QUANTUM TECHNOLOGIES

… FROM CONCEPT TO PRODUCTION

Low Cost, High Efficiency, High Pressure Hydrogen Storage

DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review

Quantum Fuel Systems Technologies Worldwide, Inc.

May 2006

Project ID# STP35

Project Overview

Timeline

- Start – Jan 2004
- End – Oct 2007
- 40% complete

Barriers

- High cost of raw materials
- Weight of storage system
- Low energy density

Budget

- Total project funding
  - DOE: $957,257
  - QTWW: $1,435,886
- Funding from 1/04 to 10/05
  - $537,257
- Funding from 1/05 to 10/06
  - $420,000
- Funding from 1/06 to 10/07
  - $0

Partners

- General Motors

Project Objectives

Phase 1
Trade Studies
2004-2006

Track 1 – Composite Optimization

Track 2 – Sensor Integration

Track 3 – CoolFuel™ Study

Current Program Status

Proof of Concept
Tri-axial stress optimization
Localized reinforcement
Sensor effectiveness evaluation

CFD Simulation
Understand thermodynamics through CFD model

Phase 2
System Validation
2007

Combine best of Tracks 1-2 into a 5 kg storage system and validate to EIHP requirements

Initial Demonstration and Testing

Phase 3
System Demonstration
2008

Vehicle level demonstration of validated system

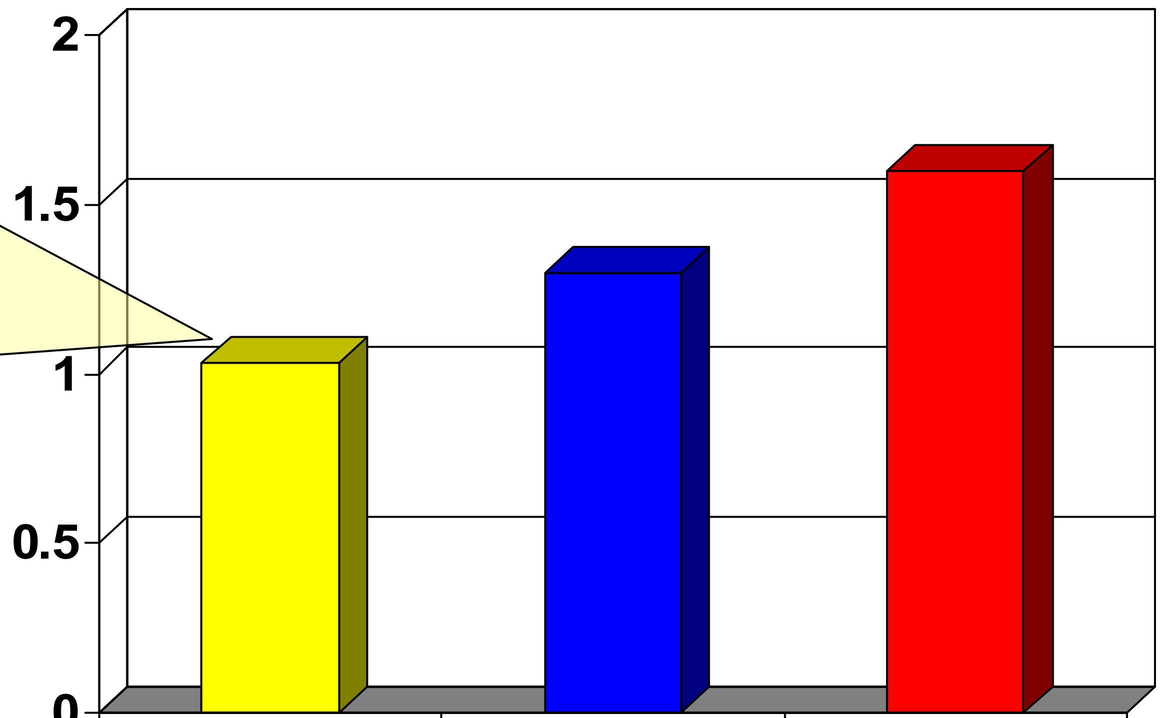
Evaluation and integration

Technical Approach

- Track 1: Composite Optimization
  - Increase fiber translation for 10,000 psi tank design
  - Utilize T700S carbon fiber wet winding for 10,000 psi service
  - Incorporate localized reinforcement design concepts
- Track 2: Sensor Integration
  - Monitor composite strain to reduce over-design requirements of regulatory specifications
- Track 3: CoolFuel™ Study
  - Investigate new technologies for low temperature gaseous hydrogen storage (about -70ºC) that does not require liquid fuel infrastructure to improve storage density
  - Develop concepts for CoolFuel™ system
  - Understand thermodynamics behavior of hydrogen storage system during fueling and de-fueling

