Low Cost, High Efficiency, High Pressure Hydrogen Storage

DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review
May 2004

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Project Objectives

Optimize and validate commercially viable, high performance, compressed hydrogen storage systems for transportation applications, in line with DOE storage targets of FreedomCar

- Lower weight and cost of storage system
  - Material optimization
  - Process evaluation
  - Use of lower cost carbon
- Reduce amount of material required through use of sensor technology to monitor storage system health
- Increase density of hydrogen by filling & storing at lower temperatures

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Budget

Description	Budget Amount
Direct Charges	$627,953
Indirect Charges	$854,082
Total Cost of Project	$1,482,035
DOE Share	$593,257
Quantum Share	$888,778

DOE Storage Targets

Parameter	Quantum Current	2005	2010	2015
Usable Specific Energy (kw hr / kg)	1.1 – 1.6	1.5	2	3
Usable Energy Density (kw hr / L)	1.3	1.2	1.5	2.7
Cost (165L bus tank) ($ / kw hr)	$73	$6	$4	$2
Cycle Life (Cycles, 1/4 tank to full)	15,000	500	1,000	1,500
Refueling Rate (kg H_2 / min)	2.0	0.5	1.5	2.0

Technical Barriers

- Sufficient fuel storage for acceptable vehicle range
  - Volume (Vehicle packaging limitation: bus vs. car or SUV)
  - Pressure (10ksi thick-walled pressure vessel challenges)
- Materials
  - Weight
  - Volume
  - Cost
  - Performance
- Balance-of-plant (BOP) components
  - Weight
  - Cost
  - Availability/development

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Technical Approach

- Optimize materials, design, and process to improve weight efficiency, costs, and performance
  - Increase fiber translation for 10ksi tank design
  - Optimize use of “Low-cost” fiber for 10ksi service
  - Minimize processing steps
- Develop sensor integration technique to improve weight efficiency and costs
  - Monitor composite strain to reduce design burst criteria from EIHP = 2.35(SP) to 1.8(SP)
- Study feasibility of hydrogen storage at lower temperatures to increase energy density
  - Develop techniques for maintaining “Cool Fuel”

