2013 DOE Hydrogen Program

Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels

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Project ID # MN008

Overview

Timeline

- Project start date: 09/2008
- Project end date: 09/2013
- Percent complete: 85%

Budget

- Total project funding
  DOE share: $3,399,826
  Contractor share: $1,920,397
- Funding received in FY12: $185,000
- Funding for FY13: $332,928

Barriers

- Lack of Low-cost Carbon Fiber
- Lack of Low-cost Fabrication Techniques for Storage Tanks

Partners

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

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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

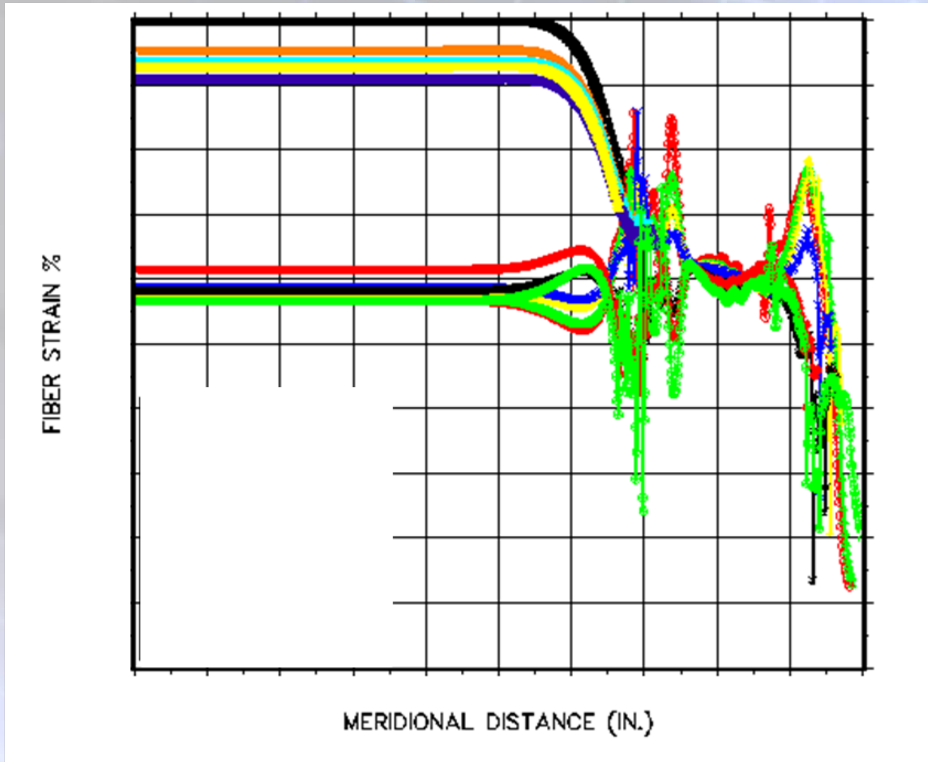
With the aim of addressing the barriers by achieving a manufacturing process with:

1. lower composite material usage
2. higher manufacturing efficiency

Approach

Quantum

- **Upgraded kWind to mWind**
  - kWind was developed for the filament winding process
    - Models full layers of material from one end to the other end of the tank
      - Layers can only stop at specific end points in the model
      - Extensive manual rework of the model is required to include fiber placement layers
    - Provides a 2D axisymmetric solid finite element model for ANSYS computer software

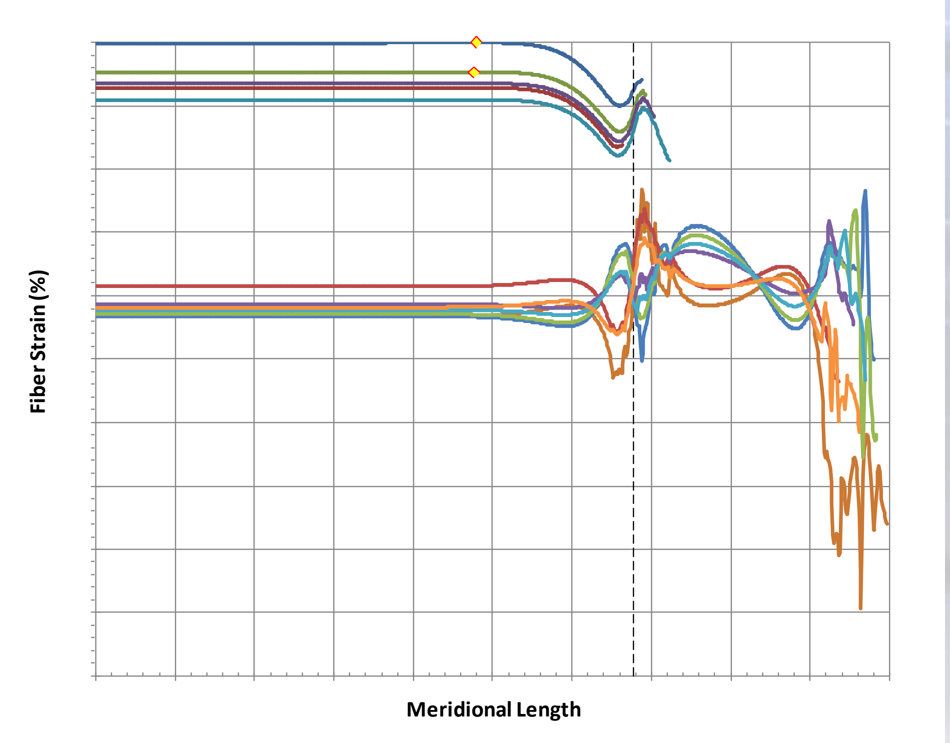


Approach

Quantum

▪ Upgraded kWind to mWind (cont.)

