DESIGN AND MANUFACTURE OF A HIGH PERFORMANCE, HIGH MASS EFFICIENT GAS TANK FOR THE VEGA AVUM

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ABSTRACT

A high performance titanium-lined composite overwrapped pressure vessel (COPV) with high mass efficiency for either gaseous helium or nitrogen was designed for ESA's Vega Launch Vehicle. The Vega Gas Tank is common for both the Liquid Propulsion System (LPS) and the Attitude Control System (ACS) for the fourth stage of the Vega Launch Vehicle's Attitude and Vernier Upper Module (AVUM).

This tank has a nominal volume of 87 liters (5309 cubic inches) and a nominal weight of 23 kg (50.7 pounds). The maximum expected operating pressure is 310 bar (4496 psi), 50 cycles. Proof pressure requirement is 465 bar (6744 psi), 5 cycles, and the minimum burst pressure is 620 bar (8996 psi). The tank is designed to hold 25.94 kg (27.24 pounds) of gaseous nitrogen (GN_2).

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

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 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 Toray T1000GB carbon fiber and Epon 826 cured resin system. Several composite layers were applied, including helical and hoop wraps.

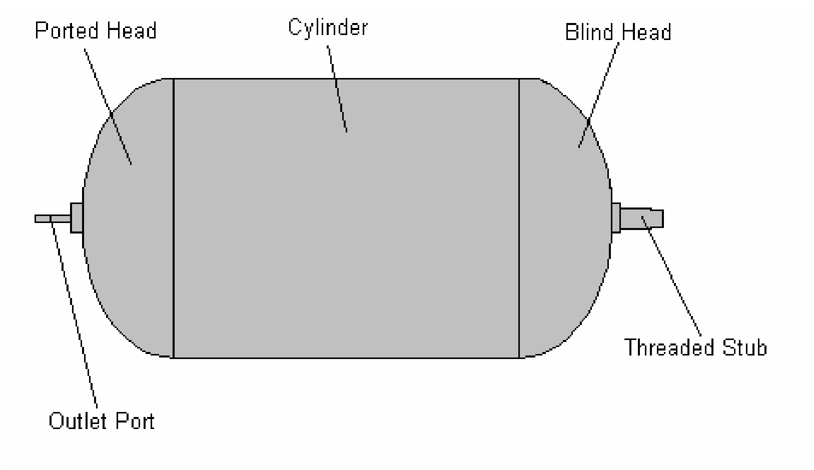
A complete qualification program was conducted to verify the tank design, including a destructive burst pressure test. The tank successfully completed qualification testing on 29 September 2006.

INTRODUCTION

A gas storage pressure vessel with unique characteristics is needed for the Vega Launch Vehicle 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 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.

OSR 07-S-1347

Figure 1: The VEGA Gas Tank



The tank is mounted to the Launch Vehicle by polar bosses located on the tank centerline axis. The ported boss is attached to the Launch Vehicle by six M6 bolts. The blind stinger boss mounts on a slip joint bearing. The blind end is designed to accommodate the tank's axial growth during pressurization. Two Gas Tanks are required for the Vega Launch Vehicle.

The VEGA Gas Tank was designed to the following requirements:

Table 1: VEGA Gas Tank Design Requirements

PARAMETERS	REQUIREMENTS
Maximum Expected Operating Pressure (MEOP)	310 bar (4496 psi), 10 cycles minimum
Proof Pressure	465 bar (6744 psi), 5 cycles minimum
Burst Pressure	620 bar (8996 psi) minimum
Gas Weight	25.94 kg (57.2 lb) GN_2
Size	336.7 mm ∅ x 682.8 mm long, (13.26" ∅ x 26.9" long), boss to boss
Overall Length	841.8 mm (33.14 inches) nominal
Tank Weight	23 kg (50.7 lb) maximum
Tank Capacity	87 liters (5309 in^3) minimum, unpressurized
Natural Frequency	>120 Hz
Compatibility	Argon, IPA, Helium, Nitrogen, and DI water
Shell Leakage	$<1x10^{-6}$ std cc/sec He @ MEOP
Operating Temperatures	-50°C to +60°C (-76°F to 140°F)

This tank is also designed to withstand shock and vibration loads and acceleration of 22.5 g's in any direction. All design requirements were verified by analysis or qualification testing.

