Design, Analysis and Manufacture of Composite Overwrapped Xenon Propellant Tank

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Abstract: The xenon propellant tank was designed for electrical propulsion subsystem of TURKSAT 6A (T6A) Communication Satellite. T6A, which will be the first indigenous GEO satellite of Turkey and will be operated 15 years in-orbit. Challenging nature of satellite systems requires high performance and lightweight propellant tank for the electric propulsion subsystem. The qualification tests were carried out after design stage in order to verify the design. Qualification tank prototype showed successfully enough results giving an ambition to pursue the following models for manufacturing.

Keyword: Composite overwrapped pressure vessel, ultra-thin metallic liner, aerospace composites.

Nomenclature

COPV	=	Composite overwrapped pressure vessel
EM	=	Engineering Model
EPS	=	Electrical Propulsion Subsystem
FEM	=	Finite Element Method
FM	=	Flight Model
MEOP	=	Maximum Expected Operating Pressure
STM	=	Structural and Thermal Model
TIG	=	Tungsten Inert Gas
T6A	=	TURKSAT6A Communication Satellite
XPT	=	Xenon Propellant Tank

I.Introduction

TURKSAT 6A (T6A) Communication Satellite, T6A, which will be the first indigenous GEO satellite of Turkey, will be operated 15 years in-orbit, minimum. Challenging nature of satellite systems requires high performance and lightweight Xenon Propellant Tank (XPT) for Electrical Propulsion Subsystem (EPS). Composite overwrapped pressure vessels (COPVs) are preferable especially for such a challenging application owing to its high strength, low weight, superior mechanical efficiency and safety. First of element of COPV's is typically a thin, lightweight metal alloy layer, which is called liner. The liner gives its structural shape to the tank thereby providing a leakage barrier and accommodates mechanical connections on its port openings for filling and evacuating the fluid. Composite overwrap is the structural element that carries the mechanical load. Since the lightweight design is one of the ultimate requirements for satellite systems, the composite overwrap consists of high performance advanced carbon fibers and epoxy resin system.

The XPT is a COPV that is uniquely designed for T6A mission and it possesses original properties in order to provide specific requirements of T6A. XPT is responsible for the storage of high pressurized xenon gas in T6A and all its material and manufacturing processes are compatible to satellite environment. Figure 1 represents the schematic of XPT.

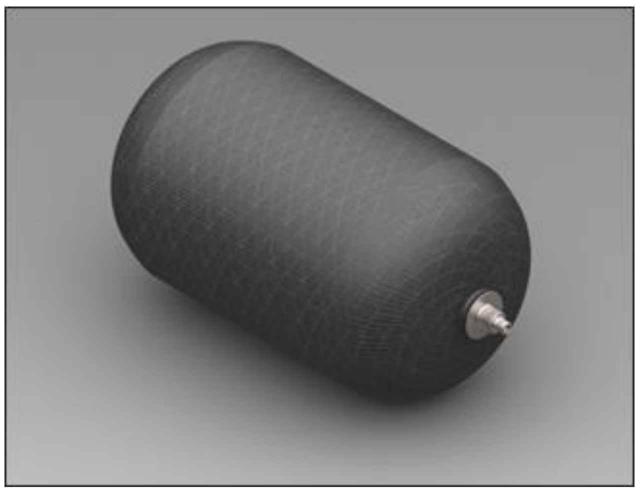

Figure 1. Schematic of the XPT

Table 1. XPT Design Requirements

Parameters	**Requirements**
Maximum Expected Operating Pressure (MEOP)	150 bar (2175 psi)
Proof Pressure	225 bar (3263 psi)
Burst Pressure	min 300 bar (4351 psi)
Operation Cycle	min 50 cycles
Tank Size	Ø204.5 mm OD x 382 mm long, boss to boss
Propellant Weight	min 10 kg (22 lb) Xenon gas
Tank Weight	3.7 kg (8.15 lb)
Tank Capacity	min 8.3 lt (506.5 in^3)
Compatibility	Xenon, Argon, Helium
Leakage	<1x10-6 std cc/s He @ MEOP
Operating Temperatures	-5 ˚C to 65 ˚C (23 ˚F to 149 ˚F)
Natural Frequency	>140 Hz, filled

