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Cryo-Hydrogen Storage Workshop

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Crystal Gateway Marriott
Crystal City, Virginia

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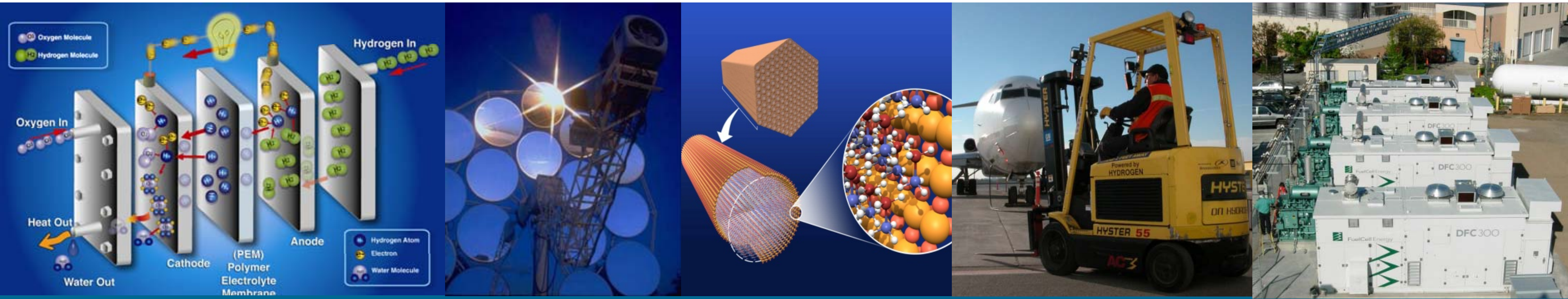
U.S. Department of Energy

Presentation Overview

- Welcome and Introductions!
- Recap of Compressed Gas Workshop (Feb. 14th)
- Introduction to cryo-compressed and cryo-sorbent storage
- Objective of Workshop
- Scope of Workshop



Key Workshop and DOE Contacts

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The Workshop Team

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Recap of cH_2 Workshop

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- Carbon Fiber
  - ORNL pursuing low cost precursors for high-strength CF
  - Multiple fibers with matched strength/modulus would allow optimization of fiber use on tanks
  - Appropriate CF packaging will reduce labor/manufacturing steps
  - QC at CF and tank manufacturers can reduce cost and weight
- Balance of Plant
  - Consider consolidation versus separate functionalities
  - Match safety factors of BOP and tank components
  - Component standards needed
- Alternative
  - Type II, hoop wrapped, tanks
  - Linerless and/or bladder lined tanks
  - Nanofiber addition to CF matrix
  - Optimization of multi-tank configurations

Why storage at cryogenic temperatures?