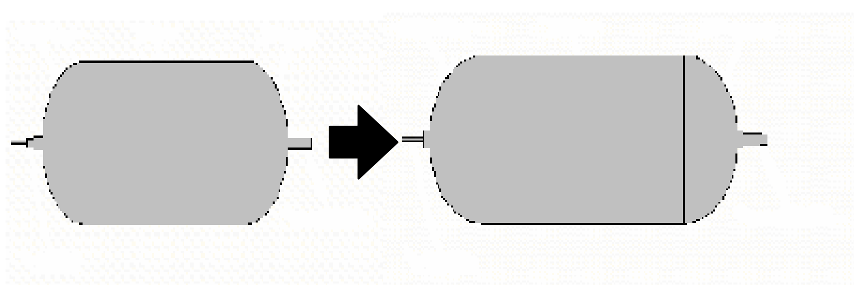
DESIGN HERITAGE

ATK-SSI has designed other titanium lined COPV's that are similar in design and construction. These tanks are also titanium lined and T1000 carbon fiber overwrapped. The VEGA Gas Tank draws its heritage from those programs (Reference AIAA 2002-4349). The manufacturing technology established by those pioneering programs has matured and the VEGA Gas 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 this flight heritage, the design of the VEGA tank blind head is nearly identical to the blind head of the heritage Pressurant Tank, including the mounting features. The Vega tank ported head also exhibits similar features as the Pressurant Tank ported head, as shown in Figure 2. Both liner center sections have the same method of construction.

The liners of both tanks are made of CP titanium. The selection of CP titanium was made to satisfy the design requirements. The filament wrap remains the same T1000 carbon fiber.

Figure 2: Design Heritage of the VEGA Gas Tank



DESIGN ANALYSES

The basic approach in designing the Vega Gas Tank is to maximize heritage by adapting as many Pressurant 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 VEGA Gas Tank, including:

- Finite element analysis to conduct the liner material trade study and selection.
- Nonlinear axisymmetric analysis to design the Gas Tank ported and blind heads. Figure 3 shows the ported and blind heads as modeled by the analysis.
- Three-dimensional finite element model for the modal analysis. The analysis is conducted to predict the natural frequencies of the Gas 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.
- Random vibration analysis to determine stress and fatigue effects of random vibration on the vessel. See Figure 5. 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.

Figure 3: Nonlinear Axisymmetric Finite Element Models

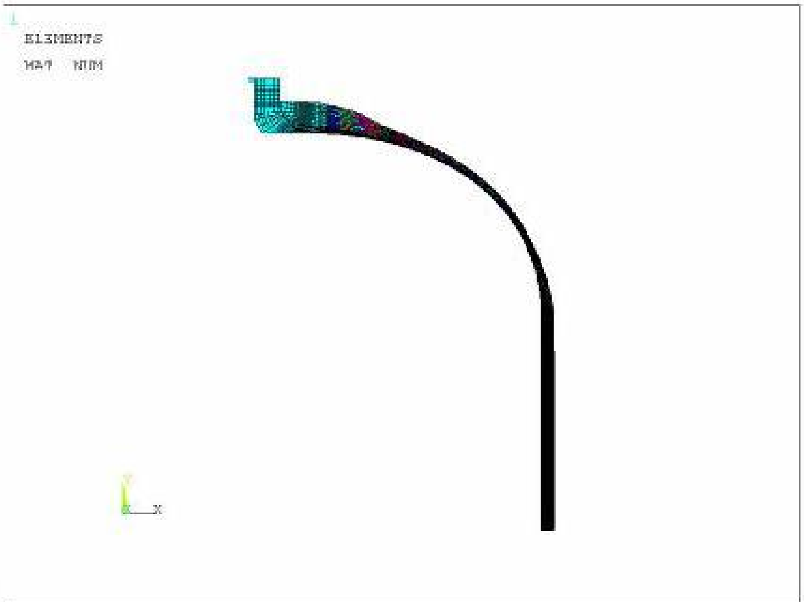
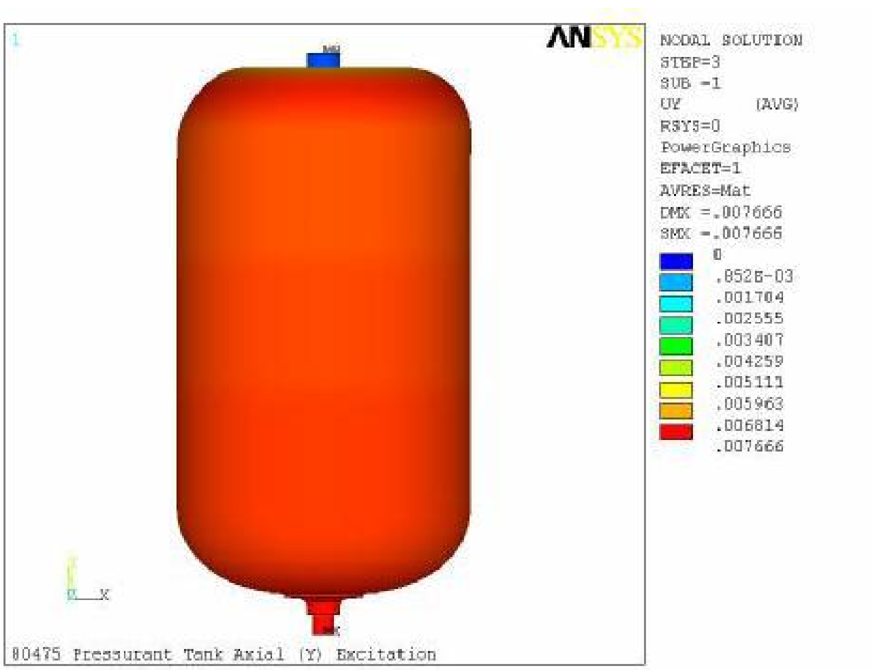


