Low Cost, High Efficiency, High Pressure Hydrogen Storage

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

Ken Newell, PhD
Sr. Engineering Manager
Quantum Technologies, Inc.
Irvine, CA

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

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

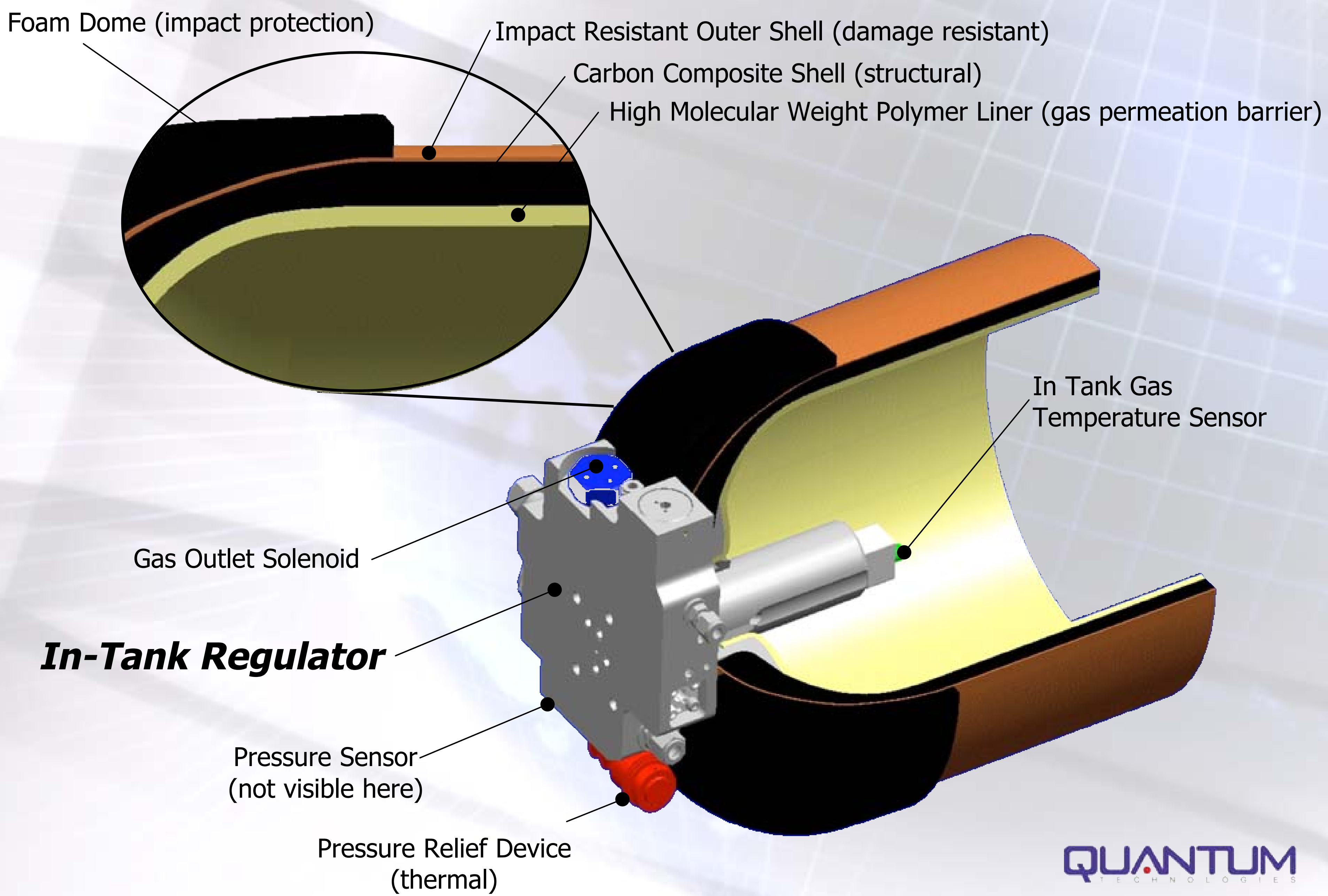
QUANTUM TECHNOLOGIES

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"

