

COMPOSITE CRYOTANK TECHNOLOGIES AND DEVELOPMENT 2.4 AND 5.5M OUT OF AUTOCLAVE TANK TEST RESULTS

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ABSTRACT

The Composite Cryotank Technologies and Demonstration (CCTD) project substantially matured composite, cryogenic propellant tank technology. The project involved the design, analysis, fabrication, and testing of large-scale (2.4-m-diameter precursor and 5.5-m-diameter) composite cryotanks. Design features included a one-piece wall design that minimized tank weight, a Y-joint that incorporated an engineered material to alleviate stress concentration under combined loading, and a fluted core cylindrical section that inherently allows for venting and purging. The tanks used out-of-autoclave (OoA) cured graphite/epoxy material and processes to enable large (up to 10-m-diameter) cryotank fabrication, and thin-ply prepreg to minimize hydrogen permeation through tank walls.

Both tanks were fabricated at Boeing using automated fiber placement on breakdown tooling. A fluted core skirt that efficiently carried axial loads and enabled hydrogen purging was included on the 5.5-m-diameter tank. Ultrasonic inspection was performed, and a structural health monitoring system was installed to identify any impact damage during ground processing. The precursor and 5.5-m-diameter tanks were tested in custom test fixtures at the National Aeronautics and Space Administration Marshall Space Flight Center. The testing, which consisted of a sequence of pressure and thermal cycles using liquid hydrogen, was successfully concluded and obtained valuable structural, thermal, and permeation performance data. This technology can be applied to a variety of aircraft and spacecraft applications that would benefit from 30 to 40% weight savings and substantial cost savings compared to aluminum lithium tanks.

1. INTRODUCTION

The Game Changing Development Program (GCDP), through the NASA Marshall Space Flight Center (MSFC), contracted The Boeing Company to design, manufacture, and test a 2.4-m-diameter (2.4m) and a 5.5-m-diameter (5.5m) composite cryotank. The two tanks would incorporate the design features and strain levels that represent a full-scale (8.4-m-diameter) Space Launch System (SLS) propellant tank.

NASA is exploring advanced composite materials and processes to reduce the overall cost and weight of liquid hydrogen (LH₂) cryotanks while maintaining the reliability of existing designs. The fundamental goal of the CCTD project is to develop innovative cryotank technologies that enable human space exploration to destinations beyond low Earth orbit such as the moon, near-Earth asteroids, and Mars.

The current NASA SLS has an 8.4-m-diameter (8.4m) upper stage. NASA selected a 5.5m test article for CCTD to enable industry to produce and test this size tank using existing infrastructure, thereby greatly reducing costs compared to a full-scale tank program. A 5.5m cryotank is of sufficient scale to identify and reduce scale-up risks. Future spinoff applications may include LH₂ tanks for launch vehicles, in-space propulsion systems, on-orbit propellant depots, and liquid oxygen (LO₂) tanks.

During a Phase 1 contract, NASA contracted Boeing and other industry contractors for material equivalency testing, a preliminary design, and a manufacturing plan of a 10-m-diameter (10m) composite cryotank (Figure 3-1). Design requirements were for an early version of the SLS that was 10 m in diameter, rather than the current 8.4m tank. The material testing results showed that three materials tested possess the required strength for composite cryotank application that will yield 25 – 30% weight savings. The results further showed that thin plies (65 or 70 gsm) are effective in resisting microcracks and thereby minimizing LH₂ permeation. Boeing's design and analyses showed that when designing to a 5,000 $\mu\epsilon$ limit strain level, a 39% weight saving over a comparable aluminum-lithium tank designed using mature materials and manufacturing techniques can be realized. A cost analysis effort showed that 20-25% cost saving can be achieved by utilizing an automated fiber placement process.

