Scheme Design of Xenon Composite Over-wrapped Pressure Vessel for Electric Propulsion System

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Abstract. The composite over-wrapped pressure vessel (COPV), which were made by ultra-thin metal liner and high strength carbon fiber reinforced plastic (CFRP), has high performance factor (PV/W). COPV were widely used in electric propulsion system (EPS) of space system. ANSI/AIAA S-081-2000 is a general standard for pressure vessel of aerospace field at home and abroad, it specified the design elements, references, specifications, requirements in detail. The materials selection of liner, CFRP and skirt are introduced respectively. The design contents of liner and CFRP are explained. The liner is designed in terms of equal strength principle and the composite structure was designed in term of hoop fiber layers and spiral fiber layers alternately over-wrapped. The skirt is composite structure, with X-X carbon fiber over-wrapped the TC4 titanium alloy. The titanium liner thickness is 0.8mm, Cycle life is at last 100 times when the liner thick is ultra-thin. The safe life was designed, including stress-rupture life and low cycle fatigue life. The leak before burst (LBB)safe failure mode was analyzed. The results show that the structure design meets the technical requirements.

1. Introduction
The Xenon composite over-wrapped pressure vessel (X-COPV) is the necessary gas storage for xenon EPS. This X-COPV must be high performance, light weight, and designed to withstand severe launch and operation loads. Additionally, it requires an unusual shape that the length of column is very short\cite{1-3}. So it needs precise and optimized computation and mature manufacture process. The reliability and safety performance of X-COPV is very important\cite{4-5}. LIP have developed a lot of COPV for satellite, spacecraft, launch vehicle, military aircraft, and all of applied COPV have no negative example, there is no difficulty for our company to apply idea obtained ANSI/AIAA S-080-1998 of COPV design, so the strong desire for us to try for this X-COPV mission. This report is refer to the scheme design to X-COPV, it contains the specification, design idea, Qualification and Acceptance Test and conclusion.

This X-COPV shall be designed in terms of ANSI/AIAA S-081-2000. Therefor, the design requirements was considered systematically, including material Corrosion and oxidation resistance requirement, material Stress Corrosion and pitting corrosion resistance requirement, material high cycle fatigue and low cycle fatigue performance requirement, material forming, matching, welding, heat treatment, over-warp and curing process properties requirement, pressure and load environment, strength and stiffness requirement, thermal vacuum and cycle requirement, stress rapture life and fatigue-Life requirement, leak-before-burst safe failure mode requirement, impact damage Control
Requirement, liner and CFRP fabrication and process control requirement, inspection techniques, acceptance testing and qualification testing requirement.

2. Design input

2.1. Design references
The references of X-COPV design were summarized according to technology input from the user and our investigation, the X-COPV was designed principally in terms of ANSI/AIAA S-081-2000, and other reference standards were also helpful for the design, many NASA papers about COPV which were also referenced were not shown here, the references for X-COPV were shown in table 1.

Table 1. The introduction of references for X-COPV.

| The Number of Standard | The Title of Standard |
|------------------------|-----------------------|
| MIL-STD-1522A-1984     | Standard general requirements for safe design and operation of space pressurized missiles and space systems |
| ANSI/AIAA S-080-1998   | Space systems- metallic pressure vessels, pressurized structures, and pressure components |
| ANSI/AIAA S-081-2000   | Space systems- composite overwrapped pressure vessels (COPVs) |
| ISO-14623-2003         | Space systems- pressure vessels and pressurized structure- design and operation |
| AIAA S-110-2005        | Space systems- structures, structural components, and structural assemblies |
| ISO 11119-3-2002       | Gas cylinders of composite construction - specification and test methods - Part 2: Fully wrapped fiber reinforced composite gas cylinders with load-sharing metal liners |

2.2. Design specification
The Specification of X-COPV design was summarized according to technology input from the user, which was shown in table 2. It is necessary and significant for us to communicate with user about the detailed information for X-COPV, and some improvement modification advices were summarized in terms of other experiences[6-7].

Table 2. The Specification of X-COPV

| Parameter             | Introduction | Parameter     | Introduction |
|-----------------------|--------------|---------------|--------------|
| Medium                | Xenon Gas    | Liner material| Titanium     |
| Design pressure       | 8.6MPa       | Diameter      | 907mm        |
| Water volume          | 268L         | Length        | 673mm        |
| Design standard       | AIAA S-081   | Mass          | 22kg         |
| Temperature           | 25℃~ 50℃    | Mass of medium| 450kg        |

2.3. Design Requirement
The COPV development in terms of AIAA S081 was shown in table 3, There 24 requirement for COPV development, the all of requirement shall be satisfied for X-COPV of space system.

