2014 DOE Hydrogen and Fuel Cells Program

Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels

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Project ID # MN008

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Overview

Timeline

- Project start date: 09/2008
- Project end date: 09/2014

Budget

- Total Funding Spent*: $5,068,361
- Total Project Value: $5,068,361
- DOE Share: $2,924,826
- Cost Share Percentage: 40%

* as of 3/31/14

Barriers

Hydrogen Storage

- M. Lack of Low-cost Carbon Fiber
- N. 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)

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

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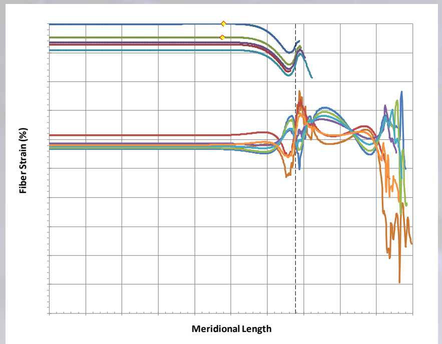
Overall Approach

Quantum, Boeing, PNNL

- QT modified the existing in-house software to support hybrid vessel designs for reducing carbon fiber usage
- QT designed the hybrid vessels
- Boeing built the AFP dome caps per QT designs
- QT installed the dome caps and manufactured the vessels with FW
- QT performed tests per EC79/2009 standard to verify the vessel designs using the latest software
- Test result confirmed the software was sufficient for hybrid vessel designs
- PNNL prepared cost model to compare baseline and hybrid vessels
- PNNL studied polymer liner compatibility in hydrogen



Approach

Quantum

- **Tests Completed per EC79/2009**

Test	Passing Criteria
Burst	Burst pressure to exceed 157.5 MPa (2.25 x 70 MPa)
Ambient Cycle	Cycle count ≥ 15,000 times with no leakage
Accelerated Stress Rupture	Burst pressure to exceed 133.9 MPa (85% x 157.5 MPa)
Impact Damage	No rupture within the first 9,000 cycles (0.6 x 15,000 cycles) and may fail by leakage afterward
Extreme Temperature Cycle	No leakage during leak test, Burst pressure to exceed 133.9 MPa (85% x 157.5 MPa)

These tests are the most critical/influential to the hybrid design

- **Validated modeling software with burst test result**

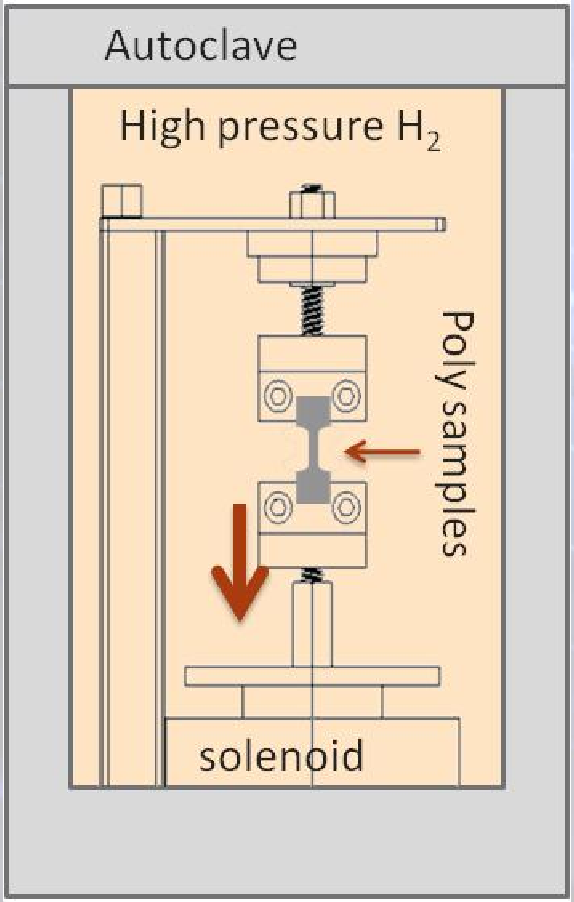
Approach
Boeing

- **Continuous Quality Improvements on AFP Dome Caps**
  - Software re-programming
  - Upgraded fiber creel system