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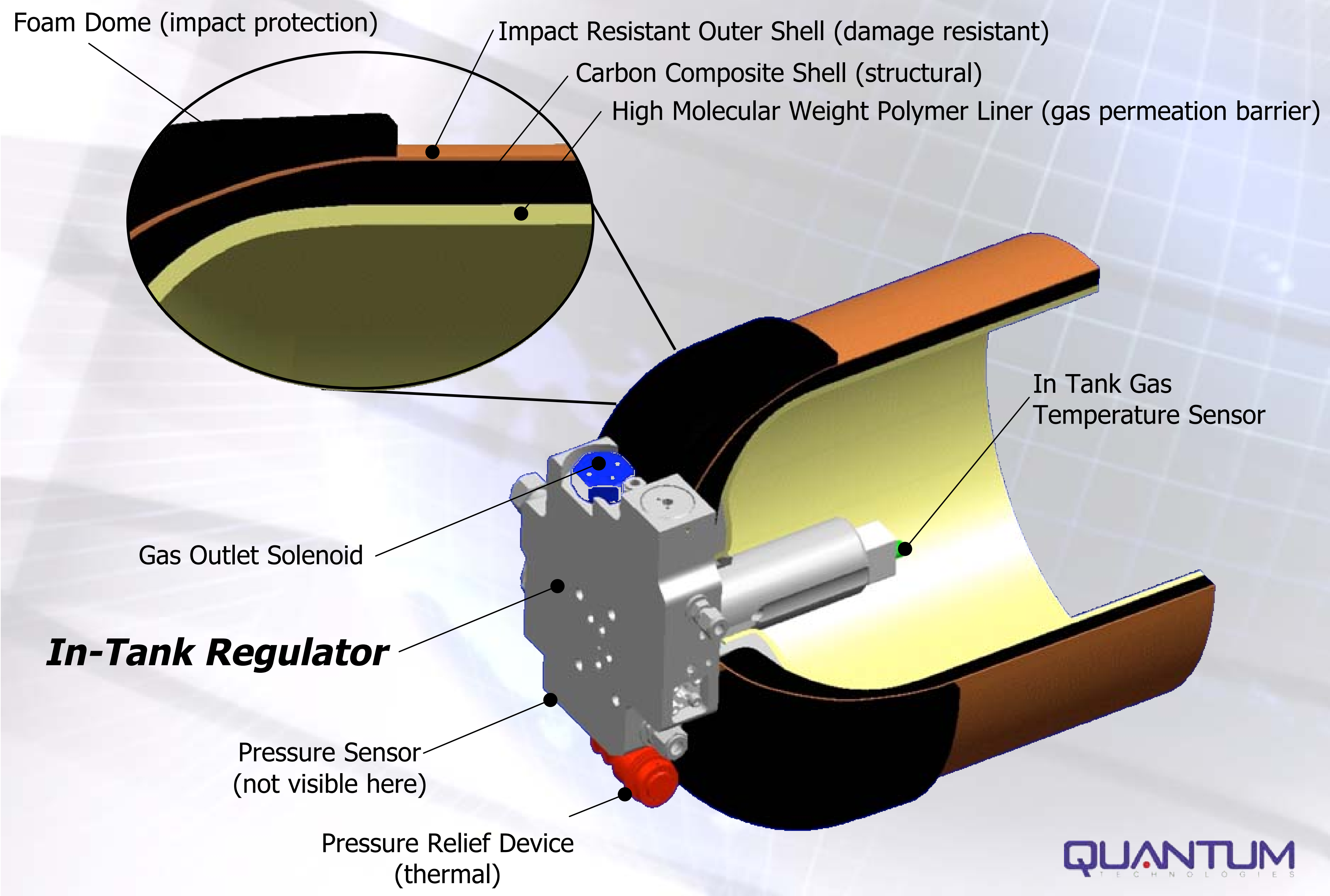
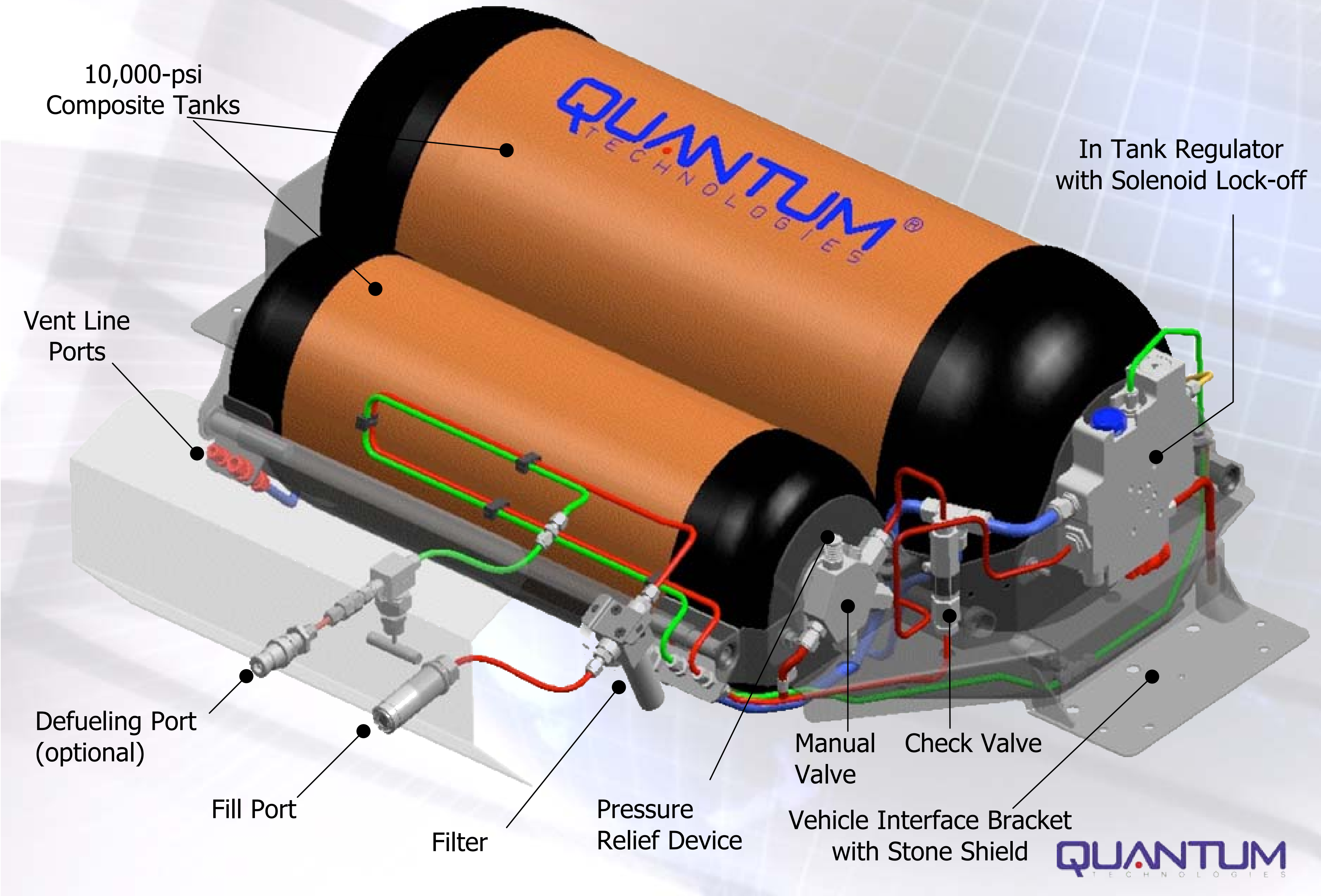
Compressed Hydrogen Type-IV Storage



