COMPOSITE TECHNOLOGY DEVELOPMENT, INC.

ENGINEERED MATERIAL SOLUTIONS

Optimizing the Cost and Performance of Composite Cylinders for H_2 Storage using a Graded Construction

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Project ID # ST110

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Project Start Date: Feb 2013
- Project End Date: Nov 2013 (end of Phase I – further funding TBD at a later date)
- Percent Complete: 30%

Barriers

- Type IV Pressure Vessel Cost
- Price and availability of low cost carbon fiber
- Composite properties of lower cost carbon fibers

Budget

- Total Project Funding: $ 155K
- Funding Received in FY12: $0
- Funding for FY13: $ 155K

Partners

- Oak Ridge National Laboratory
  - Low cost carbon fiber
- Luxfer Gas Cylinders
  - Cost analysis
  - High rate manufacturing

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Relevance

- Hydrogen fuel cell vehicles require on-board H_2 storage systems to support driving distance of >300 miles
  - 5 kg H_2 storage required
  - Requires 700 bar (10,000 psi) storage capability
  - Current Type III and Type IV COPV will not meet long term cost/performance targets*
    - Storage system cost significantly higher than 2017 targets
  - Carbon fiber identified as primary driver of storage system cost

Phase I Goal: Demonstrate technology to reduce cost of Type IV H_2 Storage vessel by 10% with the potential to reach Project Goal of 25%

* "Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications", September 2010, published on the DOE/FCT website: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressedtank_storage.pdf

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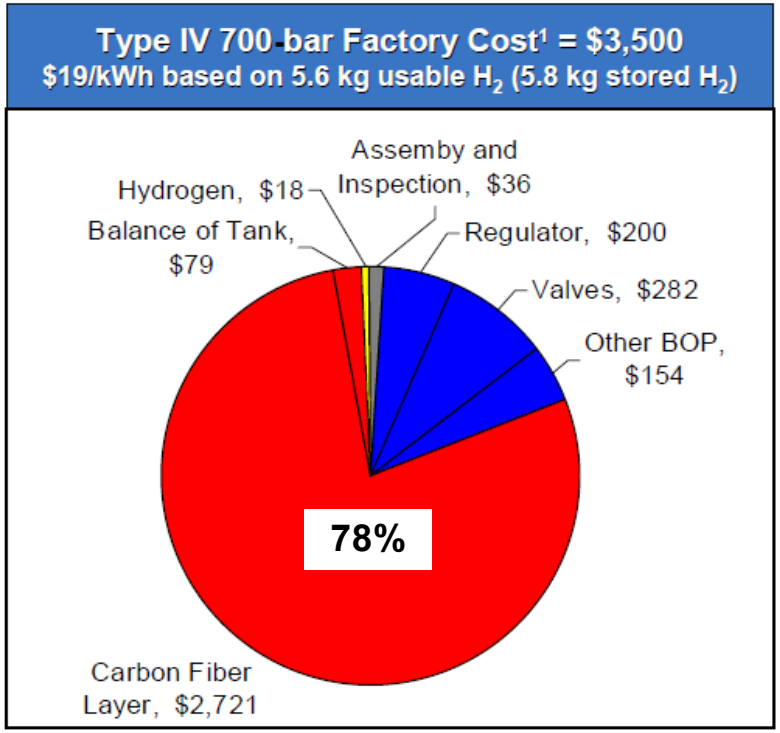
Relevance – Cost Breakout for Type IV H_2 Storage Systems



Graphic from "Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications", September 2010, published on the DOE/FCT website: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressedtank_storage.pdf

Reducing quantity and cost of carbon fiber represents the best opportunity to reduce Type IV tank cost while maintaining performance properties

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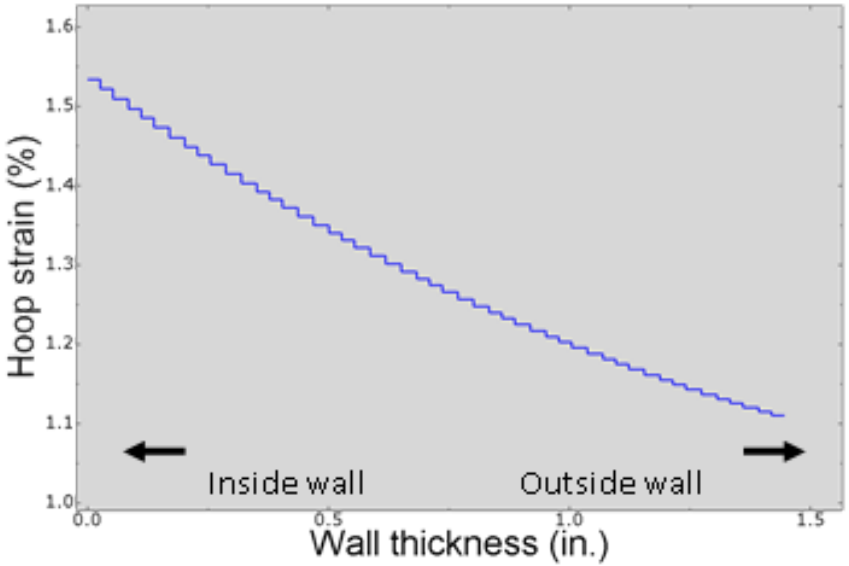
Approach – Pressure Vessel Mechanics

