DESIGN AND MANUFACTURE OF THE ETS VIII
COMPOSITE OVERWRAPPED XENON PRESSURE VESSEL

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ABSTRACT

A titanium-lined composite overwrapped pressure vessel (COPV) for Xenon storage was designed for the ETS VIII spacecraft. This tank has a nominal propellant volume of 50 liters (3050 cubic inches) and a nominal weight of 7 kg (15.4 pounds). The operating pressure is 150 bar (2175 psi), and the minimum burst pressure is 225 bar (3264 psi). The tank is designed to hold 89 kg (196 pounds) of Xenon.

The ETS VIII Xenon tank has many similar features as a flight-qualified Xenon tank to take advantage of its design and flight heritage. To minimize risk, this tank is fabricated using only existing manufacturing technology.

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. Development and Qualification testing verified the design margins and showed the design analyses to be conservative.

The liner is constructed from 6Al-4V titanium. This material was chosen 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 T1000GB carbon fiber and Epon 826 cured resin system. Several composite layers were applied, including helical and hoop wraps.

A leak-before-burst (LBB) demonstration program was conducted to verify the LBB characteristics of the Xenon tank. A complete qualification program was conducted to verify the tank design, including a destructive burst pressure test. The tank successfully completed qualification testing on 10 September 1999.

INTRODUCTION

A Xenon storage pressure vessel with unique characteristics is needed for the ETS VIII spacecraft Xenon propulsion system. 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 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: The ETS VIII Xenon Tank

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 ported end is designed to accommodate the tank’s axial growth during pressurization. Two Xenon tanks are required for the ETS VIII spacecraft.

The ETS VIII Xenon tank was designed to the following requirements:

Table 1: ETS VIII Xenon Tank Design Requirements

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>REQUIREMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Expected Operating Pressure (MEOP)</td>
<td>150 bar (2175 psi), 50 cycles minimum</td>
</tr>
<tr>
<td>Proof Pressure</td>
<td>187.5 bar (2719 psi), 5 cycles minimum</td>
</tr>
<tr>
<td>Burst Pressure</td>
<td>225 bar (3264 psi) minimum</td>
</tr>
<tr>
<td>Collapse Pressure</td>
<td>-1 bar (-14.7 psi), 20 cycles minimum</td>
</tr>
<tr>
<td>Propellant Weight</td>
<td>89 kg (196 lb) Xenon gas</td>
</tr>
<tr>
<td>Size</td>
<td>336.7 mm Ø x 682.8 mm long, (13.26&quot; Ø x 26.9&quot; long), boss to boss</td>
</tr>
<tr>
<td>Overall Length</td>
<td>841.8 mm (33.14 inches) nominal</td>
</tr>
<tr>
<td>Tank Weight</td>
<td>7 kg (15.4 lb) maximum</td>
</tr>
<tr>
<td>Tank Capacity</td>
<td>50 liters (3050 in³) minimum, unpressurized</td>
</tr>
<tr>
<td>Compatibility</td>
<td>Xenon, Argon, IPA, Helium, Nitrogen, PF 5060, and DI water</td>
</tr>
<tr>
<td>Shall Leakage</td>
<td>&lt;1x10⁻⁶ std cc/sec He @ MEOP</td>
</tr>
<tr>
<td>Failure Mode</td>
<td>Leak-before-burst</td>
</tr>
<tr>
<td>Operating Temperatures</td>
<td>5°C to 55°C (41°F to 131°F)</td>
</tr>
</tbody>
</table>

This tank is also designed to withstand shock and vibration loads and acceleration of 12 g’s in any direction. All design requirements were verified by analysis or qualification testing.
**DESIGN HERITAGE**

PSI has designed two titanium lined COPV’s that are similar in design and construction – one a high pressure helium tank\(^1\), the second a high pressure conical Xenon tank\(^2\). Both tanks are titanium lined and T1000 carbon fiber overwrapped. The ETS VIII Xenon tank draws its heritage from both programs. The manufacturing technology established by these two pioneering programs has matured and the ETS VIII program did not attempt to establish any new technology.