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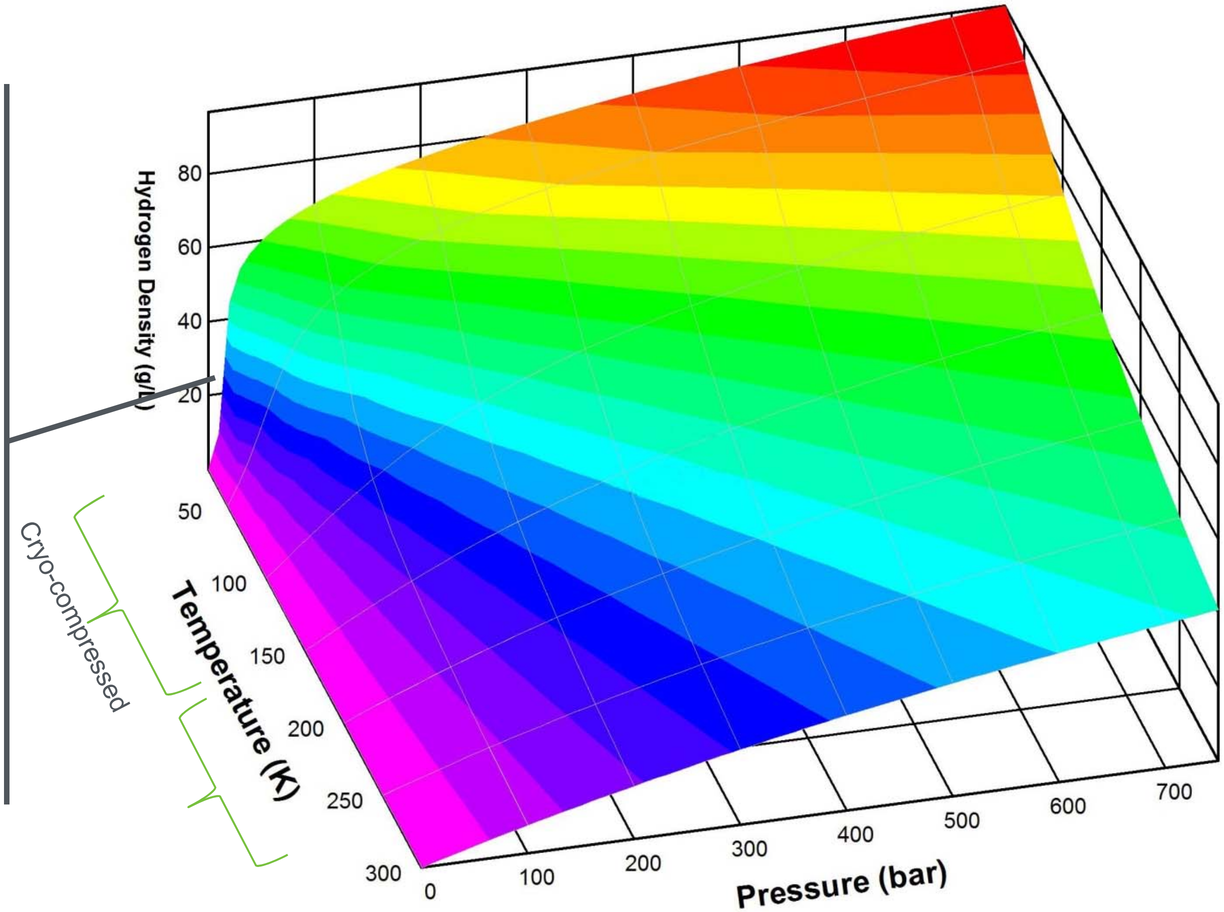
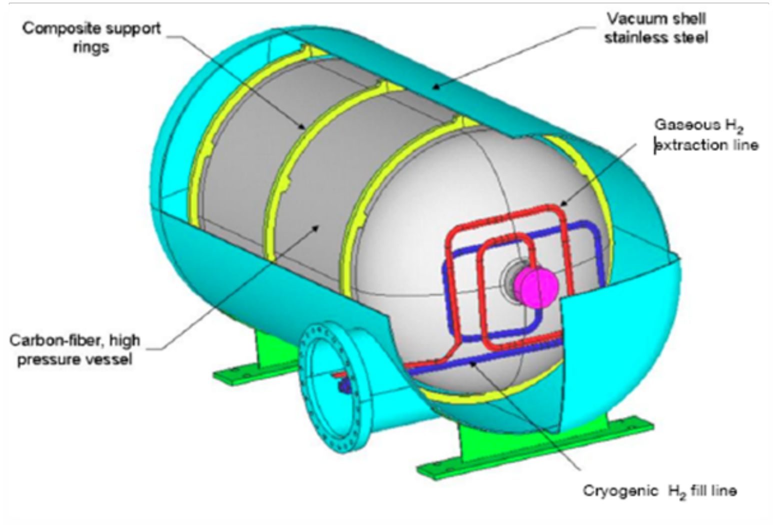
Temperature can be use along with pressure to increase density

