Department of Energy Workshop

High Pressure Hydrogen Tank Manufacturing

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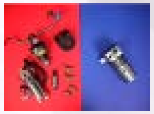
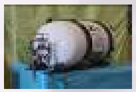
QUANTUM TECHNOLOGIES

History of Innovations…

1999

Announced breakthrough in all-composite lightweight, high capacity, low-cost fuel storage technologies.





- Developed a series of robust, OEM compatible electronic control products.

Awarded patent for integrated module including in-tank regulator

- Achieved record of 11.3% H2 tank efficiency, the highest weight efficiency ever demonstrated, in partnership with Lawrence Livermore National Lab and Thiokol.

2000

Developed H_2 storage system for SunLine Tran-sit Hythane® bus.

- Developed high efficiency H_2 fuel storage systems for DOE Future Truck programs

First to fill a H_2 storage cylinder with compressed H_2 at 5,000 psi at California Fuel Cell Partnership developed for the Hyundai Santa Fe Fuel Cell Vehicle.

- Awarded patent on injectors for dry gaseous fuels

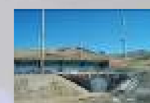
2001

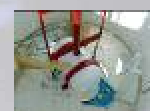
First to demonstrate an all-composite H_2 Storage Tank that stores at 10,000 psi

- Developed 10,000 psi in-tank pressure regulator module incorporating two regulators and solenoid valve

First to certify 10,000 psi H_2 Storage Tank to International Standards.

- Opened world's first 10,000 psi hydrogen gas test facility and performs extreme tests





2002

First to ship 10,000 psi H_2 storage fuel system with patented in-tank regulator module

- Opened state-of-the art SULEV emissions testing Facility.

Developed 2nd generation in-tank regulation system for Toyota

- Developed an integrated plug-and-play fuel storage system for GM HyWire FC concept vehicle

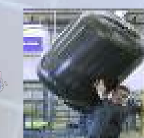
Awarded patent for mobile hydrogen refueling systems

- Developed portable hydrogen refueling devices and supplied for multiple customer applications

2003

Developed H_2 storage and metering system for Toyota's FCEV platform.

- Developed 13.3 wt% hydrogen tank and 0.75 kg regulator for NASA/ AeroVironment



2004

First to certify 10,000 psi systems in Japan

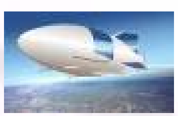
- Designed, developed and validated advanced fuel storage systems for DaimlerChrysler

Developed FC hybrid electric "Aggressor" for the US Army, from the ground-up

- Developed on-tank automatic valve system for 10,000 psi H_2

2005

Developed electrolyzer based H_2 mobile refueling system for the US Army



- Developed ultra-light hydrogen systems for high altitude applications

Validated H_2 injectors and developed advanced hydrogen metering systems for FC stack

- Developed innovative Hydrogen ICE hybrid electric vehicles for SCAQMD

2006

Developed and implemented advanced process controls, based on experience in producing over 1,600 hydrogen tanks

- Launched R&D targeting next generation storage and metering systems

2007

Quantum and Fisker form: Fisker Automotive (**Q-Drive**)

GM's Sequel - First Hydrogen Fuel Cell vehicle to go 300 miles without refueling

2008

Began developing additional H2 ICE hybrid platforms - to follow CNG and PHEV

2nd Generation Military Vehicle intro of **Q-Force**

2009

- Launched in production CNG (21x60) vessel lightest in class by 35%

Electrification of LLV - **Quantum Quiet Drive™**

2010

First in the industry with drop in CNG tank replacement for HD diesel 25" & 26" tanks

Began development and verification of the Saturated Injector

H_2 Fuel Systems

External Regulator 0 First Stage
- 87.5 MPa max inlet pressure
- 3 MPa nominal outlet pressure
- EIHP Certified

Mid-Stage Valve
- 3 MPa nominal working pressure
- Electronically controlled shut-off valve using PWM Peak and Hold current
- Pressure gauge port
- Auxiliary defueling port with integral flow control orifice

Regulator – Second Stage
- 3 MPa nominal inlet pressure
- 500 kPaG nominal outlet pressure
- Outlet pressure gauge port

Low Pressure Lock-off
- Normally closed
- 230 psig maximum working pressure
- Maximum flow 5g/sec @ 10 psiD
- Coil resistance 12 Ohms @ 25ºC
- Normal operating voltage 9.6 to 16.5 VDC
- Saturated current
- Operating temperature -40ºC to 85ºC

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Manufactured Fuel System Components

