NASA Composite Cryotank Technology Project
Game Changing Program

Presented by:
John Vickers
Project Manager
NASA Marshall Space Flight Center
December 1st, 2015
Overall Project Objective

The fundamental goal of this project was to provide new and innovative cryotank technologies that enable human space exploration to destinations beyond low earth orbit such as the moon, near-earth asteroids, and Mars.

The goal … to mature technologies in preparation for potential system level flight demonstrations through significant ground-based testing and/or laboratory experimentation.
## Objective:
Advance technologies for lightweight cryotanks for heavy lift vehicles + spin-off capabilities for multiple stakeholders - NASA, DOD, and Industry

## Concept:
Develop and demonstrate composite tank critical technologies – Materials, Structures, and Manufacturing - Out-of-Autoclave

## Approach:
Focus on achieving affordability, technical performance, verified through agreement between experimental results and analysis predictions

## Goal:
Produce a major advancement in technology readiness; successfully test a 5.5-meter diameter composite hydrogen fuel tank, achieve:

- 25-30% weight savings
- 20-25% cost savings
NASA Project Organization and Key Personnel

Composite Cryotank

STMD Game Changing Program

Partnerships:
- Government Agencies
- Industry
- Academia
- International

J. Vickers – Project Manager
J. Fikes – Deputy Project Manager
J. Jackson – Project Engineer
MSFC

Composites for Exploration (CoEx)
- M. Shuart
- ESMD / LaRC

Office of the Chief Engineer
- C. Finnegan
- MSFC

1.0
Project Management
MSFC

J. Sutter / GRC

2.0
Materials

3.0
Manufacturing
L. Pelham / MSFC

4.0
Structural Analysis
T. Johnson / LaRC

5.0
Testing & Evaluation
M. White / MSFC

Phase I Contracts
“Industry”

Phase II Contract
Boeing Organization

Composite Cryotank

STMD Game Changing Program

Boeing Technical Advisory Team

Suppliers
Janicki
Southern Research Institute

CCTD Phase Two
Program Manager
Dan Rivera

Aeromechanics Technology
Naveed Hussain

Materials & Manufacturing Technology
Gerould Young

Structures Technology
Steve Yahata
Structural Concepts
Nick Melillo

Materials & Manufacturing Technology
Carlos Guzman
Doug McCarville

Design & Analysis
Tin Luu

Design
Mike Hand

Analysis
Chinh Cao
Mike Robinson (ATF)

SHM
Jerry Huang (TF)

Boeing Technical Advisory Team
- Dallas Bienhoff, BDS Advanced Space Exploration
- Gail Hahn (TF), Next Gen Materials & Labs
- Brice Johnson (TF), Composites & Non-Metallics
- Don Barnes (ATF), BDS/Exploration Launch Sys
- Al Olsen, Propulsion Technology
- Marc Piehl (TF), Primary Structural Bonding
- Kurtis Willden (ATF), Composite Fabrication
- Richard Bossi (STF), Non-Destructive Evaluation

Integrated Test
Cat Mazzola

Functional Support Team
- MSFC Integration
- Precursor Testing
- 5 Meter Tank Testing

Functional Support Team
- Kurt Braaten, Contracts
- Ros Campbell, Schedule
- David Sanchez, Finance
- Mark Mihalco, Supplier Mgmt
- Denise Boss, Data Mgmt
- Roger Smith, Quality
- Charlie Conway, Safety
- Jeff Fukushima, ERB/MRB/CCB
Building Block Program Culminated With 5.5m Cryotank

Composite Cryotank

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Available to support 5.5m Tank

2.4 meter Precursor Tank

5.5 meter Tank

Manufacturing Demonstration Units

Joint Testing

Coupon Testing

Building block approach essential to successful technology maturation
Schedule Overview

Composite Cryotank

STMD Game Changing Program

<table>
<thead>
<tr>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
</table>

- **ATP**
- **PDR**
- **CDR/MRR**
- **Fab Complete**
- **Testing Complete**

- **Preliminary Design & Tool Fab**
- **Material Procurement, Coupon & Joint Tests**
- **Detailed Design**
- **Tank Shell Fabrication**
- **Testing**
- **Final Report**
- **CDR**
- **Fab Complete**
- **Pressure Test Complete**
- **Precursor Design & Fab**
- **Test**

