Composites Australia Conference
Composite Cryotank Project
Structures for Launch Vehicles

John Vickers
NASA Marshall Space Flight Center
March 5, 2013
The National Aeronautics and Space Administration

**NASA Game Changing Development Program**

Human Exploration and Operations

Science

**Composite Cryotank Project**

Space Technology

Aeronautics Research

*Marshall supports three of the NASA Mission Areas*
Space Technology Mission Directorate Approach

**Enabling Our Future in Space:** By investing in high-payoff, disruptive technologies that industry cannot tackle today, Space Technology matures the technology required for NASA’s future missions in science and exploration while proving the capabilities and lowering the cost for other government agencies and commercial space activities.

**NASA at the Cutting Edge:** Pushing the boundaries of aerospace technology and seizing opportunities, Space Technology allows NASA and our nation to remain at the cutting edge.
The Game Changing Program

The Game Changing Mission

To focus on transformative space technologies that will lead to advances in space and terrestrial capabilities, serve as a stimulus to the US economy while providing inspiration and opportunity to our nation’s youth

Goals

• Develop Game Changing technologies that produce dramatic impacts for NASA’s Space Exploration and Science Missions

• Capitalize on opportunities to leverage funding and cost-share from external organizations in technology area mutually benefiting NASA and the other organizations

• Formulate and implement technology projects that deliver the required performance to stakeholders on schedule and within cost

• Deliver technology knowledge that is used internally for NASA missions as well as externally throughout the aerospace community
Composites Manufacturing Supports Agency and National Needs

NASA Game Changing Development Program

Composite Cryotank Project

- Supports all Mission Directorates: Aeronautics Research, Science, Human Exploration and Operations, Space Technology
- Supports Advanced Manufacturing National Initiative, and National Network for Manufacturing Innovation
- Other Government Agencies: DOD, DARPA, DOE
- Identified in NASA’s Space Technology roadmap TA12 (light weight materials and structures among the highest priorities identified by NRC)
- Spans multiple Centers and disciplines
- Industry and Research community

Materials used in 787 body
- Fiberglass
- Aluminium
- Carbon laminate composite
- Carbon sandwich composite
- Aluminium/steel/titanium

Total materials used by weight
- Composites: 50%
- Other: 5%
- Aluminium: 15%
- Steel: 10%
- Titanium: 15%

By comparison, the 777 uses 12 percent composites and 50 percent aluminium.
NASA Game Changing Development Program

Full Integrated Research Across TRL Spectrum

NASA Composite Cryotank Project

TRL 1-3

Develop New Resins and Fibers
Pre-Pregging of Composite Tows

TRL 4-6

Develop Advanced Manufacturing and NDE Processes

TRL 7+

Test and Analyses of Composite Structures
Post-Cure, In-Situ NDE of Composite Structures

Design and Manufacture of Composite Structures

Manufacture of Flight Vehicle Structures

Fully Integrated Research Across TRL Spectrum

Spectrum

Spectrum

Spectrum

Spectrum

Spectrum
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, Manufacturing, and Structures; Autoclave and/or Out-of-Autoclave

Approach: Focus on achieving affordability, technical performance, through agreement between experiment and analysis

Goal: Produce a major advancement in a demonstrated readiness; successfully test 5-meter diameter composite hydrogen fuel tank, achieve 30% weight savings and 25% cost savings compared to state-of-the-art

John Vickers Level III, PM
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March, 2013
• NASA and industry continuously strive to reduce the weight and cost of the launch vehicles
  • Ares Upper Stage incorporated an extremely difficult common bulkhead configuration to save weight, approx. 1400 lbs (#1 project risk)
  • Shuttle External Tank - Standard weight tank 77,000 lb, light weight tank 66,000 lb, super light weight tank 58,500 lb

• "Of all the technologies that may reduce the mass fraction composite materials for the primary structures and for the liquid hydrogen tanks is projected to have the greatest potential" (Harris, Starnes, and Shuart, Journal of Aircraft, July-August 2002.)

