A Brief Overview of Hydrogen Storage Issues and Needs

George Thomas and Sunita Satyapal

Joint Tech Team Meeting
Delivery, Storage and Fuels Pathway Tech Teams
May 8-9, 2007

Storage Tech Team Roles & Responsibilities

Automotive Industry

Scott Jorgensen (GM) – Industry Co-Chair

Mei Cai (GM) – Materials Properties Modifications

Don Siegel (Ford) – Basic Science Liaison (Theory/Modeling)

Andrea Sudik (Ford) – High Surface Materials

Mark Mehall (Ford) –Triad Representative

Tarek Abdel-Baset (DCX) - Fuel Cell Team Liaison (Water/thermal management)

Scott Freeman (DCX) – BPG Representative

Fuel Industry

Farshad Bavarian (Chevron) – Fuel Industry Tech Team Lead + SC&S Liaison

Paul Meier (ConocoPhillips) – Delivery Team Liaison

Alexei Gabrielov (Shell) – International Activities

Joe Kaufman (ConocoPhillips) – Fuel Operating Group Representative

Silvia Boschetto (BP) – BP Hydrogen Technology Manager- Systems/Balance of Plant Issues

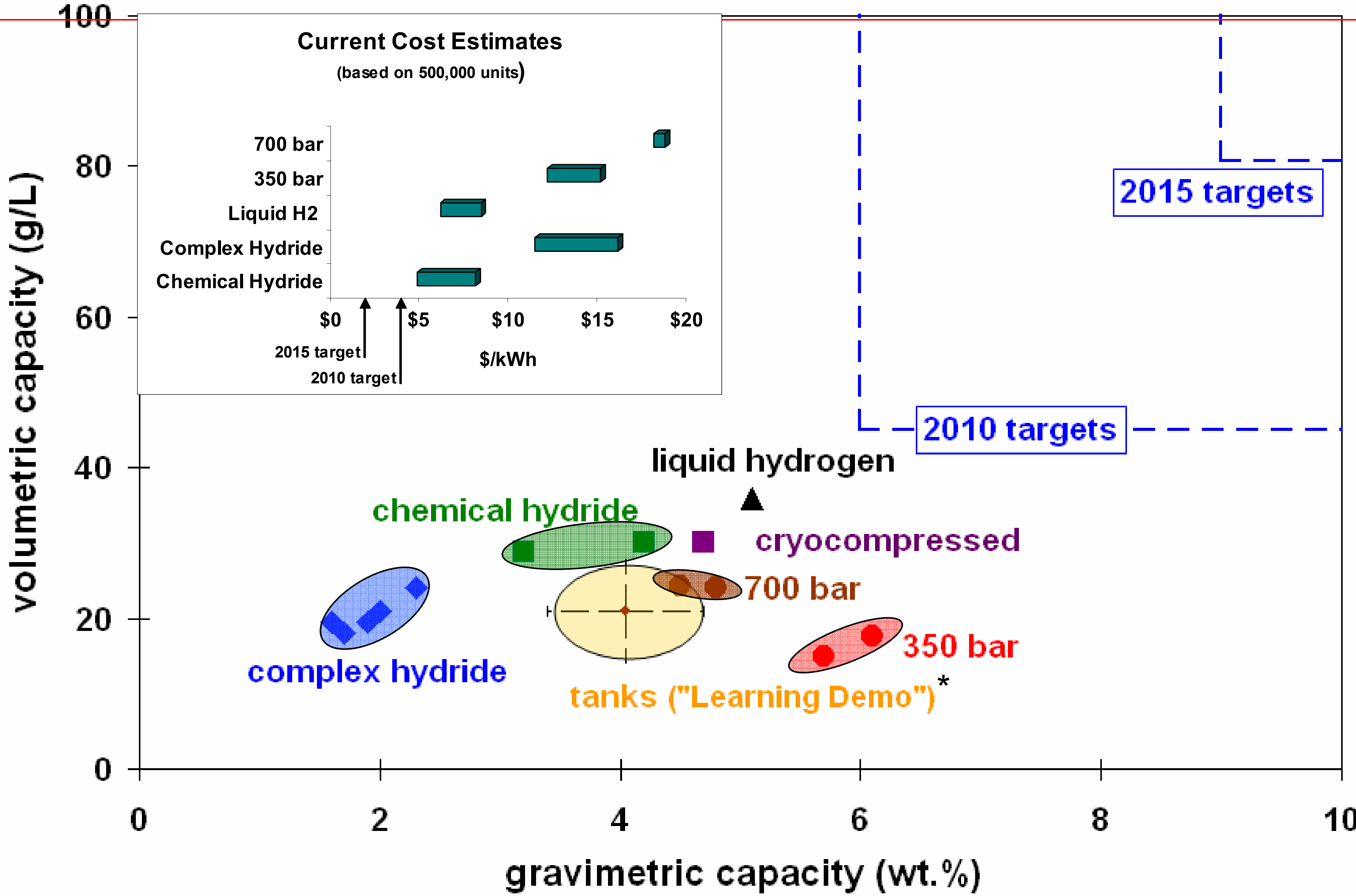
Government

Sunita Satyapal (DOE) – Government Co-Chair

Walt Podolski (ANL) – Fuel Cell Team Liaison (Contaminant Specifications, SAE Liaison)

George Thomas (SNL) – Basic Materials & Materials Testing

Current Status vs. Targets



Costs exclude regeneration/processing.

