... FROM CONCEPT TO PRODUCTION

Manufacturing for the Hydrogen Economy

Status & Direction for Onboard Hydrogen Storage

Andy Abele
Quantum Fuel Systems Technologies Worldwide, Inc.

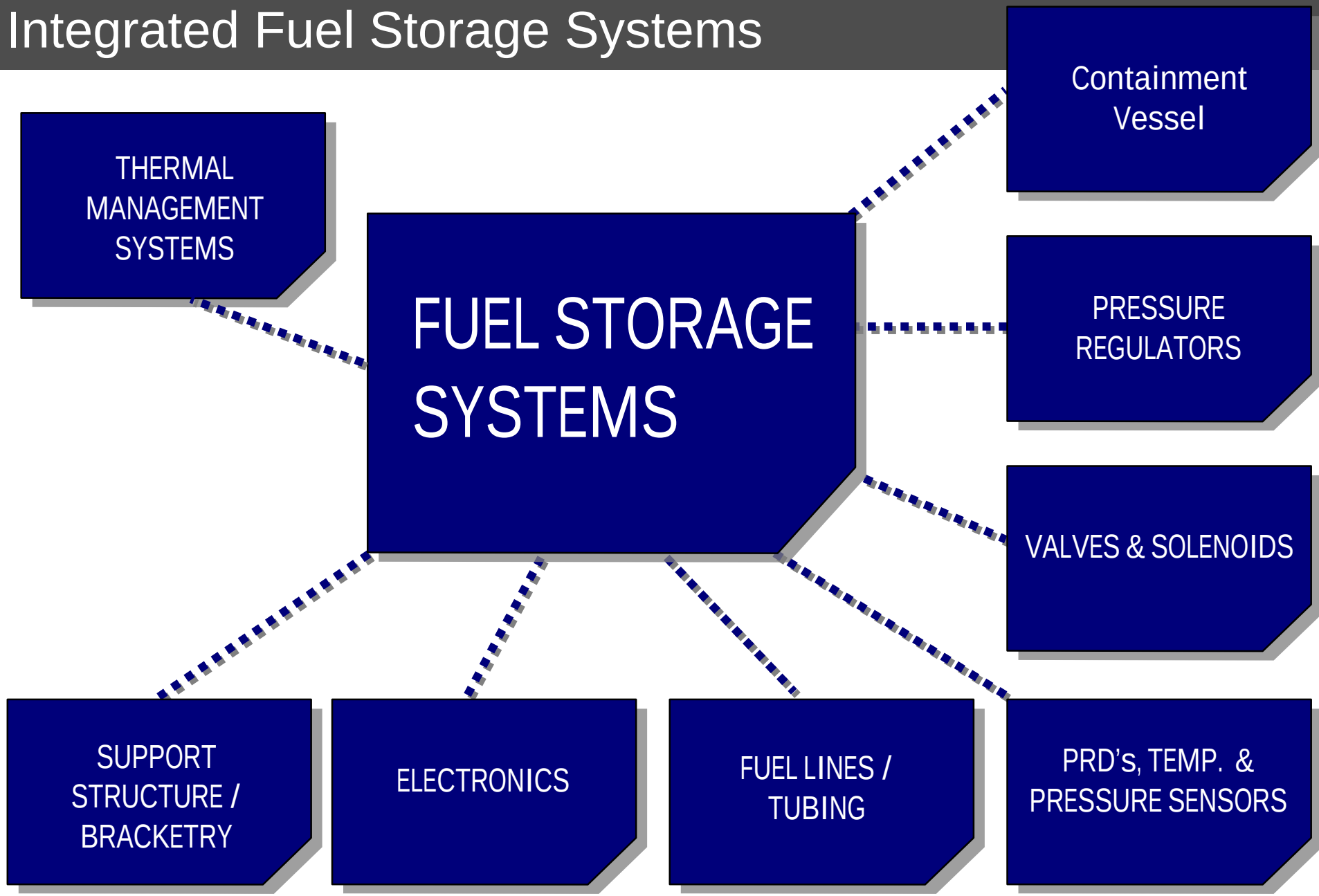
July 2005

Hydrogen Storage – It's More Than a Tank

Hydrogen storage systems on H_2 vehicles must:

- Contain
- Control
- Regulate
- Monitor
- Distribute
- Meter
- Refill
- Survive

Integrated Fuel Storage Systems



Current Hydrogen Storage Options & Challenges

Compressed:

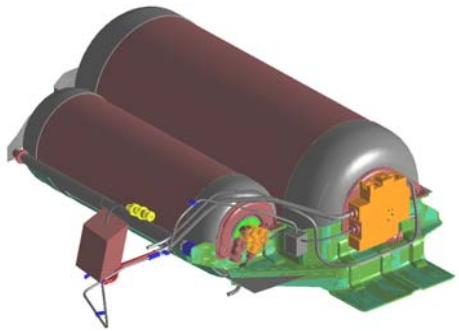
- Storage Capacity
- Safety Perception
- Cost

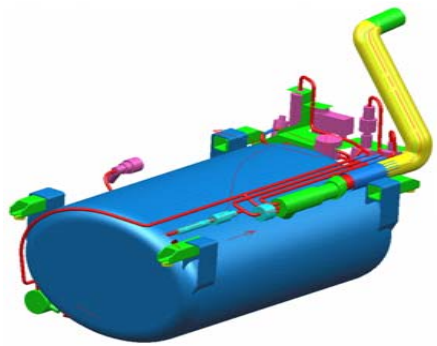
Liquid:

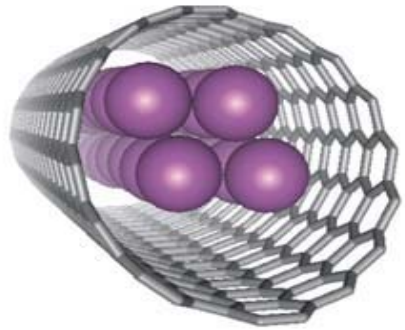
- Cost
- Storage Capacity
- Evaporation Losses
- High Energy Cost of Liquefaction
- Handling of Cryogenic Fuel

Solid-State:

- Maturity
- Weight
- Storage Capacity
- Containment
- Extraction







Present OEM Fuel Storage System Focus

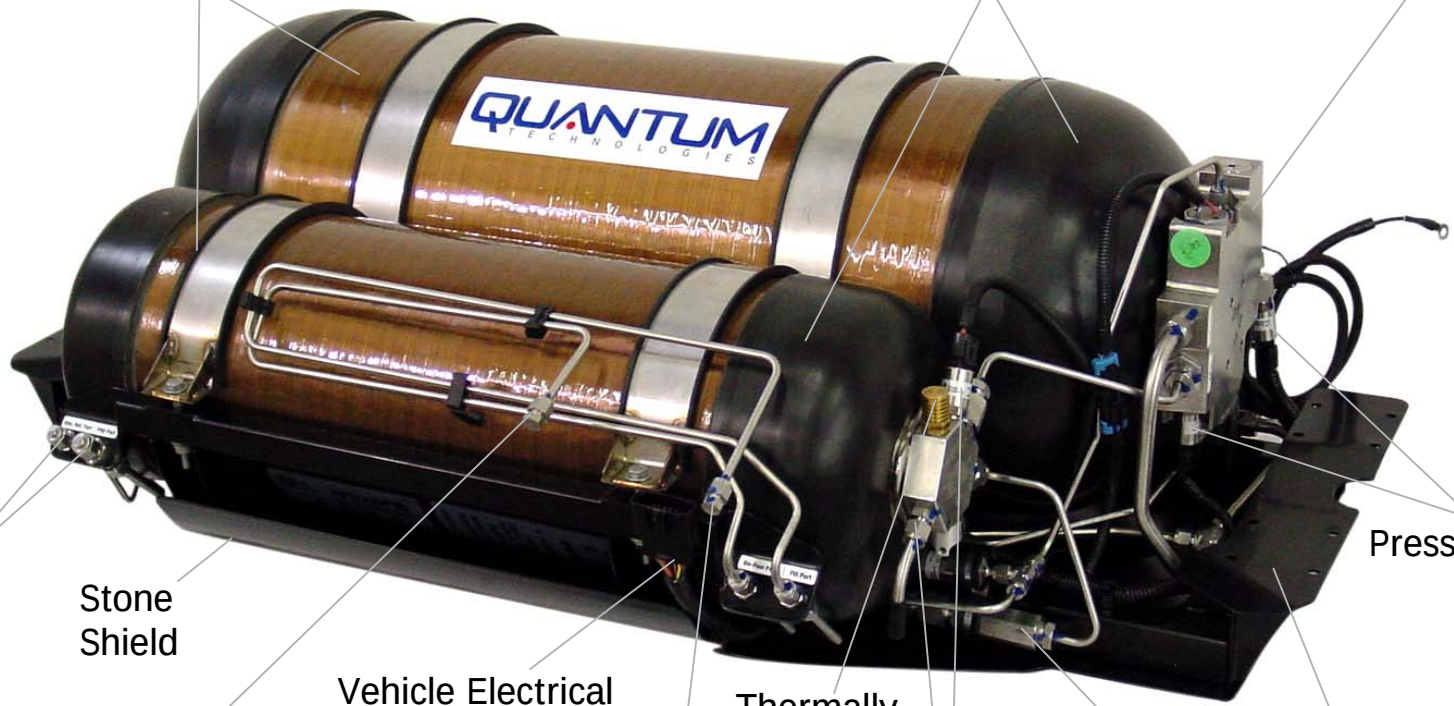
- **Compressed**

- **Liquid**

Liquid H_2 Storage Cost Drivers

- Components
  - Heat exchanger
  - Cryogenic valves
  - Valves and fittings
  - Sensors (temperature, pressure, hydrogen)
- Materials
  - Vessel
  - Insulation
  - Plumbing
  - Seals
- Manufacturing
  - Production volumes

Compressed Hydrogen Fuel Storage System



Type IV 70 MPa Composite Tanks

Foam Domes (Handling Safety Feature)

In Tank Regulator with Solenoid

Vent Line Ports

Stone Shield

Vehicle Electrical Interface Connector

Thermally Activated PRD

Pressure Sensors

Defueling Port (optional)

Refueling Port

Fill Line Check Valve

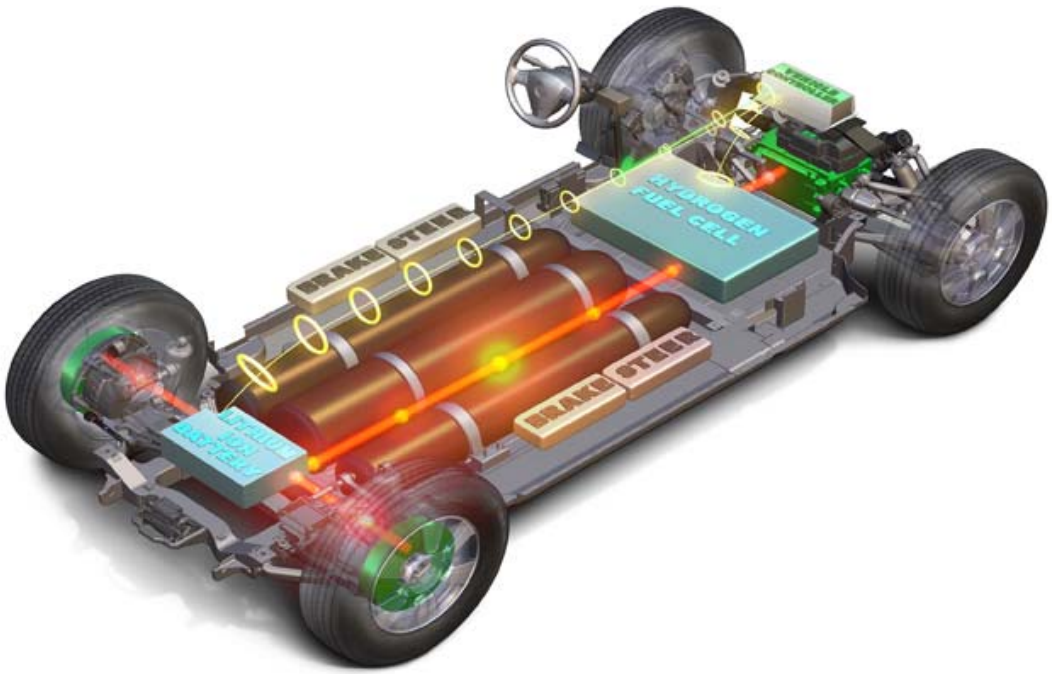
Pressure Sensors

Vehicle Interface Bracket

GM Sequel

Storage Centric Design:

- **Vehicle designed around fuel storage module**
- **Three longitudinally mounted 70 MPa compressed hydrogen Type IV tanks**
- **8.0 kg usable hydrogen capacity**



Compressed Hydrogen Storage System Costs

Approximately 65% of System Costs are Carbon Fiber

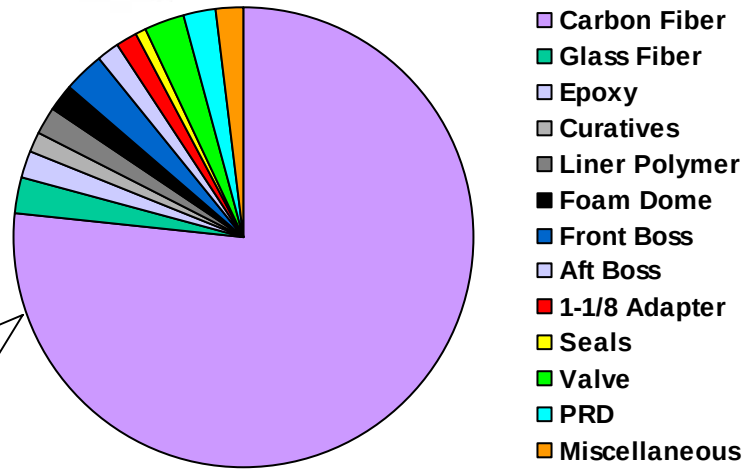
Manufacturing = 3%

Components = 13%

Pressure Regulator
Valves
Sensors (T, p)
Coupling
Fittings
PRD

Vessel = 84%

Carbon Fiber
Liner Material
Epoxy Resin
Pipes
Components



DOE Storage Targets

Parameter	Quantum Current*	2005	2010	2015
Usable Specific Energy (kW hr / kg)	1.3	1.5	2	3
Usable Energy Density (kW hr / L)	0.8	1.2	1.5	2.7
Cost ($ / kW hr)	$10-$17	$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

* Single 160L 70 MPa tank, 500k production volume, optimized carbon, health monitored storage system.

Composite Pressure Vessel Manufacturing

- Annual production ~ 750,000
  - All sizes, applications, and “types”
  - Highest growth rate for medical cylinders and paintball guns
- Manufacturing status
  - Computer-controlled, multi-spindle, high-speed filament winding
  - Liner production varies by type and manufacturer

Achieving DOE Targets with Advanced Manufacturing

Realistic Path for Compressed Hydrogen Technology -

- **Storage Centric Vehicle Design**

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Achieving DOE Targets with Advanced Manufacturing

Realistic Path for Compressed Hydrogen Technology -

- **Storage Centric Vehicle Design**
- **Single Longitudinal 160L 70MPa Storage Module**

Achieving DOE Targets with Advanced Manufacturing

Realistic Path for Compressed Hydrogen Technology -

- **Storage Centric Vehicle Design**
- **Single Longitudinal 160L 70MPa Storage Module**
- **On Tank Automatic Valve**

Achieving DOE Targets with Advanced Manufacturing

Realistic Path for Compressed Hydrogen Technology -

- **Storage Centric Vehicle Design**
- **Single Longitudinal 160L 70MPa Storage Module**
- **On Tank Automatic Valve**
- **External Low Cost Pressure Regulation Components**

Achieving DOE Targets with Advanced Manufacturing

Realistic Path for Compressed Hydrogen Technology -

- Storage Centric Vehicle Design
- Single Longitudinal 160L 70MPa Storage Module
- On Tank Automatic Valve
- External Low Cost Pressure Regulation Components
- Health Monitored Tank (1.8 SP Burst Ratio)

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Realistic Path for Compressed Hydrogen Technology -

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- Integrated Filament Winding w/ Fiber Placement

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- Revision of Codes & Standards enabling Fiber Placement
- Chilled Hydrogen Supply for Fast Fill

Achieving DOE Targets with Advanced Manufacturing

Estimated Performance –

Achieving DOE Targets with Advanced Manufacturing

Estimated Performance -

Usable Specific Energy
(kW hr / kg) > 2.0

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Achieving DOE Targets with Advanced Manufacturing