The tank is mounted to the satellite by using brackets from its domes. The ported dome accommodates outlet port and it slides freely along the mounting bracket. The blind dome has four threaded holes and is attached to the mounting bracket by using four bolts. The mounting interface is seen in the front and side views of XPT, see Figure 2. The space between dome surface and the mounting bracket is designed by considering the axial displacement of the tank during pressurization. The T6A xenon tank has a nominal propellant volume of 8.3 liters (506.5 in^3) and a nominal weight of 3.7 kg (8.15 lb). The XPT is designed so that its maximum expected operation pressure is 150 bar (2175 psi) and the minimum burst pressure is 300 bar (4351 psi). Expected minimum operating cycle for the tank is 50. Table 1 presents the T6A xenon tank requirements.

II. DESIGN, DEVELOPMENT AND ASSEMBLY

Throughout the project, a Structural and Thermal Model (STM), two Engineering Models (EM) and a Flight Model (FM) will be manufactured. The STM is only the structural and thermal representative of the FM, having the same mass properties, same dynamic responses, same thermal responses, and the same mechanical interface. And this model will be used on the STM of the satellite system. The EM is the same as FM, having the same properties, materials, design and manufacturing procedures. One of the EM will be used on system level EM and the other EM will be used for qualification procedures, such as equipment level testing and inspection. The FM will be used on the FM of the satellite.

A. Design Analyses

The design process is initiated with the netting analysis and is followed by finite element methods (FEM) in order to simulate various loading conditions. Finite element analysis is conducted to predict proof, sizing, ultimate burst pressure and natural frequencies and eventually the qualification prototype is tested to determine the actual values.

The design of the tank is started with selecting the dome and cylinder geometry. A commercially available titanium sheet is selected in order to minimize the manufacturing costs and the dome shape is basically a geodesic model so that leads the stress distributed identically among the fibers. Classical netting analysis is then made in order to design the composite overwrap. Although netting analysis gives a good background on design, finite element analysis is additionally employed to better understand the dynamic behavior of the XPT.

XPT has an axial growth pattern under pressure which yields an axial deformation of 1.19 mm (0.047 inch) under MEOP. The value from the FEM is confirmed by a one cycle pressure testing with a value of 0.73 mm (0.029 inch). By considering the axial expansion, the bracket geometry on the free end is designed so that it allows axial displacement until 5mm (0.197 inch).