Data based on R&D projections and independent analysis (FY05-FY06). To be periodically updated. * Learning Demo data shows range across 63 vehicles

Summary of Current Assessment

Challenges are technology specific: Pros and Cons for each
Progress is being made but too early to eliminate whole areas

Key 2010 Targets:	High P Tanks	Chemical Hydrides	Metal Hydrides	Carbon/ Sorbents
Volume (1.5 kWh/L)	H	M	M	M/H
Weight (2.0 kWh/kg)	M	M	M/H	M
Cost ($4/kWh)	M/H	M/H[1]	M/H	M/H
Refueling Time (3 min, for 5 kg)	L[2]	L	M/H	M
Discharge Kinetics (0.02 g/s/kW)	L	M	M	L/M
Durability (1000 cycles)	L	M	M	M

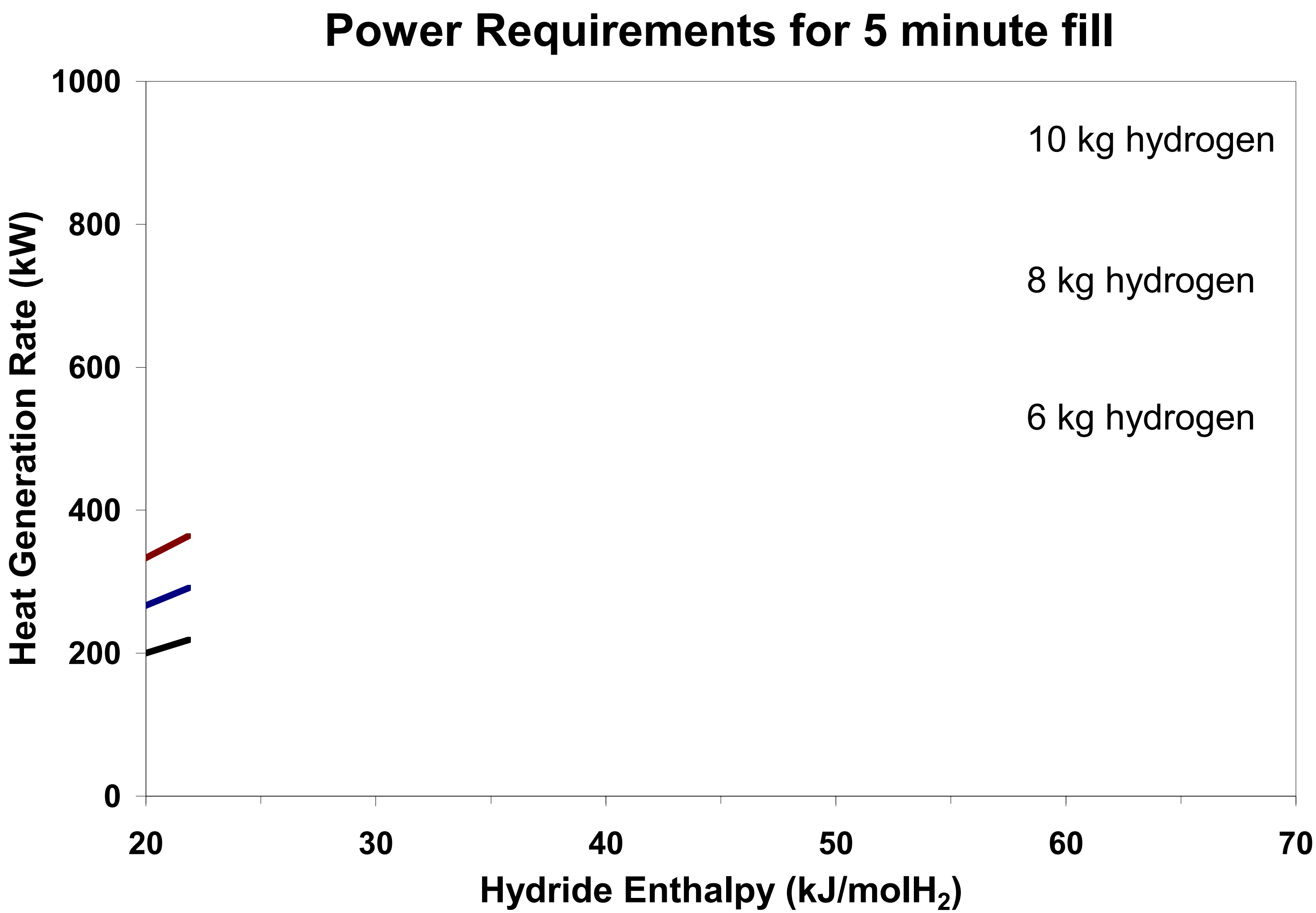
Thermal Mgmt: Key Issues for MH (CH, C) (applies to Refueling Time, Discharge Kinetics, Durability)

