Carbon Fiber Composite Material Cost Challenges for Compressed Hydrogen Storage Onboard Fuel Cell Electric Vehicles

Fuel Cell Technologies Office Webinar
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Fuel Cell Technologies Office
U.S. Department of Energy
• Please type your questions into the question box
DOE Fuel Cell Technologies Office

Focus

Early phase applied research, development and innovation of hydrogen and fuel cell technologies that enable energy security, resiliency, and a strong domestic economy in emerging markets.

2020 Targets by Application

<table>
<thead>
<tr>
<th>Sub-Programs</th>
<th>Fuel Cell Cost</th>
<th>Durability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research and Development (R&amp;D)</td>
<td>$40/kW</td>
<td>5,000 hrs</td>
</tr>
<tr>
<td>Safety Codes and Standards</td>
<td>$1,000/kW*</td>
<td>80,000 hrs **</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>$1,500/kW**</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Fuel - Production - Delivery - Storage</td>
<td></td>
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<tr>
<td>Technology Acceleration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂ Storage Cost (Onboard)</td>
<td>$10/kWh</td>
<td>1.0 kWh/L, 1.5 kWh/kg</td>
</tr>
<tr>
<td>H₂ Cost at Pump</td>
<td>&lt;$4/gge</td>
<td>&lt;$7/gge (early market)</td>
</tr>
</tbody>
</table>

*For Natural Gas **For Biogas

Strengthening U.S. energy security and the economy through R&D on hydrogen and fuel cells
Objective: Develop H₂ storage technologies with performance to enable fuel cell products to be competitive with conventional technologies

For Light-Duty Vehicles:
- Comparable driving range
- Similar refueling time (~3 minutes)
- Comparable passenger and cargo space
- Equivalent level of safety
- Cost

Goal: Develop advanced hydrogen storage technologies to enable successful commercialization of hydrogen fuel cell products
Hydrogen Storage R&D – Strategy

Dual Approach

Near-Term Approach
- Hydrogen Storage
  - 700 bar Compressed
  - Cold / Cryo-Compressed
  - Metal Hydrides
  - Sorbents
  - Chemical H₂ Storage

Longer-Term Approach

Technology Focus

700 bar Compressed

Cold / Cryo-Compressed

Metal Hydrides

Sorbents

Chemical H₂ Storage

Barriers and R&D Focus

- Lower Cost Carbon Fiber
- Improved Composites
- Conformable designs
- Lower Cost BOP

- System Engineering
- Advanced Insulation
- Improved Dormancy
- Composite Development

- Higher Material Capacity
- System Cost
- Fill Time
- Onboard Efficiency

- Higher Material Capacity
- System Cost
- Dormancy
- WTP Efficiency

- Lower Cost Off-board Regen
- System Cost
- Gravimetric Density

Near-term: Address cost and performance of 700 bar compressed hydrogen storage
Long-term: Develop advanced technologies with potential to meet all targets
The Challenges of Compressed Hydrogen Storage Onboard Fuel Cell Vehicles
Challenges for Hydrogen as an Energy Carrier

H₂ fuel tanks onboard vehicles are larger than typical gasoline tanks
... even with efficiency of the fuel cell is considered

Gasoline

Hydrogen @ 700 bar

~3.5x gasoline

Energy Density Comparison (kWh/L)

~ Three times more energy by mass than most other fuels but need higher volumes to store

H₂ has very low Energy Density

Even when compressed to high pressures, H₂ has low energy by volume compared than most other fuels!

Hydrogen is a low-density gas under all practical conditions on earth
Lowest cost, but most difficult to package onboard a vehicle

Baseline system projections based on single tank design
More Challenges for H₂ as an Energy Carrier

High-pressure H₂ tanks are larger and have rigid cylindrical shapes

![Image of high-pressure H₂ storage tank]

Conventional gasoline tanks are highly conformable

![Image of conventional gasoline tank]

Much higher costs!

<table>
<thead>
<tr>
<th>Balance of Plant Components</th>
<th>Carbon fiber composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3950 for 5 kg H₂</td>
<td>$2455 for 5 kg H₂</td>
</tr>
</tbody>
</table>

Analysis for a single tank design

- 2020 Target
- Ultimate Target

Balance-of-Plant (BOP) is expensive and increases complexity & costs when more tanks are added

High-pressure H₂ storage tanks are expensive and difficult to package onboard vehicles
Higher cost, but more effective to package onboard a vehicle

All current commercial FCVs have dual tank designs
Hydrogen Fuel Cell Vehicles are Now Available!

