Department of Energy
Fuel Cell Technologies Office (FCTO)

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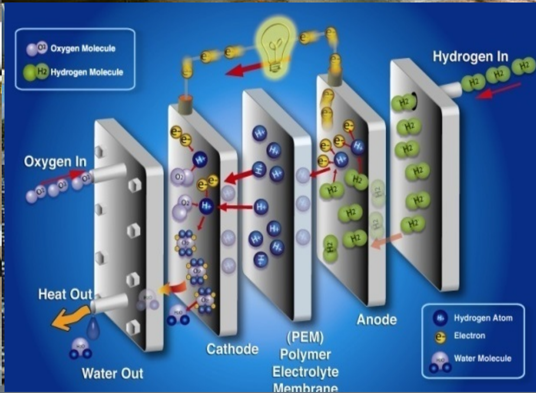

Cold/Cryogenic Composites for Hydrogen Storage Applications in FCEVs

Dallas, TX **October 29, 2015**

Dr. Ned Stetson

H_2 Storage Program Manager
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http://energy.gov/eere/fuelcells/fuel-cell-technologies-office

Mission and Focus

To enable and accelerate the **successful commercialization of hydrogen fuel cell technologies through development of advanced hydrogen storage technologies** able to cost-effectively meet application performance requirements.

Light-duty fuel cell electric vehicles

- Primary focus
- Driving range of at least 300 miles without compromising passenger and cargo space or vehicle performance
- Cost & performance targets established in consultation with automotive OEMs

High-value, non-automotive applications

- Secondary Focus
- Support advancement of FCEVs:
  - Infrastructure / supply chain development (e.g., material handling equipment)
  - Leverage prior DOE-supported R&D
- Targets for MHE and portable power established with stakeholder input

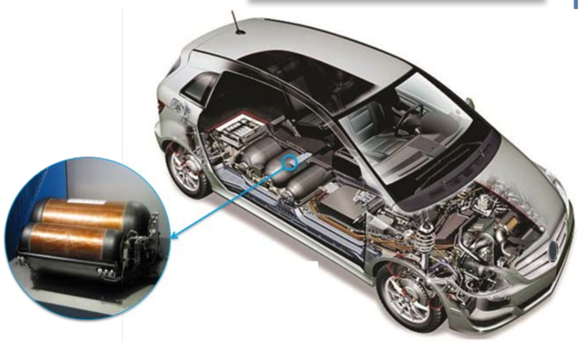
Advanced Hydrogen Storage technologies are critical for successful commercialization of hydrogen fuel cell technologies

Dual strategy to address near and long-term needs

Dual approach

Hydrogen Storage

- Near-Term Approach
- Longer-Term Approach



Technology Focus / Barriers and R&D Focus

700 bar Compressed

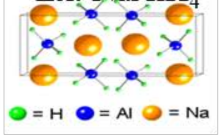
- Lower Cost Carbon Fiber
- Improved Composites
- Conformable designs
- Lower Cost BOP

Cold / Cryo-Compressed

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

Metal Hydrides

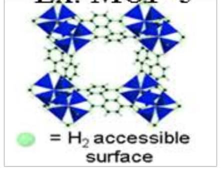
Ex. $NaAlH_4$



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

Sorbents

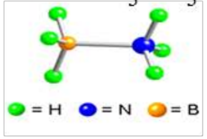
Ex. MOF-5



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

Chemical H_2 Storage

Ex. NH_3BH_3

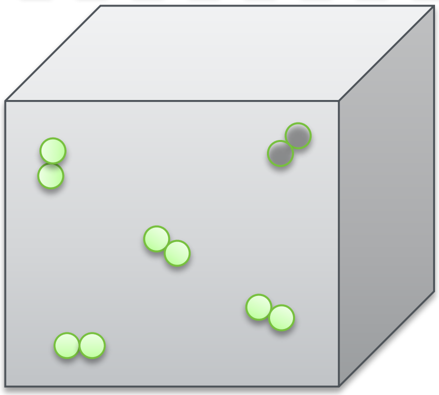


- Lower Cost Off-board Regen
- System Cost
- Gravimetric Density

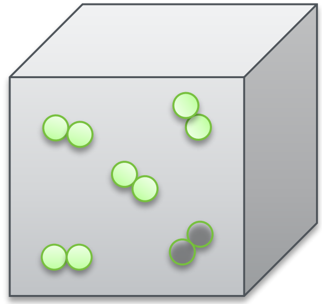
Near-term – address cost and performance of 70 MPa H_2 storage;
Long-term – develop advanced technologies with potential to meet all targets