H = High (Significant challenge) M/H = Medium/High M = Medium L = Low (minimal challenge)

For CH, MH and S- assessment based on potential to meet targets, though systems not yet demonstrated in most cases.
[1]For CH: Storage system may meet cost but fuel cost of $2-$3/kg is challenge for CH regeneration.
[2] Assumes communication protocols

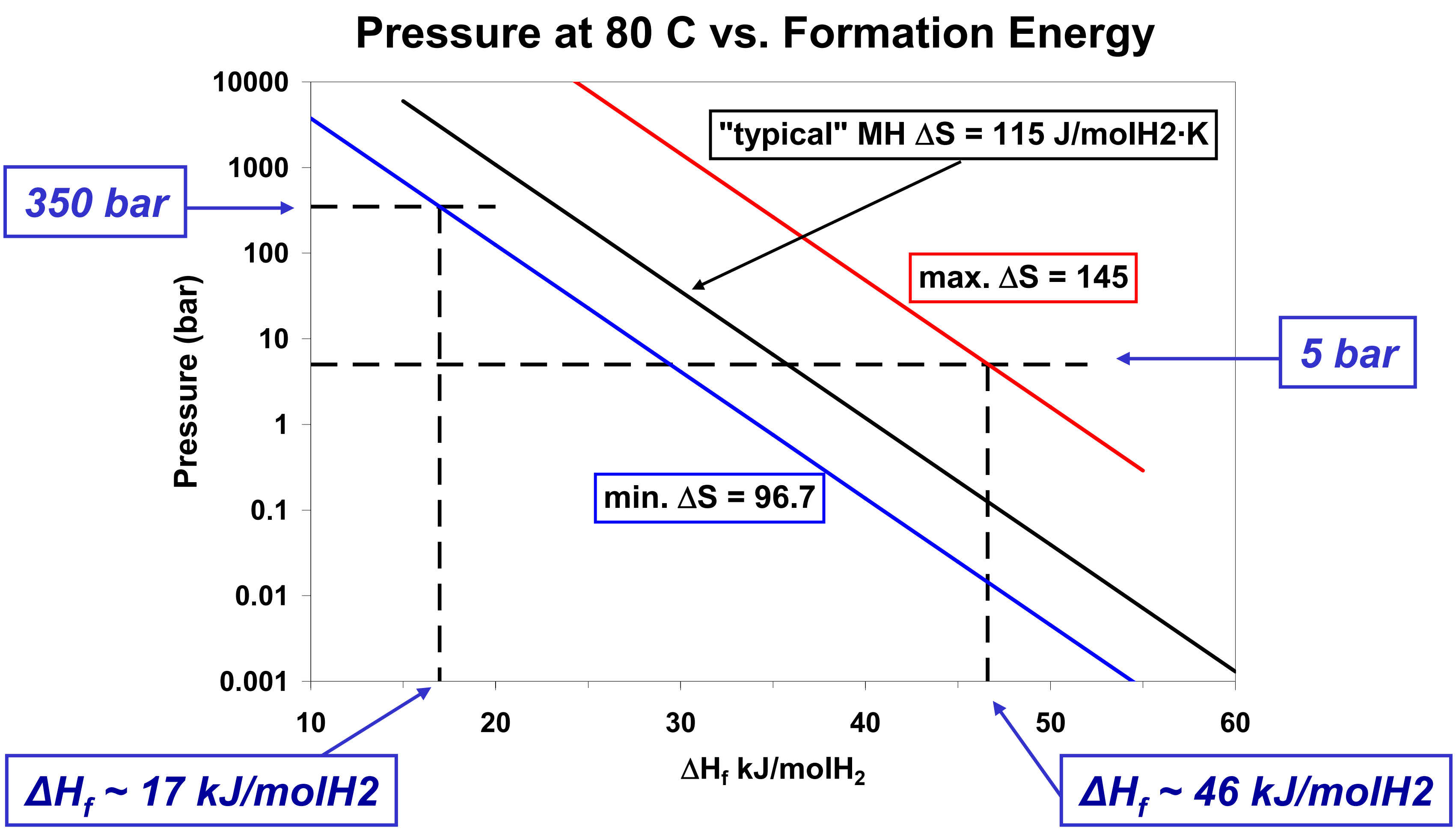
Metal hydride ΔH$_f$ impacts refueling

higher ΔH$_f$ increases cooling requirements



ΔH_f, ΔS define hydride operating pressure

higher ΔH_f results in lower equilibrium pressure



Range of ΔS values estimated from hydride database

All storage technology options are currently open

Storage option	Potential forecourt needs
• Compressed gas 350 bar, 700 bar	Compressors, hi P onsite storage, gas cooling? (for rapid refueling)
• Cryocompressed gas ~350 bar, ~20 – 100 K	Liquid H_2, liquid N_2, onsite cryogenic storage, cryo hi P gas/liquid delivery
