Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks

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Pacific Northwest National Laboratory

May 16, 2012

Project ID # **ST101**

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Overview

Timeline

- Start date: April 2012
- End date: Jan 2015
- Percent complete: *New Start*

Budget

- Total project funding
  - DOE share: $2,100K
  - Contractor share: $525K
- Funding received in FY11: NA
- Funding for FY12: $600K pending receipt of funds

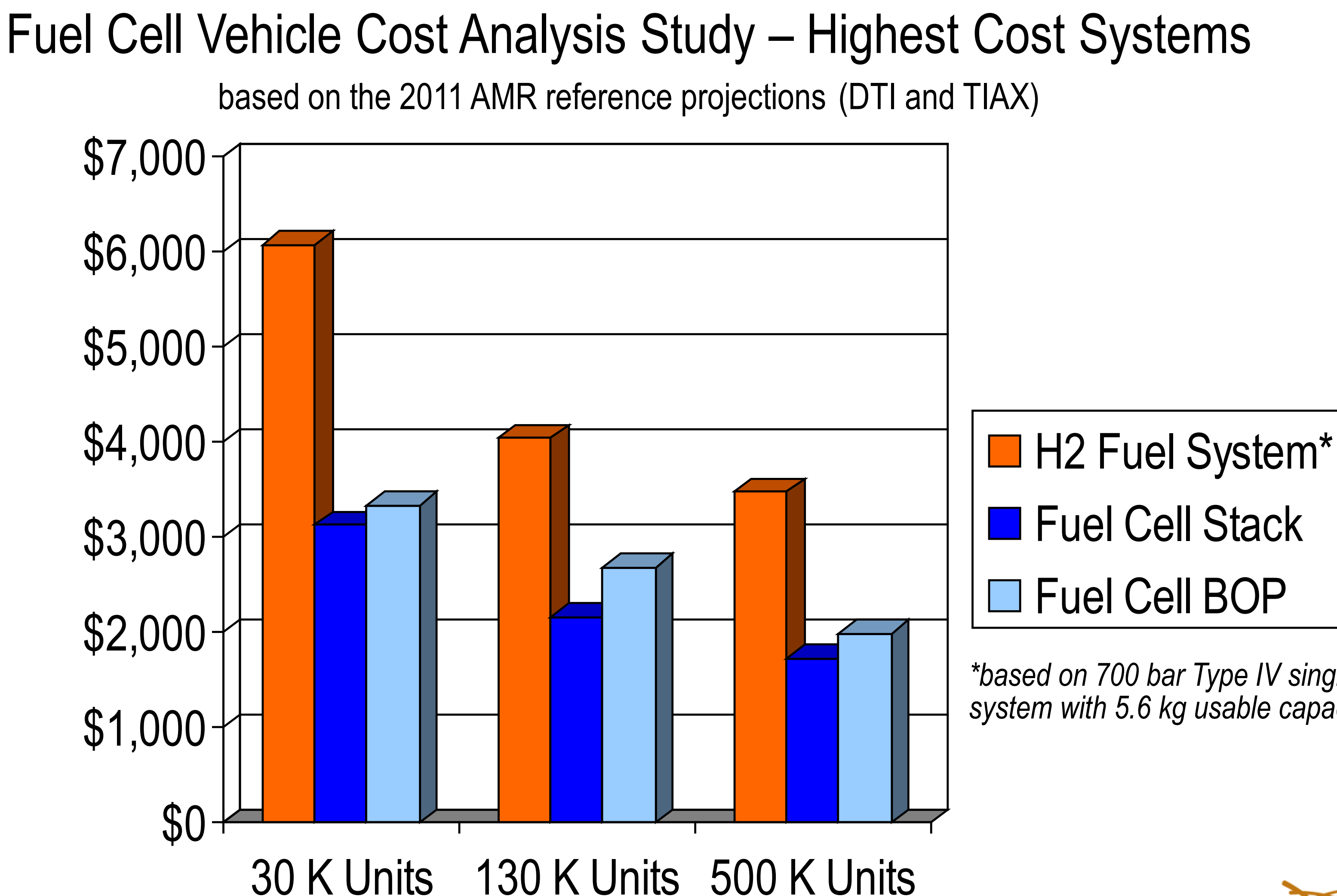
Barriers

- Barriers addressed
  - A. System Weight and Volume
  - B. System Cost
  - C. Materials of Construction
  - D. Improved material properties to reduce carbon fiber use