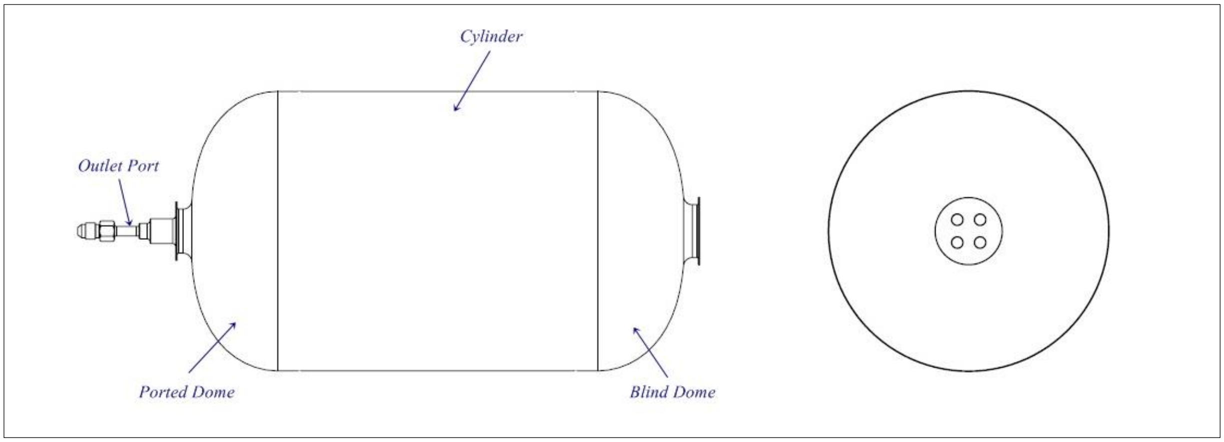

Figure 2. The Front and Side Views of XPT

The modal analysis is carried out in order to predict natural frequencies of the XPT. First and the second modes are in axial direction, whereas the third and the forth modes are in lateral direction. The XPT's first axial and first lateral modes are shown in Fig 3. The first axial natural frequency is 345 Hz, while the first lateral natural frequency is 770 Hz. The modal analysis values are confirmed by the vibration tests during the qualification stage.

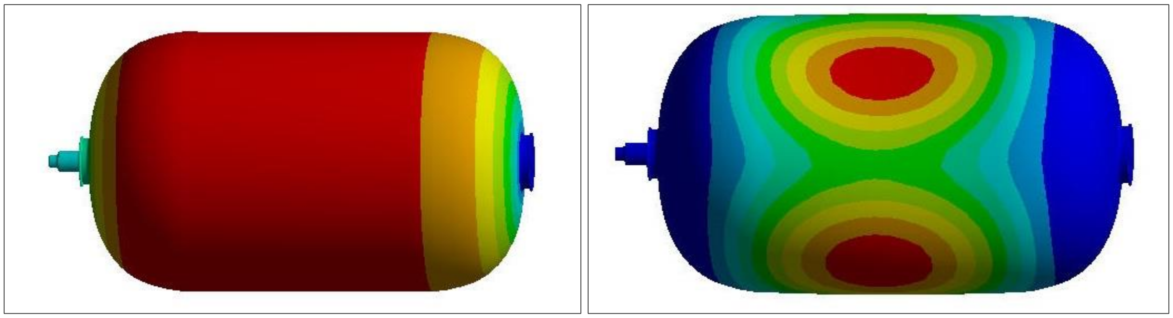

Figure 3. XPT's First Axial and Lateral Modes

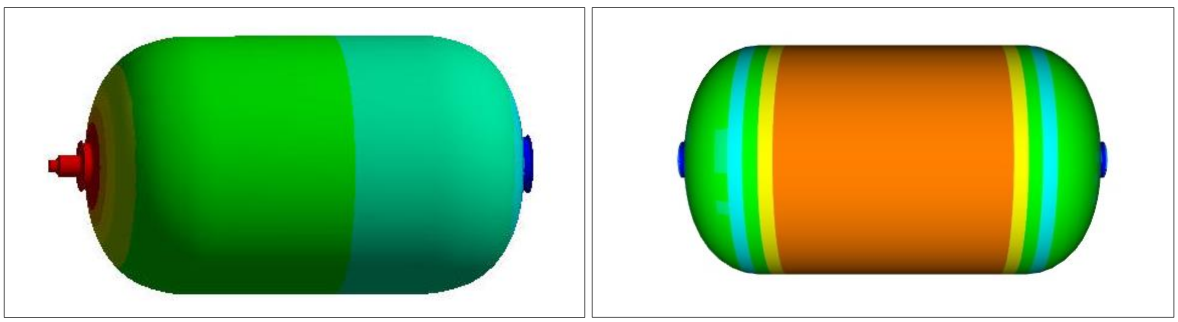

Figure 4. Axial deformation of liner and stress distribution of composite overwrap under MEOP

The stress analysis is performed after the modal analysis to obtain the stress distribution on the composite overwrap and the liner, deformation on the liner part and the safety margins for the structural elements. The pictures taken from the stress analysis results are given in Figure 4 and the safety margins and the deformation results are listed in Table 2.