Gravimetric Result for First Localized Reinforcement Tank

Current analytical tools inadequate to address unique behavior of localized reinforcement, resulting in less than optimum design



	1st Attempt	Status Using Current Methods	Theoretical Potential
Gravimetric Efficiency (kWh/kg)	1.03	1.3	1.6

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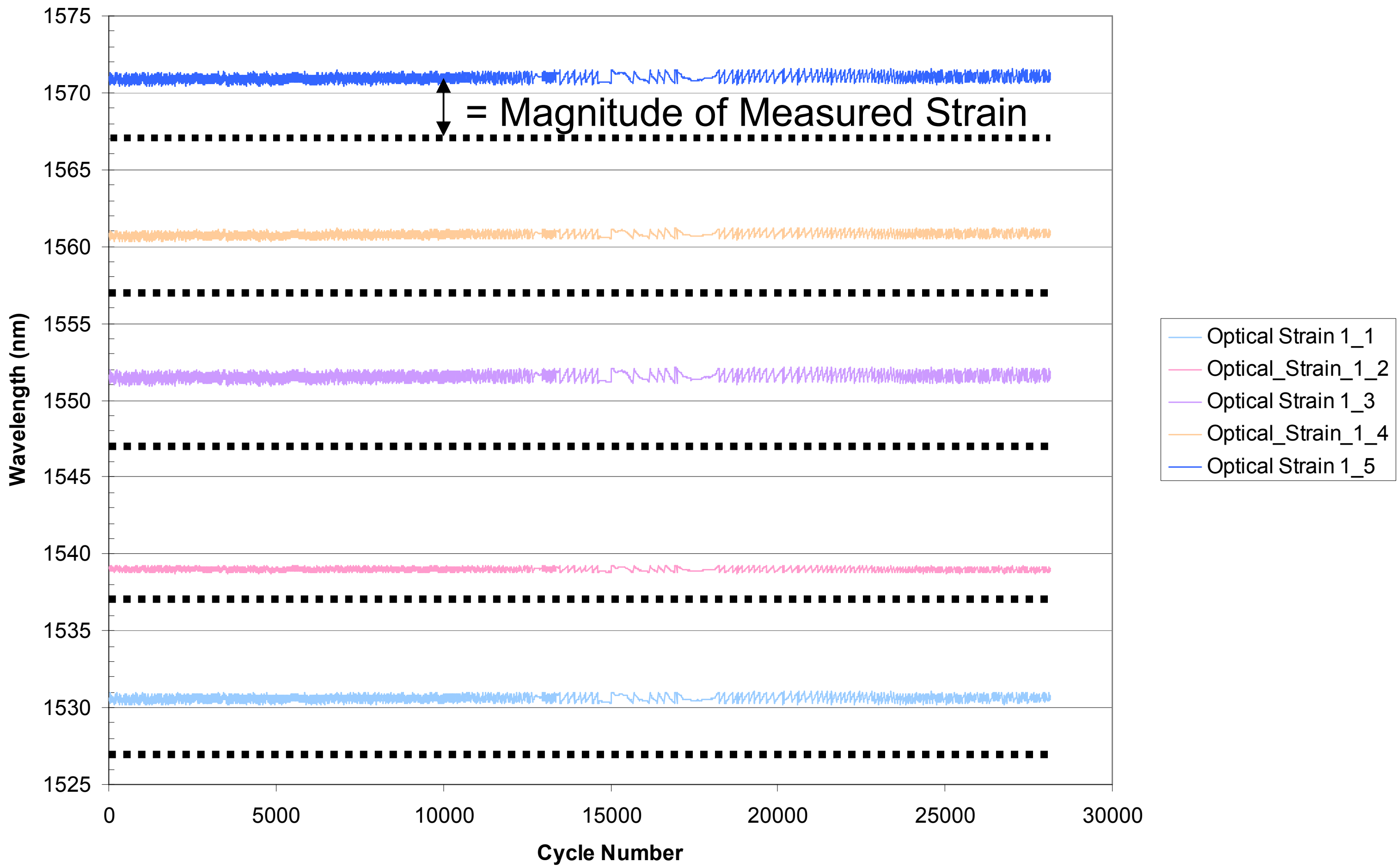
Track 1: Accomplishments