- **Efficient composite maximizes fiber strain**
- **700 Bar tank analyzed as thick walled shell**
  - **Thickness/radius > 0.1 invalidates uniform hoop stress distribution through wall**
  - **In thick shell there is a gradation of strain from inner to outer wall**
  - **The outer fibers are strained 20-30% less than the inner fibers at incipient burst failure**

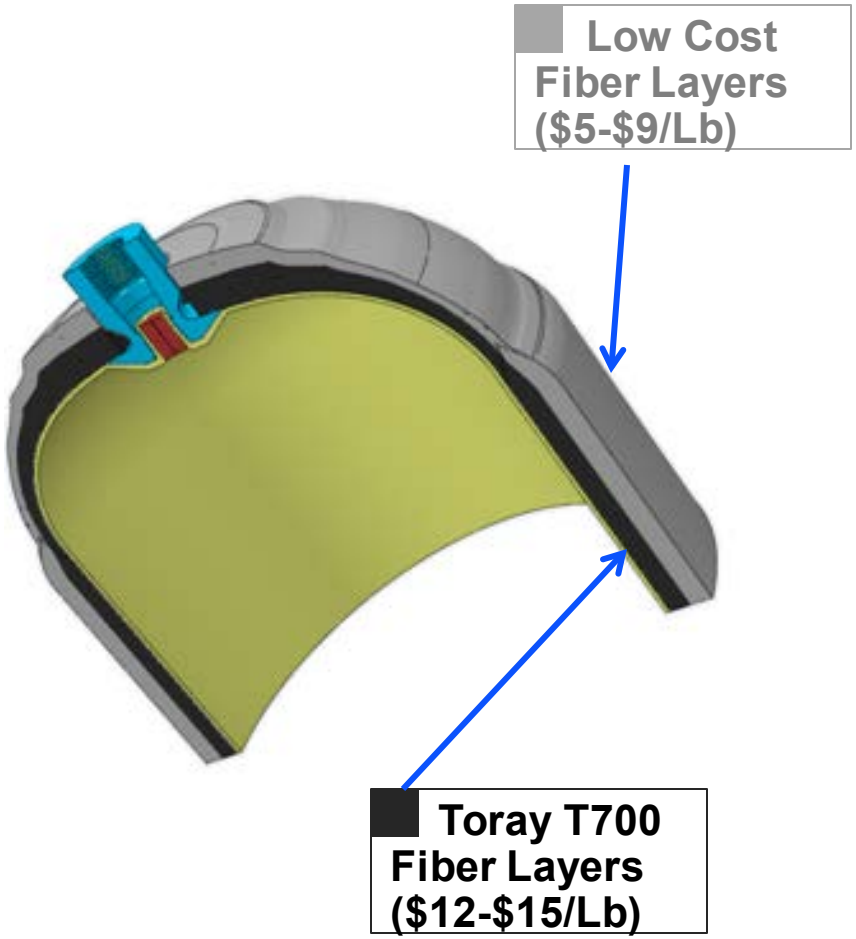


- **Thick composite performance also depends on**
  - **Damage due to microcracking and delamination during hydrostatic pressurization as well as fatigue cycling**
  - **Understanding and incorporation of progressive failure mechanisms is essential to optimize design**