Compressed Hydrogen Storage System



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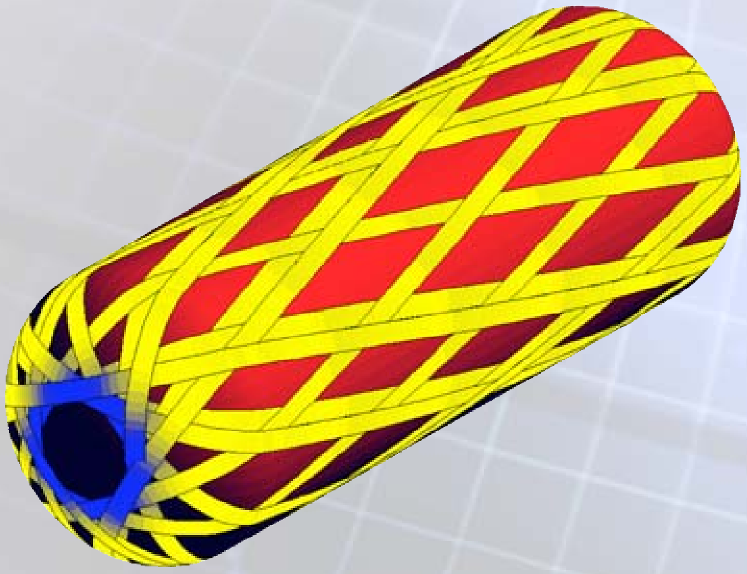
Optimization of materials & design



- Increasing fiber translation will reduce amount of fiber required
- Composite fibers have the maximum strength when pulled in pure tension
- Translation is the ratio of the actual fiber strength in a structure to the pure tensile strength
- Several factors improve fiber translation
  - Resin consolidation
  - Fiber wetting by resin
  - Reduced number of helical cross-overs
  - Load transfer to outer shell in thick-walled vessel

$$T = \frac{\sigma_{max}}{\sigma_f} = \frac{\sigma_{analysis} \times P_{burst}}{\sigma_f \times P_{analysis}}$$

