Low Cost, High Efficiency, High Pressure Hydrogen Storage

DoE Review
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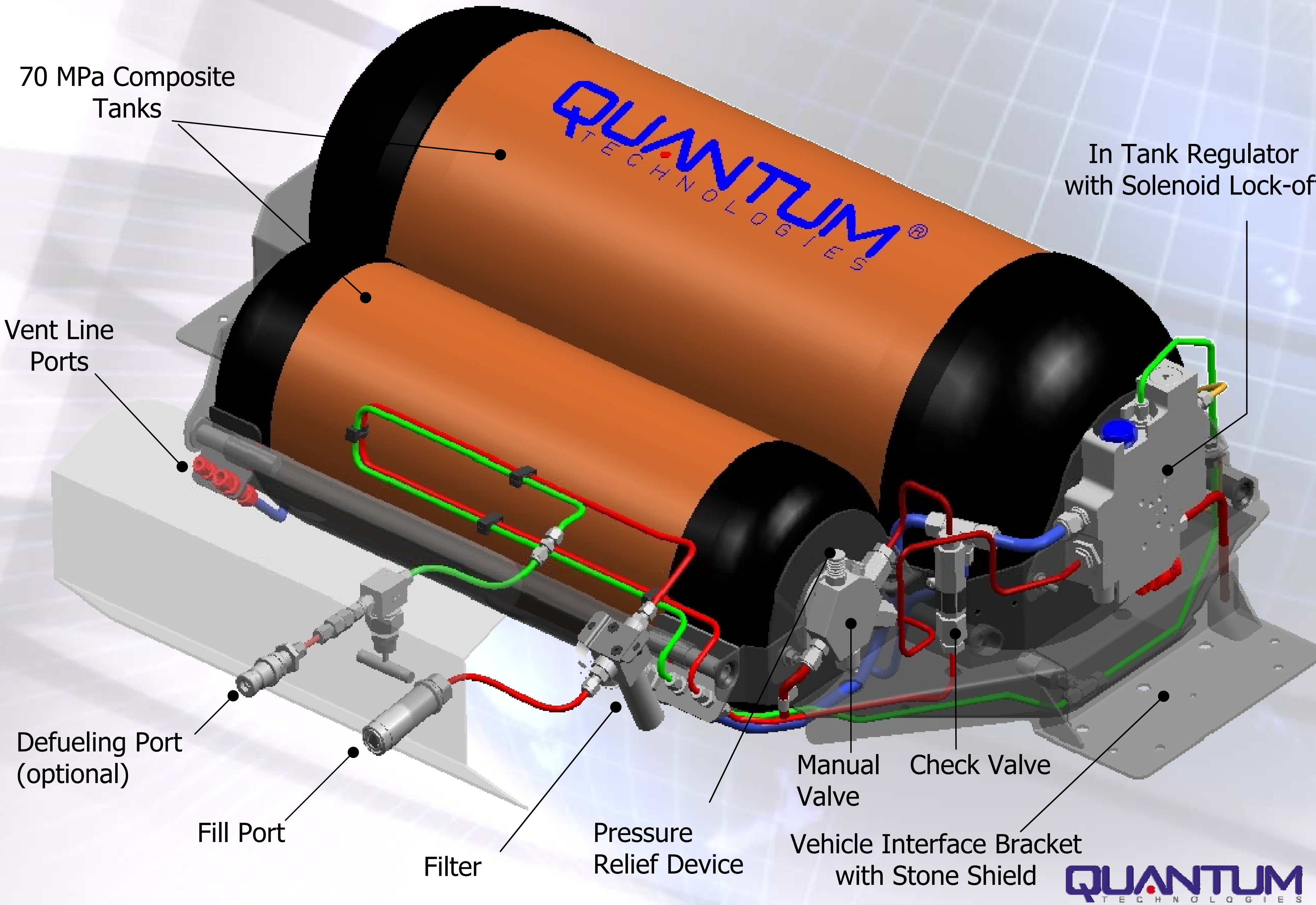
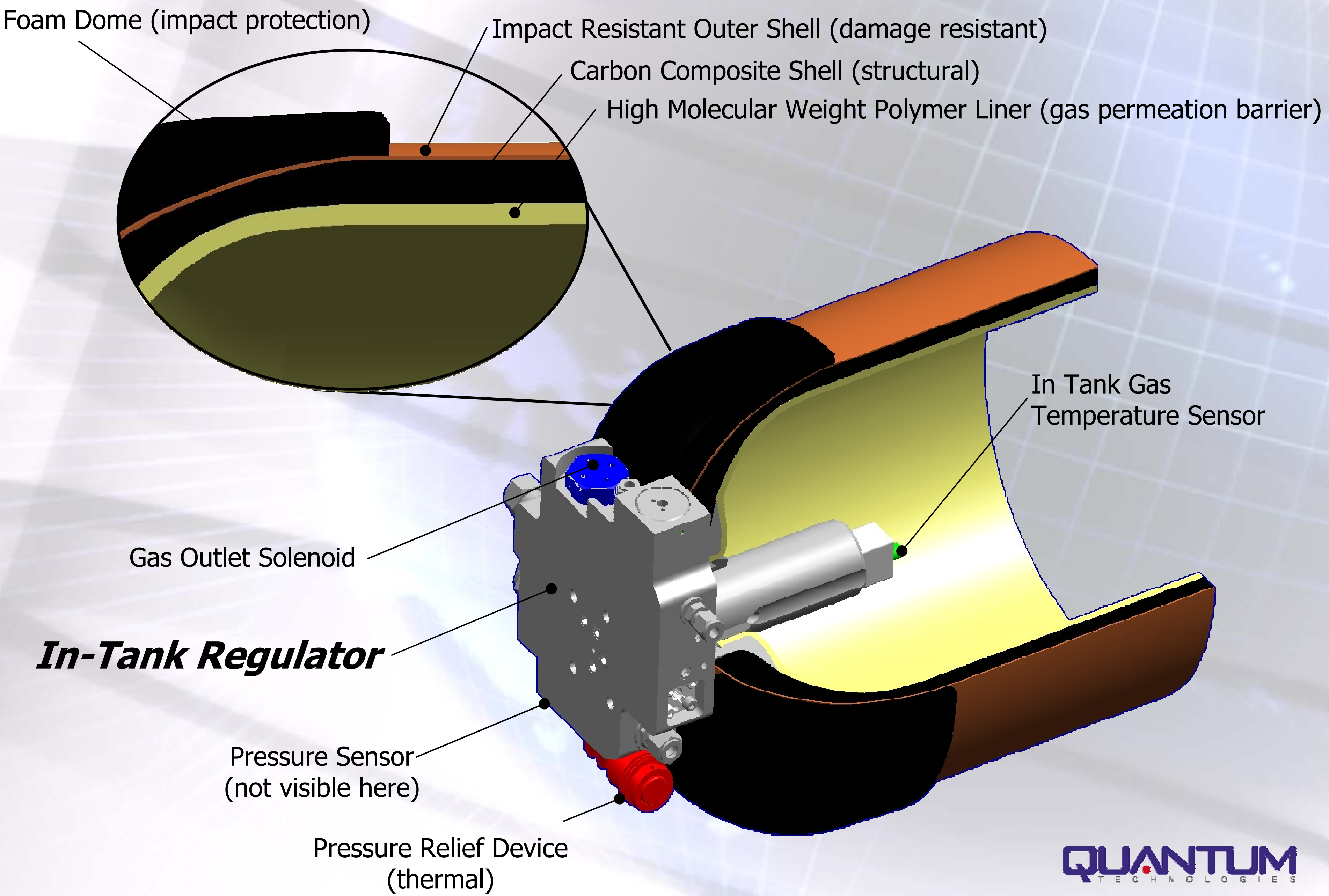
Compressed Hydrogen Storage System