Several conical Xenon tanks are currently operating in orbit. To maximize this design and flight heritage, the design of the ETS VIII tank blind head is nearly identical to the blind head of the conical Xenon tank, including the mounting features. The ETS VIII tank ported head also exhibits very similar features as the conical Xenon tank ported head, as shown in Figure 2. Both liner center sections have the same wall thickness and have identical method of construction.

**Figure 2: Design Heritage of the ETS VIII Xenon Tank**

The liner material remains titanium, although the ETS VIII liner is constructed of 6AL-4V titanium, while the conical Xenon tank liner is made of CP titanium. The filament wrap remains the same T1000 carbon fiber.

**DESIGN ANALYSES**

The basic approach in designing the ETS VIII Xenon tank is to maximize heritage by adapting as many conical Xenon tank design features as possible while enhancing the manufacturability of the liner and overwrap. To minimize risk only existing manufacturing technology is used.

Several analyses were conducted to design and analyze the ETS VIII Xenon tank, including:

- Finite element analysis to conduct the liner material trade study and selection.
- Nonlinear axisymmetric analysis to design the Xenon tank ported and blind heads. Figure 3 below shows the ported and blind heads as modeled by the analysis.

**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 Xenon tank. The actual frequency of the tank is determined at vibration test. Figure 4 below shows a typical lateral mode of the Xenon tank.

**Figure 4: Three-dimensional Finite Element Model**

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

- Shock analysis to determine stress responses due to shock. 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 ETS VIII liner consists of 1 sizing (autofrettage) cycle and 2 design service lifetimes, including proof pressure cycles, operating pressure cycles, and axial and random vibration cycles. A modified Goodman diagram is constructed to present the results of the fatigue analysis, as shown below in Figure 5.

**Figure 5: Modified Goodman Diagram**

- Fracture mechanics analysis to verify the leak-before-burst failure mode.

- Fastener analysis to verify thread shear and bolt shear margins.
LINER DESIGN AND FABRICATION

Prior to designing the ETS VIII Xenon tank, a material trade study was conducted to compare material properties of CP-3, CP-70 and 6AL-4V titanium to aid material selection. It was found that 6AL-4V is the only material that can (1) meet the criteria for elastic behavior between zero pressure and MEOP, (2) meet the stated desire for LBB analysis instead of LBB demonstration test, and (3) meet the overall tank weight requirement.

Typical of most COPV’s, The composite overwrap for the ETS VIII Xenon tank 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 Xenon gas and provides a defined shape to apply the filament overwrap. To minimize weight the liner wall is kept as thin as practical. However, the design of the liner also takes into account the mass property of the heavy Xenon gas and the high vibration loads during launch, both conditions that result in high boss loads. The high strength, low weight 6AL-4V titanium is ideal for this application.

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 ETS VIII Xenon tank liner is a five-piece construction that consists of two heads, a cylinder, a tube adapter, and an outlet tube, as shown in Figure 6.

Figure 6: Components of the Xenon Tank Liner
The outlet tube is made from 6.35mm (0.250 inch) outside diameter tubing. The tube adapter is made from titanium bar. The ported head and the blind head are machined from raw forgings. The center section is fabricated from 0.8 mm (0.032 inch) thick 6AL-4V 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 conical Xenon tank center section.

The liner is assembled with two girth welds and two tube assembly welds using the same weld technique and weld schedule as the conical Xenon tank. Each weld is radiographic and penetrant inspected for acceptance. The completed liner is leak tested prior to the filament wrap operation.

Although the ETS VIII Xenon tank liner was designed to mirror the construction of the conical Xenon tank liner, a modification was incorporated to improve the liner fabrication. As mentioned previously, the ETS VIII liner blind head is similar in configuration to the conical tank liner blind head. However, the blind head of the conical liner is a welded assembly made from an end fitting and a formed dome. It was determined that the two additional dome welds can be eliminated from the ETS VIII liner by machining the heads from forgings. The forging is designed such that both heads can be machined from the same forging configuration. This modification minimized the number of hardware for processing, and also eliminated several operations such as the assembly weld and the post-weld radiographic and penetrant inspection. This change makes the ETS VIII Xenon tank inherently more reliable by minimizing the number of welds in the liner.