Table 2. XPT Safety Margins

Pressure (MPa)	Regions	Stress (MPa)	Safety Margin	Total Axial Deformation (mm)
15	Liner Cylinder	246	2.57	1.18 (0.047 inch)
	Liner Dome	400	1.2	
	Composite Cylinder	360	3.27	
	Composite Radius	518	1.97	

B. Liner Design and Fabrication

The XPT's liner is a three-piece structure that involves a ported dome, a blind dome and a cylinder. These three pieces are seam welded by electron beam to each other and inspected by radiography and dye penetrant inspection methods after welding process. The liner cylinder is rolled from a titanium sheet. The bosses are machined from titanium blocks except the tubing which is machined from a rod of 14 mm. The titanium tubing is also welded to the free end of liner.

The titanium material is Ti-6Al-4V and same for all the titanium parts. The Ti-6Al-4V is one of the most well-known titanium alloy that makes the material more available. The advantages of Ti-6Al-4V compared to other titanium alloys are not too distinctive but Ti-6Al-4V has some microstructural benefits in terms of fatigue strength [1]. The photograph of the liner is shown in Figure 5 and the X-ray view of the liner can be seen in Figure 6.

Figure 5. XPT's liner

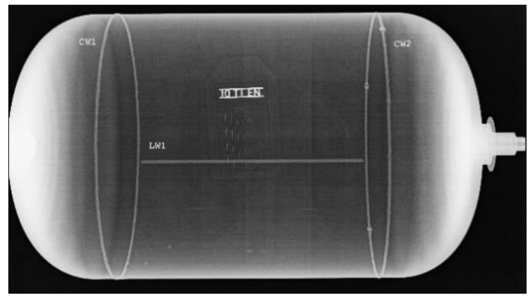

Figure 6. **X-ray Front View**

C. Composite Overwrap Design and Fabrication

The XPT's overwrap has layers of helical and hoop windings. The wet filament technique is used for the composite production. The machine is computer controlled, uses dry fibers impregnating into a resin bath having a constant temperature. The machine has a tension control unit providing the repeatable winding quality for each production. In the composite overwrap, Huntsman LY 556 epoxy system and Tenax IMS 65 carbon fibers are used. The filament IMS 65 is an intermediate modulus carbon fiber manufactured by Toho Tenax. Both the resin system and the carbon fiber have aerospace heritage and exhibit low outgassing properties.

D. Weight Distribution

The weight limitation is one of the main challenge in this project. The XPT assembly weight distribution is shown in Table 3. The total weight with Xenon gas is 18.7 kg (41.23 lb), nevertheless, it is conservatively taken as 20 kg (44.09 lb) in calculations to be on the safe side.

Table 3. XPT Assembly Weight Distribution

XPT	3.7 kg (8.16 lb)
Brackets and Conections	1.3 kg (2.87 lb)
Xenon Gas	15 kg (33.07 lb)
Total	**18.7 kg (41.23 lb)**

III.Qualification Test Program

Having completed the FEM calculations, the qualification testing is carried out. A qualification prototype is fabricated for the qualification test program. The qualification test program is based on the ECSS testing standard [2] and as follows:

- Visual inspections
- Volumetric capacity examination
- Proof pressure test
- Volumetric capacity examination
- External leak test

- Sinusoidal and random vibration tests
- External leak test
- Pressure cycle test
- External leak test
- NDE – Weld examination
- Final examination
- Burst test

Test procedures and the success criteria are based on the ECSS Testing Standard [2]. After the prototype passes the final examinations, it is eventually subjected to a destructive burst test and the ultimate pass/fail decision is made based on the result of the burst test.

E. Volumetric Capacity Examination

The weight of water method at ambient temperature is utilized to evaluate the volume of tank. Deionized water is used to conduct this examination. The tank volumes before and after the proof pressure tests are measured to verify that the tank satisfies the requirement.

F. Proof Pressure Test

The proof pressure test is conducted at the pressure of 225 bar (3263 psi) for 5 minutes and subsequently, helium leak test and volumetric capacity examination are made. As a result of proof pressurization XPT is undergo a permanent volumetric growth of 1.6%, which is under 5% limit, mentioned in [3].

