperature profile of the Qualification Tank during pressurization is shown in Figure 4.

Cleanliness Verification: After the external leak test, each flight tank is cleaned to the cleanliness level specified in Table 4.

Table 4: Xenon Tank Cleanliness Level

Particle Size Range (Microns)	Maximum Allowed per 1000 ml
0 to 10	No silting of particles
11 to 20	750
21 to 30	400
31 to 40	225
41 to 50	100
51 to 60	25
61 and over	0

QUALIFICATION TEST PROGRAM

There are two qualification programs for the Xenon Tank:

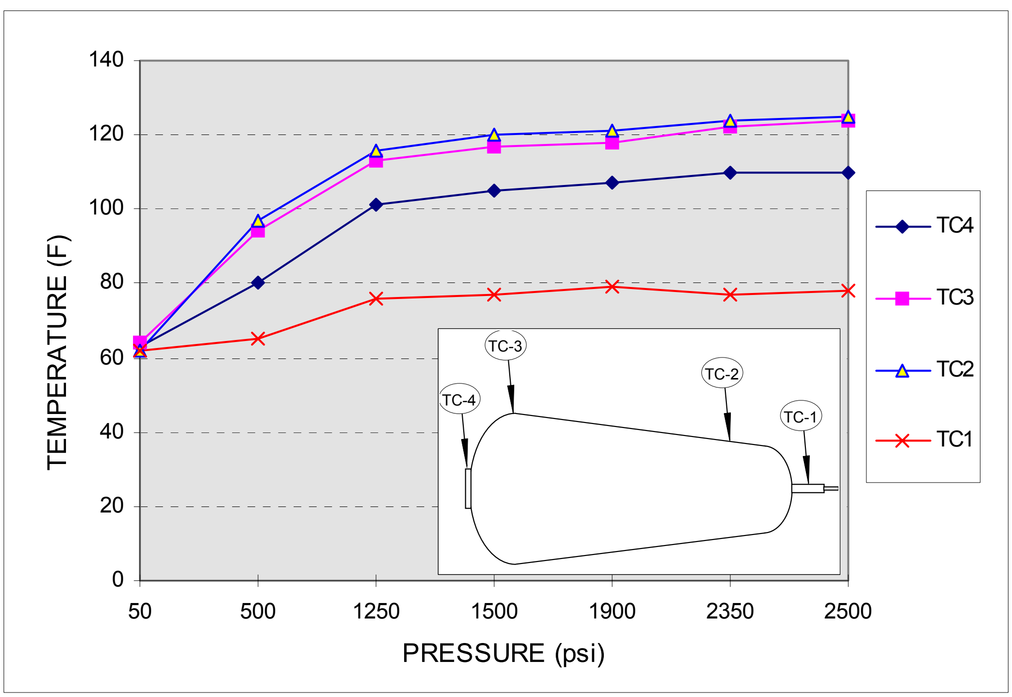
1. Pedigree Burst
2. Full Qualification

Pedigree Burst: The Pedigree Burst Tank is acceptance tested and followed immediately by a destructive burst test. The tank burst at 5298 psi or 1548 psi (41%) over the minimum design burst pressure requirement. The test result represents an actual burst factor of 2.11 to 1. The design burst factor is 1.5 to 1. The performance efficiency rating (PV/W) of this tank is 0.8 x 10^6 inches.

Full Qualification: The Full Qualification Test Program consists of a series of tests intended to verify the Xenon tank design in the following areas:

- Volumetric Capacity
- Tank shell integrity
- Low cycle fatigue
- High cycle fatigue
- Burst margin

Figure 4: Temperature Profile During Helium Pressurization, External Leak Test



Pass/Fail criteria consists of acceptance type external leak tests and non-destructive evaluations conducted at intervals throughout the test program. After the tank passes the final external leak test, it must undergo a final burst pressure test. A successful burst certifies the tank for flight use.

The Qualification Tank is subjected to the acceptance tests (except cleanliness) followed by these qualification tests:

- Evacuation cycles
- Pressure cycles
- External leakage
- Pressure hold
- External leakage
- Sinusoidal and random vibration
- External leakage
- Final examination
- Destructive burst pressure

Evacuation Cycles: The Xenon tank is evacuated during the flight tank fill operation, and the tank must withstand an external pressure of 14.7 psi. Twenty-four evacuation cycles from 0 to -14.7 psi were conducted on the Qualification Tank to verify this requirement.