Partners

- Project Lead - PNNL
- Collaborating Team Members

Relevance

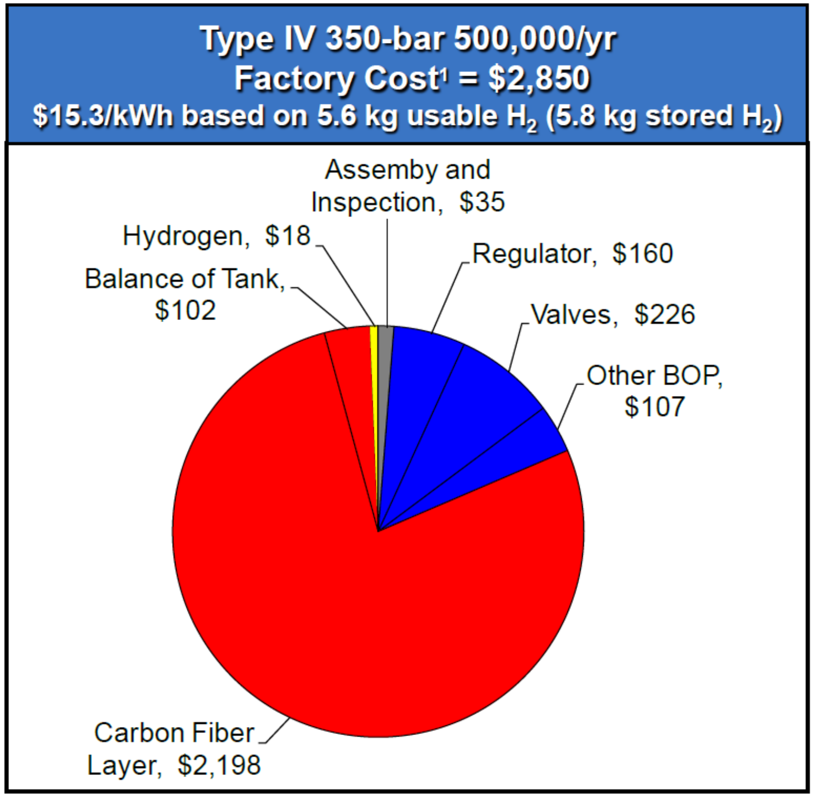


**based on 700 bar Type IV single tank system with 5.6 kg usable capacity*

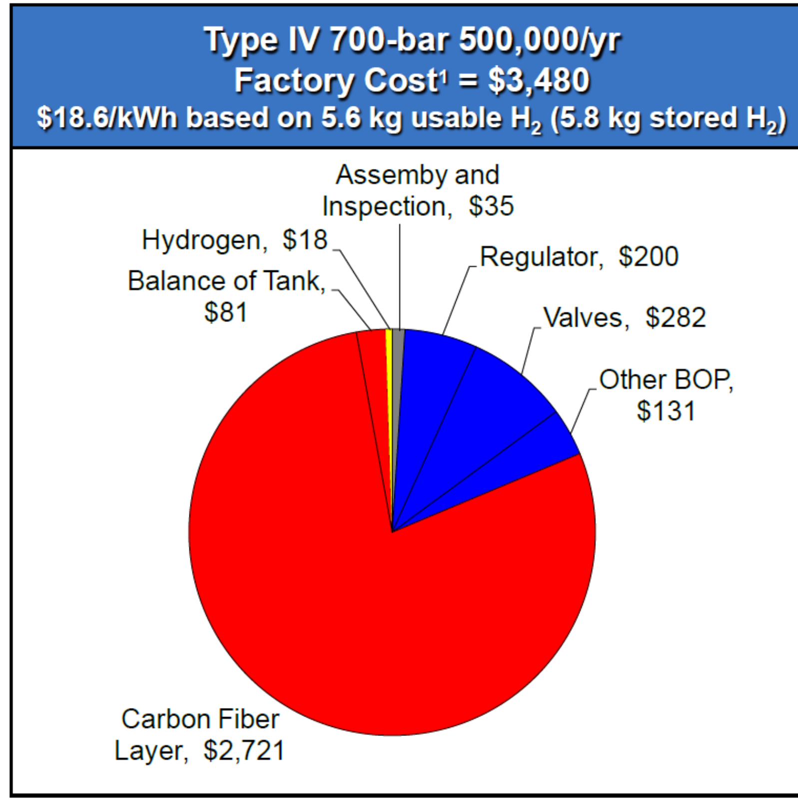
The hydrogen fuel system is one of the most expensive systems on a fuel cell vehicle.

Relevance

TIAX Cost Analysis Study – High Volume -based on the 2011 AMR reference projections



[1] Cost estimate in 2005 USD. Includes processing costs.