$$\sigma_{max} = \sigma_{analysis} \frac{P_{burst}}{P_{analysis}}$$

$$\varepsilon_{max} = \varepsilon_{analysis} \frac{P_{burst}}{P_{analysis}}$$

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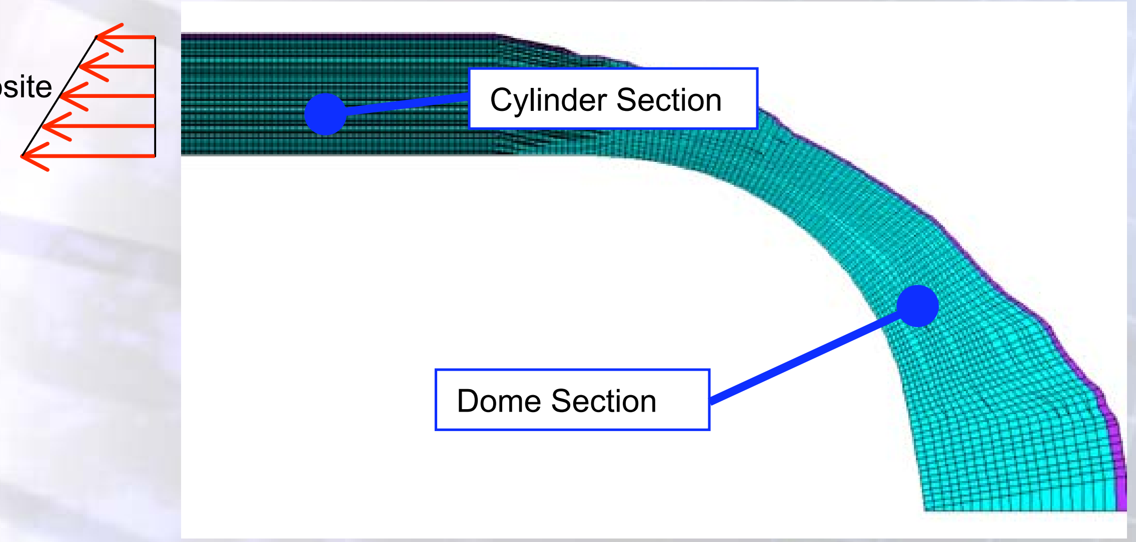
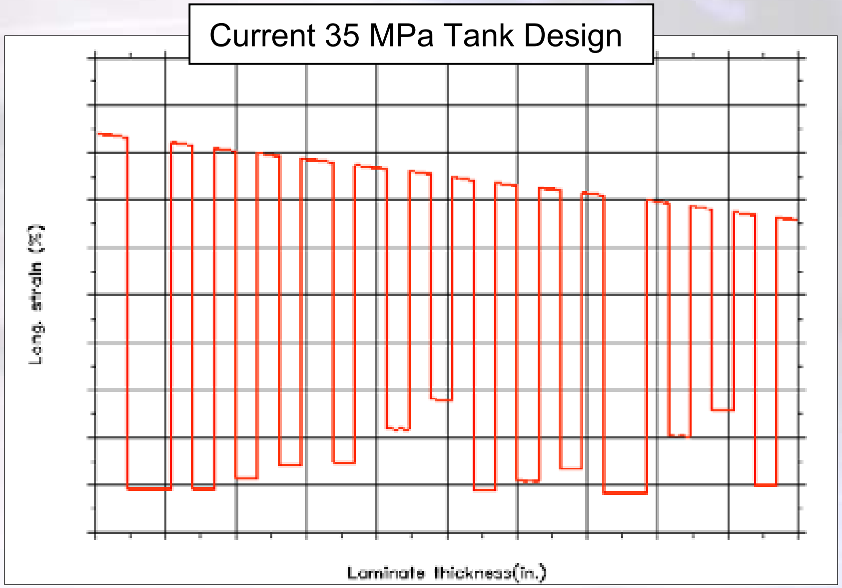
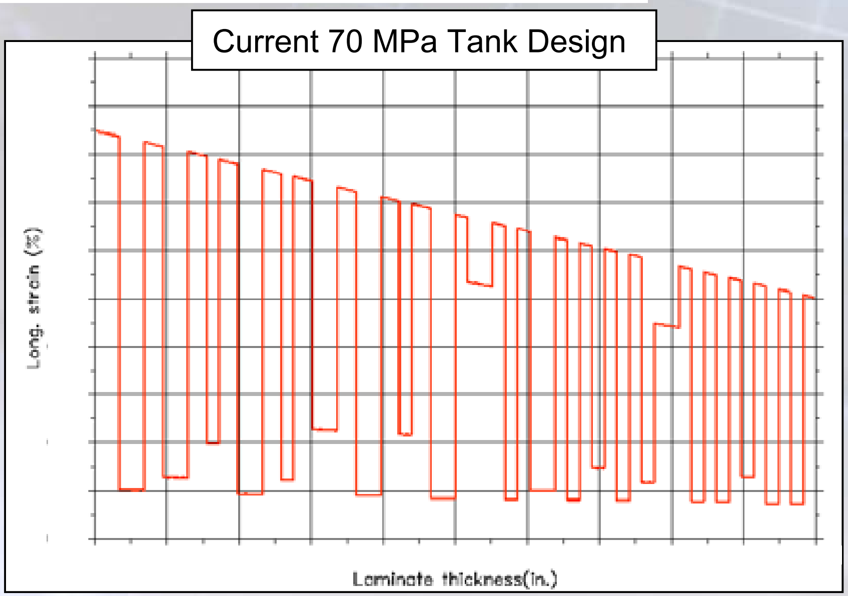
Optimization of materials & design

Fiber Stress/Strain
through the composite
thickness







Optimization of materials & design

- Current 35 MPa tanks achieve 78-85% fiber translation
  - Thin-walled Pressure Vessel
- Current 70 MPa tank achieve about 58-68% fiber translation
  - Thick-walled Pressure Vessel

Fiber	# of Filaments	Tensile Strength		Tensile Modulus		Elongation (%)	Approximate Dry Fiber Cost ($/kg)	Cost per Strength metric
		(ksi)	(MPa)	(ksi)	(GPa)			
High Performance	12K	900	6,370	42.7	294	2.2	$170	6.8
Mid Performance	18K	790	5,490	42.7	294	1.9	$58	2.6
Low Cost	24K	711	4,900	33.4	230	2.1	$20	1.0