• Tank Materials - Composites offer the potential for the greatest mass reduction of all of the materials (Committee on Materials Needs and R&D Strategy for Future Military Aerospace Propulsion Systems; National Research Council, May 2011)

• HEFT Affordability – Develop architecture scenario options that have potential to increase affordability & HLV current designs may not be affordable, based on existing cost models, historical data, and traditional acquisition approaches

• Projected budgets for the U.S. Air Force’s Evolved Expendable Launch Vehicle (EELV) program will rise by more than 50 percent over the next few years as the cost of materials has increased sharply. (Space News, Fri, 14 January, 2011)

• Headline New Delhi “Boeing has offered to partner with India on manned space missions, including on the very significant "composite cryogenic tanks" for launch and propulsion control." (India Strategic, February 2011)
Why Composite Cryotanks

NASA chief technologist Robert Braun: “We intend to take considerable risks” to innovate

Dr. Pete Rustan, retired Deputy, NRO,: “U.S. technological leadership was not achieved by people who were afraid of failure.”

DARPA chief Regina Dugan: “Failure is okay for us”

Gene Austin, X-33 program manager, "X-vehicle programs are about taking risks and pushing the envelope. That is how we break through barriers that previously held us back. While composite technologies are a promising part of future space transportation, they require further research. “

Final Report of the X-33 Liquid Hydrogen Tank Test Investigation Team (May 2000)

- The tank design is highly innovative, pushing the limits of technology and combining many unproven technology elements. The interaction and integration of these elements created a highly complex system...
- The most probable cause of the failure was determined to be a combination of the following phenomena:
  - Microcracking of the inner facesheet with gaseous hydrogen (GH2) infiltration
  - Cryopumping of the exterior nitrogen (N2) purge gas
  - Reduced bondline strength and toughness
  - Manufacturing flaws and defects
  - Infiltration of GH2 into the core, which produced higher than expected core pressures
The Problem

- Agency’s need for an affordable lightweight heavy lift vehicle - Greater payload capability is required to enable future exploration missions
- No composites experience at this scale
- Cryo – LH₂ presents severe environment
- OoA technologies are untested
- Many materials, design and manufacturing challenges
Approximately 60% of the dry mass of a launch vehicle is the fuel and oxidizer tanks. A composite material can produce a cryotank structure that weighs 30% less than aluminum.
Composite Cryotank Concept

**NASA Game Changing Development Program**

- **Utilize 10 meter diameter reference design**
- **Build 5 meter diameter demonstrator**
- **Out-of-Autoclave**

**Enabling Technology Needs**

- Concept Trade Studies
- Technology trade studies
- Structural Design
- Materials
- Manufacturing
- Long duration permeability demos
- Composite resins/chemistry
- Joints
- Damage tolerance
- Test Capability

**Mission**

- Mars
- Near Earth
- Lunar

**Capability Needs**

- Heavy Lift Vehicle
- Fuel Depot
- Departure/Service Stages
- Habitats
- Composite Cryotank

**Operational System**

**Flight Demonstration**

**Subsystem / Component Demonstration**

**Technology Maturation**

**Out of Autoclave**

- **Operational System**
- **Flight Demonstration**
- **Subsystem / Component Demonstration**
- **Technology Maturation**
Composite Cryotank Concept

NASA Game Changing Development Program

- Development demonstration activity: Design, Build, Test (accelerated building block), 5 meter diameter test articles in a relevant environment (autoclave and/or OOA)

- Tackle Critical Technologies
  - Materials -- out of autoclave (mechanical properties/porosity/out time - e.g. 25% improvement), processing, microcracking density/permeability level (quantitative measurement of permeation at defined temperatures and strain levels)
  - Structures -- conservative design/analysis/allowables criteria (geometries, loads/environments, factors of safety/knockdowns) philosophy of incorporating 10M tank features (thickness/pressure), accelerated building block approach
  - Manufacturing -- large scale, automated systems, design for manufacturing/affordability (facilities, equipment, lay down rates, producibility/tooling issues)
  - Test -- full scale element test articles, precursor/subscale ~ 2 meter test, structural/cryo test of 5 meter diameter cryotank (key performance parameters)

