2012 DOE Hydrogen Program

Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels

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May 17, 2012

Project ID # MN008

Overview

Timeline

- Project start date: 09/2008
- Project end date: 03/2013
- Percent complete: 75%

Budget

- Total Budget: $5,486,848
  DOE Share: $2,566,451
  QT/Boeing Share: $1,920,397
  FFRDC Share: $1,000,000
- Funding received in FY11: $522,814
- Funding for FY12: $150,000

Barriers

- High-Cost Carbon Fiber
- Lack of Carbon Fiber Fabrication Techniques for Conformable Tanks

Partners

- Quantum Technologies, Inc. (QT)
- The Boeing Company (Boeing)
- Pacific Northwest National Laboratory (PNNL)

Collaborations

Partner	Prime	Sub	Industry	Fed Lab	Within DOE H_2 and FC Program	Collaboration
Quantum Technologies, Inc.	X		X		X	Design and test hybrid pressure vessels manufactured with combination of FW and AFP
Boeing Research and Technology		X	X			Develop AFP process for vessel manufacturing and provide material testing capabilities
Pacific Northwest National Laboratory		X		X	X	Develop cost model for hybrid vessel manufacturing and study the impact of H_2 absorption in polymer liners

Relevance

Objectives: To manufacture Type IV H_2 storage pressure vessels, utilizing a new hybrid process with the following features:

- Optimize elements of advanced fiber placement (AFP) & commercial filament winding (FW)
- Improve understanding of polymer liner H_2 degradation

With the aim of addressing the barriers by achieving a manufacturing process with:

1. lower composite material usage
2. lower cost fiber
3. higher manufacturing efficiency

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Approach

Quantum

- **Utilize lower cost fiber on outer layers of AFP/FW hybrid vessel**
  - Outer layers do not experience as much load; no need of high strength fiber
  - Lower cost fiber with higher modulus than that of baseline fiber
  - Replace the maximum number of outer baseline fiber layers without significantly increasing the total number of layers while satisfying the burst requirement

- **Test vessels to national standards on critical tests that might be affected by AFP/FW hybrid process**

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Approach

PNNL

Polymer Tank Liner Hydrogen Compatibility – In-situ Testing

- PNNL built and tested an in-situ tensile rig for high-pressure H_2
- Motivation: Hydrogen degrades polymers
- Prior ex-situ testing demonstrates
  - Blistering
  - Modulus, strength decreases
  - Time dependent
- Degradation affects leak rate, durability, lifetime
- Need in-situ device to achieve full understanding of actual liner environment

Left: In-situ tensile rig
Right: High pressure hydrogen autoclave

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Accomplishments and Progress

Quantum

Continue with next critical test that verifies the hybrid process

Failure mode understood;
Move forward with lower cost fiber

Vessel 7
(Baseline fiber with AFP)
Passed burst test at 22,925 psi
Pass criteria: 22,843 psi

Vessel 8
(Built identically to Vessel 7)
Failed cycle test
13,000 out of 15,000

Vessel 9 – two day wound
(Less baseline fiber with AFP + lower cost fiber on outer layers)
Failed burst test at 22,083 psi

Believed a continuous wound would bring up burst pressure to pass

Vessel 10 – one day wound
(Built identically to Vessel 9)
Failed burst test at 22,388 psi

Vessel 11
(More baseline fiber placed back in Vessel 9)
Failed burst test at 20,026 psi

Upgrade in-house program to generate FEA models for higher accuracy

Next to verify the existing program is sufficient for hybrid design

Next to verify design margin was too small

Accomplishments and Progress

Quantum

- **Vessel 9 Design**
  - Hybrid vessel integrated with lower cost fiber
  - Utilize lower strength fiber on the vessel outer layers (vessel has lower stress on the outer layers)
  - Utilize higher modulus fiber on the vessel outer layers (allow those layers to take the load earlier before the inner layers fail)
  - Replaced 37% of baseline fiber on the outer layers of Vessel 7 design with lower cost fiber
  - More than 5% cost savings (based on $13/lb for lower cost fiber vs. $16/lb for baseline fiber) than Vessel 7
  - Less than 2% increase in weight than Vessel 7 due to two additional helical patterns
  - 22,083 psi burst pressure; 760 psi short of the requirement