Challenge of H_2 Storage – Energy Density

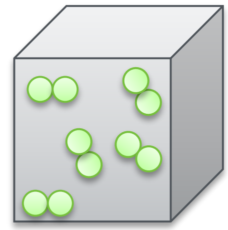
Physical Storage



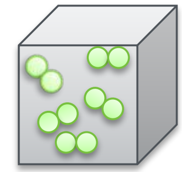
1 bar
normal
0.1 g/L



150 bar
lab cylinders
12 g/L



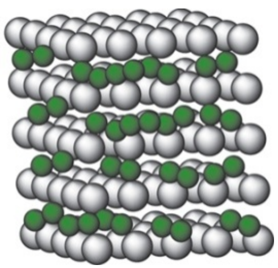
350 bar
Gen 1 vehicles
24 g/L



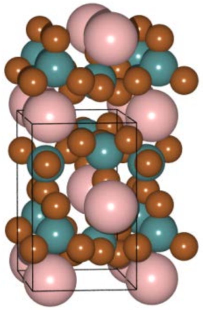
700 bar
Gen 2 vehicles
40g/L

liquid H_2
71 g H_2/L
@ 20 K

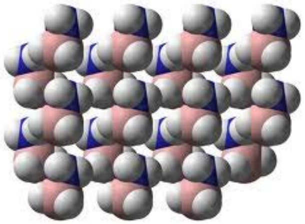
Materials Storage



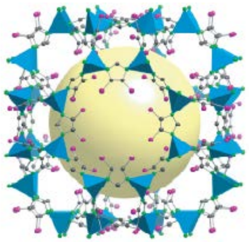
interstitial hydrides
~100-150 g H_2/L



complex hydrides
~70-150 g H_2/L



chemical storage
~70-150 g H_2/L



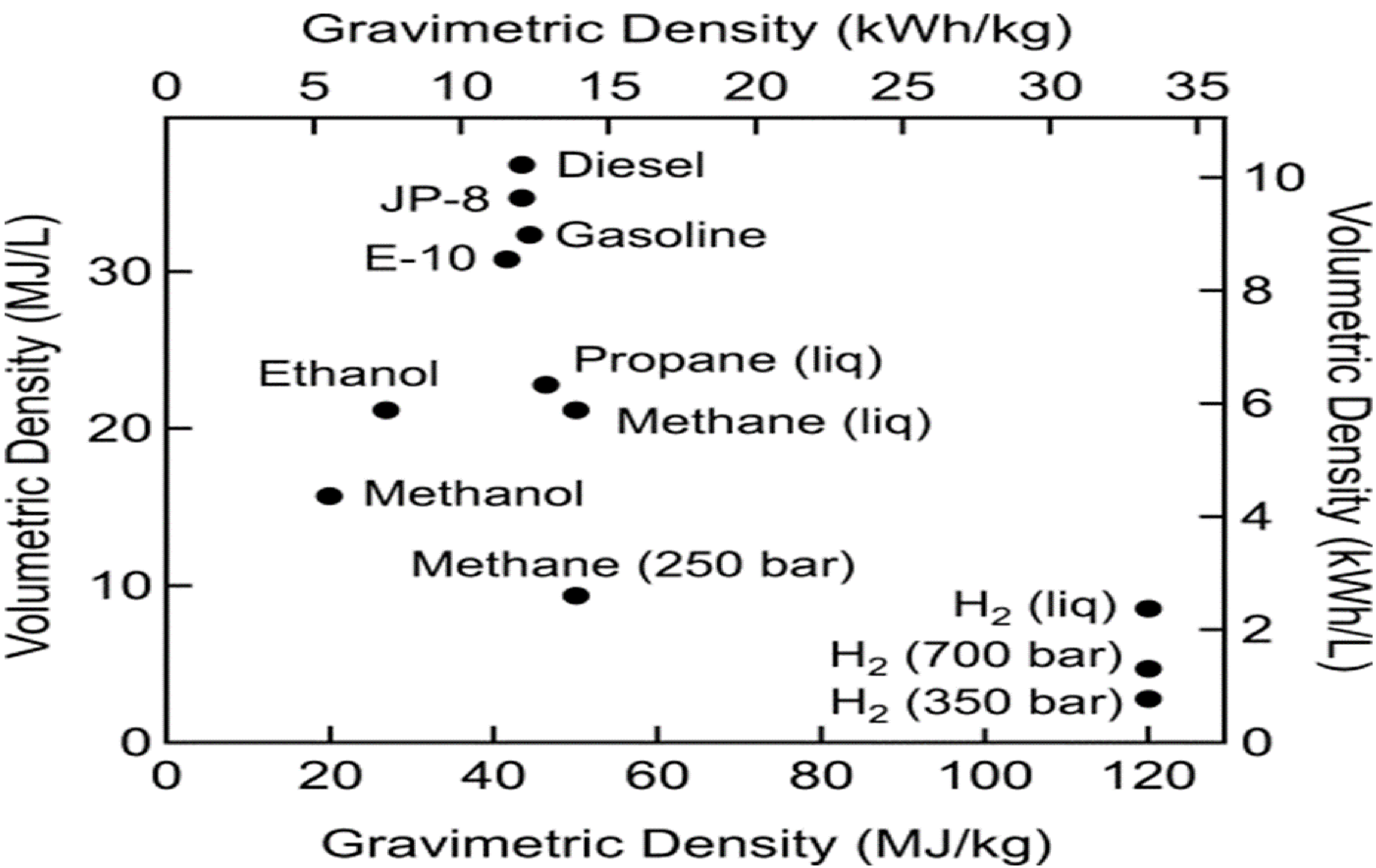
sorbents
≤ 70 g H_2/L

Reference

water
111 g H_2/L

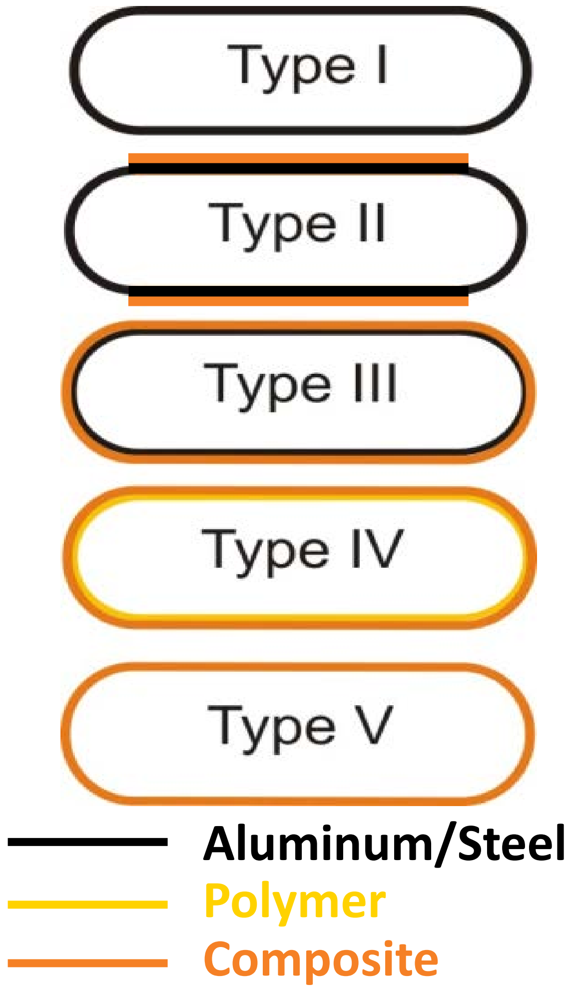
Efficiently storing adequate amounts of hydrogen in an acceptably small volume

Comparison of H_2 with other fuels

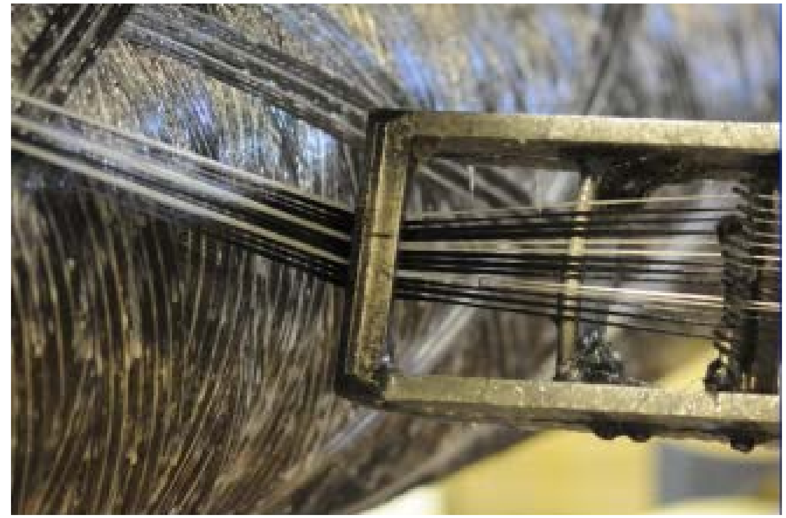


Hydrogen has high energy by mass but low energy by volume

Types of Pressure Vessels



Source: Lightweighting matters in energy storage (Part 1) (2014)



