LH2 Tank Composite Coverplate Development and Flight Qualification for the X-33

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ABSTRACT

In this paper, the development history for the first cryogenic pressurized fuel tank coverplates is presented along with a synopsis of the development strategy and technologies which led to success on this program. Coverplates are the large access panels used to access launch vehicle fuel tanks. These structures incorporate all of the requirements for a pressure vessel as well as the added requirement to mount all of the miscellaneous access points required for a fuel management system. The first composite coverplates to meet the requirements for flight qualification were developed on the X-33 program. The X-33 composite coverplates went from an open requirement to successful finished flight hardware with multiple unique configurations, complete with verification testing, in less than eighteen months. Besides the rapid development schedule, these components introduced several new technologies previously unseen in cryogenic composites including solutions to cryogenic shrinkage, self-supporting sealing surfaces, and highly loaded composite bosses with precision sealing interfaces. These components were proven to seal liquid hydrogen at cryogenic temperatures under maximum loading and pressure conditions.

KEY WORDS: COMPOSITE, Liquid Hydrogen, Launch Vehicles, MPS, X-33

1.0 INTRODUCTION

Lockheed Martin Space Systems Company- Michoud Operations (LM Michoud) is a world leader in large cryogenic tank technology. LM Michoud has been fabricating external tanks for the Space shuttle for over 25 years. For X-33, Lockheed Martin VentureStar, X-34, and other future launch vehicles, LM Michoud has used this expertise to make these launch vehicles practical.

1.1 Launch Vehicle Configuration: The X-33 is an experimental prototype vehicle for proving technologies needed for single stage reusable launch vehicles. These machines require higher weight efficiency than current launch vehicles because they must also carry the fuel, thermal protection, lift devices, and landing gear necessary to recover the vehicle. When the vehicle must do all of this with a single-stage configuration, the issue of weight becomes even more critical. While the components of a conventional launch vehicle need only be durable enough to be used once, a reusable vehicle must be robust enough to survive repeated use. At the same time, economic realities of space flight indicate a practical reusable vehicle must furthermore have components resilient enough to be re-used without time consuming inspections or repairs.

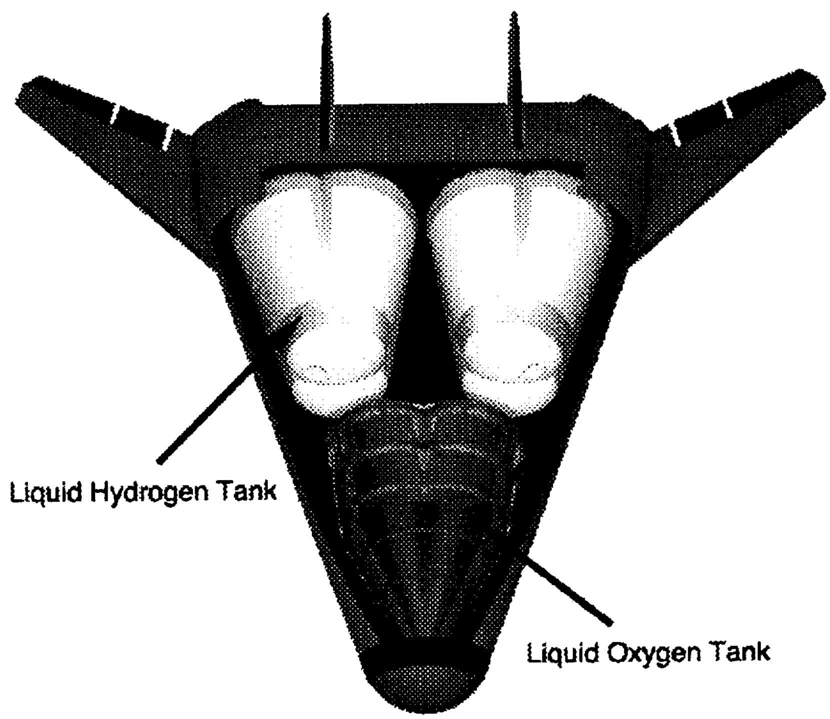

Figure 1: Internal Layout Of The X-33 Technology Demonstrator Vehicle

As seen in Figure 1, the X-33 vehicle largely consists of the tanks needed to contain the cryogenic oxygen and hydrogen propellants. These structures not only make up the bulk of the vehicle's volume, but they also form the primary load bearing structure. In the case of the X-33, this means the fuel tanks support a large number of interfaces including the engine thrust structure, wings and stabilizers, the landing gear, and the outer aeroshell. The fuel tanks are pressurized to maintain their cryogenic fuel and drive it into the feedline system to the engines at a controlled rate. Pressure in the tanks is maintained continuously after the vehicle is assembled to maintain structural stability.