Estimated Performance -

Usable Specific Energy (kW hr / kg)	> 2.0
Usable Energy Density (kW hr / L)	0.9

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Achieving DOE Targets with Advanced Manufacturing

Estimated Performance -

Usable Specific Energy (kW hr / kg)	> 2.0
Usable Energy Density (kW hr / L)	0.9
Cost ($ / kW hr)	< $10

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Achieving DOE Targets with Advanced Manufacturing

Estimated Performance -

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Usable Energy Density (kW hr / L)	0.9
Cost ($ / kW hr)	< $10
Cycle Life (Cycles, 1/4 tank to full)	15,000

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Achieving DOE Targets with Advanced Manufacturing

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Cost ($ / kW hr)	< $10
Cycle Life (Cycles, 1/4 tank to full)	15,000
Refueling Rate (kg H_2 / min)	> 2.0

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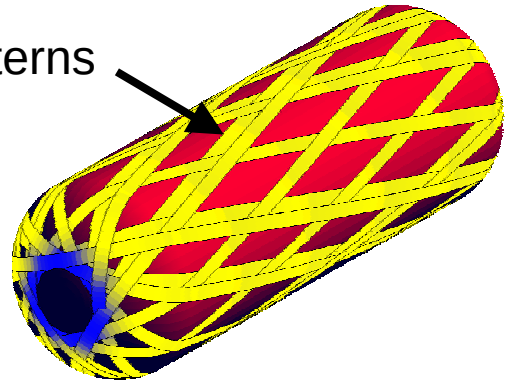
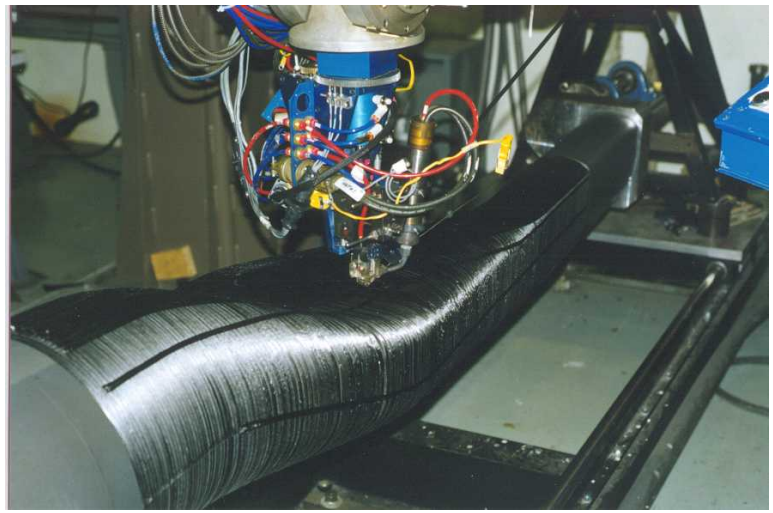
Integrated Filament Winding & Fiber Placement

Reduction in Fiber Usage -

- Eliminates need for “most” helical patterns on 70 MPa tank reducing carbon fiber usage by 20 – 30% depending on length & diameter.
- Long/Large diameter tanks benefit most.
- Enables use of thermal plastic matrix to improve damage tolerance & fatigue life.
- Improves placement & functionality of strain monitoring devices.





