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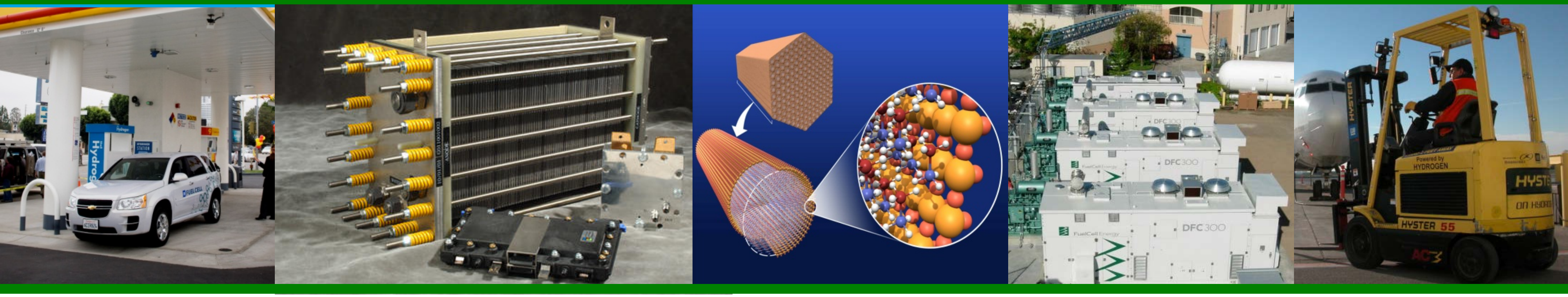


Hydrogen Storage Program Area

-Plenary Presentation-

Ned T. Stetson

Fuel Cell Technologies Office

2014 Annual Merit Review and Peer Evaluation Meeting

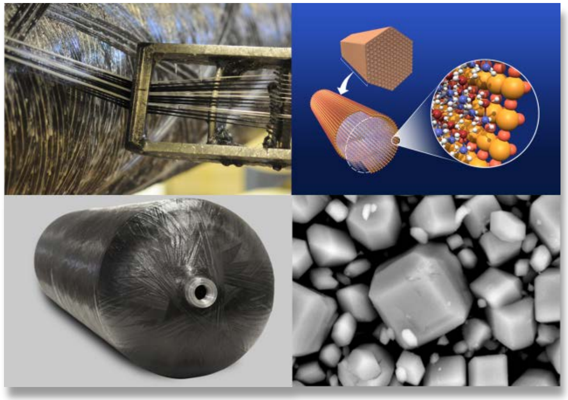
June 16 - 20, 2014

Goals and Objectives

GOAL: Develop and demonstrate advanced hydrogen storage technologies to enable successful commercialization of fuel cell products in transportation, portable, and MHE applications

Objectives

- By 2017, develop onboard vehicle H_2 storage systems achieving 1.8 kWh/kg (5.5 wt% H_2) and 1.3 kWh/L (40 g H_2/L) at \$12/kWh (\$400/kg $H_{2\ stored}$) or less.
- By 2020, demonstrate H_2 storage systems in material handling equipment applications achieving 1.7 kWh/L (50 gH_2/L) and able to be recharged with 2 kg of H_2 within 2.8 minutes at \$15/kWh (\$500/kg $H_{2\ stored}$) or less.
- For widespread commercialization of fuel cell electric vehicles across the full range of vehicle platforms, ultimately develop onboard H_2 storage technologies achieving 2.5 kWh/kg (7.5 wt.% H_2) and 2.3 kWh/L (70 g H_2/L) at \$8/kWh (\$266/kg $H_{2\ stored}$) or less.
- Other specific objectives are in the Hydrogen Storage Section of the MYRD&D Plan.



Strategy

Comprehensive strategy to address barriers for near-term and long-term technologies

Barriers
Cost
Volume
Weight
Refill time
Cycle-life

Strategy

Near-term
High-pressure Compressed H_2 Systems

Long-term
Cold/Cryo-compressed H_2
Materials-based H_2 storage

R&D Focus
Cost reduction
Advanced designs
Improved manufacturing

R&D Focus
Advanced designs
Novel materials discovery
Performance Analysis

KEY AREAS

Pressure Vessels
Lower cost carbon fiber
Improved composite
Conformable designs
Lower cost BOP

Cold/Cryo-compressed
System engineering
Advanced insulation
Improved dormancy
Composite development

Materials-based H_2 Storage
Materials development
Materials characterization
System engineering
Materials/system manufacture

Balanced, Two-pronged Strategy

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- **Near-term:** initial commercial introduction of fuel cell electric vehicles using 700 bar compressed H_2 storage:
  - Reduce system costs
    - Develop lower cost precursors for carbon fiber
    - Develop alternative materials to carbon fiber
    - Identify alternative materials to SS316L for balance-of-plant components
  - Develop innovative tank concepts with improved performance
- **Longer-term:** develop and demonstrate technologies with potential to meet all storage performance targets simultaneously.
  - Develop and demonstrate cold/cryo-compressed hydrogen storage technologies
  - Develop materials-based hydrogen storage technologies
  - Investigate novel, innovative concepts

Budget

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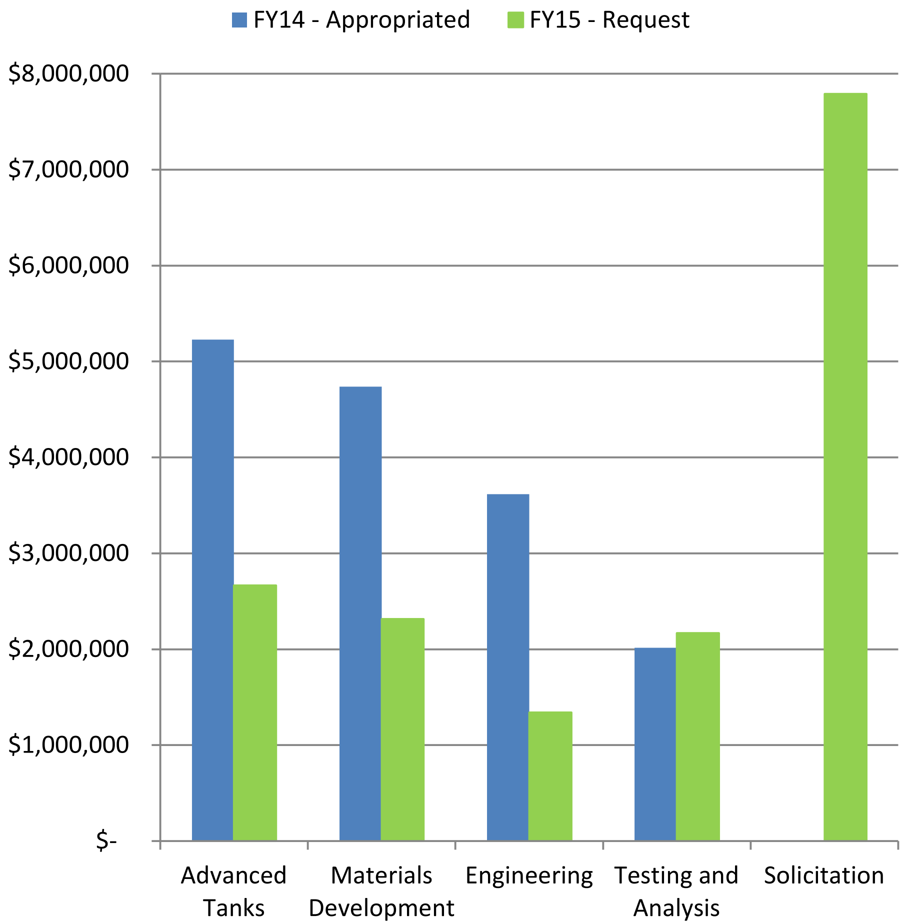
FY 2014 Appropriation = $15.6M