Injectors - Hydrogen

- Dynamic Flow: 8.50 mg/pulse (4%), air @ 345 kPa
  3.5 ms pulse width @ 100Hz
- Static Flow: 3.2 g/s (5%) air @ 345 kPa
- Maximum Operating Pressure: 345 kPa
- Tip Leakage: 0.5 cc/min
- H2 compatible seal materials
- 200M Cycles

Injectors - CNG

- Dynamic Flow: 8.50 mg/pulse (4%), air @ 345 kPa
  3.5 ms pulse width @ 100Hz
- Static Flow: 3.2 g/s (5%) air @ 345kPa
- CNG compatible seal materials
- Tip Leakage: 0.5 cc/min
- Certified to ECE R110 in 2003
- 500M Cycles

On-Tank Valve

- 87.5 MPa max working pressure
- Electronically controlled shut-off valve
  using PWM Peak and Hold current
- Auxiliary bypass valve
- Thermally activated PRD w/ vent port
- Tank pressure & Gas Temp sensors
- Integral check valve on fill line
- Water Heating channels

Intermediate Pressure Regulator

- Maximum inlet pressure: 2.07 MPaG
- Adjustable outlet pressure ranges
- Flow up to 1.8 m^3/min, 20 g/s air
- Operating temperature -40ºC to 125ºC
- Aluminum body
- CNG compatible seal materials

Fuel Lines

- 10,000 psi nominal working pressure
- O-ring face seal connections
- CNC bent to CAD data
- 316 Stainless Steel (Other materials available)
- Welded end form or Parflange (Parker)
- Flex line available

High Pressure Fuel Rails

- 304 Stainless Steel or 6061 Aluminum
- Brazed construction (SS)

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Tank Manufacturing Barriers

- Cost
- Weight
- Unification of standards
- Availability of automotive gaseous hydrogen components

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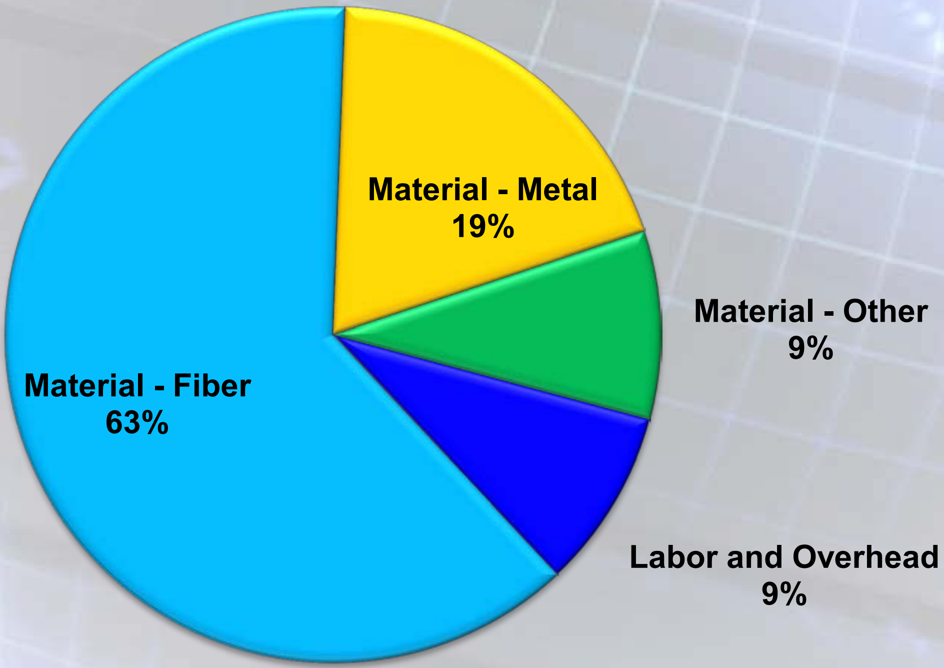
Tank Cost Breakdown

Cost Breakdown Uses Following Assumptions:

- 125 liter 10,000 psi H_2 tank
- Traditional manufacturing processes
- Type IV (plastic liner) tank
- Annual Production Quantity 10,000
- Carbon fiber cost at $15/lb
- Metal components are 316L stainless steel

Tank Total Manufacturing Cost



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Tank Manufacturing Process

Quantum Cost Reduction Efforts

- Advance manufacturing process combining filament winding with Fiber placement
- Hybrid tank design using lower cost carbon fiber on exterior layers
- Alternative fiber evaluation (Basalt)
- Manufacturing Process Automation

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Filament Winding/Fiber Placement Concept

To manufacture 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)

With the aim of addressing the barriers by achieving a manufacturing process with:

1. lower composite material usage
2. higher manufacturing efficiency

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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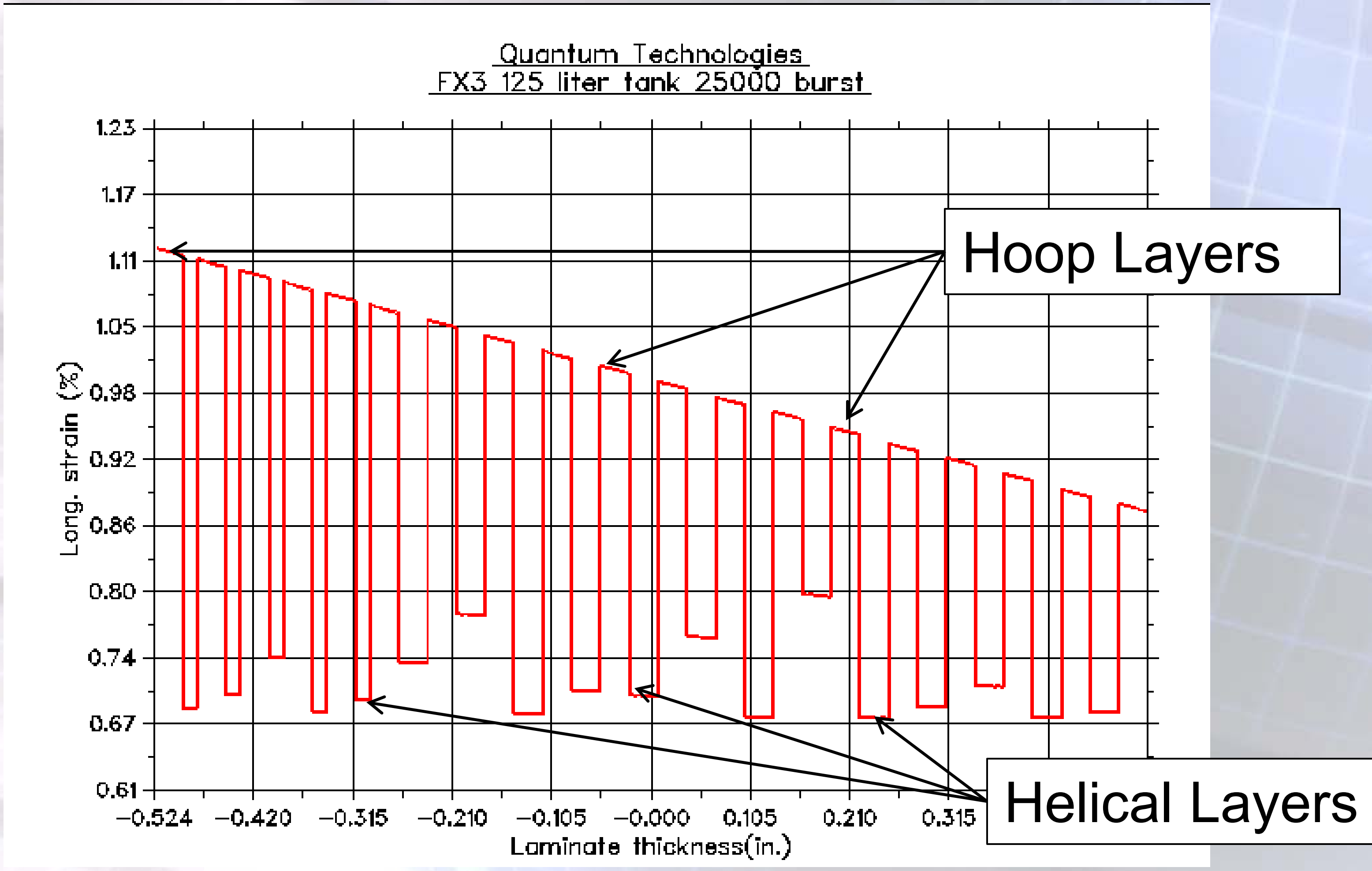
Overall Accomplishments: Material & Cost Saving

	Baseline 129L	Vessel 1	Vessel 7
Summary Table		FY-2010	FY-2011
	Filament Wound	Hybrid FW + AFP	Hybrid FW + AFP
Total Composite Mass, kg	76	64.9	58.63
Mass Savings, kg		11.1	17.4
Mass Savings, %		14.6	22.9
Specific Energy, kWh/kg	1.50	1.67	1.78
$11/lb Carbon, Cost Effic, $/kWh	$23.45	$21.75	$20.80
$6/lb Carbon, Cost Effic, $/kWh	$18.74	$17.63	$17.01

Improvements made between Baseline and Vessel 7:

- Composite mass reduced from 76 kg to 58.63 kg (22.9% reduction)
- Specific energy increased from 1.5 to 1.78 kWh/kg
- Cost efficiency reduced from $23.45 to $20.80/kWh for $11/lb carbon fiber
- Cost efficiency would reduce from $18.74 to $17.01/kWh for $6/lb carbon fiber