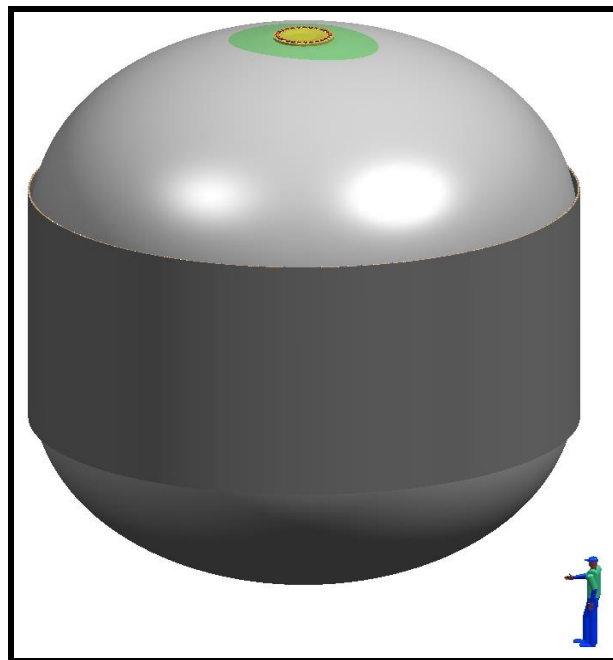


Figure 1. 10m Diameter Composite Cryotank

1.1 Project Scope

The Composite Cryotank Technologies and Demonstration (CCTD) project, a phase 2 effort, involved the design, manufacture, and testing of large-scale composite cryotanks. Project scope included material selection, material allowables testing, and manufacturing demonstration units to support the design, manufacturing, and testing of 2.4m and 5.5m diameter composite cryotanks. The scope is shown as a building block program in Figure 2.

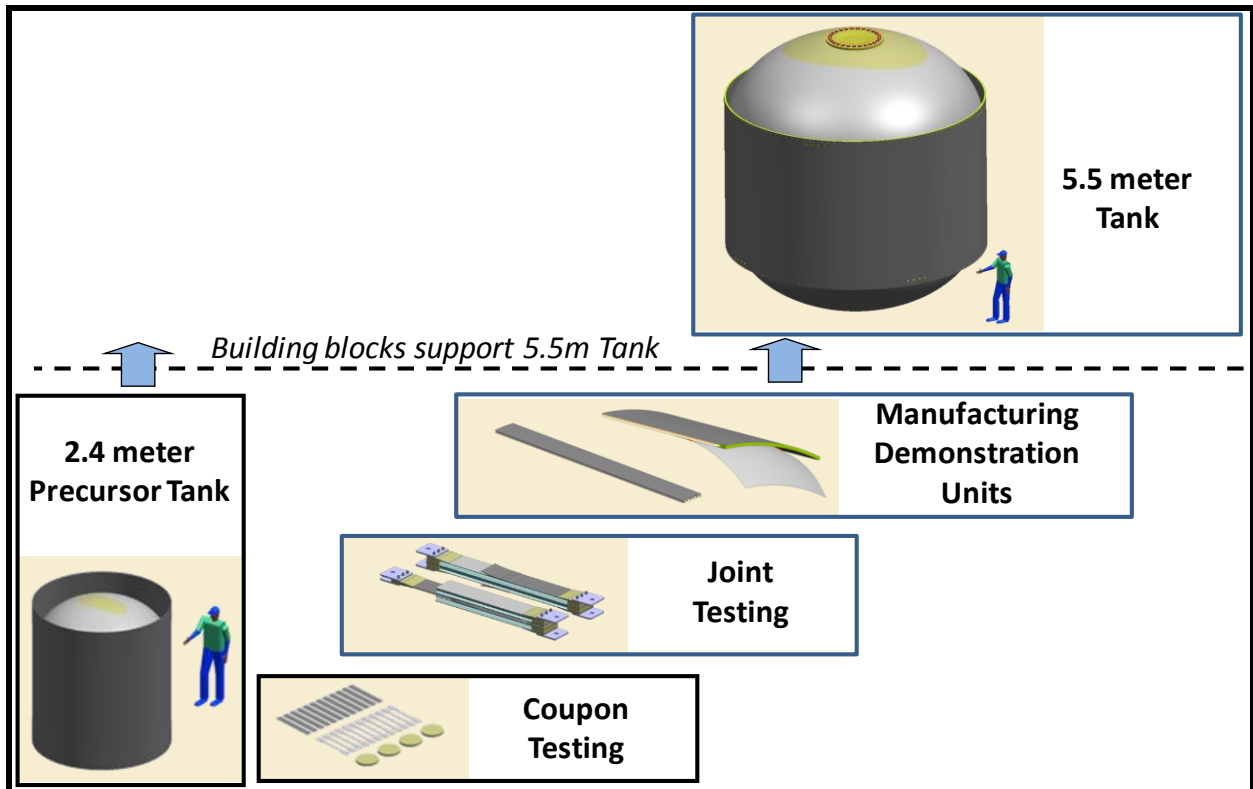


Figure 2. Overview of CCTD Task Order Scope

1.2 Schedule Overview

The effort began with a 26-month period of performance. A significant amount of work was conducted in parallel Figure 3. The 2.4m cryotank design, fabrication, and test; 5.5m cryotank preliminary design; 5.5m cryotank tooling design, coupon design, fabrication and test, joint design, fabrication, and test; and 5.5m cryotank detailed design were all performed in parallel. The parallel approach saved approximately 13 months compared to running the project in a low-risk, conventionally serial manner. The schedule saving was achieved mainly by conducting the coupon and joint testing before starting the 5.5m detailed design effort.