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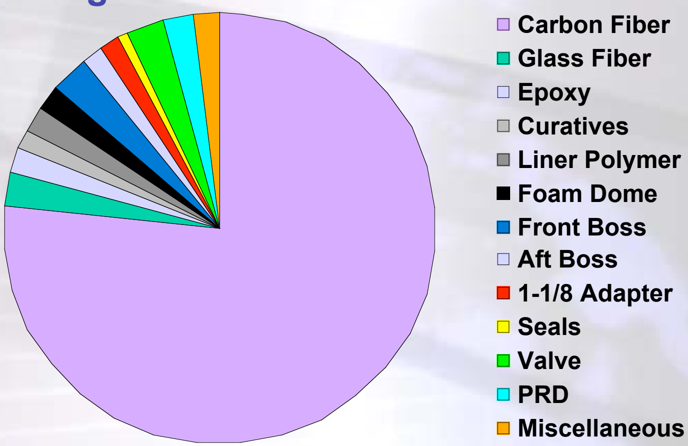
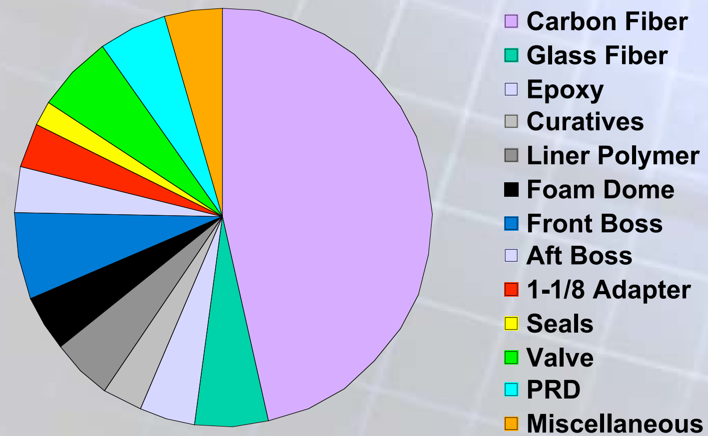
Cost Drivers

- Primary driver is material cost
  - 40 - 80% is carbon fiber cost
  - Significant opportunities for cost-reduction

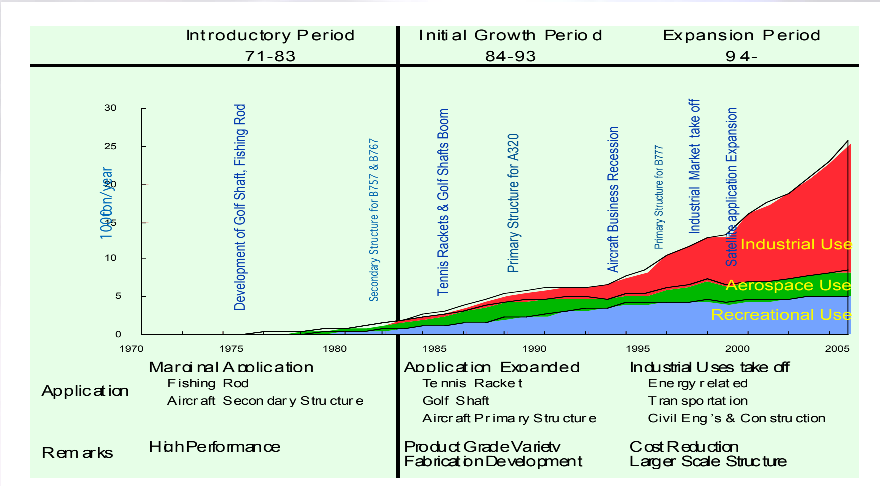
High Performance Fiber



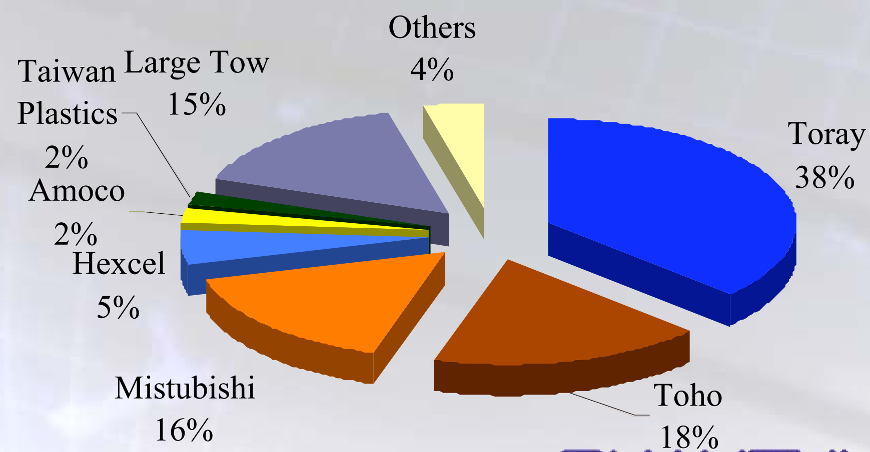
Low Cost Fiber



Carbon Fiber Worldwide Supply



Carbon Fiber Market Share



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Project Safety

Certification Status:

Storage Pressure	Approvals / Compliance
3,600 psi (250 bar)	NGV2-2000 (modified) DOT FMVSS 304 (modified)
5,000 psi (350 bar)	E.I.H.P. / German Pressure Vessel Code DBV P.18 NGV2-2000 (modified) FMVSS 304 (modified) KHK
10,000 psi (700 bar)	E.I.H.P. / German Pressure Vessel Code DBV P.18 FMVSS 304 (modified)