All current commercial FCVs use two 700 bar composite overwrapped pressure vessels for onboard hydrogen storage.

Initial vehicle rollout occurring with compressed 700 bar pressure hydrogen storage.
• Shown is the projected **2015** status of 700-bar, Type IV COPV systems with the Program’s **2020** and **Ultimate targets**

• Approximately **50%** cost reduction is needed to meet the **Ultimate cost target** at high volumes (i.e. 500k units/yr.)

• Based on the Storage Targets, there is a need for **~2X higher energy density**

<table>
<thead>
<tr>
<th>Storage Targets</th>
<th>Gravimetric kWh/kg (kg H₂/kg system)</th>
<th>Volumetric kWh/L (kg H₂/L system)</th>
<th>Costs $/kWh ($/kg H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>1.5 (0.045)</td>
<td>1.0 (0.030)</td>
<td>$10 ($333)</td>
</tr>
<tr>
<td>2025</td>
<td>1.8 (0.055)</td>
<td>1.3 (0.040)</td>
<td>$9 (300)</td>
</tr>
<tr>
<td>Ultimate</td>
<td>2.2 (0.065)</td>
<td>1.7 (0.050)</td>
<td>$8 ($266)</td>
</tr>
<tr>
<td><strong>Current Status</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 bar compressed</td>
<td>1.4 (0.042)</td>
<td>0.8 (0.024)</td>
<td>$15 ($500)</td>
</tr>
</tbody>
</table>

1 Projected at 500,000 units/year

*Cost reductions must be met without decline in hydrogen storage system performance*
Cost remains a key challenge

Based on FCTO Program Record 15013.
Fuel cost assumes central SMR delivery and dispensed
How to meet the DOE cost targets?

- 2013: $17/kWh (-12%)
- 2015: $15/kWh (-33%)
- 2020: $10/kWh (-20%)
- Ultimate: $8/kWh (-47%)
Composite Overwrapped Pressure Vessels

- State-of-the-art hydrogen storage uses compressed H₂ gas at **350 or 700 Bar** in Composite Overwrapped Pressure Vessels (COPV)
- COPVs are constructed using **carbon fiber reinforced polymers** that are wrapped about **metallic (Type-III)** or **polymeric (Type-IV)** liners

A detailed schematic of a 700-bar Type-IV COPV for on-board FCV hydrogen storage (Credit: Argonne National Laboratory)

COPV manufacturing process via filament winding (Credit: Quantum Technologies, 2012)

*Composite materials enable high-strength and lightweight on-board hydrogen storage*
Carbon Fiber Reinforced Polymer (CFRP) Composite Material Supply Chain

Areas for cost reduction are precursor, conversion, and processing

S. Das et al. (2016), “Global Carbon Fiber Composites Supply Chain Competitiveness Analysis”, Oak Ridge National Laboratory
**Carbon Fiber Market Potential - Example**

**Est. World Carbon Fiber Supply (2020)**

<table>
<thead>
<tr>
<th>Application</th>
<th>Tank Quantity</th>
<th>CF Quantity</th>
<th>Projection</th>
<th>CF needed</th>
<th>Potential Market Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Car &amp; Light Trucks</td>
<td>2 Type III/IV tanks</td>
<td>700 bar</td>
<td>~75 kg per car</td>
<td>^180,000 cars</td>
<td>~13.5M kg or ~15,000 tons</td>
</tr>
<tr>
<td>Fuel Cell Buses</td>
<td>4 Type III/IV tanks</td>
<td>350 bar</td>
<td>~320 kg per bus</td>
<td>^44,000 buses</td>
<td>~14M kg or ~15,500 tons</td>
</tr>
</tbody>
</table>


**Significant market share of carbon fiber could be used for fuel cell vehicles**
Current Status – 700 Bar Compressed H₂ Storage System Cost Breakout

• Shown is the **cost breakdown** for systems made at **500k units/yr**.

• The high manufactured volume (i.e. 500k units/yr.) system cost is **dominated**, 72%, by **composite materials and filament winding**

• This is broken down further into:
  – Carbon fiber precursor material
  – Carbon fiber precursor conversion
  – Resin material
  – Filament winding of the COPV

**Reduce the costs of carbon fiber composites to drive down the hydrogen storage cost**

Technical Challenges and R&D Needs

What composite materials R&D could address these high cost items?