2.4. Design criterion
The first and important step of the X-COPV design was the Selection of Criterion, as the X-COPV was designed principally in terms of ANSI/AIAA S-081-2000, the ANSI/AIAA S-081-2000 was systematically studied by us. It prescribes that the liner of COPV is designed in terms of ANSI/AIAA S-080-1998 when the liner is elastic in the state of COPV working, and the region of inlet and outlet was not strengthened by carbon fiber, so the liner was the primary structure to withstand the interior pressure, the region of inlet and outlet design need the ANSI/AIAA S-080-1998. There are many
C4 titanium alloy nut was good, here is carbon fiber. By synthetical discussion in our company technology department, the carbon fiber reinforced plastic was designed by ANSI/AIAA S-081-2000. The analysis conclusion is that we need two standards for the design of X-COPV, the one is ANSI/AIAA S-081-2000, the other is ANSI/AIAA S-080-1998.

### Table 3. The Requirement of COPV design

| S/N | Requirement                                      | S/N | Requirement                                      |
|-----|-------------------------------------------------|-----|-------------------------------------------------|
| 1   | Load, pressure, and design environment          | 13  | Metallic material requirement                   |
| 2   | Strength requirement                            | 14  | Composite material requirement                  |
| 3   | Stiffness requirement                           | 15  | liner fabrication and process control           |
| 4   | Thermal requirement                             | 16  | Over-wrap fabrication and process control       |
| 5   | Stress analysis requirement                     | 17  | Inspection techniques requirement               |
| 6   | Fatigue-life requirement                        | 18  | Inspection data requirement                     |
| 7   | Safe-life requirement                           | 19  | Operation and maintenance requirement           |
| 8   | Stress-rupture requirement                      | 20  | Operating procedures requirement                |
| 9   | Leak-before-burst requirement                   | 21  | Storage requirement                             |
| 10  | Damage control requirement                      | 22  | Documentation requirement                       |
| 11  | Corrosion and Stress Corrosion Control          | 23  | Acceptance test requirement                     |
| 12  | Em-brittle control requirement                  | 24  | Qualification testing requirement               |

### 3. Material selection

#### 3.1. Material selection of liner
The selection of X-COPV material was decided in terms of ANSI/AIAA S-081-2000. The technology input from the user determines that liner material is titanium. By synthetical discussion in our company technology department, the TA1 titanium alloy was selected as the liner material of X-COPV, the reason for this choice is introduced. The outstanding characteristic of TA1 titanium alloy was introduced: Good corrosion resistance, good oxidation resistance, good pitting corrosion resistance, good stress corrosion resistance, low cycle fatigue performance, high cycle fatigue performance, good forming properties, good matching properties, good welding properties, good mechanical characteristics, high strength-to-weight ratio, good performance characteristics, good galvanic corrosion resistance with CFRP, good stress and strain consistent with CFRP[8-10].

The other reason for this selection is there is lot of successful examples for the XENON COPV. Further more, there is much design and manufacture experience of TA1 titanium alloy liner in our company. To use our strongpoint and minimize risk of material selection, the TA1 titanium alloy was selected. The liner outlet material is TA3 titanium alloy.

#### 3.2. Material selection of CFRP
The technology input from the user determines that composite material is carbon fiber. By synthetical discussion in our company technology department, the X-X carbon fiber was selected as the composite material of X-COPV, the reason for this choice is introduced. X-X carbon fiber is universal material for fiber over-wrapped COPV in the field space system today[11-13].

#### 3.3. Material selection of skirt
The technology input from the user does not mention the skirt material. By synthetical discussion in our company technology department, the carbon fiber reinforced plastic with TC4 titanium alloy nut was selected as the skirt material of X-COPV, the reason for this choice is introduced. The demand of X-
COPV mass specification is 22kg, through many times optimization computations, a conclusion we find that the mass specification can not get if the metal skirt was used. The carbon fiber reinforced plastic was the better choice for skirt material, the fiber initially was selected as X-X carbon fiber. the COPV skirt development of MT Aerospace in German was searched by AIAA paper, a very similar structure to our product was introduced, its skirt was fabricated by carbon fiber reinforced plastic, the titanium nut was over wrapped by fiber. This manufacture process was successfully used in space system, a good inheritable design was the most simple and directly to use[14-16].

3.4. The performance of X-COPV material
The performance parameter of X-COPV material is shown in table 4. The performance parameter was get in terms of material standard and our manufacture experience.