- mWind
  - Includes filament wound and fiber placement layers
    - Layers can start and stop at any point in the model
  - Model output includes ANSYS and Abaqus models
    - 2D Axisymmetric Solid model
    - 2D Axisymmetric Shell model
    - 3D Shell model
  - Additional read and write capabilities with other computer programs
    - Microsoft Excel
    - Export fiber strain data for contour plotting



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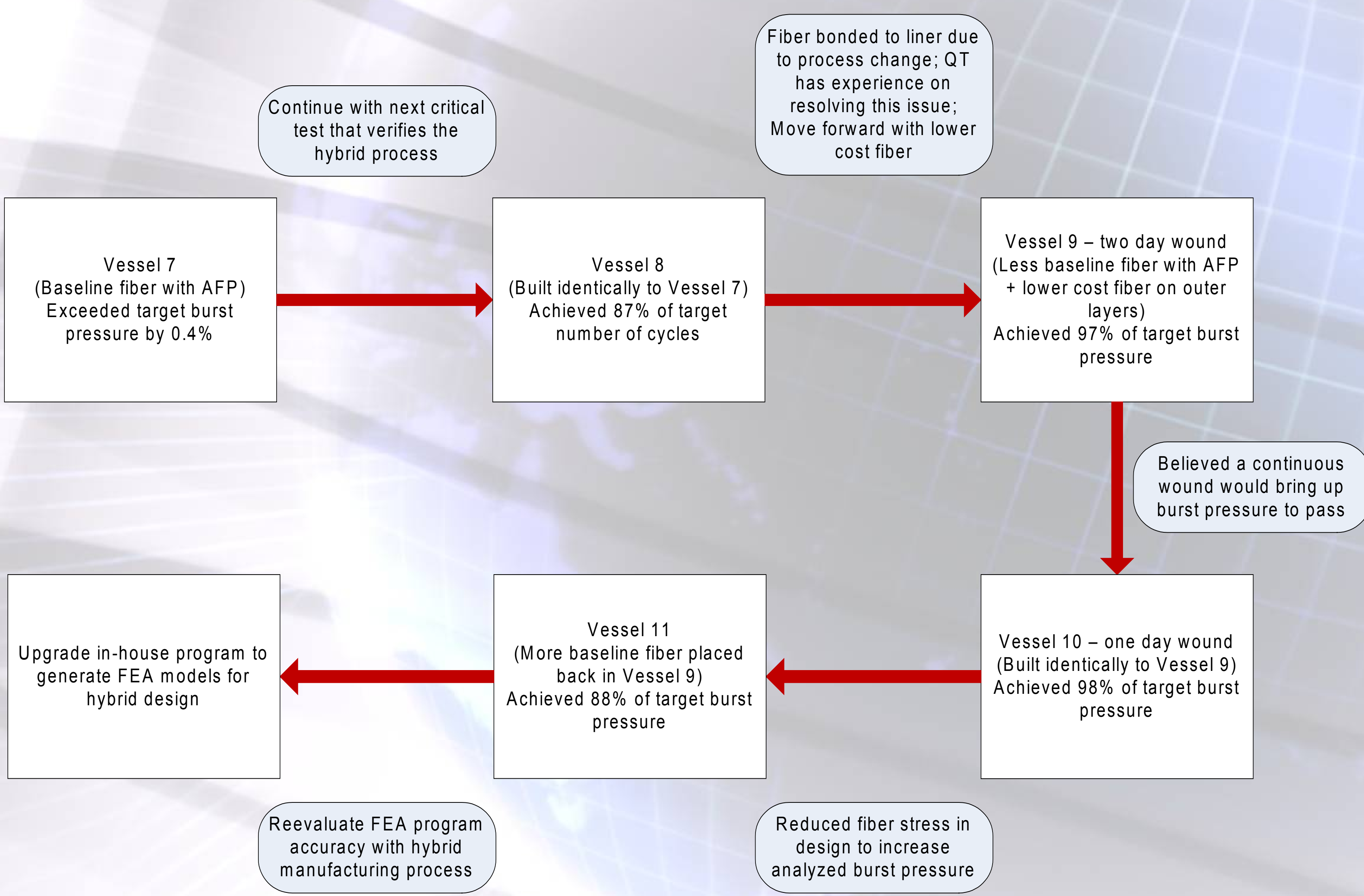
2011 Accomplishments and Progress

Quantum



2012 Accomplishments and Progress

Quantum

kWind was upgraded to mWind to generate FEA model for Vessel 12

Vessel 12 (Dome cap AFP layers increased from 10 to 12 and extend further into cylinder section) Achieved 92% of target burst pressure

Bridging was observed in the cylinder section after reviewing FEA model.

Latest carbon fiber pricing shows baseline fiber is still the highest performance per dollar. Will focus on next vessel design with baseline fiber only.