• Liquid hydrogen ~20 K, <200 psi	Liquid H_2, onsite cryogenic storage, cryogenic liquid delivery
• Sorbents ~77 K, <100 bar	Liquid H_2 or liquid N_2, onsite cryogenic storage, cryogenic gas delivery
• Metal hydride reversible, < 350 bar	Low/hi P onsite storage, up to 350 bar H_2, heat exchanger (up to ~ 500 kW)
• Chemical hydride offboard regeneration	Charged carrier storage, spent carrier storage, delivery/removal method

Delivery and storage options are not totally independent

- hydrogen pre-processing required for all storage options (e.g., liquefaction, pressurization, cooling)
- there will be efficiency gains from using consistent storage methods

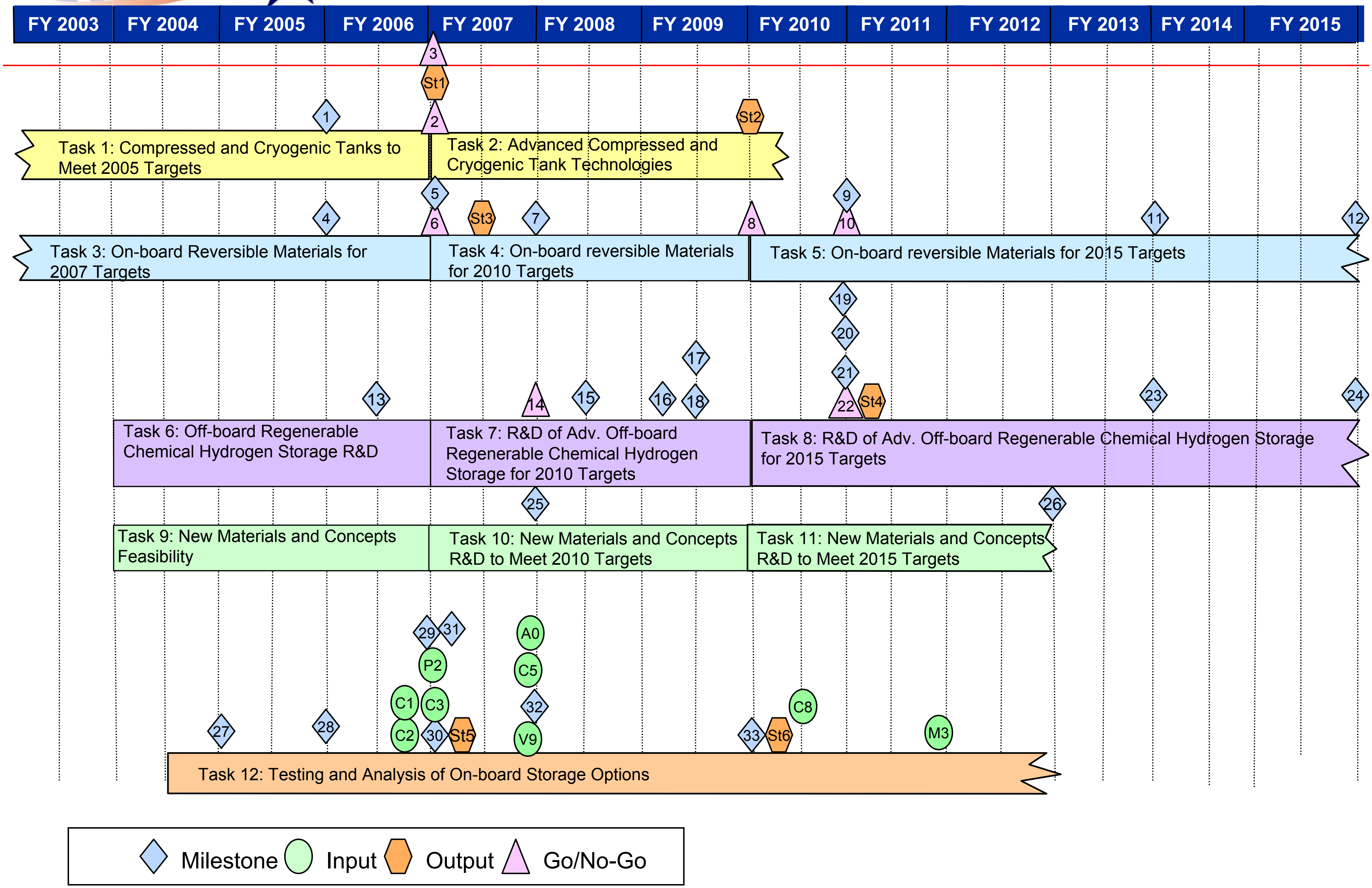
production	→	delivery	→	forecourt	→	onboard
LH2		LH2		LH2		LH2
CHG		CHG		CHG		CHG
LH2		LH2		LH2		sol. state
LH2		LH2		sol. state		sol. state
chem. carrier	⇄	chem. carrier	⇄	chem. carrier	⇄	chem. carrier
chem. carrier	⇄	chem. carrier	⇄	chem. carrier	→	sol. state

