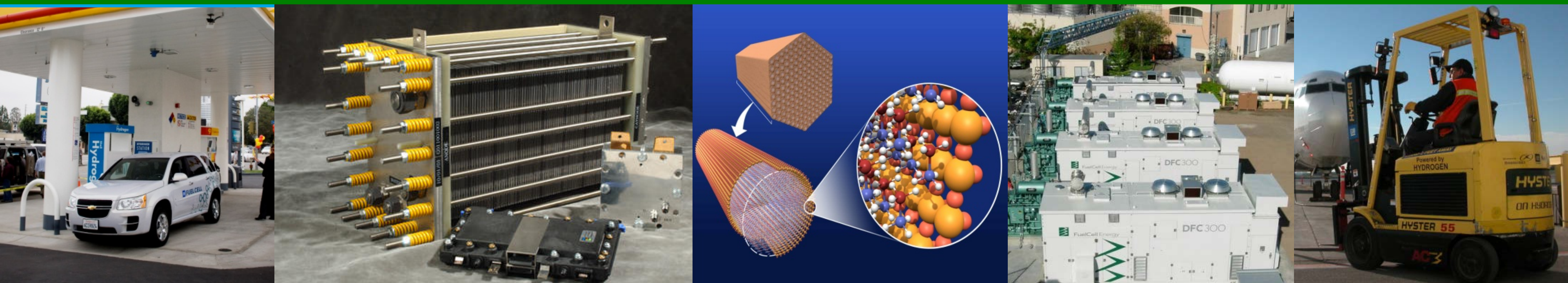
U.S. DEPARTMENT OF
ENERGY



Hydrogen Storage Program Area
-Plenary Presentation-

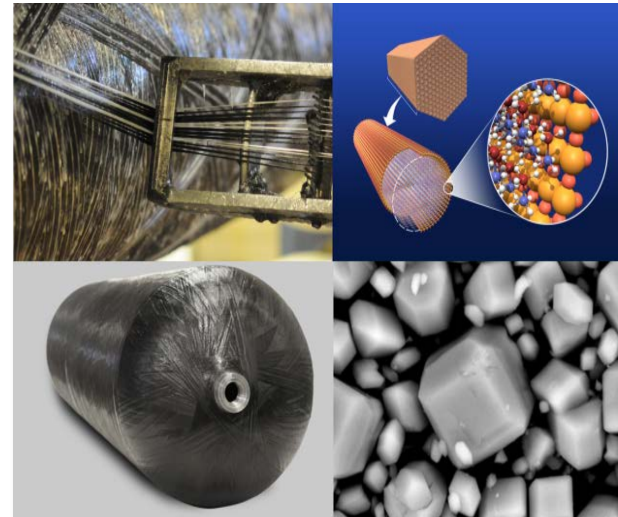
Ned T. Stetson
Fuel Cell Technologies Office

2015 Annual Merit Review and Peer Evaluation Meeting
June 8 - 12, 2015

Goals and Objectives

Objectives

- By 2020, 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 **$10/kWh** ($333/kg $H_{2\ stored}$) or less.
- By 2020, demonstrate H_2 storage systems in MHE applications achieving **1.7 kWh/L** (50 gH_2/L); ability to recharge with 2 kg of H_2 within 2.8 minutes at **$15/kWh** ($500/kg $H_{2\ stored}$) or less.
- Ultimate targets: to develop onboard H_2 storage systems 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.



GOAL: Develop advanced hydrogen storage technologies to enable successful commercialization of hydrogen fuel cell products

Hydrogen Storage Team - Strategy and Barriers

Dual approach

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

Technology Focus

700 bar Compressed (Near-Term Approach)

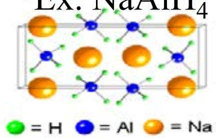
Barriers and R&D Focus:
- Lower Cost Carbon Fiber
- Improved Composites
- Conformable designs
- Lower Cost BOP

Cold / Cryo-Compressed (Longer-Term Approach)

Barriers and R&D Focus:
- System Engineering
- Advanced Insulation
- Improved Dormancy
- Composite Development

Metal Hydrides (Longer-Term Approach)

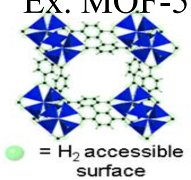
Ex. $NaAlH_4$



Barriers and R&D Focus:
- Higher Material Capacity
- System Cost
- Fill Time
- Onboard Efficiency

Sorbents (Longer-Term Approach)

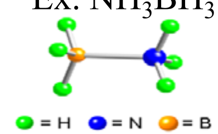
Ex. MOF-5



Barriers and R&D Focus:
- Higher Material Capacity
- System Cost
- Dormancy
- WTP Efficiency

Chemical H_2 Storage (Longer-Term Approach)

