Hydrogen Storage (I)

The key to an efficient energy storage

Why Hydrogen?

- High gravimetric energy density
- Clean
- Abundant, the most numerous element in the universe!
- Therefore affordable, once made

Why Hydrogen Storage?

What are the problems?

- Mediocre volumetric energy density
- Do we have a hydrogen mine?
- Gaseous under most circumstances

Typical H Storage Means

- High pressure
- Cryogenic
- Chemical Hydrides
- Metal Hydrides
- Physical Sorption

Basic H Storage Requirements

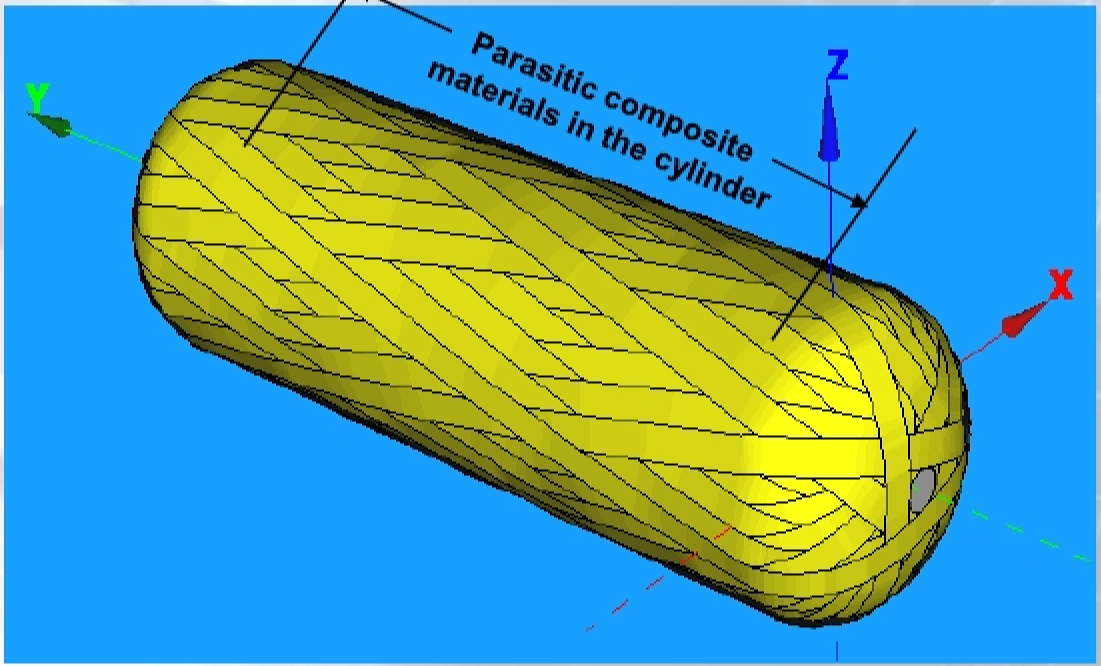
- H mass percentage (~ 6%-wt at least)
- Volumetric density (~0.15 kg/liter at least)
- Low cost
- Ease of recharge or regeneration
- Fast release, fast recharge
- Environmentally sound

High Pressure H Storage

- 3000, 5000, 7000 psi, maybe up to 10000
- Gravimetric density up to 3%-wt H
- Volumetric density ~ 0.06 kg/liter
- Cost high for bottles > 7000 psi
- Environmentally sound
- But how about safety? it's like a bomb!
- Relative ease of refueling though taking time
- Composite construction with metal liner