Approach

PNNL

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



In-situ tensile testing

Accomplishments and Progress

Quantum

Test to be performed

Design objective

Non-destructive verification method

Burst Test

Vessel 13
Achieved 91% of target burst pressure

Improved bridging and voids on the aft end

2012

2013

Burst Test

Vessel 14
Achieved 90% of target burst pressure

High Speed Camera

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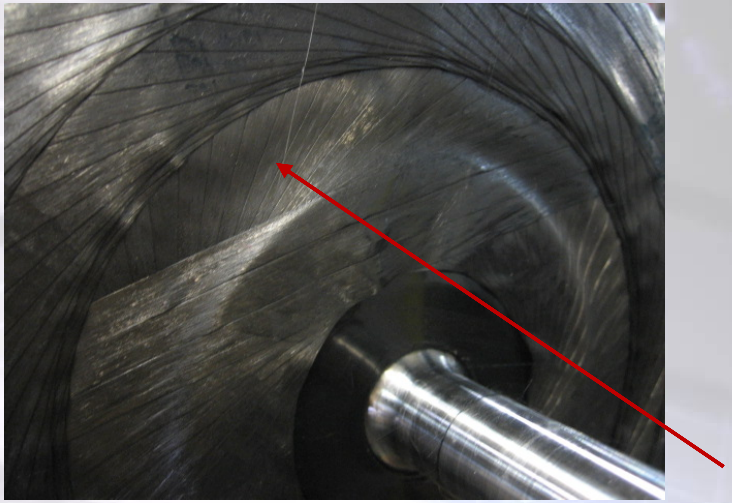
Accomplishments and Progress

Quantum

- Vessel 14
  - Reduced composite weight by 5.7% from previous design by
    - Reducing AFP dome cap layers
    - Optimizing FW layup
  - Aft AFP dome cap design had a dip (potentially cause composite voids)
  - Burst pressure was 90% of requirement



