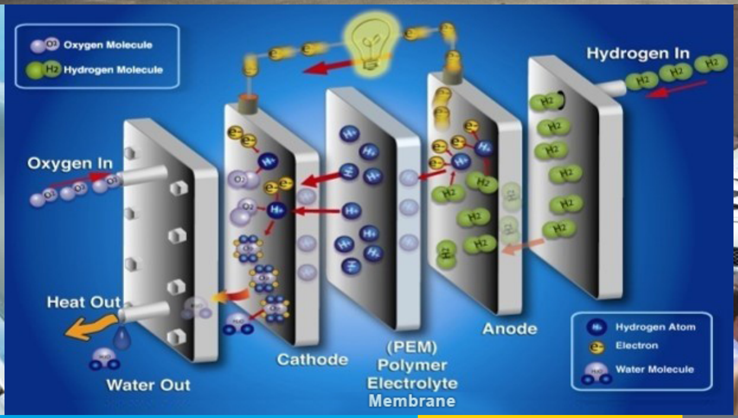
Carbon Fiber Composite Material Cost Challenges for Compressed Hydrogen Storage Onboard Fuel Cell Electric Vehicles

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Fuel Cell Technologies Office Webinar

Washington, D.C., USA

Tuesday, July 25, 2017

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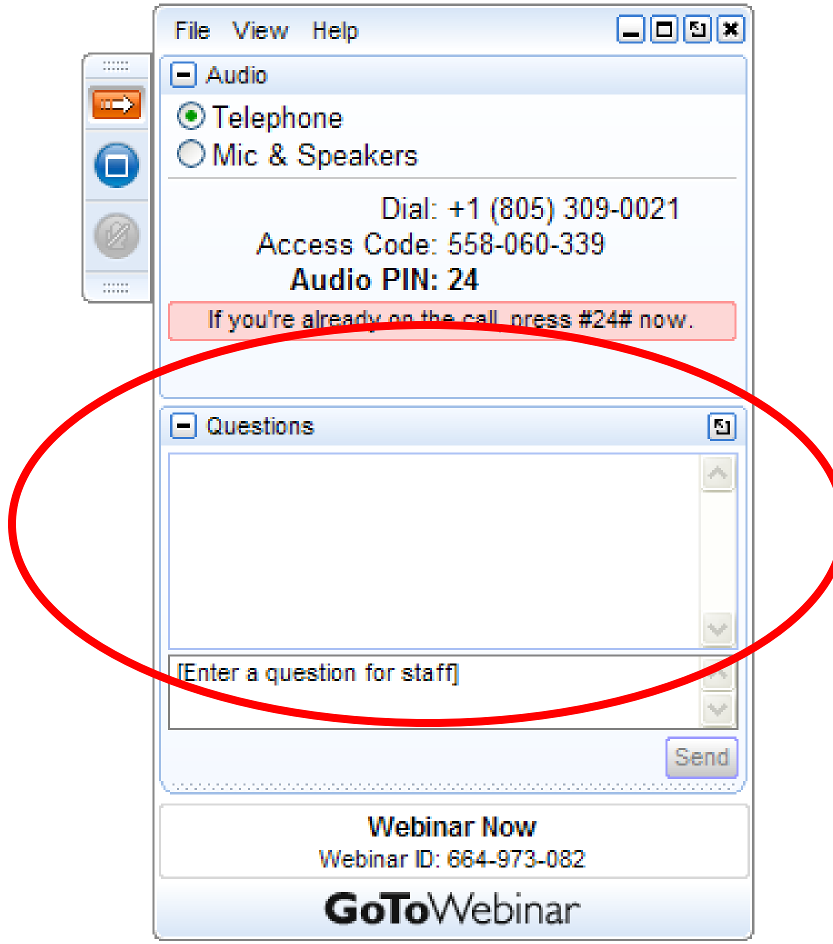
Hydrogen Storage Program
Fuel Cell Technologies Office
U.S. Department of Energy

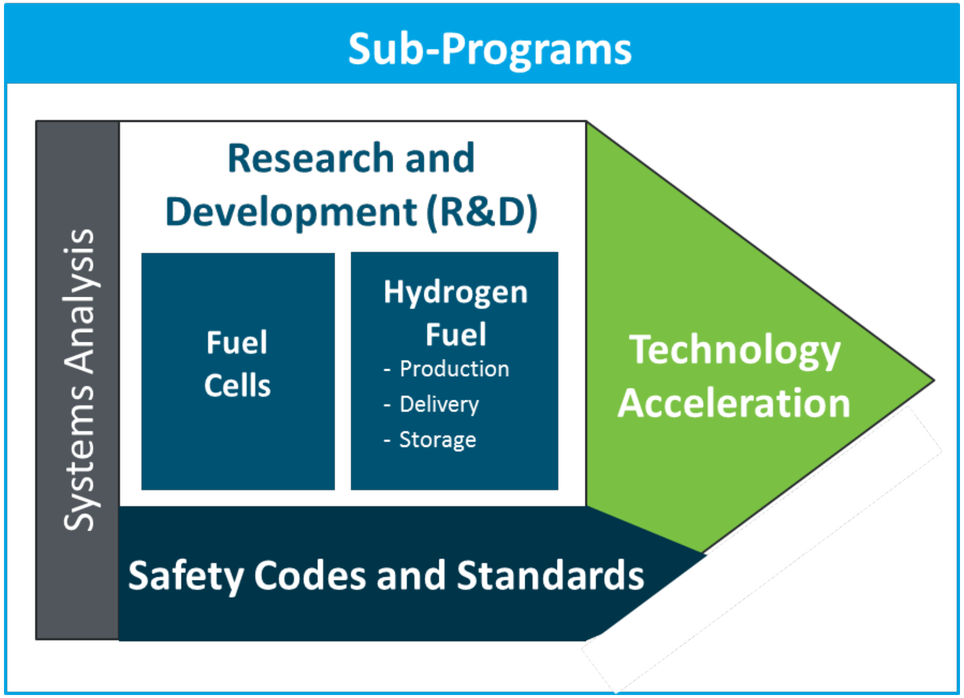
Question and Answer

- Please type your questions into the question box



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

Fuel Cell Cost	$40/kW	$1,000/kW* $1,500/kW**
Durability	5,000 hrs	80,000 hrs
H_2 Storage Cost (Onboard)	$10/kWh 1.0 kWh/L, 1.5 kWh/kg	
H_2 Cost at Pump	<$4/gge <$7/gge (early market)	

*For Natural Gas
**For Biogas

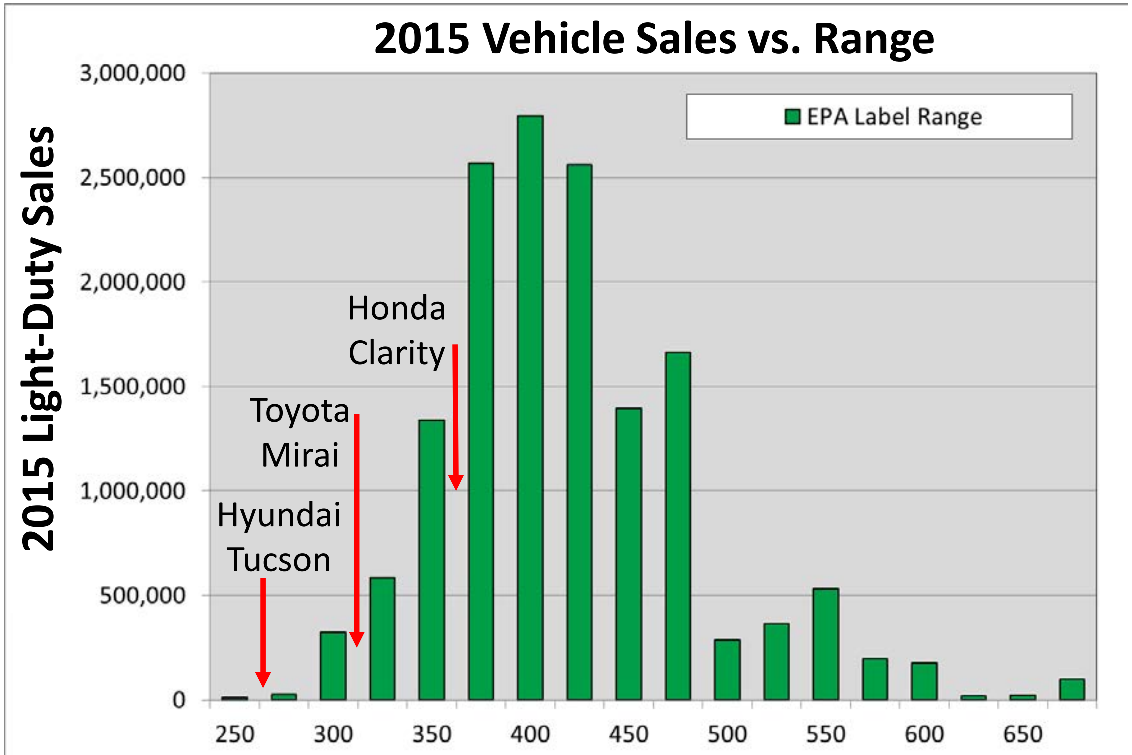
Strengthening U.S. energy security and the economy through R&D on hydrogen and fuel cells

FCTO H_2 Storage Program: Goals and Objectives

Objective: Develop H_2 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



Courtesy of Marc Melaina and Eleftheria Kontou (NREL), and David Greene (ANL)

<u>Goal</u>: Develop advanced hydrogen storage technologies to enable successful commercialization of hydrogen fuel cell products

Hydrogen Storage R&D – Strategy

Dual Approach

- Hydrogen Storage
  - Near-Term Approach
  - Longer-Term Approach

Composite Materials R&D Focus

Technology Focus / Barriers and R&D Focus

700 bar Compressed

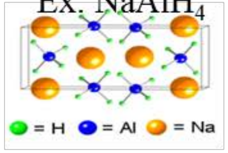
- Lower Cost Carbon Fiber
- Improved Composites
- Conformable designs
- Lower Cost BOP