Pressure Cycles: The Xenon tank is designed to accommodate a minimum of 4 proof pressure cycles and 50 operating pressure cycles. The four proof cycles consume 4% of the service life, and the 50 operating cycles consume 16.8% of the service life, according to the fatigue analysis. A total of 4 proof cycles and 55 operating cycles were conducted on the Qualification Tank.

Pressure Hold Test: A long duration (300 hours minimum) pressure hold test was conducted with the tank at operating pressure. The actual test period was 311 hours.

Vibration Test, Sine 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 5 and 6.

Sinusoidal vibration sweep rate is 2 Oct/minute. Random vibration responses are limited to 15 g for the X and Z axes and 17 g for the Y axis. Random vibration test duration is 3 minutes in each axis.

Table 5: Qualification Level Sinusoidal Vibration Test Environment

Axes	Frequency (Hz)	Acceleration (g 0-Peak)	Displacement (in. DA)
Z	5 - 7 7 - 100	- 1.25	13 mm (0.5 in)
X,Y	5 - 6.3 6.3 - 100	- 1.0	13 mm (0.5 in)

Table 6: Qualification Level Random Vibration Test Environment

Axes	Frequency (Hz)	PSD (g^2/Hz)	PSD (dB/Oct)	grms
X,Y,Z	20	0.0029		9.42
	20 - 118		+6	
	118 - 560	0.1		
	560 - 2000		-6	
	2000	0.008		

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 with a mass simulator installed in the fixture. A low level sine sweep and a full level random vibration test were conducted on the mass simulator prior to the actual Qualification Tank testing.

The Qualification Tank vibration test was conducted with the tank fully loaded with 116 lbs of test fluid and pressurized to 1100 psig. The test fluid was specifically chosen to simulate the mass properties of the Xenon gas. The 1100 psi represents launch pressure.

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 along the plane of the tank center of gravity to monitor the tank responses. Strain gauges were also installed on both end fittings near the tank membrane to determine axial and bending strains during vibration testing. Strain readings were recorded throughout the test, as follows:

- As gauged and zeroed;
- Installed into the fixture and torqued;
- Pressurized but prior to test;
- During vibration testing;
- Depressurized.

The vibration test included low level sine sweep, full level sine sweep, low level random vibration, notched full level random vibration, and a final low level sine sweep. The same sequence of tests was conducted in all three axes. Peak response of the full level qualification random vibration run for each axis is shown in Table 7:

Table 7: Random Vibration Qualification Runs (Peak Response)

Axis	Minimum Required	Actual
X-Axis	15.0 g	17.0 g
Y-Axis	17.0 g	18.5 g
Z-Axis	15.0 g	14.6 g

The predicted vibration modes and frequencies for the Xenon tank at 1100 psi are shown in Figure 5. The actual test results correlate well with the predicted values.

A photograph of the vibration test setup is shown in Figure 6.

Destructive Burst: After the completion of the qualification tests, the Qualification Tank was subjected to a final destructive burst pressure test. The Qualification Tank burst at 5370 psig or 1620 psi (43%) over the design burst pressure and 72 psi over the Pedigree Burst Tank burst pressure. This data represents a burst factor of 2.15 to 1, and a performance efficiency rating (PV/W) of 0.8 x 10^6 inches.

Figure 7 presents a photograph of the tank after burst.

Qualification Tank Pressure Log: In summary, the Qualification Tank has undergone the following pressure cycles:

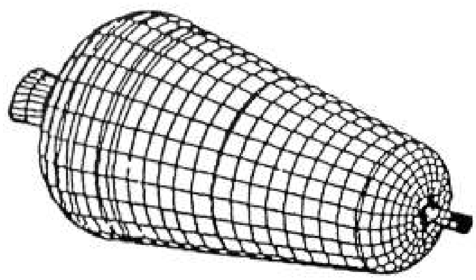
Table 8: Summary of Qualification Tank Pressure Cycles

Pressure	No. Cycles	Description
3125 psig, Proof pressure	4	1 proof test, 3 proof cycles
2500 psig, Operating pressure	61	1 capacity test, 55 operating cycles 4 external leaks 1 pressure hold
1100 psig, Launch pressure	4	32 hours during vibration test
-14.7 psig External pressure	24	24 vacuum cycles