Compressed Hydrogen Type-IV Storage Tank



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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 optimization and evaluations
  - Use of lower cost carbon fibers
- 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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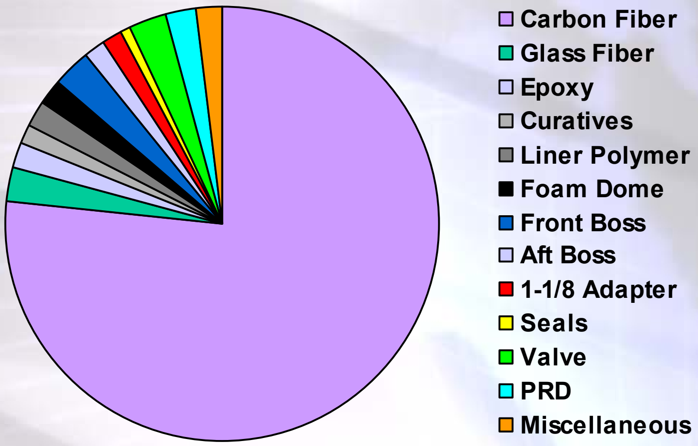
Technical Barriers

- Sufficient fuel storage for acceptable vehicle range
  - Volume (Vehicle packaging limitations)
  - Pressure (70 MPa thick-walled pressure vessel challenges)
- Materials
  - Weight
  - Volume
  - Cost
  - Performance
- Balance-of-plant (BOP) components
  - Weight
  - Cost
  - Availability/development

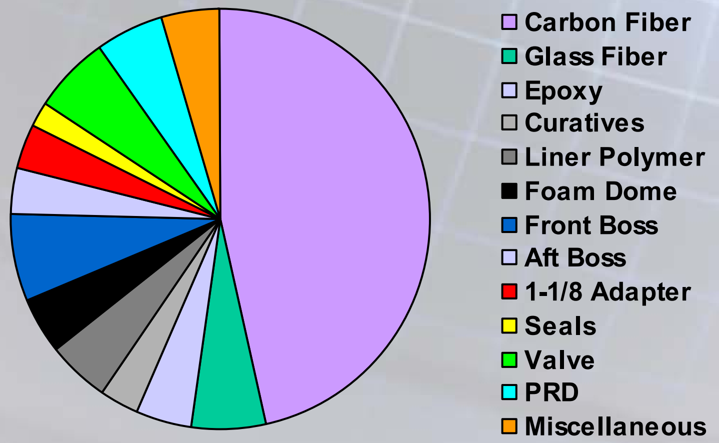
Cost Drivers

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

High Performance Fiber



Low Cost Fiber



Technical Approach

- Track 1: Optimize materials, design, and process to improve weight efficiency, costs, and performance
  - Increase fiber translation for 70 MPa tank design
  - Optimize use of “Low-cost” fiber for 70 MPa service
  - Minimize processing steps
- Track 2: 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)
- Track 3: Study feasibility of hydrogen storage at lower temperatures to increase energy density
  - Develop techniques for maintaining “Cool Fuel”

Project Overview

Track 1
Composite Optimization

Track 2
Sensor Integration

Track 3
CoolFuel™ Study

Phase 2
System Validation
(FY 2005)

Combine best of Tracks 1-2 into an optimized 5kg storage tank and validate the tank to EIHP Rev 12b requirements.

Initial Demonstration and Testing

Phase 3
System Demonstration
FY 2006

Vehicle level demonstration of validated system.

Evaluation and integration

Track 1: Approach

- Establish a baseline tank design for testing
  - 28-liter 70 MPa tank
- Vary materials, processing, and composite layup
- Measure tank strength and fatigue life

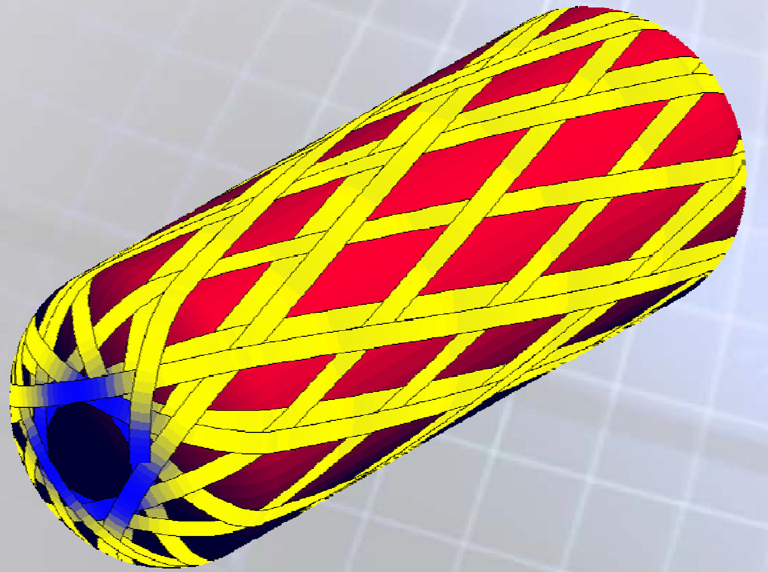
Track 1: Optimization of materials & design