The major contributors to the schedule growth observed during the project from 26 to 43 months includes (1) material selection that drove additional design cycles within the 5.5m cryotank preliminary design phase. (2) the parallel nature of the project that drove the need for a delta critical design review (CDR). (3) 2.4m Precursor test conduct that required complex analysis to support TRR assessments. (4) first article large scale fabrication of 5.5m cryotank. (5) 5.5m cryotank test conduct requiring facilities negotiations with other NASA programs.

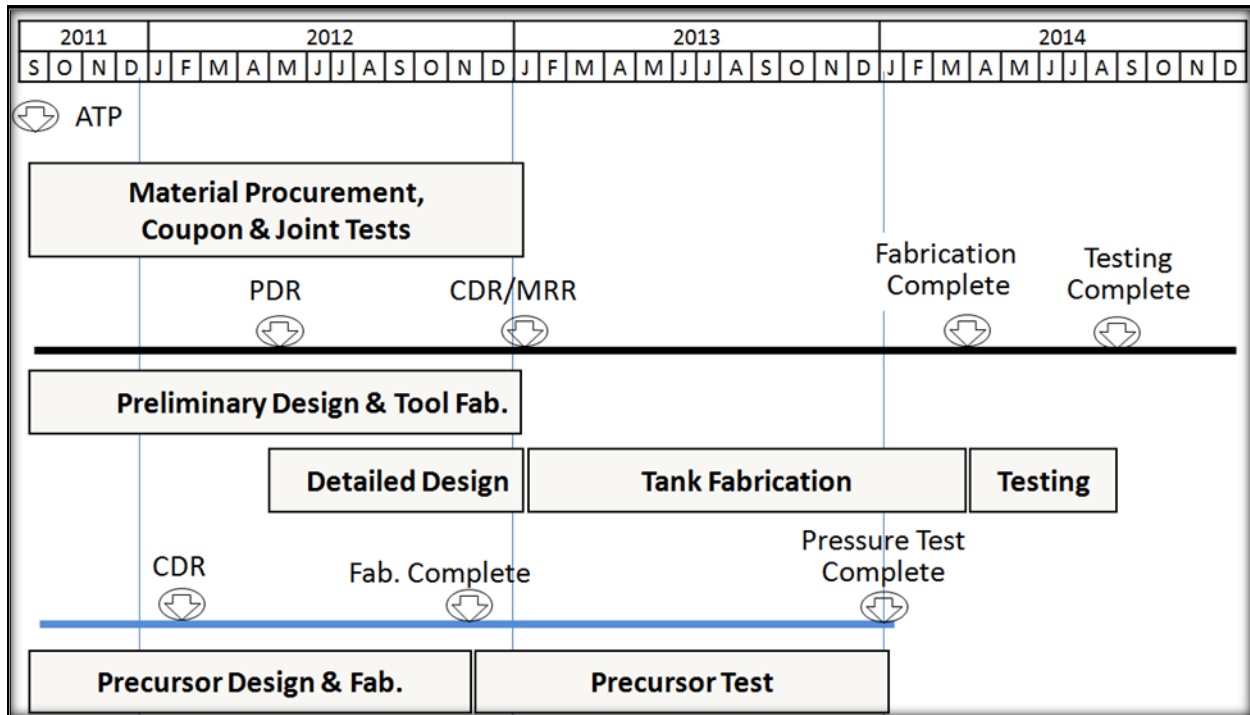


Figure 3. Project Schedule Showing Major Milestones and Work Scope

2. EXPERIMENTATION

2.1 Material Selection

The material and processing eventually selected was out of autoclave (OoA); specifically, Cytac 5320-1/IM7 material. This decision had significant effects on all aspects of the project, including schedule, cost, permeation, laminate quality, and allowables. At the time the decision was made, there was no autoclave large enough to cure a 10m cryotank, and having a design and manufacturing solution directly traceable to a 10m cryotank was a major project objective.