QUANTUM Participates in:

- E.I.H.P (European Integrated Hydrogen Project) Code Committee
- ISO Hydrogen Storage Standard Committee
- CSA – America NGV2 Hydrogen TAG

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Project Safety

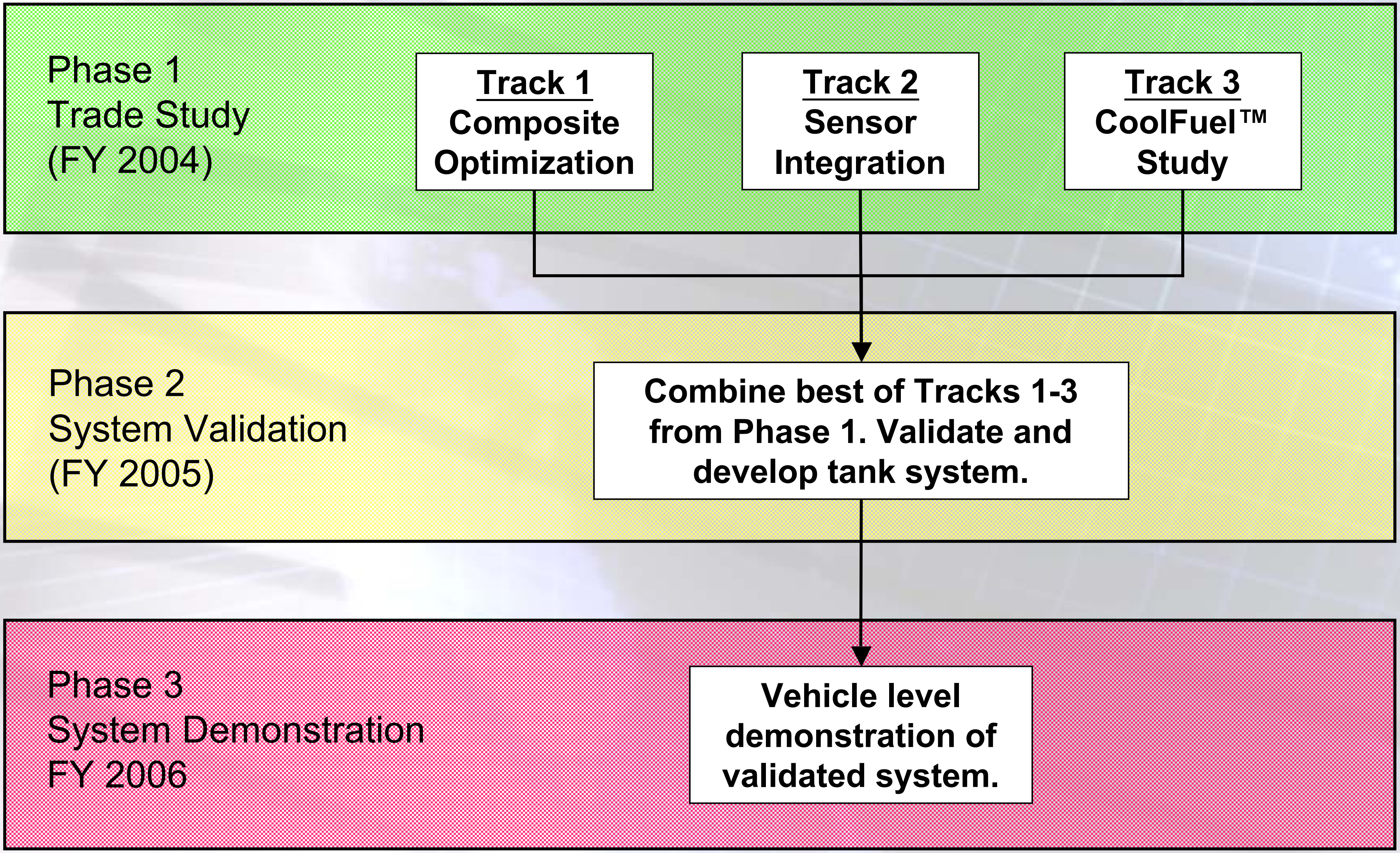
Regulatory Agency Approval

- ISO 15869 - **International**
- NGV2 - **US/Japan/Mexico**
- FMVSS 304 - **United States**
- NFPA 52 - **United States**
- KHK - **Japan**
- CSA B51 - **Canada**
- TÜV - **Germany**

Validation Tests

- Hydrostatic Burst
- Extreme Temperature Cycle
- Ambient Cycle
- Acid Environment
- Bonfire
- Gunfire Penetration
- Flaw Tolerance
- Accelerated Stress
- Drop Test
- Permeation
- Hydrogen Cycle
- Softening Temperature
- Tensile Properties
- Resin Shear
- Boss End Material