Type III and type IV vessels face different challenges for cryogenic applications

70 MPa System Performance

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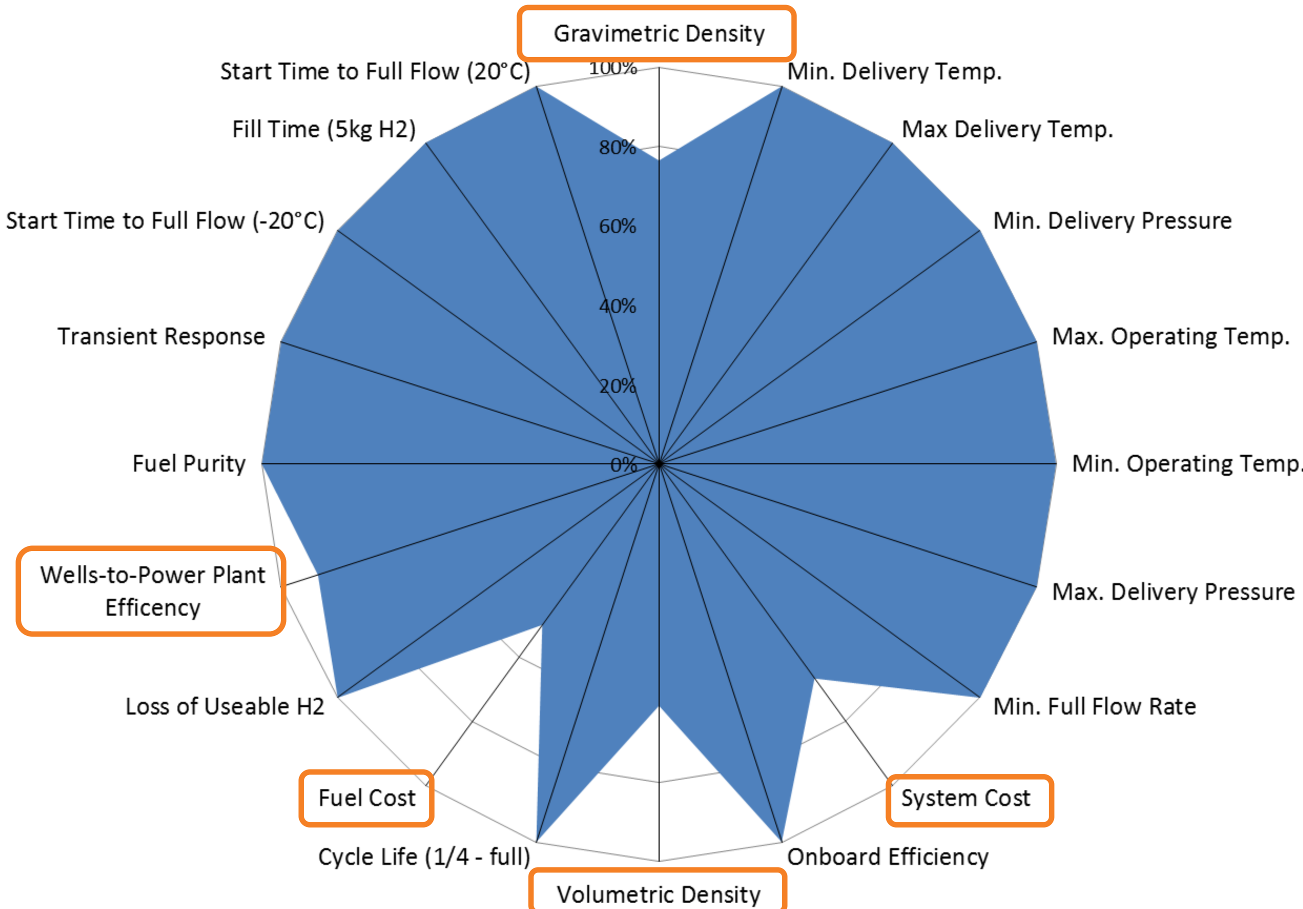
Projected 700 Bar Type IV System Compared Against 2020 Targets (Single Tank)



