This presentation does not contain any proprietary or confidential information.
Hydrogen storage systems on H$_2$ vehicles must:

- Contain
- Control
- Regulate
- Monitor

- Distribute
- Meter
- Refill
- Survive
Integrated Fuel Storage Systems

- Containment Vessel
- Pressure Regulators
- Valves & Solenoids
- PRD’s, Temp. & Pressure Sensors
- Fuel Lines / Tubing
- Electronics
- Support Structure / Bracketry
- Thermal Management 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 H₂ 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
- Vent Line Ports
- Stone Shield
- Defueling Port (optional)
- Refueling Port
- Vehicle Electrical Interface Connector
- Thermally Activated PRD
- Fill Line Check Valve
- Pressure Sensors
- Foam Domes (Handling Safety Feature)
- In Tank Regulator with Solenoid
- Vehicle Interface Bracket
- QUANTUM
- TECSTAR
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
## DOE Storage Targets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quantum Current*</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable Specific Energy (kW hr / kg)</td>
<td>1.3</td>
<td>1.5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Usable Energy Density (kW hr / L)</td>
<td>0.8</td>
<td>1.2</td>
<td>1.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Cost ($ / kW hr)</td>
<td>$10-$17</td>
<td>$6</td>
<td>$4</td>
<td>$2</td>
</tr>
<tr>
<td>Cycle Life (Cycles, 1/4 tank to full)</td>
<td>15,000</td>
<td>500</td>
<td>1,000</td>
<td>1,500</td>
</tr>
<tr>
<td>Refueling Rate (kg H₂ / min)</td>
<td>2.0</td>
<td>0.5</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

* 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
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)
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)
- Integrated Filament Winding w/ Fiber Placement
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)
- Integrated Filament Winding w/ Fiber Placement
- Revision of Codes & Standards enabling Fiber Placement
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)
- Integrated Filament Winding w/ Fiber Placement
- 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
Achieving DOE Targets with Advanced Manufacturing

Estimated Performance -

Usable Specific Energy
(kW hr / kg) > 2.0

Usable Energy Density
(kW hr / L) 0.9
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
Achieving DOE Targets with Advanced Manufacturing

<table>
<thead>
<tr>
<th>Estimated Performance -</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable Specific Energy</td>
</tr>
<tr>
<td>(kW hr / kg)</td>
</tr>
<tr>
<td>&gt; 2.0</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Usable Energy Density</td>
</tr>
<tr>
<td>(kW hr / L)</td>
</tr>
<tr>
<td>0.9</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cost</td>
</tr>
<tr>
<td>($ / kW hr)</td>
</tr>
<tr>
<td>&lt; $10</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cycle Life</td>
</tr>
<tr>
<td>(Cycles, 1/4 tank to full)</td>
</tr>
<tr>
<td>15,000</td>
</tr>
</tbody>
</table>
### Achieving DOE Targets with Advanced Manufacturing

<table>
<thead>
<tr>
<th>Estimated Performance -</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable Specific Energy</td>
<td>&gt; 2.0</td>
</tr>
<tr>
<td>(kW hr / kg)</td>
<td></td>
</tr>
<tr>
<td>Usable Energy Density</td>
<td>0.9</td>
</tr>
<tr>
<td>(kW hr / L)</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>&lt; $10</td>
</tr>
<tr>
<td>($ / kW hr)</td>
<td></td>
</tr>
<tr>
<td>Cycle Life</td>
<td>15,000</td>
</tr>
<tr>
<td>(Cycles, 1/4 tank to full)</td>
<td></td>
</tr>
<tr>
<td>Refueling Rate</td>
<td>&gt; 2.0</td>
</tr>
<tr>
<td>(kg H₂ / min)</td>
<td></td>
</tr>
</tbody>
</table>
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.
Fiber Placement Process

- Consolidation Force
- Incoming Tape
- Direction of Travel
- Hot Gas Torch
- Heated Nitrogen

Diagram components:
- Incoming Tow
- Vortex Tube
- Tow Feed Housing
- Manual Feed Knob
- Tow Chute
- Tow Cutter Blade
- Compaction Roller
- ADF Assembly
- Drive System Cover
- Head Extend/Retract Cylinders

Automated Dynamics
Advanced Fiber Placement Technology

Quantum Tecstar
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

Automated Dynamics

ADVANCED FIBER PLACEMENT TECHNOLOGY

QUANTUM • TECSTAR
Crossover Issues that Impact H₂ 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
CLEAN POWER
... FROM CONCEPT TO PRODUCTION

QTWW.COM
Nasdaq: QTWW