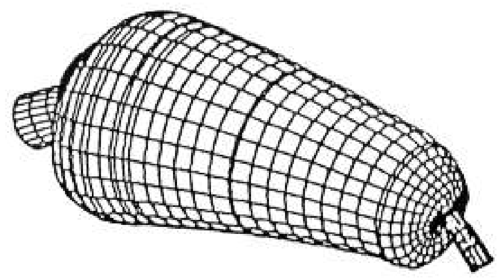
The tank had been either inadvertently or deliberately overtested during the rigorous test program. The successful completion of the Qualification Test Program is an excellent demonstration of the tank's robust design.

Figure 5: Predicted Vibration Modes and Frequencies

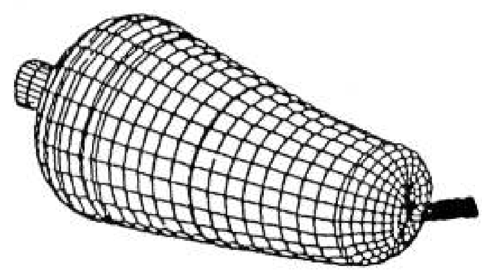
MODE 1: 114.6 Hz, 1st Torsional



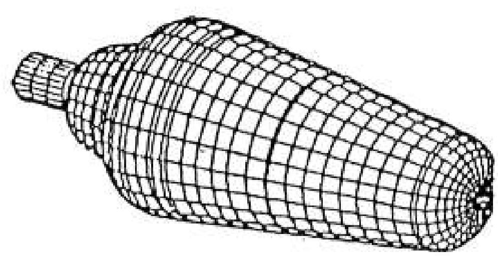
MODE 2: 139.2 Hz, 1st Lateral (Y)



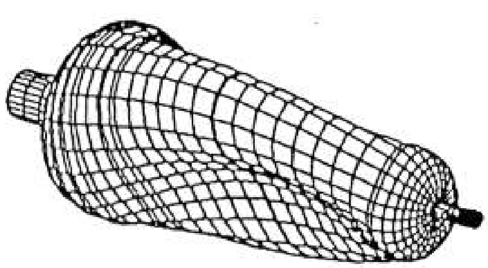
MODE 3: 170.9 Hz, 1st Lateral (Z)