Project Timeline



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Phase 1 Milestones

Sensor Technology Selected and Integration Process Developed
7/04

Technical Results for All 3 Tracks Available
1/05

Jan 2004

July 2004

Jan 2005

Material, Design, and Process Optimized
9/04

CoolFuel™ Feasibility Study Complete
12/04

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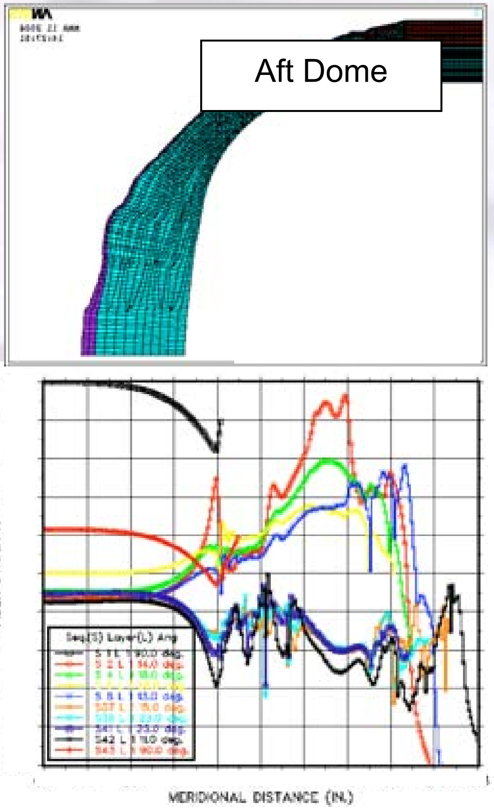
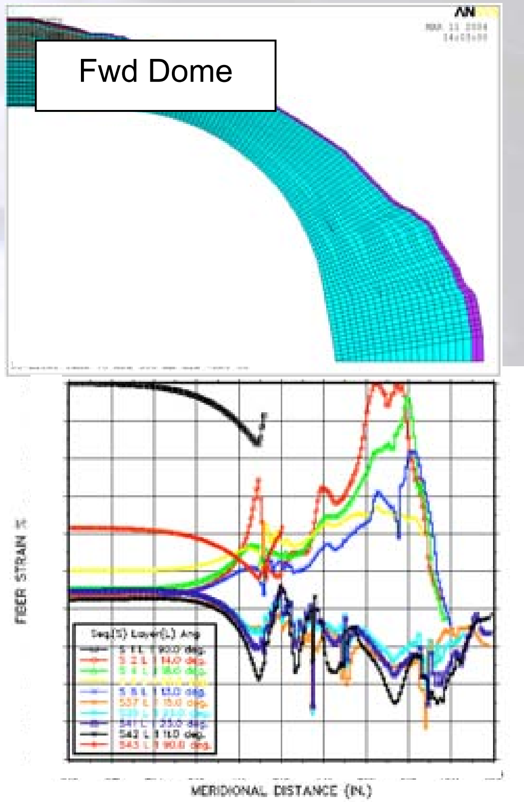
Accomplishments - Technical Progress

- Designed/built/tested "Baseline" 10ksi tanks
- Built and burst (2) 10ksi "Low Cost" tanks
- Initiated "Low Cost" design optimization
- Initiated effort to reduce fuel storage system manufacturing costs
- Tested fabrication techniques on "Baseline" tank with integrated sensors
- Initiated sensor technology evaluation
- Initiated develop of thermodynamic models for refueling refrigeration and passive system design

Accomplishments - Technical Progress

- Baseline tanks built and tested
  - 70MPa (10ksi), Mid-performance fiber, 28 Liter, 300mm x 801mm
  - Baseline material cost = $2600





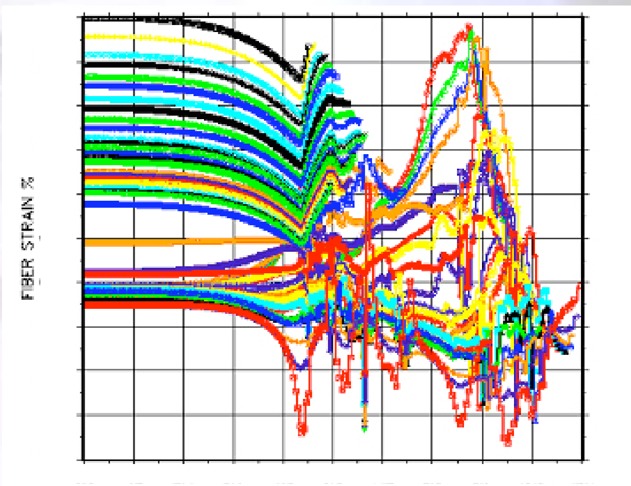
Tank	Burst Pressure		% of Required Burst
	(psi)	(MPa)	
#1	25,110	173.13	107%
#2	26,988	186.08	116%
#3	25,750	177.54	110%
Average	25,949	178.9	111%
Standard Deviation	955	6.6	
Coefficient of Variation	3.7%	3.7%	