Ex. NH_3BH_3



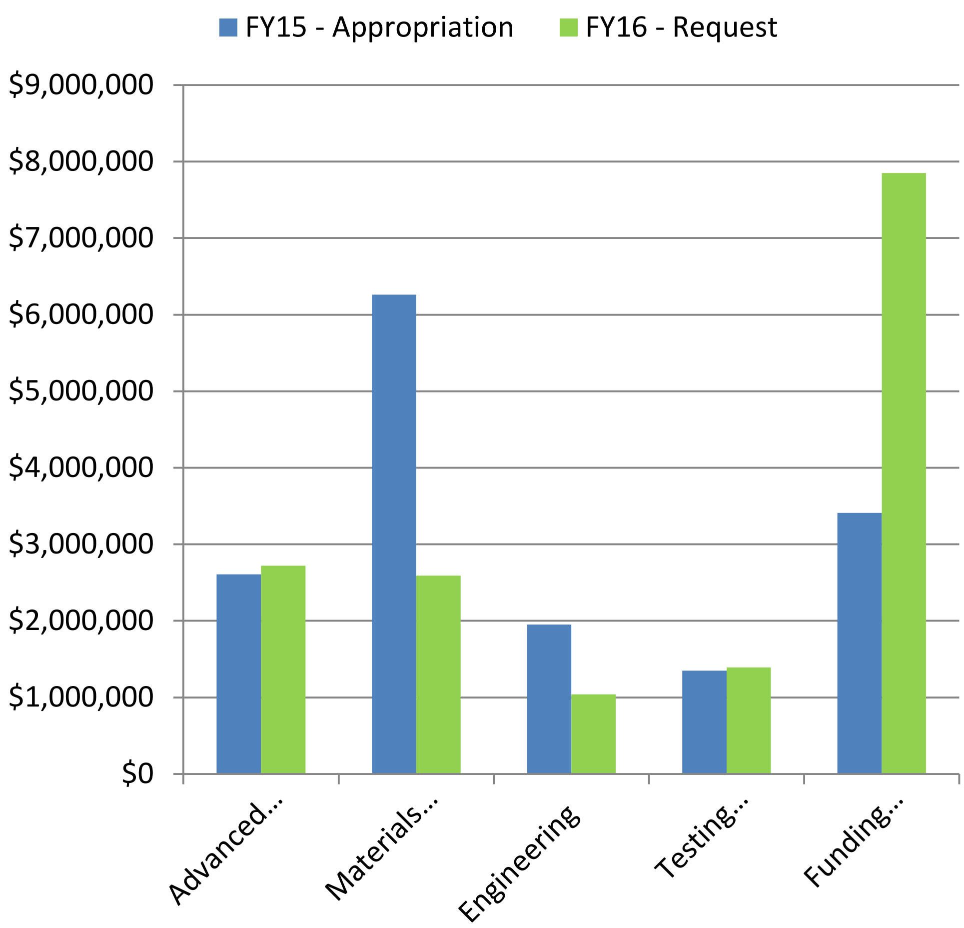
Barriers and R&D Focus:
- Lower Cost Off-board Regen
- System Cost
- Gravimetric Density

Objective: Achieve a driving range >300 miles for full span of light-duty vehicles, while meeting packaging, cost, safety, & performance requirements

Budget

FY 2016 Request = $15.6M

FY 2015 Appropriation = $15.6M



EMPHASIS

- Close coordination with EERE Offices on carbon fiber composites, including AMO, VTO and BETO
- Focus on cost reduction for high pressure tanks
- Increase materials development efforts focused on materials with characteristics needed to meet onboard storage targets
- Portfolio is balanced between mid- and long term

Current Status of H_2 Storage Technologies

Storage Targets	Gravimetric kWh/kg (kg H_2/kg system)	Volumetric kWh/L (kg H_2/L system)	Costs \$/kWh (\$/kg H_2)
2020	1.8 (0.055)	1.3 (0.040)	\$10 (\$333)
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

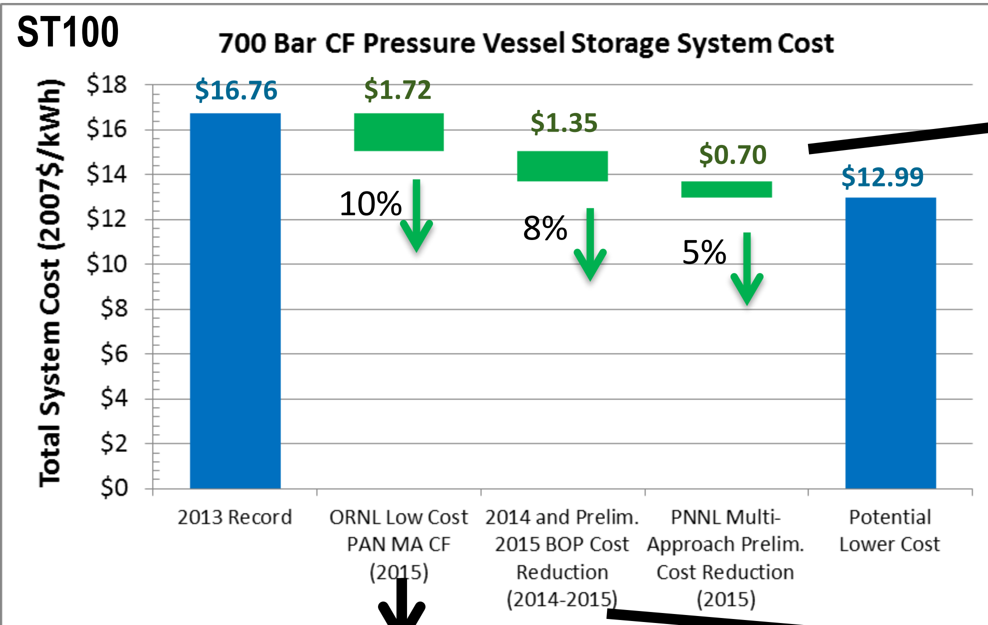
Projected H_2 Storage System Performance (5.6 kg H_2 usable)	Gravimetric kWh/kg	Volumetric kWh/L	Costs* \$/kWh
700 bar compressed (Type IV)	1.5	0.8	17
350 bar compressed (Type IV)	1.8	0.6	13
Metal Hydride ($NaAlH_4$/Ti)	0.4	0.4	43
Sorbent (MOF-5, 100 bar) MATI, LN2 cooling [HexCell, flow-through cooling]	1.2 [1.2]	0.7 [0.6]	16 [15]
Chemical Hydrogen Storage (AB-50 wt.%) [AlH_3 – 60 wt.%]	1.5 [1.1]	1.4 [1.2]	17 [22]

- 700 bar and 350 bar compressed H_2 system projections based on 2013 Program Record #13010
- Materials-based system projections from Hydrogen Storage Engineering Center of Excellence (5/2015)