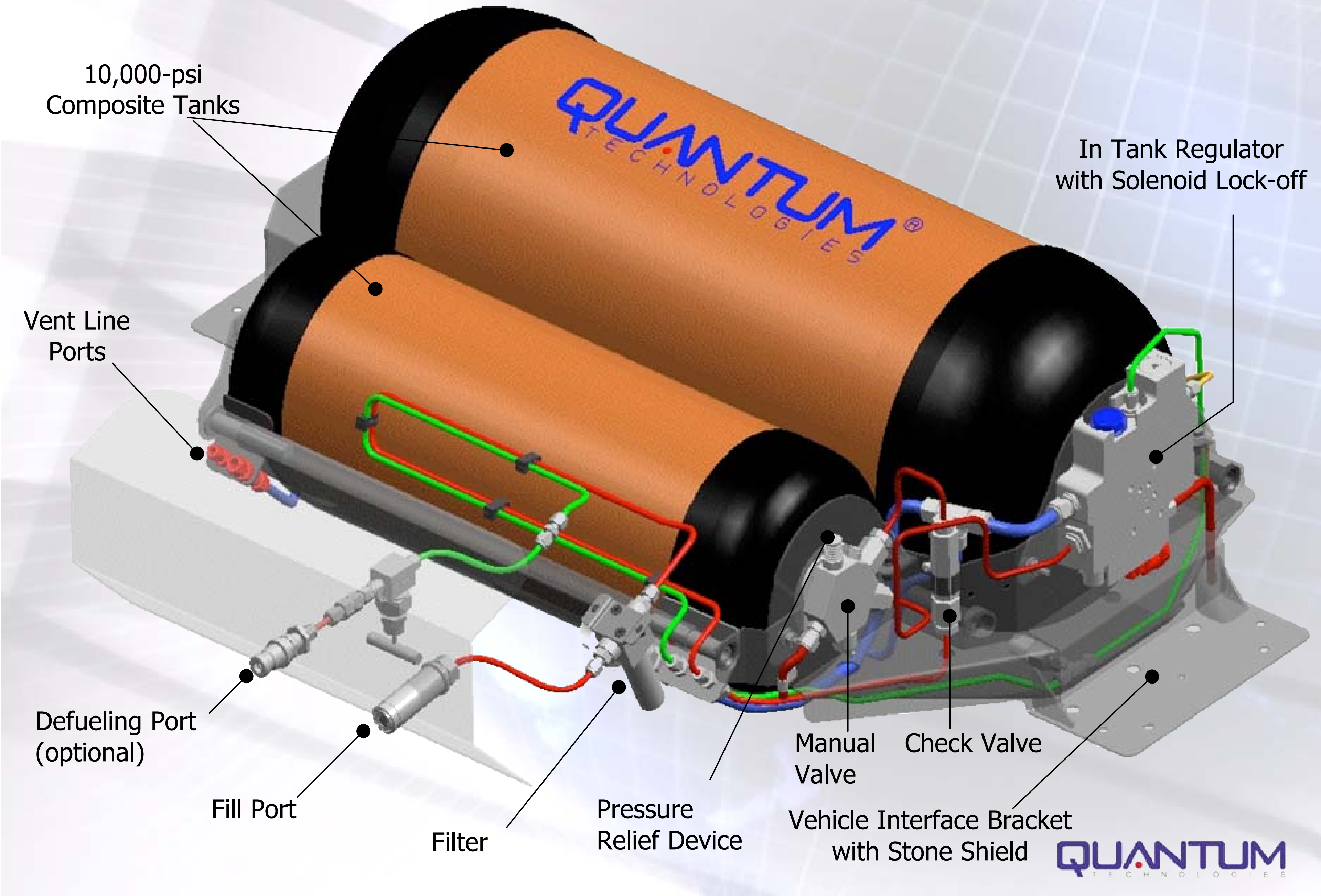
QUANTUM TECHNOLOGIES

Compressed Hydrogen Type-IV Storage



QUANTUM TECHNOLOGIES

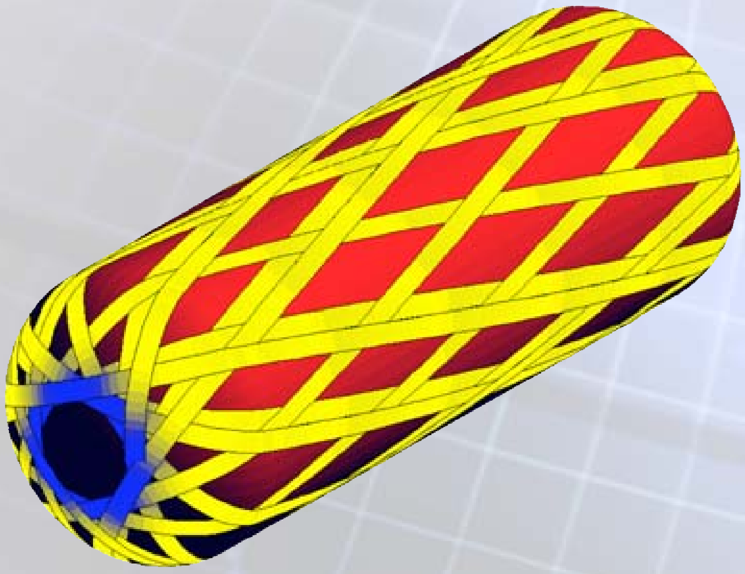
Compressed Hydrogen Storage System



QUANTUM TECHNOLOGIES

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 <u>actual</u> fiber strength in a structure to the <u>pure tensile</u> 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



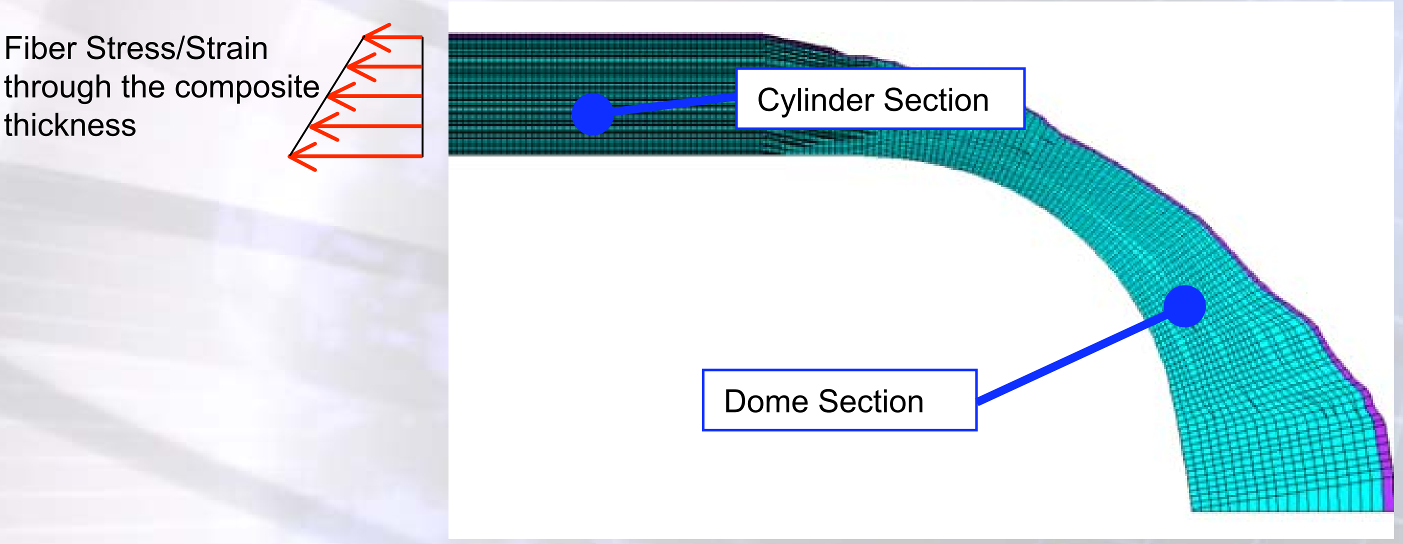
$$T = \frac{\sigma_{max}}{\sigma_f} = \frac{\sigma_{analysis} \times P_{burst}}{\sigma_f \times P_{analysis}}$$