Composite layup redesign of Vessel 14 reduced composite usage and weight by 5.7%

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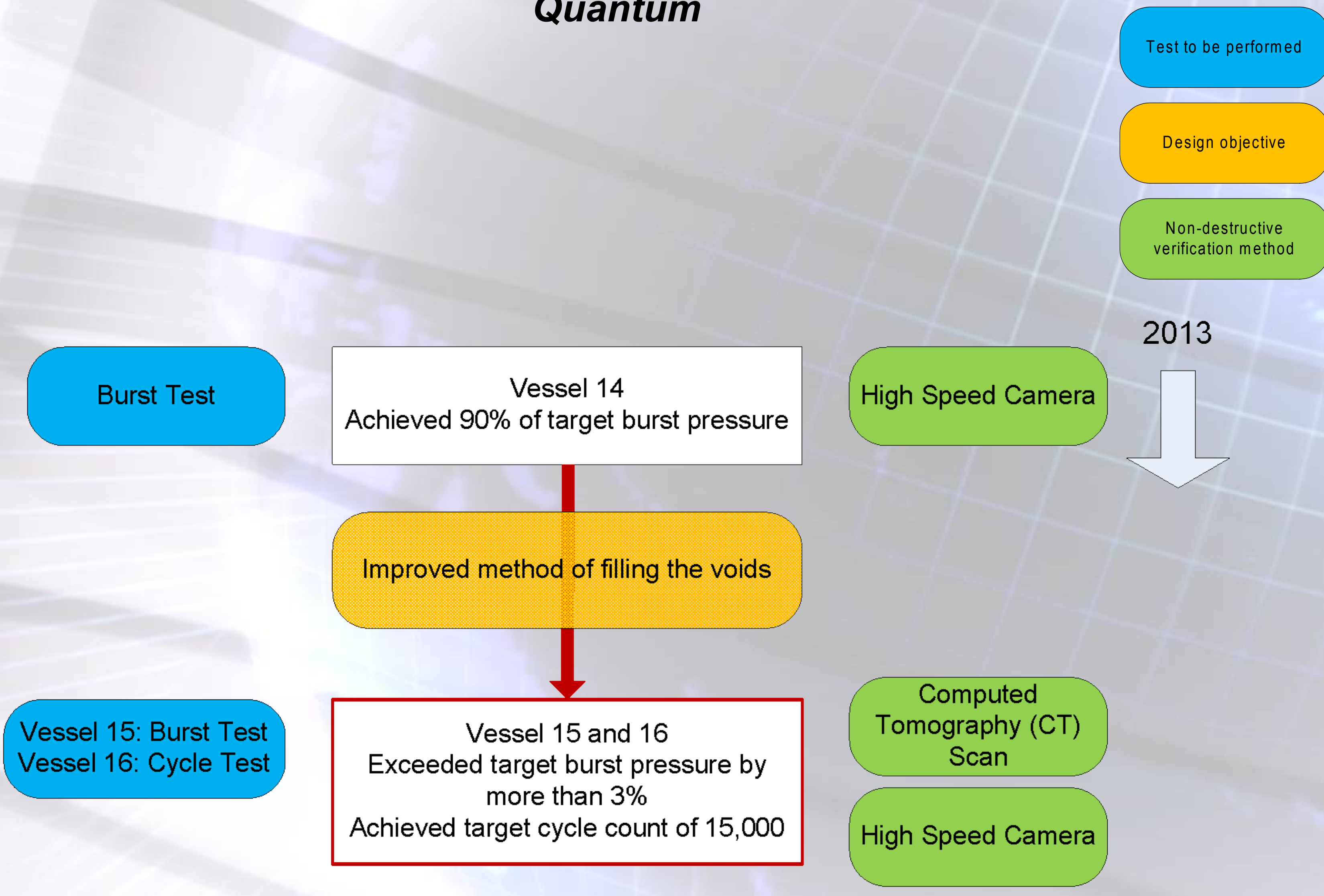
Accomplishments and Progress

Quantum



Accomplishments and Progress

Quantum

- Vessel 15 & 16
  - Same AFP dome cap design as Vessel 14
  - Filled the dip on the AFP dome cap with carbon fiber woven fabric rings

  - CT scan showed no voids

  - Vessel 15 – Achieved 103% of required burst pressure in mid cylinder
    Confirmed the in-house software is sufficient for hybrid design

  - Vessel 16 – Achieved target cycle test count of 15,000

Test results showed the latest design meets EC79 burst and cycle requirements

Accomplishments and Progress

Quantum

Test to be performed

Non-destructive verification method

Vessel 15: Burst Test
Vessel 16: Cycle Test

Vessel 15 and 16
Exceeded target burst pressure by more than 3%
Achieved target cycle count of 15,000

Computed Tomography (CT) Scan

High Speed Camera

Manufactured per Vessel 15 design

Vessel 17: Accelerated Stress Rupture Test
Vessel 18: Impact Damage Test

Vessel 17 and 18
Exceeded target burst pressure after Accelerated Stress Rupture Test by more than 14%
Achieved target cycle count of 11,658 before leak after Impact Damage Test

Accomplishments and Progress

Quantum

- Vessel 17 & 18
  - Identical design to Vessel 15
  - Vessel 17 (Accelerated stress rupture test) – Achieved 114% of the required burst pressure

Vessel 17 showed the hybrid design is resistant to creep degradation at high temperature

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Accomplishments and Progress

Quantum

- Vessel 18 (Impact damage test) – Achieved cycle count of 11,658 before leakage

Vertical drop

Horizontal drop

45° drop

- Post test analysis shows large gap between fiber placed domes and liner, resulting in leakage

Design was sufficient to meet drop requirement
Process improvement required for better fit between AFP and liner

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Accomplishments and Progress

Quantum

Test to be performed

Vessel 17: Accelerated Stress Rupture Test
Vessel 18: Impact Damage Test

Vessel 17 and 18
Exceeded target burst pressure after Accelerated Stress Rupture Test by more than 14%
Achieved target cycle count of 11,658 before leak after Impact Damage Test