* Projected to 500,000 units / year

Physical Storage

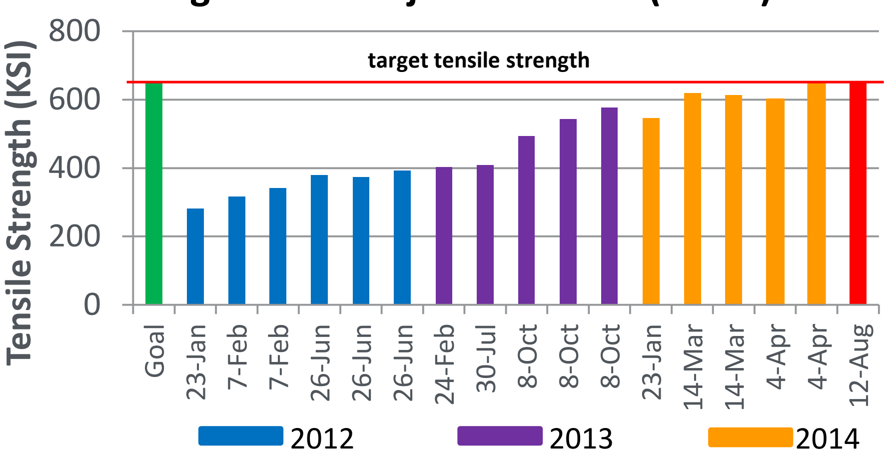
700-Bar Compressed H_2 System Cost Analysis



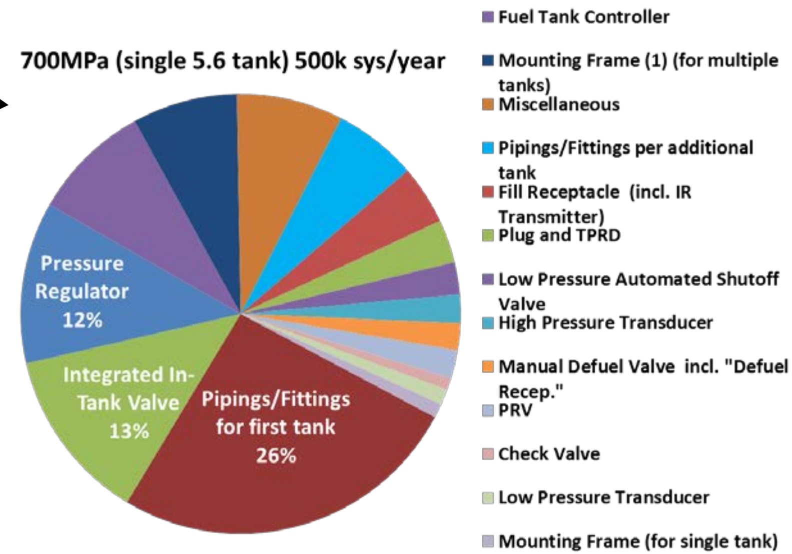
Alternative resin development (PNNL)

Description	Measured Data Relative to Baseline		Estimated Mass at
	Mass	Burst	100% Burst
Baseline	100.0%	100.0%	100.0%
Low Cost Resins			
Baseline + Resin 1 Substitution	95.3%	100.0%	95.3%
Baseline+Resin1+12kT700+Alt. Sizing	93.2%	101.2%	92.3%

Strength over Project Duration (ORNL)



BOP cost analysis (SA/ANL)



Preliminary analyses project more than 20% reduction in cost from 2013 baseline

Accomplishments - Project Highlights

Low-cost CF precursors [ORNL/VT]

- Approach: Melt-spinning process
- Goal: ~30% lower cost than conventional PAN precursor fibers
- Based on prior BASF technology

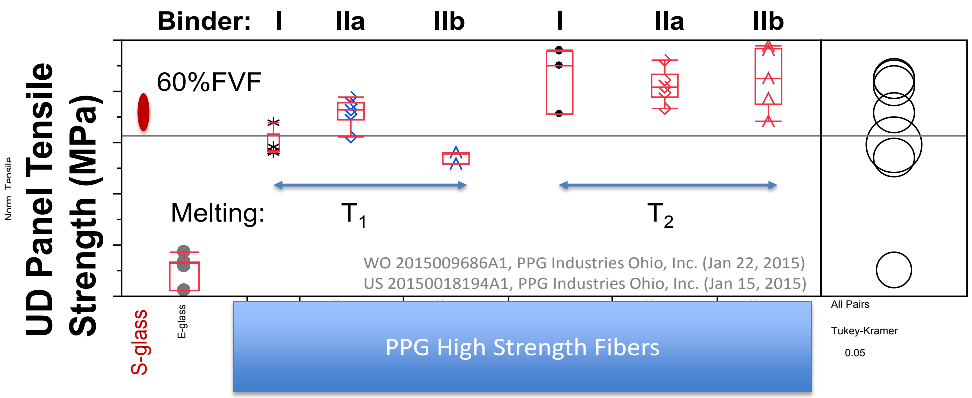
PAN precursor filaments produced through melt-spinning process

ST093

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
- Novel fiber glass manufacturing process
- Characterizing stress rupture properties to determine required safety factor

Tensile strength analyses



Fiber Glass Chemistry

ST115

Reducing cost of composites for use in H_2 storage vessels

Accomplishments - Project Highlights

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

- Approach: low-viscosity, high-toughness resin with VARTM manufacturing process
- Goal: 35% reduction in composite costs
- Potential for optimized winding patterns with fewer defects

Thick panel produced through infusion process with less than 1% voids by volume

ST114

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
- Identified Panex 35 ™ as potential candidate fiber, evaluating fibers from ORNL

Potential cost reduction of 1-30%

T700 Price Range = \$13 - \$20
Low Cost Fiber Price Range = \$7 - \$12

50% T700 Toray/50% Low Cost Fiber				
		Low Cost Fiber (\$/lb)		
		\$ 7.00	\$10.00	\$12.00
T700 Toray (\$/lb)	\$13.00	20.4%	9.1%	1.6%
	\$15.00	24.3%	14.5%	7.9%
	\$20.00	30.6%	23.2%	18.3%

60% T700 Toray/40% Low Cost Fiber				
		Low Cost Fiber (\$/lb)		
		\$ 7.00	\$10.00	\$12.00
T700 Toray (\$/lb)	\$13.00	15.9%	6.9%	0.8%
	\$15.00	19.1%	11.2%	6.0%
	\$20.00	24.3%	18.3%	14.4%