*Saved 13 months in comparison to typical Serial Development*
CCTD Key Terminology

**Major Components**
- Fwd Door
- Fwd Cover
- Tank Shell
- Skirt
- Sump Cap
- Sump

**Major Joints**
- Bolted Door
- Fwd Scarf
- Y-Joint
- Aft Scarf
- Bolted Sump
Technologies Matured by CCTD

- Large Scale, OoA (5320-1/IM7) Design & Manufacturing
- Structurally Efficient Bonded Scarf Joints
- Automated Fiber Placement of Thin Tow
- Permeation Resistant Hybrid Laminate
- Composite Cryogenic Bonded Joints
- Shear Peak Reduction Structures
- Ventable and Purgeable Sandwich Structures
- Structural Health Monitoring Using Acoustic Emission Sensor Array
Major Accomplishments

- Large AFP test article using 5320-1/IM7
- 70gsm fiber placed cryotank (hybrid laminate)

Benefits:
- Enables Out-of-Autoclave manufacturing
- Meets material out time
- Provides permeation barrier
Janicki - Large scale, spherical segmented tool

- Enables lightweight, 1-piece tank shell
- Successfully used to fabricate cryotank
- Successfully extracted
Major Accomplishments

- Large scale, Gr/Ep fluted core sandwich & NDI
Major Accomplishments

- Cold temperature softening strip.
- All composite bolted cover joints.
**Permeation Reduction:**

- Hybrid laminate with thin plies prevented microcracking and reduced permeation levels.

- Design meets upper stage & booster stage calculated permeation allowable.

- To improve performance further:
  - Improve OoA AFP materials & processes
  - Increase number of thin plies
  - Autoclave cure
Permeation Coupon Measurements

Composite Cryotank

STMD Game Changing Program

Multiple tests performed using both setups with coupons cut from same parent panel, SRI exhibited no detectable permeation on all tests. MSFC rig detected excessive permeation on all OOA cured hybrid laminates. 100% of autoclave cured laminated had 0% permeation on both tests, and all OOA cured, all thin ply laminates had 0% permeation on both tests.
In-Situ Permeability Measurement

- Metallized film bag/Composite bag underneath foam insulation collects permeated hydrogen and helium carrier gas.
- Bag effluent gas is collected in bottles at specified times; bottles taken to MSFC chem labs for gc-ms analysis. Measured total effluent flow rate at test site and composition from gas analysis gives permeation rate.
- Same equipment and procedure for 2.4-m and 5.5-m tanks.
- Accurate permeability measurements are difficult under ideal conditions. Performing the measurement on an industrial scale offers a unique set of challenges.
Permeation Results

Max. Allowables:

- Boost Stage: 4 - 6 minutes
- Upper Stage / Earth Orbits: 49 min – 7.5 hrs
- Long Duration (i.e. Lunar Lander): 8-25 days

Permeation vs Strain

- 2.4m, LH2 / -423F
- 5.5m, LH2 / -423F
- 5.5m, GH2 / 78F
- 5.5m, GH2 / Adj. for T
- SRI

Allowables depend on:

- Boil off
- Draw off
- Total Allowable Losses
- Leakage through penetrations
- Residuals
- Mission Duration
- Explosive mixture limits

Increasing Permeation

Increasing Strain

CCTD Average

Tank Requirement

Upper Bound

Lower Bound

Upper Stage / Earth Orbits
Implication of OOA on Hybrid Laminate

- **Objective:** Determine Effects of OOA vs. Autoclave Cures
- **Approach:** Hybrid laminates fiber-placed panels produced at Boeing and LH2 tested at MSFC
  - Hybrid laminate 12 plies of 5.4mil with 5 plies of 2.5 mil material
  - OOA cured laminates exhibit ~4% porosity
Laminate Micro-Cracks

- Micro cracks formed in thin plies primarily due to presence of porosity
- To eliminate permeation
  - Increase number of thin plies
  - Reduce porosity
    - Autoclave cure
    - Improved OoA AFP processes