Continue manufacturing per Vessel 15 design

Vessel 19: Extreme Temperature Pressure Cycle Test

Vessel 19
Achieved cycle count of 3,679

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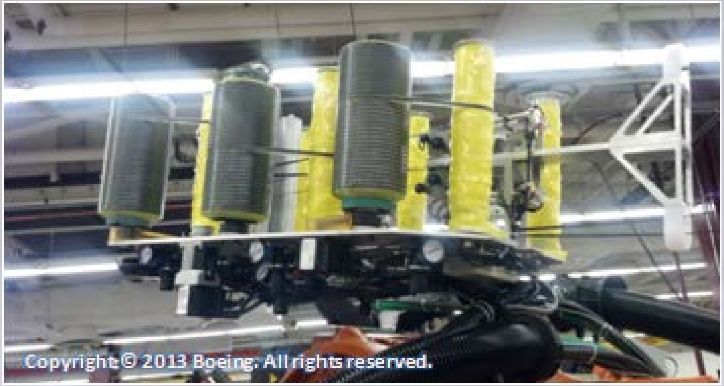
Accomplishments and Progress

Boeing

Continuous Quality Improvements

- Improved fiber placement
  - Within 2° of the angle specified
  - Within 0.05 inch of polar openings
- Upgraded fiber creel system
  - New smart-motor control system
  - Newly designed dancer system
    - Dynamically-control, closed-loop-active tow tensioning
    - Allowing for consistent tension on each tow regardless of tow direction or speed