FY 2015 Request = $16.3M



EMPHASIS

- Systems approach through the Engineering CoE, in collaboration with independent materials development projects, to achieve light-duty vehicle targets
- Close coordination with EERE Offices on carbon fiber composites, including Advanced Manufacturing, Vehicle Technologies and Bioenergy Technologies Offices
- Focus on cost reduction for high pressure tanks
- Increased analysis efforts for low to high production volumes, particularly analyses of balance-of-plant costs
- Portfolio is balanced between mid- and long term
- More emphasis on early market applications

Current Status of H_2 Storage Technologies

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Storage Targets	Gravimetric kWh/kg (kg H_2/kg system)	Volumetric kWh/L (kg H_2/L system)	Costs $/kWh ($/kg H_2)
2017	1.8 (0.055)	1.3 (0.040)	$12 ($400)
Ultimate	2.5 (0.075)	2.3 (0.070)	$8 ($266)

Full comprehensive sets of hydrogen storage targets can be found in the Program's Multi-year Research, Development and Demonstration Plan: http://energy.gov/sites/prod/files/2014/03/f12/storage.pdf

Projected H_2 Storage System Performance	Gravimetric kWh/kg	Volumetric kWh/L	Costs* $/kWh
700 bar compressed (Type IV)	1.5	0.8	17
350 bar compressed (Type IV)	1.8	0.6	13
Metal Hydride (NaAlH4)	0.4	0.4	TBD
Sorbent (MOF-5, 100 bar) MATI, LN2 cooling [HexCell, flow-through cooling]	1.1 [1.2]	0.7 [0.6]	16 [13]
Chemical Hydrogen Storage (AB-50 wt.%)	1.7	1.3	16

- Compressed H_2 system projections from Strategic Analysis & Argonne National Laboratory
- Material-based system projections from Hydrogen Storage Engineering Center of Excellence

* Projected to 500,000 units / year

Strategy: Understanding System Costs

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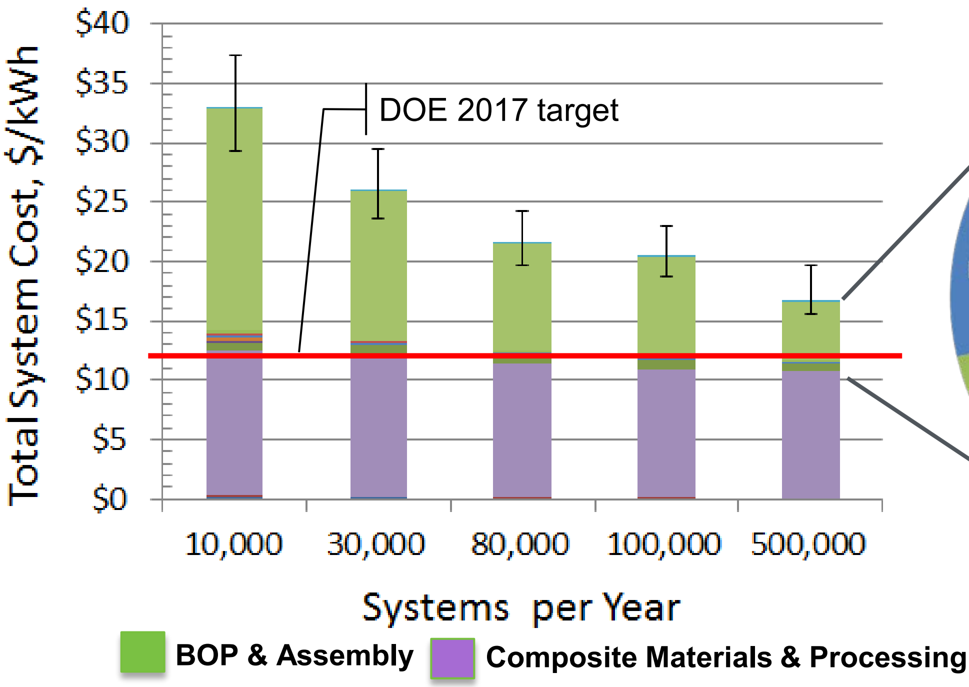
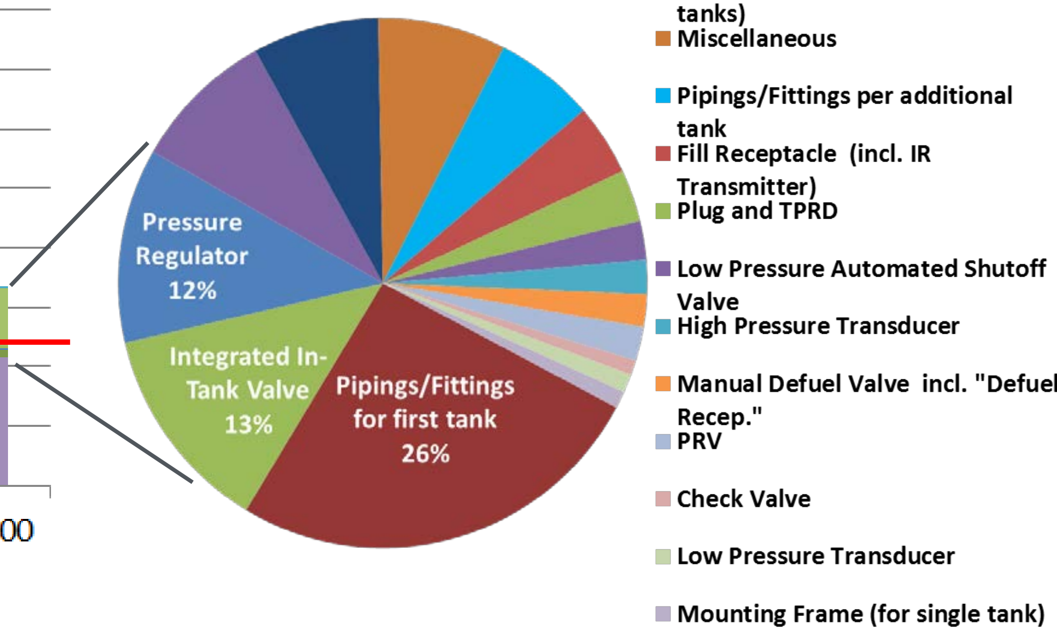
Carbon fiber composite cost dominate costs at high manufactured volumes, while BOP can dominate costs at low volumes for high-pressure H_2 systems