Table 4. The performance parameter of X-COPV material

| Parameter                  | TA1  | TC4  | 5A06 | 301  | CFRP |
|----------------------------|------|------|------|------|------|
| Tensile strength (MPa)     | 370  | 890  | 315  | 506  | 6400 |
| Yield strength (MPa)       | 290  | 760  | 155  | 482  | -    |
| Tensile modulus (MPa)      | 105  | 109  | 66.6 | 180  | 290  |
| Plastic modulus (GPa)      | 102  | -    | -    | -    | -    |
| Density (g/cm3)            | 4.51 | 4.54 | 2.7  | 7.8  | 1.8  |
| Extend ratio(%)            | 30   | 9    | 16   | 18   | 2.2  |
| Poisson’s ratio            | 0.33 | 0.33 | 0.33 | 0.33 | -    |

4. Design of X-COPV

4.1. The Structure of X-COPV
The X-COPV is composed of three parts, the first is liner, the second is composite fiber reinforced plastic, and the third is skirt, the composition of X-COPV was shown in figure 1, and the function of the X-COPV parts was shown in table 5.

Table 5. The introduction of references for X-COPV.

| The Number of Standard | The Title of Standard                  |
|------------------------|---------------------------------------|
| Liner                  | Guarantee X-COPV airproof             |
|                        | Guarantee X-COPV enough stiffness      |
|                        | Transmit the gas to spacecraft        |
|                        | The mould of fiber over-wrapped       |
| Composite fiber        | Withstand the primary interior pressure|
| Composite skirt        | Fix the X-COPV to spacecraft          |

4.2. The strength design of CFRP
The X-COPV was over-wrapped by two pattern, the one is spiral pattern, the other is hoop pattern, the spiral fiber can withstand the vertical stress and hoop stress, and the hoop fiber can withstand the hoop stress, with several over-wrap CFRP, the COPV strength increased. The composite fiber reinforced plastic was calculated in terms of net theory, this theory was very popular and applicable in space COPV design field, the net theory is followed:

$$\sigma_{f_{ba}}K_{f_{ba}} + \sigma_{f_{ba}}K_{f_{ba}}^b + \frac{b}{a}Lb = R^b$$  
$$\sigma_{f_{ba}}K_{f_{ba}}^b + \frac{b}{a}Lb = 0.5R^b$$  

(1)  
(2)
The size and fiber reinforced composite structure is shown in figure 1. The function of protective cover is to avoid galvanic corrosion between the liner material and composite material, the hoop fiber and spiral fiber was alternately over-wrapped, the inside and outside of composite is hoop fiber, and the spiral fiber is over-wrapped on the inter-space of hoop fiber. The primary length of COPV is 673mm. After fiber over-wrapped, and the overall length of COPV is 790mm, it satisfies the demand of technology input.

![Figure 1. Composite structure illustration.](image)

4.3. The structure design for X-COPV liner
There are many COPV developed by our company, through many years experiences a suitable design ways for COPV liner were summarized. The liner was decomposed by many regions, which is shown in figure 2. The illustration of skirt is shown in figure 3 and figure 4.

![Figure 2. Liner structure illustration.](image)

4.4. The life Design and safety design for X-COPV

4.4.1. safe life design. The most important factor of COPV design as described in the requirement is safe life design, including stress-rupture life and cycle life.

4.4.2. COPV LBB safe fail mode. The COPV Stress-Rupture Life, cycle life and leak before burst safe fail mode were chiefly determined by COPV liner. The idea of this COPV liner design is equal strength design, it is feasible for X-COPV to have leak before burst safe fall mode theoretically, and the LBB also can be validated by LBB test, which is to make failure on the liner before fiber over-wrapped.
Stress-rupture life is chiefly checked by theoretical computation. It is insignificant to test, because time for test is too long, we have the computation formula to accurately compute the Stress-rupture life and cycle life.

4.4.3. Design result. The liner was designed in form of equal strength to get enough stress-rupture life, and the thickness of liner is 0.8mm, it is the most optimized value for X-COPV design to have enough cycle life, and the cycle life of liner is shorter than CFRP make the leak before burst safe fail mode became reality. Cycle life is at last 100 times when the liner thick is 0.8mm, leak before burst safe fail mode can be realized when the liner cycle life is shorter than CFRP.

Figure 3. The illustration of the composite skirt structure.

Figure 4. The illustration of TC4 titanium alloy structure.

5. Conclusion
The specification of X-COPV was determined by technology input from the user, and the design standard was selected as ANSI/AIAA S-081-2000. The scheme design of X-COPV was finished. The liner material is TA1 titanium alloy, the outlet material is 301 CRES stainless steel, the fiber material is X-X Carbon fiber, the skirt is composite structure, with X-X carbon fiber over-wrapped the TC4 titanium alloy. The liner is designed in terms of equal strength principle by our special liner design way. The composite structure was designed in term of hoop fiber and spiral fiber alternately over-wrapped. The skirt was fixed by X-X carbon fiber hoop over-wrapped. The design of X-COPV satisfied the demand of technology input from the user, the reliability and safety of X-COPV satisfy the demand.

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