ST110

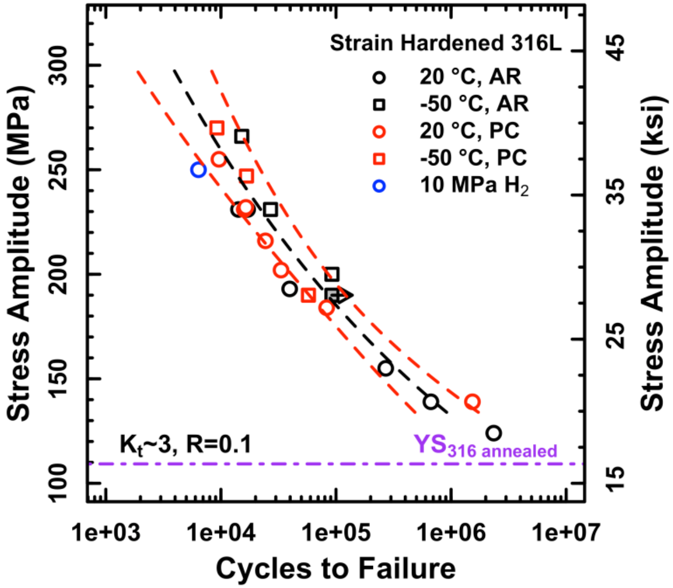
Reducing cost of H_2 storage vessels through alternative manufacturing

Accomplishments - Project Highlights

Alternative materials for BOP [SNL/Hy-Performance Materials]

- Approach: Screening based on fatigue stress and computational material design
- Goal: Reductions in BOP of up to 50% in weight and 35% in cost
- Established baseline for strain-hardened type 316L SS

Fatigue life comparisons: ambient and low-T, as-annealed, pre-charged and in H_2



ST113

New Project: Conformable 700 bar H_2 Storage Systems [CTE/HECR/UT]

- Approach: Development of an over-braided, coiled pressure vessel for 700 bar H_2 storage
- Goal: Surpass DOE system targets for specific energy (3.7 kWh/kg) and cost (< $10/kWh)
- Using proven technology for self-contained breathing apparatuses as design basis
- Achieves efficient onboard vehicle packaging through use of a shaped corrugated core over-braided with aramid fiber for strength

ST126

Alternative materials for BOP and conformable designs

Cold-compressed H_2 storage [PNNL/Ford/Hexagon Lincoln/AOC/Toray]

- Approach: Synergistically consider pressure vessel and operating conditions
- Goal: 30% reduction in system cost over 2013 baseline cost for 700 bar system
- Targeting 500 bar and 200 K operation
- Identified alternative, lower cost resin – being considered for commercial use by a PV manufacturer

~50% reduction in tank mass possible with 500 bar and 200 K operation

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

ST101

Cryo-compressed H_2 storage [LLNL/BMW/Linde/Spencer]

- Approach: Develop a thin-lined, pressure capable, cryogenic vessel
- Goal: Demonstrate 3 kWh/kg and 1.7 kWh/L system capacities at 700 bar
- Design incorporates a type III pressure vessel within a MLVSI jacket
- Installed high-efficiency, high-throughput liquid cryo-pump

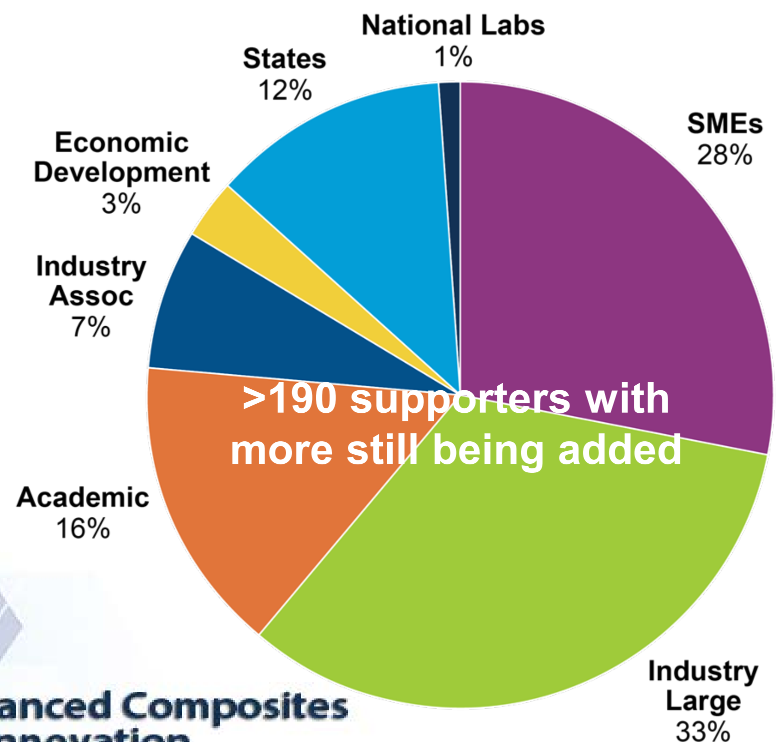
Cryo-compressed dispensing station at LLNL

ST111

Cold and cryo-compressed H_2 storage for improved performance

Cross-cutting Effort: Institute for Advanced Composites Manufacturing Innovations

- President Obama announced the selection on January 9, 2015 in Tennessee.
- Part of the National Network of Manufacturing Innovation
- <u>Managed through the EERE Advanced Manufacturing Office</u>
- IACMI is currently negotiating the Cooperative Agreement with DOE.