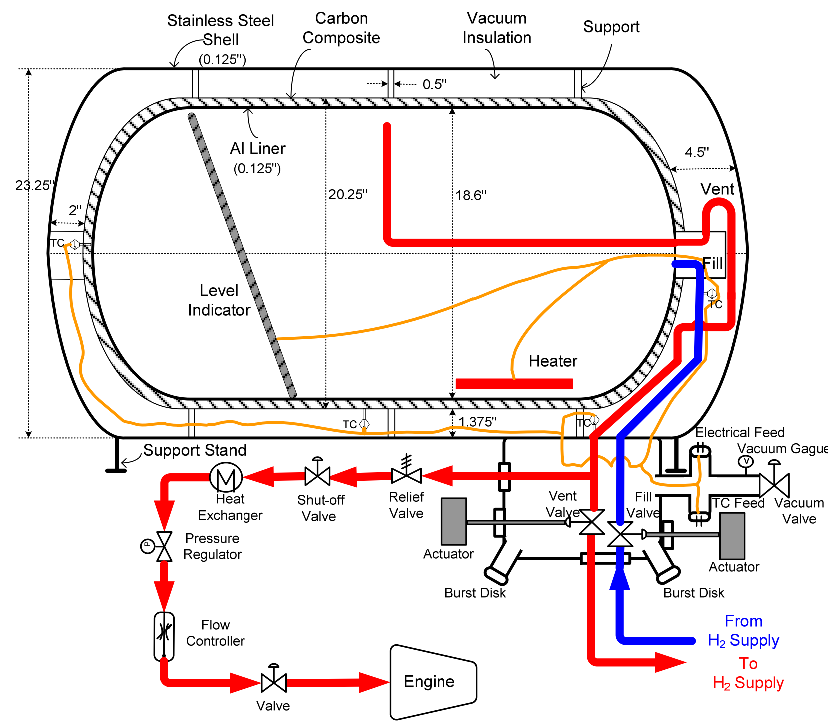
Above the critical temperature (33K), H_2 density increases rapidly with pressure.

Supercritical fluid densities greater than the liquid hydrogen density (71 g/L) are possible.



Cryo-compressed hydrogen systems

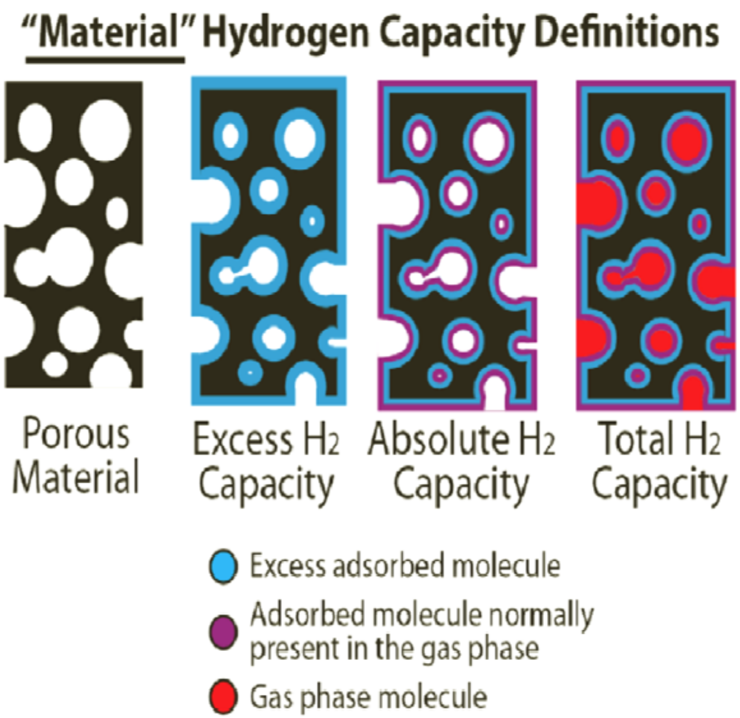




- High-pressure capable cryo-vessels
  - Double-walled vessels
  - Inner vessel: high-P Type III cylinder
  - Multi-Layer Vacuum Super Insulation (MLVSI)
  - Improved dormancy vs. liquid
  - > 40 g/L H_2 system density possible
  - > 6 wt.% is achievable

Figure sources: ANL, LLNL

- High surface area, porous materials
  - Diatomic molecule adsorbs on surface
  - Excess capacity reaches a maxima at a specific pressure, above which advantages are minimized
  - For carbon-based materials, ~1 wt% per 500 m^2/gm specific surface area