Cost estimates for variable volume manufacturing of 700-bar Type IV compressed H_2 systems



Other Manufacturing Processes account for ~3%

Breakout of BOP (single 5.6kg H_2 tank @ 500K units/yr)



Piping/fittings, integrated in-tank valve and pressure regulator are the high cost items for BOP (SA – ST100)

Accomplishments: Lower cost precursors for carbon fiber

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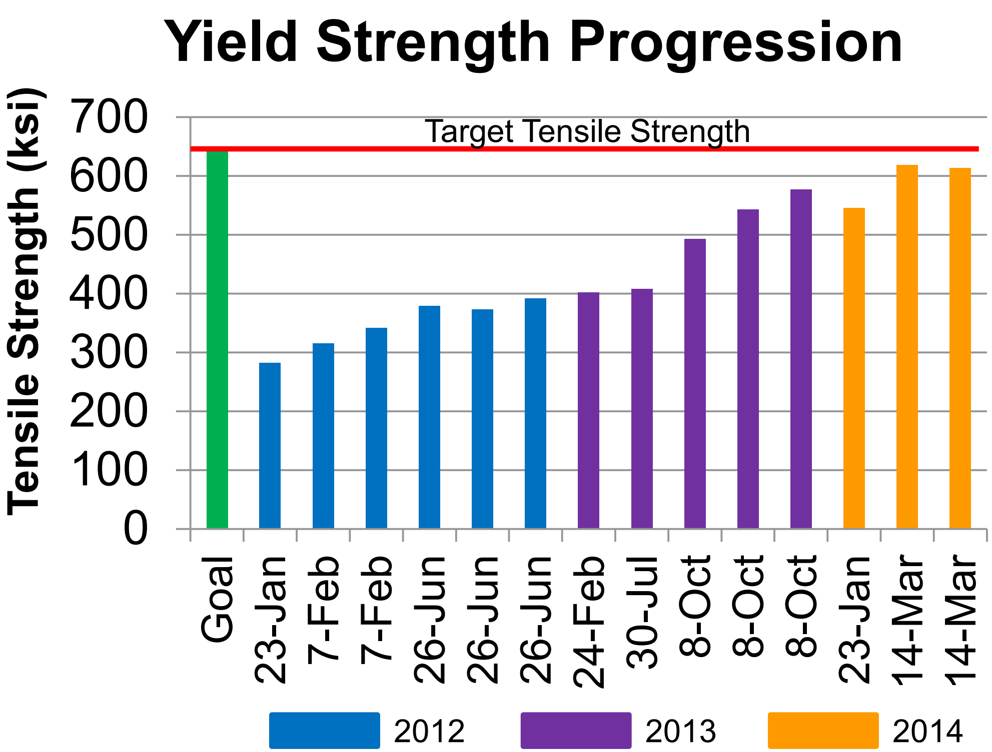
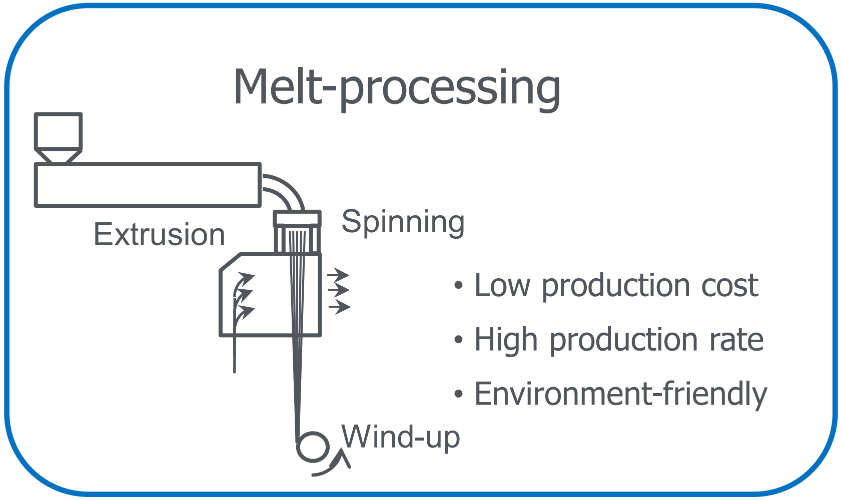
Commercial Textile (PAN/MA) Precursors
(ORNL - ST099)

- **Precursors account for ≥55% of cost of carbon fibers**
- **Textile PAN fibers ~25% lower cost than conventional PAN fiber precursors**
- **Potential fast-track, drop-in replacement precursor**



Melt Processable PAN Precursors
(ORNL - ST093)

- **Target: >25% reduction in costs of manufacturing of carbon fiber**
- **Cost reduction achieved through lower capital costs and lower processing costs vs conventional wet spinning processes**
- **Alternative melt processable formulations to be developed and demonstrated**
- **Feasibility demonstrated, scale-up in process**



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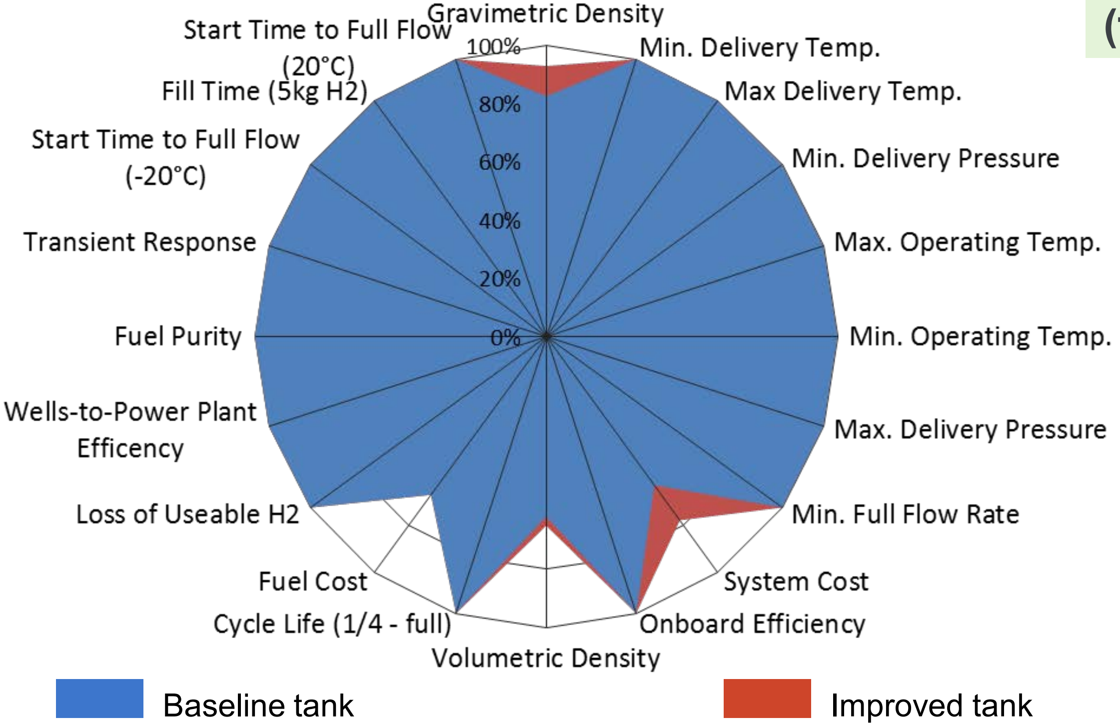
Enhanced Materials and Design Parameters for Reduced Cost H_2 Storage Tanks
(PNNL - ST101)