Autoclave cured panel extensive micro cracks post LH2 cycling in 5mil plies but no permeation
Permeation Conclusions

Tank level permeation measurements
- Meet upper stage and booster stage allowable
- Exceed CCTD, lunar lander based, requirement

Permeation is sensitive to
- Laminate quality
- Number of thin plies

To eliminate permeation
- Increase number of thin plies
- Reduce porosity
  - Autoclave cure
  - Improved OoA Material Architecture and AFP processes
2.4m Test Summary

- 135 psi achieved with tank filled with LH2
- 20 press./de-press. cycles between 20 psi & 100 psi conducted
- Permeation measurements conducted at multiple test conditions:

Results Previously Presented NSMMS 2014
• **AE Sensors:**
  
  – Thirty-two (32) acoustic emission sensors uniformly spaced around the circumference of the tank barrel and on both domes
  
  – Identified on Boeing SHM Instrumentation drawing, ZE154071
  
  – Tank barrel – four sensors evenly spaced (at 90 degrees) in forward section of tank; four evenly spaced sensors in aft section of tank offset by 45 degrees from forward sensors
5.5m Structural Test Arrangement

Composite Cryotank

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- Existing STE Modifications
- New STE Design
- Boeing Provided
- CCTD Test Hardware

14 Axial & 2 Shear Load Lines

- Upper Spider
- Pedestal
- Access Platform
- Boeing Load Ring
- Shear Beam
- CCTD Test Article
- Boeing Load Struts
- Lower Spider
- Shear Towers
## 5.5m Test Summary

<table>
<thead>
<tr>
<th>Testing Summary</th>
<th>Date</th>
<th>Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient pressure test (nitrogen) was successfully conducted</td>
<td>5/22/2014</td>
<td>Ambient (Nitrogen)</td>
<td>Achieved target pressure and reached 80% of target strain</td>
</tr>
<tr>
<td>Liquid hydrogen cryogenic pressure test was successfully conducted</td>
<td>7/20/2014</td>
<td>Cryogenic (Liquid Hydrogen)</td>
<td>Achieved pressure and 100% of strain in the forward dome acreage. (Permeation samples taken)</td>
</tr>
<tr>
<td>Combined ambient pressure (nitrogen) and load test was successfully conducted</td>
<td>7/30/2014</td>
<td>Ambient (Nitrogen)</td>
<td>Achieved 100% desired pressure with 100% load on the tank</td>
</tr>
<tr>
<td>Liquid hydrogen combined cryogenic pressure and load test was performed</td>
<td>8/16/2014</td>
<td>Cryogenic (Liquid Hydrogen)</td>
<td>The test was prematurely stopped at 20% mechanical loads due to mechanical issues with applying the loads in the test facility (Permeation samples taken)</td>
</tr>
<tr>
<td>Liquid hydrogen cryogenic pressure cycle test was successfully conducted</td>
<td>8/17/2014</td>
<td>Cryogenic (Liquid Hydrogen)</td>
<td>Achieved our goal of 80 pressure cycles (20% to 90% max pressure) on the tank. (Permeation samples taken)</td>
</tr>
<tr>
<td>Permeation with gaseous hydrogen test was conducted</td>
<td>8/22/2014</td>
<td>Ambient (Gaseous Hydrogen)</td>
<td>Achieved desired pressure. Issues with a leak in facility piping and a leak in the bag prevented any useful permeation data.</td>
</tr>
<tr>
<td>Permeation with gaseous hydrogen test was conducted</td>
<td>8/28/2014</td>
<td>Ambient (Gaseous Hydrogen)</td>
<td>Achieved desired pressure. Obtained permeation data.</td>
</tr>
</tbody>
</table>
## Critical Safety Factors