MODE 4: 180.2 Hz, 1st Axial



MODE 5: 270.0 Hz, 1st Radial



MODE 6: 352.4 Hz, 2nd Radial

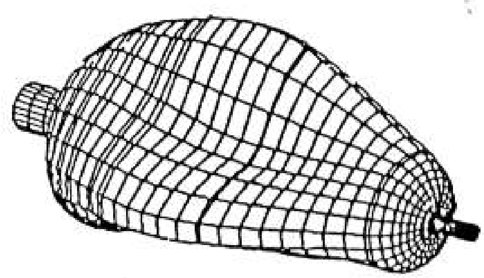


Figure 6: Xenon Qualification Tank Vibration Test Setup

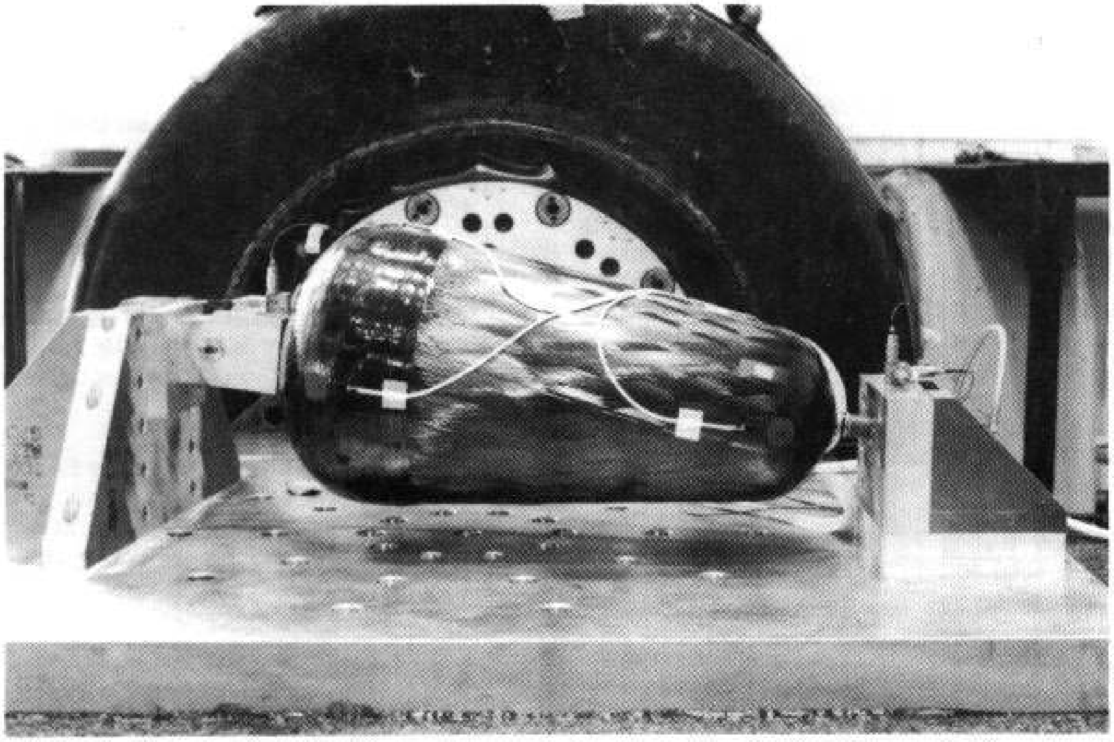
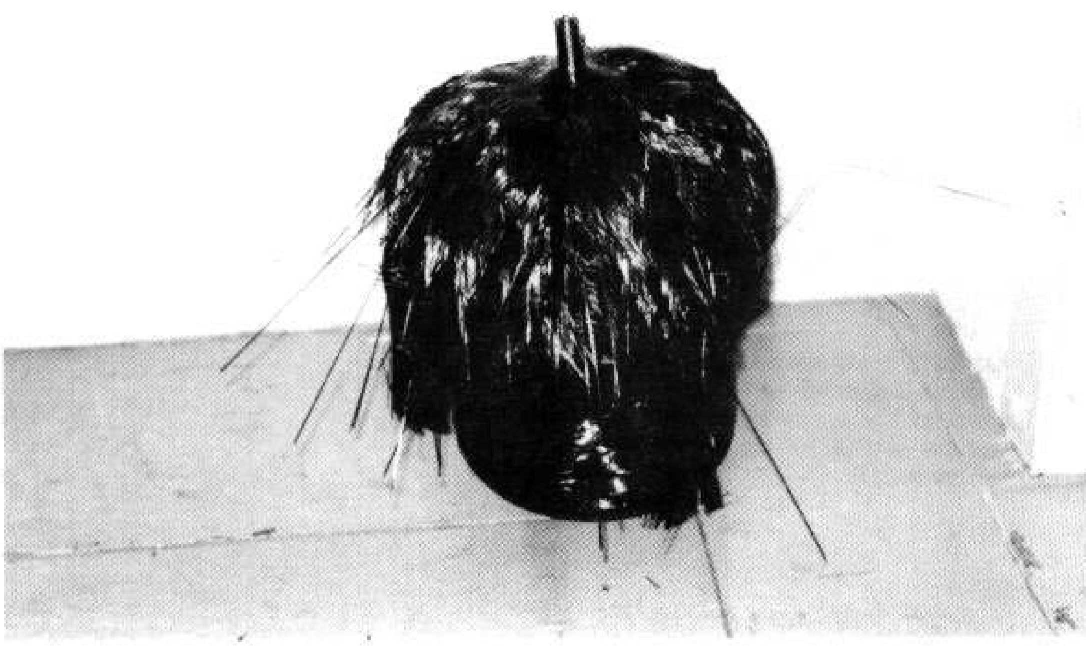


Figure 7: Xenon Qualification Tank After Burst



CONCLUSION

The Xenon tank has successfully concluded qualification testing without failure. The production program is currently underway and four flight tanks have been delivered to date.

The tank is light weight, high performance, and easy to manufacture. The composite overwrap and the liner components use 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 about 3 to 6 months shorter than a comparable all-metal tank. Acceptance testing is simple and does not require special testing typical of an all-metal pressurant tank.

Most importantly, the successful qualification of this tank marks a milestone in which a composite overwrapped pressure vessel with a titanium liner is being used for an aerospace application.

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