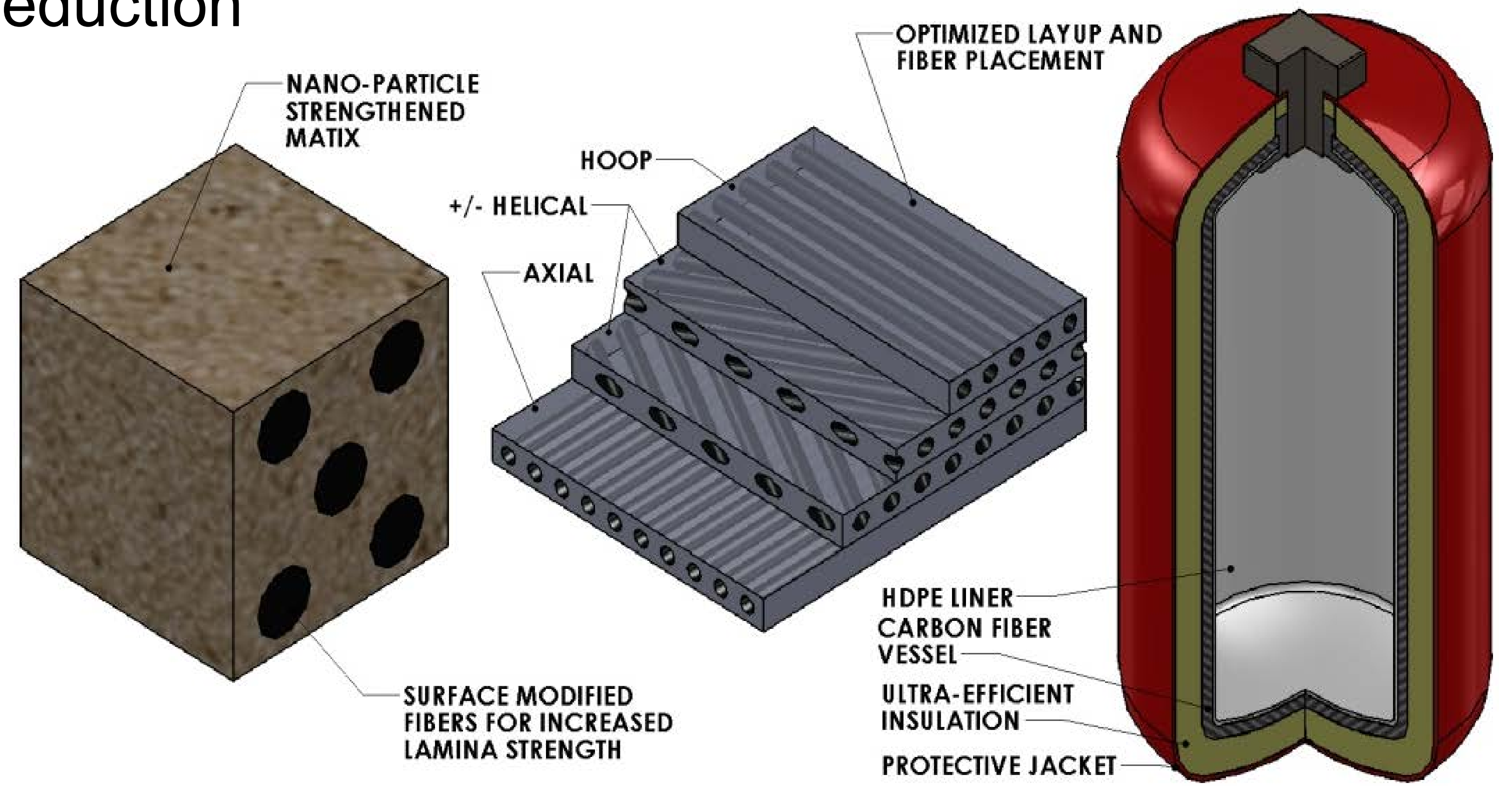


[1] Cost estimate in 2005 USD. Includes processing costs.

The carbon fiber layer (fiber and resin) is the dominant cost (~80%) of the hydrogen fuel system which is the focus of this project.

Project Approach

- Improvement of the individual constituents for synergistically enhanced tank performance and cost reduction

