Overview of Storage Development
DOE Hydrogen Program

Safe, efficient and cost-effective storage is a key element in the development of hydrogen as an energy carrier

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Hydrogen storage requires something more than a can or a bucket

Hydrogen has the highest mass energy density of any fuel:

120 MJ/kg (LHV) 144 MJ/kg (HHV)

however

At ambient conditions (300 K, 1 atm.):

the energy content of 1 liter of H_2 is only 10.7 kJ,

three orders of magnitude too low for practical applications.

Issues:

1. What are the options available for storage?
2. What are the theoretical limits to storage density and how close can we come?
3. How do we organize a development program to achieve adequate stored energy in an efficient, safe and cost-effective manner?

Mass energy densities for various fuels

Increasing molecular wt.

Fuel	Hydrogen weight fraction	Ambient state	Mass energy density (MJ/kg)
Hydrogen	1	Gas	120
Methane	0.25	Gas	50 (43)[2]
Ethane	0.2	Gas	47.5
Propane	0.18	Gas (liquid)[1]	46.4
Gasoline	0.16	Liquid	44.4
Ethanol	0.13	Liquid	26.8
Methanol	0.12	Liquid	19.9

(1) A gas at room temperature, but normally stored as a liquid at moderate pressure.
(2)The larger values are for pure methane. The values in parantheses are for a "typical" Natural Gas.

Maximum energy density is achieved in liquid state

Fuel	Hydrogen weight fraction	Ambient state	Liquid volumetric energy density (MJ/liter)	Hydrogen volumetric energy density in liquid (MJ/liter)
Hydrogen	1	Gas	8.4 – 10.4[3]	8.4 – 10.4[3]
Methane	0.25	Gas	21 (17.8)[2]	12.6 (10.8)[2]
Ethane	0.2	Gas	23.7	12
Propane	0.18	Gas (liquid)[1]	22.8	10.6
Gasoline	0.16	Liquid	31.1	13.2
Ethanol	0.13	Liquid	21.2	12.3
Methanol	0.12	Liquid	15.8	11.9

(1)A gas at room temperature, but normally stored as a liquid at moderate pressure.
(2)The larger values are for pure methane. The values in parantheses are for a "typical" Natural Gas.
(3)The higher value refers to hydrogen density at the triple point.

Hydrogen energy content in liquid fuels

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Hydrogen density is nearly the same in all fuels.
This narrow range suggests a natural benchmark for comparison of storage performance.

Maximum storage densities (w/o system)