High Pressure H Storage

Construction



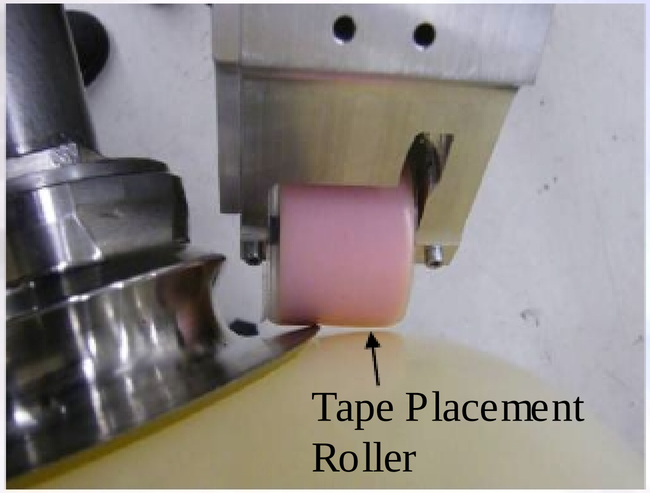
64.9 kg composite usage in the 1st hybrid vessel vs. 76.0 kg in the baseline tank (FW alone)

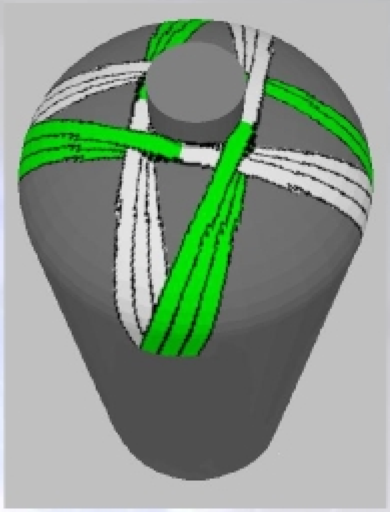
- The end-user H_2 storage system weight efficiency = 1.67 kWh/kg vs. 1.50 kWh/kg in the system with the baseline tank
- The end-user H_2 storage system cost efficiency:
  - $11/lb CF Baseline $23.45 Fully Integrated $21.91 Fully Separate $21.75
  - $6/lb CF Baseline $18.74 Fully Integrated $17.79 Fully Separate $17.63

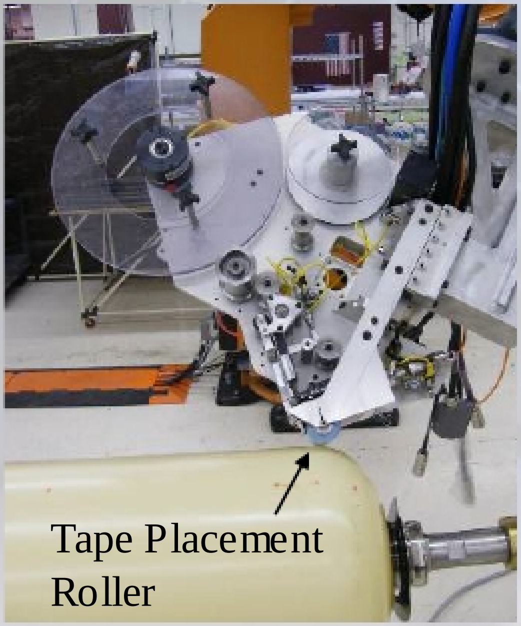
QUANTUM TECHNOLOGIES BOEING Pacific Northwest National Laboratory Lawrence Livermore National Laboratory

Approach: Advanced Fiber Placement- Boeing

- **Advanced Fiber Placement:** A CNC process that adds multiple strips of composite material on demand.
  - Maximum weight efficiency - places material where needed
  - Fiber steering allows greater design flexibility
  - Process is scalable to hydrogen storage tanks
  - Optimize plies on the dome sections with minimal limitation on fiber angle
  - Reinforce dome without adding weight to cylinder

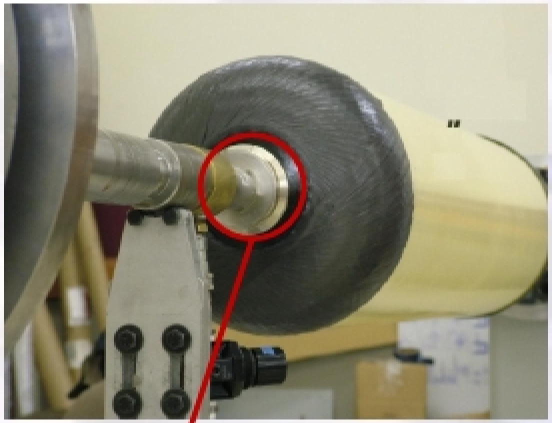






Strength

- Tank preparation and validation test



Representative smallest polar opening that the AFP process can currently make

The localized reinforcement protected the dome regions very well

- Static Burst Result: 23420 PSI > 22804 PSI, EN standard (New European Standard superseding EIHP)
- 64.9 kg composite usage in the 1st hybrid vessel vs. 76 kg in the baseline tank (FW alone)