- **Improvements in Gravimetric Capacity, Volumetric Capacity and System Cost vs. Baseline 700 bar Type IV tank identified through:**
  - Nanoscale resin additives
  - Alternative fiber placement and multiple fiber types



- **Further improvements projected through:**
  - Reduced temperature operation (200 K (-73 °C)) with
  - Reduced pressure operation (500 bar)
- **Similar H_2 density w/ substantially reduce system mass & cost (targeting 30% total cost reduction)**

	Current H_2 Tank	Enhanced H_2 Tank
Operating Conditions	700 bar at 15 °C	500 bar at -73 °C
Gas Density	40 g/l	42 g/l
Tank Mass	93.6 kg	48.2 kg

Accomplishments: Hydrogen Sorbent Systems

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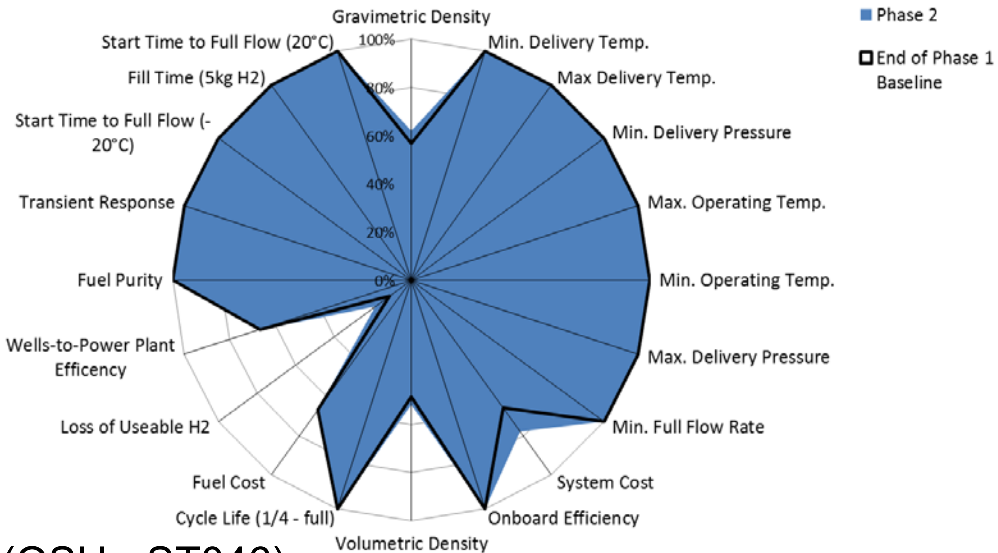
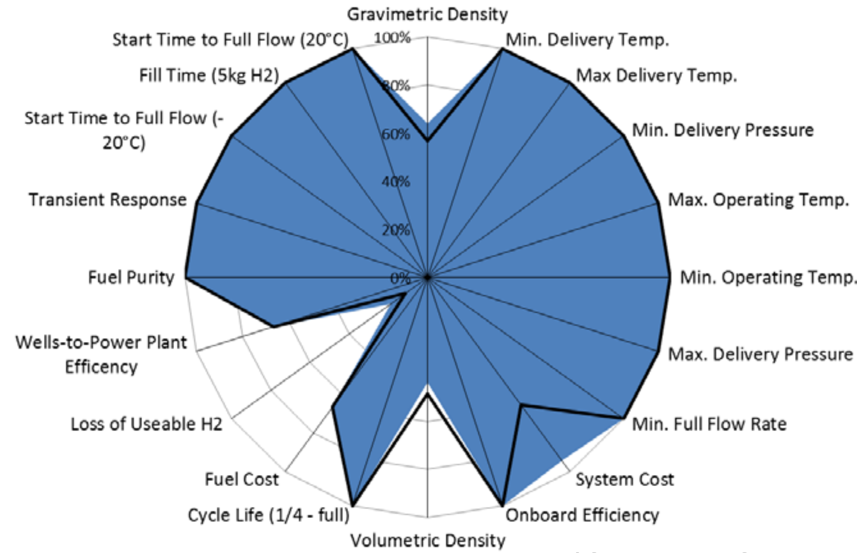
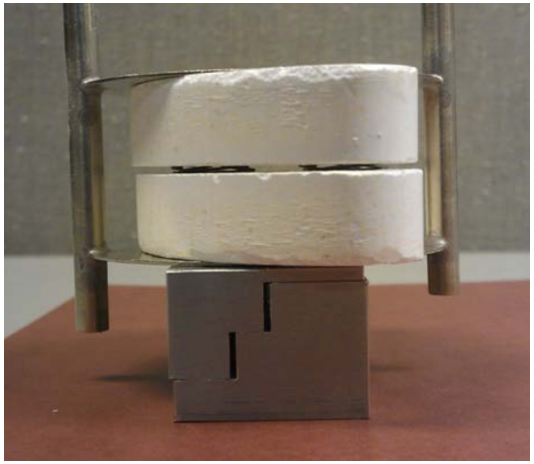
End of Phase 2 MATI System



End of Phase 2 Hex-Cell System



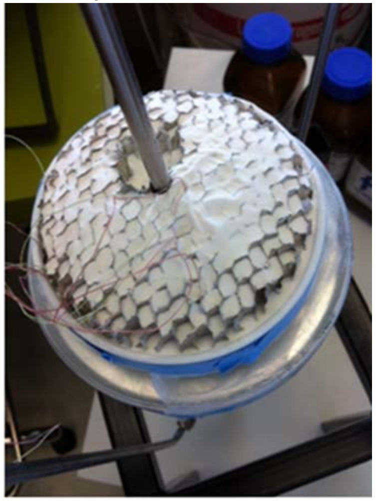
(OSU - ST046)



Phase III of HSECoE: construct, test & evaluate 2 sorbent prototypes using 2 different heat exchanger (HX) concepts:

- "Hex-Cell" – a passive HX loaded w/ sorbent powder & flow-through H_2 gas for cooling
- "MATI" – an active microchannel HX w/ compacted sorbent & liquid N_2 cooling.

(SRNL - ST044)



Performance of prototypes will validate system models and be evaluated against DOE targets.