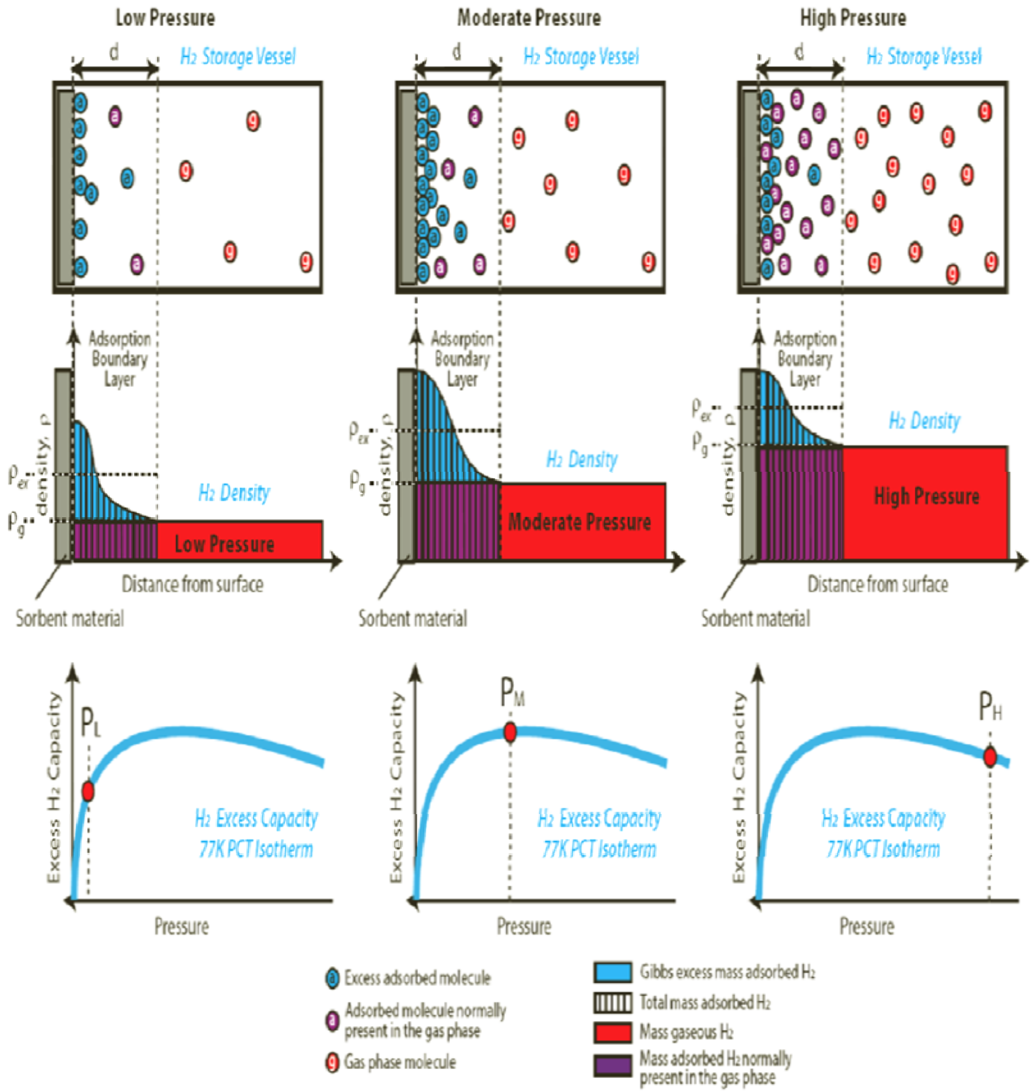
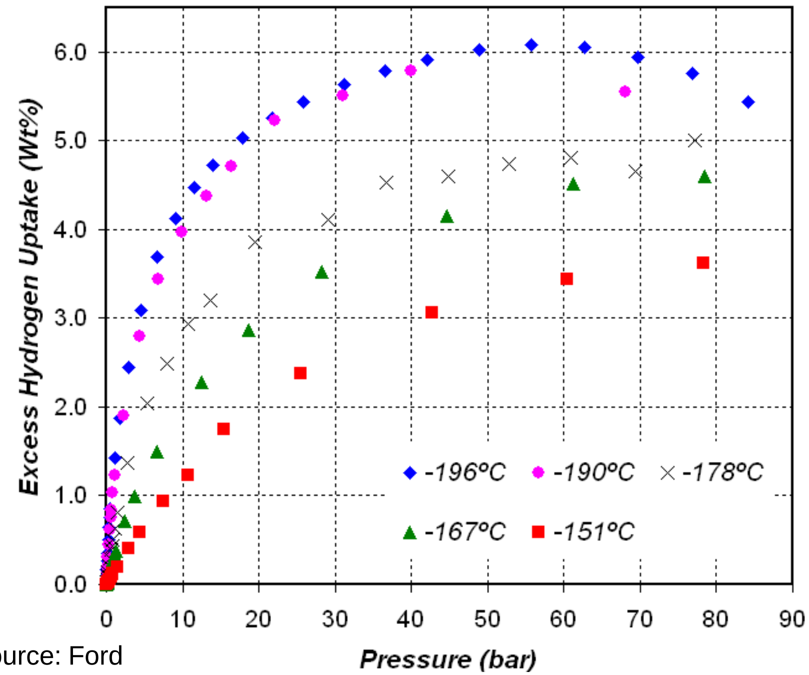