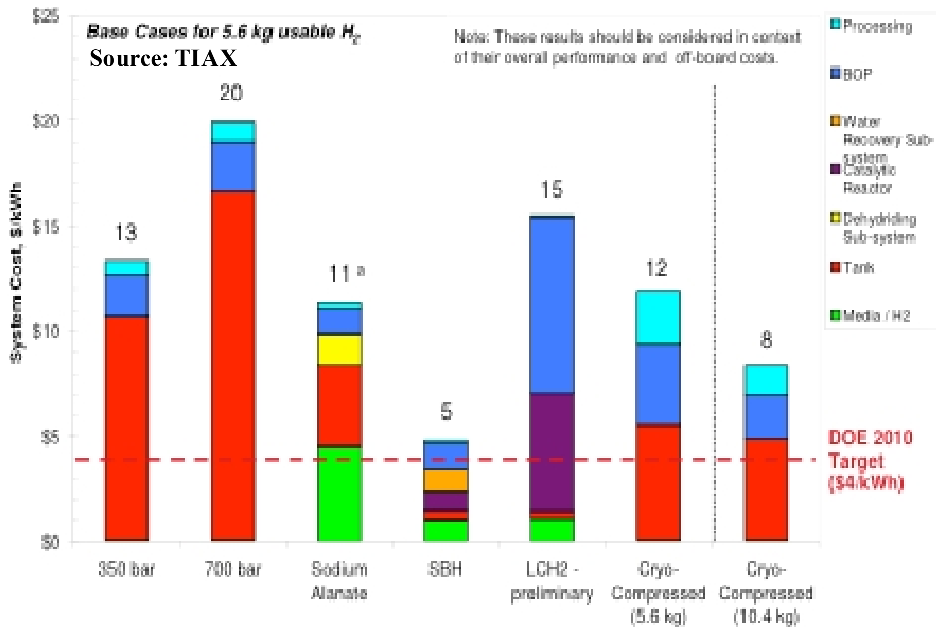
11.1 kg (14.6%) Savings!

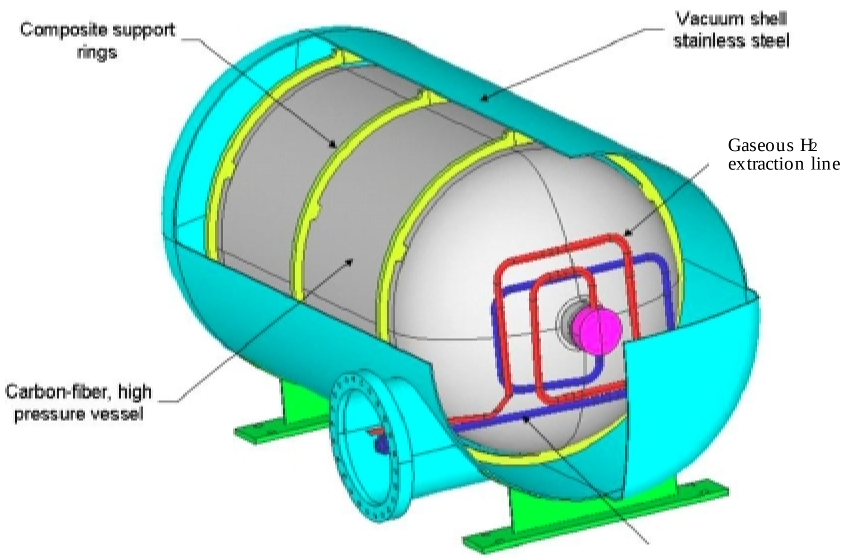
QUANTUM TECHNOLOGIES BOEING Pacific Northwest NATIONAL LABORATORY Lawrence Livermore National Laboratory