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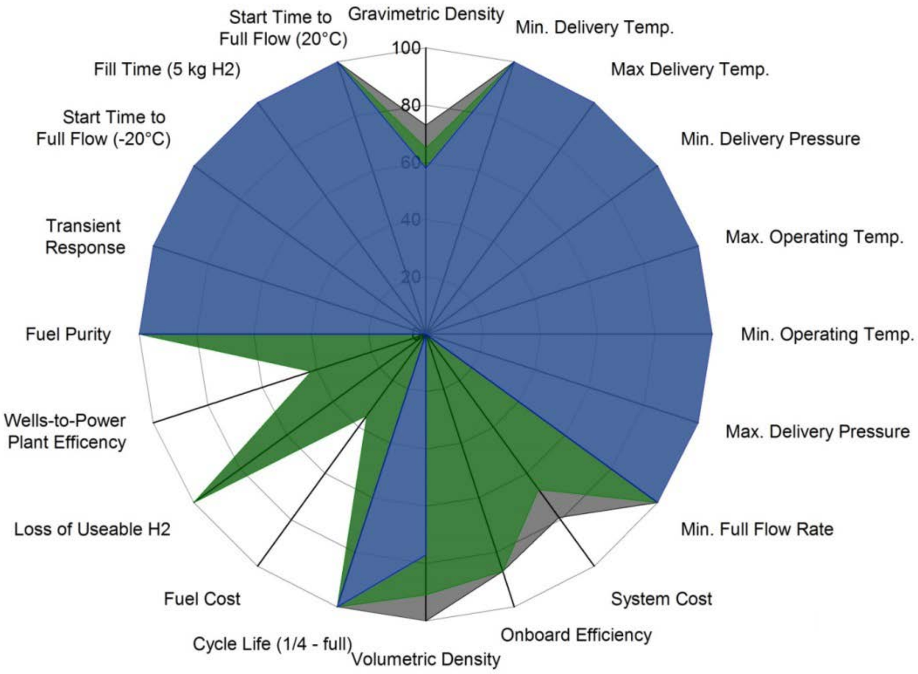
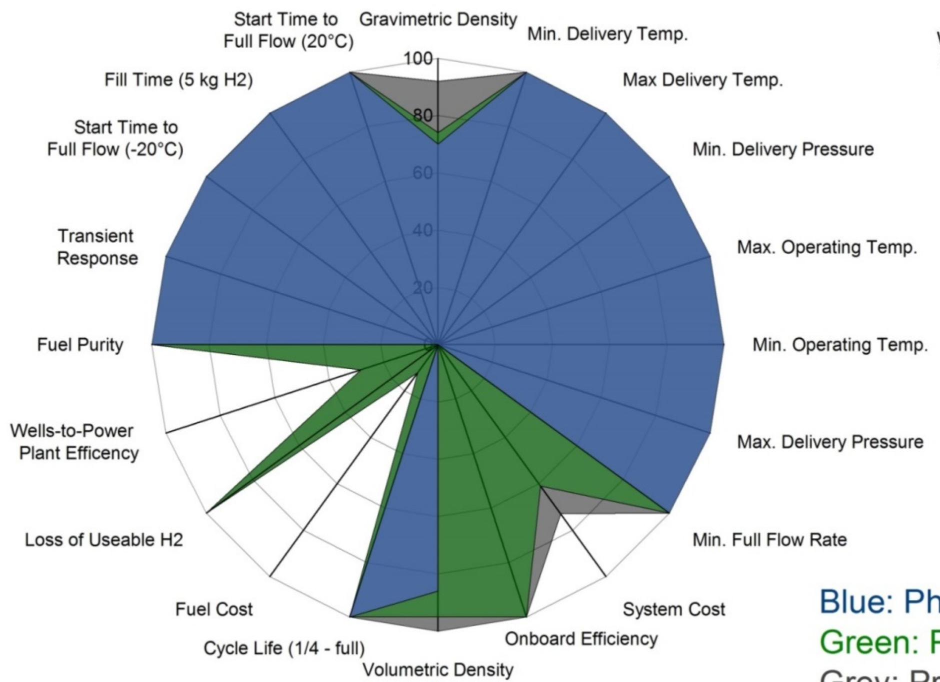
Validation of HSECoE system models indicate off-board regenerable chemical hydrogen storage systems have potential to meet many of the onboard storage targets (LANL - ST007)

Alane



Ammonia Borane



Blue: Phase 1
Green: Phase 2
Grey: Projected

(HSECoE Estimates)

Breakthrough needed in development of fluid phase chemical hydrogen storage materials able to be regenerated at low-cost with high-efficiency.

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HSECoE system modeling helps with determination of chemical hydrogen storage materials' property requirements (LANL - ST007)

– provides guidance for materials discovery efforts

Parameter	Units	Range*
Minimum Material capacity (liquids)	g_{H2} / $g_{material}$	~ 0.078 (*0.085*)†
Minimum Material capacity (solutions)	g_{H2} / $g_{material}$	~ 0.098 (*0.106*)†
Minimum Material capacity (slurries)	g_{H2} / $g_{material}$	~ 0.112 (*0.121*)†
Endothermic Heat of Reaction	kJ / mol H_2	≤ +17 (*15*)†
Exothermic Heat of Reaction	kJ / mol H_2	≤ -27
Maximum Reactor Outlet Temperature	°C	250
Impurities Concentration	ppm	No *a priori* estimates can be quantified
Media H_2 Density	kg H_2 / L	≥ 0.07
Regeneration Efficiency	%	≥ 66.6%
Viscosity	cP	≤ 1500