	Vessel 7	Vessel 9
Summary Table	FY-2011	FY-2011
	Hybrid (FW + AFP)	Hybrid (FW [Baseline + Low Cost Fiber] + AFP)
Total Composite Mass, kg	58.63	59.63
Mass Savings, kg	N/A	-1
Mass Savings, %	N/A	-1.71%
Total Cost	$2,124	$2,012
Cost Savings	N/A	$112
Cost Savings, %	N/A	5.27%
Notes		Did not pass burst test

Prior Accomplishments: Material & Cost Saving

Quantum

	Baseline 129L	Vessel 1	Vessel 7
Summary Table		FY-2010	FY-2011
	Filament Wound	Hybrid FW + AFP	Hybrid FW + AFP
Total Composite Mass, kg	76	64.9	58.63
Mass Savings, kg		11.1	17.4
Mass Savings, %		14.6	22.9
Specific Energy, kWh/kg	1.50	1.67	1.78
$11/lb Carbon, Cost Effic, $/kWh	$23.45	$21.75	$20.80
$6/lb Carbon, Cost Effic, $/kWh	$18.74	$17.63	$17.01

Improvements made between Baseline and Vessel 7:

- Composite mass reduced from 76 kg to 58.63 kg (22.9% reduction)
- Specific energy increased from 1.5 to 1.78 kWh/kg
- Cost efficiency reduced from $23.45 to $20.80/kWh for $11/lb carbon fiber
- Cost efficiency would reduce from $18.74 to $17.01/kWh for $6/lb carbon fiber

Accomplishments and Progress

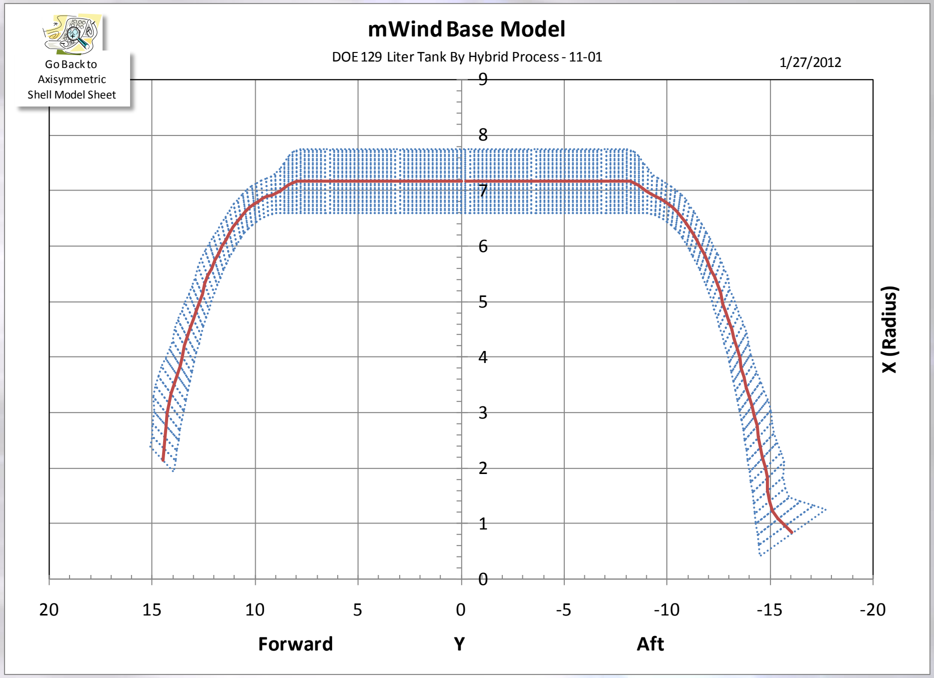
Quantum

- Updated the current in-house finite element computer program
  - Added start locations of layers
    - Allows the user to specify start and stop location of each composite layer
  - Modified output to use more than one model type
    - Axisymmetric shell elements (complete)
    - 3D shell elements (complete)
    - 2D axisymmetric continuum elements (in progress)
- Finite element model generator recoded in Microsoft® Visual Basic