CTD Approach – Graded Composite

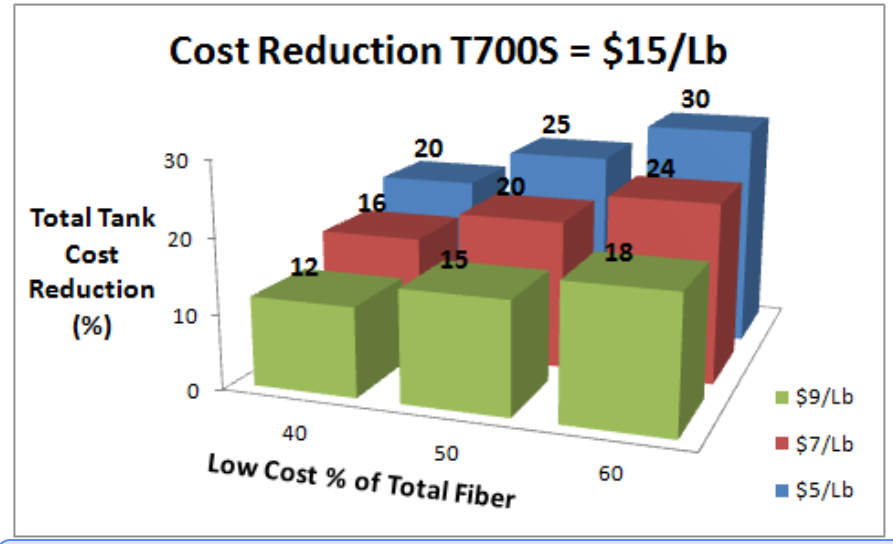
- **Carbon fiber is the highest cost component in 700 Bar composite tanks**
  - Reducing the cost or quantity of carbon fiber in a tank can yield the biggest savings
- **Lower cost carbon fibers tend to have lower strain capabilities than high priced fibers**
  - In thick walled shell – outer most fibers are stained to lower levels
  - By using a graded composite where high strain fibers are used in the inner portion and lower strain fibers on the outside can reduce tank cost

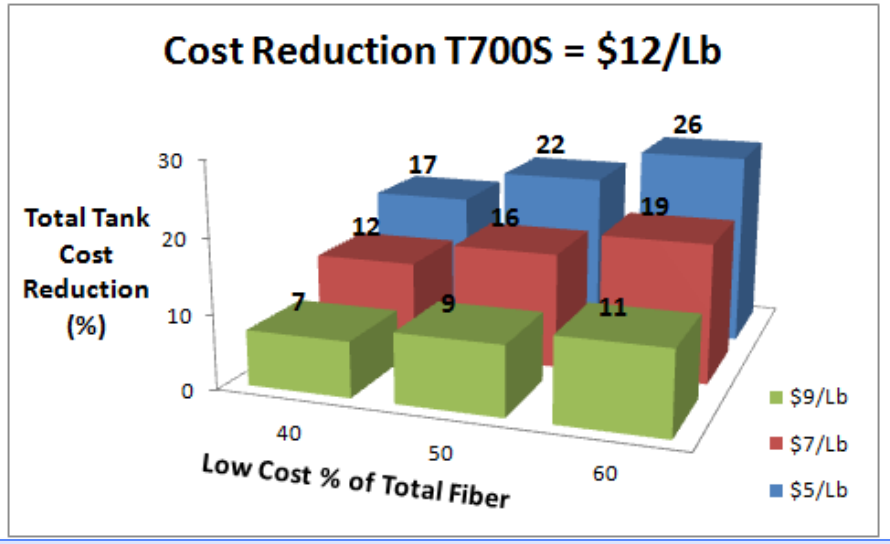
Graded Composite Structure



Approach – Preliminary Cost Analysis

- Cost reduction potential based on
  - T700S over cost range of $12-15/Lb
  - ORNL low cost carbon fiber range of $5-9/Lb
  - Percentage of low cost fibers used in tank wall between 40%-60%
  - Assumed zero mass change relative to current design





Lower Cost Fibers and Graded Composite Can Enable 25% Cost Reduction

Values Calculated using cost breakout from "Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications", September 2010, published on the DOE/FCT website: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressedtank_storage.pdf

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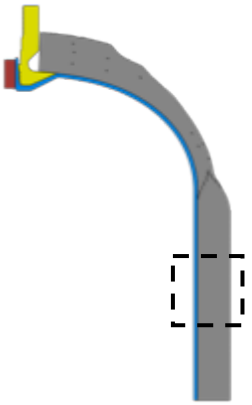
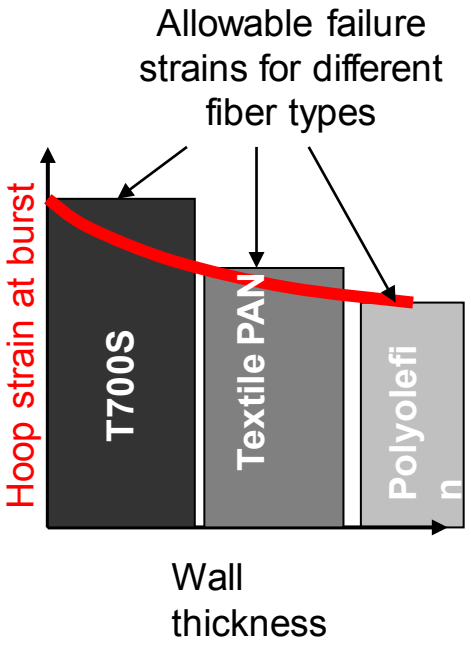
Approach – Project Goals