1.2 Coverplate Requirements: To simplify the design for the cryogenic fuel tanks and minimize manufacturing risks, the coverplate closeouts in the ends of the tank have all of the smaller interfaces to the tanks. The covers on the X-33 liquid hydrogen tanks, seen in Figure 2, incorporate all of the primary interfaces needed for filling and draining the tanks, electrical wiring pass-thrus, venting and pressure regulation, and pressure measurement. Although it is generally easier to control interface location tolerances for a coverplate than for a larger tank, there are significant issues with concentrations of interfaces on a relatively small part with highly loaded joints. For example, the control valves for venting the tank are mounted directly on the upper coverplates.

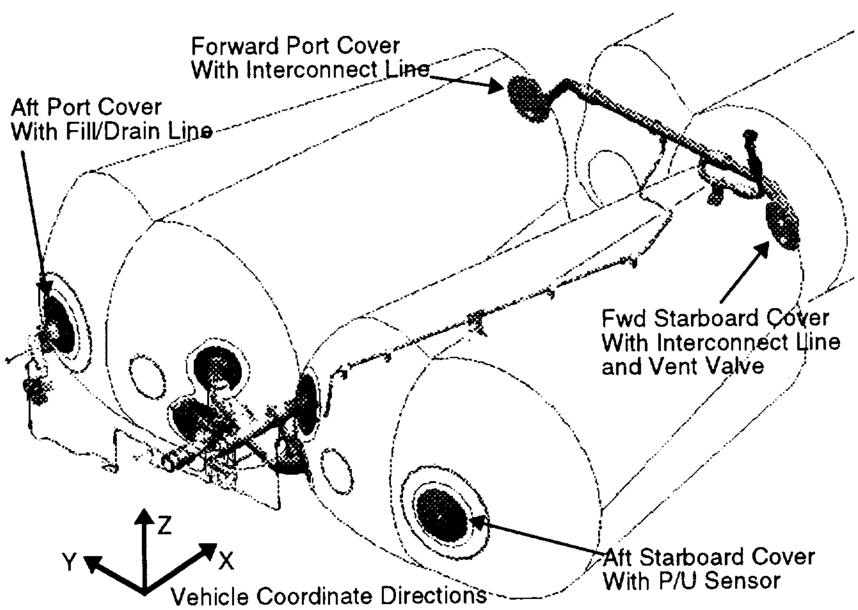

Figure 2: Schematic For The X-33 Internal Layout with Coverplates

As a result of having the covers mount all of the tank pass-thru features, the coverplates all have unique designs. Although some similarity could be carried through in overall configuration between left and right covers, the unique set of interfaces on each tank location required individually specialized designs for the coverplates. An example of one of the coverplates for the X-33 with its primary features can be seen in Figure 3.

Conducting the required development testing, effecting the coverplate designs, designing and producing tooling, laying-up the coverplates, performing machining, finishing the seal interfaces, flight qualification testing, and proof testing for the flight units had to be completed in eighteen months to meet the vehicle assembly schedule. As a result, very careful engineering judgment had to be used to control risks and leave margin for modifications.