Hybrid tank design using lower cost carbon fibers on exterior



~25% strain decrease from inside to outside layers

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Hybrid tank design using lower cost carbon fibers on exterior

- By replacing outside layers with lower cost fiber overall fiber cost can be decrease with no or little impact on tank weight
- Preliminary calculation give a weight increase of 2.7% and a cost savings of 4%
- Outer layers also utilize higher modulus than inner layers allowing shift of part of the load to outer layers
  - This is based on outer layer fiber cost being 80% of inner layer fiber cost
  - Development of lower cost standard modulus (~30 Msi) fiber could make this concept more effective

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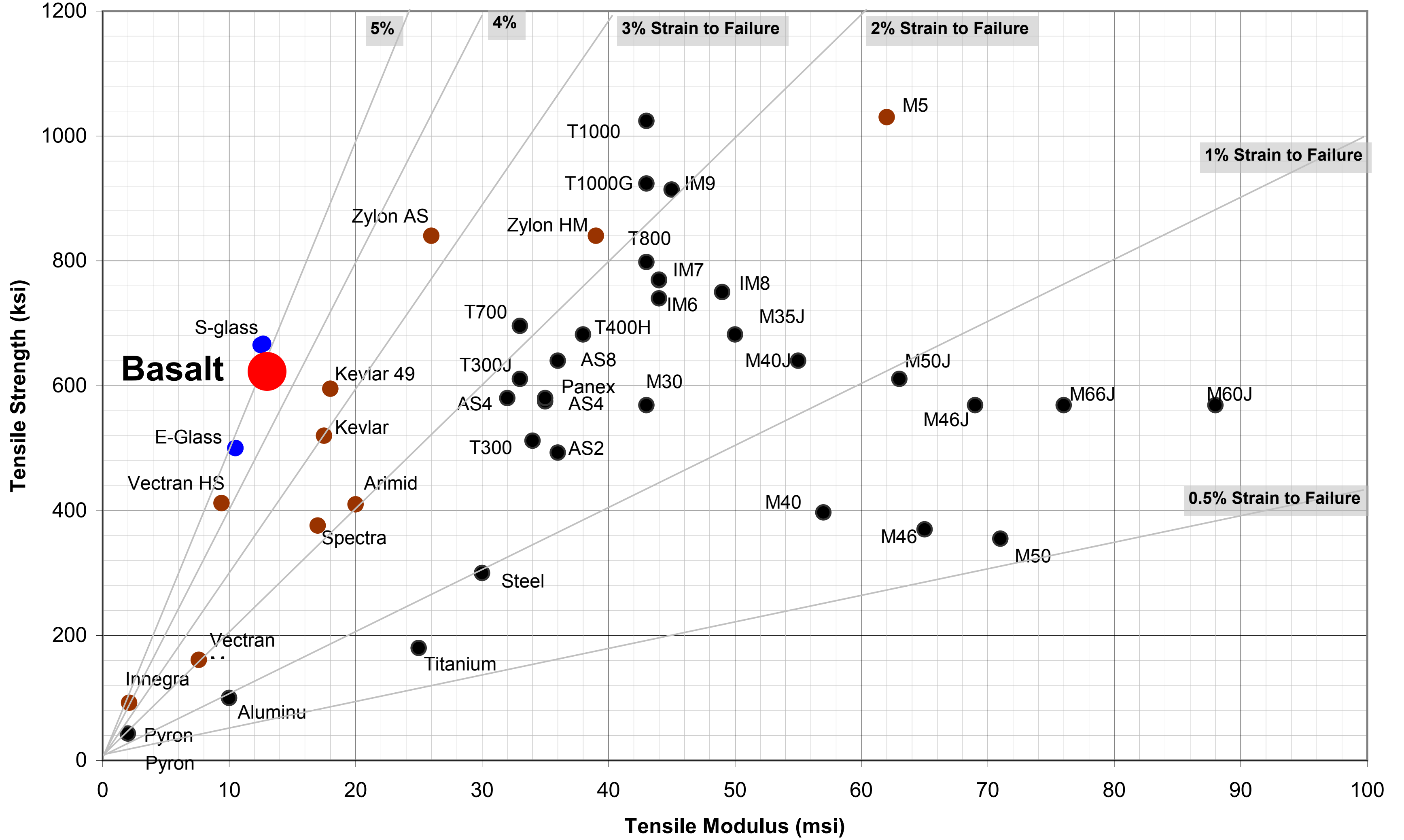
Alternative fibers to Carbon

- Evaluate basalt fiber (produced from volcanic basalt mineral) as an alternative to Toray T700S