- Multiple competing approaches, requirements, conceptual designs, modeling, cost, risk, TRL/MRL analysis, R&D equivalency testing (permeability, OOA materials)

- Increase the composite tank value enough to trigger a switch from existing solutions (Innovation!)
Why Now

• Critical technologies are converging
  • Advances in out-of-autoclave processing
    • Key technology developments in resin formulation, DoD investment in OOA ~$20 million
  • Materials and manufacturing technologies enable reduced manufacturing costs as well as diameters in excess current autoclave dimensions -- Airbus SAMPE 2011 “The Challenges for the future are Cost and Rate!”
• Substantial growth in aerospace composites markets projected in next decade
• Structures discipline is actively leveraging the explosion in computational capabilities and advances in simulation, -- to rethink/revise standard practices, – to rethink/revise testing requirements… NESC
• The Mission -- aligned with SLS, HEFT, HAT, and NASA Space Technology Roadmaps
  • Push technology for future architectures time is now
  • Affordability is top figure of merit - Innovative new processes, techniques, or best practices to improve the safety, cost, schedule, or performance
  • Required - Lightweight Structures and Materials (HLLV), Lightweight Structures and Materials (In-Space Elements)
• Phase I Project significant milestone – 10-meter diameter Composite Cryotank final design reviews with Lockheed Martin, Boeing and Northrop Grumman

• Background: NASA provided a reference design for an aluminum-lithium cryotank design that was a point of departure for developing a 10-meter diameter composite cryotank design

• Targets for weight and cost savings were 25-30% and 20-25%, respectively.

• Summary & Conclusions:

  • Drastic weight savings were consistently predicted over the Al-Li baseline, 43% to 47%! (~12,000 lbs vs 7000 lbs)
  
  • Moderately good life-cycle cost reduction predictions ranged from 15% to more than 30%

  • Evidence was presented that permeation rates due to microcracking can be controlled or eliminated with thin ply composite material
## Projected Composite Cryotank Benefits

<table>
<thead>
<tr>
<th>Year</th>
<th>Launch Vehicle</th>
<th>Upper Stage</th>
<th>Common Booster Core</th>
<th>Weight Savings</th>
<th>Dollar Value of Weight Savings PER LAUNCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>DC-XA</td>
<td>(both tanks)</td>
<td></td>
<td>33%</td>
<td>N/A (experimental vehicle)</td>
</tr>
<tr>
<td>2004</td>
<td>Delta IV</td>
<td>Upper Stage (both tanks)</td>
<td>43% &amp; 26%</td>
<td>$4.3M - $9.3M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 meter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Al-Li</td>
<td>Upper stage LH₂ tank only</td>
<td>39%</td>
<td>$17M - $37M</td>
<td></td>
</tr>
</tbody>
</table>

**Aluminum (unless otherwise specified)**

- Estimated unit production cost savings: $7M
Aviation Week & Space Technology
By Frank Morring Jr.
(Sep 21, 2011) “Boeing Will Test Composite Cryotanks For NASA”
(October 7, 2011) “Jumping-Off Point - New Space Economy”
(November 12, 2011) “Technology Readiness”

“CCTD in the News”

NASA Game Changing Development Program

NASA eyes a lighter heavy-lift
By Leo Roop
America’s next deep-space rocket may carry its fuel in lightweight tanks light enough to save millions in costs and make room for thousands of pounds of extra fuel and supplies.

NASA announced Tuesday that Huntsville’s Marshall Space Flight Center will lead a new project to develop fuel tanks made of composites for future spacecraft. It’s an effort to modify the greatest source of weight on a spacecraft, to 60 or 70 percent of the total craft’s mass, into something lighter.