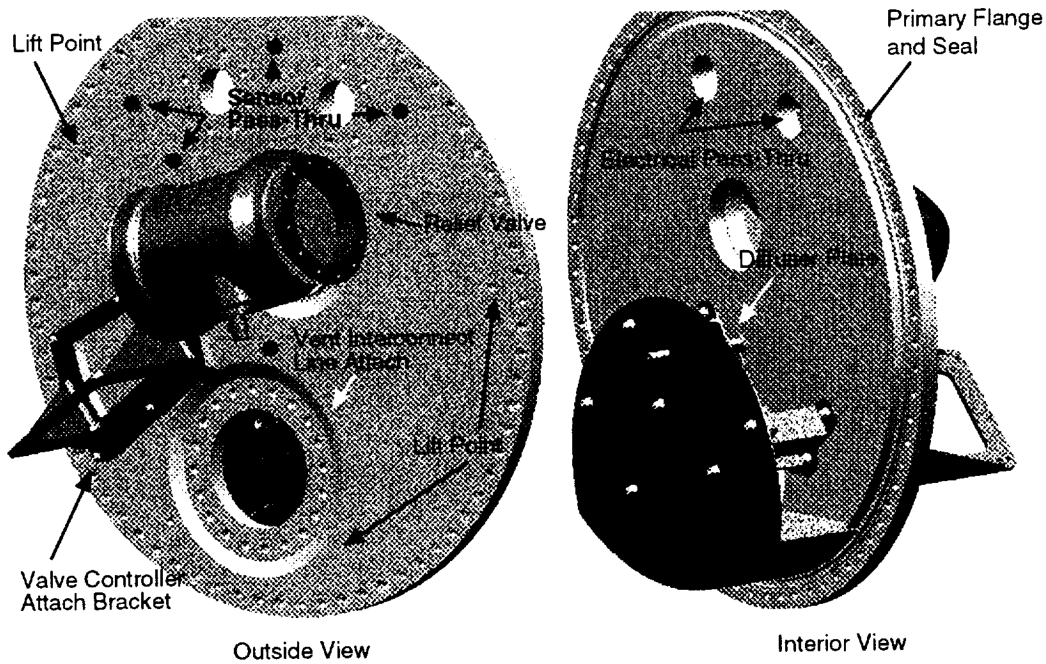

Figure 3: Forward Starboard Coverplate for X-33 LH2 Tank

2.0 COMPOSITE COVERPLATE DEVELOPMENT

2.1 Coverplate Technology Development: Several basic issues presented themselves from the start in coverplate development. For example, the coverplates have to close out the tanks and support the seals needed to prevent leakage. Therefore, each coverplate must have an interface to the tank which allows it to function as part of a pressure vessel and seal the interface against leakage. At the same time, the covers had to carry significant loads from the lines and valves they supported. As a result, there were significant issues for the coverplate structure to overcome. In Table 1, a summary of the technical issues and their causes is listed.

The development program for the coverplates started by examining the real issues the coverplates faced and generating a family of solutions to each of the problems listed in Table 1. From there, analysis determined whether different approaches should be kept in the design or should be eliminated. Finally, the most promising concepts were evaluated for practical usage, durability, producibility, and cost. The concepts which did best under these criteria went forward for testing.

Table 1: Coverplate Technological Development Issues

Issue	Areas Affected	Cause and Explanation
Laminate Permeation and Leakage	Entire Cover	The fluid the covers must contain, liquid hydrogen, consists of the smallest possible molecule. The extremely low operating temperatures, significant pressure, and additional loads can drive leakage right through laminates if they are not carefully designed
Coverplate Loads	Entire Cover	The loads on the coverplate are from the tank ullage pressure used to drive fuel into the feedlines, the launch loads on the vehicle, and the induced loads from hardware mounted to the coverplates. The resultant loads are quite high for thin flat plates to resist.
Bolt Clamp-up Loss	Outer Bolt Circle, Primary Seals	The thermal contraction of the laminate through the thickness causes bolt preload to be lost which in turn causes joint relaxation which may cause leakage.
Primary Seals	Coverplate Seals	Seals had to be supported by the coverplate since no seal groove would be placed in the tank boss itself. No self-supporting sealing surface had been attempted before.
Secondary Interface Seals	Pressure lines, fill/drain line, pressure ports	Each of the secondary interfaces on the coverplate has a through-penetration to the tank interior. These interfaces must be reliably sealed against hydrogen leakage.
Interface Tolerance	Coverplate Interface	The main flange of the coverplate had to match the boss it would be bolted against. Errors in tolerance could cause binding up during cool down, leakage, or misalignment of interfaces on the coverplate.
Secondary Interface Tolerance	Interfaces on Coverplate	The secondary interfaces had to match up with vent lines and other structures spanning long distances. As a result, these had to be in precise locations in space as well as having precise alignment for the components to line up.
Outer Edge Loads	Outer Coverplate Flange	The outer flange on the coverplate has to take all of the loads applied to the coverplate and transmit them to the tank boss. As a result, this structure has large bending moment loads applied to it. The flange must be able to take the input loads without opening up and leaking.
Secondary Interface Loads	All interior attachments used to support hardware	The secondary interfaces all have bolted flanges to make installation and removal of other hardware simple. However, these parts have large loads applied to them and the interface must be able to transmit this load to the laminate without adding a leak path.