Vessel 13 (Dome cap AFP layers increased from 12 to 19 (forward) and 20 (aft), filled cylinder section with hoops to even with dome caps) Achieved 91% of target burst pressure

Computed Tomography (CT) Scan

High Speed Camera

Strain Measurements

Bridging was observed in the aft end build up

Non destructive tests to verify and improve mWind, and to understand failure mode if needed

Vessel 14 (Currently being designed to incorporate all lessons learned)

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

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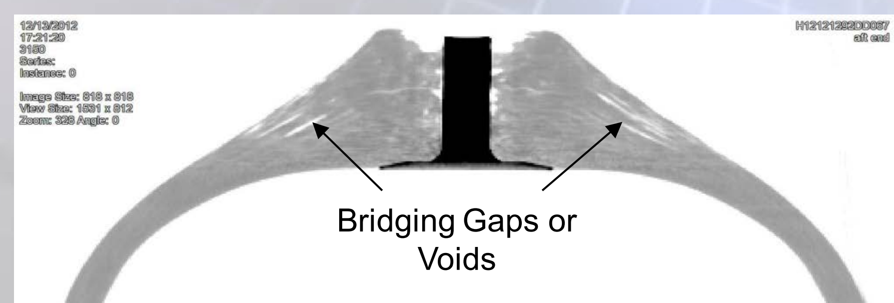
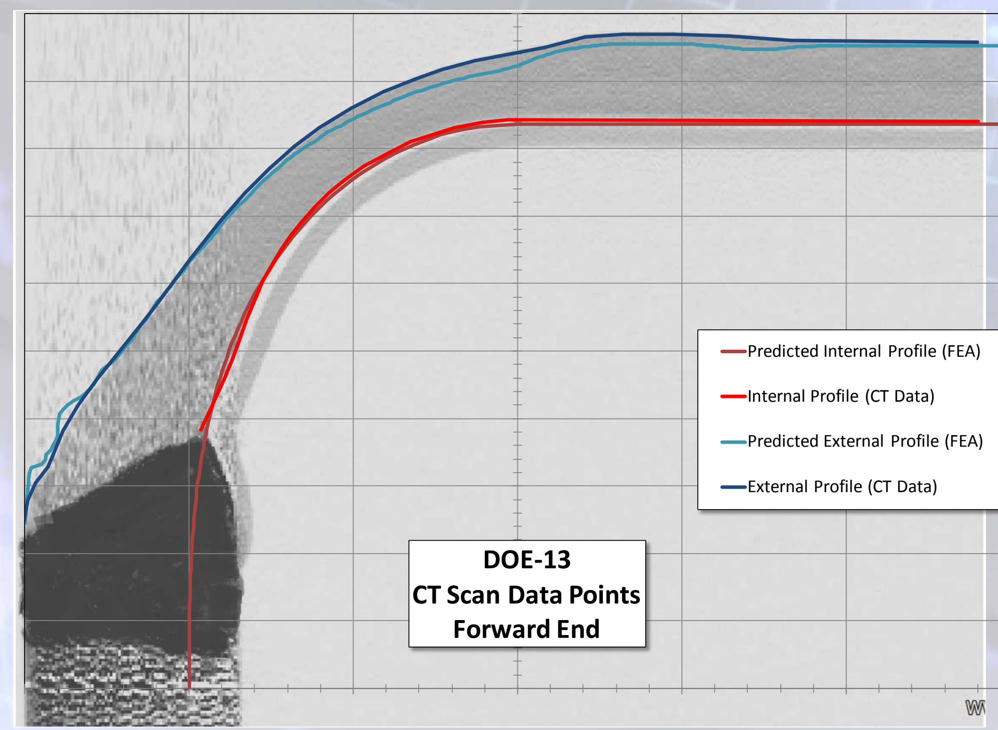
Accomplishments and Progress

Quantum

- CT Scan
  - Helps understand tank rupture mode (fiber bridging) and was used to improve mWind fiber buildup predictions
  - Less buildup was predicated by mWind at the transition region due to termination of AFP fibers and hoop fibers

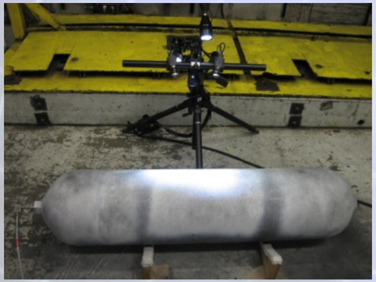




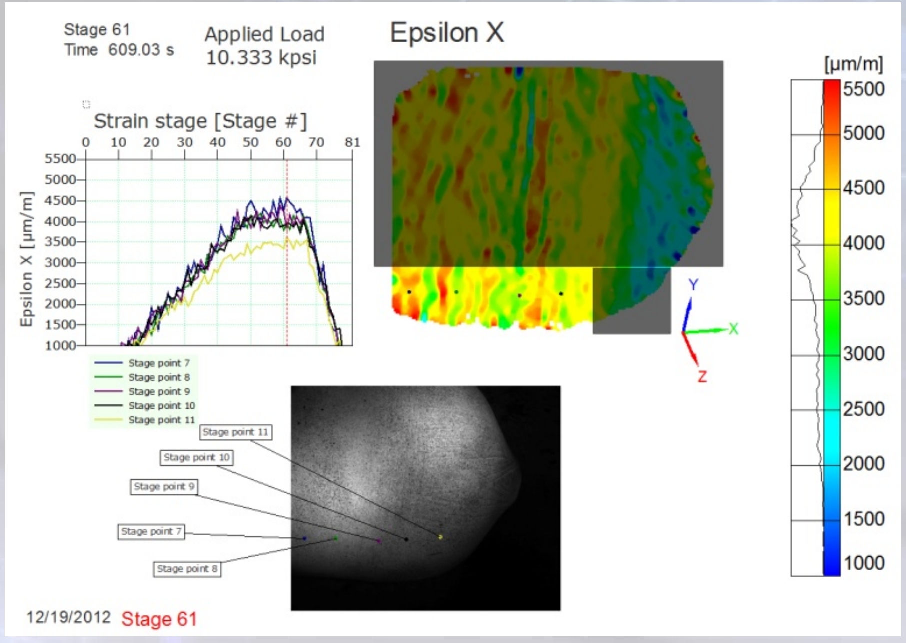
CT scan data were useful to improve the fiber buildup calculation algorithm in mWind