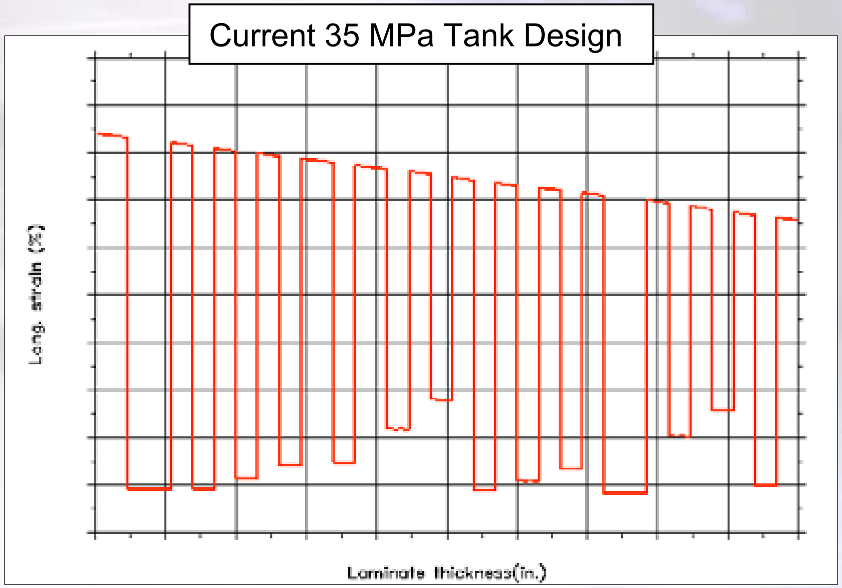
$$\sigma_{max} = \sigma_{analysis} \frac{P_{burst}}{P_{analysis}}$$

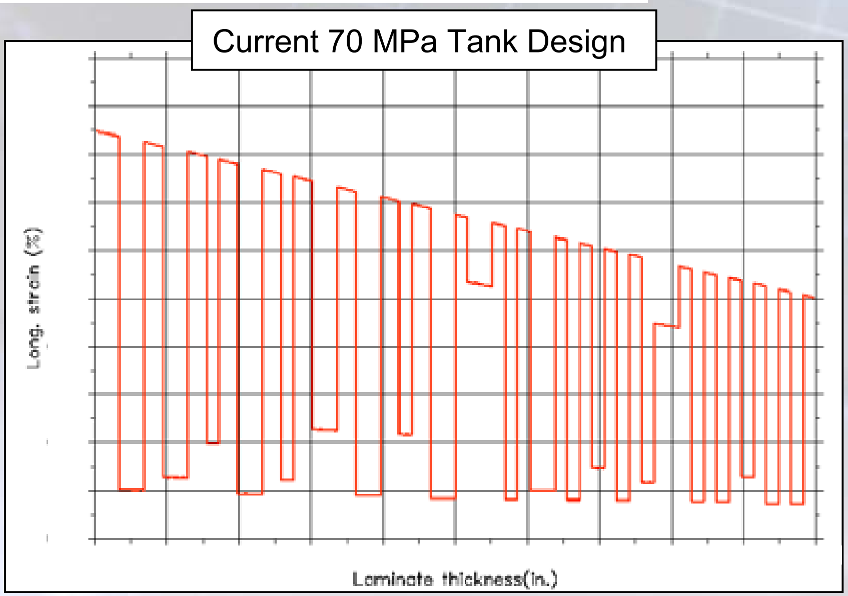
$$\varepsilon_{max} = \varepsilon_{analysis} \frac{P_{burst}}{P_{analysis}}$$