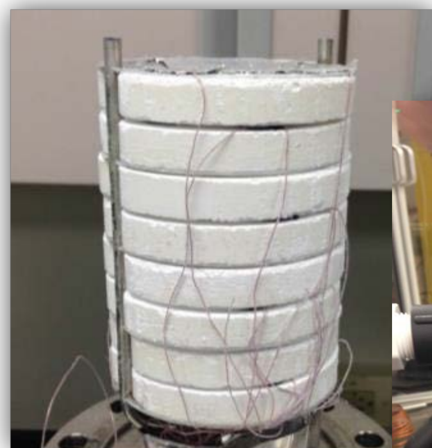
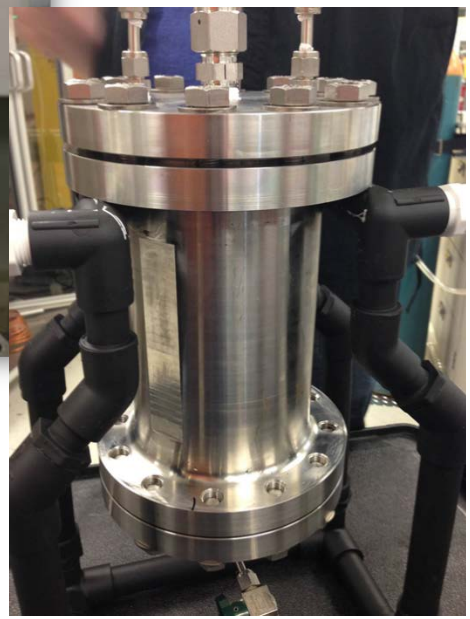


iacmi
Institute for Advanced Composites Manufacturing Innovation

Materials Based

Accomplishments – H_2 Storage Engineering CoE

Designed and built two sorbent prototype systems for evaluation:

MATI


Hexcell

Posted system models online for research community use:

- MH acceptability envelope
- MH finite element model
- MH framework model
- Physical H_2 framework models
- Chemical hydrogen framework model
- Adsorption framework model
- Adsorption finite element model (coming)
- Tank volume/cost model

Prototype sorbent systems being evaluated and validated system models released

Accomplishments – H_2 Storage Engineering CoE

Highlights from 6 years of the HSECoE:

- Baseline system performance established, based on current materials, for reversible metal hydrides, chemical hydrogen storage materials, and hydrogen sorbents
- Integrated framework developed to project materials-based system performance in fuel cell electric vehicle application – available to the R&D community
- Validated performance of models through empirical testing – available online
- "Reverse engineered" from systems to materials to predict required material characteristics needed for systems to meet DOE system targets
- Technology advancements/developments (non-exhaustive list):
  - Integrated framework model with vehicle, fuel cell and H_2 storage modules (NREL/Ford/UTRC)
  - Microchannel catalytic burner – received "Transformational Idea" award at 2014 FLoW competition and is being commercialized by Micro-Steel (OSU)
  - Developed and demonstrated efficiency NH_3 and diborane scrubbers (LANL/UTRC)
  - Developed compact, efficient novel gas/liquid separator (UTRC)
  - Developed compact microchannel heat exchanger for use in H_2 storage systems (OSU)
  - Developed flow-through sorbent system design (SRNL/UQTR)
  - Demonstrated ability to increase volumetric efficiency through sorbent densification (Ford)

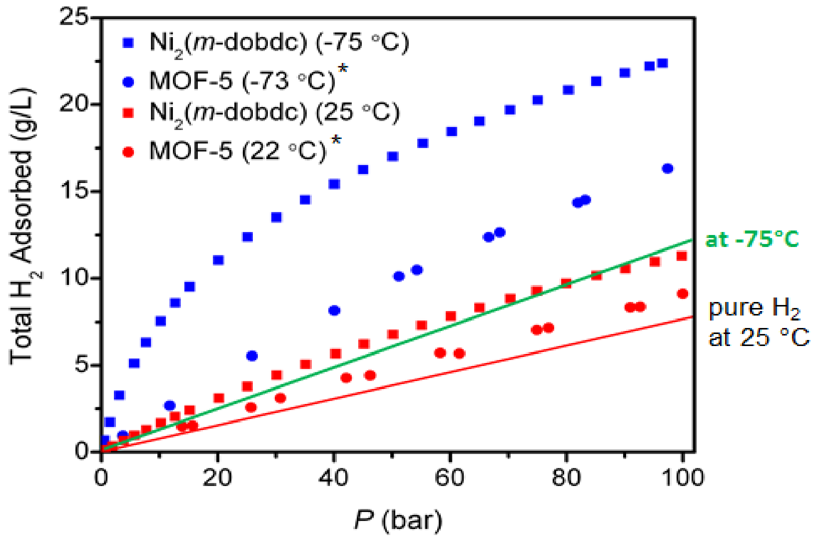
HSECoE is in the last year of its multi-year effort

Accomplishments - Project Highlights

Improved H_2 sorbent development [LBNL/NIST/GM]

- Approach: novel MOFs with open metal centers with stronger binding
- Goal: MOFs with significant capacity at ambient temperature and 100 bar or less
- Developed new Ni_2 (*m*-dobdc) with volumetric performance exceeding MOF-5

Sorption isotherms for Ni_2(*m*-dobdc), and MOF-5

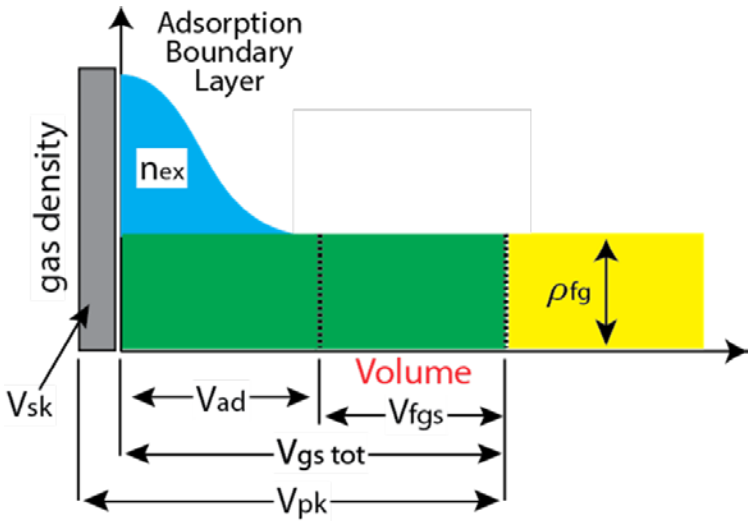


ST103

Accurate and verified sorption results [NREL/H_2 Tech Consulting]