Cold / Cryo-Compressed

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

Metal Hydrides

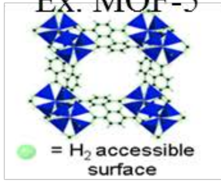
Ex. $NaAlH_4$



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

Sorbents

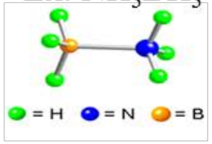
Ex. MOF-5



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

Chemical H_2 Storage

Ex. NH_3BH_3



- 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

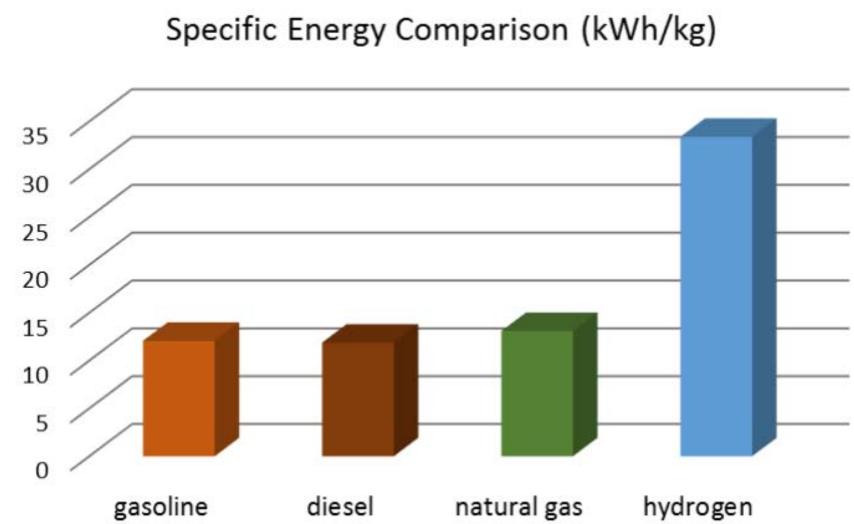
H_2 fuel tanks onboard vehicles are larger than typical gasoline tanks

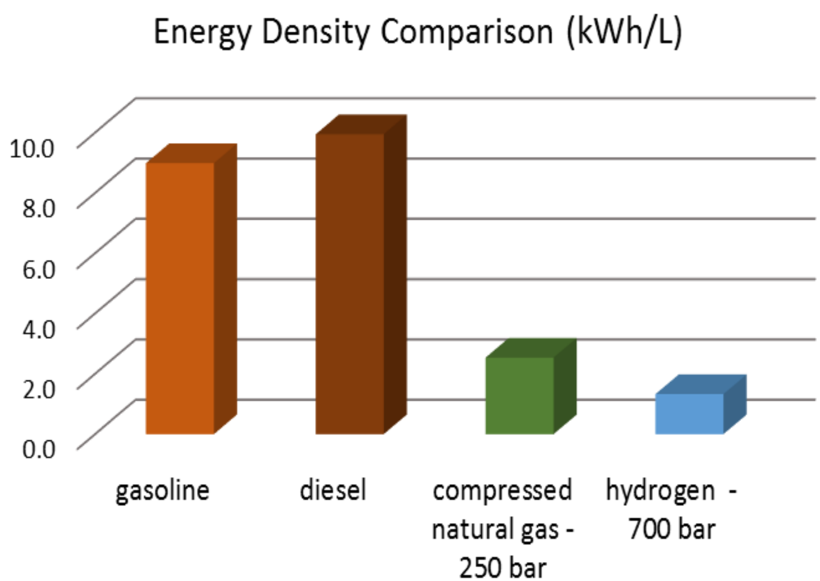
… even with efficiency of the fuel cell is considered

Gasoline

Hydrogen @ 700 bar

~3.5x gasoline





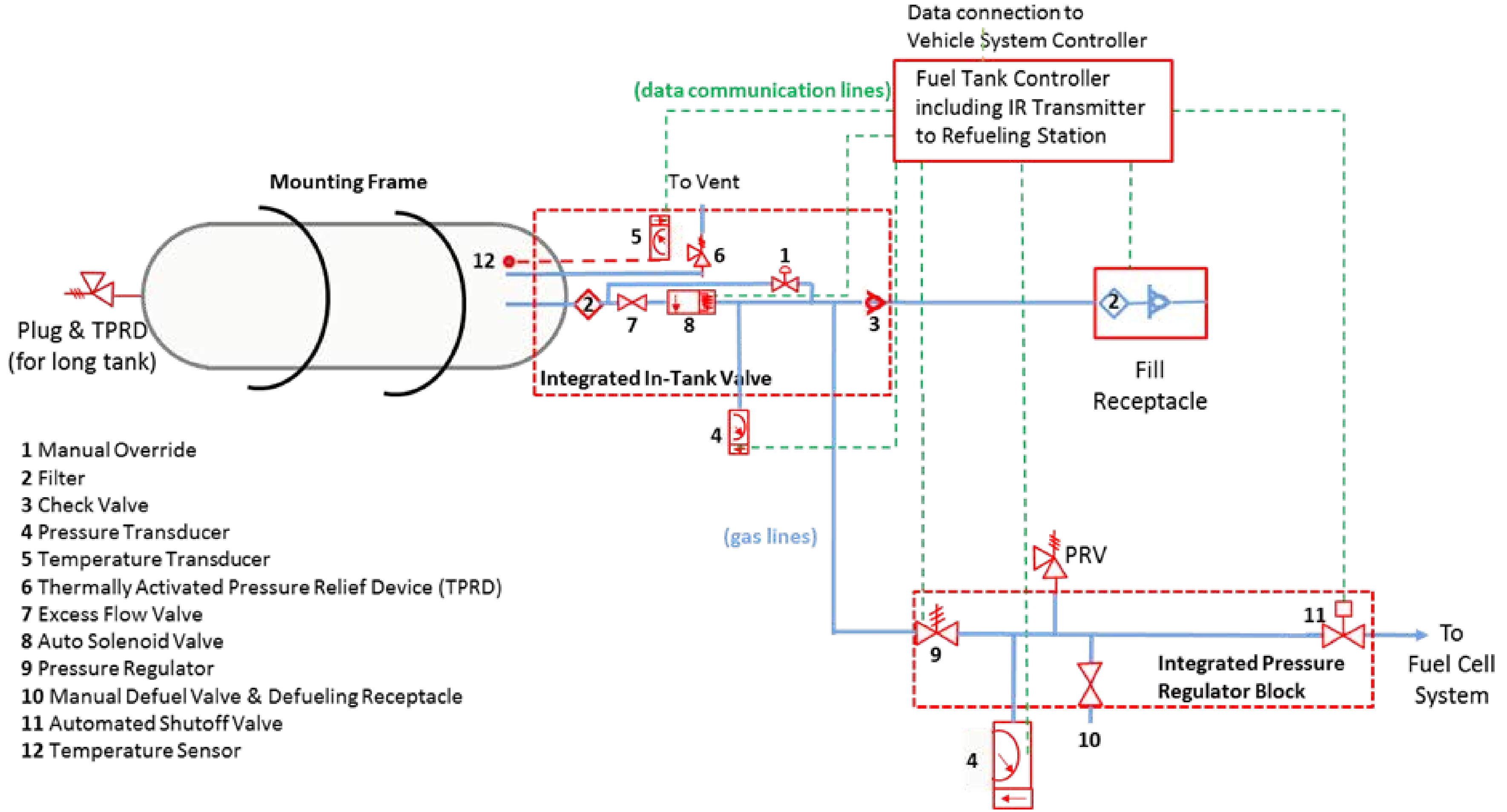
~ *Three times* more energy by mass than most other fuels but need higher volumes to store

H_2 has very low Energy Density

Even when compressed to high pressures, H_2 has low energy by volume compared than most other fuels!

Hydrogen is a low-density gas under all practical conditions on earth

Single Tank System Schematic

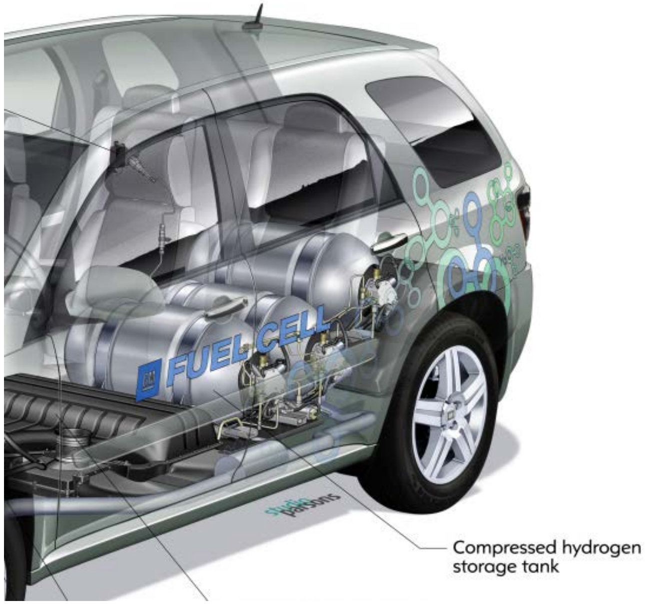


Lowest cost, but most difficult to package onboard a vehicle

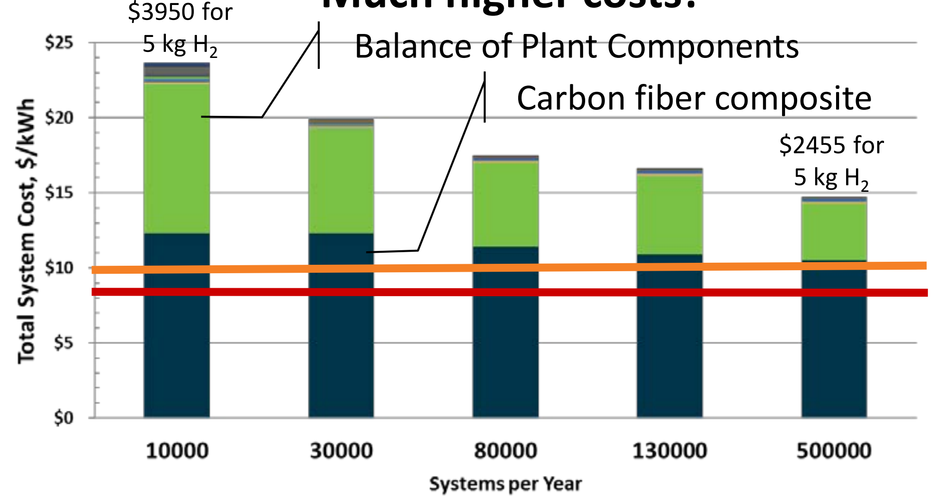
Baseline system projections based on single tank design

More Challenges for H_2 as an Energy Carrier

High-pressure H_2 tanks are larger and have rigid cylindrical shapes

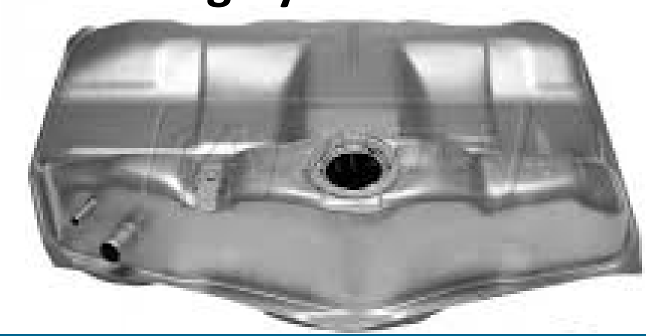


Much higher costs!