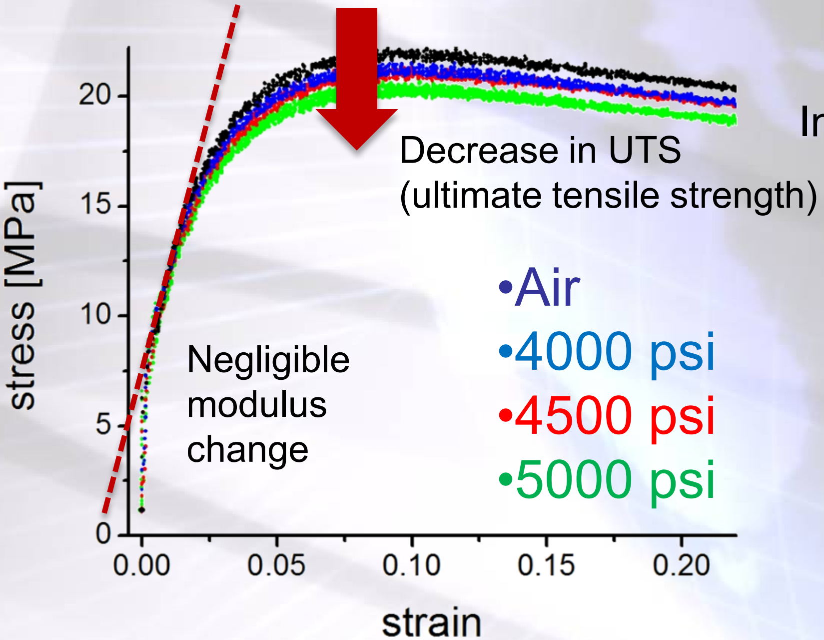
High consistency from part to part

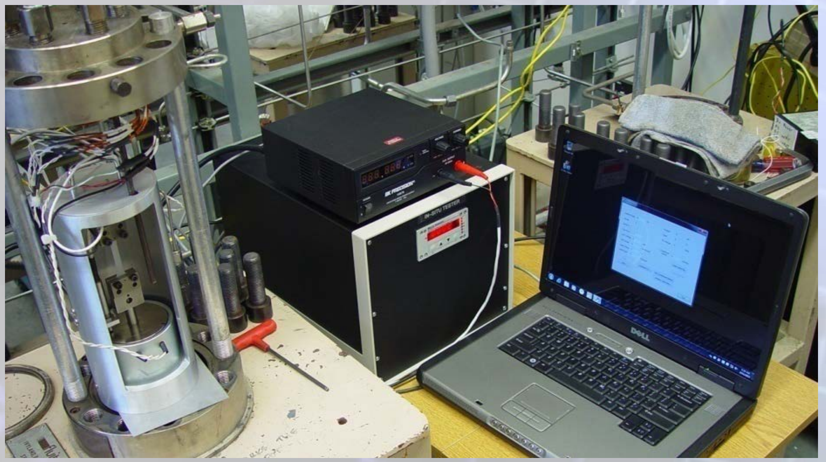
Accomplishments and Progress

PNNL

In-situ High Pressure Hydrogen Testing

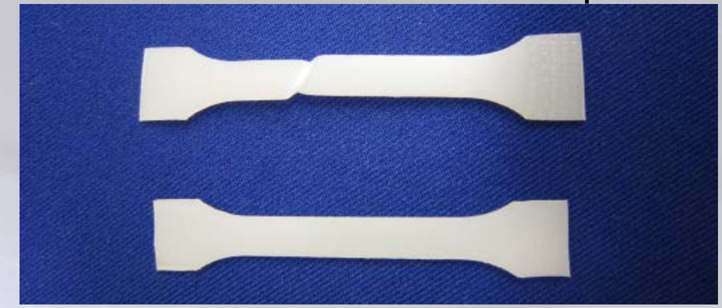
- In-situ tensile tests of HDPE liner material in high pressure hydrogen
  - Upgraded in-situ tensile tester
  - 100% hydrogen at 4000 psi, 4500 psi, 5000 psi tests





In-situ tensile tester for high pressure hydrogen

Pulled HDPE mini tensile sample



As cut HDPE mini tensile sample

Noticeable drop in UTS with negligible change in modulus when hydrogen pressure increases

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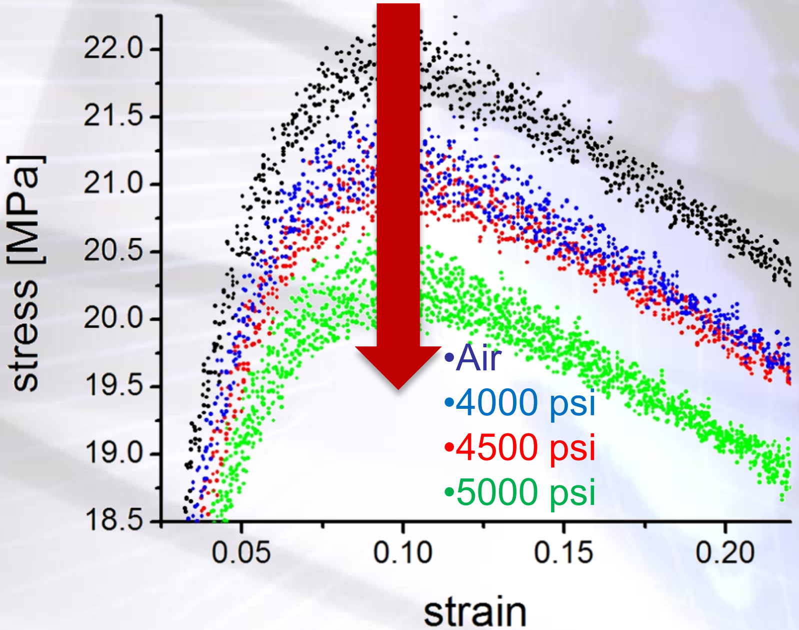
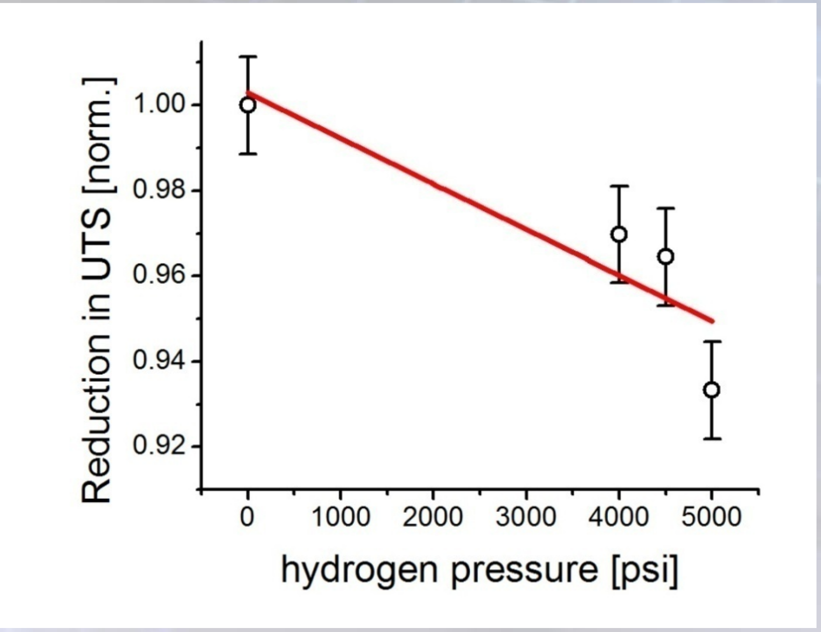
Accomplishments and Progress