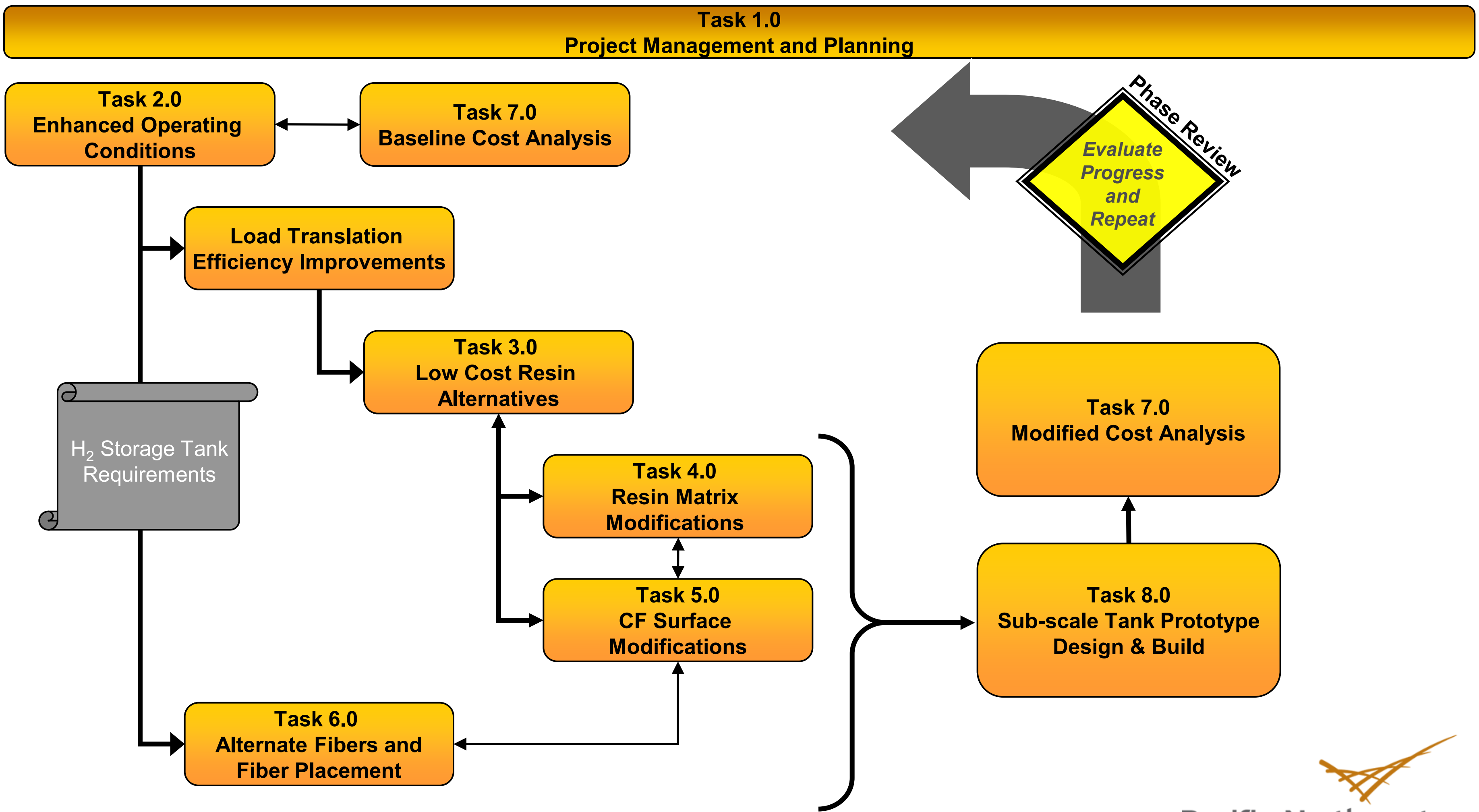


From engineered material properties to efficient use of carbon fiber

Proposed Tasks and Assignments

- Task 1.0 – Project management and planning (Lead Org. – PNNL)
- Task 2.0 – Enhanced operating conditions (Task Lead – Ford)
- Task 3.0 – Low cost resin alternatives (Task Lead – AOC)
- Task 4.0 – Resin matrix modifications (Task Lead – PNNL)
- Task 5.0 –CF Surface modifications (Task Lead – Toray)
- Task 6.0 – Alternative fibers & fiber placement (Task Lead – Lincoln)
- Task 7.0 – Cost analysis (Task Lead – PNNL)
- Task 8.0 – Sub-scale tank prototype (Task Lead – Lincoln)

Project Structure and Workflow



Flow chart to illustrate the inner relationship of each task

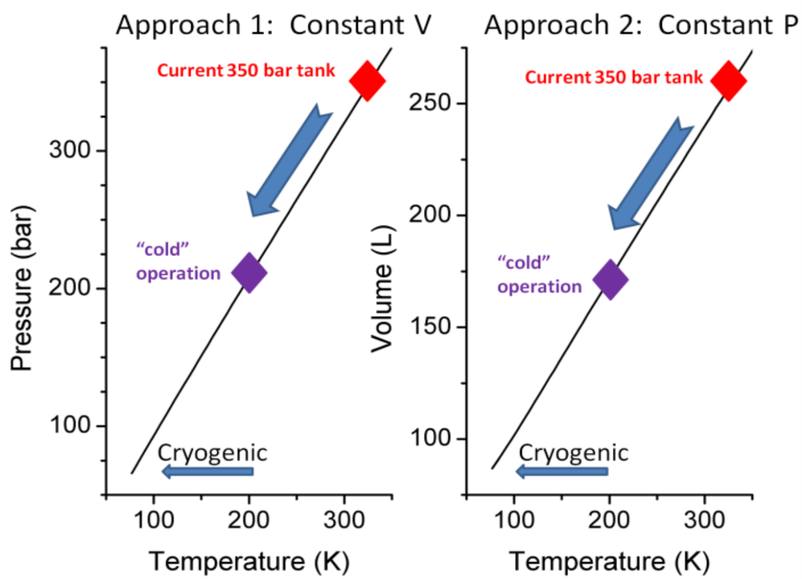
FY12 Milestones and Deliverables

Phase 1: Synergistic Development of CF-Reduction Approaches (Phase 1 – FY 2012)

	Milestones	Date
M1	Develop a baseline cost model for an on-board vehicle capacity tank with resin, fiber, liner, bosses, and processing and compare cost against prior DOE studies with TIAX and ANL	**6/30/2012**
M2	Design and model new tank design with enhanced operating parameters of pressure and temperature for an equivalent 200 liter tank with alternate fibers and/or new fiber placement technique and develop cost model for the new improved tank and compare against DOE target of 50% cost reduction	**9/30/2012**
D1.1	Semi-annual report on progress to date to DOE Program Manager	**4/30/2012**
D1.2	Annual report on yearly progress to DOE and other reports, workshops and reviews as set by the DOE Program Manager	**9/30/2012**
G1.1	**Report on feasibility of a 10% absolute cost reduction with a total end goal of 37% reduced tank costs as demonstrated by cost model and identified individual technical approach progress**	**3/31/2013**

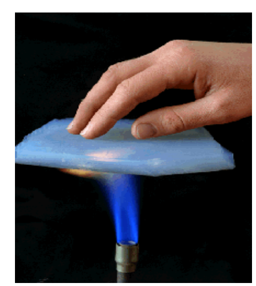
Enhanced Operating Conditions

- Approach is to assess the operating condition alternatives



	Current H_2 Tank	Enhanced H_2 Tank	Current H_2 Tank	Enhanced H_2 Tank
Operating Conditions	**350 bar at 15° C**	**350 bar at -73° C**	**700 bar at 15° C**	**700 bar at -73° C**
Density	**24 g/l**	**32 g/l**	**40 g/l**	**51 g/l**
Improvement	**35% density increase** (or 110 bar pressure reduction for Constant V)		**27% density increase** (or 225 bar pressure reduction for Constant V)	

- Key Phase 1 Activities:
  1. Confirm baseline attributes
  2. Conduct operational trade-off study
  3. Investigate insulation concepts
  4. Establish hydrogen tank requirements



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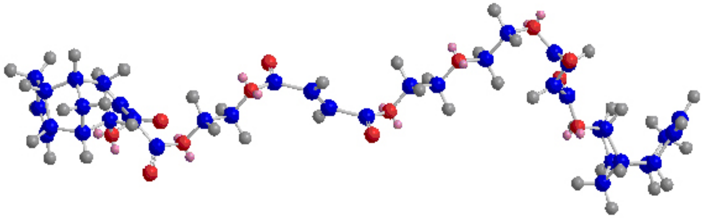
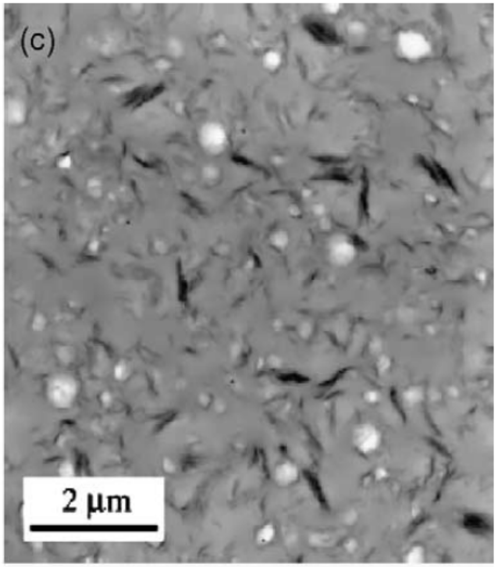
Low Cost Resin Alternatives