G. External Leak Tests

Helium leak test is applied to XPT after following tests: (1) Proof Test (2) Pressure cycle test (3) Vibration tests. The leak test is performed under MEOP according to [2]. The tank is placed in a vacuum chamber and is evacuated to under $1x10^{-2}$ mbar, which is seen in Figure 7. Eventually, all helium leak tests satisfy the limit value of $1x10^{-6}$ scc/s.

Figure 7. Helium Leakage Test Setup

H. Vibration Tests

Resonance search, sinusoidal and random tests are performed in the qualification stage and all tests are carried out with respect to [2]. In contrast with other tests, XPT assembly, which presents the actual satellite installation with interface and orientation, is tested in vibration tests. The xenon gas weight is furthermore taken into consideration for the vibration tests. A test fluid 3M PF5060 is used in order to maintain the equivalent weight with that filled with xenon gas. Additionally, XPT is subjected to MEOP during vibration tests.

1. Resonance Search

Resonance search is conducted along each of three axes prior to and after performing the vibration tests. During vibration tests, the rigid aluminum test fixture having first natural frequency below 2000 Hz is employed. Test results are compared with each other and maximum 10% of frequency shift and maximum 20% of amplitude shift are allowed, as stated in [2].

2. Sinusoidal Vibration

Sinusoidal tests are conducted in the launch configurations for all axes. The qualification test level is selected based on [4] by considering the fact that the equipment is below 100kg. Table 4 presents the vibration test environment.

During the sinusoidal tests, two control accelerometers are placed on the fixture in the vicinity of brackets in order to control the inputs driven by the shaker. One response accelerometer is installed on the middle of the tank and the other two are placed on each bracket walls. In each axis, resonance search is additionally made to check the frequency and amplitude shift. Furthermore, a detailed examination is carried out prior and after the test to check the visual damage.

Table 4. Sinusoidal Vibration Test Environment

Axis	Frequency	Qualification	Acceptance
	Hz	g	-
Out-of-plane	(5-20)	15 mm (0-peak)	9.9 mm
	(20-100)	24 g (0-peak)	16 g
In Plane	(5-20)	9.9 mm (0-peak)	6.6 mm
	(20-100)	16 g (0-peak)	10.7 g

3. Random Vibration

Random tests are performed for three axes of the XPT. Again, the same accelerometer placement pattern with that of sinusoidal test is preferred. Random qualification test level is calculated from the equation stated in [4]. The test environment is tabulated in Table 5. Resonance search is also performed before and after the random test to evaluate the equipment integrity. The aforementioned criteria are used to determine the test result.

Table 5. Random Vibration Test Environment

Equipment Location	Axis, Duration, grms	Frequency	Input
Located ext. panel	Vertical (x) 2.5 min/axis 9.768 grms	(20-100) Hz	+6 dB/octave
		(100-400) Hz	0.098
		(400-2000) Hz	-3 dB/octave
Located ext. panel	Lateral (y,z) 2.5 min/axis 6.669 grms	(20-100) Hz	+6 dB/octave
		(100-200) Hz	0.098
		(200-2000) Hz	-4 dB/octave

I. Pressure Cycle Test

The XPT will be subjected to minimum 50 cycles during the operation life. Pressure cycling test is carried out with 55 pressure cycle in MEOP. Additionally, the qualification tank is subjected 1 proof pressure cycle, 1 MEOP cycle and additional MEOP cycles for each Helium leakage tests which totally makes 61 pressure cycles. The qualification tank is not shown any leakage after the total pressurizations.

J. Burst Test

Finally, the qualification tank is subjected to destructive burst test and is resisted to pressurization until much higher values. The burst is occurred approximately at 700 bar (10152 psi), which provides a 1.33 safety margin on burst pressure. The failure after burst of the qualification tank is shown in **Figure 8**.

Figure 8. Failure of XPT after Burst Test

IV. CONCLUSION

The qualification tests are successfully completed with a coherent result with the design and analysis results. The qualification tanks will lead the other models. Actually, two more engineering models and one flight models are planned to be manufactured within the year. The XPT is basically a filament wound composite tank special with its specific strength. The mechanical performance achieved is based on its design and production. Eventually, the results motive us to manufacture the following models for the T6A Project.

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