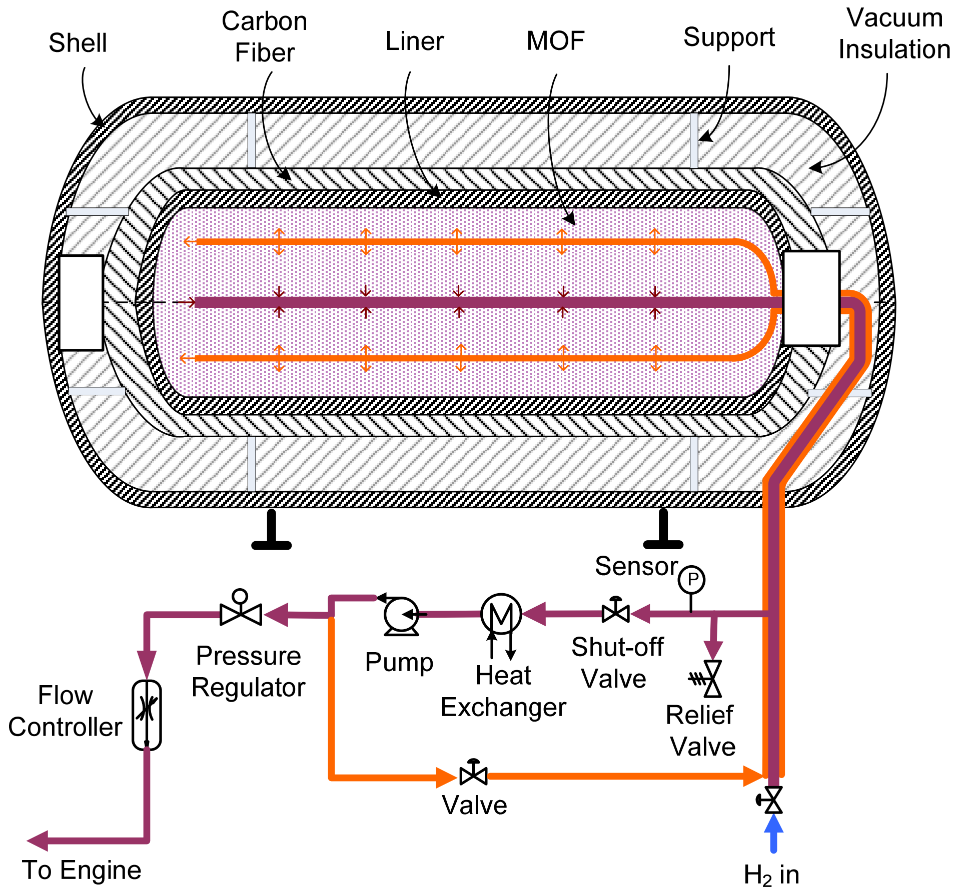
Figure sources: Karl Gross, H_2 Technology Consulting

- Adsorption is through weak physisorptive interactions
  - Van der Waals-type interactions
  - For carbon-based materials, ~4-6 kJ/mol H_2
  - Capacity drops off as temperature increases

Adsorption isotherms for MOF-5



Source: Ford



Source: Ahluwalia, ANL, DOE 2010 Hydrogen Program Annual Merit Review Proceedings, http://www.hydrogen.energy.gov/pdfs/review10/st001_ahluwalia_2010_o_web.pdf