Areas of potential collaboration between tech teams

- Regeneration efficiency for H carriers
  - Round-trip efficiency analysis
- Low T needs at fueling station for sorbents
  - Energy, cost requirements, liq. N_2
- Cryo-compressed refueling needs
  - Liquid H_2, cryo-high and low P options
- Energy cost analysis for metal hydrides
  - High ΔH vs. high P

Back up slides

Hydrogen Storage R&D Milestone Chart



Hydrogen Storage R&D Milestones

Milestones

1	Complete preliminary feasibility study of cryogenic adsorbent tank concept (4Q 2005)
2	Go/No-Go: Decision on compressed and cryogenic tank technologies for on-board vehicular applications (4Q 2006)
3	Independent evaluation of gravimetric and volumetric capacities of cryo-compressed tanks (4Q 2006)
4	Reproducibly demonstrate 4wt% material capacity on carbon nanotubes (4Q 2005)
5	Complete prototype metal hydride system and evaluate against 2007 targets (4Q 2006)
6	Go/No-Go: Decision point on carbon nanotubes (4Q 2006)
7	Down-select on-board reversible metal hydride materials (4Q 2007)
8	Go/No-Go: Decision point on advanced carbon-based materials (4Q 2009)
9	Complete materials-based lab-scale prototype system and evaluate against 2010 targets (4Q 2010)
10	Go/No-Go: Decision on reversible metal hydride R&D (4Q 2010)
11	Down-select on-board reversible hydrogen storage materials with potential to meet 2015 targets (4Q 2013)
12	Complete lab-scale prototype system and evaluate against 2015 targets (4Q 2015)
13	Complete preliminary estimates of efficiency for off-board regeneration (2Q 2006)
14	Go/no-go: Decision point on sodium borohydride (4Q 2007)
15	Down-select chemical hydrogen storage materials and accompanying regeneration processes (2Q 2008)
16	Demonstrate regeneration processes at laboratory-scale, and estimate efficiency (1Q 2009)
17	Complete chemical hydrogen storage life-cycle analyses (2Q 2009)
18	Down-select chemical hydrogen storage approaches for 2010 targets (2Q 2009)
19	Complete lab-scale prototype chemical hydrogen storage system and evaluate against 2010 targets (4Q 2010)
20	Demonstrate multiple cycle regeneration at laboratory-scale (4Q 2010)
21	Identify advanced regeneration laboratory process with potential to meet 2015 targets (4Q 2010)
22	Go/No-Go: Decision point on chemical hydrogen storage R&D (4Q 2010)
23	Down-select chemical hydrogen storage approaches for 2015 targets (4Q 2013)
24	Complete chemical hydrogen lab-scale prototype and evaluate against 2015 targets (4Q 2015)
25	Down-select from new material concepts to meet 2010 targets (4Q 2007)
26	Down-select the most promising new material concepts with potential to meet 2015 targets (4Q 2012)
27	Complete construction of materials test facility (4Q 2004)
28	Complete verification of test facility for adsorbent materials (4Q 2005)
29	Complete verification of test capabilities for metal hydride materials (4Q 2006)
30	Complete baseline analyses of on-board storage options for 2010 targets (4Q 2006)
31	Establish testing capabilities for chemical hydrides (1Q 2007)
32	Update onboard storage targets (4Q 2007)
33	Complete analyses of on-board storage options for 2010 and 2015 targets (4Q 2009)

Outputs

St1 Output to Technology Validation: Report on compressed/cryogenic liquid storage tanks and evaluation against 1.5 kWh/kg and 1.2 kWh/L (4Q 2006)

St2 Output to Technology Validation: Report on advanced compressed/cryogenic tank technologies (4Q 2009)