Based on FCTO Program Record 15013

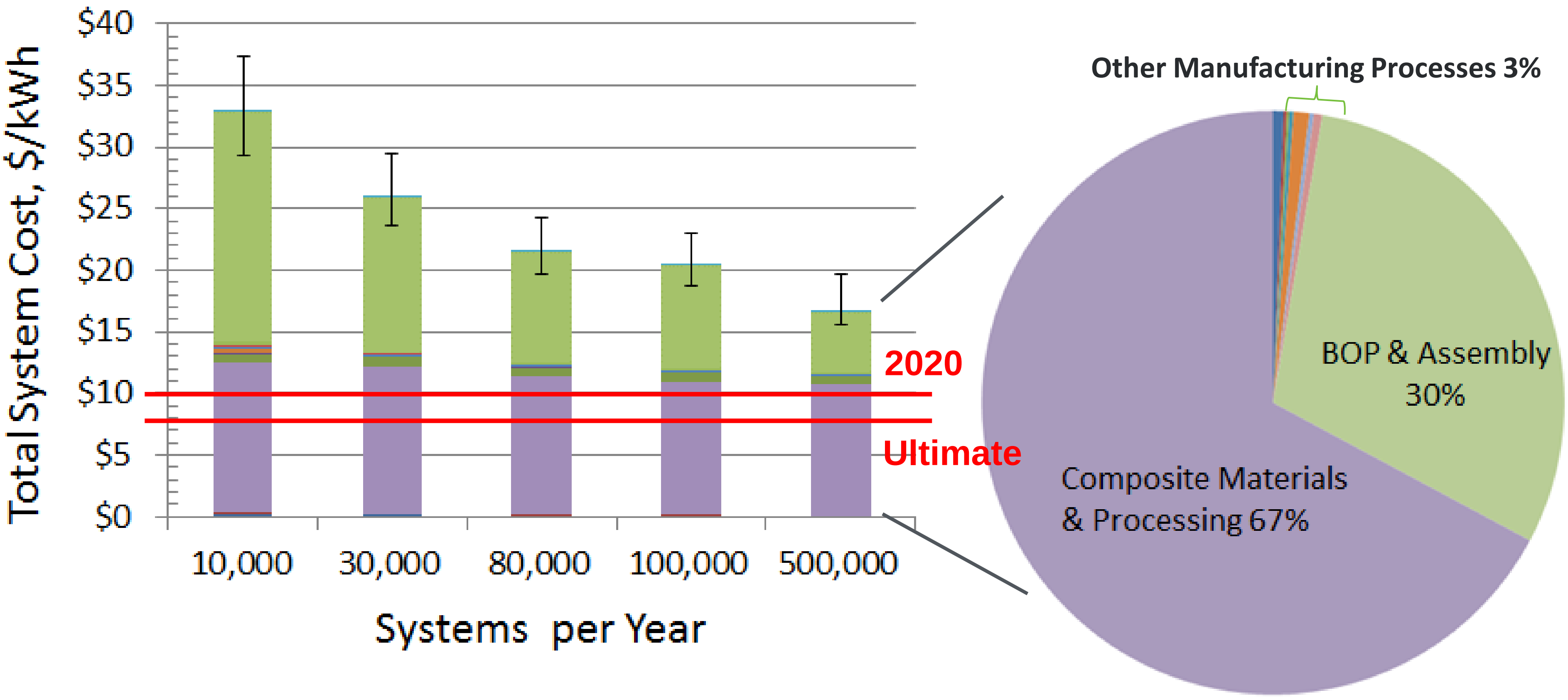
While performance meets many 2020 targets, certain targets still remain a challenge:

- System cost
- Volumetric Density
- Gravimetric Density
- Fuel Cost
- WtPP Efficiency

70 MPa compressed hydrogen storage has theoretical limitations that prevent it from meeting all onboard targets

Compressed H_2 Critical Storage Costs

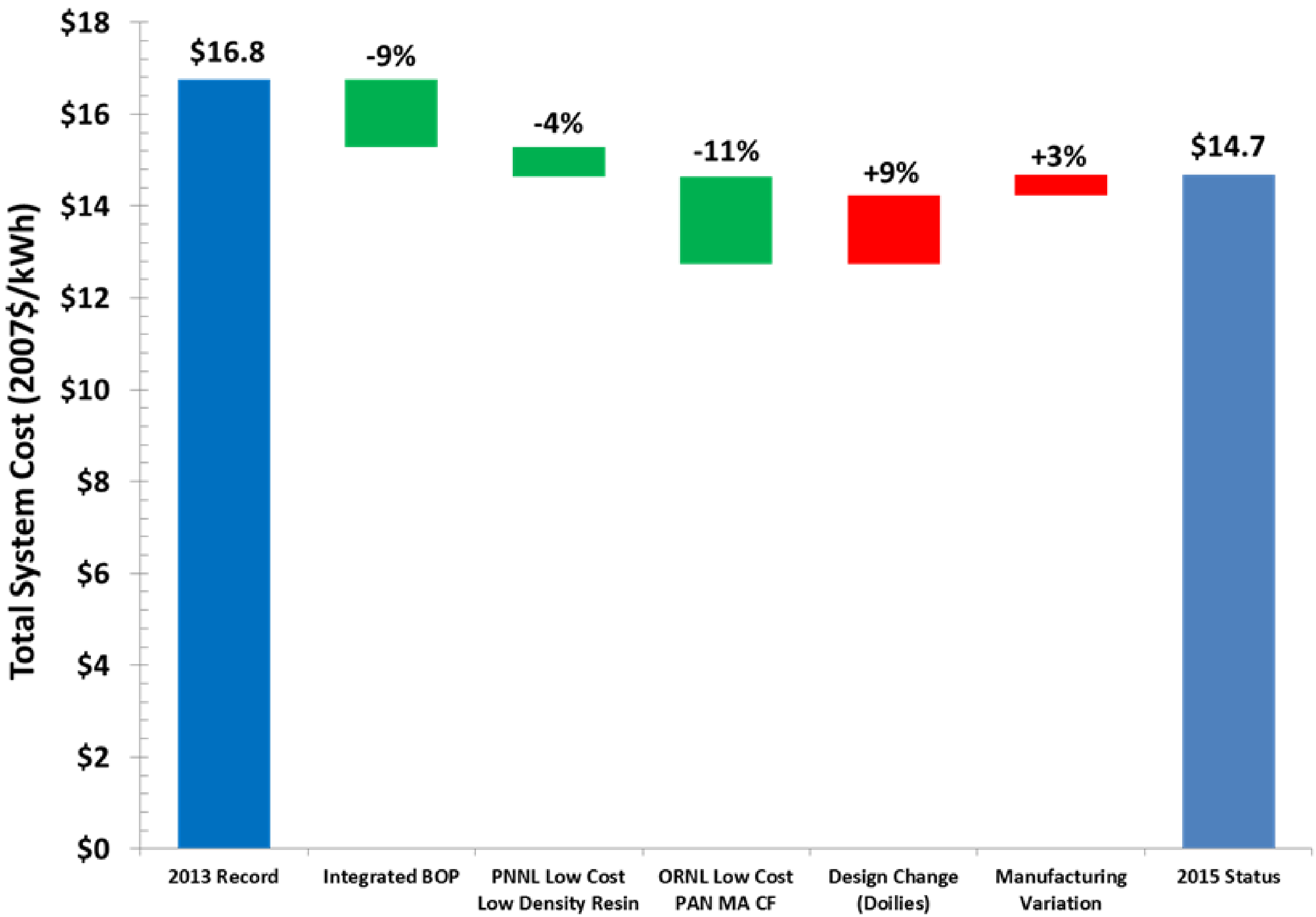
Cost breakdown for 700-bar H_2 Storage Tank*



*Single tank holding 5.6kg H2 total, cost in 2007$, 500,000 systems/yr – 2013 baseline projections

Composite materials & processing is the largest single cost contributor

Recent progress in reducing cost of H_2 Storage



FCTO Office data record 15013, in preparation

2$/kWh reduction in cost projected for high manufactured volume (500k/yr) Type IV 700 bar H_2 storage systems, compared to 2013 baseline cost

Current Program Activities

Low-cost CF precursors [ORNL/VT]