- Investigated process options for implementing localized reinforcement
  - Considered equipment and manufacturing capabilities
  - Evaluated vendor engineering capabilities
- Fabricated sub-scale tank with vacuum bagging
  - Tank burst at 25,250 psi
  - Technique did not yield significant improvement when used in conjunction with the wet winding process
- Developed and fabricated first full scale tank design using localized reinforcement
  - Lack of adequate design and analysis tools limited Quantum's ability to fabricate the tank as intended and achieve the desired results
  - Resultant tank burst at 6,050 psi (original intent was 23,500 psi) but full design was not fabricated due to inaccurate design modeling
- Reviewed lesson's learned for second tank design
  - Include ability to model discontinuous fiber and longitudinal fiber path in analytical design tools
  - Improve fiber compaction
  - Develop tooling that allows fiber termination for localized reinforcement layers
  - Evaluate adding an additional degree of freedom to current filament winding equipment

Track 2: Accomplishments

Hydraulic cycle testing using optical strain gauges



Tank showed no signs of failure via increased strain and strain gauges show consistent measurements during test

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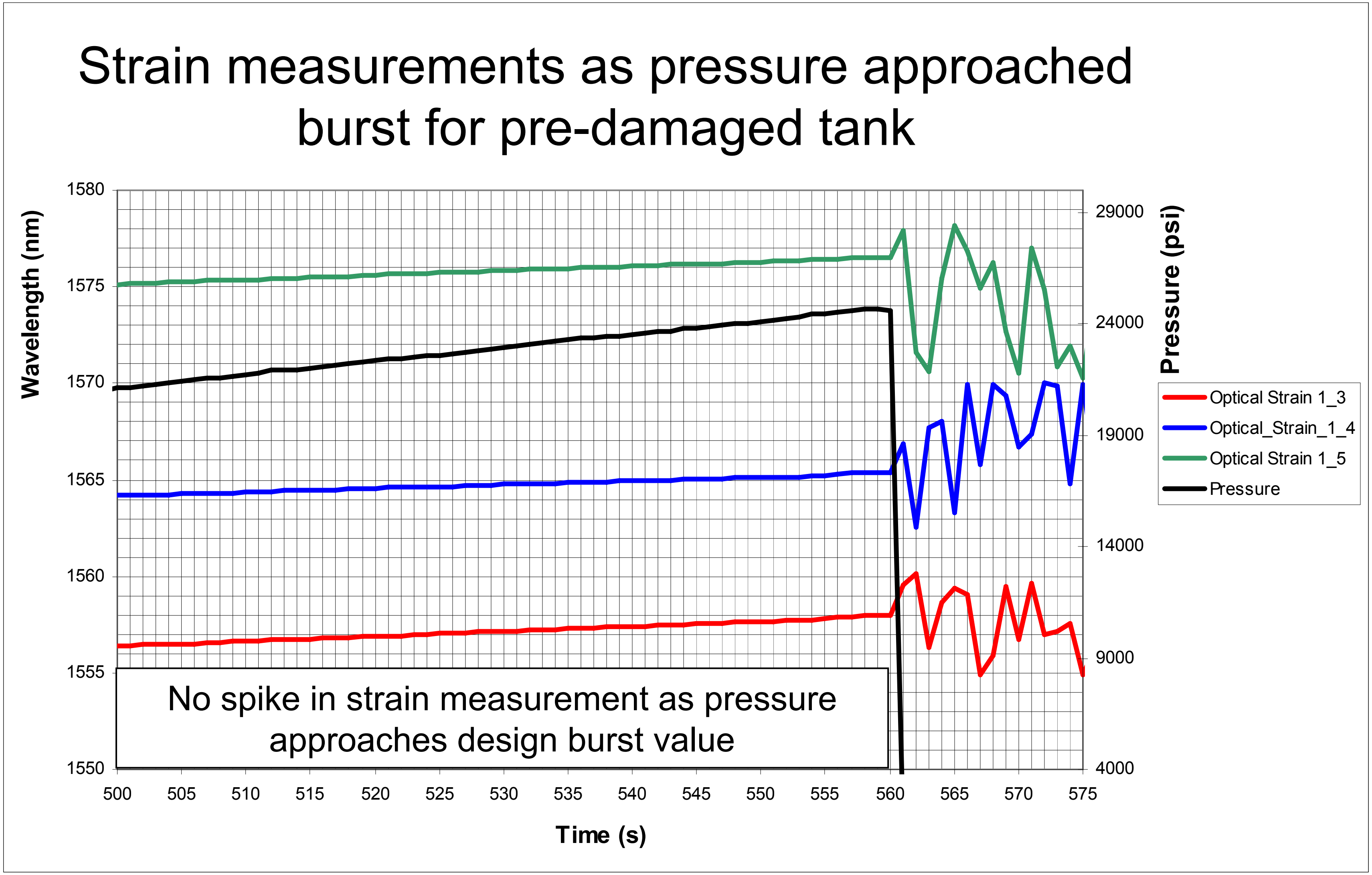
Track 2: Accomplishments