Accomplishments and Progress

Quantum and Boeing



- Strain Measurements
  - Strain gages – hoop strain, axial strain and 45°
  - Optical strain measurements (ARAMIS)
- Strain Measurement Comparison
  - Certain strain gages failed after initial pressure cycle
  - ARAMIS measures hoops strain of 4,000 – 4,500 μm/m at transition area between aft dome cap and cylinder section
  - Strain gages measure ~5,000 micro strain at the same location
  - Values are within 10 to 25% of each other with two methods
  - ARAMIS measurements help to verify the strain calculations from mWind



ARAMIS is sufficiently accurate to measure strain optically and be used for verification purposes

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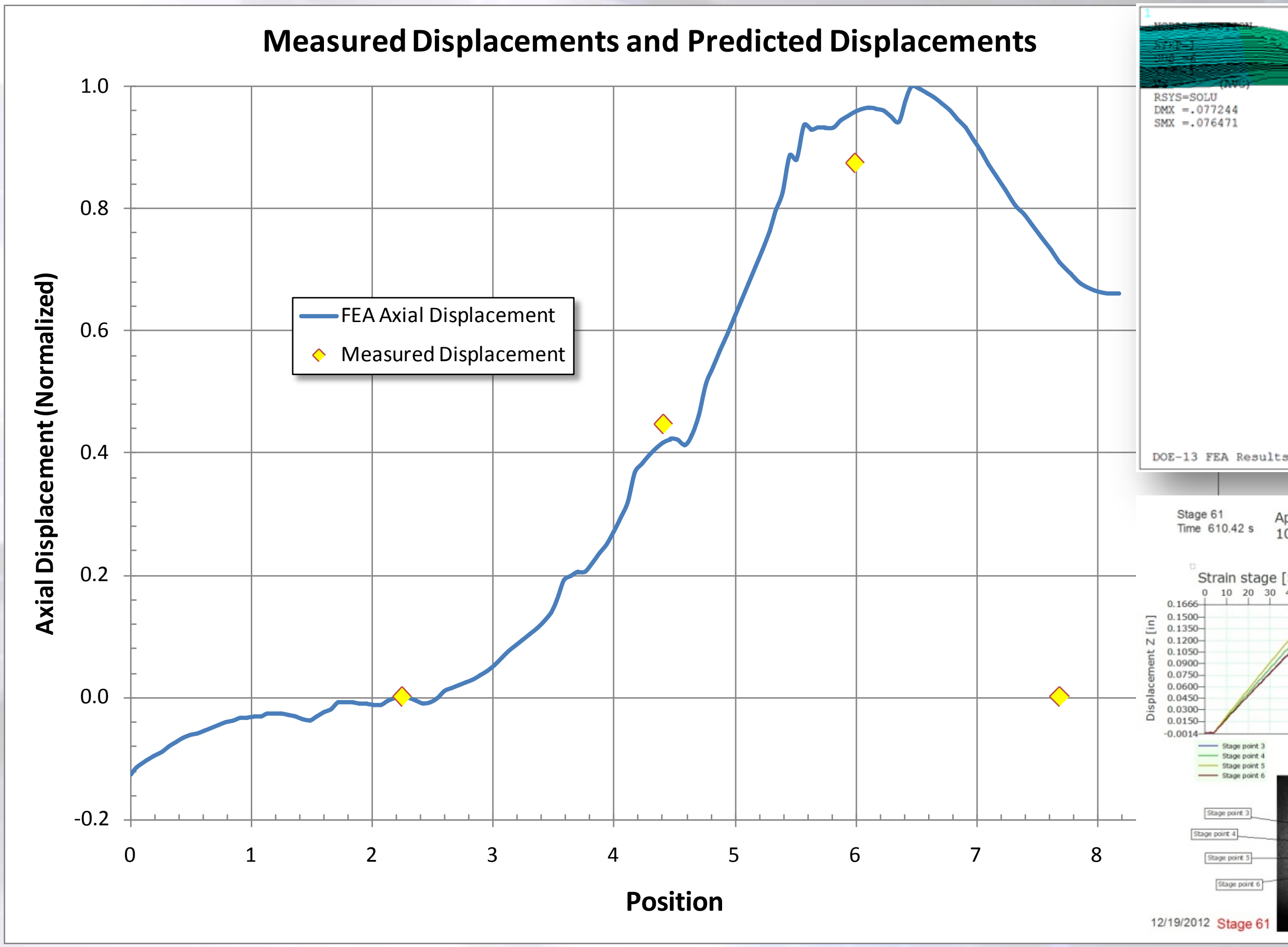
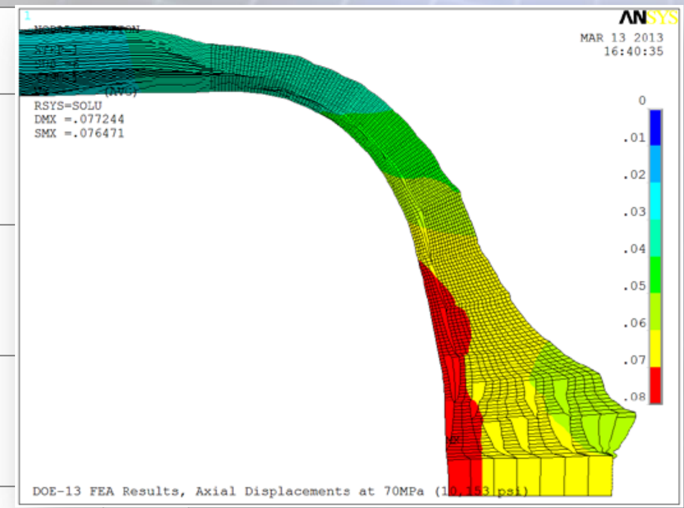
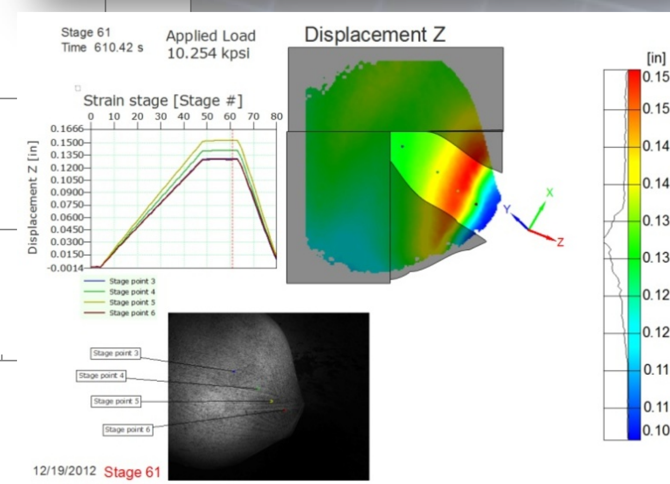
Accomplishments and Progress