**COMPOSITE OVERWRAP DESIGN AND FABRICATION**

The ETS VIII Xenon tank composite overwrap contains several layers of high angle, helical and hoop wraps. The same wet filament winding technique used on the conical Xenon tank is applied to the ETS VIII Xenon 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 T1000GB 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 225°F cure temperature. The glass transition temperature (Tg) of the cured system is 87°C (189°F), providing a comfortable margin over the tank's maximum operating temperature of 55°C (131°F).

A computer-controlled filament winding machine is used to perform the composite overwrap operation. See Figure 7. A computer code was generated to wrap the development tank. After development testing this code was revised and finalized to wrap the LBB, Qualification, and flight tanks. The entire wrap process is automated to insure quality and repeatability. As an example, the LBB tank and the Qualification tank were wrapped on the same day. The weight difference between these two tanks is 9 grams (0.02 lb), representing a 0.1% variance.

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.

**Figure 7: Automated Filament Winding**
WEIGHT DISTRIBUTION

The Xenon tank weight distribution is summarized in Table 2 below:

<table>
<thead>
<tr>
<th>Item</th>
<th>Nominal Weight (kg)</th>
<th>Nominal Weight (lbn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liner</td>
<td>4.31</td>
<td>9.50</td>
</tr>
<tr>
<td>Adhesive</td>
<td>0.18</td>
<td>0.40</td>
</tr>
<tr>
<td>Composite</td>
<td>2.44</td>
<td>5.37</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>6.93</strong></td>
<td><strong>15.27</strong></td>
</tr>
</tbody>
</table>

The actual weight of the Qualification tank is 6.96 kg (15.3 lb).

DEVELOPMENT TESTING PROGRAM

A development test program was conducted that included liner development, wrap development, and development testing. A Development Tank was manufactured to validate the manufacturing technology and tested to validate the design assumptions prior to fabricating the qualification tank. The Development Tank was acceptance tested, followed by proof and MEOP pressure cycle testing and collapse pressure cycle testing. After pressure cycles the Development Tank was burst pressure tested to determine the burst margin. The Development Tank failed at 314 bar (4557 psi), showing a burst margin of 40% above minimum requirement.

Upon completion of the development testing, it was determined that the liner as designed was acceptable and no liner modification was made. The filament wrap was slightly modified to reduce the tank weight.

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 flaws are located on the cylinder, and the third flaw is located on the blind head near the girth weld, as shown in Figure 8. The flaws are fabricated into liner components prior to assembly. All flaws are located at the high stress concentration regions where the liner is most likely to fail.

The LBB Tank was fabricated along with the Qualification Tank, using the same manufacturing processes and procedures. The LBB Tank successfully completed autofrettage and survived 166 pressure cycles before developing a liner rupture at the 167th cycle. The rupture initiated at the pre-fabricated flaw above the cylinder seam weld as shown in Figure 9. There were several frayed fibers due to high-pressure discharge of test fluid upon liner rupture. However, the tank did not experience a catastrophic burst. After test completion, the LBB Tank was machined to the deliverable tank configuration and provided to the customer as the Thermal Test Model.
Figure 8: LBB Tank Flaw Locations

Figure 9: Location of the Liner Rupture in the LBB Tank
TANK GROWTH

The Xenon tank undergoes expansion as it is being pressurized. The tank expansion data for the Qualification tank is summarized below in Table 3:

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Linear Growth</th>
<th>Volumetric growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEOP (150 bar/2175 psi)</td>
<td>5.5 mm / 0.215 inch</td>
<td>1.36 liters/83.2 in³</td>
</tr>
<tr>
<td>165 bar/2391 psi</td>
<td>5.8 mm / 0.229 inch</td>
<td>---</td>
</tr>
<tr>
<td>178 bar/2582 psi</td>
<td>6.3 mm / 0.247 inch</td>
<td>---</td>
</tr>
<tr>
<td>Proof Pressure (187.5 bar/2719 psi)</td>
<td>6.6 mm / 0.261 inch</td>
<td>1.68 liters/102.7 in³</td>
</tr>
<tr>
<td>200 bar/2900 psi</td>
<td>6.9 mm / 0.271 inch</td>
<td>---</td>
</tr>
</tbody>
</table>

TANK SIZING

The Xenon tank is subjected to a sizing operation (autofrettage) after the tank is wrapped and the resin system is cured. The autofrettage pressure is selected to achieve the specification requirement of elastic behavior between zero pressure and MEOP. 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.