Accomplishments - Technical Progress

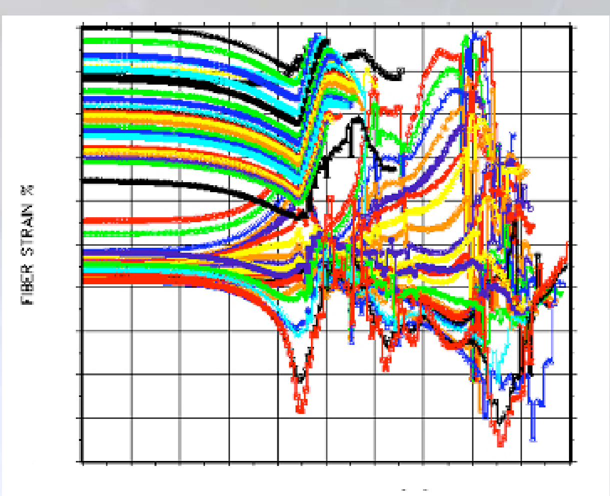
- Verification of 10ksi “Low Cost Fiber” tanks
  - Low cost fiber
    - Good mid-cylinder burst @ 25,250 psi
    - Material cost = $1600
  - Low cost fiber w/modified cure process
    - Good mid-cylinder burst @ 27,510 psi
    - Material cost = $1300

Accomplishments - Technical Progress

- Optimization of winding pattern
  - Investigating non-traditional winding patterns
  - Focused on increasing translation
- Promising results from first iteration
  - Reduced “Low-cost” fiber requirement by 10%
  - Reduced maximum fiber strain by 12%
  - Decreased Hoop-to-Helical stress ratio 8%



Baseline



Optimized

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Accomplishments - Technical Progress

- Sensor technology evaluation
  - Three sensor technologies are being investigated for feasibility, cost, complexity, sensitivity, service life and power consumption
    - Resistance strain gage Monitoring
    - Fiber-Optic Strain gage Monitoring
    - Acousto-Ultrasonic Monitoring
- Integrated sensors placement
  - Sensors wound into shell

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Accomplishments - Technical Progress

- Resistance strain gage monitoring
  - Advantages
    - Traditional method of monitoring strain levels in tank shell (good history)
    - Low cost sensor
    - Known level of performance
    - Known cost for signal conditioning
  - Disadvantages
    - Small gage areas (currently investigating “Belly Bands”)
    - Challenges to incorporate into tank shell
    - Need a large array of sensors

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Accomplishments - Technical Progress

- Fiber-Optic strain gage monitoring
  - Advantages
    - Can monitor large area of shell surface
    - Can be wound into composite shell with fiber
    - Has been testing in tank structures
  - Disadvantages
    - Signal generation and analysis size and cost
    - Fiber sensitive to pre-installation damage
    - Connector and cabling durability
    - Complexity and cost

Accomplishments - Technical Progress

- Acousto-Ultrasonic strain gage monitoring
  - Advantages
    - Sensor array can monitor large area of shell surface
    - Can be wound into composite shell with fiber
    - Low cost sensor
    - Can detect sudden damage due to impact
  - Disadvantages
    - Signal generation and analysis size and cost
    - Very limited real world testing
    - Indirect (non-strain) method of monitoring tank health
    - Complexity and cost

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Responses to Previous Year Comments

- Too much emphasis on weight reduction instead of safety, cost, and refueling
  - Safety → Weight → Cost
  - Refueling → Task 3 analytical effort
- Investigate more “out of the box” technology
- Not enough technical details provided on progress and future plans

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Future Plans

- Refueling Strategy
  - Thermal Management with Fast-Fill ('04)
- Structural Optimization
  - Tanks, Liners, Components ('04)
- Materials
  - Lower Cost Fibers
  - Strength & Cycle Life Trade-off
  - Liner Materials ('04)
- Vehicle Hydrogen Safety
  - Impact Simulation/Testing, Crash Statistics ('05)
- Smart Tanks
  - Integrated Sensor System to Support Lower Burst Ratio ('05)

Conclusions

- DOE 2005 performance targets are achievable
- Cost targets remain an industry-wide challenge
- Use of available low cost fiber and optimized winding technologies promise 60-80% cost savings
- Integrated sensor technologies promise improved safety as much as reducing cost
- Active and passive techniques for improving fuel density and fill rates continue to be investigated.
- Safety will remain an industry priority!