For example, one of the most basic issues was determining what sort of construction the coverplates should have. The options examined for coverplate structure and the associated advantages, applicability, and limitations of each are shown in Table 2. In the case of the X-33 coverplates, the different locations for the coverplates affected what decision was made for the design of the cover for that application. In the case of the forward coverplates, the interfaces had a smaller diameter than the aft coverplates while at the same time the forward covers had many more pieces of hardware to attach to them.

Work done at LM Michoud on liquid hydrogen containment indicated the monocoque options for the coverplates would be the most resistant to leakage. At the same time, the thicker single shell laminates used in these designs were far more forgiving for manufacturing flaws or for repairing damage. The main problem this design encountered in preliminary analysis was the weight hit for the part. However, further design work started to show very large interface penalties for the other designs due to the fittings needed to install the secondary fittings, and the monocoque coverplates were still 35% lighter than their metallic counterparts while actually having greater strength. In the end, a flat plate monocoque design was chosen for the forward coverplates while the larger diameter aft coverplates were built using a lighter spherical membrane dome monocoque design.

Table 2: Coverplate Structural Design Approaches and Their Attributes

Structure type	Applicability	Pros	Cons
Flat Honeycomb Sandwich	Flat Covers	Very light design	Difficult to verify build quality, No high load attachments available, Leakage concerns, Not forgiving of manufacturing flaws, Cryopumping concerns
Flat Foam/ Other Sandwich	Flat Covers	Very light design, Integral insulation	Difficult to verify build quality, No high load attachments available, Leakage concerns, Not forgiving of manufacturing flaws
Domed Honeycomb Sandwich	Domed Covers with interface flexibility	Very light design	Difficult to Build, Difficult to verify build quality, No high load attachments available, Leakage concerns, Not forgiving of manufacturing flaws, Cryopumping concerns
Domed Foam/Other Sandwich	Domed Covers with interface flexibility	Very light design, Integral insulation	Difficult to verify build quality, No high load attachments available, Leakage concerns, Difficult to Build, Not forgiving of manufacturing flaws
Flat Monocoque	Flat Covers	Easy to fabricate, Easy to machine, Strong interfaces possible, Low permeation, high strength, forgiving of manufacturing flaws, Easy to incorporate multipe interfaces	Heavier than sandwich designs. High through-thickness thermal shrinkage, high flat plate bending stresses
Domed Monocoque	Domed Covers with interface flexibility	Easy to fabricate, Easy to machine, Strong interfaces possible, Low permeation, high strength, forgiving of manufacturing flaws	High through-thickness thermal shrinkage, Difficult to incorporate multiple interfaces
Flat Beam Reinforced Membrane	Flat Covers	Lighter than Monocoque Designs	Complex Design, Difficult to attach interfaces, Difficult to transfer load to outer flange, Not forgiving of manufacturing flaws
Domed Beam Reinforced Membrane	Domed Covers with interface flexibility	Lighter than Monocoque Designs	Very Complex Design, Difficult to attach interfaces, Difficult to transfer load to outer flange, Difficult to incorporate multiple interfaces, Not forgiving of manufacturing flaws

2.2 Coverplate Configuration Design: Since time for the coverplate program was limited, the parts had to be very high-confidence designs. The coverplates were designed at the same time as their manufacturing process and every opportunity to streamline their design was used. The coverplates were designed to have as much commonality between elements as possible to reduce production costs and production complexity. For example, the electrical feed-thrus on the forward covers as well as the fitting for the P/U sensor on the aft starboard coverplate all used the same flange geometry so they could all use the same seal.