2.2 Technical Performance Overview

Table 1 and Table 2 show achieved safety factors for ambient and cryogenic test cases. The project adopted the term “Achieved Safety Factor” to aid in test readiness reviews and test site approval. The term avoids the need to independently discuss a safety factor requirement and the analytical margin to that requirement. With this data, the test readiness review board could more easily translate the achieved safety factors to assess test site safety. For ambient cases in Table 1, the achieved safety factors are all above 2.0 and the maximum strain is below 5,000 in/in for the selected test pressure of 45 psi. In the same table, it is important to note that most critical areas are dominated by the pressure only case, not the pressure plus flight loads case. The only exception is the Y-joint, where the achieved safety factor is lower when flight loads are added. For cryogenic cases at 53 psi the same outcome is shown in Table 2. The conducted pressure case at 58 psi has lower achieved safety factors in all areas, ignoring the insignificant difference at the Y-joint and the planned pressure plus flight loads case. Table 2 also shows that not all joint safety factors

achieved the design requirement of 2.0. The Y-joint achieved safety factor is dominated by the thermal load, not pressure or flight loads. The Y-joint achieved safety factor is 0.52 when exposed to LH2 at zero pressure using classical finite element methods.

Table 1. Achieved safety factors for ambient test cases

Location	Ambient Test Case	
	Demonstrated Pressure(45 psi)	Location
Fwd Scarf	2.06	2.16
Aft Scarf	2.79	2.76
Y-Joint	6.21	4.64
Acreage	4,534 $\mu\epsilon$	4,644 $\mu\epsilon$
Local Buckling (30psi)		3.70

Table 2. Achieved safety factors for LH2 test cases

Location	Cryogenic Test Case	
	Demonstrated LH2 Pressure (58psi)	Predicted / Not Tested LH2 Pressure (53 psi) + 100% Flight Loads
Fwd Scarf	1.49 1.63 (53 psi)	1.68
Aft Scarf	2.16 2.37 (53 psi)	2.34
Y-Joint	0.53 0.53 (53 psi)	0.52
Acreage	5,136 $\mu\epsilon$ 4702 $\mu\epsilon$ (53 psi)	4,713 $\mu\epsilon$
Local Buckling (30psi)		4.42

Tank level permeation performance is shown in Figure 4. Additional permeation measurement information is provided in the 2.4m and 5.5m testing sections. The CCTD project requirement was based on a long duration lunar lander mission and is $1E-3$ SSC/s/in**2. At the maximum test strain, nearly 5,000 micro-inches/inch, the permeation performance is slightly above the CCTD requirement, but well within the allowable for an upper stage or boost stage composite tank application. Microscopy showed microcracks formed in the thin permeation barrier plies, primarily due to porosity. This data shows that the available state-of-the-art OoA material and processing selected for this project requires further development to achieve long duration mission permeation performance. The following approaches are available to improve permeation performance: a) improve OoA materials and processes; b) increase the number of thin plies that arrest microcracks from the adjacent thick plies or from porosity; and c) use autoclave pressure to achieve high laminate quality with little porosity.