Quantum

Axial Displacement Correlation between ARAMIS and mWind







The predicted axial deflections match the measured axial displacements except where bridging occurs

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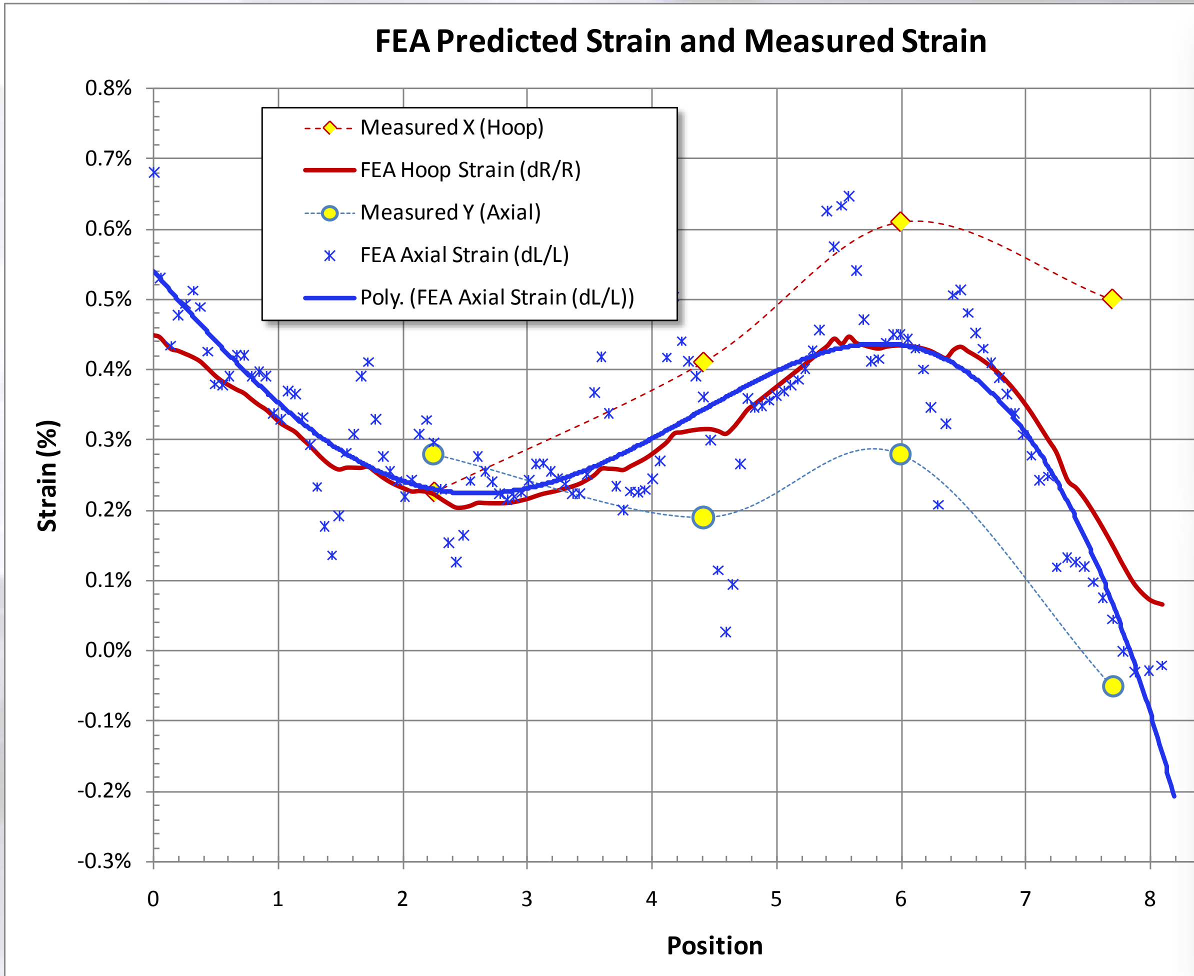
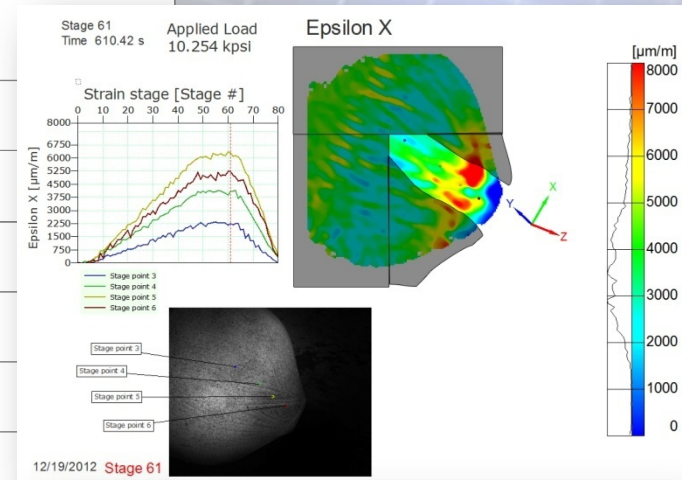
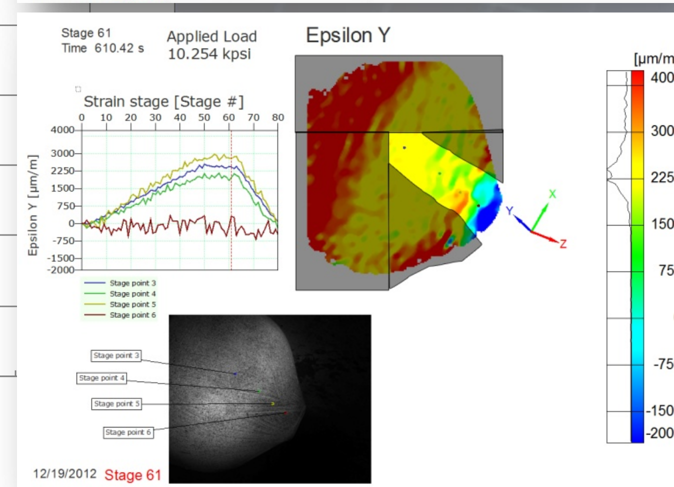
Accomplishments and Progress