Risk reduction for production was a primary design consideration given the limited time available for delivery. By introducing manufacturing and assembly commonality between covers, it was possible to reduce the number of opportunities for assembly errors. One way of doing this was by reducing the number of types of fasteners to two bolts for different applications and then performing analysis to produce a common bolt torque for all of the fasteners of each size. This step not only reduced the risk of assembling parts with the wrong bolt torque, but it also reduced the complexity of the design tasks as well. The configuration of the aft port coverplate, the most highly loaded of all the coverplates, is seen in Figure 4.

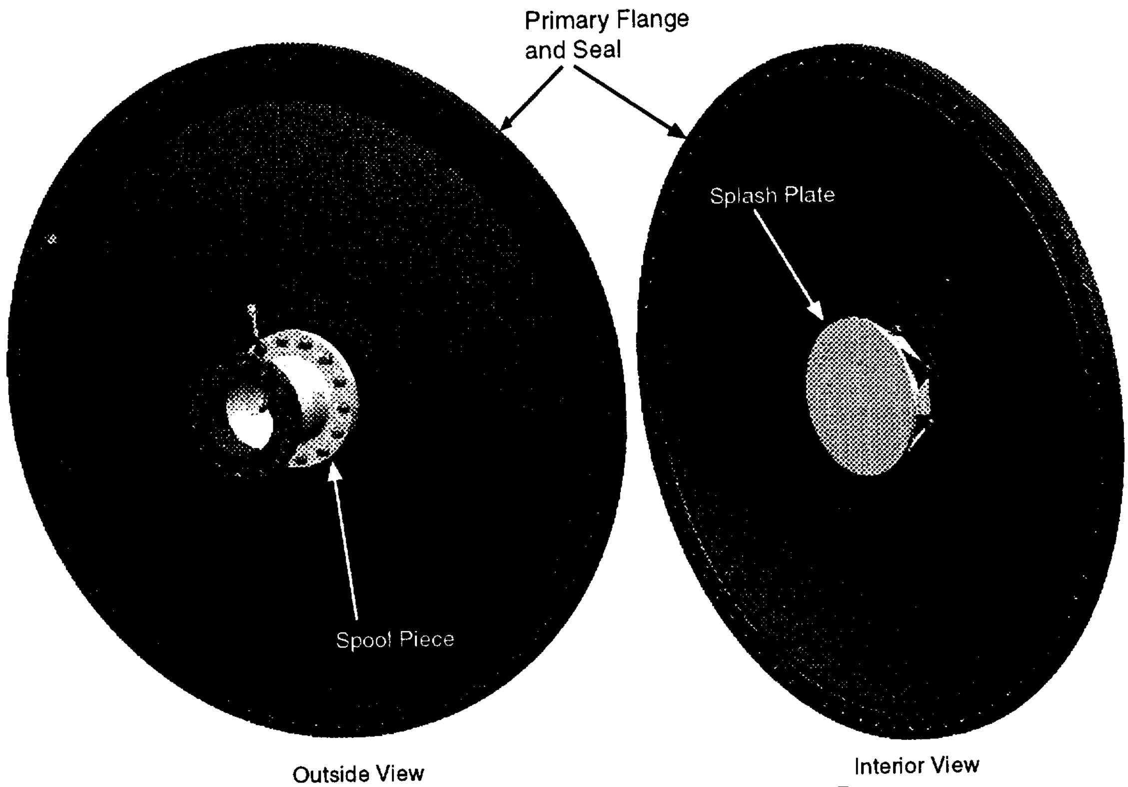

Figure 4: Aft Port Coverplate with Fill/Drain Line Fitting

Tooling for the coverplates was designed straight from the CATIA models of the parts themselves. Tolerances for the design drawings were therefore referenced from the tool face so interface locations could be very precisely controlled. By using this technique, it was possible to meet all of the interface location requirements for the coverplates and all of the secondary interfaces.

3.0 COVERPLATE FLIGHT QUALIFICATION

3.1 Production Prototype: Before the flight coverplates were built, a production prototype of one of the most difficult coverplate designs was completed to verify the engineering and manufacturing approach to the coverplates before final design and production on the flight covers began. This component was an aft starboard cover, which initially had no through penetrations of any kind in it. The design requirements for the coverplate were altered while the design was being performed to include a P/U fitting in the center of this coverplate to monitor ullage pressure in the starboard liquid hydrogen. The resulting design was the thinnest of the coverplates and thus had the least material of any of the coverplates and still had all of the primary features of all of the coverplates. By producing this part, it was possible to verify the manufacturing processes as well as the engineering decisions on how to maintain tolerances in the finished component.