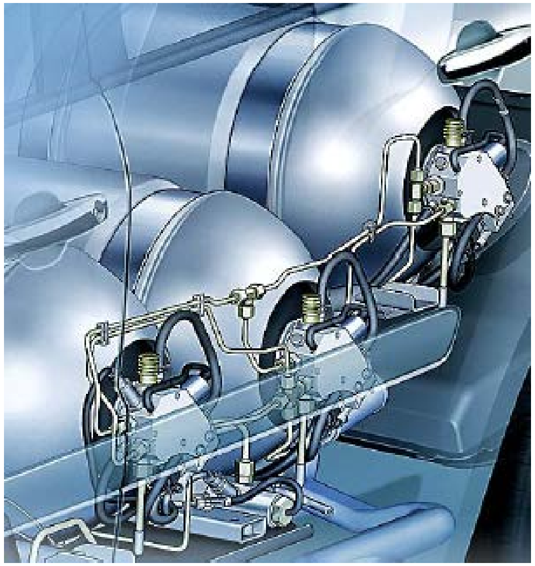


Analysis for a single tank design

Conventional gasoline tanks are highly conformable

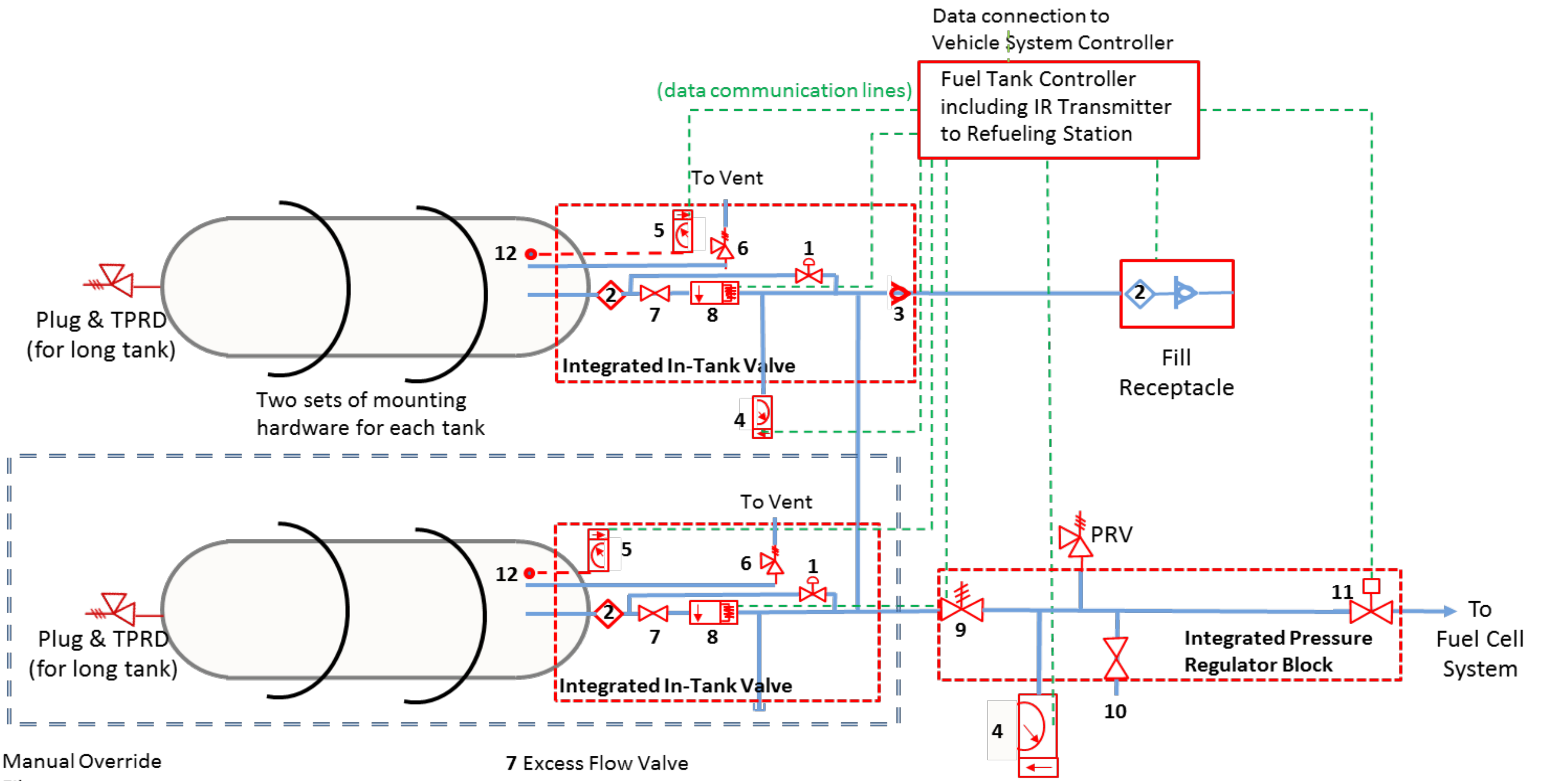


Balance-of-Plant (BOP) is expensive and increases complexity & costs when more tanks are added



High-pressure H_2 storage tanks are expensive and difficult to package onboard vehicles

Dual Tank System Schematic



1 Manual Override
2 Filter
3 Check Valve
4 Pressure Transducer
5 Temperature Transducer
6 Thermally Activated Pressure Relief Device (TPRD)
7 Excess Flow Valve
8 Auto Solenoid Valve
9 Pressure Regulator
10 Manual Defuel Valve & Defueling Receptacle
11 Automated Shutoff Valve
12 Temperature Sensor

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

Honda Clarity

Photo Credit: Honda Motor

Hyundai Tucson Fuel Cell

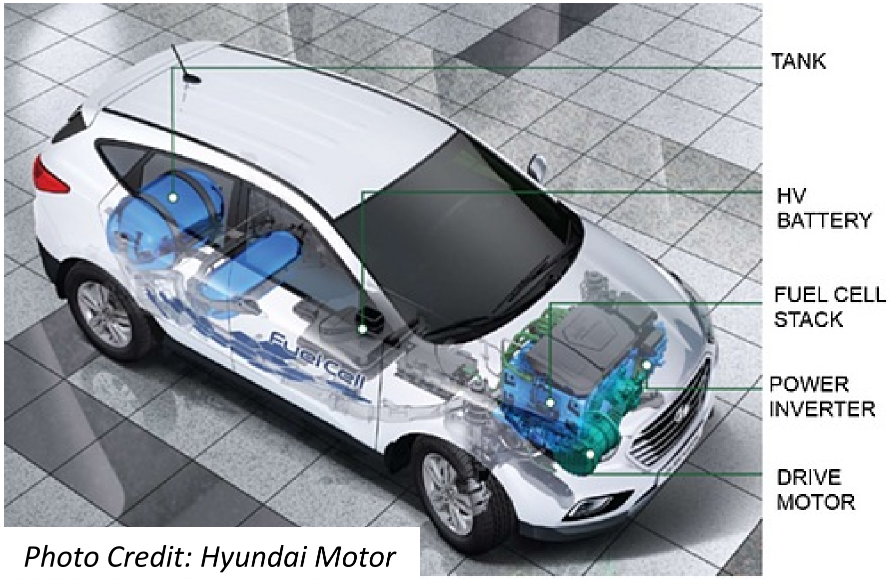


Photo Credit: Hyundai Motor

Toyota Mirai

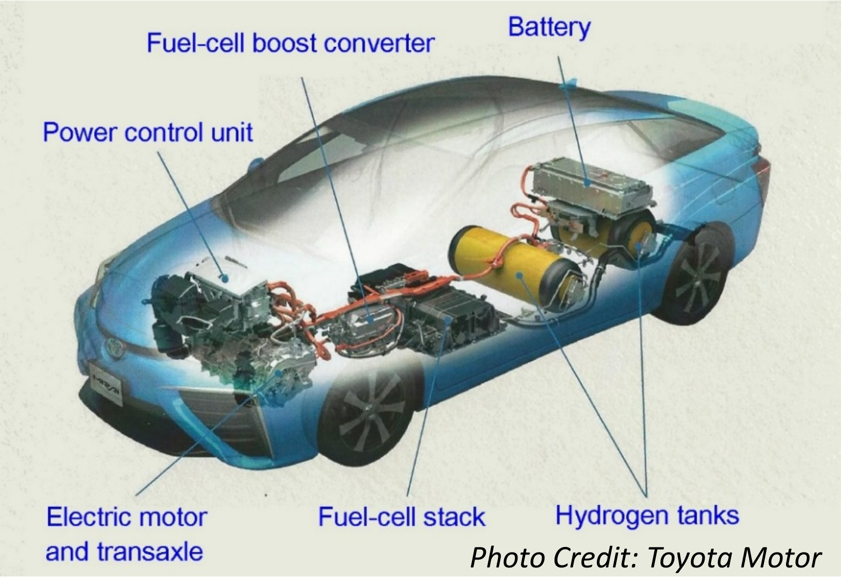


Photo Credit: Toyota Motor

Initial vehicle rollout occurring with compressed 700 bar pressure hydrogen storage