Accomplishments: Low-pressure storage for MHE

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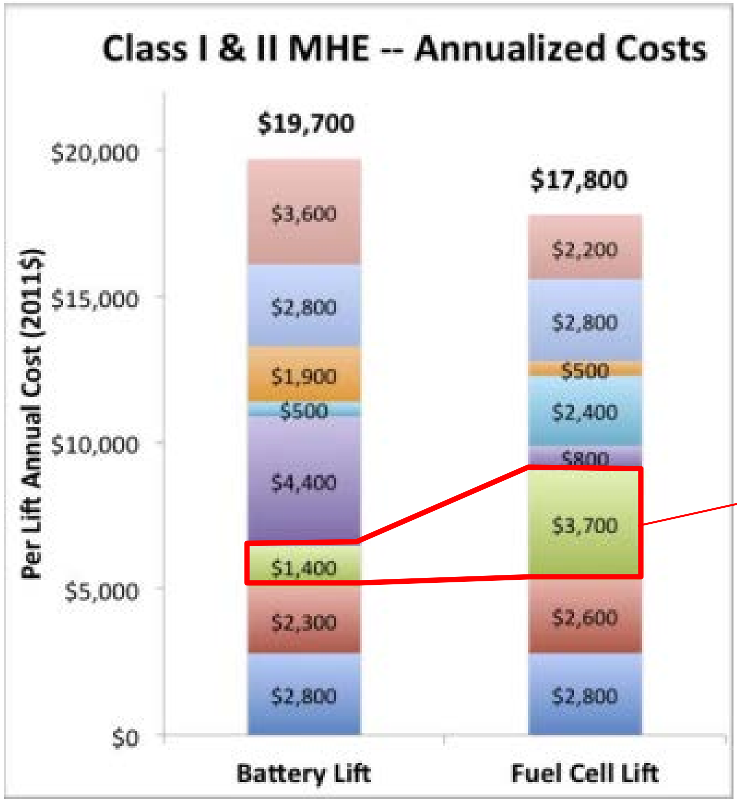
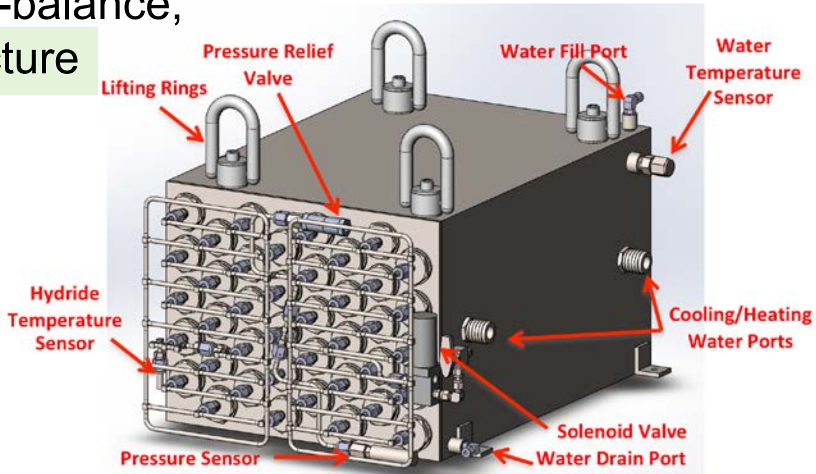
High-pressure (350 bar) refueling infrastructure a key barrier for widespread adoption of hydrogen fuel cell forklifts

(HHC - ST095)
SBIR Phase II)

Metal hydride systems offer potential for low-pressure hydrogen storage options for material handling, where the high mass of the system is an advantage for counter-balance, avoiding the high cost for 350 bar refueling infrastructure



Annualized cost of "refueling" infrastructure - (battery charging / 350 bar H_2)



NREL - *U.S. Department of Energy-Funded Performance Validation of Fuel Cell Material Handling Equipment*, UK Hydrogen and Fuel Cell Association Webinar, Nov. 27, 2013

New Efforts: Novel resin and COPV manufacturing

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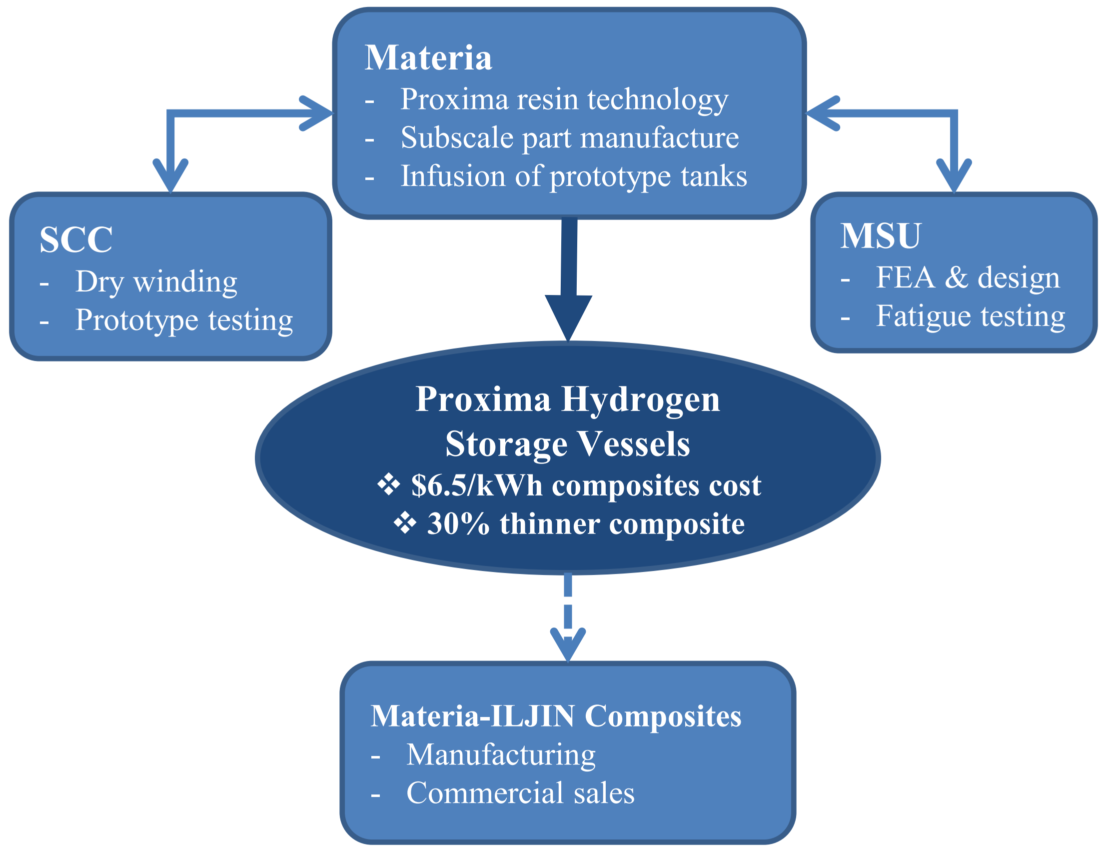
Low viscosity, high-toughness proprietary resin system coupled with Vacuum Assisted Resin Transfer Molding for lower cost, improved 700 bar tanks

New Project being initiated in FY2014 targets a >30% reduction in cost and >20% reduction in mass of carbon fiber composites for 145 L (internal) volume, 700 bar hydrogen storage tanks (Materia Inc.)