PNNL

In-situ High Pressure Hydrogen Testing (Cont.)

- Results of high pressure tensile testing
  - Noticeable decrease in UTS with increasing pressure; ~ 6% decrease at 5,000 psi
  - Potential non-linear behavior with higher pressures
  - No dilation observed upon pressurization – indicates increase in flow/lubricity
  - Small or no change in modulus





6% decrease in UTS when hydrogen pressures increases from 0 to 5,000 psi

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Accomplishments and Progress

PNNL

Cost Analysis of Advanced Hybrid Vessel Manufacturing Processes

- Cost model includes materials, labor, overhead, balance of system, manufacturing equipment, and factory space costs
- Quantum and Boeing experience provided manufacturing details to estimate $/kg of FW and AFP composites
- Hybrid composite design and testing provided the mass of FW and AFP composites used in successful vessel designs
- Designs showed separate manufacturing of AFP dome reinforcements was successful
- FW manufacturing compared with hybrid FW+AFP manufacturing
- The added cost of AFP material, manufacturing equipment, and factory space is small compared to the savings in FW composite.

Hybrid vessels save up to 20% in cost and 32% in composite mass

Accomplishments and Progress: Response to Previous Year Reviewers' Comments

The project was not reviewed last year

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

- Replace AFP end caps with localized FW process
- Incorporate polar boss feature into foam tool to minimize gap between AFP end cap and liner
- Investigate load transfer between AFP and FW due to different resin systems at extreme temperatures
- Study potential non-linear behavior of HDPE with higher pressures

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Project Summary

- Latest vessel design passed all planned tests per EC79
  - Burst test
  - Pressure cycle test
  - Accelerated stress rupture test
  - Impact damage test

  With the exception of
  - Extreme temperature cycle test
- Validated modeling software for hybrid design
- Load transfer between AFP and FW remains a challenge at extreme temperatures
- AFP process improvements to deliver parts with higher quality
- In-situ hydrogen tester built
- Approximately 6% decrease in UTS with hydrogen pressure increase from 0 to 5,000 psi
- Updated cost model with latest hybrid vessel design, showing a 20% cost and 32% composite mass savings compared to baseline vessel

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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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Comparison of Vessel Manufacturing Costs for 129L