- Approach: Standardized practices and methods for accurate, and reliable reported sorption data
- Goal: Develop and disseminate standard method for reporting sorption data
- Maintain calibrated laboratory for verifying reported sorption results

Establishing standard on how to refer to sorption data



ST014

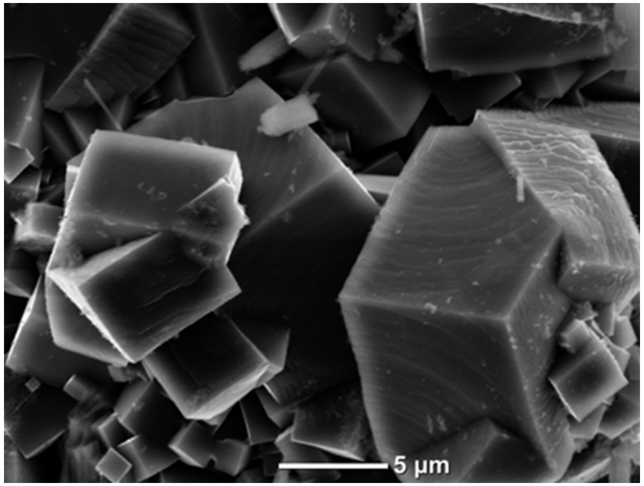
Developing improved H_2 sorbents and standard methods

Accomplishments - Project Highlights

Low-cost methods for α-alane production [SRNL]

- Approach: Develop low-cost, efficient processes for alane synthesis
- Demonstrated regeneration of electrolyte in >80% yields
- Reduction of dendrite growth a current focus
- Developing improved recrystallization processes

α-alane recrystallized from alane adduct



ST063

Low-cost methods for α-alane production [Ardica/SRI]

- Approach: Develop fluidized electrochemical process for low-cost α-alane production
- Goal: Reduce alane production costs to less than $10/kg
- Detailed cost analyses identify areas that need attention
- Demonstrated Al particle electrochemical cells

Electrochemical cell with Al particles

ST116

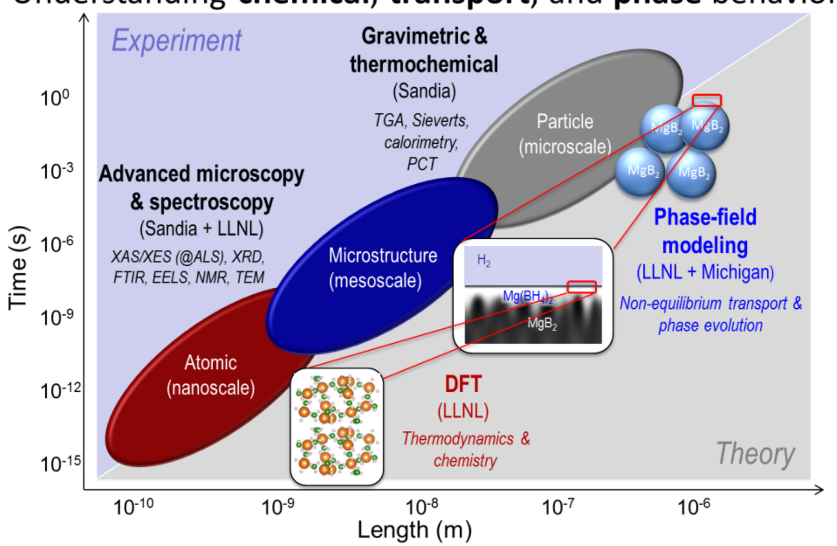
Low-cost α-alane production for commercial applications

Accomplishments - Project Highlights

Improved performance for $Mg(BH_4)_2$ [LLNL/SNL]

- Approach: Combined computational and empirical effort to identify ways to improve performance
- Goal: Develop flexible, validated, multi-scale model and use to develop practical material that satisfies DOE 2020 targets.
- Developed phase-fraction prediction framework

Understanding **chemical**, **transport**, and **phase** behavior

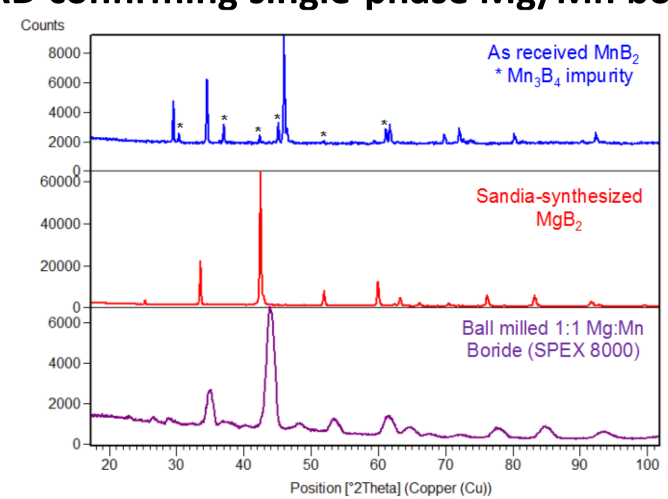


ST117

Boron-based H_2 storage materials [HRL/SNL/UMSL]

- Approach: Develop novel H_2 storage materials based on multi-metal borohydrides and lithiated boranes
- Goal: Develop reversible hydrogen storage materials with potential for >10 wt.% capacity
- Synthesized Mg/Mn ternary borides for investigation
- Calculated Li exchange enthalpies for boron frameworks