Quantum

Hoop and Axial Strain Correlation between ARAMIS and mWind







The predicted strains of mWind follows measured strains with more variation in bridging areas

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Accomplishments and Progress

Quantum

- High Speed Camera
  - Camera focused at the aft end because bridging was observed during CT scan

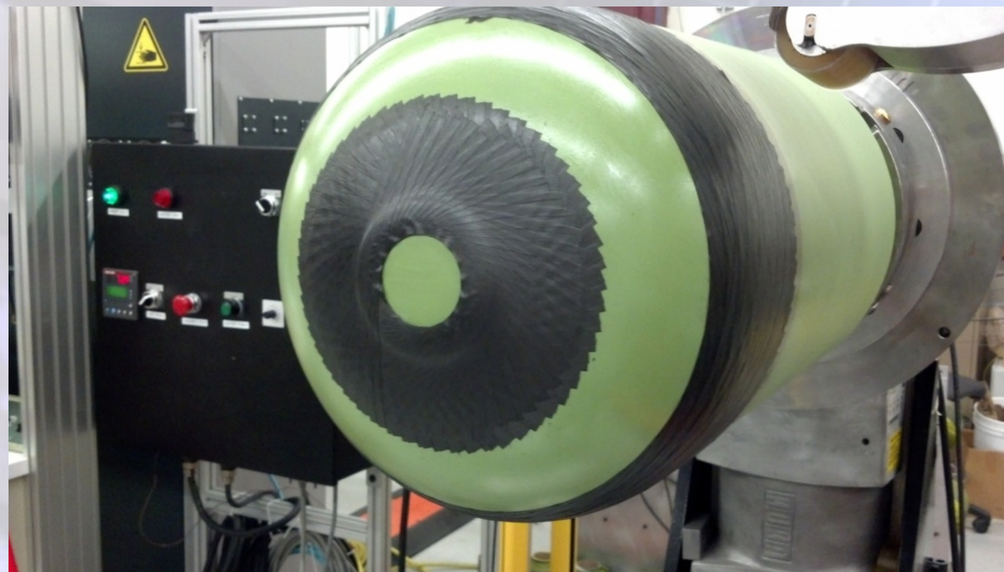
Vessel ruptured in the aft end, as expected, due to bridging

Accomplishments and Progress

Boeing

Composite Quality Improvements for AFP Dome Caps

- **Eliminated release film**
  - Stretched FEP (fluorinated ethylene propylene) film previously used for release of AFP preformed dome cap from tool
  - Caused wrinkling due to slipping of AFP material
- **Solution – Create a tooling release surface**
  - Seal foam tool (No FEP)
  - Apply release agent
- **Wrinkling is eliminated**
- **Assembly (dome cap and tool) requires freezing prior to removal**
- **Produces high quality surface on the inside of the AFP dome caps**