### Composite Cryotank

<table>
<thead>
<tr>
<th>Location</th>
<th>Demonstrated 100% target Pressure</th>
<th>Demonstrated Pressure + 100% Flight Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fwd Scarf</td>
<td>2.06</td>
<td>2.16</td>
</tr>
<tr>
<td>Aft Scarf</td>
<td>2.79</td>
<td>2.76</td>
</tr>
<tr>
<td>Y-Joint</td>
<td>6.21</td>
<td>4.64</td>
</tr>
<tr>
<td>Acreage</td>
<td>90% max allowable</td>
<td>92% max allowable</td>
</tr>
<tr>
<td>Local Buckling (67% of max pressure)</td>
<td></td>
<td>3.70</td>
</tr>
</tbody>
</table>

### STMD Game Changing Program

- Most critical areas are dominated by pressure loads
- At ambient, Y-joint is dominated by combined load case
  - Increased shear across joint
## Composite Cryotank

### Critical Safety Factors

<table>
<thead>
<tr>
<th>Location</th>
<th>Cryo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td><strong>Demonstrated</strong> LH2 Pressure 100% achieved</td>
</tr>
<tr>
<td></td>
<td><strong>Predicted / Not Tested</strong> LH2 Pressure + 20% Flight Loads*</td>
</tr>
<tr>
<td>Fwd Scarf</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>1.68</td>
</tr>
<tr>
<td>Aft Scarf</td>
<td>2.16</td>
</tr>
<tr>
<td></td>
<td>2.34</td>
</tr>
<tr>
<td>Y-Joint</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>0.52</td>
</tr>
<tr>
<td>Acreage</td>
<td>102% max allowable</td>
</tr>
<tr>
<td></td>
<td>94% max allowable</td>
</tr>
<tr>
<td>Local Buckling (67% of max pressure)</td>
<td>4.42</td>
</tr>
</tbody>
</table>

- Pressure test limited by acreage strain design limit.
- Not all Joint S.F. are above 2.0
- Buckling is above 1.5 requirement
- Y-joint strength is dominated by thermal load, not pressure or flight loads.
- **By analysis, the addition of Flight Loads do not significantly impact critical safety factors**

* Achieved 20% due to facility issues
**Major Accomplishments**

**Largest Successfully Ground Tested Composite Cryotank**

Ground Test Program
1. Ambient Pressure
2. Cryogenic Pressure
3. Ambient Pressure & Mechanical
4. Cryogenic Cyclic Pressure

Ground Test Summary
- 83 pressure cycles
- 2 thermal cycles
- 2 max pressure cases
- 1 combined load cycle

Data Acquired
- Load/strain response
- Thermal response
- Laminate permeation rate
- Bolted joint performance

Marshal Space Flight Center
### Projected Composite Cryotank Benefits

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Composite</th>
<th>Weight Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10 meter</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2011, Phase 1)</td>
<td>NASA Al-Li 11,000lbs</td>
<td>6,700lbs</td>
<td>39% (4,200lbs)</td>
</tr>
<tr>
<td><strong>10 meter</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2014, Phase 2)</td>
<td>NASA Al-Li 11,000lbs</td>
<td>7,319 lbs + 619lbs for acreage &amp; fwd joint</td>
<td>33% (3,681lbs)</td>
</tr>
<tr>
<td><strong>5 meter</strong></td>
<td>Delta IV Al – 2219</td>
<td>CCTD Phase 2 Test Article</td>
<td>33%</td>
</tr>
</tbody>
</table>
Prior Barriers
.... to Application of Large-Scale Composite LH2 Tanks

- **Manufacturability** – Scalable automated fiber placement & tooling.
- **Strain Limits** – Capable of 5,000µe.
- **Y-Joint Strength** – Achieved 58psi at LH2 temp, despite low margins.
- **Bolted Joint Seals** – Demonstrated composite joint w/ furon omniseal.
- **Hydrogen Permeability**
  - Out-of-Autoclave – Thin plies significantly reduced permeation.
  - Autoclave – Hybrid laminate coupon did not permeate.
Successful culmination of a three-year effort to design and build a large high-performance tank with new materials and new processes and to test it under extreme conditions.

Credit the NASA's Space Technology Mission Directorate, and Game Changing Development Program with goals for innovating, developing, testing and flying hardware for use in NASA's future missions.

This is a significant technology achievement for NASA, Boeing and industry. “We are looking at composite fuel tanks for many aerospace applications.”