**Alternative carbon fiber precursors**
- Need chemistries that yield high strength and low-cost CF

**Alternative carbon fiber conversions**
- Need capital and energy cost reduction

**Alternative fibers to high cost carbon**
- Need fibers that lower cost yet high strength & low weight

**Alternative resins to high cost epoxies**
- Need low-cost resins with COPV high strength & low weight

**Alternative COPV manufacturing**
- Need COPV manufacturing to reduce cost by reducing CF


*Need to reduce hydrogen storage cost, while maintaining high strength composite material*
Polyacrylonitrile (PAN) is the current state of the art precursor material to produce CF (>90% of CF market).

- PAN fibers exhibit a high degree of molecular orientation that imparts higher strength.

- Rayon and pitch-based CF are lower cost alternatives to PAN-based CF (<10% of carbon fiber market).
  - Rayon and pitch-based carbon fibers do not meet the strength and durability needed for 700-bar pressure COPV performance.


Develop a lower cost carbon fiber precursor without degrading mechanical performance.
Carbon Fiber (CF) Precursor Chemistry: Alternatives

- Alternative carbon fiber precursor chemistries require expensive chemical processes to create the chained polymer structures needed to form high-strength, cross-linked CF

**Mesophase Pitch**
High Modulus, Moderate Strength

**Lignins**
Strength Properties not yet proven

**Rayon**
Expensive and use for Ablative

**Polyethylene**
Properties not yet proven

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**Challenging to source alternative carbon fiber precursors with high-strength at low cost**
• PAN fibers are usually produced using solution spinning processes
  – Orient the polymer chains
  – Remove the solvent
  – Obtain desired diameter
  – Handling and recovery of used hazardous solvents adds significant costs!

• Melt and spinning processes are typically lower cost
  – Co-monomers and plasticizers are added to PAN to lower the melting point -> engineering challenge!
  – Allows polymer extrusion without significant degradation
  – Currently no PAN precursors are commercially produced for conversion to high-strength CF using melt spinning


Process optimization of carbon fiber precursor may yield cost savings downstream
Carbon Fiber Precursor Processing: Conversion

- Carbon fiber precursor conversion involves a series of thermal treatments
  - i.e. **Stabilization**, **carbonization**, and **graphitization**
- Temperatures, heating rate, and applied tension are controlled
  - **Control** determines desired CF **tensile strength** and **modulus** – **Expensive**!
- Possible cost reduction by alternative precursors needing less temperature for carbon fiber conversion

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**PAN Precursor (Creels)**

**Pretreatment (Stretch)**

**Stabilization and Oxidation**

- ~200-300 °C

**Low Temperature Carbonization**

- ~300 to ~1300 °C

**High Temperature Carbonization**

- ~2500 °C

**Graphitization (Optional)**

**Spool (Winders)**

**Sizing**

**Surface Treatment**

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**Carbon fiber precursor conversion is very energy intensive and high cost**
Carbon Fiber Precursor Processing: Conversion

- Oxygen and/or oxidative species needs to diffuse through the oxidized PAN “skin”
- Diffusion of oxygen to reactive sites is restricted, with subsequent reactions following more slowly
- The limiting or controlling factor is **diffusion**
- Ex. It requires 2.1 lbs of PAN precursor to make 1 lb of carbon fiber, due to elemental mass losses

*Excess time and energy costs inhibit maximizing CF yield during precursor conversion*

EERE R&D Examples: CF Precursors and Conversion

High-Volume Textile (PAN/MA) Precursors [ORNL]
- Precursors account for ~55% of cost of carbon fibers
- Textile PAN fibers ~25% lower cost than conventional PAN

Low-Cost CF Precursors [ORNL/VT]
- Approach: Melt-spinning process to produce PAN/comonomer fiber for use as precursor for high-strength CF production
- Goal: ~30% lower cost CF than with conventional PAN precursor fibers

Advanced Conversion Using MAP [ORNL]
- Microwave Assisted Plasma (MAP) is a technology for carbonizing carbon fibers at higher speeds and lower costs
  - Lower residence time
  - Lower temperature operation
  - Cost savings


*Lower cost carbon fiber precursor -> lower cost carbon fiber -> lower cost hydrogen storage!*
Precursor development for low-cost, high-strength carbon fiber (CF) for use in composite overwrapped pressure vessel applications

- Resulting CF to have properties similar to Toray T700S
- Target cost of $12.60/kg of CF

Areas of interest:

- PAN-based fibers formulated with co-monomers and additives that permit lower cost processing to produce the PAN fiber than conventional solution spinning processes, and or that reduce the conversion cost of the PAN-fiber to CF;
- Polyolefin-based fibers capable of being cost effectively converted into high-strength CF;
- Novel material precursor fibers that can lead to low-cost, high-strength CF production.
New FY2017 FOA Selections: *Low-Cost CF Precursors*