Figure 4a: First Axial Mode

Figure 4b: First Lateral Mode

Figure 5: Three-Dimensional Finite Element Model, Axial (Y) Displacement Response



- Fatigue analysis to determine the cumulative damage factor due to fatigue. The fatigue life requirements for the Vega 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

LINER DESIGN AND FABRICATION

Prior to designing the Vega Gas 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 CP-3 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 Vega Gas 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 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 gas and the high vibration loads during launch, both conditions that result in high boss loads. The high strength, low weight CP-3 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.

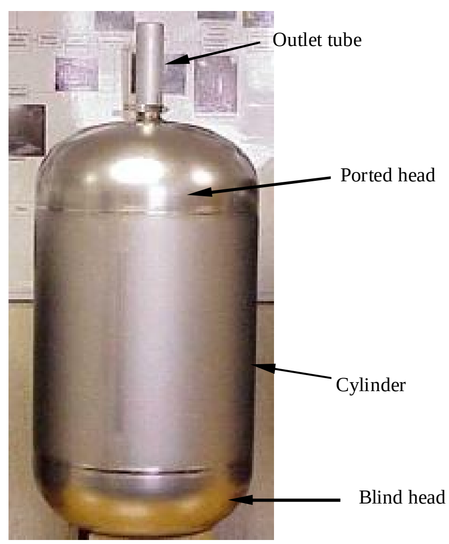
The Vega Gas Tank liner is a four-piece construction that consists of two heads, a cylinder and an outlet tube, as shown in Fig 6.

The outlet tube is made from 6.35mm (0.250 inch) outside diameter tubing. 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 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 heritage Pressurant Tank center section.

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

The Vega Gas Tank liner was designed to mirror the construction of the Pressurant Tank liner. The forging is designed such that both heads can be machined from the same forging configuration. This modification minimizes the number of components for processing, and eliminates several operations such as the assembly weld and the post-weld radiographic and penetrant inspection. This makes the Vega Gas Tank inherently more reliable by minimizing the number of welds in the liner.

Figure 6: Components of the Gas Tank Liner



COMPOSITE OVERWRAP DESIGN AND FABRICATION

The Vega Gas Tank composite overwrap contains several layers of high angle, helical and hoop wraps. The same wet filament winding technique used on the Pressurant Gas Tank is applied to the Vega Gas 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 Toray 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 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 7. A computer code was generated to wrap the development tank. After development testing this code was revised and finalized to wrap the flight tanks. The entire wrap process is automated to insure quality and repeatability.

Figure 7: 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 Gas Tank weight distribution is summarized in Table 2 below:

Table 2: Gas Tank Weight Distribution

Item	Nominal Weight (kg)	Nominal Weight (lbm)
Liner	4.31	9.50
Adhesive	1.36	3.00
Composite	17.33	40.8
TOTAL	**23.0**	**50.7**

The actual weight of the Qualification tank is 21.51 kg (47.44 lb).

Table 3: Gas Tank Growth

Tank Pressure	Linear Growth	Radial Growth
Growth at 1000 psig	.030 inch	.006 inch
Growth at 2000 psig	.056 inch	.014 inch
Growth at 3000 psig	.084 inch	.024 inch
Growth at 4000 psig	.109 inch	.033 inch
Growth at 5000 psig	.133 inch	.043 inch
Growth at 6000 psig	.156 inch	.051 inch
Growth at 6744 psig	.169 inch	.058 inch

TANK GROWTH

The Gas Tank undergoes expansion as it is being pressurized. The tank expansion data for the Qualification tank is summarized in Table 3. The measured tank growth closely matches the predicted values.

TANK SIZING

The Gas 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 Vega Gas 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
- External leakage
- Sinusoidal and random vibration
- External leakage
- Pressure Surge
- Thermal Cycling
- External leakage
- NDE – Weld Examination
- Final examination
- Destructive burst pressure test

Volumetric Capacity Examination: The volumetric capacity of the Gas 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 Gas Tank was manufactured successfully.