QUANTUM TECHNOLOGIES

Optimization of materials & design







QUANTUM TECHNOLOGIES

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

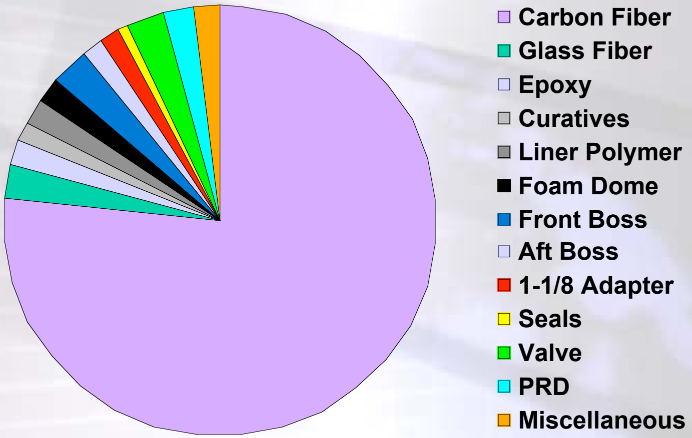
Fiber	# of Filaments	Tensile Strength		Tensile Modulus		Elongation (%)	Approximate Dry Fiber Cost ($/kg)	Cost per Strength metric
		(ksi)	(MPa)	(ksi)	(GPa)			
High Performance	12K	900	6,370	42.7	294	2.2	$170	6.8
Mid Performance	18K	790	5,490	42.7	294	1.9	$58	2.6
Low Cost	24K	711	4,900	33.4	230	2.1	$20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