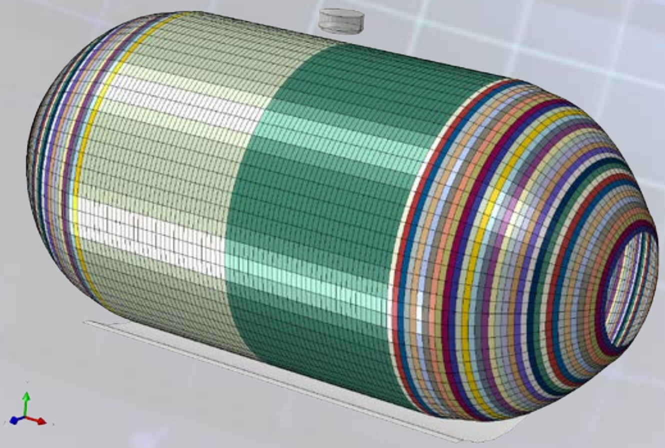
Accomplishments and Progress

Quantum

Axisymmetric Shell Model



3D Shell Model



Accomplishments and Progress

Boeing

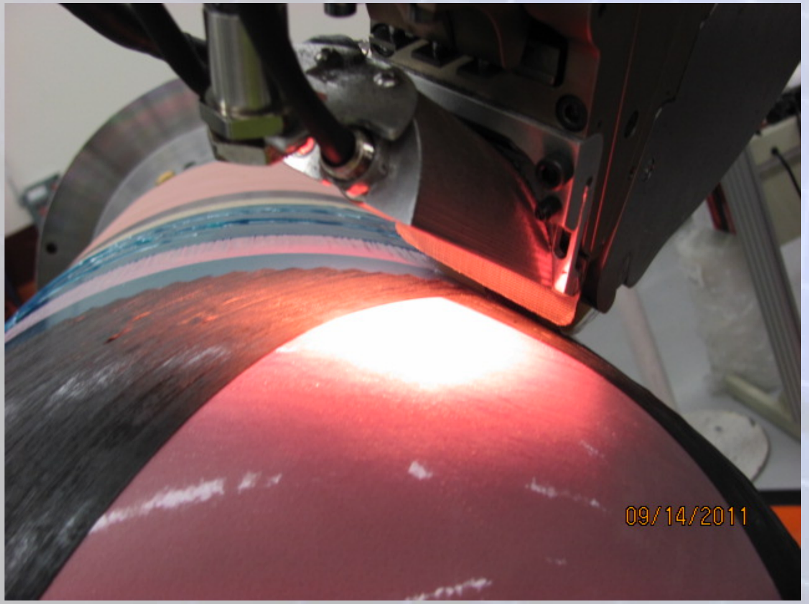
- Fabricated 6 end dome sets for test vessels
  - Used new fiber placement cell specifically designed for end domes
- Implemented IR heating for higher process reliability
- Updated tensioners to low cost active control
  - Consistent tension
  - Avoid slack conditions during head and arm movements
  - Passive Feedback controls
- Currently Working on Rev B of tensioner controls
  - More consistent tension
  - Faster response in directional change
  - Active Feedback controls
- Conducted process improvements to reduce marcelling and wrinkling in end dome plies

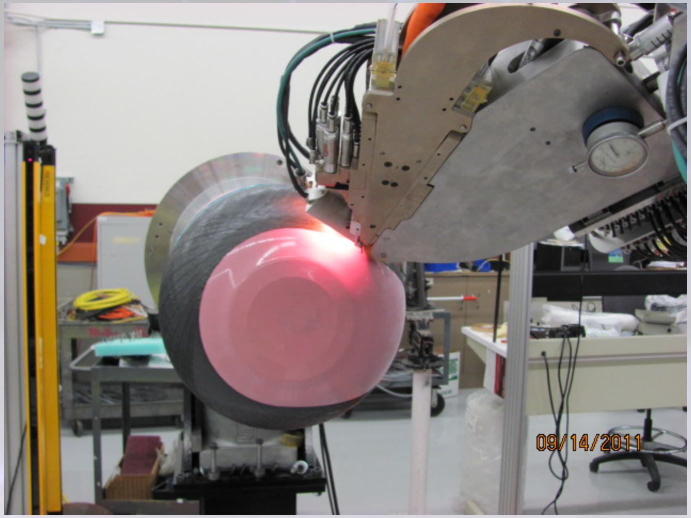
Accomplishments and Progress

Boeing (Continued)