- **Oak Ridge National Laboratory (ORNL)**
  - Novel Plasticized Melt Spinning Process of PAN Fibers Based on Task-Specific Ionic Liquids
  - PI: Sheng Dai

- **The Pennsylvania State University (PSU)**
  - Developing A New Polyolefin Precursor for Low-Cost, High-Strength Carbon Fiber
  - PI: Mike Chung

- **University of Kentucky (UK)**
  - Precursor Processing Development for Low-Cost, High-Strength Carbon Fiber for Composite Overwrapped Pressure Vessel Applications
  - PI: Matthew C. Weisenberger
Alternative Fibers to High Cost Carbon

E-Glass fibers are low-cost at approximately 1/10th the cost of Toray T-700S CF.

- E-Glass is unsuited for onboard H₂ storage.
- Lower relative strength, lower stress rupture performance, and higher density.
- Higher strength S-Glass is difficult to manufacture with limited suppliers.

Safety factor for COPVs dependent on the fiber stress rupture performance:

- Safety factor for CF-based COPVs is 2.25.
- Glass fibers require a 3.0-3.5 safety factor.
- Higher safety factor means more material is needed, adding mass and costs!

EERE R&D Example: High-Strength Glass Fiber

Low-cost alternative fibers to CF [PPG/Hexagon Lincoln/PNNL]

- Approach: Ultra-high strength fiber glass
- Goal: New fiber glass with tensile strength exceeding Toray T700 CF at ~50% of cost
- Demonstrated pilot scale high temperature glass fiber manufacturing process and produced 1200 lb of glass.
- High strength fiber tanks outperformed the reference fiber tanks on burst pressure and cyclic pressure tests.

Low cost, high-strength alternative fibers may be fit for hydrogen COPVs.
Alternative Resins to High Cost Epoxies

Type-IV COPVs are made using polymer epoxy resins. Expensive and high density!

A challenge with resins is permeability into dry fibrous porous media (inter/intra-tow)

Resin is critical for the distribution of shear stresses during cyclic H₂ loadings

The goal is to fully infiltrate resin into fibers in acceptable time-scales

Need compatibility with processing, while remaining low-cost and high performance

Voids can lead to premature failure under cyclic pressure and temperature loadings

EERE R&D Example: Alternative Low-Cost Resins

**Synergistic approach to reduce cost of H₂ storage tanks**

[PNNL/Ford/Hexagon Lincoln/AOC/Toray]

- Approach: Synergistically consider pressure vessel and operating conditions (500 bar, 200 K)
- Goal: 30% reduction in system cost over 2013 baseline cost for 700 bar system
- Vinyl ester and epoxy resin composites both show improved strength at 200 K
- Lower-cost vinyl ester resin (XR-4079) able to match epoxy performance with 5-7% weight reduction

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Epoxy Relative Burst</th>
<th>Vinyl Ester Relative Burst</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No Impact</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burst</td>
<td>105%</td>
<td>111%</td>
</tr>
<tr>
<td>Cycle A</td>
<td>100%</td>
<td>103%</td>
</tr>
<tr>
<td>Cycle B</td>
<td>99%</td>
<td>95%</td>
</tr>
<tr>
<td><strong>Impact test round 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burst</td>
<td>57%</td>
<td>55%</td>
</tr>
<tr>
<td>Cycle A</td>
<td>67%</td>
<td>DNF</td>
</tr>
<tr>
<td>Cycle B</td>
<td>58%</td>
<td>63%</td>
</tr>
<tr>
<td><strong>Impact test round 2</strong></td>
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<td></td>
</tr>
<tr>
<td>Burst</td>
<td>70%</td>
<td>82%</td>
</tr>
<tr>
<td>Cycle A</td>
<td>55%</td>
<td>74%</td>
</tr>
<tr>
<td>Cycle B</td>
<td>62%</td>
<td>67%</td>
</tr>
</tbody>
</table>

Find resins at lower cost, lower density, and higher performance to better use carbon fiber
Alternative COPV Manufacturing: Vacuum-Assisted Composites Processing

Another cost reduction strategy is to reduce the CF needed in COPVs

CF reduction without sacrificing performance is a cost advantage

COPVs are traditionally made via filament winding

Advantage: Well understood in industry and repeatability

Consider uniform compaction around fibers before, during, and after infusion

Provides an opportunity to reduce needed CF and resin to meet safety factor

Key is to engineer COPV material and processing to maximize the fiber utilization

Challenge: Lack of uniform fiber compaction and resin dripping

Additional wall thickness is applied to meet safety factor, adding cost

EERE R&D Example: COPV Manufacturing

Alternative resin and manufacturing [Materia/MSU/Spencer Composites/Hypercomp Engineering]

- Reducing composite volume/mass through use of alternative resin and manufacturing processes
- Improved process cut resin infusion time in half for prototype tanks

Reduce carbon fiber use with better fiber utilization through alternative manufacturing
EERE R&D Example: COPV Manufacturing

Optimized cost and performance of COPVs [CTD/ORNL/Adherent Tech.]