- 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

Track 1: Optimization of materials & design

- Translation is the ratio of the actual fiber strength in a structure to the pure tensile strength
  - Increasing fiber translation will reduce amount of fiber required
  - Composite fibers have the maximum strength when pulled in pure tension
- 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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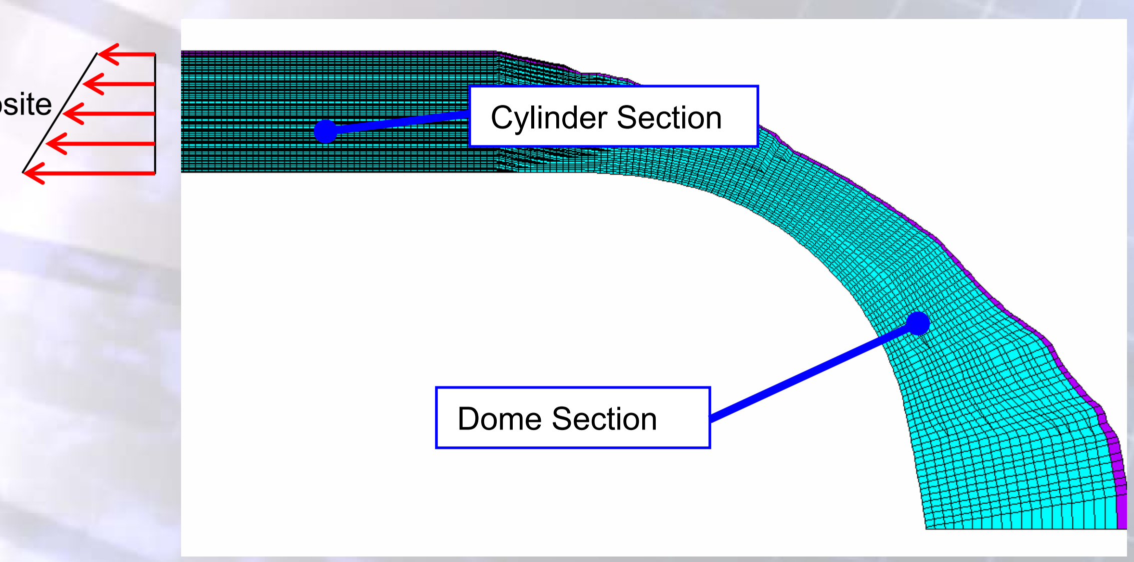
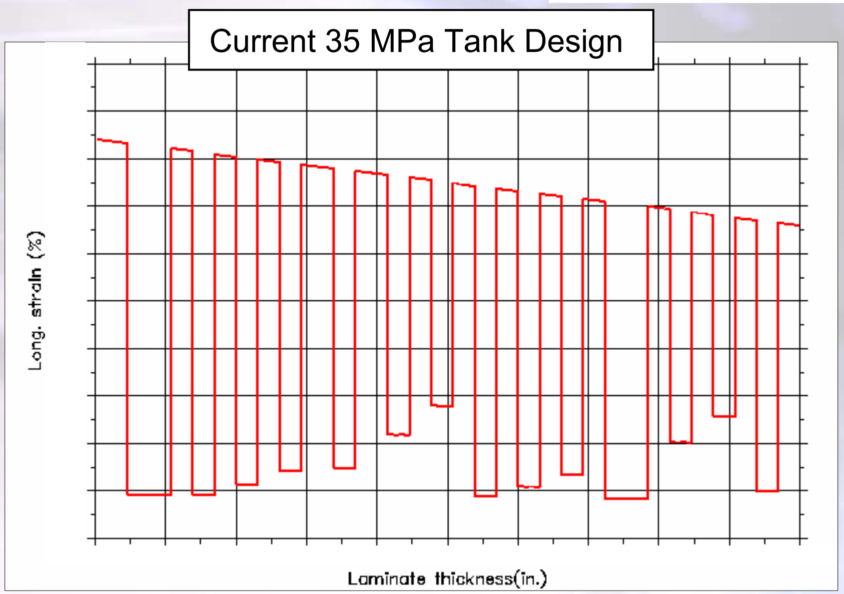
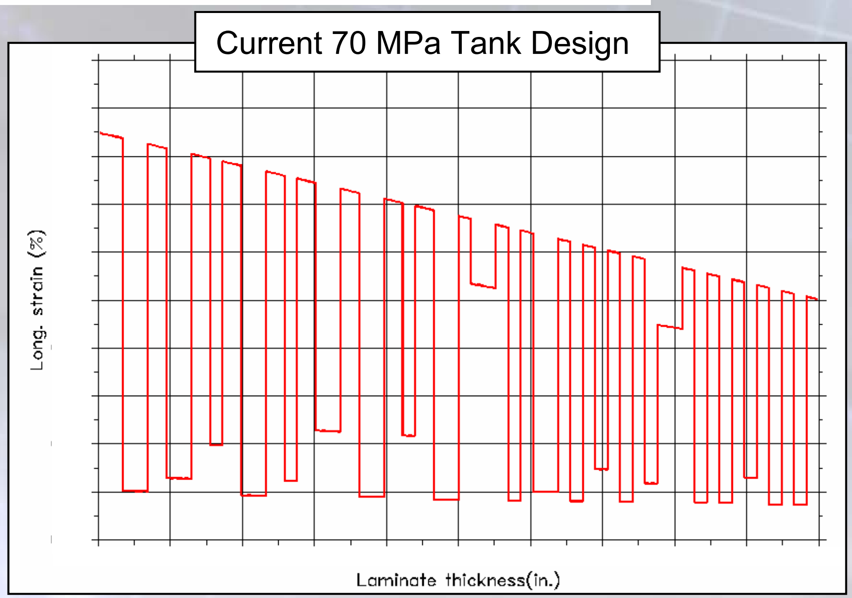
Track 1: Optimization of materials & design