Fiber	Cost ($/lb)	Comments
Basalt	2.20	Design criteria not set
Ceramic	274.00	Design criteria not set
Boron	1,308.00	Design criteria not set
Silicon Carbide	4,000.00	Design criteria not set
Saffil	No Quote	No continuous tow available
Carbon	11 - 16	2.25 factor of safety
Glass	1.35 - 10	3.5 factor of safety

Fiber Properties



Carbon fiber, Glass, Aramid

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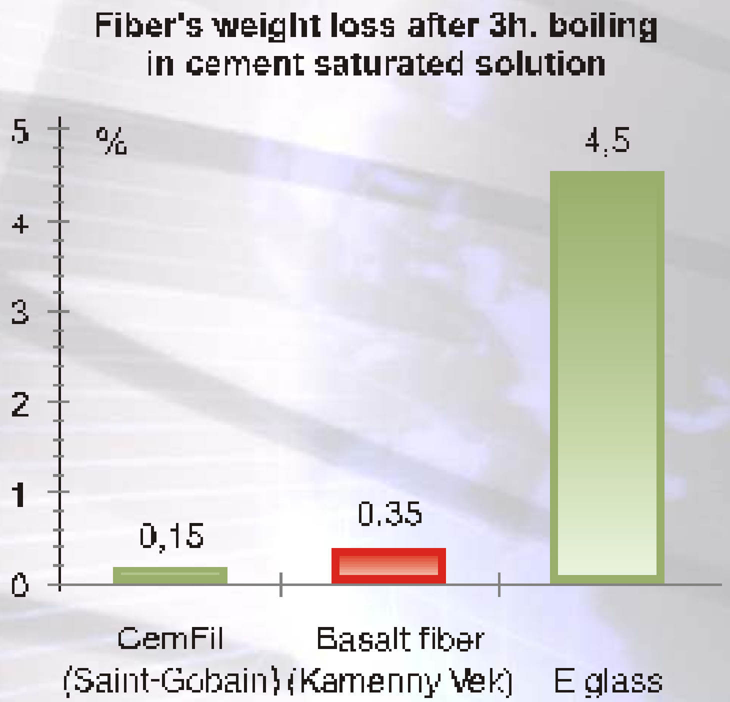
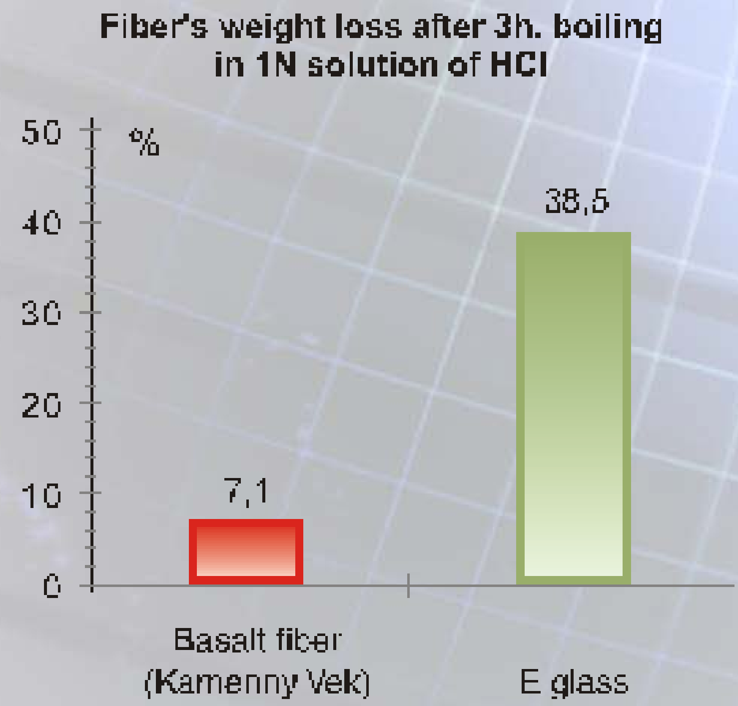
Chemical Resistance





Source: Kamenny Vek 2010.