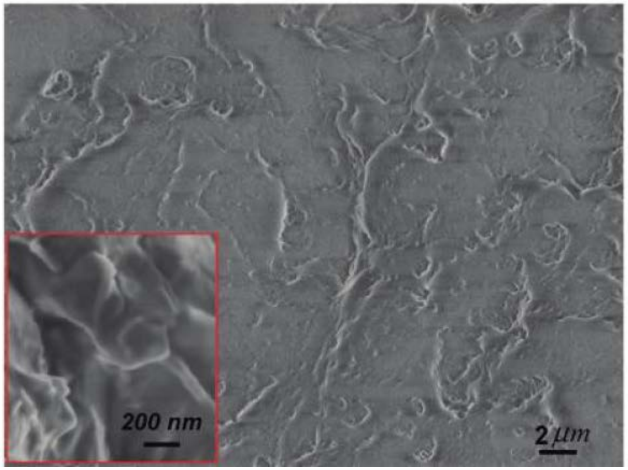
- We will develop and evaluate resin system(s) including, but not limited to, vinyl esters and polyesters that meet the requirements of this application (i.e. toughness, elongation, corrosion resistance)
- We will develop and evaluate an optimized carbon fiber sizing for adhesion with the chosen resin system(s) if necessary.
- Experience through involvement in DOE's "Development of surface treatment and sizing for the next generation low-cost carbon fibers and processes" R&D program.
- Experience through involvement in the development of filament wound gas transport modules in North America and propane storage tanks in Asia.



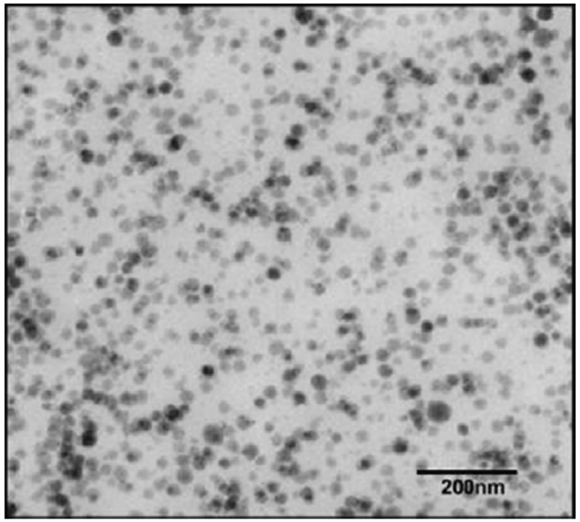
Resin Matrix Modifications



Organosilicate additives 5.5% from Balakrishnan et al. Polymer, 46, 2005



Graphene loaded epoxy 0.1% from Rafiee et al. ACS Nano, 3, 2009



Silica nanoparticle loaded epoxy 15% from Uddin et al. Comp. Sci. Tech., 68, 2008

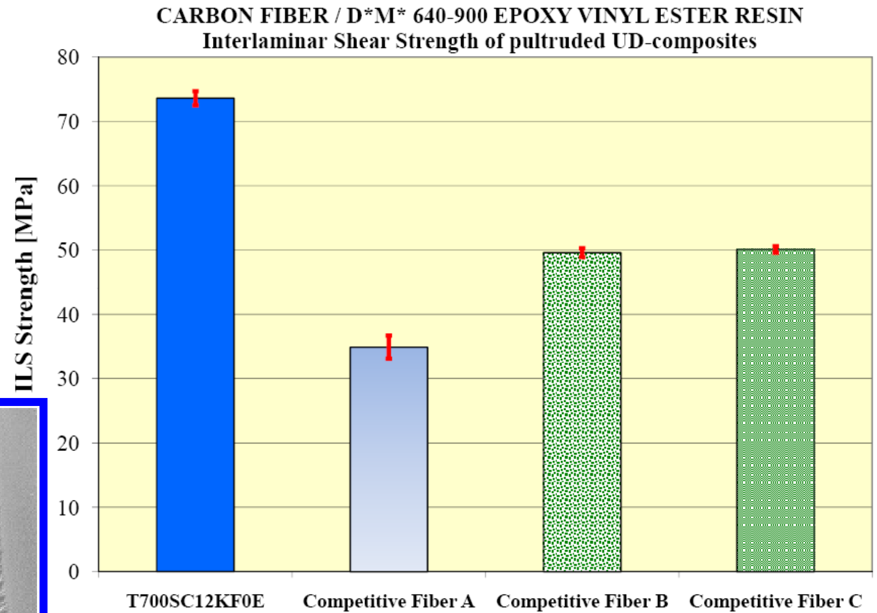
CF Surface Modifications for Load Translation Efficiency Improvements