Cryogenic H Storage

- **-252.87°C !**
- Very energy consuming to cool
- Energy consuming to maintain
- Gravimetric density up to 8~9%
- Volumetric density ~ 0.08 kg/liter
- Cost high
- Environmentally sound and safe
- Relative ease of refueling
- Vacuum Dewar

Relevance: High density cryogenic hydrogen enables compact, lightweight, and cost effective storage



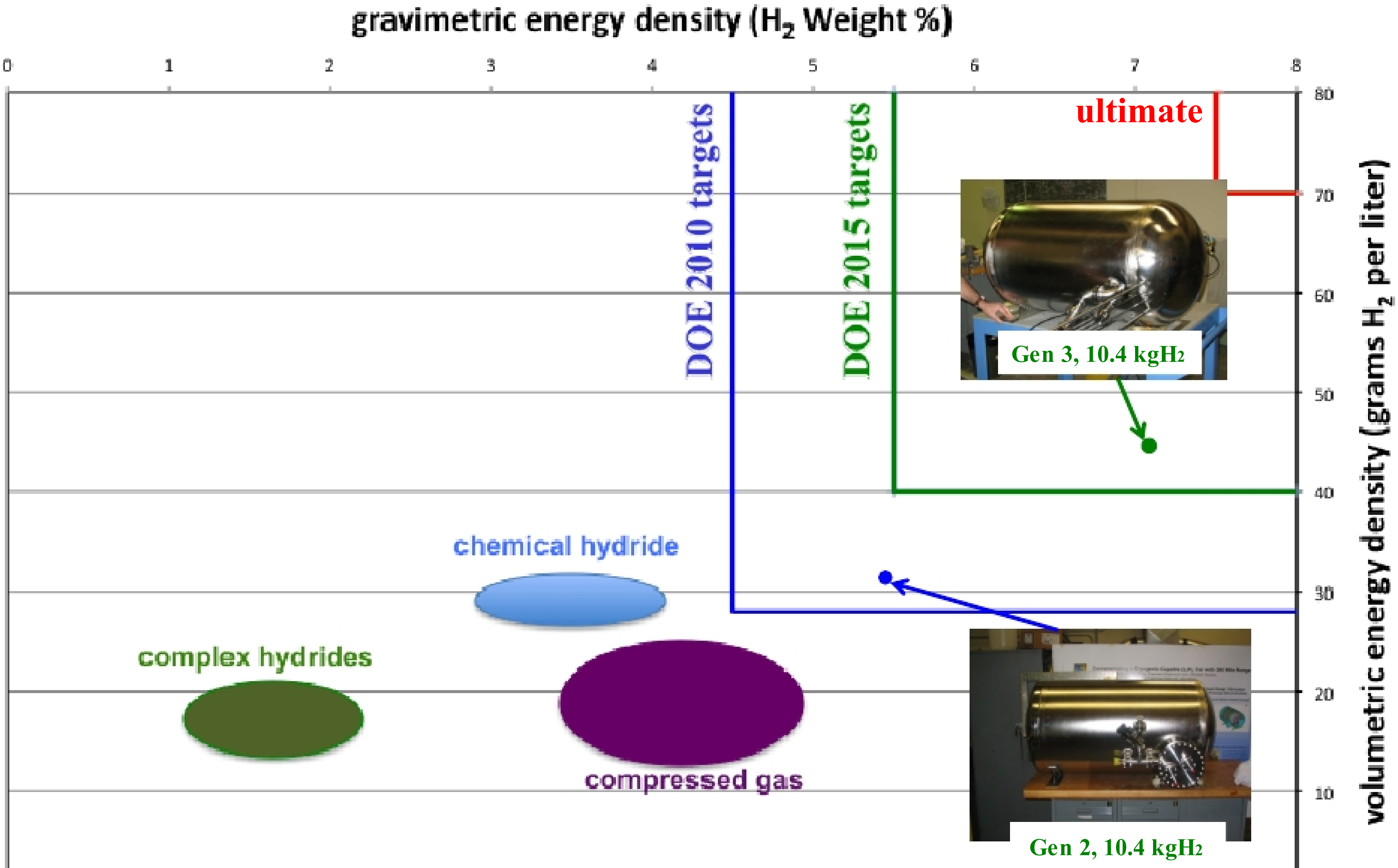


Hydrogen annual merit review, LLNL, June 8, 2010, p. 3

- *Cost effective:* **Cryogenic vessels use 2-4x less carbon fiber, reducing costs sharply at higher capacity**