IR Heater

- Implemented New IR heating system to increase process reliability
  - Reduced frequency of cutter jams due to excessive heating in the cutter region from previous hot gas heating method
  - Precise control of heated area
  - IR heater integrated into robot controller for process controls
    - Temperature vs. velocity profiles
    - Turn off heater when off surface or when stopped on surface



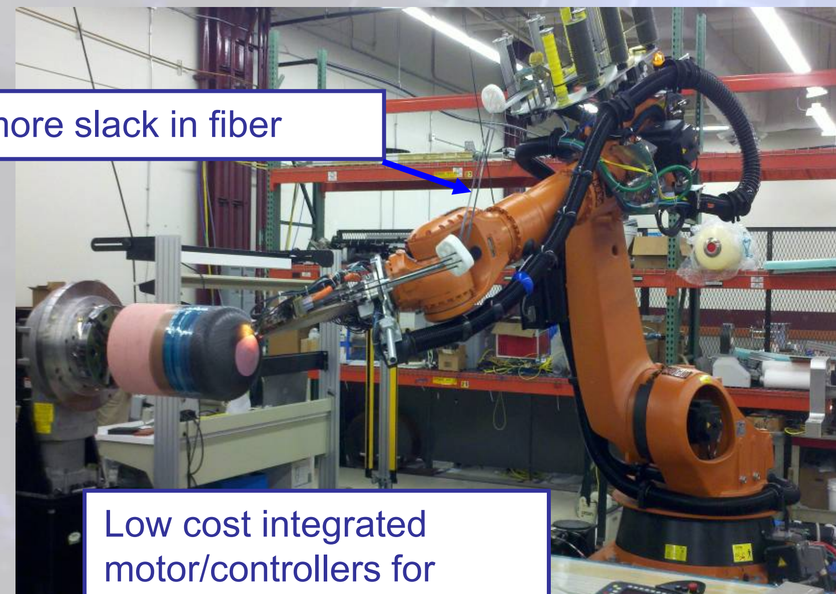


Accomplishments and Progress

Boeing (Continued)

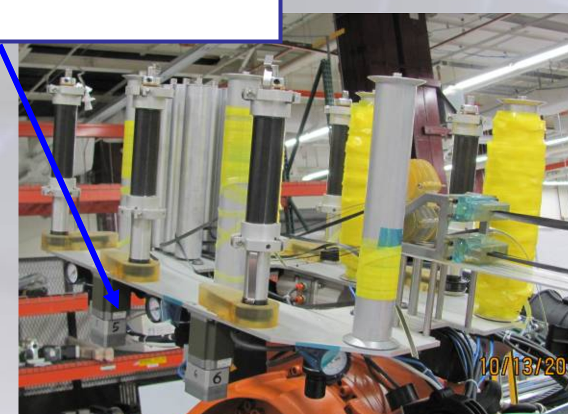
Creel System with Passive Tension

- Passive tension control
  - Eliminate slack/twists in the system
  - Able to rewind excess tow during lay-up
  - Eliminate tow interference
  - Better control of tension



No more slack in fiber

Low cost integrated motor/controllers for tension



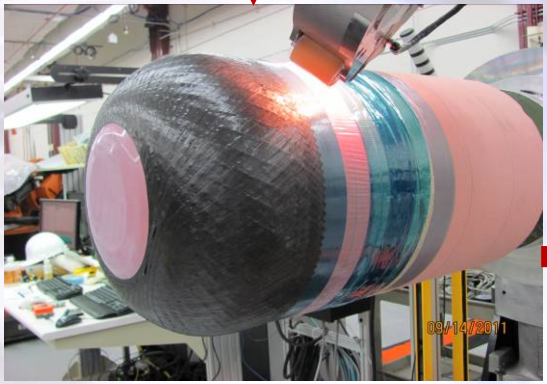
Upgraded Fiber Path

- Redesigned “lollypop” guide
- More direct fiber path to delivery head
- Reduces twists in system