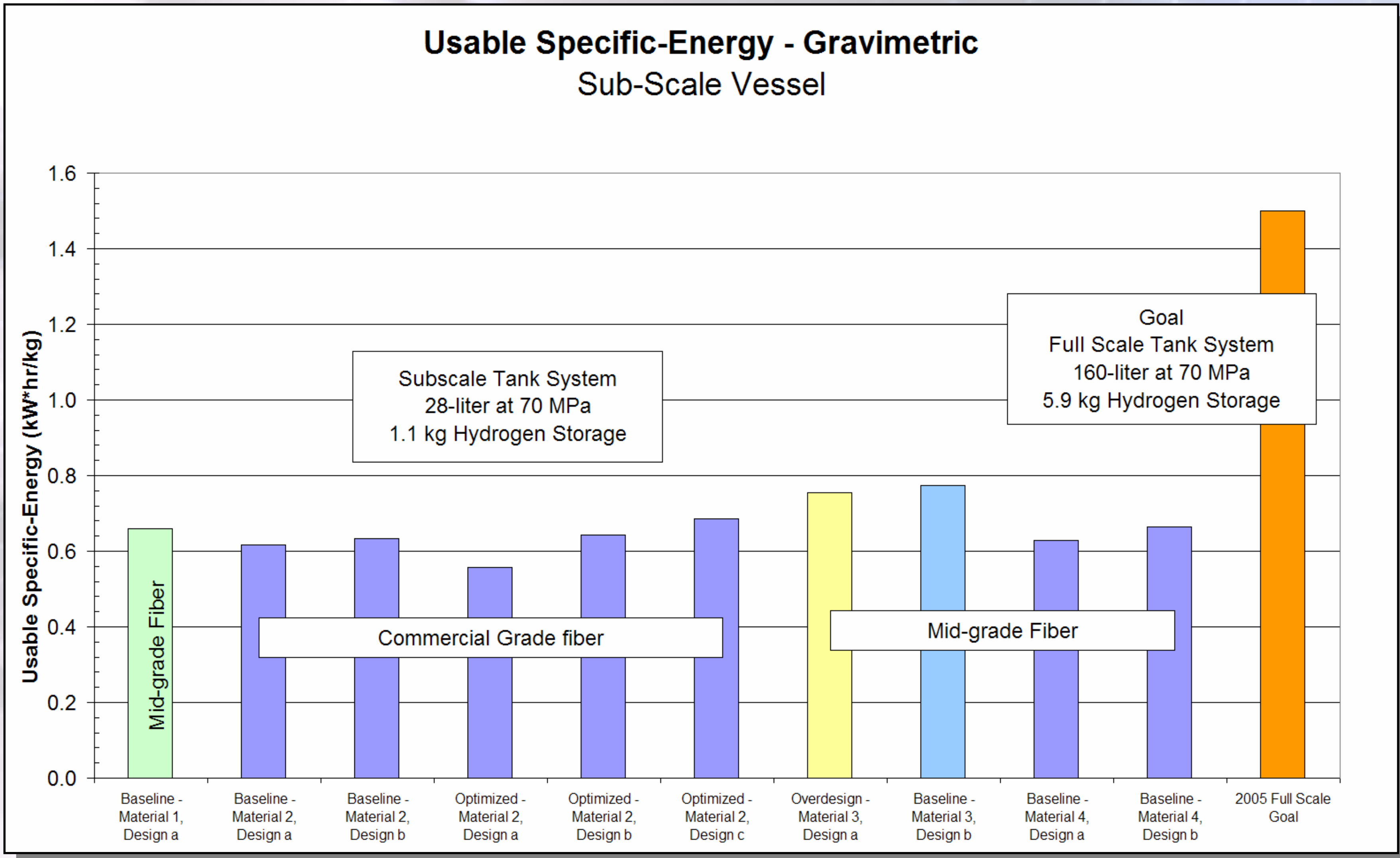
Fiber Stress/Strain through the composite thickness