EC79: Carbon fiber safety factor (SF) = 2.25, glass fiber SF = 3.5
2.25 < Basalt SF < 3.5

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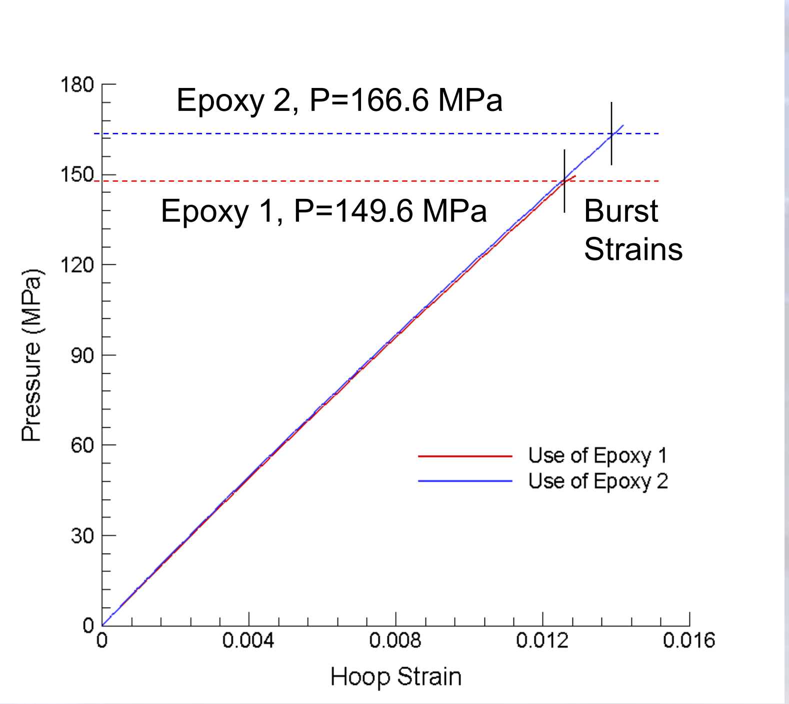
High Modulus Resin

PNNL's Approach and Technical Progress

- Predicted vessel burst pressure by comparing two different resin systems
- Modeled cylindrical part of the vessel with ABAQUS and multiscale composites model, EMTA-NLA (Eshelby-Mori-Tanaka Approach for Non-Linear Analyses)
- Predicted burst pressure is higher with high modulus resin (Epoxy 2)



Epoxy	Predicted Burst Pressure, MPa (ksi)
1	149.6 (21.7)
2	166.6 (24.2)

~11% increase in predicted burst pressure

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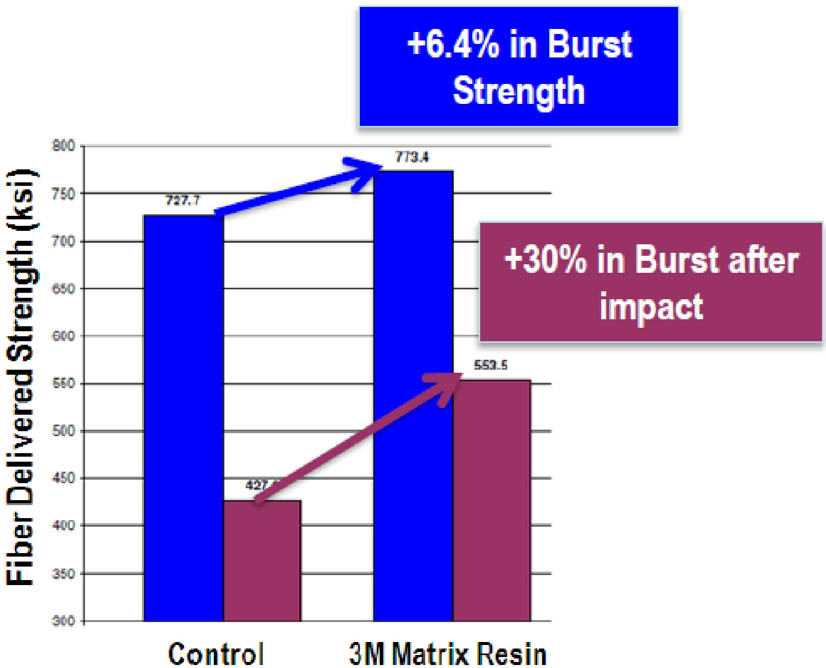
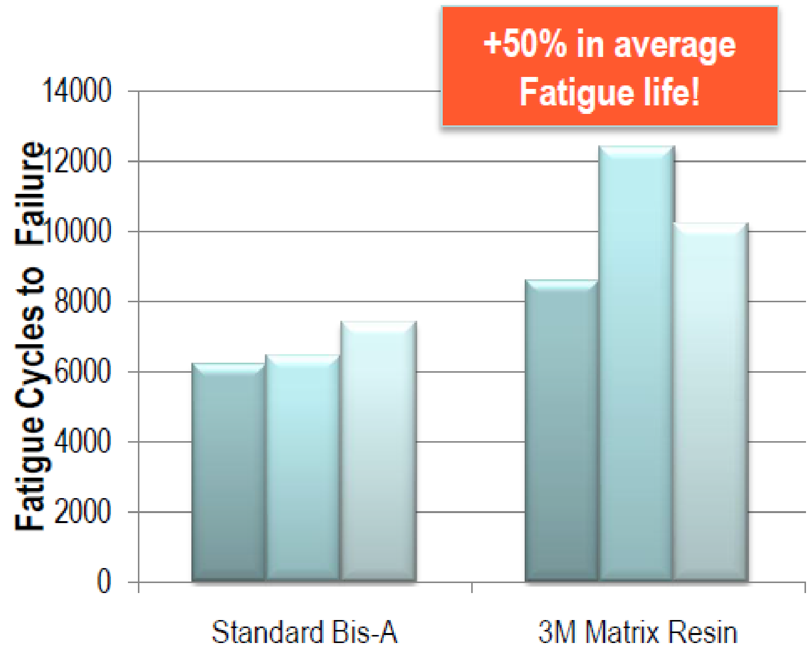
Nano-particle Resin