- Proxima thermoset resin
  - Lower viscosity – 10x faster infusion rates
  - Lower density – lower mass contribution
  - Higher fatigue-resistance compared with epoxy resins
- Vacuum Assisted Resin Transfer Molding
  - Eliminates wet winding
  - Reduces resin waste
  - Eliminates void defects – better performance



New Efforts: Lower costs through alternative materials

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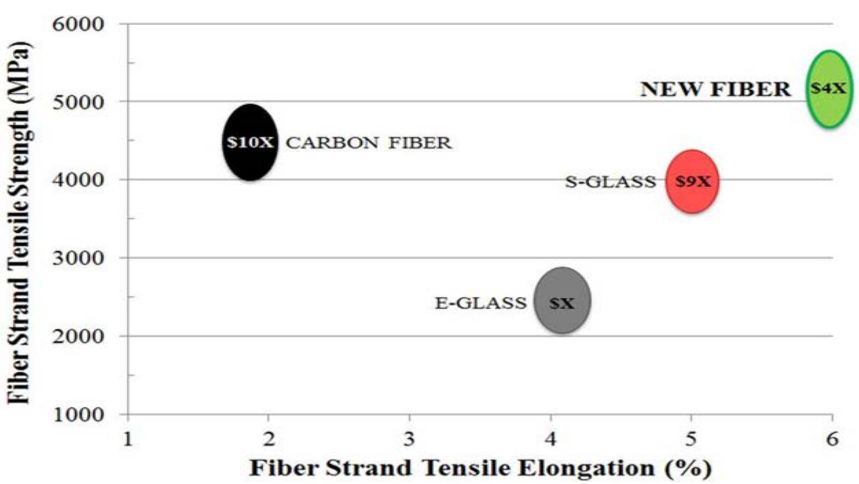
Driving down the costs of hydrogen storage systems through lower costs composites and alternative materials for balance-of-plant components

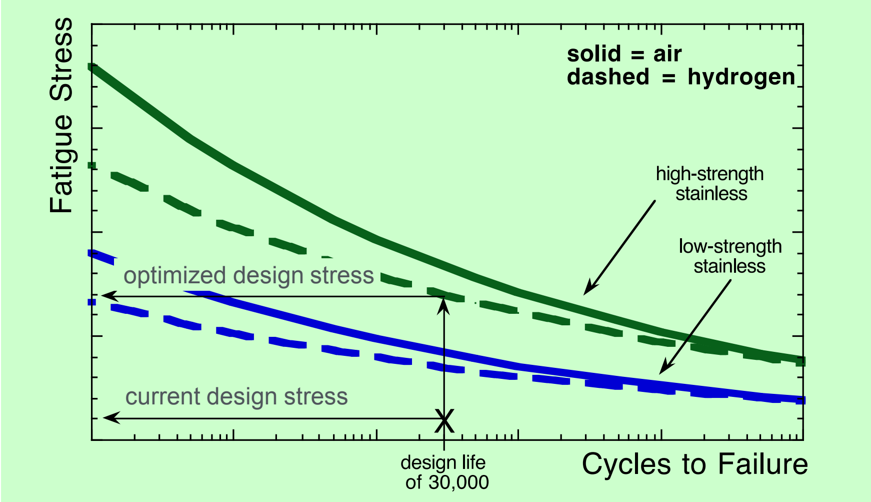
New project to develop ultra-high strength glass fiber for ~50% reduction in fiber composites costs for 700 bar Type IV H_2 Storage Systems (PPG Industries)

- Novel glass fiber exceeds tensile strength of T-700 carbon fiber
- Novel glass fiber manufacturing process
- Substantially lower cost fiber composites compared with T-700 carbon fiber composites
- Will determine stress rupture behavior to establish required safety factors



New project to screen and identify alternative lower-cost, high-strength steels for use in balance-of-plant components in place of 316L stainless steel (SNL)

- Will determine maximum allowable stress to achieve a design life of 30,000 fatigue cycles
- Will establish CSA CHMC1 method for qualifying materials for H_2 service

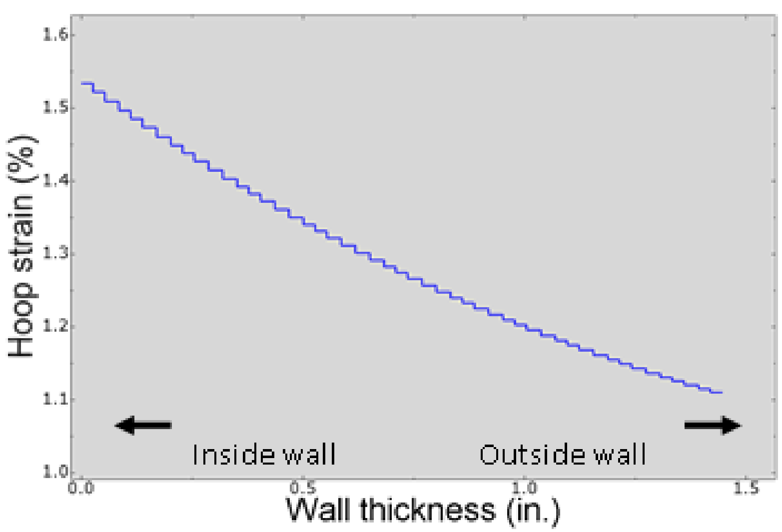


New Efforts: Advanced System Designs

Lower costs through optimization of use of fiber composite properties and advanced designs for improved performance and packaging

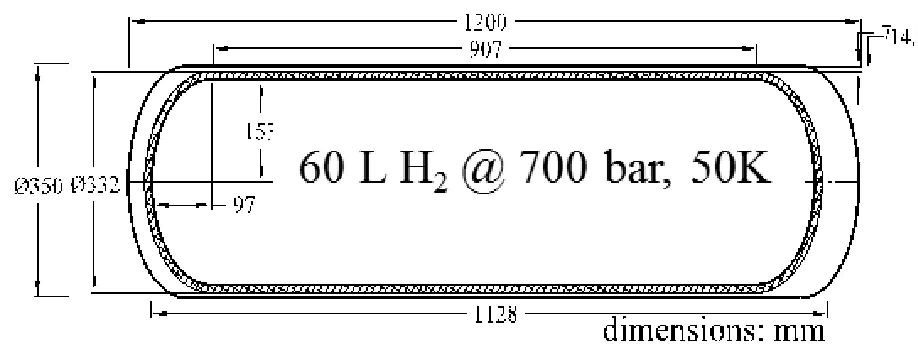
New SBIR Phase II project to investigate use of graded construction to reduce cost of carbon fiber composites in 700 bar H_2 Storage Systems (CTD - ST110)

- Targets demonstration of 10-25% cost reduction
- Due to thick wall effect, outer composite layers strained 20-30% less than inner layers
- Cost reduction realized through use of lower cost, lower strength fibers in outer layers



New project to design advanced cryo-compressed H_2 storage systems and evaluate high-pressure cryo-pump refueling (LLNL – ST111)

- Evaluate 875 bar, 100 kg/hr delivery cryo-pump for fast fill refueling of cryo-compressed H_2
- Evaluate high L/D ratio cryo-compressed 700 bar tanks with:
  - thin vacuum gap
  - high fiber content composites
  - sized for 5.6 kg H_2 useable capacity
  - demonstrate cycle-life of fill 1500 cycles
- Targets exceeding 6 wt.% H_2 and 40 g H_2/L



New Efforts: Advancing H_2 Storage Materials Development

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Innovative hydrogen storage materials development and production processes to advance the state-of-the-art in materials-based hydrogen storage

Improve the kinetics and thermodynamics of $Mg(BH_4)_2$ for Hydrogen Storage (a 14 wt.% material) (LLNL)

- Uses a combined theory/experiment approach
  - Multi-scale modeling of kinetics and reaction pathways for nanoparticles
  - Novel synthesis and characterization approach for direct validation of predictions