• Approach: Graded construction utilizing thick wall effect
• Goal: demonstrate potential for 10-25% lower cost through graded-construction approach
• Evaluated Panex 35™ as potential lower-cost candidate fiber to replace portion of Toray T700S
• Cost reduction potential of 9-33%


Hybridization of high-cost carbon fiber with lower cost alternatives to reduce total cost
Alternative COPV Manufacturing: Conformable Compressed H₂ Storage Vessels

An approach to improve onboard packaging is conformable COPV designs

Conformable designs allow for more flexibility in packaging onboard FCVs

Automotive OEMs have to design around large, rigid cylindrical COPVs that limit flexibility

To overcome this, all current commercially available FCVs use multiple, smaller COPVs

Adds cost since each COPV requires BOP such as shut-off valves, pressure relief devices, etc.

EERE R&D Example: Conformable Design

Conformable 700 bar H₂ Storage Systems
[CTE/HECR/UT/Stan Sanders]

- Developing conformable 700 bar pressure vessels without use of carbon fiber composites
- Demonstrated vessel with a 34,000 psi burst (2345 bar), exceeding the 2.25 safety margin for 700 bar systems

Schematics of conformable compressed H₂ storage tanks

Kevlar Over-Braided Coiled Vessels

Conformable designs may permit for optimized COPV packaging to reduce carbon fiber use
Cross-Cutting: IACMI-The Composites Institute

Institute for Advanced Composites Manufacturing Innovation

- Institute of Manufacturing USA
- Managed by the EERE Advanced Manufacturing Office
- Technology Focus Areas:
  - Vehicles
  - Wind Turbine Blades
  - Compressed Gas Storage Vessels
  - Design, Modeling & Simulation
  - Composite Materials & Processes

Leveraged project: Thermoplastic Composite Compressed Gas Storage Tanks

- Project lead: DuPont
- Partners:
  - Composite Prototyping Center (CPC)
  - Steelhead Composites
  - University of Dayton Research Institute (UDRI)
- Kick-off: FY2017, Q1
Recent Progress on Cost Reduction

Shown for the 2013 baseline to the 2015 updated cost for 700-bar compressed H₂ storage systems at 500k units/yr.

Based on Program Record 15013

12% net hydrogen storage system cost reduction in two years attributed to R&D activities
### Examples:

<table>
<thead>
<tr>
<th>Category</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unmanned Aerial Vehicles (UAV)</td>
<td></td>
</tr>
<tr>
<td>Unmanned Underwater Vehicles (UUV)</td>
<td></td>
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<tr>
<td>Portable Power Systems</td>
<td></td>
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<tr>
<td>Materials Handling Equipment</td>
<td></td>
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<tr>
<td>Airport Ground Equipment</td>
<td></td>
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<tr>
<td>Fuel Cell Range Extenders of EVs</td>
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<tr>
<td>Energy Carrier for Electrical Grid Storage</td>
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<tr>
<td>Fuel Cell Electric Vehicles</td>
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<tr>
<td>Stratospheric Satellites</td>
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<td>Robotics</td>
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<tr>
<td>Transport Refrigeration Units</td>
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</tr>
<tr>
<td>Fuel Cell Aircraft Systems</td>
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</table>


*Wide variety of high-value automotive & non-automotive applications of H₂ fuel cell technologies*
Successful FCV rollout requires cost reductions of the hydrogen storage system

700-bar compressed hydrogen storage relies on carbon fiber composite materials technologies

Significant R&D is needed to reduce the carbon fiber composite materials costs to meet DOE system targets

Innovation and early stage R&D are needed in areas such as fiber & resin technologies and COPV manufacturing

**DOE-FCTO has a multi-prong approach for addressing the technical challenges and R&D needs of on-board hydrogen storage systems**
Acknowledgements

The DOE-FCTO Hydrogen Storage Team:

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
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<tbody>
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<td>Program Manager</td>
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The team would like to acknowledge and thank the respective Principal Investigators and their project teams cited in this work supported by DOE-FCTO’s Hydrogen Storage Program who have contributed to the Program’s mission to advance hydrogen storage systems for successful FCV rollout.

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• Please type your questions into the question box
Thank You!

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