QUANTUM TECHNOLOGIES

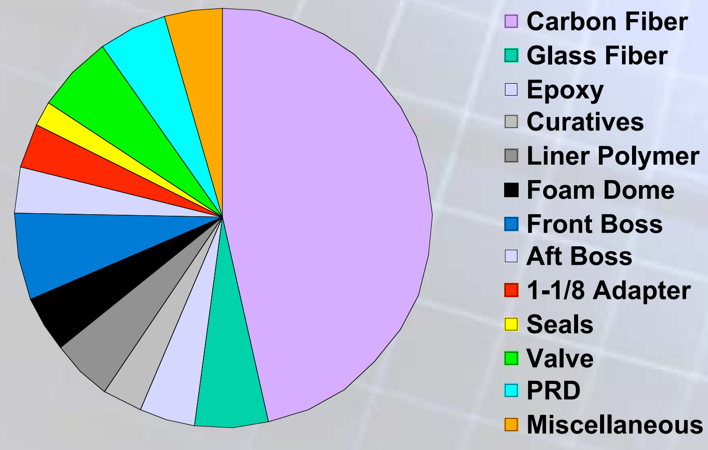
Cost Drivers

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

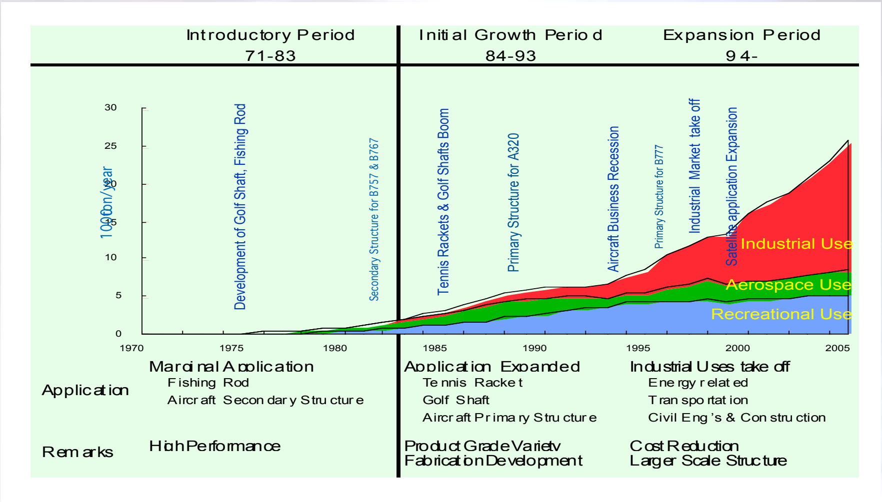
High Performance Fiber



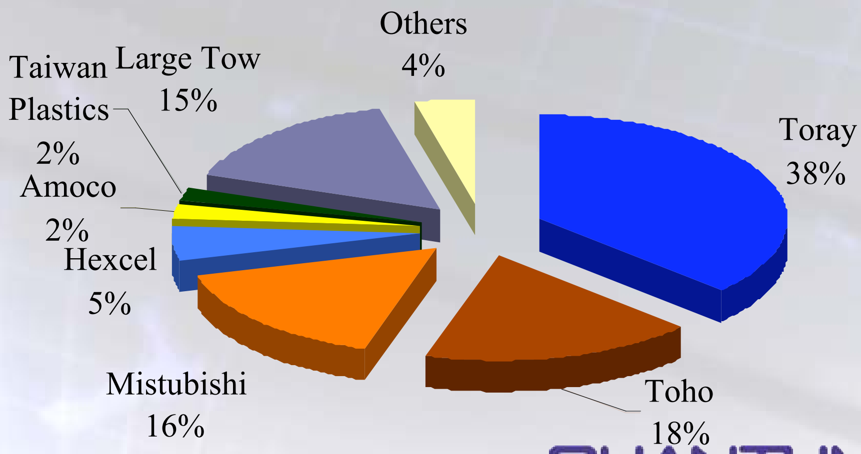
Low Cost Fiber



Carbon Fiber Worldwide Supply



Carbon Fiber Market Share



QUANTUM TECHNOLOGIES

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

QUANTUM TECHNOLOGIES

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

Phase 1
Trade Study
(FY 2004)

Track 1
Composite Optimization

Track 2
Sensor Integration

Track 3
CoolFuel™ Study

Phase 2
System Validation
(FY 2005)

Combine best of Tracks 1-3 from Phase 1. Validate and develop tank system.

Phase 3
System Demonstration
FY 2006

Vehicle level demonstration of validated system.

Phase 1 Milestones

Jan 2004

Sensor Technology Selected and Integration Process Developed
7/04

July 2004

Material, Design, and Process Optimized
9/04

CoolFuel™ Feasibility Study Complete
12/04

Technical Results for All 3 Tracks Available
1/05

Jan 2005

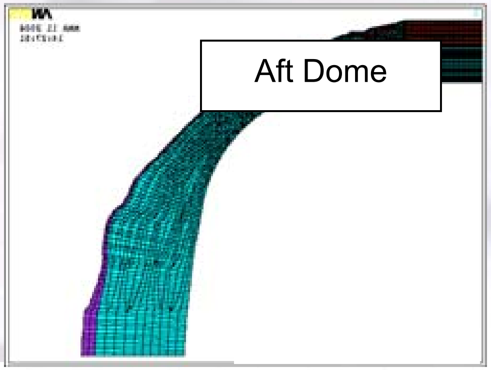
Accomplishments - Technical Progress

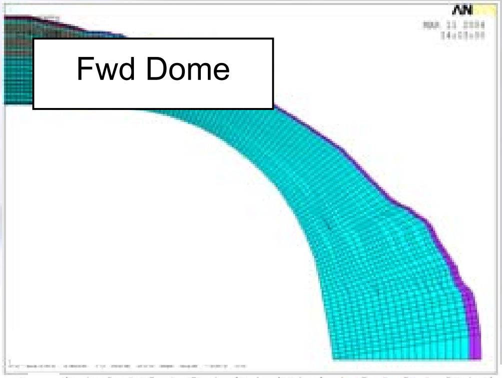
- Designed/built/tested “Baseline” 10ksi tanks
- Built and burst (2) 10ksi “Low Cost” tanks
- Initiated “Low Cost” design optimization
- Initiated effort to reduce fuel storage system manufacturing costs
- Tested fabrication techniques on “Baseline” tank with integrated sensors
- Initiated sensor technology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