Boron-based hydrogen storage: ternary borides and beyond (potential for ≥ 11 wt.% materials) (HRL Laboratories)

- Mixed-metal borohydrides ($M_aM_b(BH_4)_2$ designed to maintain single hydrogenated and dehydrogenated phases
  - Improved kinetics by avoiding solid phase diffusion of non-hydrogen atoms
- Lithiated boranes – a new class of materials
  - Reversible exchange between B-H/Li-H and B-Li/H_2
  - Fast kinetics expected due to elimination of rearrangement of boron networks

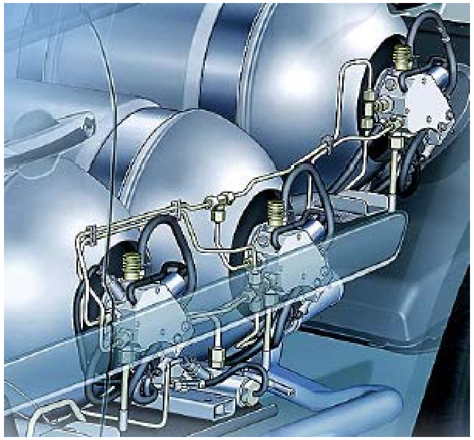
Low-cost α-alane (AlH_3) production - a 10wt.%, 149 g H_2/L hydrogen storage material (Ardica Technologies)

- Develop an economical electrochemical cell design for large-scale production of α-alane based on SRNL demonstrated process
  - Alane to be used in low-power military and consumer electronic fuel cell power devices
- Targets α-alane production costs of <$5/kg

Gaps and other areas to be addressed further

Interface between onboard the vehicle and fueling infrastructure

- Discussions between fuel infrastructure and vehicle stakeholders to understand issues related to fast fueling for high-pressure compressed H_2
- Requirements for fueling of materials-based storage technologies better understood from HSECoE efforts



Balance-of-plant components

- Costs of BOP can exceed cost of carbon fiber composites at low-volume of manufacture
- Multi-tank systems have considerably higher BOP costs
- Materials of construction currently almost exclusively SS316L
- Starting to address issue with more thorough analysis and identification of alternative materials of construction

Advanced H_2 Storage Systems for Early Markets

- One SBIR Phase II project developing low-pressure metal hydride systems for FC forklift application
- New project for low-cost alane for use in low-power FC products

Collaborations

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Applied R&D is coordinated among national and international organizations

INTERNATIONAL ACTIVITIES

- IEA HIA Task 32 Hydrogen-based Energy Storage
  - 17 countries
  - ~50 subject matter experts

DOE – EERE - FCTO
Hydrogen Storage Applied R&D

- Physical Storage
- Fiber Composites
- Materials-based Storage
- System Engineering
- Testing and Analysis

INDUSTRY

- U.S. DRIVE Tech teams:
  - H_2 Storage
  - H_2 Delivery
  - Codes & Standards
  - Fuel Cells
  - Fuel Pathways
  - Vehicle Systems

TECHNOLOGY VALIDATION

National Collaborations (inter- and intra-agency efforts)

DOE - EERE
VTO; BETO; AMO; SETO

DOE – ARPA-E
- MOVE
- RANGE

DOC - NIST
- Neutron scattering
- Measurements

DOD
DOD/DOE MOU

Recent and Upcoming Activities

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Low-cost Compressed H_2 Systems:

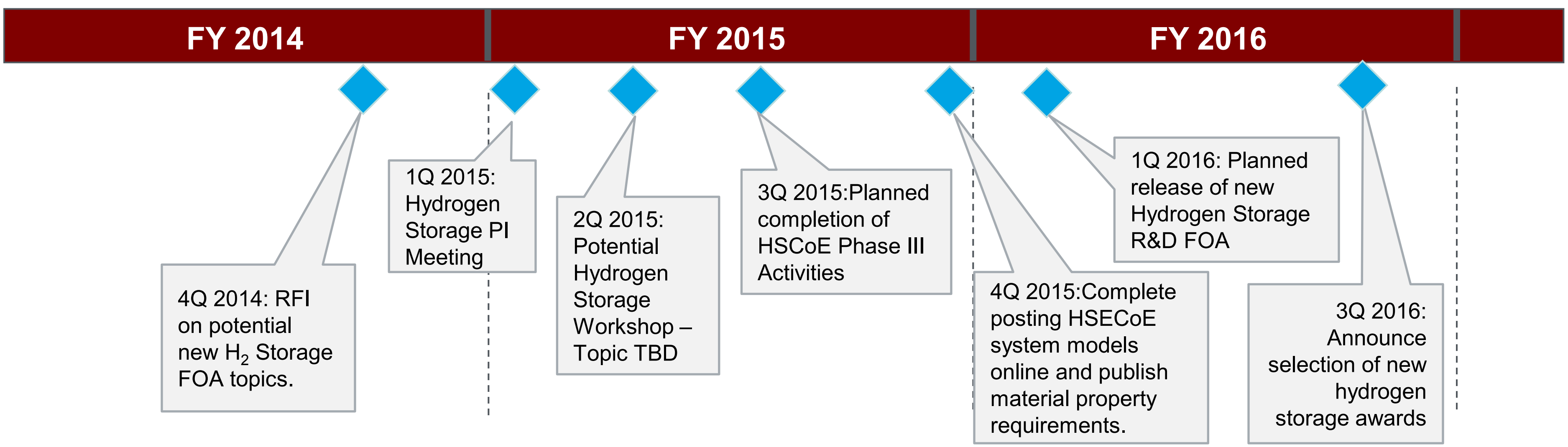
- Achieving tensile strength with low-cost, textile-grade PAN precursors
- Initiating new efforts investigating alternative resins, fibers, materials for BOP and manufacturing processes

Hydrogen Storage Engineering Center of Excellence:

- Phase III has commenced, focused on 2 prototype sorbent systems
- Phase II showed Chemical Hydrogen Storage Systems able to meet most onboard storage targets, but not well-to-powerplant efficiency or fuel cost

Advanced Hydrogen Storage

- Continuing efforts on cold/cryo-compressed H_2 storage
- Continuing efforts developing novel hydrogen storage materials



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http://energy.gov/eere/fuelcells/fuel-cell-technologies-office

Collaborations

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Energy Efficiency & Renewable Energy

Energy Efficiency and Renewable Energy

- Vehicle Technologies Office
- Bioenergy Technologies Office
- Advanced Manufacturing Office
- Solar Energy Technologies Office

Advanced Projects Agency - Energy

- Methane Opportunities for Vehicular Energy (MOVE)
- Robust Affordable Next Generation Energy Storage Systems (RANGE)

Government-Industry

- U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE)

Interagency

- U.S. Department of Defense (DOD-DOE MOU)
- U.S. Department of Commerce (NIST)

International

- International Energy Agency – H_2 Implementing Agreement
    - Task 32 – Hydrogen-based energy storage
        - 17 countries with ~50 participating experts

HYDROGEN IMPLEMENTING AGREEMENT