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 ETS VIII Xenon tank design in the following areas:

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

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

The Qualification Tank is subjected to the following qualification tests:

- Proof pressure test
- Volumetric capacity
- External leakage
- Pressure cycles
- Collapse pressure cycles
- External leakage
- Resonant frequency
- Sinusoidal and random vibration
- External leakage
- Final examination
- Destructive burst pressure test
**Volumetric Capacity Examination:** The volumetric capacity of the Xenon tank is measured using the weight of water method at ambient condition. 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 tank volume meets the specification requirement and that the proof pressure test does 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 Xenon tank was manufactured successfully.

**Proof Pressure Test:** The hydrostatic proof pressure test is conducted at 187.5 bar (2719 psig) for a pressure hold period of 5 minutes. Successful completion of the proof pressure test and the subsequent volumetric growth and leakage verification indicate that the tank was manufactured successfully.

**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 $1 \times 10^8$ std cc per second after a 30-minute stabilization period. For example, the leak rate of the Qualification Tank was $1.6 \times 10^8$ scs/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.

**Pressure Cycles:** The Xenon tank is designed to accommodate a minimum of 5 proof pressure cycles and 50 operating pressure cycles. As a practice, several operating pressure cycles were added to qualify the tank for additional service. A total of 5 proof cycles and 55 operating cycles were conducted at this pressure cycle testing. Additionally, the Qualification Tank experienced another operating pressure cycle during volume measurement, 3 operating pressure cycles for the 3 external leakage tests and 8 more operating pressure cycles during vibration testing. The cumulative total of operating pressure cycles is 67, or 17 cycles over the minimum requirement.

**Collapse Pressure Cycles:** The ETS VIII Xenon tank is evacuated during the tank fill operation, and the tank must withstand a maximum external pressure of 1.0133 bar (14.7 psi). Twenty collapse pressure cycles were conducted on the Qualification Tank to verify this requirement.

**Resonant Frequency Search:** The ETS VIII Xenon tank is designed to avoid any resonant frequency of 100 Hz or below and to minimize the response levels at resonant frequencies in the random vibration range of 20 to 2000 Hz. A resonant frequency search is conducted to determine the natural frequency of each ETS VIII Xenon tank. Both lateral and axial resonant frequencies are above 140 Hz.

**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 4 and 5.

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 ensure the fixture meets the testing requirements.
### Table 4: Qualification Level Sinusoidal Vibration Test Environment

<table>
<thead>
<tr>
<th>Axes</th>
<th>Frequency (Hz)</th>
<th>Acceleration (g 0-peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X,Y,Z</td>
<td>5 – 19.77</td>
<td>12.7 mm (0.5 in) DA</td>
</tr>
<tr>
<td></td>
<td>19.77 – 50</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>50 – 100</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Sweep Rate</td>
<td>2 Oct./min</td>
</tr>
</tbody>
</table>

### Table 5: Qualification Level Random Vibration Test Environment

<table>
<thead>
<tr>
<th>Axes</th>
<th>Frequency (Hz)</th>
<th>PSD (g²/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X,Y,Z</td>
<td>20 – 100</td>
<td>+6 dB/Oct.</td>
</tr>
<tr>
<td></td>
<td>100 – 800</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>10.5 gRMS</td>
</tr>
<tr>
<td></td>
<td>Duration</td>
<td>120 sec.</td>
</tr>
</tbody>
</table>

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 location of the response accelerometers were selected to record the maximum stress as predicted in the analytical model. The vibration test included fixture survey, resonant frequency search, full level sinusoidal and full level random runs. The same tests were conducted in all three axes.