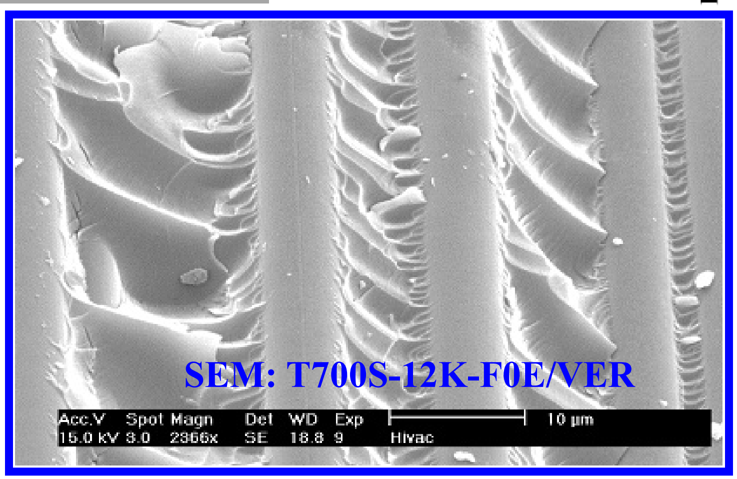
TORAYCA® Carbon Fibers:
Widest Range of Surface Treatments/ Sizings for Carbon Fibers

TORAYCA fibers are treated with various sizing agents to enhance the handleability and bonding characteristics with various resin systems. Below are the sizing types developed for TORAYCA fibers. Not all sizings are available with every fiber. Please see the data sheets for available sizings of a particular fiber.

Sizing Type	Resin System Compatibility
1	Epoxy
3	Epoxy
4	Epoxy, phenolic, BMI
5	General purpose: Epoxy, phenolic, polyester, vinyl ester
6	Epoxy
F	Designated for vinyl ester, compatible with epoxy

Defined in Product Code:
T700SC-12000-50C





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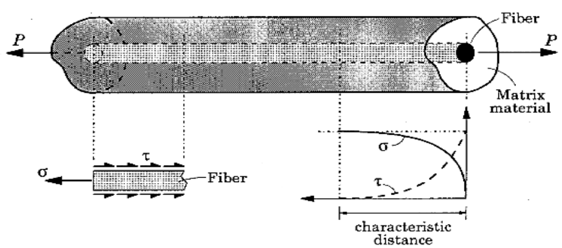
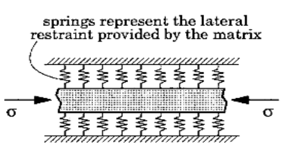
CF Surface Modifications

Single Fiber Fragmentation Test (SFFT) for adhesion analysis

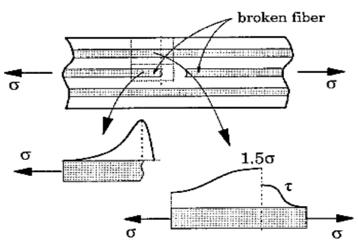
Mechanics of Stress Transfer At Fiber Break



(a)

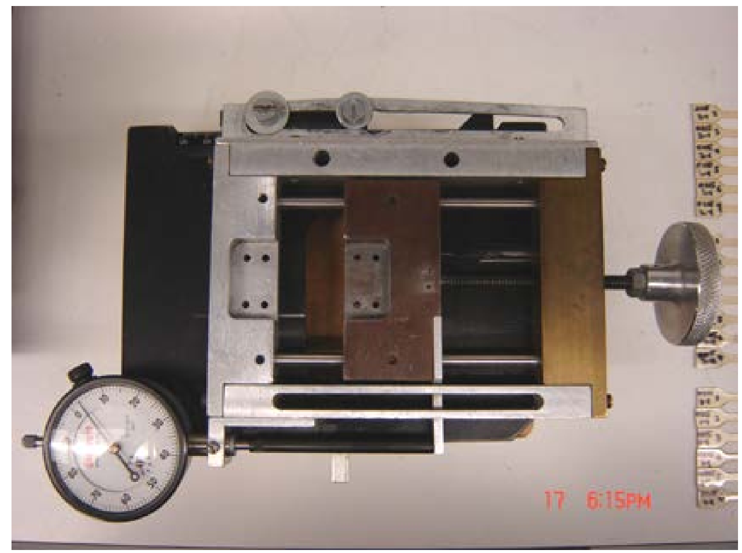


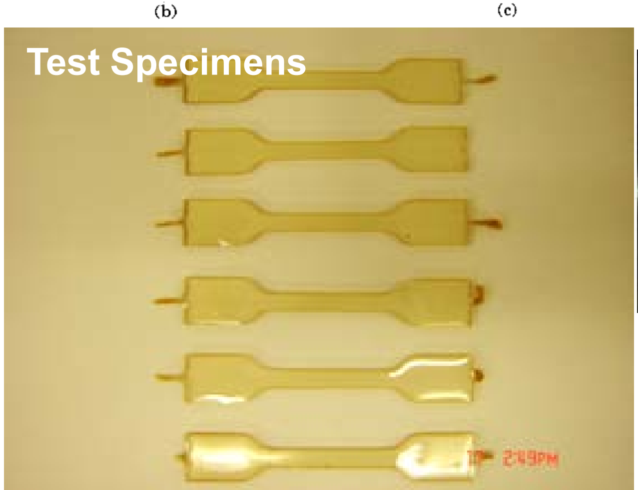
(b)



(c)

SFFT Fixture To Measure Interfacial Shear Stress (IFSS)