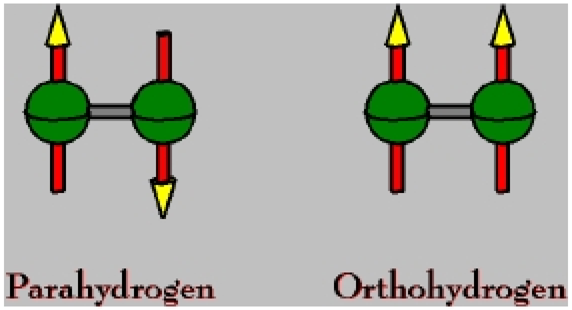
- *Compact:* **235 L system holds 151 L fuel (10.3-10.7 kg H_2)**

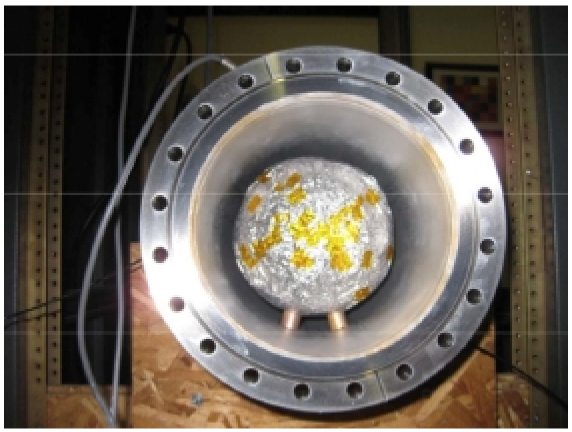
Relevance: Cryogenic pressure vessels can *exceed* 2015 H_2 storage targets and approach *ultimate*



Hydrogen annual merit review, LLNL, June 8, 2010, p. 4

Approach: reduce/eliminate H_2 venting losses by researching vacuum stability, insulation, and para-ortho conversion