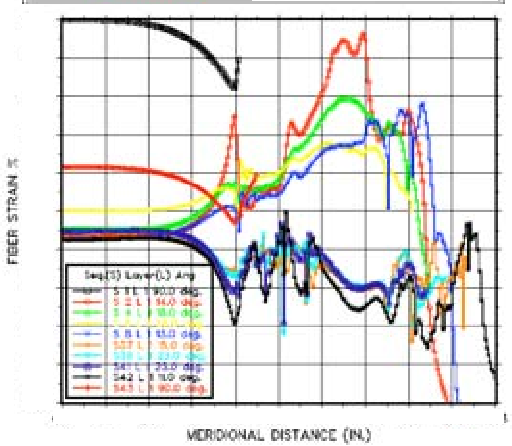
QUANTUM TECHNOLOGIES

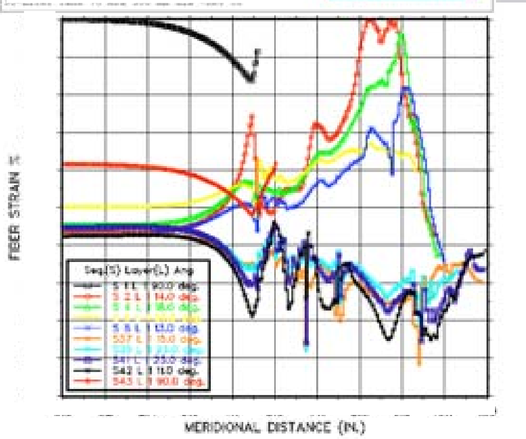
Accomplishments - Technical Progress

- 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%	

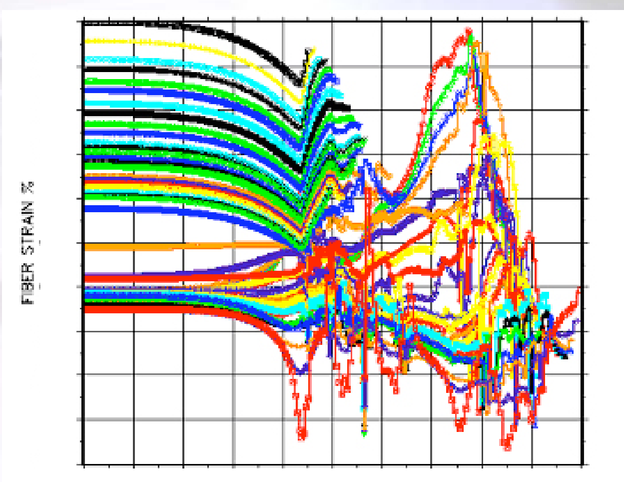
Accomplishments - Technical Progress

- 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

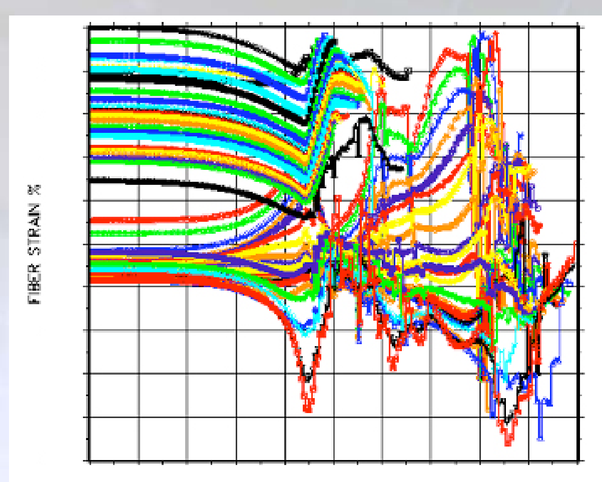
QUANTUM TECHNOLOGIES

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

QUANTUM TECHNOLOGIES

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

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

QUANTUM TECHNOLOGIES

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

QUANTUM TECHNOLOGIES

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

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

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!

QUANTUM TECHNOLOGIES