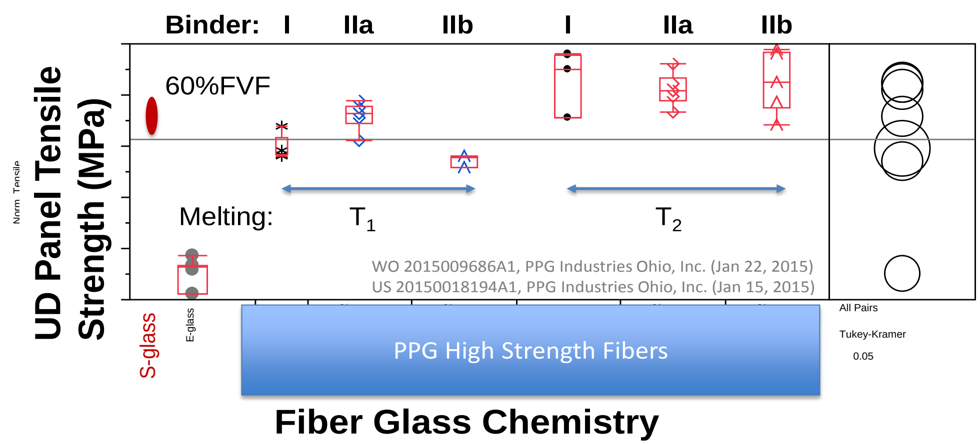
- Approach: Melt-spinning process
- Goal: ~30% lower cost than conventional PAN precursor fibers
- Based on prior BASF technology

PAN precursor filaments produced through melt-spinning process

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



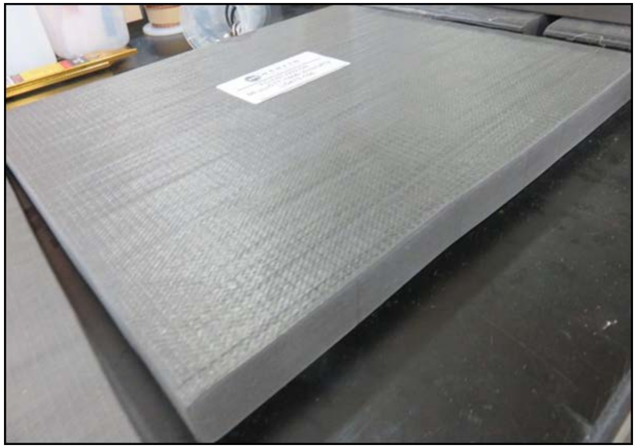
Reducing cost of composites for use in H_2 storage vessels

Current Program Activities

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



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%

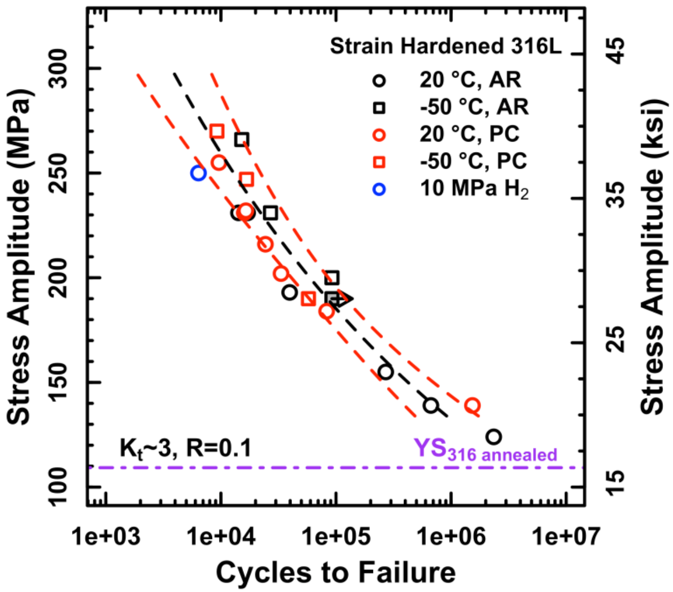
Reducing cost of H_2 storage vessels through alternative manufacturing

Current Program Activities

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

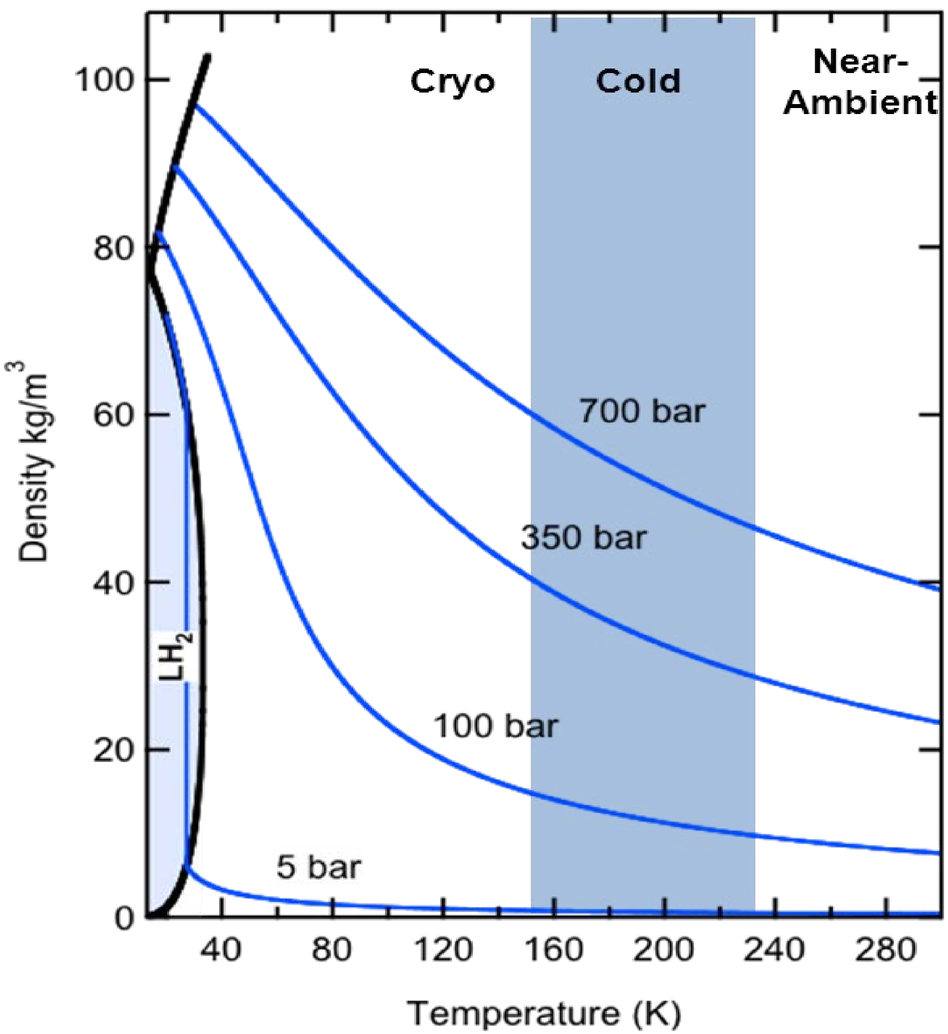


New Project: Conformable 700 bar H_2 Storage Systems [CTE/HECR/UT]