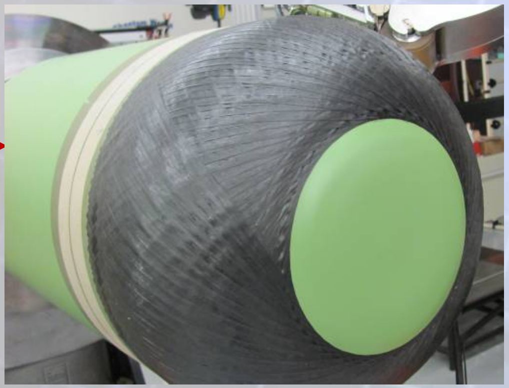
Accomplishments and Progress

Boeing (Continued)

With new head, some marcelling (wrinkling) occurs on the inside surface of the composite dome caps.



Process involves stretching FEP (fluorinated ethylene propylene) film over tool surface. Poor control of FEP over machined foam could result in material movement causing issues.



Sealed the foam tool surface to provide more secure surface for stretched FEP separator film.

Reduced the amount of wrinkling but didn’t eliminate it. Still some slipping occured.

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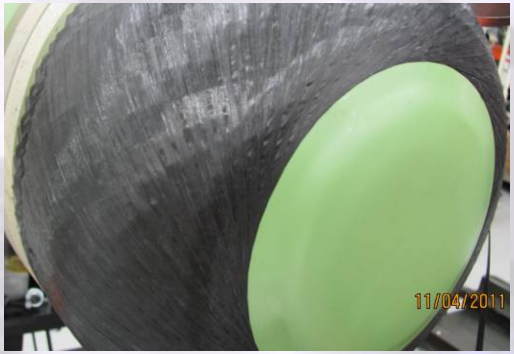
Accomplishments and Progress

Boeing (Continued)



Next, the FEP liner was removed and dome laid directly up on the sealed surface with original 3 tow layup having steering on first few plies.

Wrinkling was still observed but was much less pronounced than was shown on previous layup with FEP. Attention turned to steering of first ply as being the cause.

Repeated the first test but reduced to two tows instead of three on the first ply as well as reduced the steering on the first two plies.

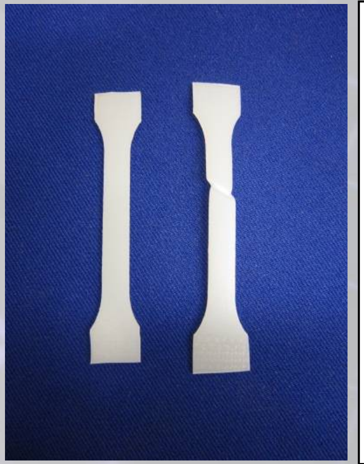
No visible wrinkling around the polar opening was observed. New standard process for domes.

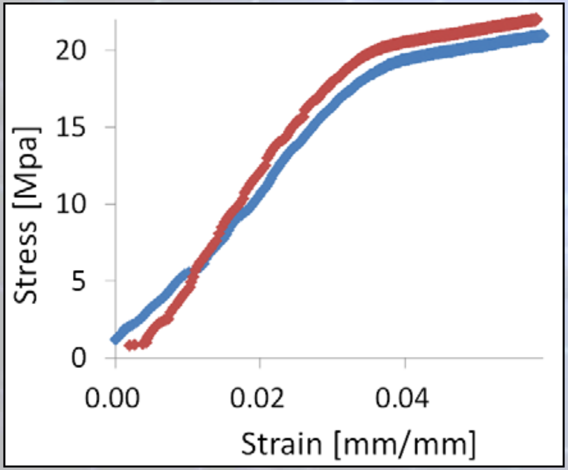
Accomplishments and Progress

PNNL

Polymer Tank Liner Hydrogen Compatibility – In-situ Testing

- In-situ tensile tester has been constructed and testing in 4,000 psi hydrogen
- All components work reproducibly in the high pressure environment
- Preliminary testing of stock HDPE (high density polyethylene) samples shows decreased modulus under high pressure hydrogen
- Setup allows material tensile tests under hydrogen up to 5,000 psi
- Modifications for heating may be possible