Boeing will build two demonstration tanks in Seattle for testing at Marshall, NASA said. For Boeing, the contract is worth $24 million.

“NASA and industry are constantly striving to reduce the weight and cost of launch vehicles,” Marshall’s John Vickers told a Tuesday teleconference. Vickers is project manager of what is formally called the Composite Cryogenic Tank Development Design at Marshall.

The goal of the test, Vickers said, is to save 20 percent cost.

The Glenn Research Center in Ohio will lead the materials work, and the Langley Research Center in Virginia will lead design and structure research.

NASA Game Changing Development Program

Composite Cryotank Project

Boeing Selected by NASA for Composite Cryogenic Propellant Tank Tests

The Engineer
www.theengineer.co.uk

Boeing set to develop new technologies for NASA
NASA Game Changing Development Program

Composite Cryotank Project

NASA & Industry Team

Partnerships: Government Agencies, industry, academia, international

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

Composites for Exploration (CExX)
M. Shuart
ESMD/LaRC

1.0 Project Management
MSFC
J. Sutter / GRC

2.0 Materials
J. Jackson / MSFC

3.0 Manufacturing
T. Johnson / LaRC

4.0 Structural Analysis
M. White / MSFC

5.0 Testing & Evaluation

Phase I Contracts
"Industry"

Phase II Contract

Janicki Industries
Tooling Packages

Boeing, Seattle
Manufacturing

Boeing, Seal Beach
PM & Design

Boeing, Huntington Beach
Coupon & Joint Tests

Cytec Industries
OoA Material (5320-1/IM7)

NASA JSC
Transportation

Southern Research Institute
Permeation Coupon Testing

NASA GRC

NASA LaRC

NASA MSFC

NASA KSC

Boeing, Huntsville
Integrated Testing
Al-Li Tank Design Overview

Orthogrid Stiffened 33 Foot tank Design

• 33 Foot Inner Diameter
• .707 Elliptical dome
• Tank Volume = 38.7 E 6 in ^3
• Weight ≈10,925 lbs
• Length ≈ 413 in
• Design is based on TRL 9+ materials and manufacturing techniques.
CCTD Tank Designs

Phase I Ten Meter Diameter Reference Tank

Phase II 5.5 Meter Diameter Test Tank

Phase II 2.4 Meter Diameter Precursor Tank
“10-Meter” Composite Cryotank

**Design Information:**

- Diameter: 33 ft (~10 m)
- Height: 34.8 ft (10.6 m)
- Volume: 22,396 ft³ (634 m³)
  ➔ 167,533 Gallons
- Operating Pressure: 42 psi (290 kPa)
- Empty Weight: 6,696 lbs (3,037 kg)
- LH2 Weight @ .00256 lb/in³: 99,072 lbs (44,938 kg)
- Full Tank Weight: 105,768 lbs (47,976 kg)

("Anthroman" is 5' 8.5" tall)
**Building Block Approach**

1. **Coupon Tests: B-Basis Level of Data**
   - Flat Coupon Testing: OHC, CAI, Sandwich Flexure, Repairs, etc...

2. **Development Tests**
   - Life-cycle tests with damage

3. **Full-Scale Qualification Test**

4. **Proof Test**
   - Flight Units
   - Proof tests to demonstrate no growth of damage accepted pre-proof and no initiation of damage during proof

5. **Building Block Tests**
   - For Damage Tolerance Verification

**Substantial materials database already exists for candidate materials**

**NASA design and certification standards are not an impediment, but they must be applied differently for composite structures:**

- More emphasis on allowables at structural scales rather than material scales.
- Collaborative approach to tailoring with U.S. industry to leverage the experience already applied to commercial aircraft, military aircraft, and EELV.
Building Block Program supports 5.5m