The first phase of the test was conducted with the tank loaded with test fluid, pressurized to MEOP, and subjected to the test environment in Tables 4 and 5. The same PF 5060 performance fluid used on the conical Xenon tank vibration testing was utilized for this test. Since the unpressurized Xenon tank does not contain enough volume to hold the required mass for the test, a pressurization setup must be incorporated such that during pressurization, the Xenon tank would expand and permit the required 89 kg of PF 5060 test fluid to enter the tank. After completing the mass-loaded testing, the test fluid was drained from the tank and the same vibration runs were repeated with the tank empty for mass-unloaded testing.

A photograph of the vibration test setup is shown in Figure 10.
**Destructive Burst:** After the completion of the pressure cycles and vibration testing, the Qualification Tank was subjected to a final destructive burst pressure test. The Qualification Tank burst at 248 bar (3599 psi), providing a 10% margin on burst pressure. This data represents a burst factor of 1.63 to 1, and a performance efficiency rating (PV/W) of $0.73 \times 10^6$ inches. Figure 11 shows the Qualification Tank after burst.

*Figure 11: Xenon Qualification Tank After Burst*
Qualification Tank Pressure Log: In summary, the Qualification Tank has undergone the pressure cycles listed in Table 6:

Table 6: Summary of Qualification Tank Pressure Cycles

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Actual # of Cycles</th>
<th>Required Cycles</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 bar (2175 psig),</td>
<td>67</td>
<td>50</td>
<td>56 operating cycles</td>
</tr>
<tr>
<td>Operating pressure</td>
<td></td>
<td></td>
<td>3 external leaks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8 pressurization cycles during vibration testing</td>
</tr>
<tr>
<td>187.5 bar (2719 psig),</td>
<td>5</td>
<td>5</td>
<td>1 proof test,</td>
</tr>
<tr>
<td>Proof pressure</td>
<td></td>
<td></td>
<td>4 proof cycles</td>
</tr>
<tr>
<td>-14.7 psig</td>
<td>20</td>
<td>20</td>
<td>20 vacuum cycles</td>
</tr>
<tr>
<td>Collapse pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

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
- External leakage
- Resonant frequency search
- Acceptance level random vibration
- External leakage
- Final examination
- Cleanliness measurement

Random Vibration: An acceptance vibration test is conducted for each ETS VIII flight tank. The tank is pressurized to MEOP pressure with gaseous nitrogen and subjected to the acceptance level random vibration environment described in Table 7 below:

Table 7: Xenon Tank Acceptance Random Vibration Level

<table>
<thead>
<tr>
<th>Axes</th>
<th>Frequency (Hz)</th>
<th>PSD (g²/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X, Y, Z</td>
<td>20 – 100</td>
<td>+6 dB/Oct.</td>
</tr>
<tr>
<td></td>
<td>100 – 800</td>
<td>0.044</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td>7 gRMS</td>
</tr>
<tr>
<td>Duration</td>
<td></td>
<td>40 sec.</td>
</tr>
</tbody>
</table>
**Cleanliness Verification:** After the final external leak test, each flight tank is cleaned to the cleanliness level specified in Table 8.

### Table 8: Xenon Tank Cleanliness Level

<table>
<thead>
<tr>
<th>Particle Size Range (Microns)</th>
<th>Maximum Allowed per 100 ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 to 10</td>
<td>600</td>
</tr>
<tr>
<td>11 to 25</td>
<td>100</td>
</tr>
<tr>
<td>26 to 50</td>
<td>25</td>
</tr>
<tr>
<td>51 to 100</td>
<td>3</td>
</tr>
<tr>
<td>Over 100</td>
<td>0</td>
</tr>
</tbody>
</table>

Photograph of a completed tank is shown in Figure 12.

**Figure 12: A completed ETS VIII Xenon Tank**
CONCLUSION

The ETS VIII Xenon tank program has successfully concluded qualification testing without failure. The qualification testing shows the Xenon tank having comfortable margins over all the operational requirements. The production program is currently in progress.

The ETS VIII Xenon 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 ETS VIII Xenon 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 Xenon 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 is manufactured efficiently and inexpensively using existing technology.

ACKNOWLEDGMENT

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REFERENCE


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