<u>Left</u>: HDPE tensile samples before and after testing in 4,000 psi hydrogen.
<u>Right</u>: Preliminary data from in-situ tensile rig. (Red) data is for HDPE pulled in air, and (blue) data is for an identical HDPE sample pulled in 4,000 psi hydrogen. Hydrogen data shows a lower modulus defined by the initial slope.

Proposed Future Work

FY12

- Continue to upgrade in-house computer program to generate finite element models for vessel design and optimization
- Design and build vessels with baseline and lower cost fiber on hybrid (AFP/FW) design
- Testing to national standards on critical tests that might be affected by AFP/FW hybrid process
  - Ambient temperature burst test
  - Ambient temperature cycle test
  - Extreme temperature cycle test
  - Accelerated stress rupture
- Improve the latest tensioner controls
- Complete analysis of high pressure hydrogen in-situ tensile tester and compile report
- Final cost model analysis of new vessel designs

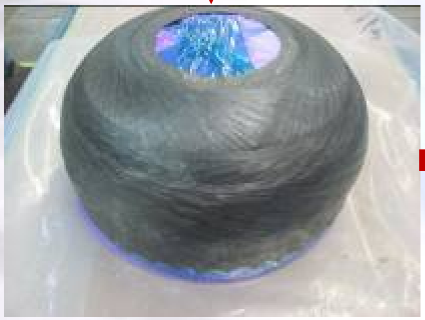
Project Summary

- In-house program for FEA model generation is in the process of being upgraded
- Implemented IR heater for AFP
- Updated AFP tensioners to low cost active control
- Reduced marcelling and wrinkling in end dome plies of AFP
- Built and tested an in-situ tensile rig for high-pressure H_2 at PNNL