Comparison against targets

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Performance and Cost Metric	Units	CcH2	MOF-177	2010 Targets	2015 Targets	Ultimate Targets
Usable Storage Capacity (Nominal)	kg-H_2	5.6	5.6			
Usable Storage Capacity (Maximum)	kg-H_2	6.6	5.6			
System Gravimetric Capacity	wt%	5.5-9.2	4.1	4.5	5.5	7.5
System Volumetric Capacity	kg-H_2/m^3	41.8-44.7	34.1	28	40	70
Storage System Cost	$/kWh	12	18	4	2	TBD
Fuel Cost	$/gge	4.80	4.6	2-3	2-3	2-3
Cycle Life (1/4 tank to Full)	Cycles	5500	5500	1000	1500	1500
Minimum Delivery Pressure, FC/ICE	atm	3-4	4	4/35	3/35	3/35
System Fill Rate	kg-H_2/min	1.5-2	1.5-2	1.2	1.5	2.0
Minimum Dormancy (Full Tank)	W-d	4-30	2.8			
H_2 Loss Rate (Maximum)	g/h/kg-H_2	0.2-1.6	0.9	0.1	0.05	0.05
WTT Efficiency	%	41.1	41.1	60	60	60
GHG Emissions (CO_2 eq)	kg/kg-H_2	19.7	19.7			
Ownership Cost	$/mile	0.12	0.15			

Source: Ahluwalia, ANL, DOE 2010 Hydrogen Program Annual Merit Review Proceedings, http://www.hydrogen.energy.gov/pdfs/review10/st001_ahluwalia_2010_o_web.pdf

Commonalities and Differences

- Cryogenic operation
  - Cryo-compressed: 20 - $^{+}$100 K
  - Cryo-sorbents: ~77 - $^{+}$100 K
- Heavily insulated pressure vessel
  - Cryo-compressed: current designs use MLVSI
  - Cryo-sorbents: may use MLVSI but other options being investigated
- Inner pressure vessel
  - Cryo-compressed: may operate up to 350 or even 700 bar
  - Cryo-sorbents: operation may be <100 but could be several hundred bar
- Need for heat exchange
  - Cryo-compressed: may need to evaporate liquid, warm exiting gas
  - Cryo-sorbents: heat of adsorption needs to be removed/added for operation
- Phase state
  - Cryo-compressed: potential for liquid, supercritical and gaseous states
  - Cryo-sorbent: most likely only gaseous and adsorbed states

Workshop Objectives

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- Identify R&D needs to validate these technologies for automotive applications, e.g.,
  - dormancy issues
  - robustness of insulation systems for vehicles
  - use of carbon fiber composites in high frequency pressure cycle application at cryogenic temperatures
  - procedures and standards to validate designs
  - low-cost manufacturability of the systems
  - understanding of potential phase changes during operation of cryo-compressed systems
- Identify common needs for both areas where efforts may benefit both
- Identify unique needs for each

Scope of Workshop

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- In-Scope:
  - the “on-board” system hardware
  - materials of construction and design
  - testing and validation of components and systems
  - on-board operation
    - understanding affect of drive cycles/use patterns
    - effect of initial conditions on refill
    - potential changes in state that may occur
- Out-of-scope:
  - off-board systems and processing, e.g.,
    - compression, storage and dispensing
  - overall efficiency
    - energy penalty for liquefaction, etc.

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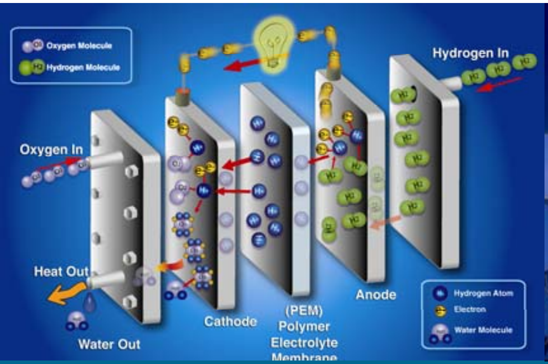
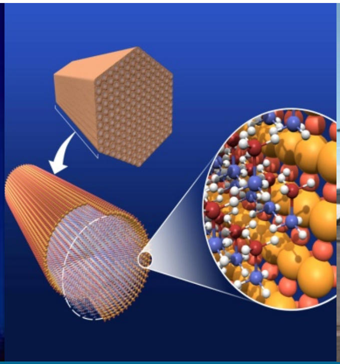
Thank you for your participation!





Breakout Topics

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1. What are the key R&D needed to validate the technologies

2. What is needed to develop codes and standards for these technologies

3. What are the balance of plant needs