- 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

Alternative materials for BOP and conformable designs

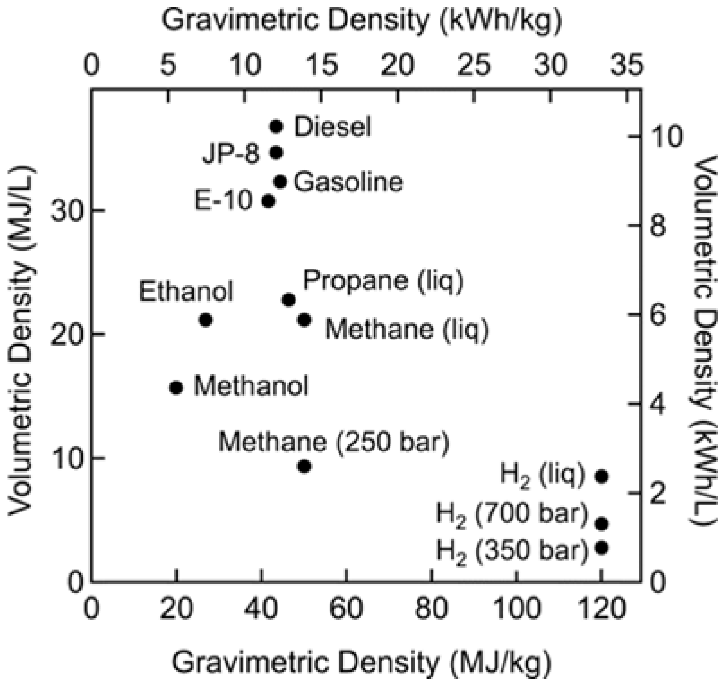
Why cryogenic H_2 storage?



Temperatures

lead to…

Energy Densities



Higher H_2 densities are achievable through use of lower temperatures

Current Program Activities

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

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

Cold and cryo-compressed H_2 storage for improved performance

BMW – pursuing cryo-compressed H_2 storage

In July of 2015, BMW demonstrated 2 prototype fuel cell electric vehicles with cryo-compressed onboard hydrogen storage: an i8 and a 5 Series GT

http://arstechnica.com/cars/2015/07/bmw-shows-off-first-hydrogen-fuel-cell-cars-5-series-gt-crazy-i8-prototype-2/

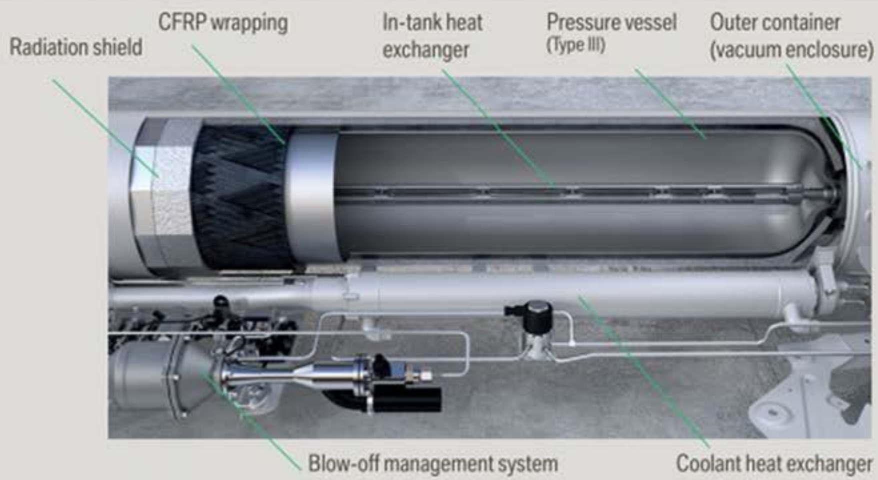
Cryo-compressed H_2 storage can provide significantly longer driving range using the same onboard space for fuel storage

BMW – pursuing cryo-compressed H_2 storage

EFFICIENT DYNAMICS 2015

BMW DEVELOPED CRYOGENIC PRESSURE VESSEL: CRYO-COMPRESSED HYDROGEN STORAGE, LONGER RANGE, TAKES UP NO MORE SPACE.

DOUBLE-WALLED INSULATED PRESSURE VESSEL FOR CRYOGENIC GAS STORAGE	
Maximum usable storage capacity	CcH_2: 7.1 kg (237 kWh) CGH_2: 2.3 kg (76 kWh)
Operating pressure	15 – 350 bar
Vent pressure	350 bar
System weight (incl. H2)	160 kg
Refuelling pressure	CcH_2: 300 bar CGH_2: 320 bar
Refuelling time	< 5 min