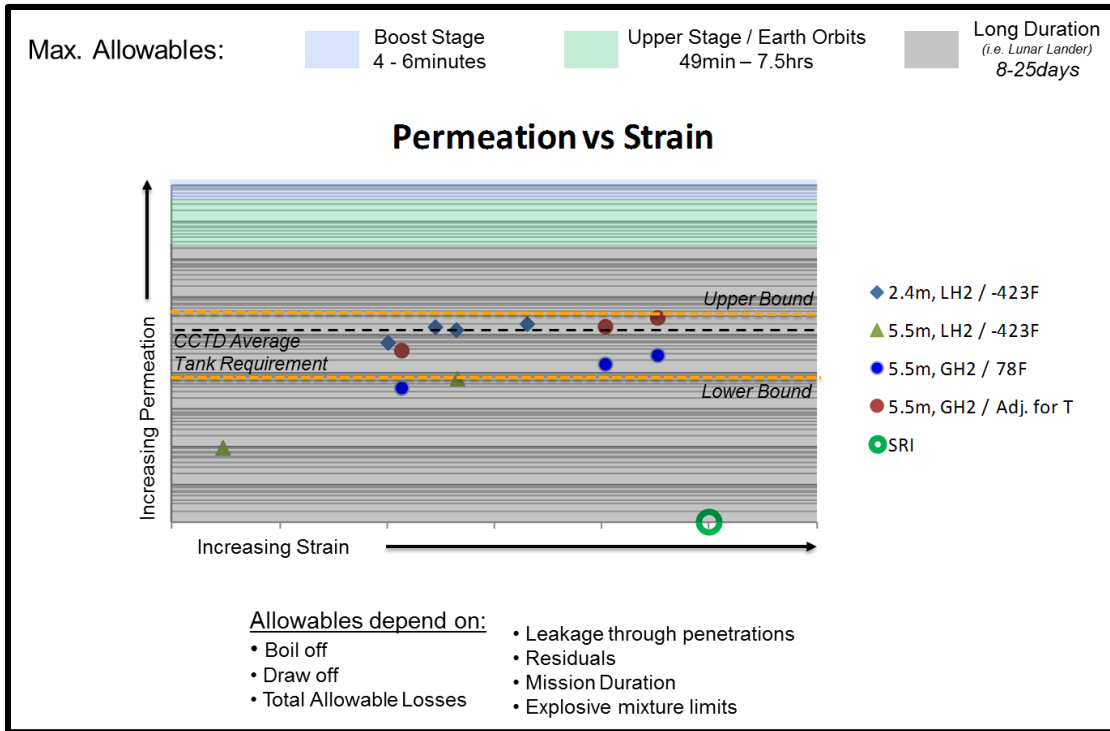


Figure 4. Permeation Performance

3. RESULTS

After successful mechanical loads and pressure influence testing to ensure that loads were being properly applied to the structure, testing was initiated. The test tank was pressurized to 45 psi with gaseous nitrogen before applying any load. The tank was taken to 100% load with 45 psi internal pressure and then reduced to 30 psi to demonstrate the maximum compression condition. Mechanical loads were then removed, and the tank was depressurized. It was noted during this test that strains in the tank and joints were unaffected by mechanical loads but were driven by tank internal pressure. All scarf joint, Y-joint, and tank acreage gages performed as predicted. The maximum strain observed was approximately 90% of the target microstrain in a forward scarf joint strain. Because this strain was unaffected by mechanical loads application, it tracked well with test data from the initial ambient pressure test. The data and observations (especially that the strains in the tank seemed to be mostly internal pressure related) gathered from this successful test would prove valuable in correlation to additional and previous testing.

It is clear from the panel testing at SRI and at NASA-MSFC that when thin plies are used and standard laminate consolidation is achieved, permeation performance requirements will be met with very large margins. The higher levels measured in the CCTD tanks are likely due to porosity, estimated to be approximately three percent, from the low-pressure curing having facilitated void and crack formation, even in the thin plies. Low porosity levels are also needed to achieve adequate interlaminar shear strength adjacent to the tank Y joints and scarf joints. At this time, it is difficult to achieve the low porosity levels needed for tanks without autoclave pressure.

The best measurement of tank permeation, hoped to be accomplished on a future program, would be to measure hydrogen loss of a tank in a vacuum chamber. Tank pressurization, fill/drain, and instrumentation ports could be sealed off and isolated and hydrogen loss through the entire tank wall surface area could be determined. Also, chamber cold walls and heaters could be used to simulate the space environment and hydrogen boil off performance could also be measured.

Based on the results of the CCTD program and other composite cryotank experience through the years, researchers at NASA and Boeing believe the way is clear for implementation of composite propellant tanks on launch vehicles and the realization of the benefits they will provide.

4. CONCLUSIONS

The CCTD Phase 2 project achieved its principal goal of demonstrating a 25 to 30% lower weight design traceable to an 8.4m upper stage liquid hydrogen tank. Two all-composite cryotanks were designed, built, and tested within 30 months of contract start. Both were successfully subjected to cyclic pressure testing with liquid hydrogen, and the 5.5m cryotank was also subjected to flight loads in combination with pressure loads. The 5.5m tank was pressurized to 58 psi, reaching a maximum average strain of 5136 microstrain and demonstrating safety factors above 1.5 in the scarf joints.

Additional data is required to improve Y-joint analytical predictions, such as destructive evaluation of one or both of the tanks. The project confirmed that composite cryotanks can achieve a 33% weight savings compared to aluminum-lithium cryotanks, and it demonstrated permeation performance that meets the allowable for upper stage and boost stage applications. Technical risks of large-scale, liquid hydrogen, composite cryotanks were substantially mitigated by demonstrating scalable manufacturing, 5,000 microstrain design allowable, Y-joint strength, all-composite bolted joint strength, and permeation performance.