Current Status vs. Revised Targets

- 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**

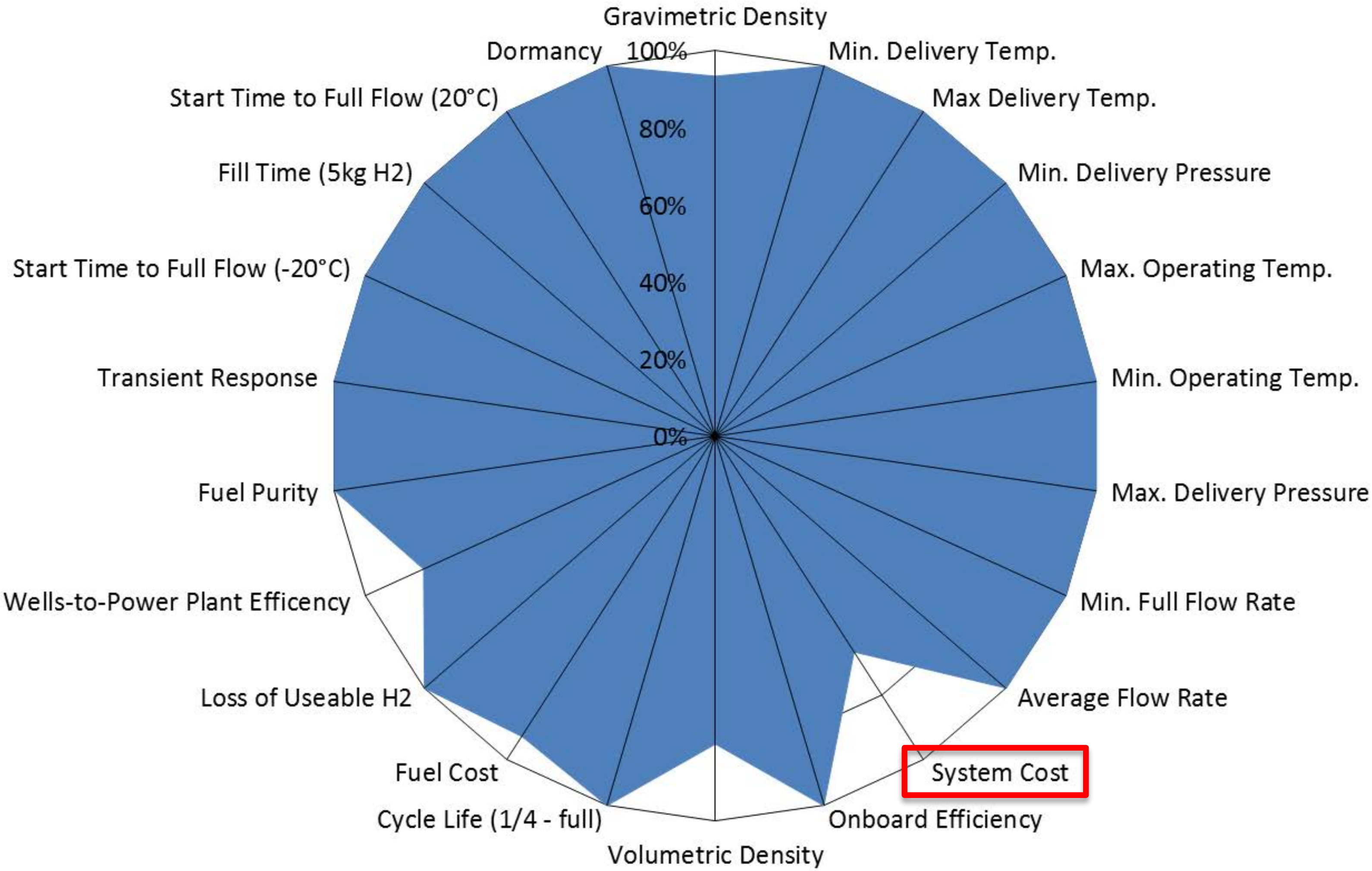
Storage Targets	Gravimetric kWh/kg (kg H_2/kg system)	Volumetric kWh/L (kg H_2/L system)	Costs [1] \$/kWh (\$/kg H_2)
2020	1.5 (0.045)	1.0 (0.030)	\$10 (\$333)
2025	1.8 (0.055)	1.3 (0.040)	\$9 (300)
Ultimate	2.2 (0.065)	1.7 (0.050)	\$8 (\$266)
Current Status [2]			
700 bar compressed (5.6 kg H_2, Type IV, Single Tank)	1.4 (0.042)	0.8 (0.024)	\$15 (\$500)

[1] Projected at 500,000 units/year
[2] FCTO Data Record #15013, 11/25/2015: https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

The full set of H2 storage targets can be found on FCTO's websites:
https://energy.gov/eere/fuelcells/downloads/doe-targets-onboard-hydrogen-storage-systems-light-duty-vehicles
https://energy.gov/eere/fuelcells/doe-technical-targets-onboard-hydrogen-storage-light-duty-vehicles

Cost reductions must be met without decline in hydrogen storage system performance

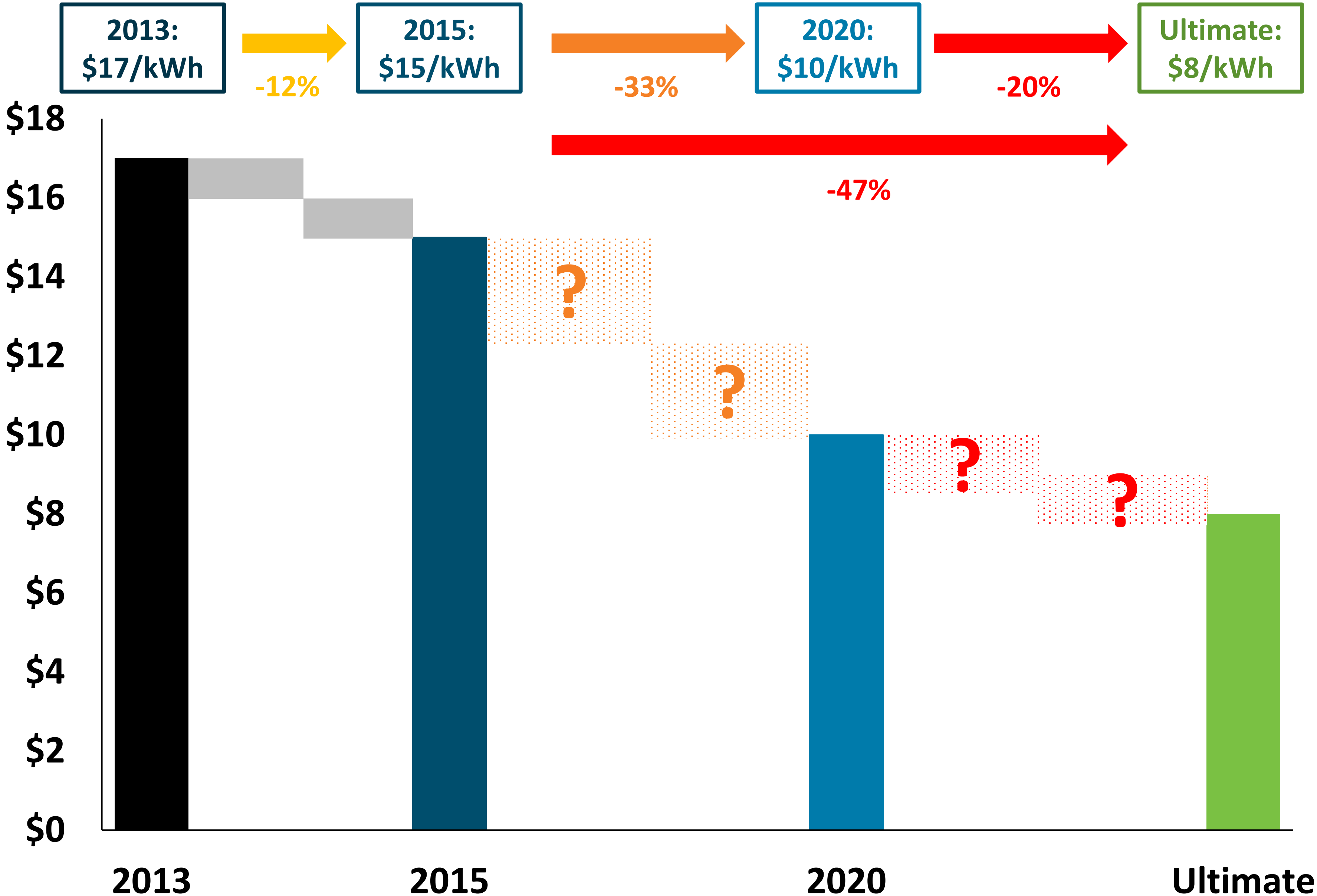
700 bar compressed status vs. 2020 targets



Based on FCTO Program Record 15013.
Fuel cost assumes central SMR delivery and dispensed

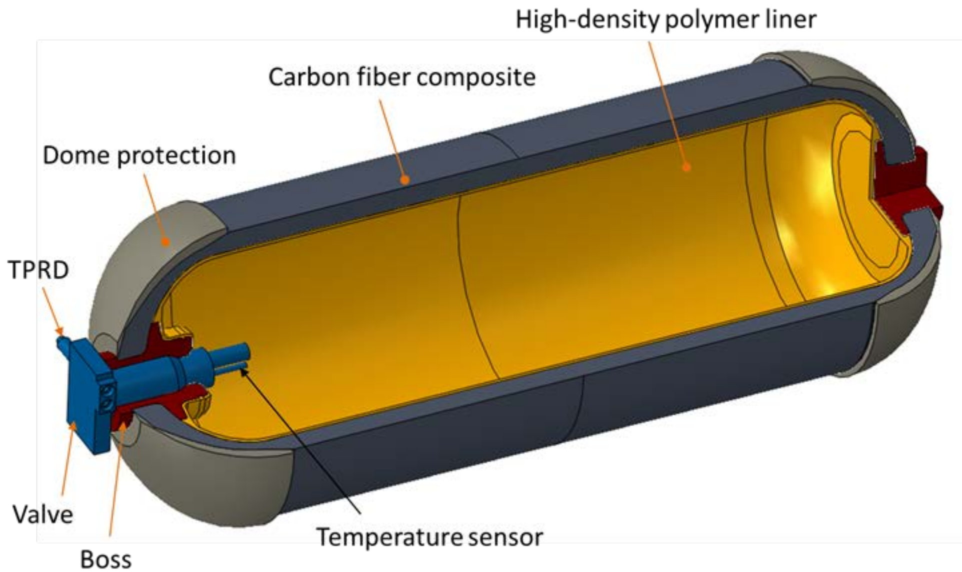
Cost remains a key challenge

How to meet the DOE cost targets?