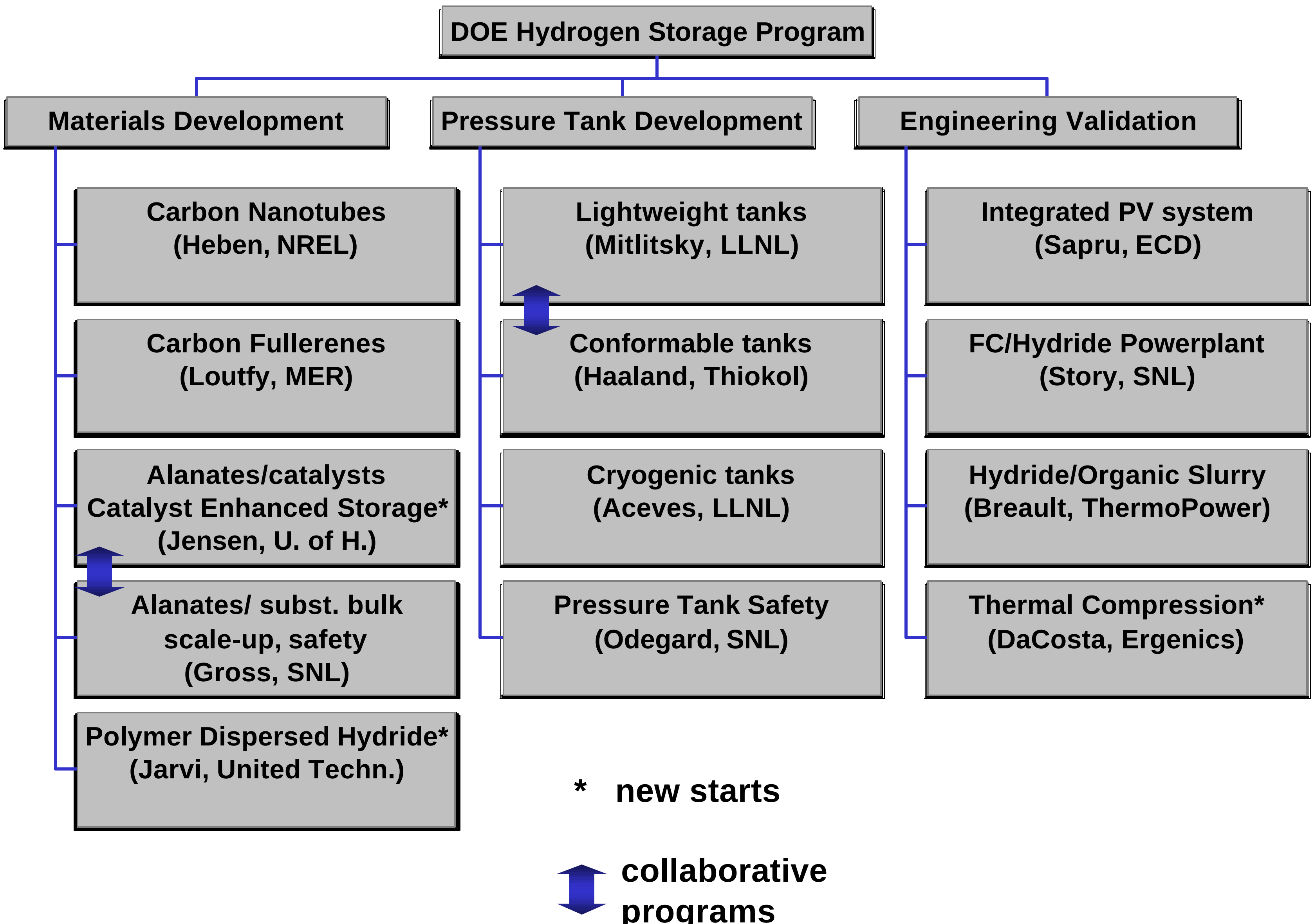
		Energy Density MJ/liter	
• High pressure gas			
– ambient temperature		3600 psi: **2.0**	5000 psi: **2.75**
– cryogenic system		150 K: **3.5**	20 K: **8.4**
• Liquid hydrogen		**8.4**	
• Reversible storage media			
– carbon structures			
• nanotubes		**?**	
• fullerenes		**?**	
– hydrides			
• intermetallics		**10.8 - 12.0**	
• alanates		**8.25**	
– composite materials		**?**	
• Chemical methods	Eff.	gasoline	methanol
– liquid fuel + reformer	50%:	**6.6**	**5.9**
	75%:	**9.9**	**8.9**
– off-board reprocessing		**?**	

Programmatic guidelines

- A balanced program between scientific discovery and engineering validation is needed.
  - Portion of program invested in high risk approaches.
  - Collaboration with industry at all levels.
  - International partnerships beneficial.
  - Leverage off other programs.

- Program should not downselect technologies too early
  - Options should be fully explored.
  - Different technologies suited for different applications.