Track 1: Accomplishments



Track 2: Approach

- Test existing strain sensors to assess health monitoring of a tank
  - Current E.I.H.P (European Integrated Hydrogen Project) Rev. 12b allows for the reduction of Burst Ratio factor from 2.35 to 1.8

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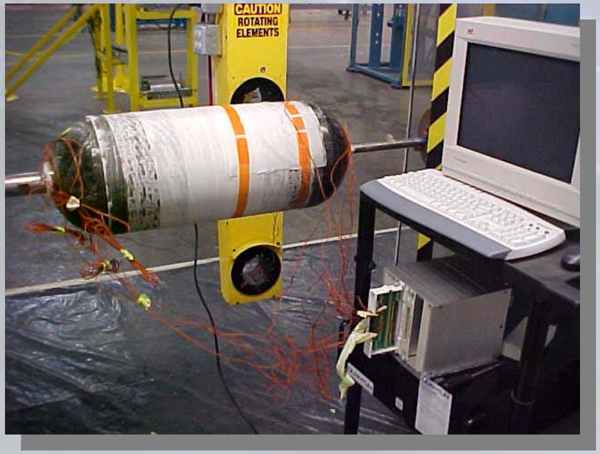
Track 2: Accomplishments

- Sensor technology evaluation
  - Three sensor technologies were investigated for feasibility, cost, complexity, sensitivity, service life and power consumption
    - Resistance strain gage Monitoring
    - Fiber-Optic Strain gage Monitoring
    - Acousto-Ultrasonic Monitoring
  - Fiber-Optic Strain gage monitoring
    - Sensors monitor a large area
    - Sensors are wound into composite shell
      - They are placed on various layers
    - Have been tested in tank structures



Track 3: Approach

- Study feasibility of hydrogen storage at lower temperatures to increase energy density
  - Develop techniques for maintaining “Cool Fuel”
  - Hydrogen gas density at -70°C and 35 MPa is the same at 15 °C and 70 MPa