Damage did not affect tank burst value, which the strain gauge confirmed

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Track 2: Accomplishments

Summary

- Analog and optical strain gauges showed consistent measurements
- The burst test provided validation that the tank was not damaged either by the drops or by the cycle test
- Optical sensor response during burst is as anticipated for a tank that is not structurally damaged

Must conduct a test that produces structural damage in order to properly define the relationship between damage and fatigue failure

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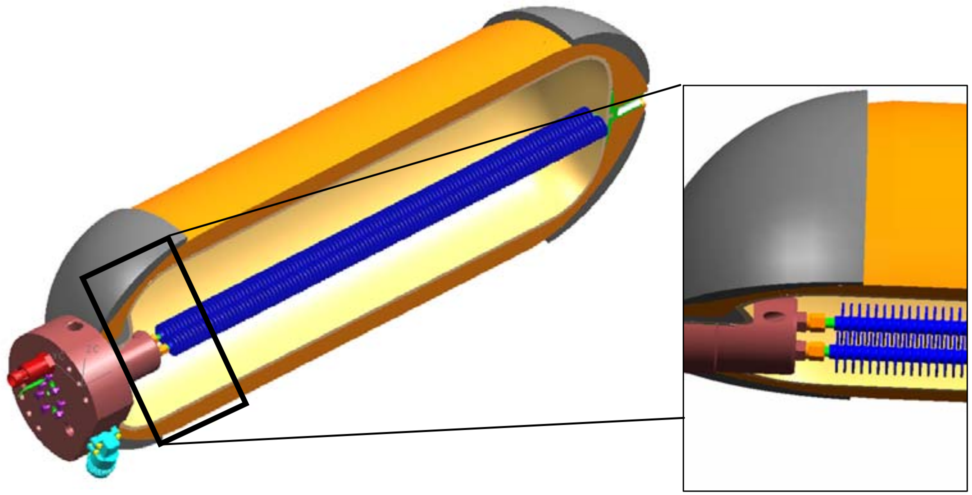
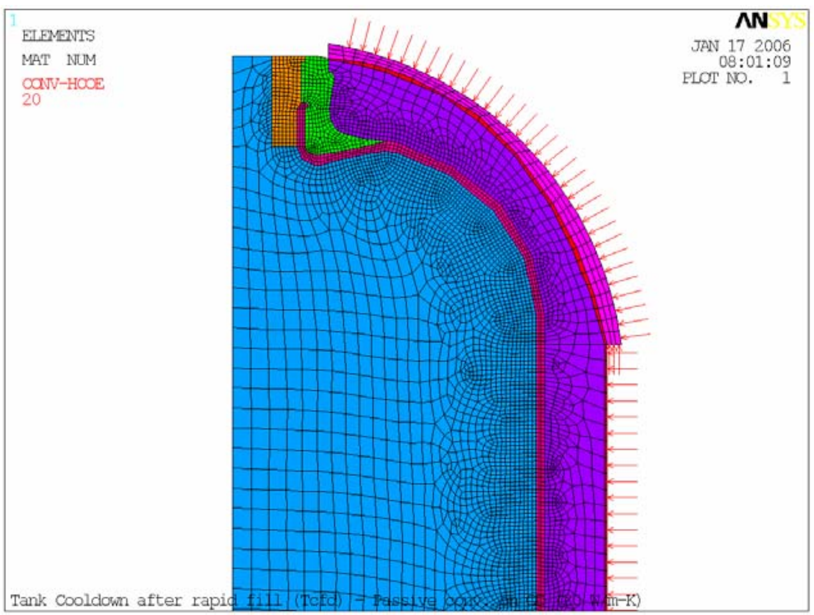
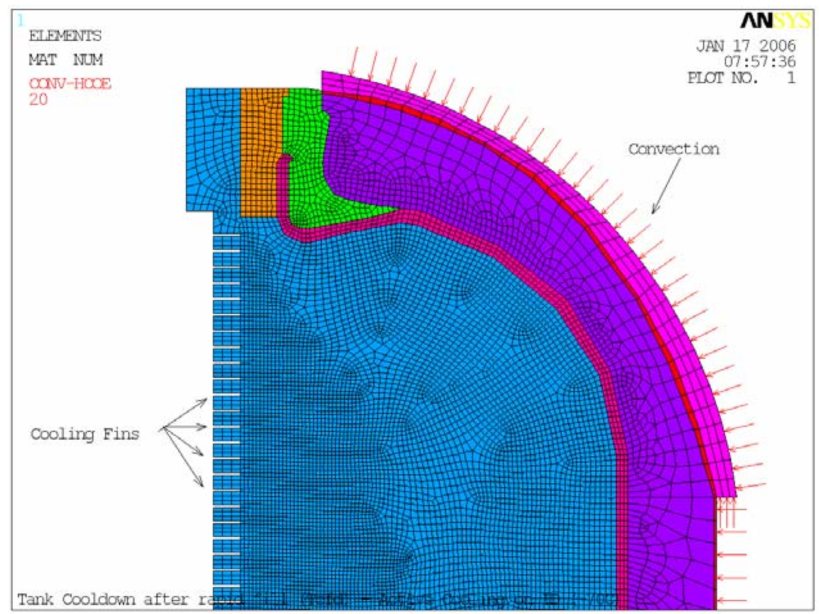
Track 3: Accomplishments