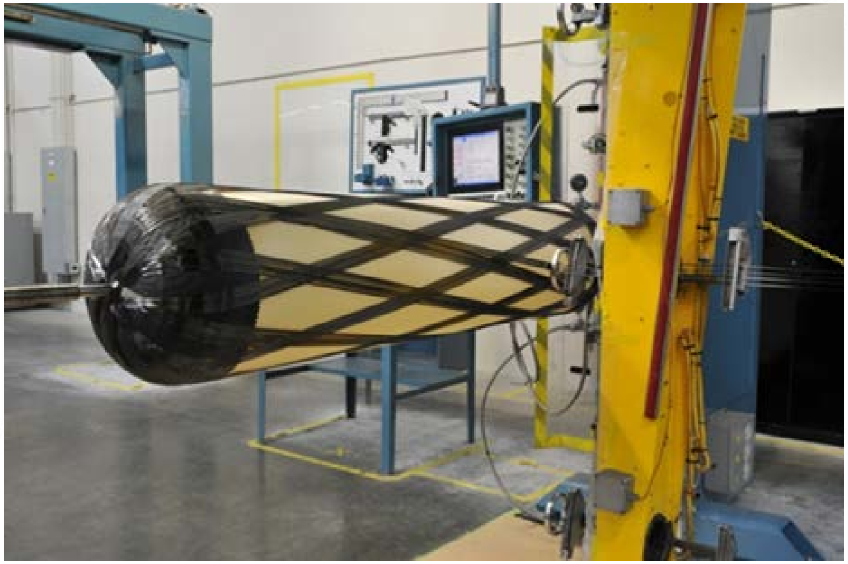


Composite Overwrapped Pressure Vessels

- State-of-the-art hydrogen storage uses compressed H_2 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

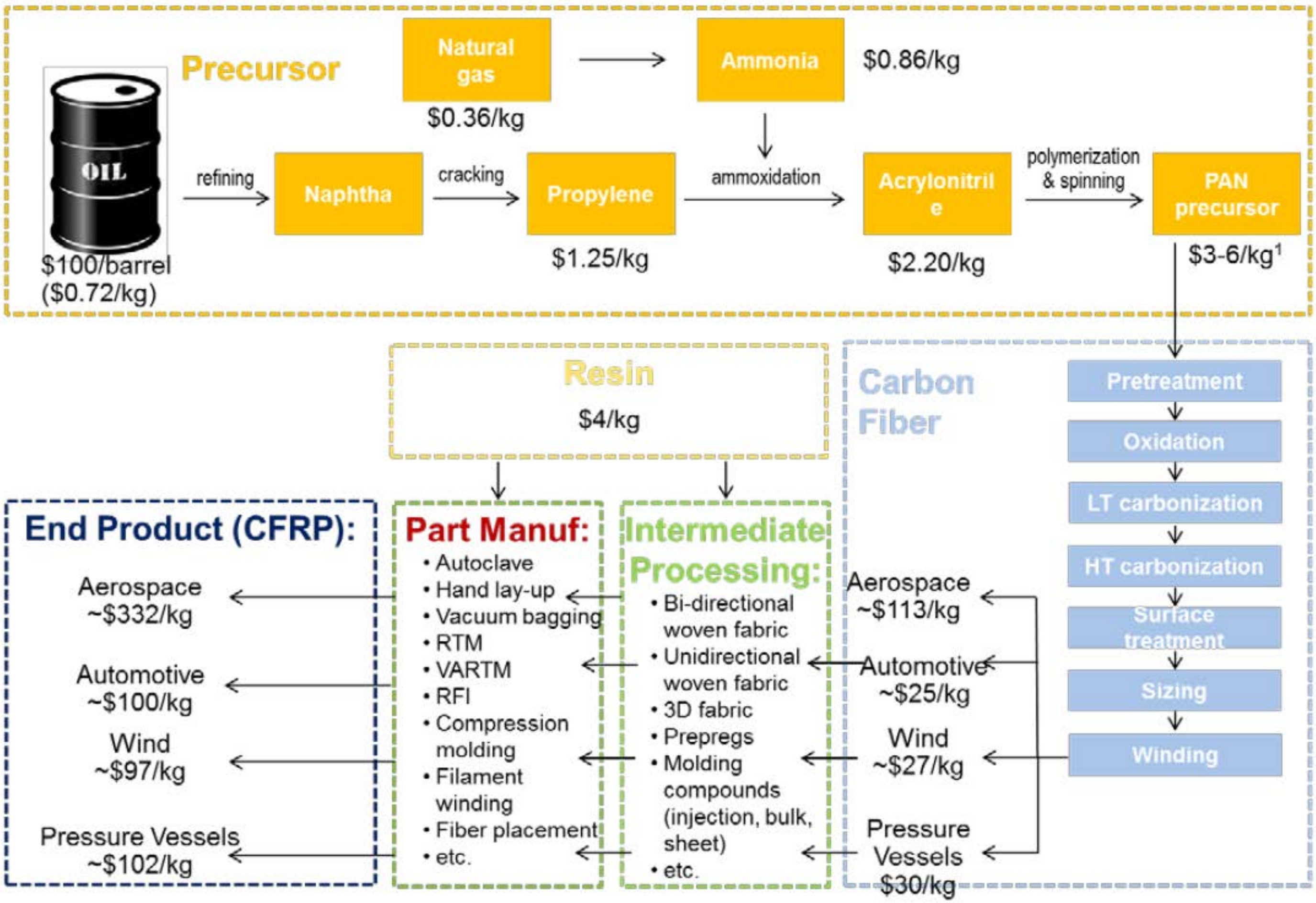


Figure 1-1. CF and CFRP value chain

kg = kilogram; RTM= Resin Transfer Molding;and VARTM = Vacuum Assisted Resin Transfer Molding; LT = low-temperature and HT = high-temperature

S. Das et al. (2016), "Global Carbon Fiber Composites Supply Chain Competitiveness Analysis", Oak Ridge National Laboratory

Areas for cost reduction are precursor, conversion, and processing

Carbon Fiber Market Potential - Example

Est. World Carbon Fiber Supply (2020)*	~130M kg or ~287M lb

A Simple Example: Future Market Potential for High-Strength Carbon Fiber

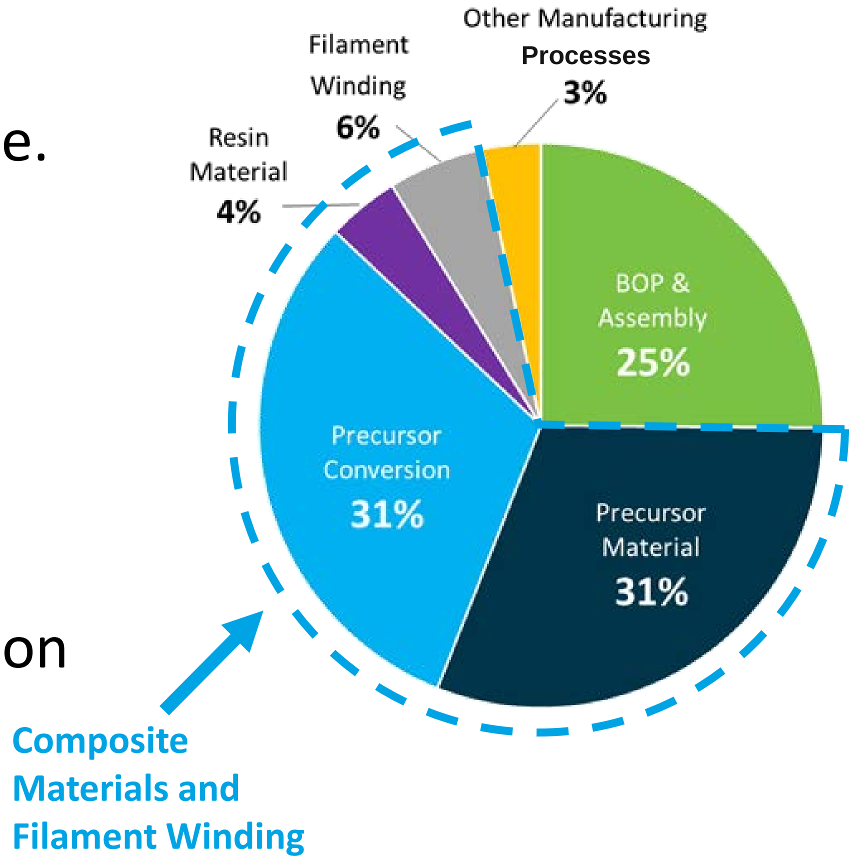
Application	Tank Quantity	CF Quantity		Projection		CF needed	Potential Market Share
Fuel Cell Car & Light Trucks	700 bar, 700 bar 2 Type III/IV tanks	~75 kg per car	X	~180,000 cars	=	~13.5M kg or ~15,000 tons	~10%
Fuel Cell Buses	350 bar, 350 bar, 350 bar, 350 bar 4 Type III/IV tanks	~320 kg per bus	X	~44,000 buses	=	~14M kg or ~15,500 tons	~10%

(*) http://www.compositesworld.com/articles/supply-and-demand-advanced-fibers-2016

Significant market share of carbon fiber could be used for fuel cell vehicles

Current Status – 700 Bar Compressed H_2 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



Ordaz, G., C. Houchins, and T. Hua. 2015. "Onboard Type IV Compressed Hydrogen Storage System - Cost and Performance Status 2015," DOE Hydrogen and Fuel Cells Program Record, https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf, accessed 5 July 2016.

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

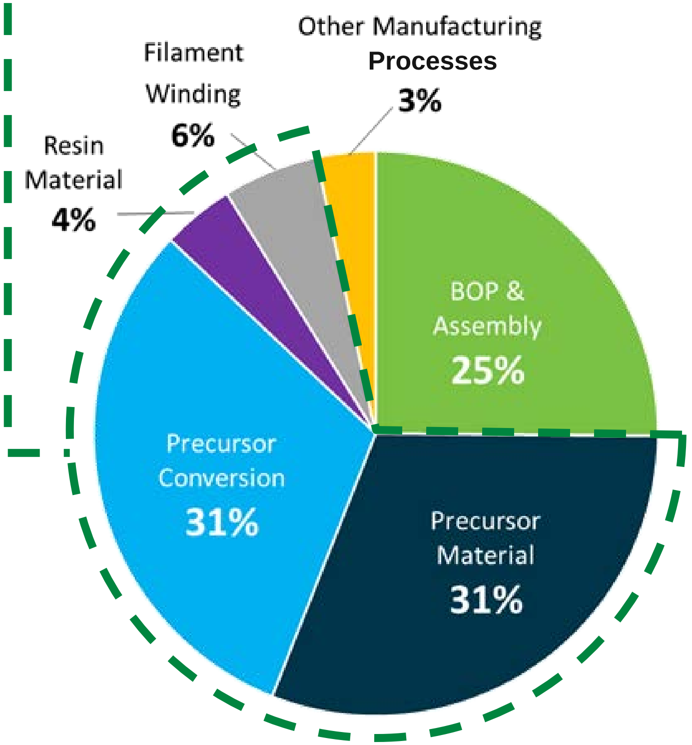
- Need fibers that lower cost yet high strength & low weight

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



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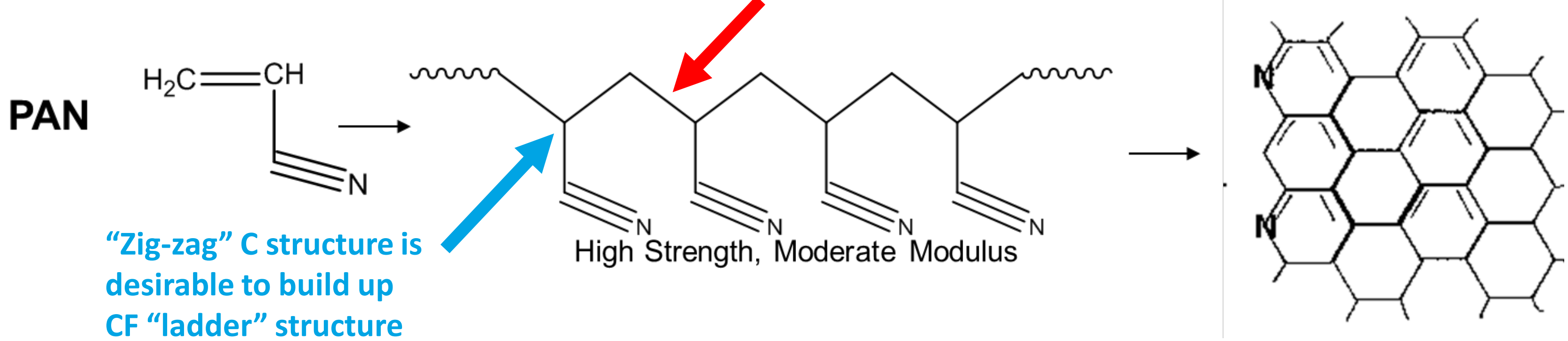
Need to reduce hydrogen storage cost, while maintaining high strength composite material

Carbon Fiber (CF) Precursor Chemistry: PAN

- **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**

Getting the "zig-zag" structure with alternative precursors is expensive!