XRD confirming single-phase Mg/Mn boride



ST118

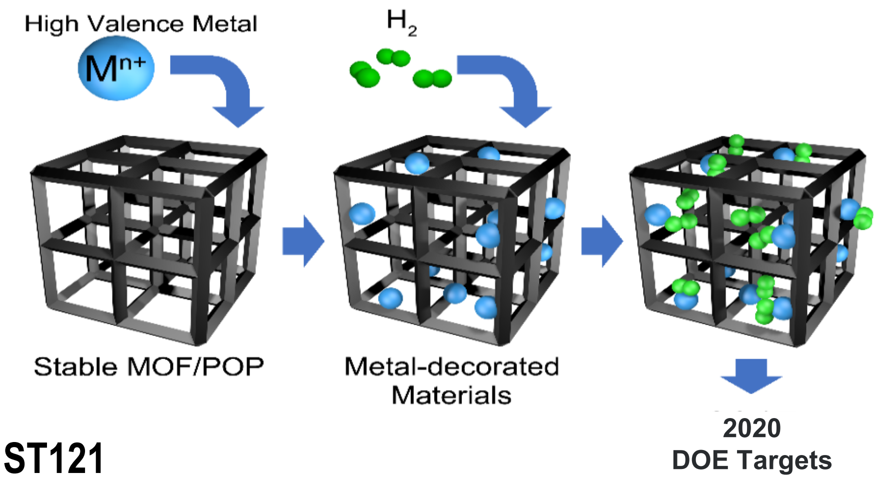
Boron-based, high-capacity H_2 storage materials

New Materials Development Projects

High-Capacity & Low-Cost Hydrogen-Storage Sorbents for Automotive Applications [Texas A&M University]

- Objective: Develop metal-organic framework (MOF) sorbents with capacities exceeding the conventional storage limit per unit surface area
- 2nd Objective: Improve system performance through enhanced thermal conductivity of sorbent/carbon composites

Goal is to achieve higher H_2 uptake trough improved H_2 sorbents interactions

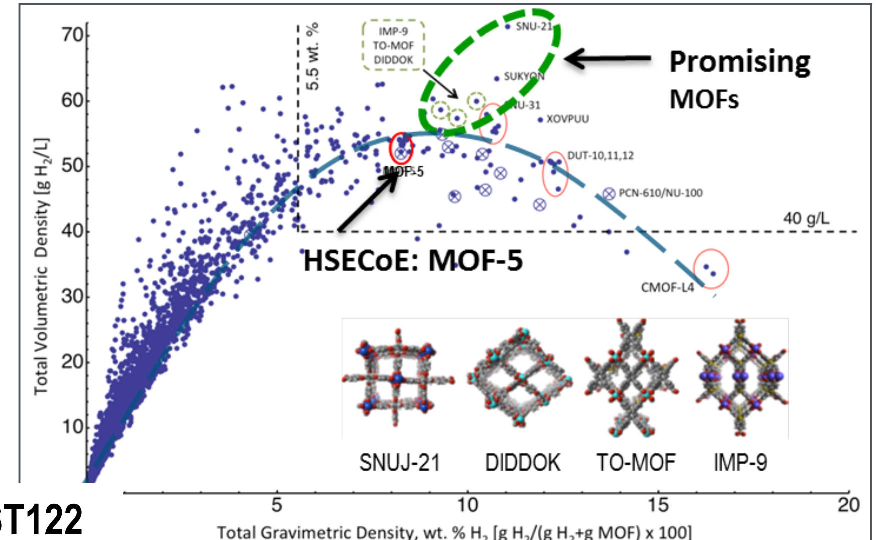


ST121

Hydrogen Adsorbents with High Volumetric Density: New Materials and System Projections [University of Michigan]

- Objective: Develop high volumetric adsorbents that also have high gravimetric capacities
- Approach: Investigate "best-in-class" sorbents identified through screening of reported structures in the Cambridge Structure Database

Goal is to achieve simultaneously higher volumetric and gravimetric density



ST122

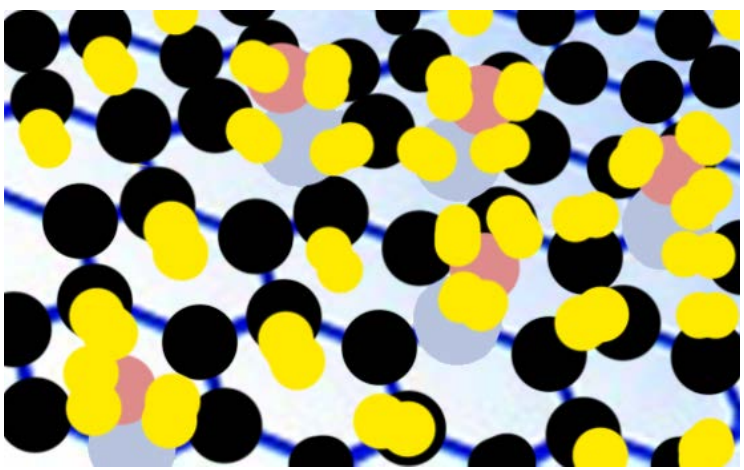
New MOF development targeting high volumetric capacities

New Materials Development Projects

Design and Synthesis of Materials with High-Capacities for Hydrogen Physisorption [California Institute of Technology]

- Objective: Develop high performing H_2 adsorbents prepared from either graphene or exfoliated graphite.
- Goal: A hydrogen storage capacity of ≥ 11 wt.%, and near-constant isosteric heat of adsorption

Functionalize graphene for high packing density H_2 storage on the surface

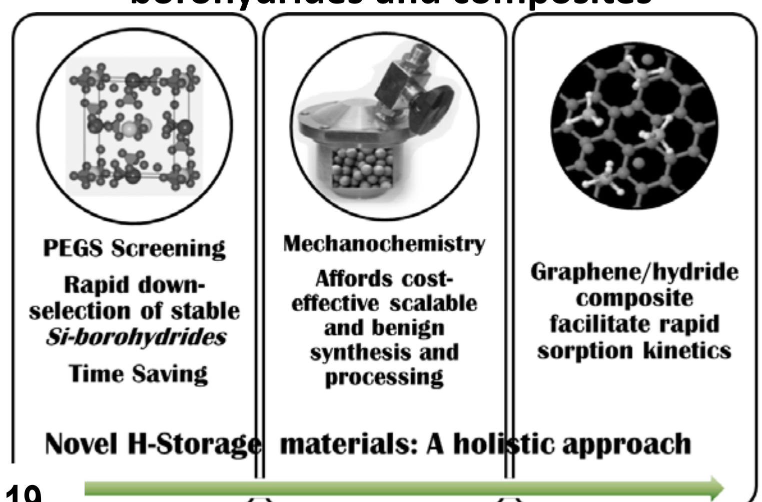


ST120

High-capacity Hydrogen-Storage Systems via Mechanochemistry [Ames Laboratory]