Thermal model completed and verified through test simulations





Passive Cooling Model



Active Cooling Model

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Usage Considerations - Dormancy

- If a vehicle is left dormant for a period of time, the temperature inside the fuel tank will increase, thus increasing the pressure. As the pressure approaches the maximum allowable operating pressure, the gas must be vented
- With adequate insulation, a tank could be left dormant for a period of approximately 10.5 hours before slow venting must begin (assumption: ~22.5 J/s/m^2 of heat transfer, achieved with insulation providing 0.005 W/m-K, or R30)
- Even if venting must occur to relieve all of the extra pressure, the worst-case result is a normal 35 MPa system
- Hydrogen that is released due to venting could be used to power auxiliary systems

Usage Considerations - Continuous Discharge

- If a vehicle is used for a short period after filling, the temperature will stay low and the pressure will decrease below the temperature compensated maximum allowable operating pressure
- CoolFuel provides an extra 44 minutes of driving at an average 0.45 g/s discharge rate before the system becomes a normal 5000 psi system and thus can warm to ambient conditions without venting

Future Plans

- Track 1
  - Verify localized reinforcement designs and techniques
  - Upgrade in-house design software to allow analysis of non-conventional tank fabrication methods
  - Fabricate and validate full scale (> 5kg hydrogen) storage vessel to EIHP requirements
- Track 2
  - Execute test plan to determine relationship between composite damage and fatigue failure
- Track 3
  - Perform additional fueling and de-fueling simulations on CFD model to predict system performance
  - Fabrication and demonstration of prototype CoolFuel™ system

Back-Up Slide

Critical Assumptions and Issues

- Track 1
  - Price of carbon fiber remains constant (no significant decrease due to increase in volume)
  - Balance of plant components can be made from less exotic metals
    - Maintain tensile strength requirements
    - Maintain hydrogen compatibility
- Track 2
  - Regulatory changes can be made to allow lower safety factors when sensors are used
- Track 3
  - Refueling infrastructure will be able to provide hydrogen gas at low temperatures