"Zig-zag" C structure is desirable to build up CF "ladder" structure

- **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

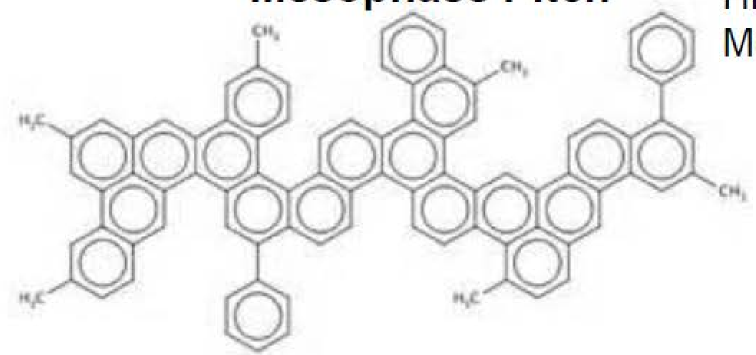
Warren, C. D., "Carbon Fiber Precursors and Conversion", Oak Ridge National Laboratory, Department of Energy Physical-Based Storage Workshop: Identifying Potential Pathways for Lower Cost 700 Bar Storage Vessels, August 24, 2016.

Develop a lower cost carbon fiber precursor without degrading mechanical performance

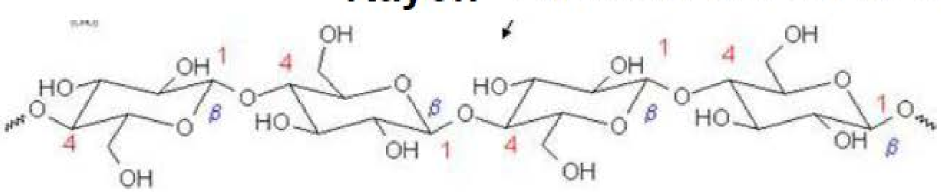
Carbon Fiber (CF) Precursor Chemistry: Alternatives

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

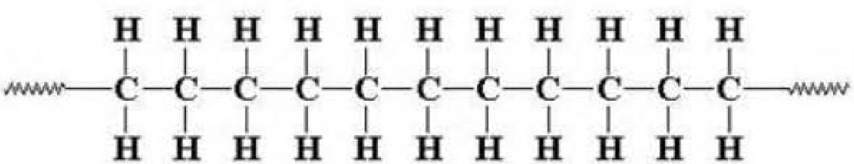
Mesophase Pitch High Modulus, Moderate Strength



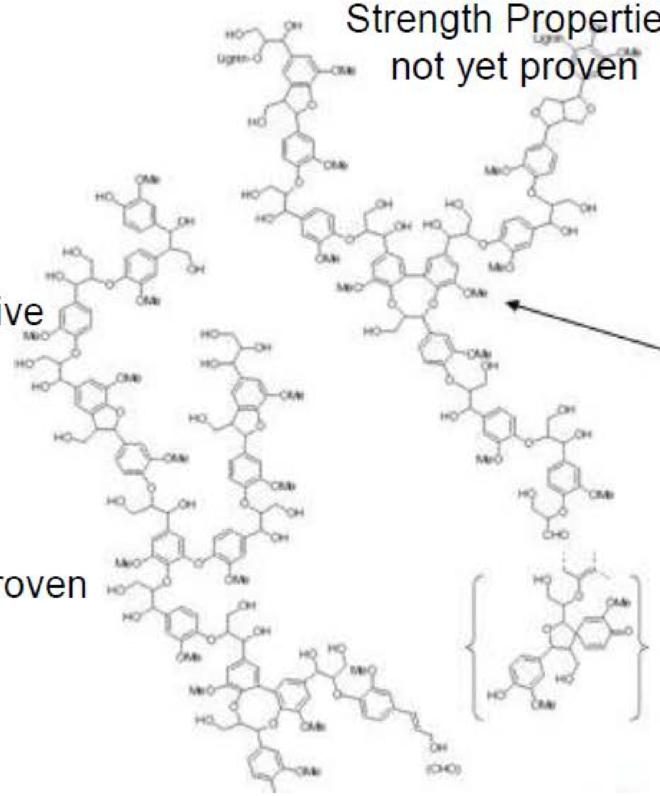
Rayon Expensive and use for Ablative



Polyethylene Properties not yet proven



Lignins Strength Properties not yet proven



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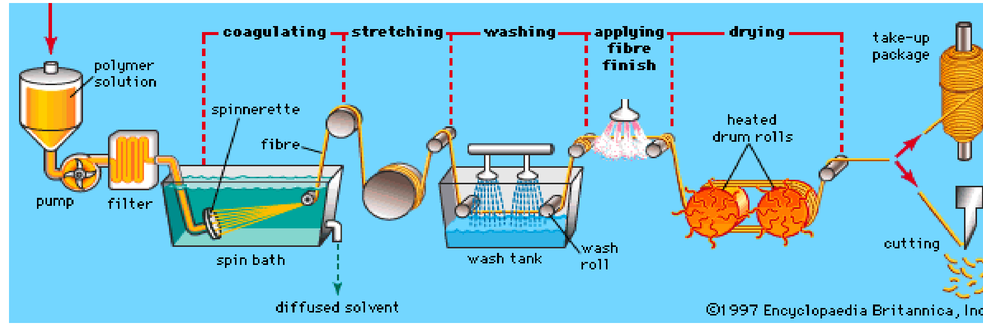
Challenging to source alternative carbon fiber precursors with high-strength at low cost

Carbon Fiber Precursor Processing: Spinning

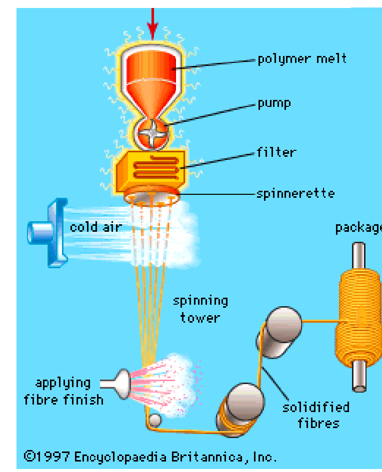
- PAN fibers are usually produced using solution spinning processes
  - **Orient** the polymer **chains**
  - **Remove** the **solvent**
  - Obtain desired **diameter**
  - **Handling and recovery** of used **hazardous solvents adds significant costs!**



Solution-Spinning

Fibrillar Network **Oriented Fibrillar Network**

- 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**



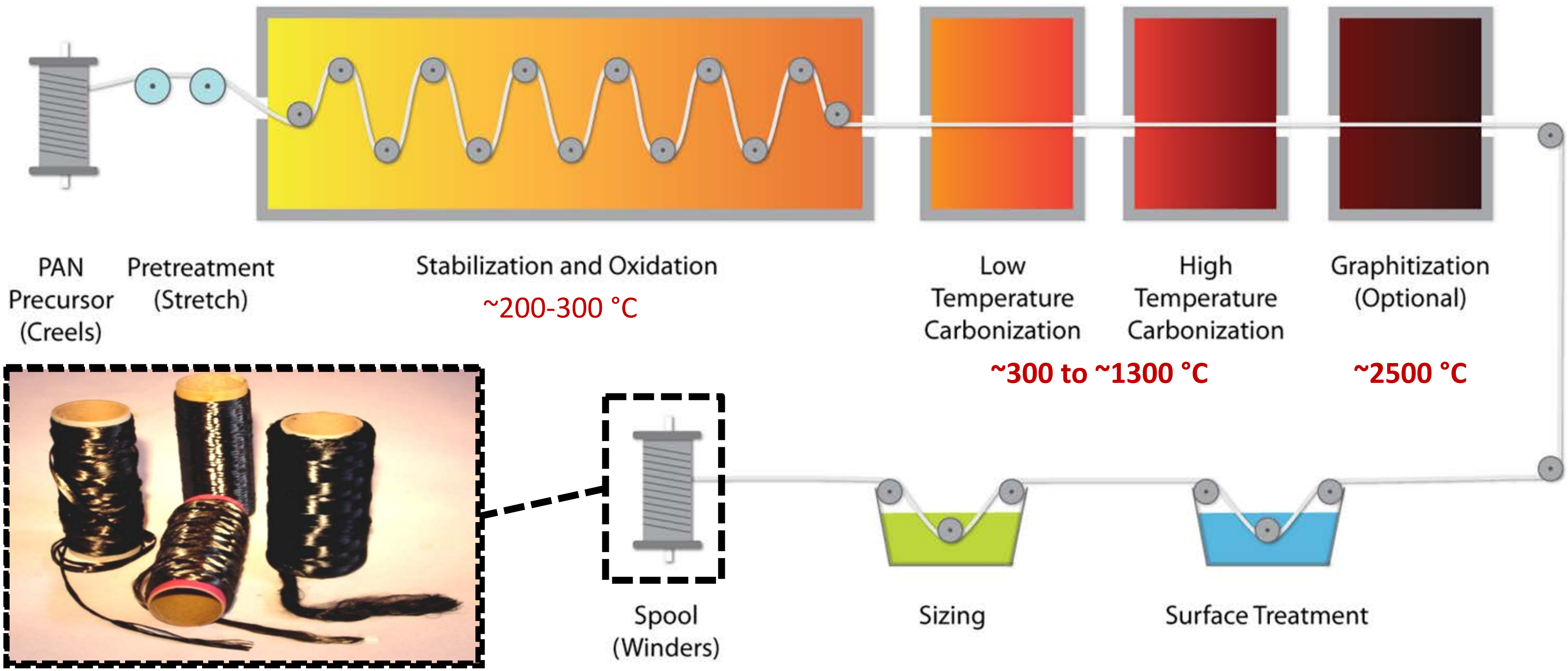
Melt-Spinning

Warren, C. D., "Carbon Fiber Precursors and Conversion", Oak Ridge National Laboratory, Department of Energy Physical-Based Storage Workshop: Identifying Potential Pathways for Lower Cost 700 Bar Storage Vessels, August 24, 2016.