Use of sealed foam tool without FEP eliminates wrinkles on dome caps

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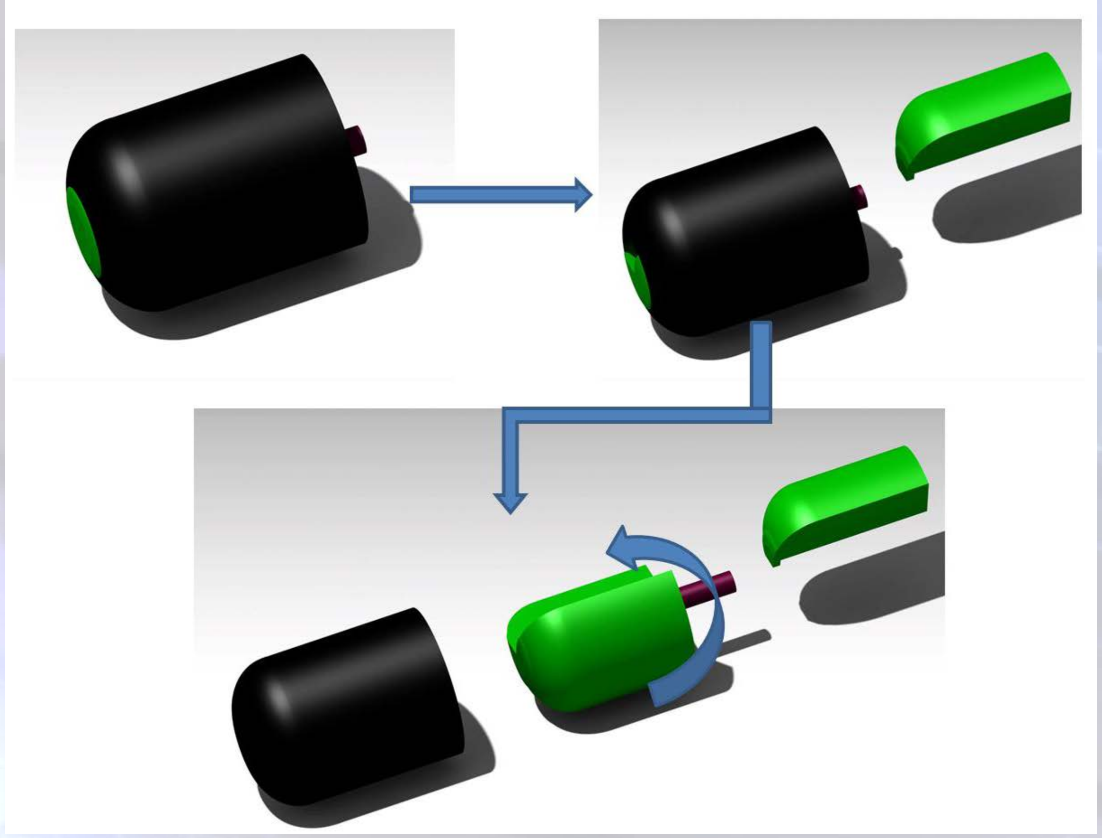
Accomplishments and Progress

Boeing (Continued)

Advanced Collapsible Tooling for AFP Dome Caps

- **Needed for fast, efficient forming of cylinder dome caps**
  - Enables quick release of AFP preformed dome cap
  - Robust manufacturing process
- **Three-piece collapsible tool**
  1. Fiber place prepreg onto forming tool
  2. Remove wedge from backside, secured in position by pin.
  3. Remove two-piece section hinge together for easy extraction
- **Increases production efficiency by reducing difficult process flow steps**
- **Eliminates freezing of fiber placed prepreg in order to remove dome cap from mandrel**



Collapsible tooling eliminates the need to freeze part to release dome cap from mandrel

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Accomplishments and Progress

PNNL

Cost Model Update with DOE Guidance on Carbon Fiber Cost

- Hybrid tanks save up to:
  - 17% Cost
  - 23% Composite Mass
- Nov. 28, 2012 – DOE H_2 Storage meeting to standardize tank cost modeling assumptions
- Largest factor is carbon fiber price
- CF = $13/lb for 500,000 tanks/year
- Hybrid tank cost model was updated from $11/lb to $13/lb carbon fiber
- Table compares tank cost and DOE measures for baseline and hybrid tanks 1 and 7 which exceeded target burst pressure

Summary Table		Baseline 129L	Filament Wound + Advanced Fiber Placement	
		Filament Wound	Tank 1 Layup	Tank 7 Layup
Composite Mass, kg	FW	76	63.4	56.2
	AFP		1.5	2.4
Total Composite Mass, kg		76	64.9	58.6
Composite Mass Savings		0%	15%	23%
Composite	FW	13.2	13.2	13.2
Placement Speed, kg/hr	AFP		0.9	0.9
Composite	FW	5.75	4.80	4.25
Placement Time, hr/tank	AFP		1.65	2.64
Total Place Time, hr/tank		5.75	4.80	4.25
# Manuf. Cells for 500K/yr	FW	191	159	142
	AFP		165	264
Tank Costs				
FW Composite		$2,604	$2,172	$1,926
AFP Composite			$103	$164
End Boss		$250	$250	$250
Manuf. Equipment		$36	$41	$45
Factory Space		$7	$7	$8
Total Tank Cost		$2,897	$2,573	$2,393
% Tank Cost Savings		0%	11%	17%
DOE Measures				
Specific Energy, kWh/kg [1]		1.50	1.67	1.78
Cost Efficiency, $/kWh [2]		$25.34	$23.40	$22.31
[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)				

Cost advantage of hybrid design is even higher with higher carbon fiber cost

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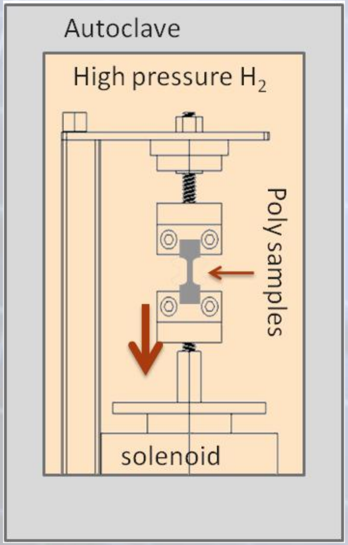
Accomplishments and Progress