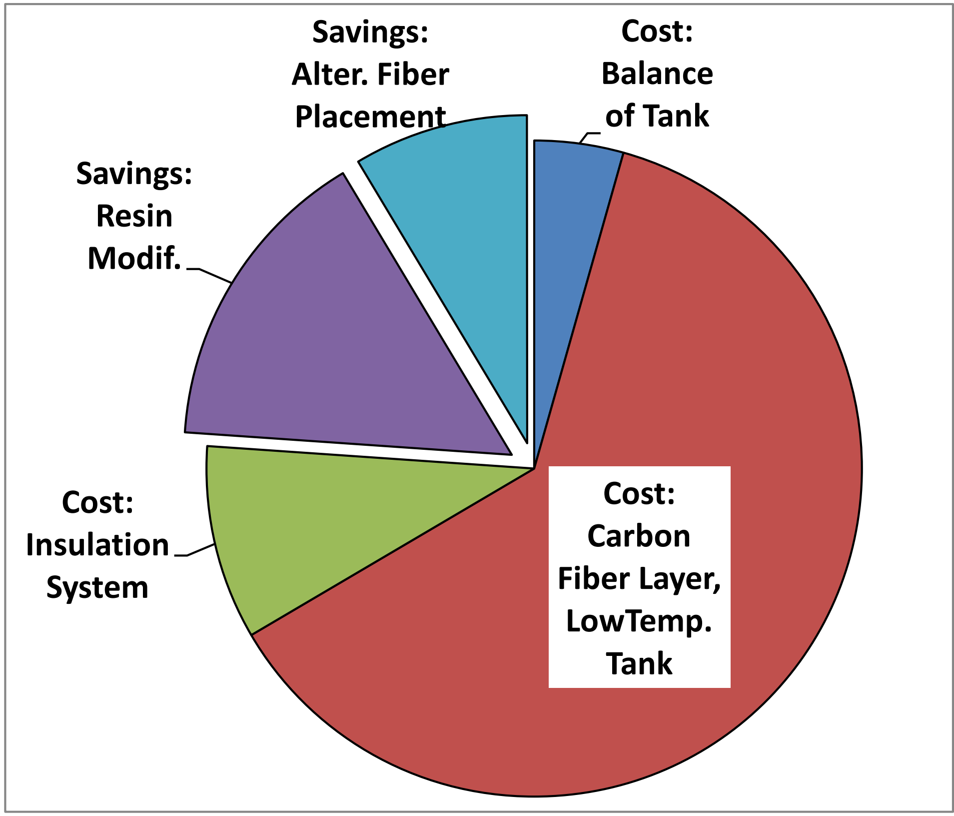


$$\text{IFSS:} \quad \tau = \frac{\sigma_f \times d}{2l_c}$$

Cost analysis

- Baseline cost model for an on-board vehicle capacity tank.
- Cost factors:
  - Carbon Fiber $/lb and mass
  - Insulation Concepts: vacuum, ultra-insulations
  - Design Alternatives: resin, fibers, liner, processing
  - Balance of Plant: regulator, valves, piping, etc.
- Compare with prior DOE cost studies by TIAX and ANL
- Cost trade-off analysis will be performed to focus on the most promising concepts.

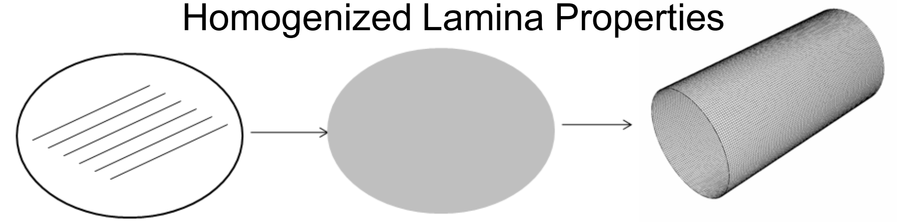
Tank Optimized for Low Temperature Operation



Burst Pressure Prediction for Alternate Tank Layups and Materials

- Approach:
  - Finite element laminate analysis
  - Multi-scale modeling
  - Resin and fiber properties
- ABAQUS with EMTA-NLA gives:
  - Progressive damage
  - Predicted burst pressure.
  - Method Correlates well with experiment (Nguyen, 2011)
- Evaluate different tank layups to focus tank prototyping and testing
  - Multiple fiber types, resins
  - Fiber angle sequences