St3 Output to Fuel Cells and Technology Validation : Report on metal hydride system and evaluation against 2007 targets (2Q 2007)

St4 Output to Delivery, Fuel Cells and Technology Validation: Report on full-cycle chemical hydrogen system and evaluation against 2010 targets (1Q 2011)

St5 Output to Delivery, Systems Analysis and Systems Integration: Baseline hydrogen on-board storage system analysis results including hydrogen quality needs and interface issues (1Q 2007)

St6 Output to Delivery, Systems Analysis and Systems Integration: Final on-board hydrogen storage system analysis results of cost and performance (including pressure, temp, etc) and down-select to a primary on-board storage system candidate (1Q 2010)

Inputs

C1 Input from Codes and Standards: Hydrogen fuel quality standard as ISO Technical Specification (3Q2006).

C2 Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks (3Q2006).

P2 Input from Production: Assessment of fuel contaminant composition (4Q2006).

C3 Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (CSA America) (4Q2006).

V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations (4Q2007).

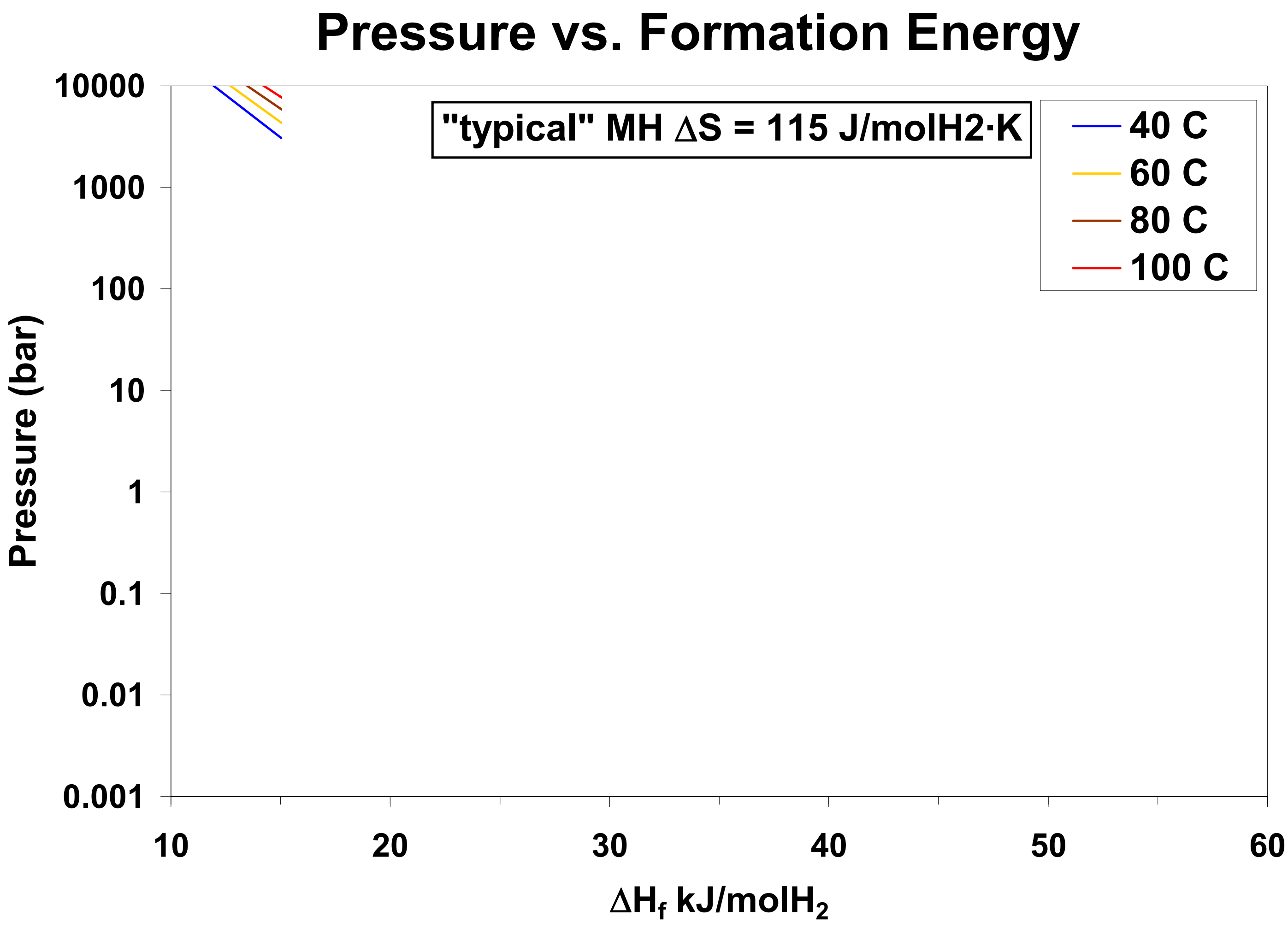
C5 Input from Codes & Standards: Materials compatibility technical reference (4Q2007).