Proof Pressure Test: The hydrostatic proof pressure test is conducted at 465 bar (6744 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 x 10^{-6} std cc per second after a 30-minute stabilization period. For example, the leak rate of the Qualification Tank was 1.9 x 10^{-7} 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.

Pressure Cycles: The Gas Tank is designed to accommodate a minimum of 20 proof pressure cycles and 50 operating pressure cycles. Additionally, the Qualification Tank experienced another operating pressure cycle during volume measurement, 3 operating pressure cycles for the 3 external leakage tests 1 operating pressure cycle in the pressure surge test, 3 more operating pressure cycles during vibration testing and 10 more operating cycles during thermal cycling. The cumulative total of operating pressure cycles is 58, or 8 cycles over the minimum requirement.

Pressure Surge: The pressure surge test was performed with the tank pressurized with GN_2 to MEOP 310 bar (4496 psi) the discharged into a 120 liter pressure vessel though a 1.9 mm orifice. The test noted no anomalies.

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-Launch Vehicle 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.

Table 4: Qualification Level Sinusoidal Vibration Test Environment

Qualification Sine Vibration Environment			
Axes	**Frequency (Hz)**	**Input Level (G)**	**Sweep Rate**
X, Y & Z	**5 – 16**	**10 mm**	**1/3 oct/min**
	16 – 35	**10.0 g**	**(11.4 min duration**
	35 - 70	**22.5 g**	**from 5-70 Hz)**
X, Y & Z	**70 - 200** **200 - 2000**	**22.5 g** **10.0 g**	**2 oct/min** **(2.4 min duration from 70-2000 Hz)**

Table 5: Qualification Level Random Vibration Test Environment

Frequency (Hz)	PSD (G_2Hz) Input Level All Axes	Overall Level (Grms)
20-60	**+3 dB/oct**	**20**
60-1000	**0.273**	
1000-2000	**-6 dB/oct**	
Total Duration	**4 minutes per Axis**	

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 test was conducted with the tank loaded with GN2, pressurized to MEOP, and subjected to the test environment in Tables 4 and 5. .

A photograph of the vibration test setup is shown in Figure 8.

Figure 8: Qualification Tank Vibration Test Setup

Figure 9: Qualification Tank After Burst

Destructive Burst: After the completion of the pressure cycles, thermal cycling and vibration testing, the Qualification Tank was subjected to a final destructive burst pressure test. The Qualification Tank burst at 904 bar (13117 psi), providing a 45% margin on burst pressure. This data represents a burst factor of 2.92 to 1, and a performance efficiency rating (PV/W) of 1.4. Figure 9 shows the Qualification Tank after burst.

Qualification Tank Pressure Log: In summary, the Qualification Tank has undergone the pressure cycles listed in Table 6. The tank had been either inadvertently or deliberately over tested during the rigorous test program. The successful completion of the qualification test program is an excellent demonstration of the tank's robust design.

Table 6: Summary of Qualification Tank Pressure Cycles

Pressure Cycles	No. of Cycles
MEOP Cycles: 310 bar (4496 psig)	58
Test Cycle: 414 bar (6000 psig)	1
Proof Cycles: 465 bar (6744 psig)	20
Autofrettage: 466 bar (6760 psig)	1
Burst 620 bar: (8996 psig)	1

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
- NDE Weld Examination
- Final examination
- Cleanliness measurement

Cleanliness Verification: After the final external leak test, each flight tank is cleaned to the cleanliness level specified in Table 7.

Table 7: Gas Tank Cleanliness Level

Particle Size Range (Microns)	Maximum Allowed per 100 ml
Less than 5	No Silting
6 to 10	1200
11 to 25	200
26 to 50	50
51 to 100	5
Over 100	0

Photograph of a completed tank is shown in Figure 10.

Figure 10: A completed VEGA Gas Tank

CONCLUSION

The Vega Gas Tank program has successfully concluded qualification testing without failure. The qualification testing shows the Gas Tank having comfortable margins over all the operational requirements.

The Vega Gas 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 Vega Gas Tank maintains excellent design and flight heritage. Its overall design and method of manufacturing are derived from several prior Pressurant Tank programs. The design of this Gas Tank is extremely conservative and all manufacturing methods are based upon existing technology with a resulting high performance and high mass efficiency. .

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

Our sincere thanks to members of the Avio and ATK-SSI team for making this program a success.

REFERENCE

1. W. Tam, P. Griffin and Art Jackson, "Design and Manufacture of a Composite Overwrapped Pressurant Tank Assembly", AIAA 2002-4349.

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