- ORNL's textile-PAN or polyolefin based fibers are still in an early stage
  - Material properties have only been explored at the fiber level
- Questions remain regarding possible composite properties
  - Fiber translation in epoxy matrix composites
  - Compatibility with the filament winding process
  - How composite design rules apply
- Develop fiber sizing and epoxy matrices to harness the maximum properties of the textile-PAN based carbon fibers
  - Prevent fiber damage during handling and filament winding
  - Damage can reduce burst, fatigue, and stress rupture performance
  - Promotes chemical compatibility and adhesion between the fiber and matrix





Provide highly efficient composite with excellent fiber translation at a minimal cost due to grading with low cost fibers through tank thickness

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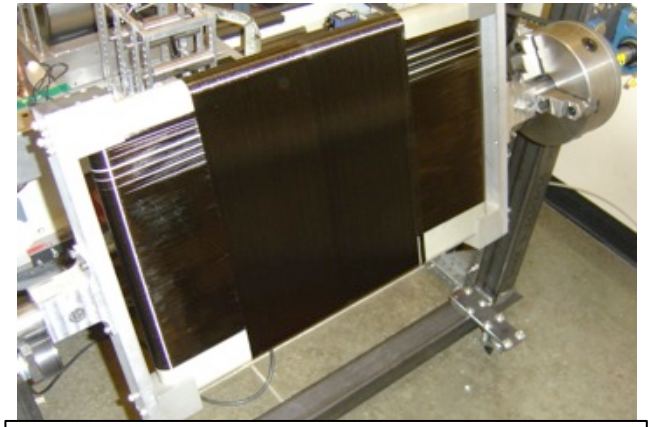
Approach – Composite Manufacturing and Test Coupons

- Processing of materials for program
  - Plate tumble winder
  - Wet winding
    - Unidirectional panels for coupon testing
  - Towpreg
    - Results in more efficient composite
      - Lower weight and less carbon
    - Minimizes fuzzing from low cost fibers
    - Fabricate unidirectional panels for coupon testing
- Coupon Testing
  - Tensile (ASTM D3039)
    - Data for design model
  - Short Beam Shear (ASTM D2344)
    - Some information regarding sizing effects
  - Data to verify/refine design models