A0 Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system (4Q2007).

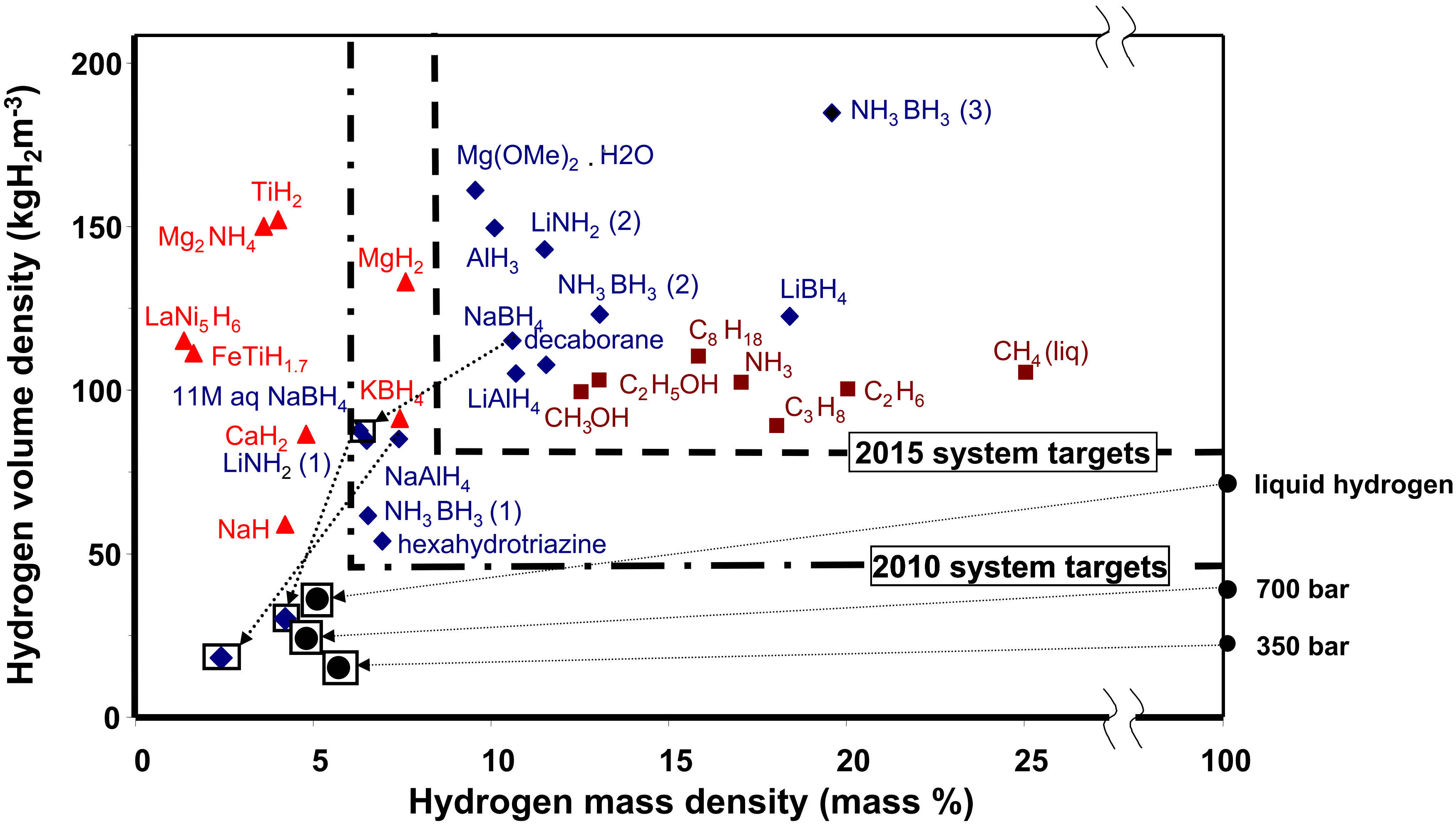
C8 Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard (2Q2010).

M3 Input from Manufacturing: Report on fabrication and assembly processes for high-pressure H2 storage technologies that can achieve a cost of $2/kWh (4Q2011).