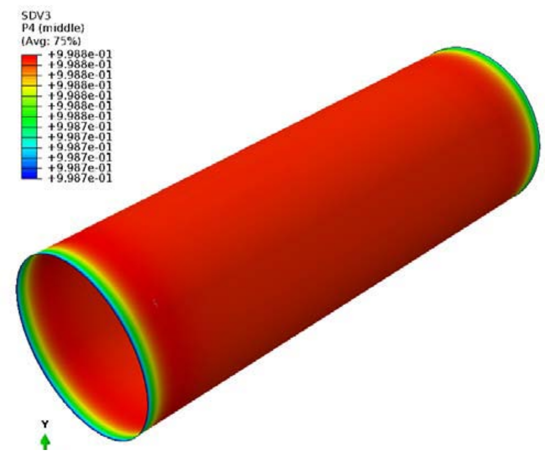
Homogenized Lamina Properties

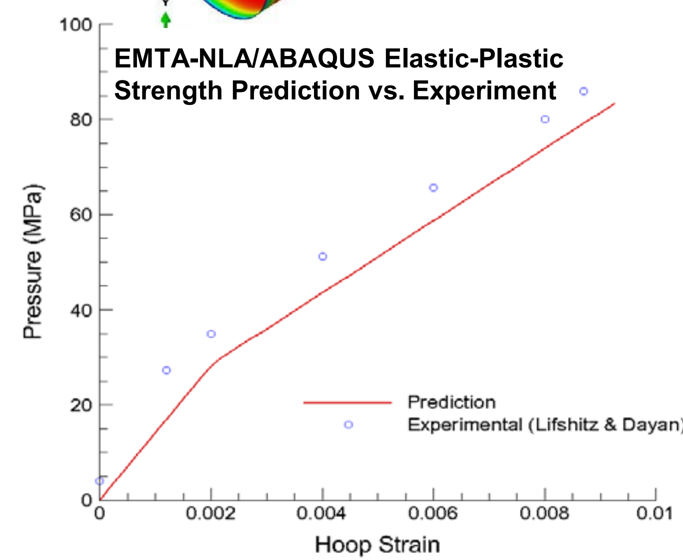


Microscale: UD elastic fibers and elastic-plastic matrix

Mesoscale: Continuum composite lamina obtained by an incremental EMTA method

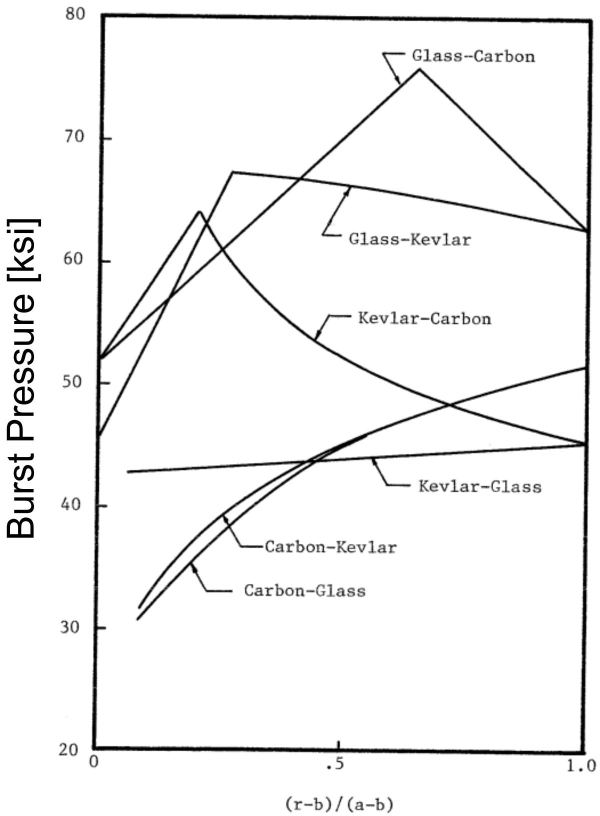
Macroscale: Filament-wound composite tank whose layers obey the incremental EMTA constitutive relations





Alternate/Multiple Fibers

- Investigate alternate carbon fibers
  - Evaluate performance/price
  - Consider heavy tow fibers
- Investigate alternate low-cost fibers
  - Evaluate performance/price
  - Consider strength and other performance issues
  - Consider manufacturability
- Look at hybrid fiber reinforcement
  - Some materials give strength
  - Some materials address durability
- Look at layering options
  - Higher modulus materials on outside to improve load share with inner layers
  - One material for helical layers, one for hoop layers



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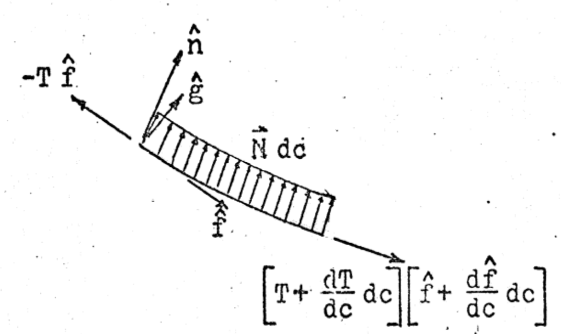
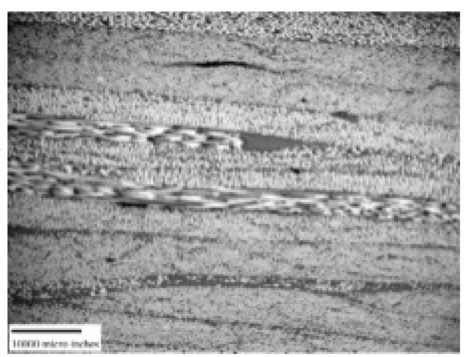
Localized Reinforcement

- Evaluate use of dome caps
  - Consider design and manufacturing issues
  - Consider stability over time (delamination)
- Evaluate use of chopped fiber reinforcement in dome
  - Example = HexMC
  - Consider manufacturing issues
  - Consider stability over time (delamination)
- Evaluate changing fiber angles within a layer
  - Ability to locally reinforce domes without cut fiber
  - Practical limits exist for how much change can be incorporated





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Technical Accomplishments FY12

- New project start expected April 2012
- Develop a baseline cost model for an on-board vehicle capacity tank with resin, fiber, liner, bosses, and processing and compare cost against prior DOE studies with TIAX and ANL
- Design and model new tank design with enhanced operating parameters of pressure and temperature for an equivalent ~200 liter tank with alternate fibers and/or new fiber placement technique and develop cost model for the new improved tank and compare against DOE target of 50% cost reduction
- Report on feasibility of a 10% absolute cost reduction with a total end goal of 37% reduced tank costs as demonstrated by cost model and identified individual technical approach progress

Collaborations

- PNNL Partners
  - Lincoln Composites – leading high pressure compressed gas storage manufacturer in the US
  - Toray CA – largest supplier of carbon fiber to compressed gas cylinder manufacturers in the world
  - AOC, LLC – leading US supplier of vinylester resins, polyester resins, and fiber surface modifiers
  - Ford – technology leader in development of hydrogen fueled vehicles
- Technology Transfer
  - Collaborations between companies will complement their respective businesses with new technology developments
  - New technology development reduces risks and gains acceptance by these industry leaders

Future Work

- FY13
  - Integration of FY12 individual constituents improvements combined with carbon fiber composites for testing synergistic improvements
  - Report on feasibility of a 20% absolute cost reduction with a total end goal of 37% reduced tank costs as demonstrated by cost model and identified individual technical approach progress
- FY14
  - Full on testing on combined composite and tank design with defined operating parameters for a 37% absolute cost reduction.

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