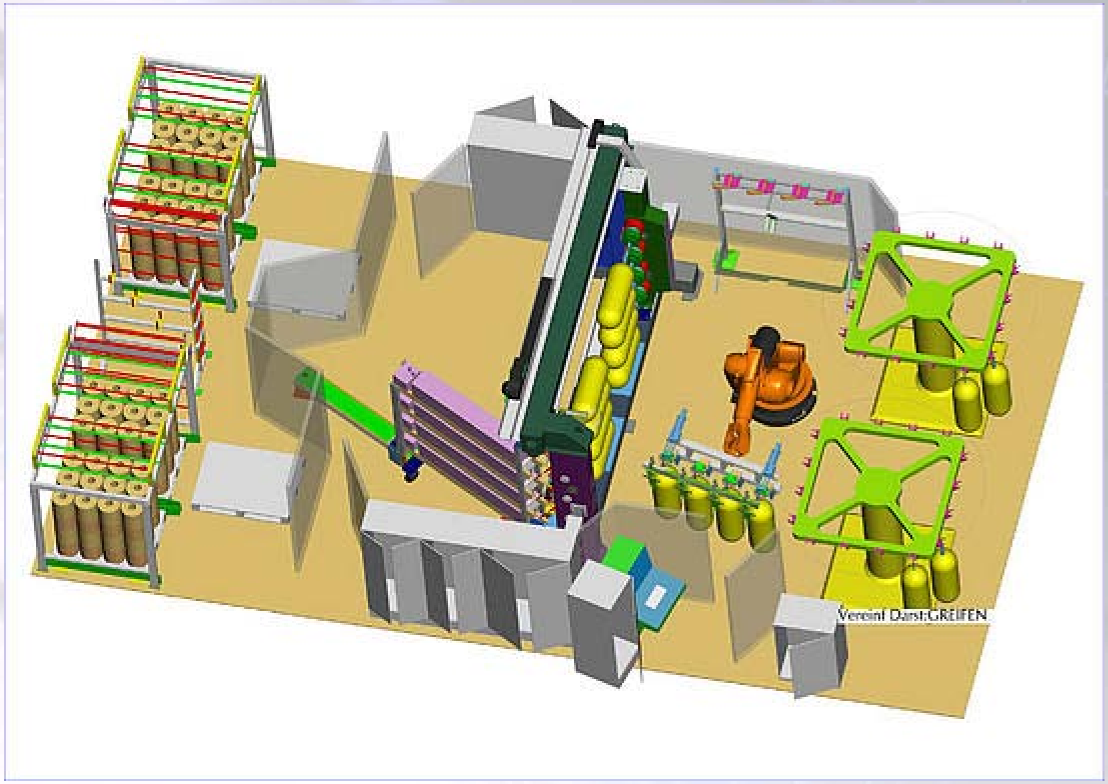




Source: 3M 2010.

Automation of Manufacturing Process

- Design multiple-eye delivery system to increase payout on each quadrant
- Automate resin mix system
- Full automated winding station