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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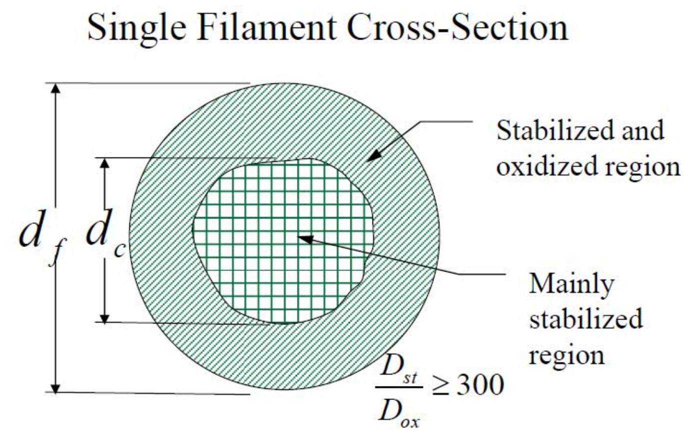
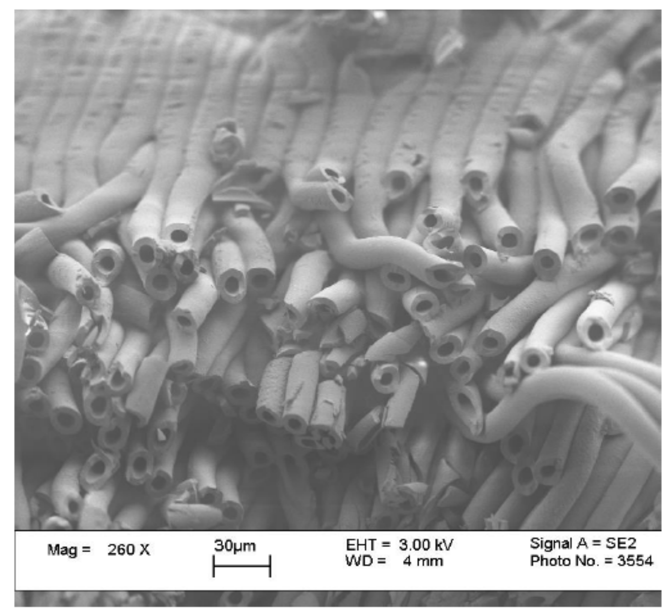
Carbon fiber precursor conversion is very energy intensive and high cost

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





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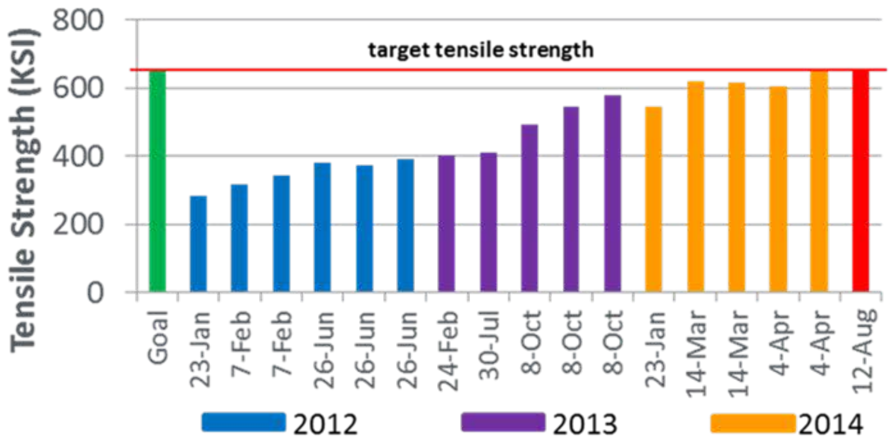
Excess time and energy costs inhibit maximizing CF yield during precursor conversion

EERE R&D Examples: CF Precursors and Conversion

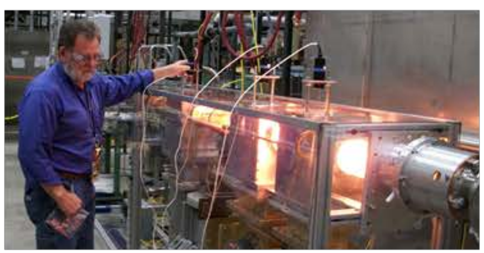
High-Volume Textile (PAN/MA) Precursors [ORNL]

- Precursors account for ~55% of cost of carbon fibers
- Textile PAN fibers ~25% lower cost than conventional PAN



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

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

Modified extruder feed

Melt-spun PAN/MA fiber

Warren, C. D., "Carbon Fiber Precursors and Conversion", Oak Ridge National Laboratory, Department of Energy Physical-Based Storage Workshop: Identifying Potential Pathways for Lower Cost 700 Bar Storage Vessels, August 24, 2016.

Lower cost carbon fiber precursor -> lower cost carbon fiber -> lower cost hydrogen storage!

Previous FY2017 FOA Topic on CF Precursors

- **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.

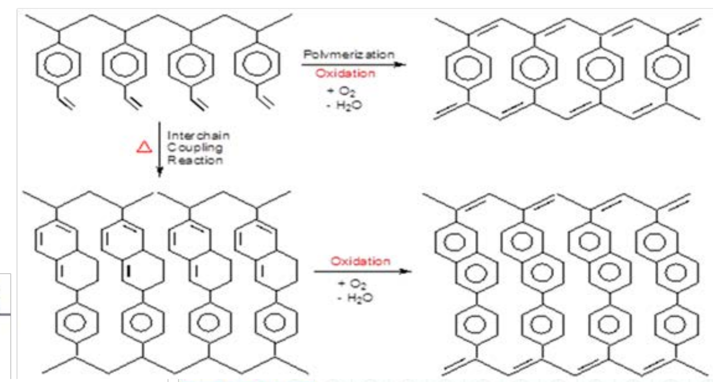
Addressing the cost of high-strength carbon fiber

New FY2017 FOA Selections: *Low-Cost CF Precursors*

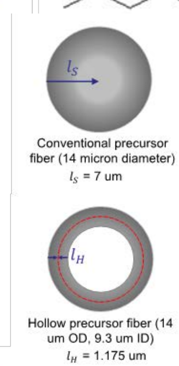
- **Oak Ridge National Laboratory (ORNL)**
  - Novel Plasticized Melt Spinning Process of PAN Fibers Based on Task-Specific Ionic Liquids
  - **PI: Sheng Dai**

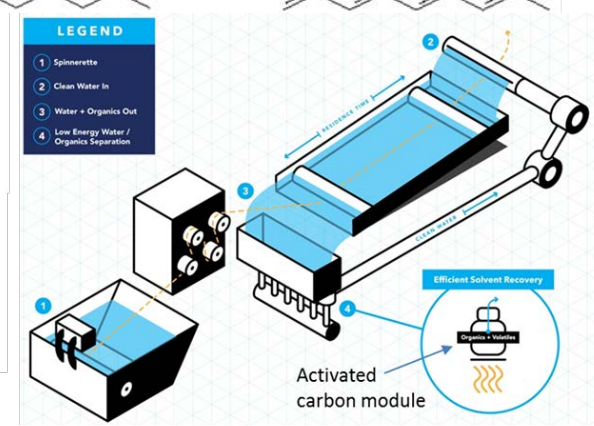
- **The Pennsylvania State University (PSU)**
  - Developing A New Polyolefin Precursor for Low-Cost, High-Strength Carbon Fiber
  - **PI: Mike Chung**

Two Reaction Mechanisms in Stabilization of New Precursor



- **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 H_2 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

Batch melting process

Vessel winding

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!

Resin is critical for the distribution of shear stresses during cyclic H_2 loadings

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

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

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

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 H_2 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

	Test Type	Epoxy Relative Burst	Vinyl Ester Relative Burst
No Impact	Burst	105%	111%
	Cycle A	100%	103%
	Cycle B	99%	95%
Impact test round 1	Burst	57%	55%
	Cycle A	67%	DNF
	Cycle B	58%	63%
Impact test round 2	Burst	70%	82%
	Cycle A	55%	74%
	Cycle B	62%	67%

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

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

COPVs are traditionally made via filament winding

Advantage: Well understood in industry and repeatability

Challenge: Lack of uniform fiber compaction and resin dripping

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

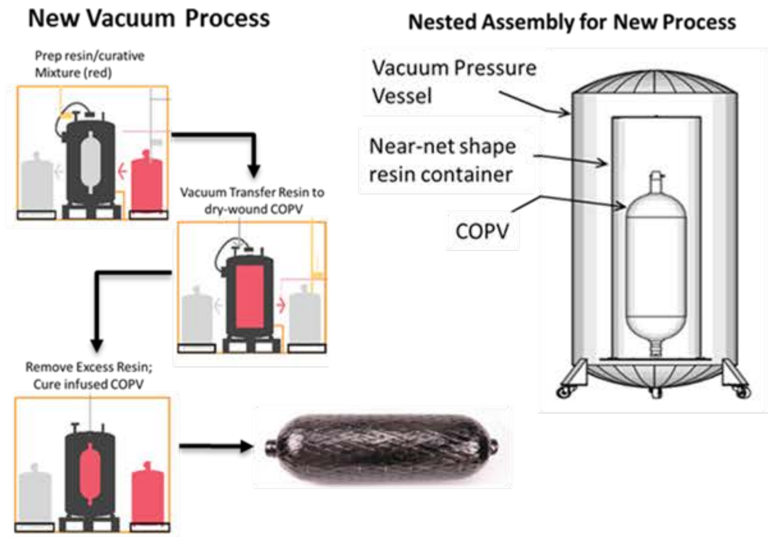
Provides an opportunity to reduce needed CF and resin to meet safety factor