2.4 meter Precursor Tank

Available to Support 5.5m Tank

5.5 meter Tank

Manufacturing Demonstration Units

2.4 meter Precursor Tank

Joint Testing

Coupon Testing

Coupon, Joint, and MDUs are Complete
Baseline Master Schedule - Overview

Saves 13 months Compared to More Typical Serial Development

NASA Game Changing Development Program
Composite Cryotank Project

Preliminary Design & Tool Fab
Material Procurement, Coupon & Joint Tests
Detailed Design
Tank Shell Fabrication
Test

Precursor Design & Fab

Pressure Test Complete

PDR
CDR/MRR

2011 2012 2013 2014
S  O  N  D  J  F  M  A  M  J  J  A  S  O  N  D  J  F  M  A

2011 2012 2013 2014
S  O  N  D  J  F  M  A  M  J  J  A  S  O  N  D  J  F  M  A

Saves 13 months Compared to More Typical Serial Development
Technologies Matured by CCTD

NASA Game Changing Development Program

Composite Cryotank Project

Large Scale, OoA (5320-1/IM7) Design & Manufacturing

Lightweight, All-Composite Tank Shell

Cryogenic Composite Joint

Vetable & Purgeable Sandwich Structures

Automated Fiber Placed, including Thin-Tape

Structural Health Monitoring to support Damage Tolerance

Thin-plies for Permeation Barrier

Matured & Demonstrated in Building Block Program
Structural Arrangement Overview

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

Major Joints:
- Bolted Door
- Fwd Scarf
- Y-Joint
- Aft Scarf
- Bolted Sump
SHM Enables Higher Strength Allowable

Impact damage is both SHM and thermography detectable
Composites Damage Tolerance Approach

- **Assess possible accidental and fabrication induced damage threats**
  - For payload fairing blunt impact damage is the most likely type of accidental damage

- **Investigate effect of damage size with respect to structural scale**
  - Boundary conditions can affect the impact energy level necessary to produce a given size of damage.

- **Repair all detectable damage**

- **Demonstrate through element and sub-component testing that under simulated flight loads the structure is insensitive to undetectable size damage**
  - Ten meter diameter curved composite sandwich panels (3ft by 5ft) representing fairing acreage were impacted at 5.5 ft-lb to produce barely visible damage (golf ball size shallow indentation) and loaded to buckling at Room and Elevated Temperatures.

Test specimens were found to be insensitive to barely visible damage.
Fluted Core Composites

Thin laminate angled web members with structural radius fillers evenly spaced between laminate face sheets

Face sheets
- Material Form (Tape/Fabric)

Web
- Thickness
- Orientation
- Material Form (Tape/Fabric)
- Fiber Modulus

- 10’ H x 13.1’ D (4m)
- Delivered to NASA/LaRC COLTS
- Test planned for August

- Web Orientation Provides Efficient Compressive Load Capability
- Integral Web to Facesheet Construction Improves Damage Tolerance
2.4m Precursor Status / Accomplishments

Thin & Thick Ply AFP – July 17

OoA Cure – July 20

NDI
2.4m Precursor Status / Accomplishments

Sept 1, 2012  Initial Skirt Plies
2.4m Precursor Status / Accomplishments

Segmented Tool Extraction
2.4m Precursor Status / Accomplishments

At NASA/MSFC: http://www.nasa.gov/topics/technology/features/cryotank.html
2.4m Precursor Status / Accomplishments

NASA-MSFC West Test Area

Dec 12, 2012

Dec 18, 2012
2.4m Status Summary

Successful Design and Fabrication. Test Site Prep In Work.
2.4m Design, Fab, and Test Summary

Accomplishments
- 1st successful large AFP test article using 5320-1/IM7
- 1st successful 70gsm fiber placed cryotank (hybrid laminate)
- 1st successful spherical segmented tool use
- 1st successful all composite bolted sump/fwd cover joint