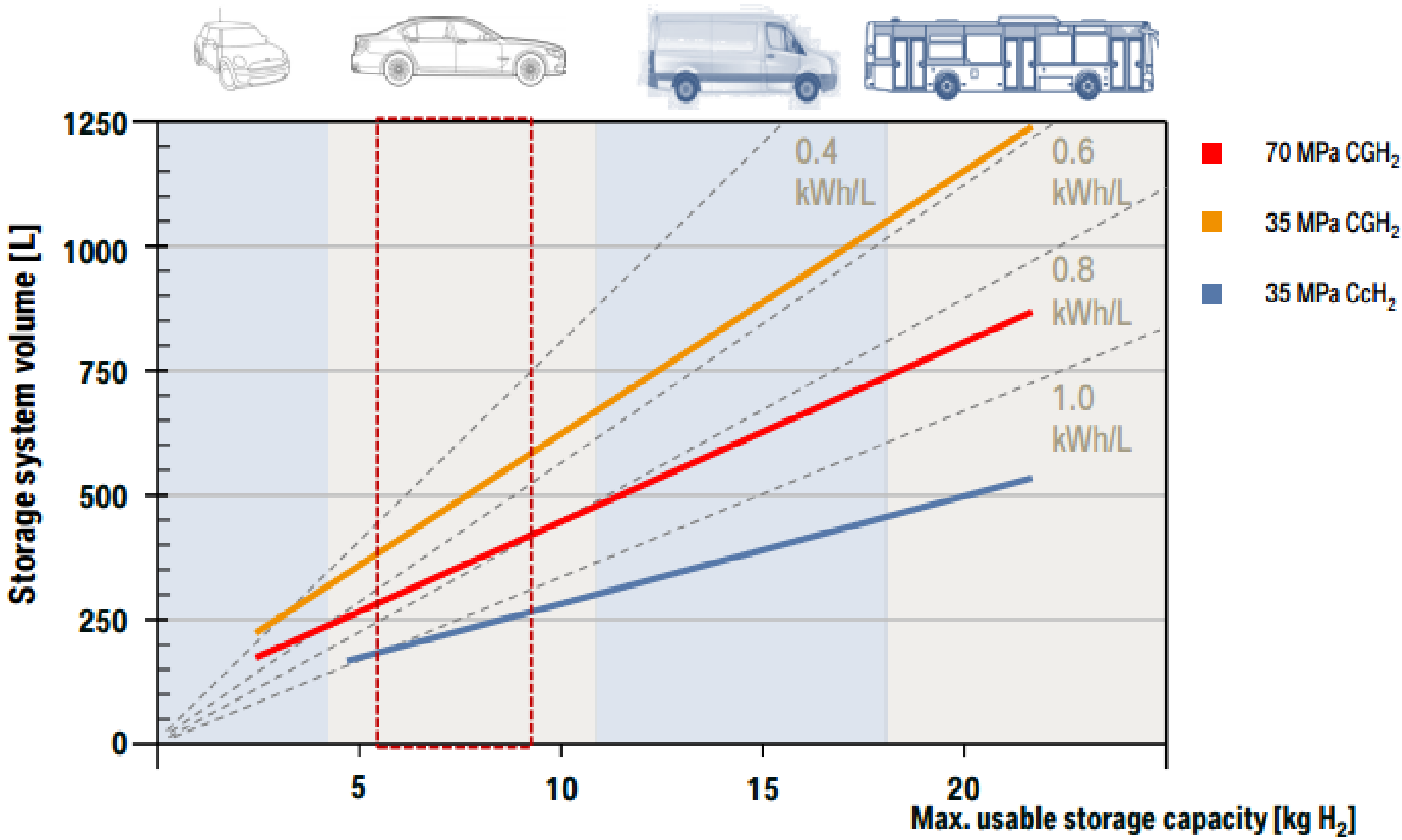
INNOVATIONS

+ Active tank pressure control with in-tank heat exchanger
+ Integrated in vehicle body with load-bearing structure
+ Additional fuel cell cooling
+ Cold and ambient refuelling possible (300 – 320 bar)

BMW GROUP

http://arstechnica.com/cars/2015/07/bmw-shows-off-first-hydrogen-fuel-cell-cars-5-series-gt-crazy-i8-prototype-2/

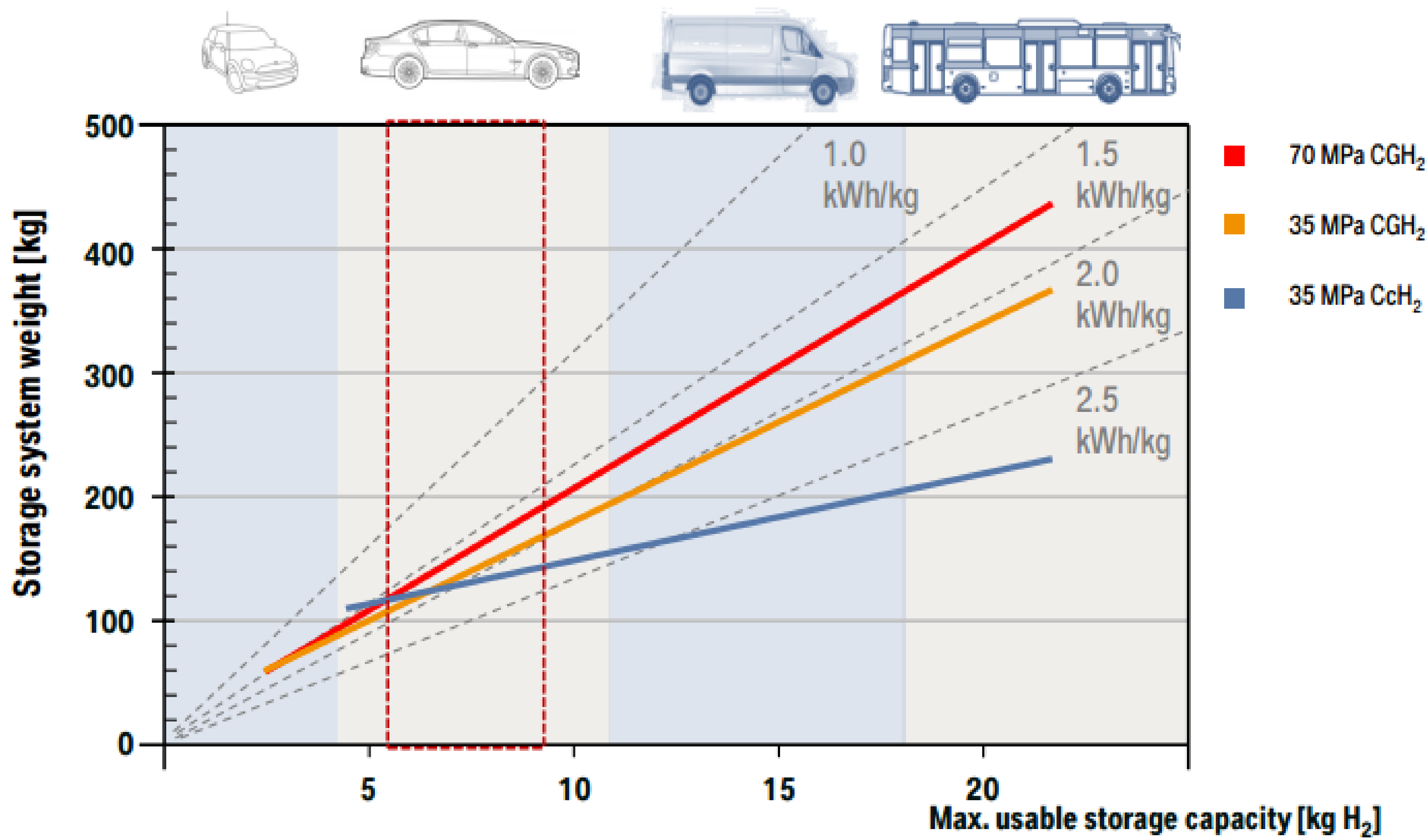
Comparison of H_2 Storage Systems by Volume (BMW)



http://www.stfc.ac.uk/stfc/cache/file/F45B669C-73BF-495B-B843DCDF50E8B5A5.pdf

Significantly improved energy density for cryo-compressed H_2, especially for larger systems