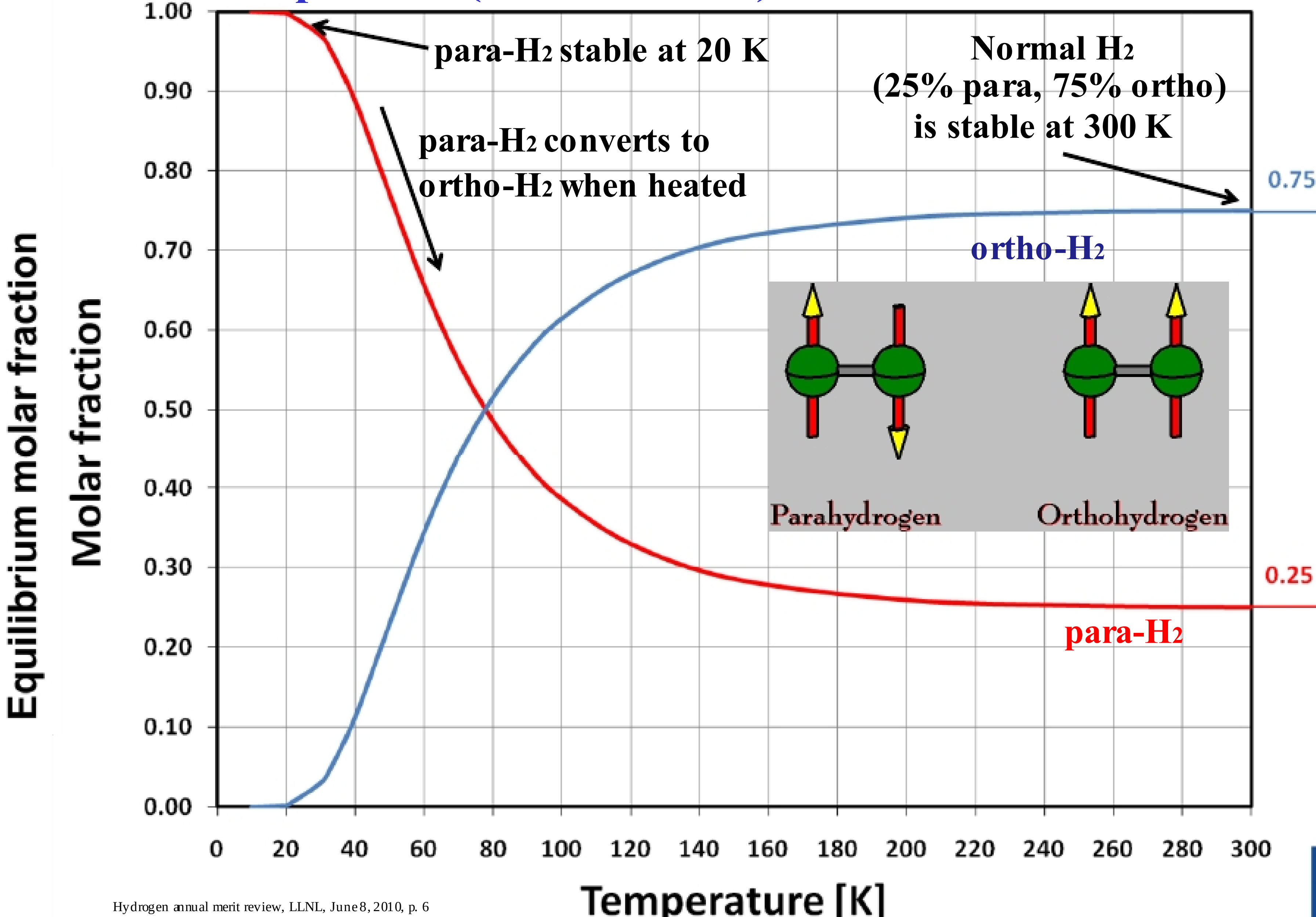




Hydrogen annual merit review, LLNL, June 8, 2010, p. 5

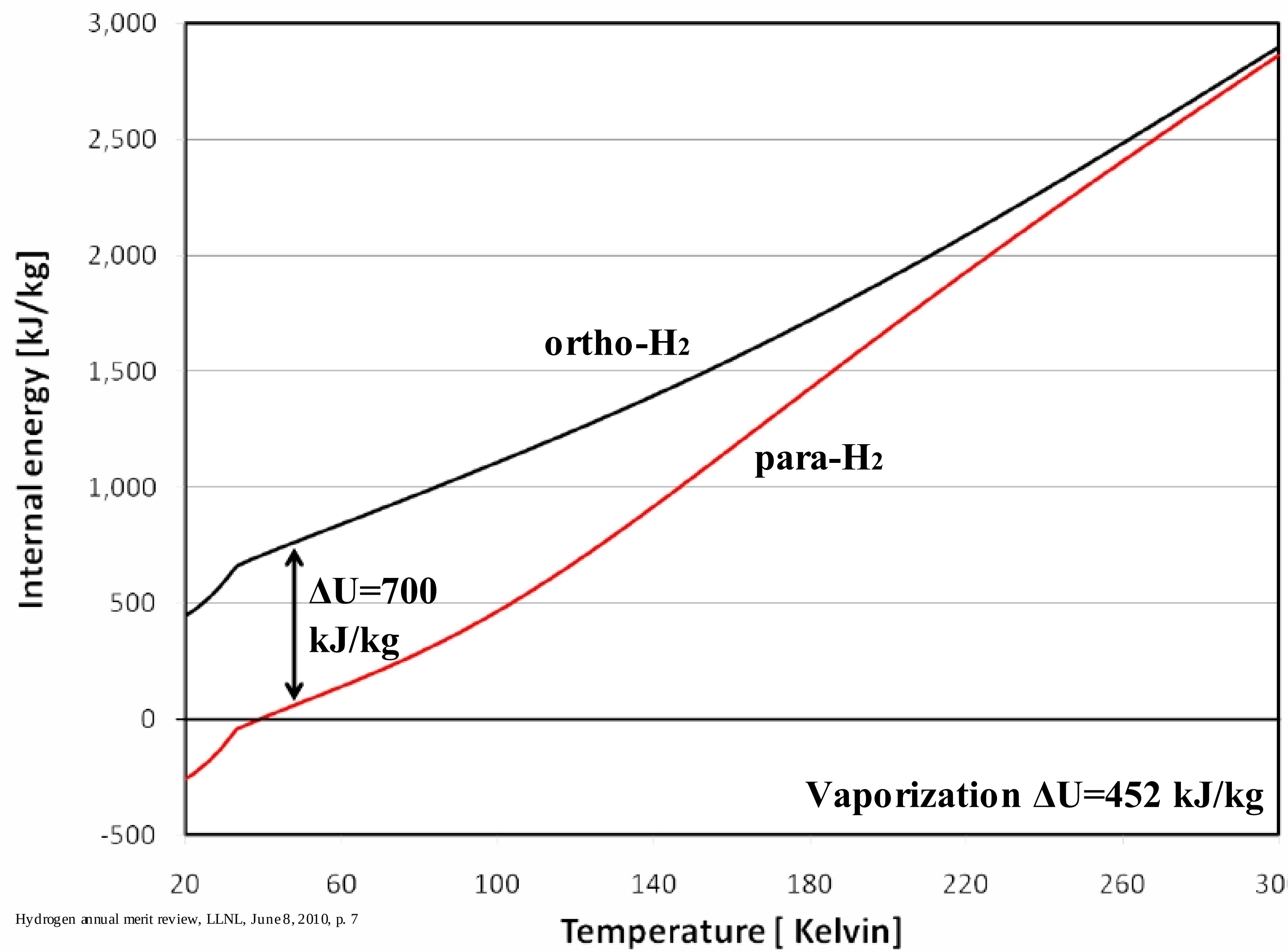
- ***Determine para-ortho effect on pressurization and venting losses***
- ***Directly measure para-ortho populations***
- ***Determine vessel heat transfer mechanism (radiation vs. conduction)***
- ***Evaluate vacuum stability by measuring pressure vessel outgassing***
- ***Test ultra thin insulation for improved vessel volume performance***
- ***Improve vessel design based on experimental results***

Hydrogen has two nuclear spin states: para-H_2 (stable at 20 K) and ortho-H_2



Hydrogen annual merit review, LLNL, June 8, 2010, p. 6

Para-ortho conversion absorbs energy & increases dormancy (equivalent to a second evaporation)



Hydrogen annual merit review, LLNL, June 8, 2010, p. 7

Chemical Hydrides

- Examples: NH_3, N_2H_4, B_2H_6, $NaBH_4$…
- Gravimetric density up to 20%-wt ($LiBH_4$)
- Volumetric density up to 0.2 kg/liter
- Many are safe and sound, but not always
- Cost high except NH_3 and hydrocarbons
- Regeneration has been problematic
- Utilization is less straight forwards than H_2.