Pressure Swing with Temperature



Examples of material capacities in comparison to system targets



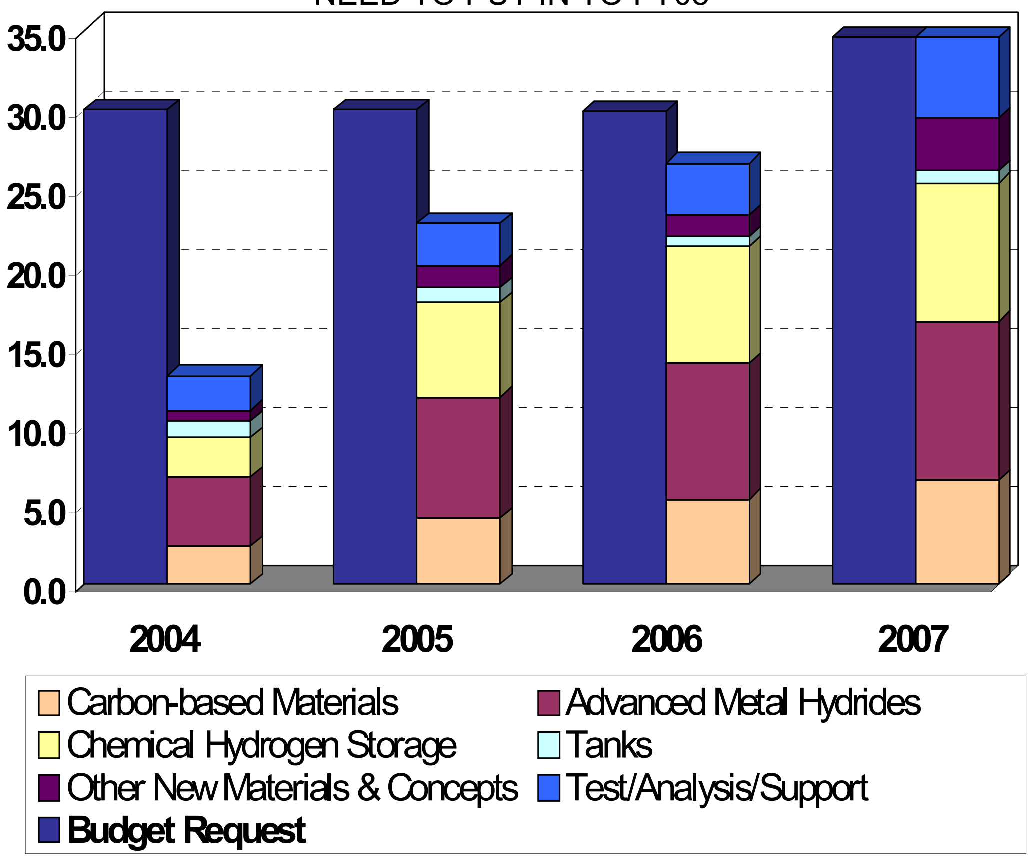
G. Thomas et al, DOE Annual Program Review
Adapted from Schlapbach et al for material capacities

Hydrogen Storage Budget

DOE- EERE

FY2007 Budget Request = $34.6M
FY2006 Funding = $26.0M

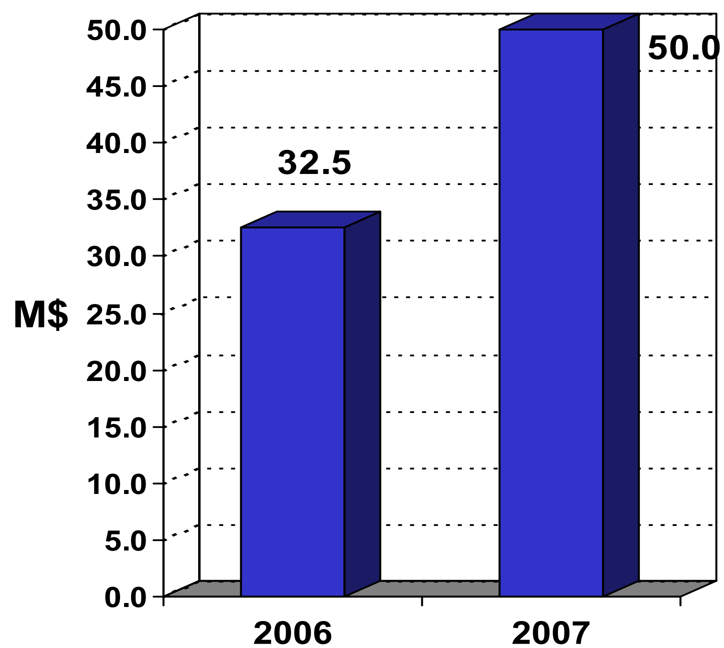
NEED TO PUT IN TO FY08



FY 08 Request: $43.9M for hydrogen storage

DOE- Office of Science

FY2007 Budget Request = $50.0M*
FY2006 Funding = $32.5M*



* For Basic Science within the Hydrogen Fuel Initiative, including hydrogen storage, membranes, catalysts, etc.

Planned funding for Basic Science in Hydrogen Storage in FY06: ~$7.5 M