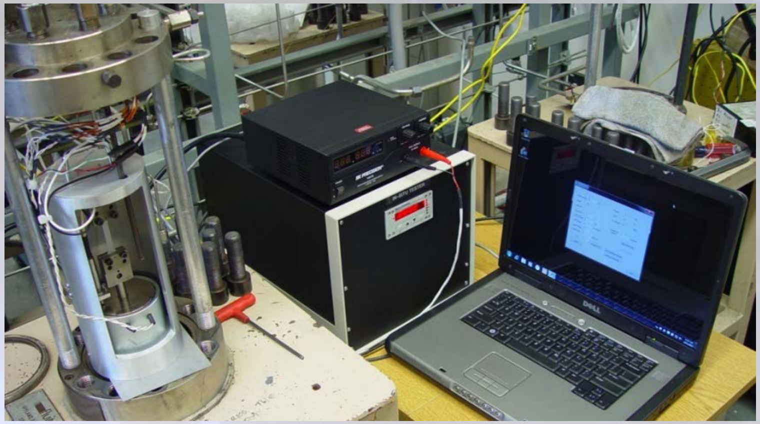
PNNL

Polymer Tank Liner Hydrogen Compatibility – In situ Testing





- **Upgraded In-situ tester**
  - Added feedback loop for constant strain rate
  - Rigid frame to remove flexing during testing
  - Increased extension range by 2x to ensure UTS (ultimate tensile strain) is measured (in progress)
  - Better software/hardware control for much improved reproducibility
  - In final stages of debugging – then testing



Constant strain rate is now achievable with in situ testing

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

Proposed Future Work

FY13

- Optimize mWind algorithm to match fabrication process
  - Investigate methods to model bridging
- Design and build vessels with baseline 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
  - Impact test
- Implement the collapsible tool for releasing dome caps
- Complete analysis of high pressure hydrogen in situ tensile tester and compile report
- Final cost model analysis of new vessel designs

Project Summary

- mWind generates improved models versus kWind for hybrid vessel analyses and designs
- CT scan data used to improve fiber buildup prediction
- Avoided wrinkling in initial AFP dome cap plies by eliminating the FEP release film
- Developed a collapsible tool concept to enable quick release of preformed dome caps
- Updated cost model with standardized carbon fiber cost
- Improved 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.

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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)						

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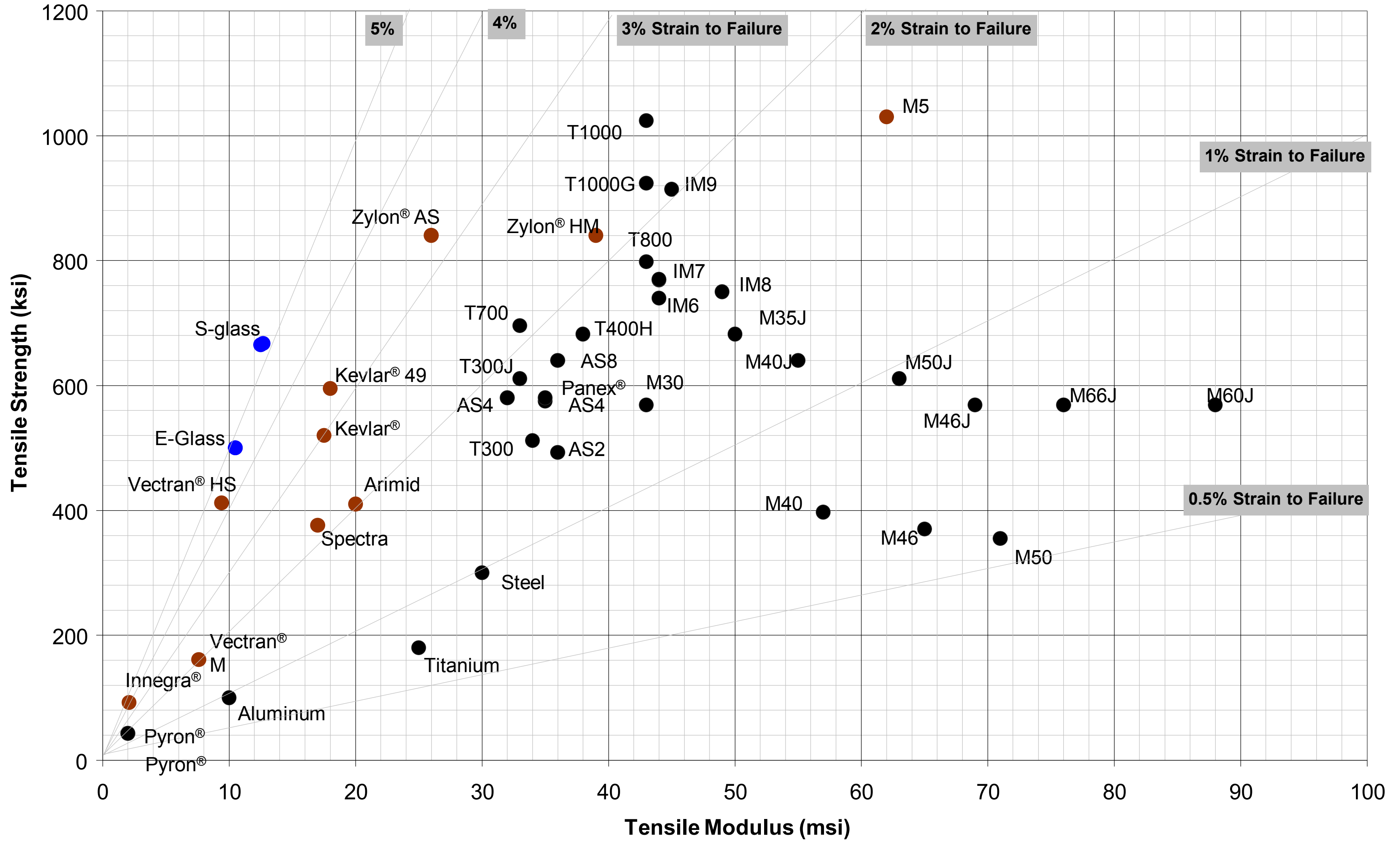
Fiber Properties



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

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