Next Steps
- Tank Leak Check
  Complete
- Test Site with Tank Leak Check
  Complete
- Facility Test Readiness Review
  2/19/13
- Ambient Proof Test (190psi)
  2/26/13
- Cryogenic Proof Test (190psi)
  3/5/13
- Test Report Delivered
  4/2/13
• Pressure wall mid-surface diameter = 216.54 in
• Pressure vessel cylinder height = 69.6 in
• Skirt end-to-end length = 131.88 in
• Dome to dome length = 229.70 in
• Volume = 3785 cu. ft.
• Two (2) 30-in dia access openings at fwd and aft dome
Test Site & Test Hardware Overview

Test Stand 4699, NASA MSFC
Test Site & Test Hardware Overview

Existing MSFC load spiders
CCTD load ring
Load adapter finger-ring
5.5 m CCTD tank
Load adapter finger-ring
Load struts
5.5m Cryotank Status / Accomplishments

5m Segmented Tool Mandrel Fabrication
5.5m Cryotank Status / Accomplishments

5m Spindle Fabrication
5.5m Cryotank Status / Accomplishments

NASA Game Changing Development Program

Composite Cryotank Project

5m Segmented Tool Assembly
5.5m Cryotank Status / Accomplishments

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Composite Cryotank Project
5.5m Robotic AFP Cell Install

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Composite Cryotank Project
5.5m Cryotank Status Overview

CDR Held. 5.5m Tank Shell Mandrel Arrived Jan 27th.
5.5m Design, Fab, and Test Next Steps

- Approval to proceed with Component Fab  
  Started

- Approval to proceed with Tank Shell Fab  
  Late March
  - At completion of Delta CDR/MRR

- 5m Pressure and Integrated Load Testing  
  1Q2014
Summary

- **Permeation**
  - Mechanism is understood
  - Solutions validated by coupon tests
  - System demo in relevant environment planned within CCTD

- **CCTD aims to mature & demonstrate several technologies**
  - 8.4m subscale designs (*increased stress at lower OoA allowables*)
  - Vetable and purgeable structures eliminates trapped gas risks
  - AFP of large structure using thin ply
  - Segmented breakdown tool use and extraction for lightweight design
Transition Potential

NASA Game Changing Development Program

- Communicate with stakeholders and customers
  - (Lockheed Martin, Boeing, Northrop Grumman, Space X, MSFC, LARC, NESC, JSC, KSC, and DOD)
- Synergy with HLV study concepts

Composite Cryotank Project

- Composite cryotank technologies for HLV (8.4m-10.0m) architectures + spin-off capabilities to meet multiple customer needs
  - NASA, DoD, and Commercial customers + in-space propulsion, propellant depot, and LOX or RP tank capabilities

- In-Space Cryogenic Propellant Depots and Landers are needed in New Exploration Architecture (The In-Space Cryogenic Propellant Storage and Transfer Demonstration Mission Concept Studies BAA)

- Multiple flight opportunity identified in phase I (benefits commercial flight)
Conclusions

The Composite Cryotank Technologies and Demonstration Project will make significant advancement to achieve 30% weight and 25% cost savings over SOA cryotanks at the 10-meter diameter scale.

- Critical Technologies
  - Materials
  - Structures
  - Manufacturing
  - Testing -- 5-meter diameter composite hydrogen tank

- Technology provides important benefits to NASA and Commercial needs plus diverse sectors of the economy/enhances global competitiveness -- Composites are important materials for the future of aerospace strategic leadership -- Leapfrogging the SOA puts NASA in a leadership position.

"The goal of this particular technology demonstration effort is to achieve a 30 percent weight savings and a 25 percent cost savings from traditional metallic tanks," said the Director of NASA's Space Technology Program, Michael Gazarik at NASA Headquarters in Washington. "Weight savings alone would allow us to increase our upmass capability, which is important when considering payload size and cost. This state-of-the-art technology has applications for multiple stakeholders in the rocket propulsion community."
Materials Modeling and Simulation

NASA Game Changing Development Program

Figure 3: Initiative overview