Summary Table		Baseline 129L	Filament Wound + Advanced Fiber Placement		
		Filament Wound	Tank 1 Layup	Tank 7 Layup	Tank 15 Layup
Composite Mass, kg	FW	76	63.4	56.2	49.6
	AFP		1.5	2.4	1.9
Total Composite Mass, kg		76	64.9	58.6	51.5
Composite Mass Savings		0%	15%	23%	**32%**
Composite	FW	13.2	13.2	13.2	13.2
Placement Speed, kg/hr	AFP		0.9	0.9	0.9
Composite	FW	5.75	4.80	4.25	3.75
Placement Time, hr/tank	AFP		1.65	2.64	2.05
Total Place Time, hr/tank		5.75	4.80	4.25	3.75
# Manuf. Cells for 500K/yr	FW	191	159	142	125
	AFP		165	264	205
Tank Costs					
FW Composite		$2,604	$2,172	$1,926	$1,699
AFP Composite			$103	$164	$128
End Boss		$250	$250	$250	$250
Manuf. Equipment		$36	$41	$45	$40
Factory Space		$7	$7	$8	$7
Total Tank Cost		$2,897	$2,573	$2,393	$2,124
% Tank Cost Savings		0%	11%	17%	**27%**
DOE Measures					
Specific Energy, kWh/kg [1]		1.50	1.67	1.78	1.93
Cost Efficiency, $/kWh [2]		$25.34	$23.40	$22.31	$20.70
[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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Comparison of Vessel Manufacturing Costs Based on New DOE Record for 129L

Summary Table		Baseline 129L	129L Filament Wound + Advanced Fiber Placement		
		Filament Wound	Tank 1 Layup	Tank 7 Layup	Tank 15 Layup
Composite Mass, kg	FW	76	63.4	56.2	49.6
	AFP		1.5	2.4	1.9
Total Composite Mass, kg		76	64.9	58.6	51.5
Composite Mass Savings		0%	15%	23%	**32%**
Composite	FW	13.2	13.2	13.2	13.2
Placement Speed, kg/hr	AFP		0.9	0.9	0.9
Composite	FW	5.75	4.80	4.25	3.75
Placement Time, hr/tank	AFP		1.65	2.64	2.05
Total Place Time, hr/tank		5.75	4.80	4.25	3.75
# Manuf. Cells for 500K/yr	FW	191	159	142	125
	AFP		165	264	205
Tank Costs					
FW Composite		$1,792	$1,495	$1,326	$1,169
AFP Composite			$71	$113	$88
End Boss		$14	$14	$14	$14
Liner		$23	$23	$23	$23
Balance of Plant		$940	$940	$940	$940
Assembly		$12	$12	$12	$12
Total Tank System Cost		$2,781	$2,554	$2,428	$2,246
% Tank Cost Savings		0%	8%	13%	**19%**
DOE Measures					
Specific Energy, kWh/kg [1]		1.5	1.7	1.8	**1.9**
Cost Efficiency, $/kWh [2]		$16.7	$15.3	$14.6	**$13.5**

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Comparison of Vessel Manufacturing Costs Based on New DOE Record for 147.3L

Summary Table		DOE 2013, 147.3L	147.3L Filament Wound + Advanced Fiber Placement		
		Filament Wound	Tank 1 Layup	Tank 7 Layup	Tank 15 Layup
Composite Mass, kg	FW	91	75.9	67.3	59.4
	AFP		1.8	2.9	2.2
Total Composite Mass, kg		91	77.7	70.2	61.6
Composite Mass Savings		0%	15%	23%	**32%**
Composite	FW	13.2	13.2	13.2	13.2
Placement Speed, kg/hr	AFP		0.9	0.9	0.9
Composite	FW	6.9	5.7	5.1	4.5
Placement Time, hr/tank	AFP		2.0	3.2	2.5
Total Place Time, hr/tank		6.9	7.7	8.3	6.9
# Manuf. Cells for 500K/yr	FW	229	191	170	150
	AFP		197	316	245
Tank Costs					
FW Composite		$2,146	$1,790	$1,588	$1,400
AFP Composite			$85	$136	$105
End Boss		$14	$14	$14	$14
Liner		$23	$23	$23	$23
Balance of Plant		$940	$940	$940	$940
Assembly		$12	$12	$12	$12
Total Tank System Cost		$3,134	$2,863	$2,712	$2,494
% Tank Cost Savings		0%	9%	13%	**20%**
DOE Measures					
Specific Energy, kWh/kg [1]		1.5	1.6	1.8	**1.9**
Cost Efficiency, $/kWh [2]		$16.8	$15.3	$14.5	**$13.4**

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