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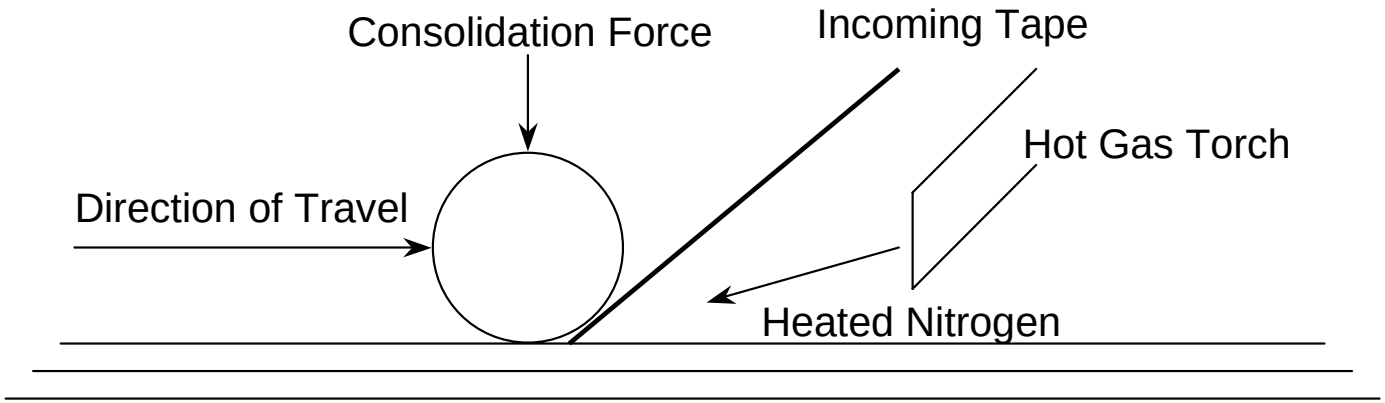
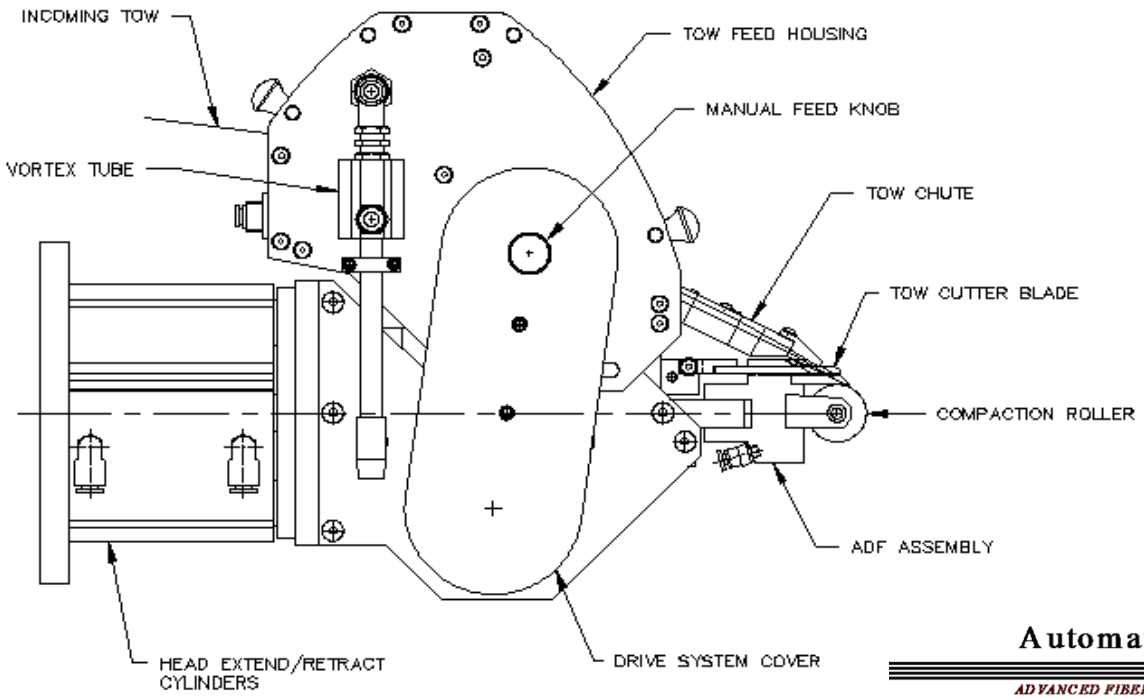
ADVANCED FIBER PLACEMENT TECHNOLOGY

Fiber Placement Process





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ADVANCED FIBER PLACEMENT TECHNOLOGY

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Aerospace Industry Fiber Placement

Mitsubishi Heavy Industries

6-axis gantry platform

8 tow thermoset delivery head

R&D work on Japanese SST (Super Sonic Transport)

Fiber Placement on Complex Surface

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ADVANCED FIBER PLACEMENT TECHNOLOGY

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Crossover Issues that Impact H_2 Storage

- Infrastructure development
  - Compressed vs. liquid
  - Centralized production/transport vs. distributed production
- Codes and standards
  - On-board vehicle storage vs. bulk transport vs. bulk (stationary) storage
  - U.S. vs. International
- Large scale stationary storage vs. on-board vehicle storage

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