Comparison of H_2 Storage Systems by Weight (BMW)



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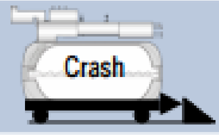
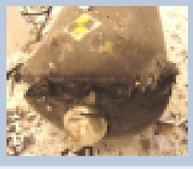
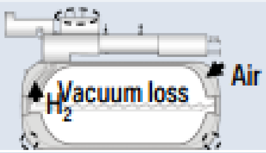
Significantly improved specific energy for cryo-compressed H_2 only for larger systems

Cryo-compressed H_2 System Safety Evaluation

Test		Explanation	Status
Vehicle crash		No additional implications compared to vehicle crash with CGH_2 storage expected. Tests will be done during vehicle qualification in 2012/2013.	
Vehicle fire	 	Vacuum insulation & multiple safety devices (PRDs & TPRDs) lower risk of vessel failure. Bonfire test validated in 2011, localized fire test in 2013.	
Burst energy		Adiabatic expansion energy in case of sudden vessel failure is mitigated in cryogenic gas storage compared to warm gas storage: Simulation: @ T < 100 K liquefaction during expansion supposable Validation: burst test under warm & cryogenic conditions show significant differences	
Sudden Vacuum Loss		Validation of safe H_2-discharge via pressure relief devices (and optional vacuum-casing burst disc) in case of Air- or H_2- sided vacuum loss. Implication of air-side vacuum-loss is mitigated compared to LH_2.	
Impact damage, penetration, chem. exposure		Vacuum enclosure lowers risk of pressure vessel damage through external impacts. Tests will be done during vehicle qualification in 2012/2013.	
Permeation and Leakage		Type III pressure vessel with welded boss, joints & vacuum casing eliminates issue of permeation & mitigates risk of leakage compared to CGH2 storage. Leakage rate << 3g/day.	

http://www.stfc.ac.uk/stfc/cache/file/F45B669C-73BF-495B-B843DCDF50E8B5A5.pdf

Initial testing has shown systems to be relatively safe

Cryo-compressed H_2 station open in Munich

THE LINDE GROUP

Press Release

New hydrogen fuelling station with technology from Linde opens in Munich

Munich, 16 July 2015 – Today, the TOTAL Multi-Energy fuelling station in Detmoldstrasse, Munich, opened its doors to drivers of hydrogen-powered fuel-cell cars. Equipped with innovative refuelling technology from Linde, the station is now home to the only public hydrogen fuelling service in the Bavarian state capital.

http://www.linde.ec/internet.global.corp.ecu/en/images/20150716_Detmoldstra%C3%9Fe_eng_v2336_166107.pdf

Cryo-compressed H_2 stations open to the public in Munich, Germany

However, R&D still needed

- Dormancy – time until system has to vent due to pressure build up from heat leakage and warming of stored hydrogen
  - Insulation efficiency – high R factors required
  - Insulation degradation – stability of vacuum systems
    - Outgassing of volatile components from composites
    - Hydrogen permeation
- Durability of composites in high pressure and thermal cycle environments
  - Match of CTE between composites and liners
  - Cycling between brittle and elastic phases
  - Effects of micro-cracking
- Certification prototcols
  - Standard duty cycles – how to define
  - Accelerated test procedures

Request for Information (RFI)

DOE has issued an RFI on Advanced Thermal Insulation and Composite Material Compatibility:

- Aim is to obtain feedback and opinions from industry, academia, research laboratories, government agencies, and other stakeholders on advanced thermal insulation for sub-ambient temperature alternative fuel storage systems.
- This RFI requests information regarding specifically:
  - How to maintain vacuum stability of systems
  - Use of advanced composites within the systems
  - Accelerated test methods to determine performance and applicability of materials and systems for long-term cold and cryogenic based alternative fuel storage systems for onboard vehicle applications
- Alternative fuels could include hydrogen or natural gas stored on board the vehicle at sub-ambient temperatures as a compressed gas, liquefied gas, or adsorbed onto a porous material.

RFI Link under DE-FOA-0001420: https://eere-exchange.energy.gov/

Email questions about the RFI to H2Storage@ee.doe.gov with "question" in the subject line

For this workshop…

Objectives:

- **Increase understanding on the technical challenges that are unique to composite materials and processing at cold and cryogenic temperatures** for automotive applications. Including:
  - Material compatibility
  - Failure mechanisms
  - Durability and Fatigue
  - Material Characterization
  - Modeling and analysis
- **Inform funding and policy decision making to advance physical hydrogen storage research, development and deployment efforts**

Frank, open and honest discussion and recommendations based on your expertise are what we are looking for!

Agenda

8:30	**Panel Presentations and Discussions: Moderator – John Gangloff (DOE - FCTO)** • **Ford Motor Company – Mike Veenstra** • **Pacific Northwest National Laboratory – David Gotthold** • **Lawrence Livermore National Laboratory – Gene Berry** • **Composite Technology Development, Inc. – Pat Hipp**
10:00	Break
10:15	**Breakout Session I – Mechanics and Materials** • Identifying constituent materials (i.e. fibers, resins, additives) that are recommended for cold / cryogenic temperatures with pressure cycling • Microstructural failure mechanisms at cold / cryogenic temperatures • Vacuum exposure on composite materials at cold / cryogenic temperatures • Durability and fatigue due to Coefficient of Thermal Expansion issues
11:15	Break
11:30	**Breakout Session II – Processing, Characterization, and Analysis** • Composite manufacturing processes suitable for cold / cryogenic applications • Material characterization methods for part verification and validation • Safety codes and standards status for cold / cryogenic temperature composites • Modeling and analysis tools for cold / cryogenic temperature composites
12:30	Adjourn

Acknowledgements

For panel session participation:

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Pat Hipp (CTD)

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David Gotthold (PNNL)

For discussions and information:

Jesse Schneider (BMW)

Thank you

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