3.2 Flight Coverplates: After the prototype coverplate was successfully machined to its final geometry, the full engineering development for the flight coverplates began. The design and analysis effort for the coverplates was synchronized with the required delivery dates to give the maximum amount of time to get the designs done and therefor the most schedule relief for the components. Each coverplate had its own set of preliminary and critical design reviews. Testing for design issues was carried out on subcomponents in time to lead the production dates for the hardware they supported.

The second coverplate configuration to be produced was an aft port design to be the qualification unit for the coverplates. The main importance of this cover for the qualification role was the fact that this part had the highest loads of any of the coverplates. This was due to the size of the interface for the fill/drain interface compared to the applied load from the fill and drain line valve at the end of a spool piece. This coverplate went into test for a series equal to four flight lifetimes to prove out long term effects for the coverplates.

3.3 Coverplate Flight Qualification Testing: Two types of testing were done on the composite coverplates. The coverplate test series and results are summarized in Table 3. Each of the flight coverplates was required to have three pressurization cycles in liquid hydrogen to 1.25 times the maximum flight pressure. Ultrasonic NDE results from before and after the test could then be compared to make sure no changes had occurred in the part. The coverplate test fixture sealed off the coverplate so the total leakage from the coverplate, its seals, and the seals on its interfaces could be measured. This was compared to the acceptable specified cumulative leakage for its seals for 99% confidence all of the seals were within specification. If the leakage went over this value, it would mean there was a possibility of a leak. The coverplates had to demonstrate leakage below this value to pass their flight readiness certification. All of the flight units were delivered after meeting this requirement.

The second type of coverplate testing was the qualification test series performed on the qualification coverplate. This coverplate was tested to verify the most highly loaded coverplate design could survive a flight lifetime. In addition, damage tolerance and overload performance tests were performed on this part to demonstrate the robustness of the design. The qualification coverplate went through the same flight qualification test as the flight units, but was then was taken to the flight limit load with the limit applied load on the fill and drain interface for an additional 44 cycles in liquid hydrogen. Half way though the series, this coverplate was removed from the test fixture to induce two impacts for damage tolerance testing. The qualification coverplate then went on to finish its test series. At the end of the second to last cycle, ultrasonic inspections were carried out on the cover to verify damage growth had not occurred. On the last cycle, the qualification coverplate was overloaded to demonstrate the component still had the required factor of safety as well as additional margin. The qualification coverplate went to 1.25 times its limit pressure and applied load without leakage and then went to 1.5 times the limit load and 1.5 times pressure without leakage.

Table 3: Coverplate Testing Summary

Item	F. S.= 1.0	F.S.= 1.25	F.S.= 1.5	External	Low Temperature		High Temperature		Test
Flight Articles	# cycles	# cycles	# cycles	Load	°C	°F	°C	°F	Result
Aft Port Flight	0	3	0	No	-253	-423	21	70	Pass
Fwd Port Flight	0	3	0	No	-253	-423	21	70	Pass
Aft Stbd. Flight	0	3	0	No	-253	-423	21	70	Pass
Fwd Stbd. Flight	0	3	0	No	-253	-423	21	70	Pass
Test Article (Aft Port Configuration)									
Aft Port Phase 1, Test 1	0	3	0	no	-253	-423	54	130	Pass
Aft Port Phase 1, Test 2	20	0	0	Yes	-253	-423	54	130	Pass
Aft Port Phase 2, Test 1	24	1 (on 44th)	1 (on 44th)	Yes	-253	-423	54	130	Pass
Totals:	44	15+1	1						

4.0 SUMMARY

The composite coverplates designed for the X-33 liquid hydrogen tanks broke new ground for building practical composite cryogenic structures. These components were the first composite parts with interfaces to mechanically clamp their own seals and mount components with sealing composite bosses. The technologies developed at LM Michoud for these components have already been employed to build large highly loaded liquid oxygen feedlines and the composite coverplates for the X-34 composite liquid oxygen tank also built by LM Michoud. Innovative engineering, good design practice, and team integration made the X-33 composite coverplates a complete success.