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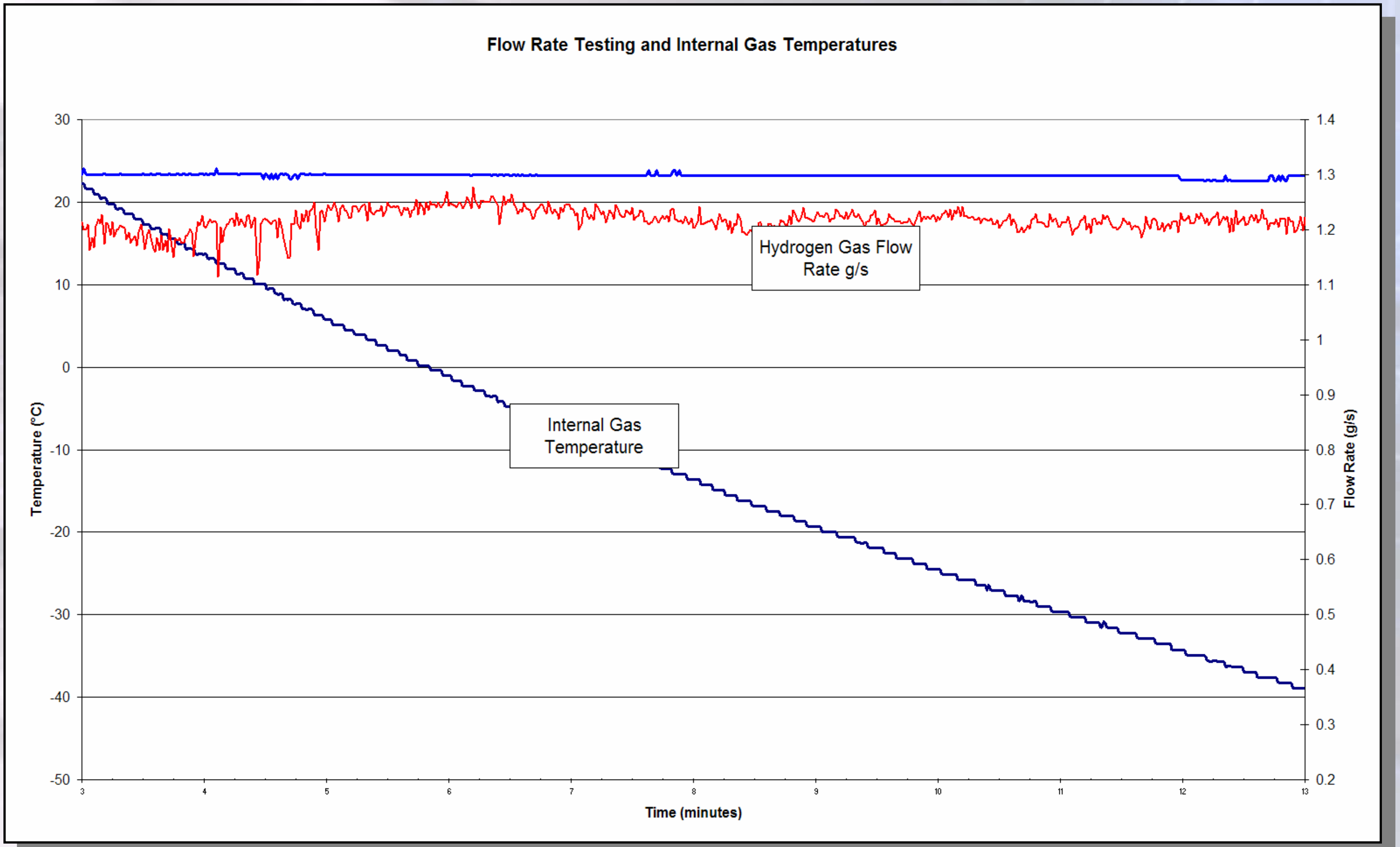
Track 3: Accomplishments

- Temperature cycle of filling and draining hydrogen tanks used to assess the thermal needs to maintain the stored gas at -70°C
- Thermal model is in development to assess the energy requirements to keep gas cool.

Track 3: Accomplishments



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Phase 2 Plans

- Track 1 and 2
  - Combine Track 1 and 2 into a full scale optimized tank (+5kg H_2)
    - Lower Cost Fibers
    - Improved processing
    - Integrated Sensor System to Support Lower Burst Ratio
  - Fabricate and validate full scale storage vessel to E.I.H.P. Rev 12b requirements
- Track 3:
  - Initial prototype fabrication and demonstration of "Cool Fuel"

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Conclusions

- Optimization of composite tank structures is achievable
- 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!

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Codes and Standards

Certification Status:

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

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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Codes and Standards

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