- Objective: Develop low-cost, reversible, high-performance H_2 storage materials
  - (1) Si-borohydride hypersalts
  - (2) borohydride/graphene composites.
- Approach: Computational modeling to guide mechanochemical processing synthetic methods

Goal is to develop Novel High H-capacity Si-based borohydrides and composites



ST119

Novel reversible, high-capacity H_2 storage materials development

Accomplishments - Project Highlights

Low-cost, Metal Hydride-based H_2 Storage System for Forklift Applications (SBIR Phase II)
[Hawaii Hydrogen Carriers LLC/SNL/Hydrogenics] [ST095]

- Objective: Develop and demonstrate a low-pressure, high-density MH-based H_2 storage system for forklift applications
- Low-pressure storage (max charging pressure =70 bar) addresses the high infrastructure costs associated with high-pressure storage onboard forklifts
- MH unit designed, built and integrated into a Hydrogenics fuel cell unit for forklift applications
- System currently undergoing testing at the Applied Research Center in Aiken, SC
- Demonstrations planned at commercial warehouse operations in SC

MH reservoir

Integrated into fuel cell unit

Installed on forklift

Low-pressure, high-density H_2 storage for material handling equipment

- **Workshop Goals:**
  - Disseminate outcomes from HSECoE on system engineering, modeling and current performance
  - Disseminate results of "reverse engineering" from system performance to material requirements
  - Discuss strategies and needs for advanced materials development to meet challenging onboard H_2 storage targets
- **Five breakout session held:** reversible metal hydrides, sorbents, chemical hydrogen storage, niche applications, & bridging fundamental and applied research
- **Over 75 participants:** representing industry, academia and national labs
- **Hosted by NREL:** January 27-28, 2015
- **Workshop Information on website:**
  - Agenda and attendee list
  - Public versions of meeting presentations
  - Breakout session report-out presentations
  - http://energy.gov/eere/fuelcells/downloads/doe-materials-based-hydrogen-storage-summit-defining-pathways-onboard

Information exchange with H_2 storage materials researchers

Collaborations

INTERNATIONAL ACTIVITIES

- IEA HIA Task 32 Hydrogen-based Energy Storage

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 – Office of Science
BES; ASCR

DOE – ARPA-E

DOC - NIST
- Neutron scattering
- Measurements

DOD
DOD/DOE MOU

Applied R&D is coordinated among national and international organizations

Recent and Upcoming Activities

Low-cost Compressed H_2 Systems:

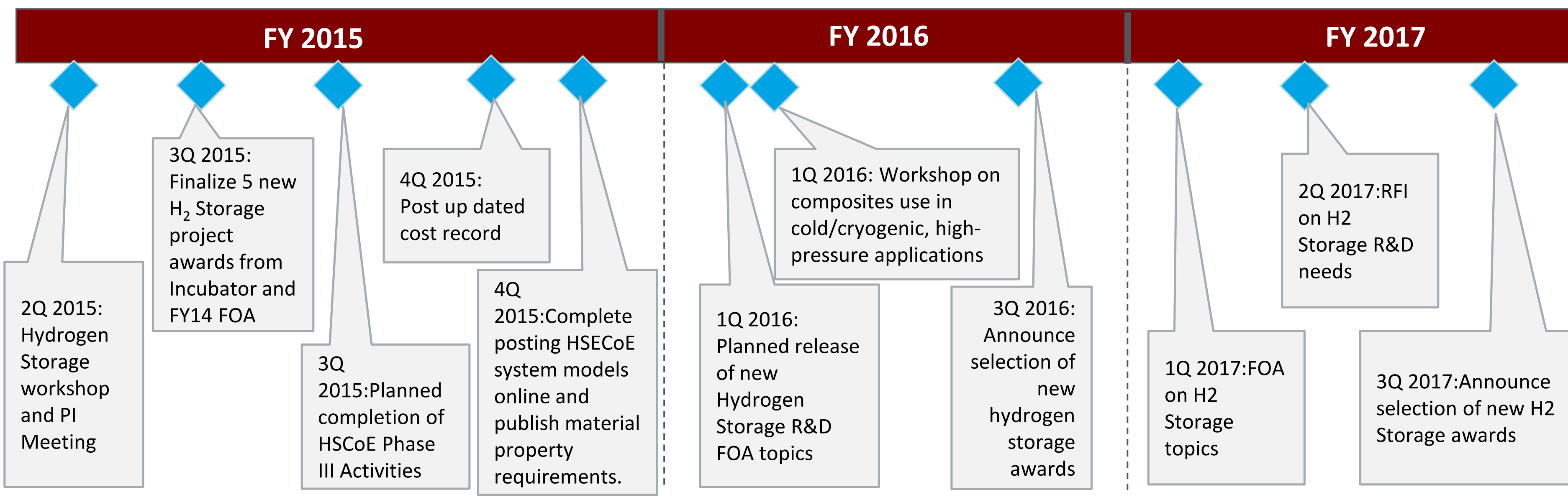
- Launched IACMI, a new CEMI Institute – compressed gas storage one of three focus areas
- Initiated new project on conformable high-pressure hydrogen storage
- Updating cost record with recent validated accomplishments from storage activities

Hydrogen Storage Engineering Center of Excellence:

- Phase III evaluation of 2 prototype sorbent systems underway
- Validated performance models posted for use by research community
- Disseminating results from “reverse engineering” from system to materials performance

Advanced Hydrogen Storage

- Held materials-based H_2 Storage Summit
- Announced new materials projects, awards now being finalized
- Planning consortium for advanced H_2 storage materials



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

Fellowship opportunity in hydrogen storage materials is now available!

For more info, visit :

https://www.zintellect.com/Posting/Details/1079