Chemical Hydrides: Examples

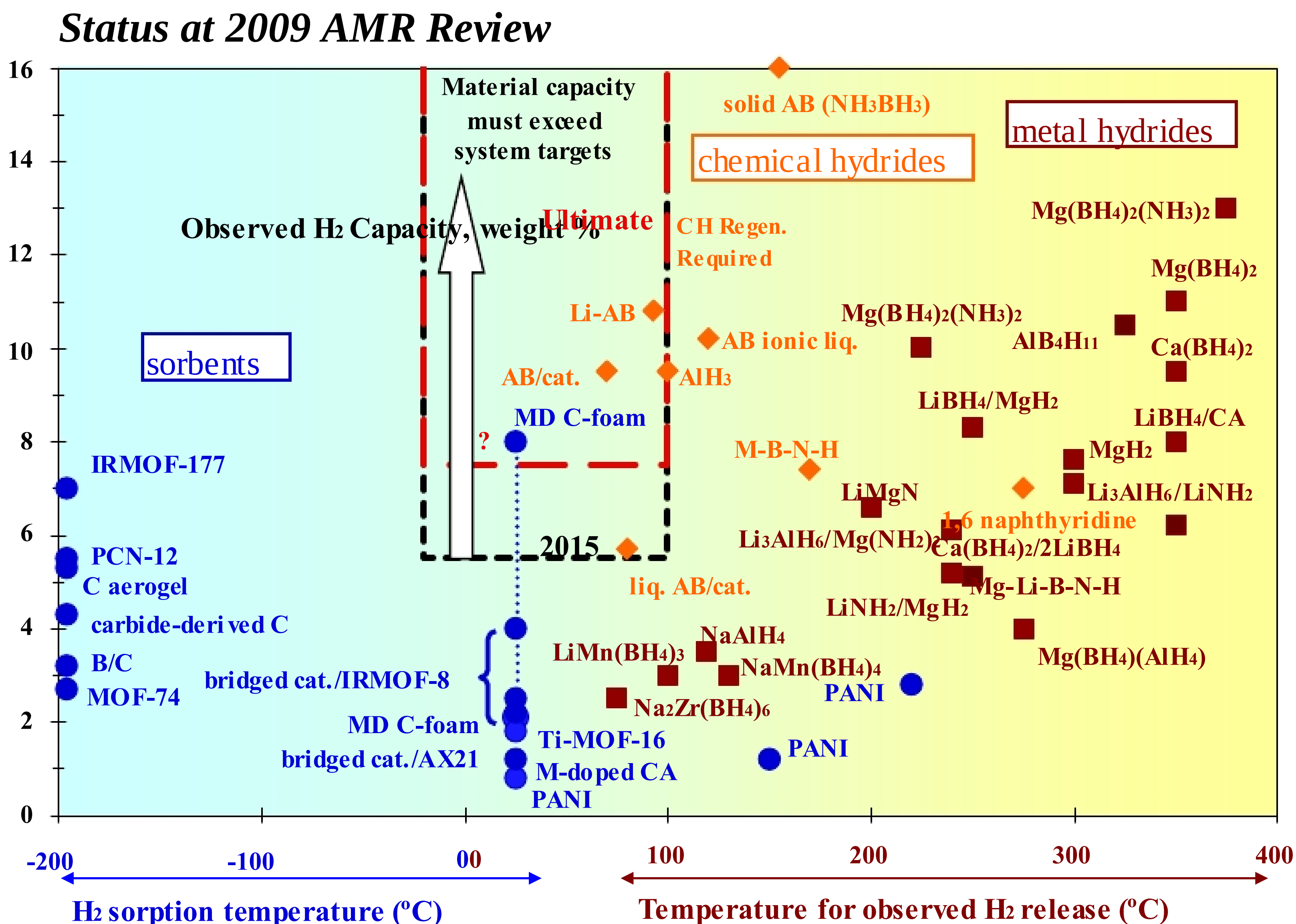
- Hydrocarbons: CH_4, C_2H_6… (complicated reforming→ H_2, dirty byproducts)
- NH_3 (Ammonia) N_2H_4 (hydrazine) (toxic and … it stinks)
- B_2H_6 (diborane) (highly toxic)
- Borohydrides ($LiBH_4$, $NaBH_4$…) (relatively safe)
- Alanates ($NaAlH_4$…) (highly reactive)

Chemical Hydrides: Borohydrides

- $LiBH_4$, very high H content, but not soluble
- $NaBH_4$, 12%-wt H dry
- $NaBH_4$, can be made to 30% H_2O solution
- $NaBH_4$, 6%-wt H in 35% H_2O stabilized with ammonium hydroxide
- Safe, low toxicity
- Still a challenge in regeneration

2009 Progress & Accomplishments

U.S. DEPARTMENT OF ENERGY



2010 Progress & Accomplishments

U.S. DEPARTMENT OF ENERGY

Open symbols denote new materials since 2009 AMR