- Realistic goals should be set as metrics for progress.
  - Evaluate goals on a continuing basis
  - continue to refine roadmap


DOE Hydrogen Storage Program
Materials Development
Pressure Tank Development
Engineering Validation
Carbon Nanotubes (Heben, NREL)
Carbon Fullerenes (Loutfy, MER)
Alanates/catalysts Catalyst Enhanced Storage* (Jensen, U. of H.)
Alanates/ subst. bulk scale-up, safety (Gross, SNL)
Polymer Dispersed Hydride* (Jarvi, United Techn.)
Lightweight tanks (Mitlitsky, LLNL)
Conformable tanks (Haaland, Thiokol)
Cryogenic tanks (Aceves, LLNL)
Pressure Tank Safety (Odegard, SNL)
Integrated PV system (Sapru, ECD)
FC/Hydride Powerplant (Story, SNL)
Hydride/Organic Slurry (Breault, ThermoPower)
Thermal Compression* (DaCosta, Ergenics)
* new starts
collaborative programs

Materials Development

- Carbon nanotubes — M. Heben, NREL
  - near-term goal: ~6 wt.%
  - synthesis, processing, hydrogen absorption/desorption
- Carbon fullerenes — R. Loutfy, MER
  - feasibility of fullerene-based storage
- Alanate hydrides — C. Jensen, Univ. of Hawaii
  - $NaAlH_4$: 5.5 wt.% hydrogen capacity
  - catalysts, properties
- Hydride development — K. Gross, SNL
  - near-term goal: 5.5 wt.% at <100 C ($NaAlH_4$)
  - bulk synthesis, scaled-up beds, characterization, safety studies
- Catalytically enhanced storage — C. Jensen, Univ. of Hawaii
  - new start
- Polymer dispersed metal hydrides — T. Jarvi, United Technologies
  - new start

Pressure Tank Development

- Lightweight tanks — F. Mitlitisky, LLNL
  - goal: >10 wt.% 5000 psi
- Conformable tanks — R. Golde, Thiokol Propulsion Co.
  - high pressure tanks with improved packing efficiency
- cryogenic hydrogen vessels — S. Aceves, LLNL
  - design and testing for improved volume density
- Composite tank testing — B. Odegard, SNL
  - comparison of high pressure hydrogen tank failure to other fuels. CNG, gasoline, methanol.

Engineering Validation

- PV/electrolysis/metal hydride — K. Sapru, ECD
  - modeling and integration of storage with renewable energy sources
- Metal hydride/ organic slurry — R. Breault, Thermo Power
  - chemical hydride for PEMFC vehicles
  - hydrogen transmission and storage
- Fuelcell/hydride powerplant — G. C. Story, SNL
  - for underground mine and tunneling locomotive
- Thermal hydrogen compression — D. DaCosta, Ergenics, Inc.
  - new start

Other hydrogen storage programs (US)

- DOE/OTT
  - Fuels for Fuel Cells Program (P. Devlin)

    Parallel development of fuel processor and onboard H storage.

- DOE/OIT
  - Low cost hydrides for mine vehicles (SRTC)

    Part of Mining Industry of the Future initiative.

- IEA
  - Task 12 will be completed Oct. 2000
  - New task being formed: Advanced Solid and Liquid State Hydrogen Storage Materials (G. Sandrock)

- Industry Projects

Other hydrogen storage programs (non US)

- Canadian Projects
  - Alanates (A. Zaluska, McGill Univ.)
  - Nanocrystalline Mg-based hydrides (Hydro-Quebec)
  - Carbon adsorption (IRH)

- European Projects
  - liquid hydrogen storage (BMW)
  - refueling station (BMW)

- WENET (Japan)
  - Metal-H complex ions (S. Suda, Kogakuin Univ.)
  - others

Some highlights from this year

- Continuing progress in nanotubes
  - high purity synthesis and processing methods.
  - > 6 wt.% appears feasible.

- Important progress achieved on alanates
  - 5.5 wt.% at low temperatures appears feasible.

- Continued improvement in lightweight and conformable tanks
  - more efficient packing of high pressure tanks

- integration of storage with applications
  - PV system
  - mine vehicle

- Three new starts
  - catalyst enhanced storage
  - polymer dispersed hydride
  - thermal hydrogen compression