Picture Courtesy: EHA

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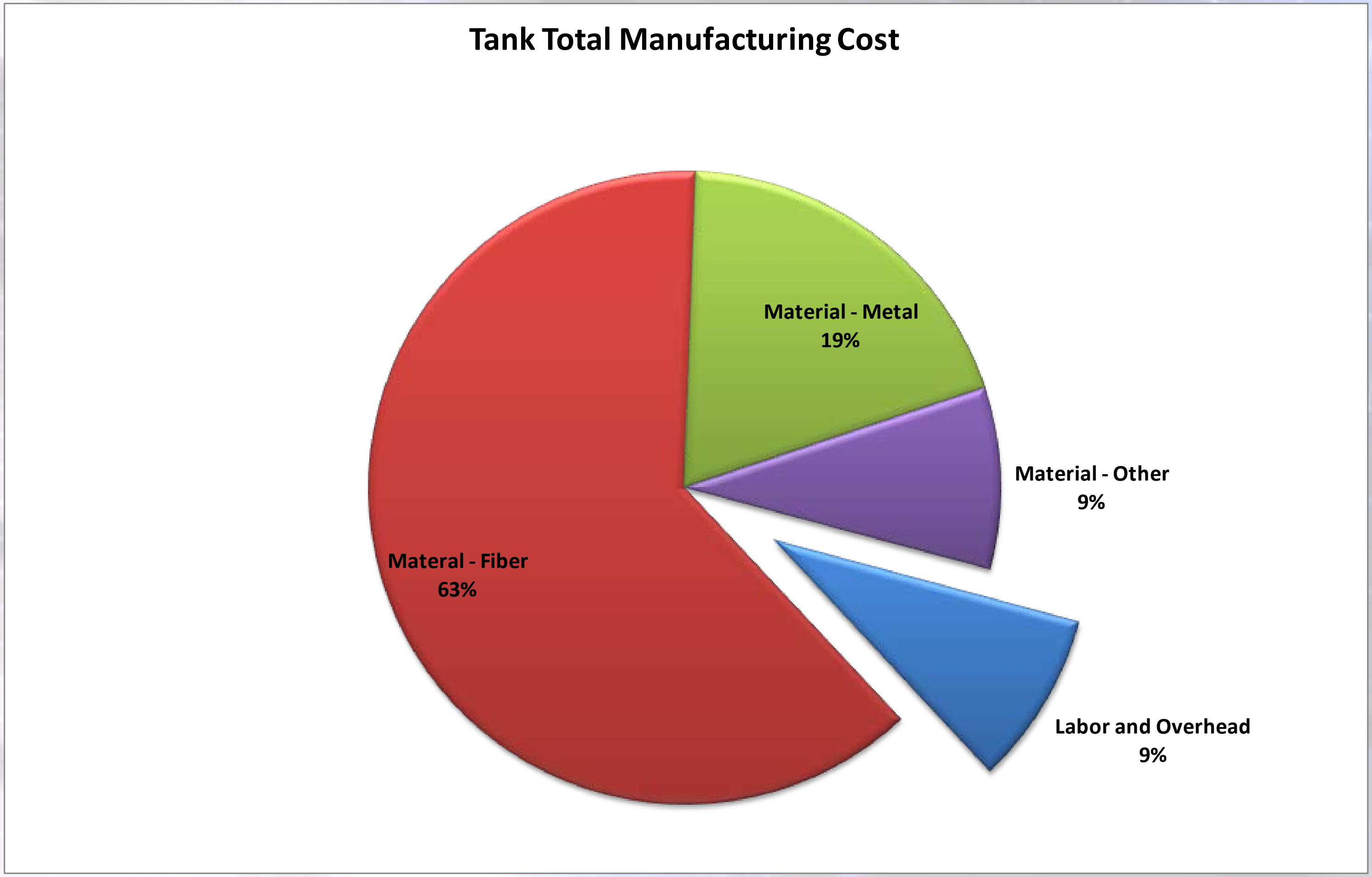
Automation of Manufacturing Process



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Automation of Manufacturing Process

- Labor and overhead only comprises 9% of total tank cost

However,

- Increase facility through put
- Reduction of product variation
- Allow higher design criteria

$$\sigma_{f_{Allowable}} = \sigma_f \times \mathrm{T} \times (1 - 4 \times C\,V)$$

$$\sigma_{\max} = \sigma_p \frac{P_b}{P_p}$$

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Current Plethora of Standards

- “Performance” Standards
  - DOT FMVSS 304 (Mandatory requirement for on-board fuel tanks)
  - NGV – 2007 (Established industry standard for on-board fuel tanks, over 40,000 Type IV composite tanks in service since 1992)
  - ISO 15869 – Draft requirements for on-board hydrogen fuel storage tanks
  - ISO IIII9-3 Final Draft requirements for the storage and conveyance of compressed gases
  - EC – 79 Type-Approval of Hydrogen-Powered Motor Vehicles
  - SAE J2579 Fuel Storage System level testing Protocol
  - JARI S 001 (Japan) Technical Standard for Containers of Compressed Hydrogen Vehicle Fuel Devices (Replaced with KHK S0128)
  - ASME Section X - Appendix 8 Class III Vessels with Non-load Sharing Liner for Gaseous Hydrogen in Stationary Service

Future Development Areas

- Metals hydrogen compatibility.
  - Currently most designs are using 316L SST or 6061-T6. Additional information needed to have design criteria for other metals
- Continued research on low cost fibers
- Conformable tanks
  - Vehicle structures are generally not ideal for single vessel systems
  - Multiple small tank result in lower volumetric efficiency and high cost

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