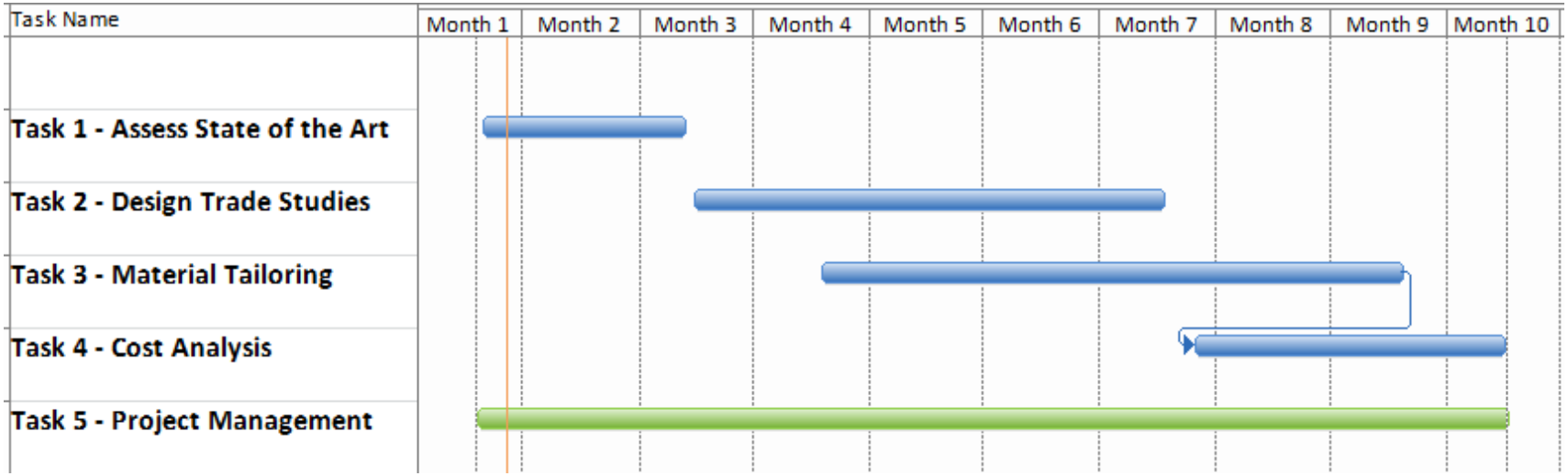
Uni and Cross Ply Panel Winding

Short Beam Shear Test

Approach – Baseline Materials

Material	Description	Comments
Toray T700	Commercial carbon fiber	• Currently used in Type IV tank construction • $15/lb
ORNL Low Cost Carbon Fiber	Non-commercial carbon fiber	• Alternate feedstocks for low cost carbon fiber production • Target price point $5-$9/lb
Zoltek Panex® 35	Commercial low cost carbon fiber	• Targeted for automotive applications • $10/lb
Standard Epoxy Sizing	Commercially available	• Primarily handling function • Some improvement in wetting/adhesion
CTD Sizing	Reactive sizing	• Improved interlaminar shear properties
Adherent Technologies AT-9307E finish	Reactive finish	• Dramatic improvements in composite strength and environmental durability
CTD-7.1	Toughened epoxy	• Wet winding • Used in KIBOKO® linerless composite tanks
CTD-9.1PX	Toughened epoxy	• Prepreg resins • Slit tapes used to construct LH2 demonstration tanks

Approach – Phase I Schedule



Accomplishments & Progress

- Preliminary parametric cost analysis performed
- Analysis models are prepared and ready for trade studies of graded construction tanks
- Fabrication of test coupons and testing has commenced
- In process of identifying and acquiring needed materials
  - Carbon fiber
    - Subcontract in place with ORNL for production of low cost carbon fiber
    - Toray T700S fiber with general purpose sizing available in house
    - Zoltek Panex® fiber as commercial low cost alternative – on order
  - Sizing selection underway
  - Selection of toughened epoxy matrix candidates underway
- Discussions with Luxfer regarding cost analysis and high-rate manufacturing

Collaborations

- **CTD: Design trade studies, material trials, product design, and commercialization**
  - **Dr. Andrea Haight – PI, Program Manager, Polymer Chemist**
    - **15 years experience in resin and sizing development at CTD and Adherent Technologies**
  - **Mr. Jacob Barker– Lead Engineer**
    - **Composite design, process development, and fabrication**
  - **Mr. Mark Haynes – Test Engineer**
    - **Leads all mechanical and tank testing at CTD**
  - **Mr. Mike Tupper**
    - **Composite design and product commercialization**
- **Oak Ridge National Laboratory (ORNL)**
  - **Provide non-commercial low-cost carbon fiber for evaluation**
- **Luxfer Gas Cylinders**
  - **Aid with cost analysis**
  - **Explore graded composites for commercial pressure vessels**
  - **Consider collaborating with CTD to develop low cost 700 Bar tank**

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Proposed Future Work – Phase II

- Demonstrate performance of a lower cost Type IV pressure vessel using graded composite construction
- Continue material development efforts
  - Further characterize and optimize graded composite construction
  - Fiber sizing and Matrix materials – increased focus on towpreg
  - Composite manufacturing
- Fabricate and test pressure vessels made with graded composite
  - CTD to manufacture and test 1.9 liter tanks
    - Large database of information and test data on 1.9 liter tank
  - Work with Luxfer to build and test Type IV tanks
    - Likely Luxfer will initially focus on 3600 psi (248 Bar) CNG tank
    - Strong interest in 700 Bar tanks for hydrogen storage
- Scale up production and secure supply chain
  - Toll manufacturers for sized fibers and matrix materials
  - Consider use of Zoltek fibers, should ORNL fibers not be market ready
  - Prepare marketing plan for tank design and material supply

Project Summary

Relevance	Decrease overall cost of on-board hydrogen storage for fuel cell powered vehicles
Approach	Type IV hydrogen storage tank based on graded composite structure incorporating low cost carbon fibers
Technical Accomplishments & Progress	Preliminary parametric cost analysis performed; analysis models prepared for design trade studies with graded composite construction; coupon fabrication and testing underway
Technology Transfer/ Collaborations	Active collaborations with Oak Ridge National Laboratory (low cost carbon fiber) and Luxfer Gas Cylinders (cost analysis, high rate manufacturing)
Proposed Future Research	Optimization of graded composite tank construction – focus on towpreg-based manufacturing; demonstrate a lower cost Type IV pressure vessel using graded composite construction; work with Luxfer to build and test Type IV tanks

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