Technical Back-Up Slides

Background on Hybrid Vessel Manufacturing

1. Highly-accurate foam mandrels. Three ¼-inch tows are placed on mandrel.



2. AFP dome caps (forward and aft) are then removed from foam tooling and brought to wind cell.

3. Both forward and aft dome caps are then transferred and installed to the hydrogen storage liner.

4. The final stage is to filament wound over the forward and aft dome caps.

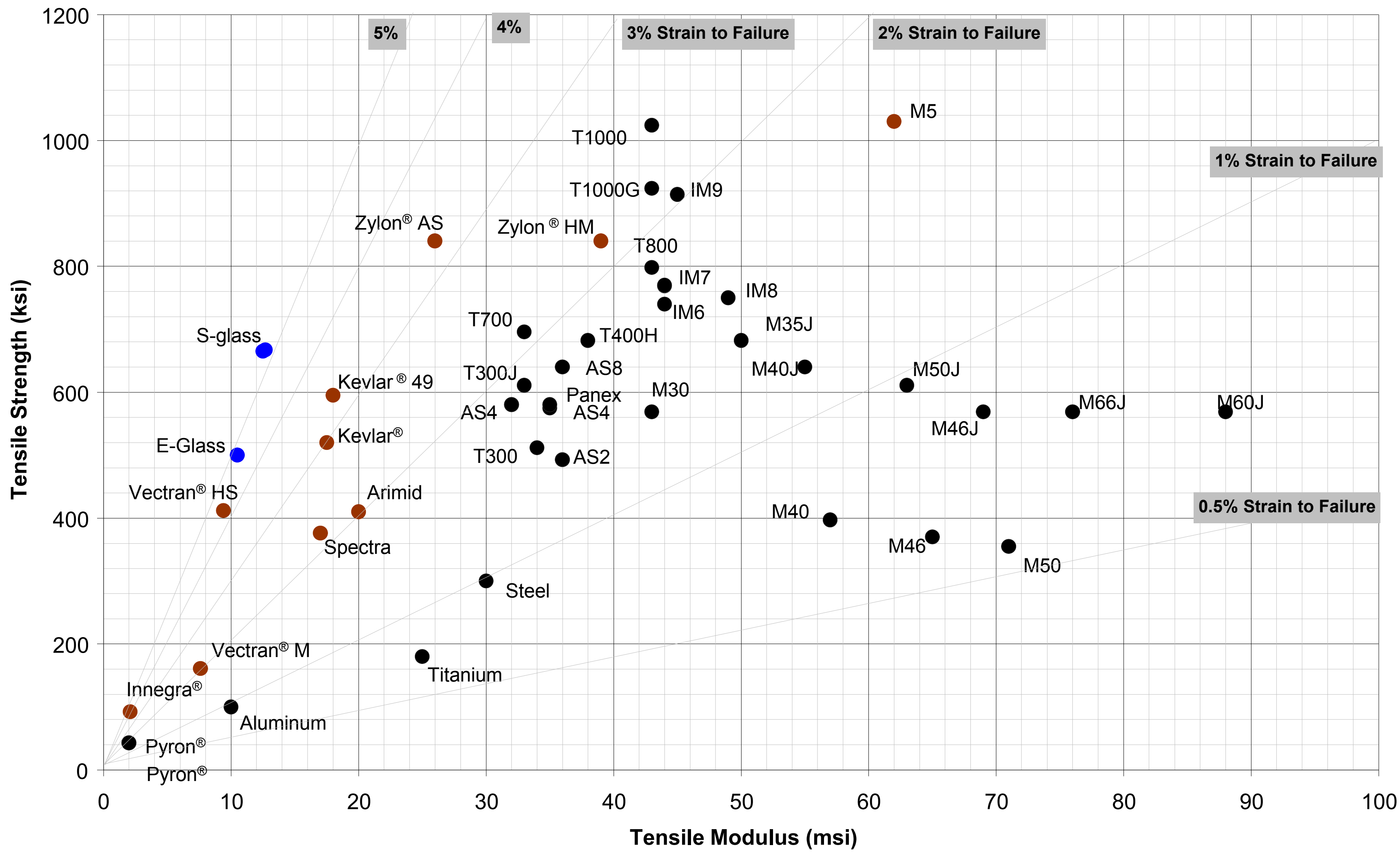
Tank Cost Analysis

PNNL's Technical Progress

500,000/yr, $11/lb Carbon Fiber

		Baseline 129L	Tank 1 Layup		Tank 7 Layup	
		Type IV Tank	Hybrid FW+ AFP Reinforced		Hybrid FW+ AFP Reinforced	
Summary Table			Fully Integrated	Separate	Fully Integrated	Separate
		Filament Wound	FW and AFP	FW and AFP	FW and AFP	FW and AFP
Composite Mass, kg	FW	76	63.4	63.4	56.23	56.23
	AFP		1.5	1.5	2.4	2.4
Total Composite Mass, kg		76	64.9	64.9	58.63	58.63
Total Place Time, hr/tank		5.75	7.27	4.80	8.21	4.25
# Manuf. Cells for 500K/yr	FW	191	242	159	273	142
	AFP		484	165	546	264
Tank Costs						
FW Composite		$2,290	$1,910	$1,910	$1,694	$1,694
AFP Composite			$90	$90	$145	$145
End Boss		$250	$250	$250	$250	$250
Manuf. Equipment		$36	$66	$41	$72	$45
Factory Space		$7	$10	$7	$11	$8
Total Tank Cost		$2,583	$2,326	$2,299	$2,171	$2,141
% Tank Cost Savings		0%	10%	11%	16%	17%
DOE Measures						
Specific Energy, kWh/kg 1		1.50	1.67	1.67	1.78	1.78
Cost Efficiency, $/kWh 2		$23.45	$21.91	$21.75	$20.98	$20.80
1 5 kg H2 * 33.31 kWh/kgH2 / (Tank+OtherComponents+H2 mass, kg) OtherCompMass=30kg						
2 (Tank+OtherComponents $$) / (5 kg H2 * 33.31 kWh/kgH2)						

Fiber Properties



Carbon fiber, Glass, Aramid; T800 – AFP, T700 – FW