4.1 Future Applications

Figure 4.1-1 illustrates some of the potential applications of composite cryotanks. Expendable launch vehicles such as the Space Launch System require large and weight-critical cryogenic propellant tanks for both the core and upper stages. Relatively smaller but greater quantity ELVs will also benefit from composite propellant tank weight savings, and the cost savings from composite fabrication. Planetary landers are especially weight critical, so composite tanks will enable many robotic and crewed missions to the Moon, asteroids, and Mars. Operationally responsive launch systems for rapid access to space may use reusable first stages with various propellants, or small launchers deployed from jet aircraft. Both will be weight and cost critical. Long duration aircraft such as Phantom Eye use LH₂ stored in thermally isolated spherical tanks. Lightweight composite tanks will improve endurance at extreme altitudes. In-space propellant depots allow flexible in-space operations by transferring propellant to long-distance spacecraft and will benefit from reduced structure weight. Future aircraft, whether subsonic or supersonic, may use cryogenic and/or high-pressure fuels.

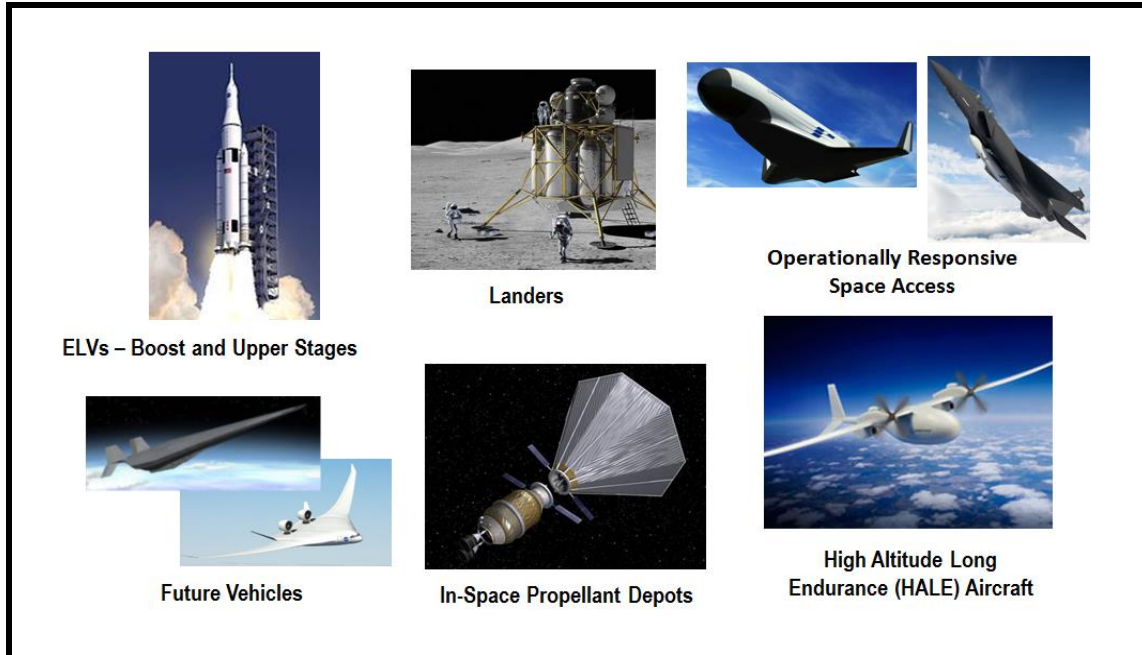


Figure 4.1-1. Potential Applications of Composite Cryotanks

4.2 Recommendations for Future Work

The following areas of study and development can further reduce the risks of implementation:

- Improve analytical predictions in areas of discontinuities: additional material testing should be considered, perhaps with a focus on fracture toughness properties, to enable application of virtual crack-closure techniques in areas of discontinuities such as the Y-joint and scarf joint.
- Investigate and conduct coupon testing of hybrid laminates under in- and out-of-plane strain to understand permeation sensitivity to number of thin plies, porosity level, and out-of-plane bending.
- Improve laminate quality and laydown rate of out-of-autoclave, automated fiber placement materials and processes.
- Improve large surface area bonding with one pre-cured structure: advance design and manufacturing for high-quality, high-strength bonds between the skirt inner mold line and tank cylinder outer mold line.
- To support the above item, improve placement and assembly of the softening strip and skirt alignment fixture.
- Improve low-cost, in-field permeation measurement techniques.

The following recommendations were out of scope of the CCTD project, but they are suggested to support transition of composite cryotanks into flight vehicles:

- Design, develop, and demonstrate a skirt end joint.
- Design, develop, and demonstrate internally bonded secondary structures, such as baffles.