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



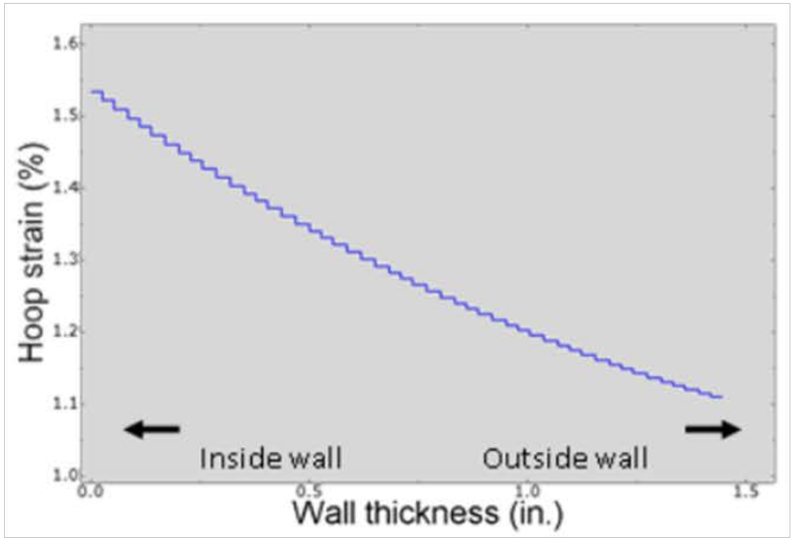
Reduce carbon fiber use with better fiber utilization through alternative manufacturing

Alternative COPV Manufacturing: Graded Construction

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%



https://www.hydrogen.energy.gov/pdfs/review16/st110_haight_2016_p.pdf

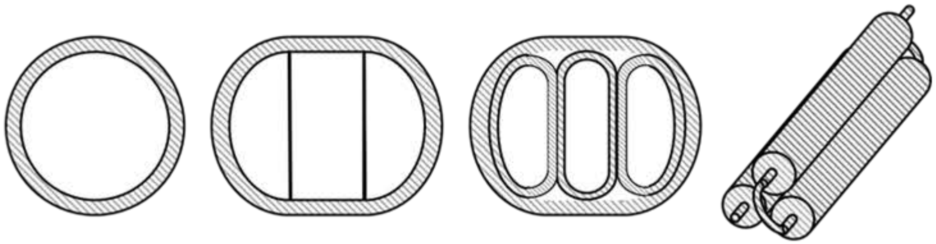
Hybridization of high-cost carbon fiber with lower cost alternatives to reduce total cost

Alternative COPV Manufacturing: Conformable Compressed H_2 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.

Schematics of conformable compressed H_2 storage tanks



EERE R&D Example: Conformable Design

Conformable 700 bar H_2 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

Kevlar Over-Braided Coiled Vessels

Conformable designs may permit for optimized COPV packaging to reduce carbon fiber use

The Institute for iacmi Advanced Composites Manufacturing Innovation

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**

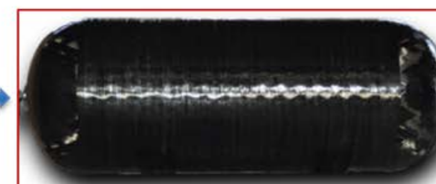
Leveraged project: Thermoplastic Composite Compressed Gas Storage Tanks

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

DuPont thermoplastic PA resins

DuPont PA impregnated Tape

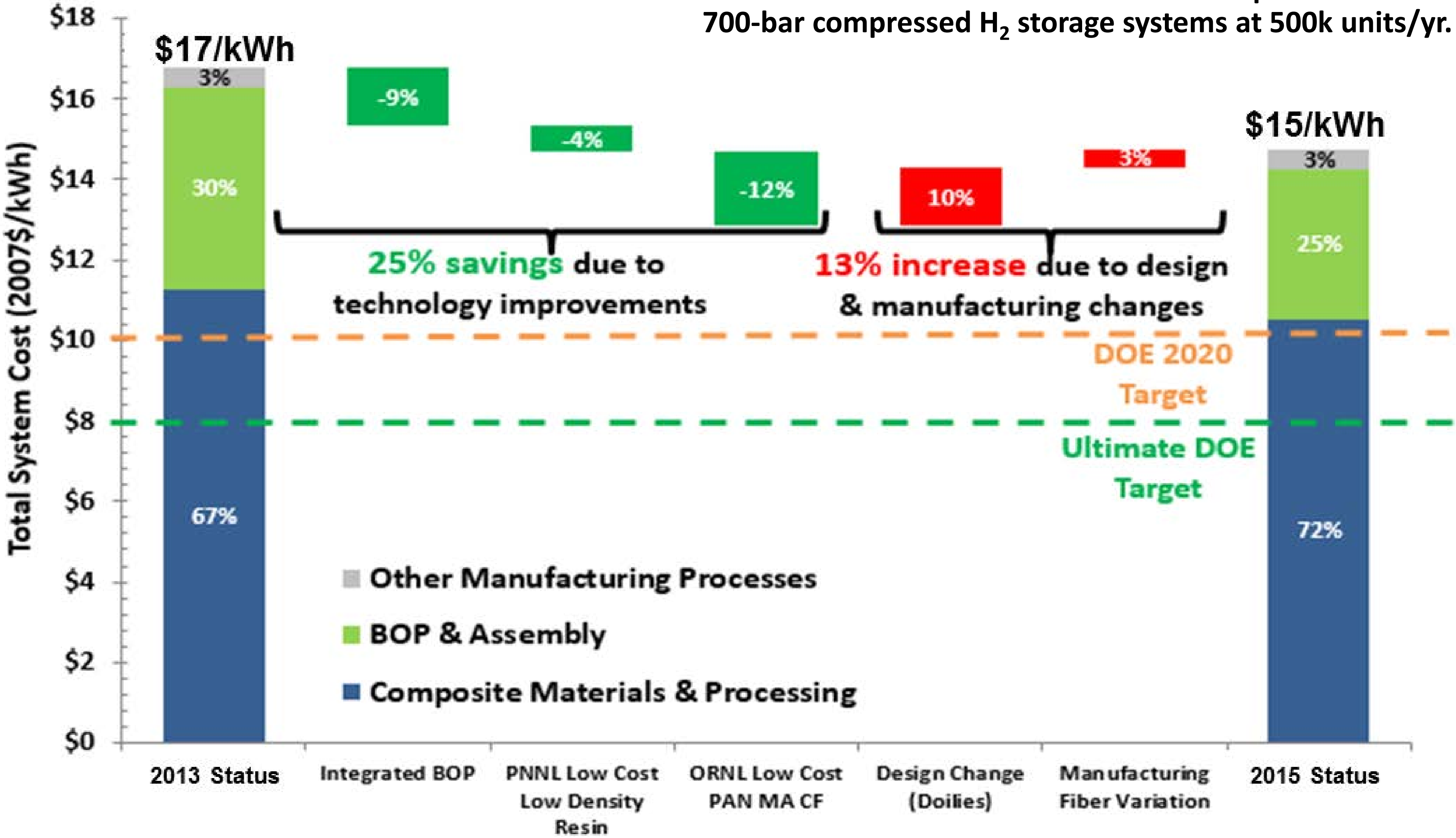
Carbon fiber heavy tow



Leveraging efforts of the Institute for Advanced Composites Manufacturing Innovation

Recent Progress on Cost Reduction

Shown for the 2013 baseline to the 2015 updated cost for 700-bar compressed H_2 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

Hydrogen Storage for Mobile Applications

Examples:

Unmanned Aerial Vehicles (UAV)	Unmanned Underwater Vehicles (UUV)	Portable Power Systems	Materials Handling Equipment
Airport Ground Equipment	Fuel Cell Range Extenders of EVs	Energy Carrier for Electrical Grid Storage	Fuel Cell Electric Vehicles
Stratospheric Satellites	Robotics	Transport Refrigeration Units	Fuel Cell Aircraft Systems

B. A. van Hassel, United Technologies Research Center (UTRC), "H2 Storage for Mobile Applications," IEA Task 32: Hydrogen-based Energy Storage January 18th-23rd, 2015 Chamonix, France.

Wide variety of high-value automotive & non-automotive applications of H_2 fuel cell technologies

Summary

- 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

The DOE-FCTO Hydrogen Storage Team:

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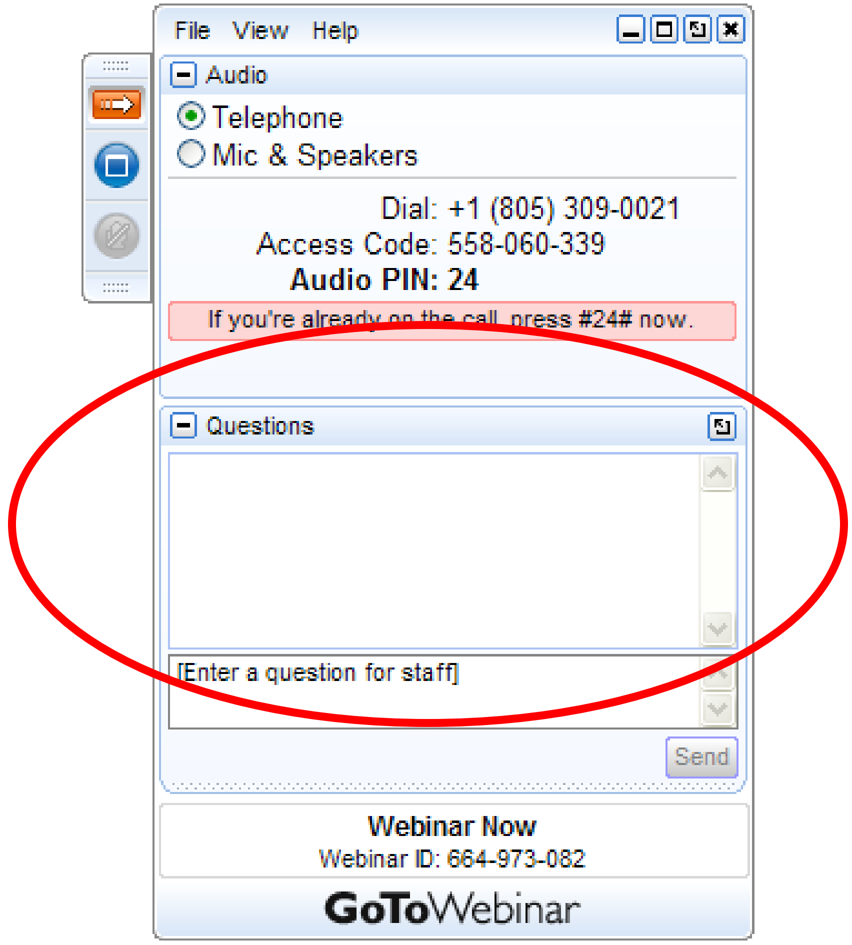
Question and Answer

- Please type your questions into the question box



Thank You!

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