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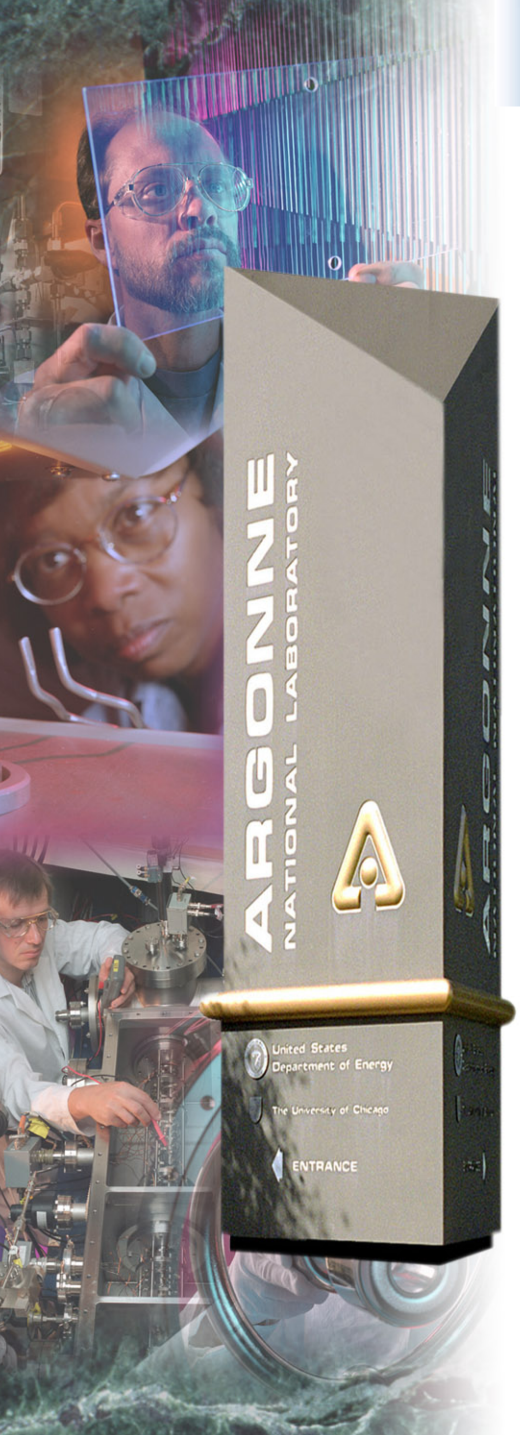

On-Board Storage Systems Analysis

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ANL's Role in H_2 Storage Systems Development

Working with DOE contractors and Centers of Excellence researchers:

- Model and analyze various developmental hydrogen storage systems
- Analyze hybrid systems that combine features of more than one concept
- Develop models that can be used to "reverse-engineer" particular technologies
- Identify interface issues and opportunities, and data needs for technology development
- Analyze life cycle efficiencies of candidate chemical hydrides

Current Activities in Storage Systems Analyses

Metal Hydrides

- Developing a tool to help scientists evaluate how well their material, when used in a full-scale device, can meet DOE's storage targets

Carbon Storage

- Determining whether activated carbons at low T & high P can meet DOE's 2007 storage targets

Cryo-Compressed Hydrogen

- Determining combinations of P & T to achieve 4.5 wt% gravimetric and 36 kg/m^3 volumetric capacity

Chemical Hydrogen

- Evaluating regeneration energy requirements and fuel cycle efficiencies of candidate materials and processes

Metal Hydride Storage

To avoid penalizing FCS efficiency, consider LTMH-FCS configuration.

- Hydrogen must be liberated from MH using stack coolant at 75-115^{o}C, Δh should be <100 kJ/gmol.

The operating SOC window is a function of several parameters: sorption kinetics, minimum H_2 delivery pressure, H_2 supply pressure, FCS/vehicle requirements.

- Minimum full-flow rate of H_2 determines lower bound of SOC
- Refueling time sets the upper bound of SOC.

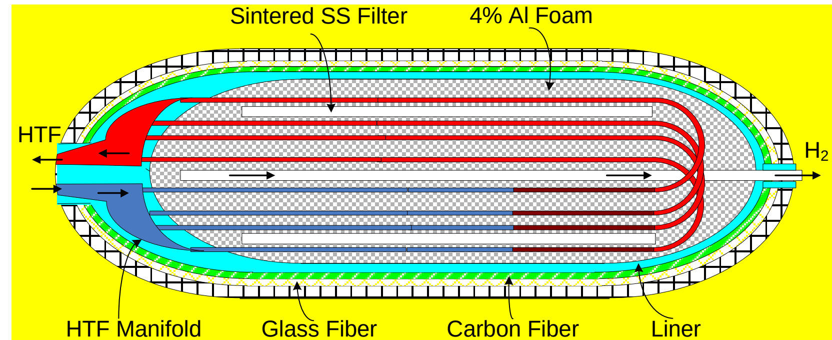
Heat transfer to and from MH is a significant issue.

- Nearly 100 MJ (5.6 kg H_2, Δh = 37 kJ/gmol) must be rejected in 3-10 minutes (150-600 kW): off-board coolant likely needed.
- Sodium alanate powder has poor thermal conductivity: heat transfer support likely needed.

MHTool: Metal-Hydride Hydrogen Storage System Analysis Tool

To develop and make available a tool for use by the material developers to

- evaluate whether the material, when used in a full-scale device, can meet H_2 storage targets;
- identify deficiencies in material properties
- assess needed improvement



1. MATERIAL CHARACTERIZATION MODULE

2. STORAGE CAPACITY MODULE

3. HEAT TRANSFER MODULE

4. SYSTEM MODULE

5. DYNAMIC MODULE

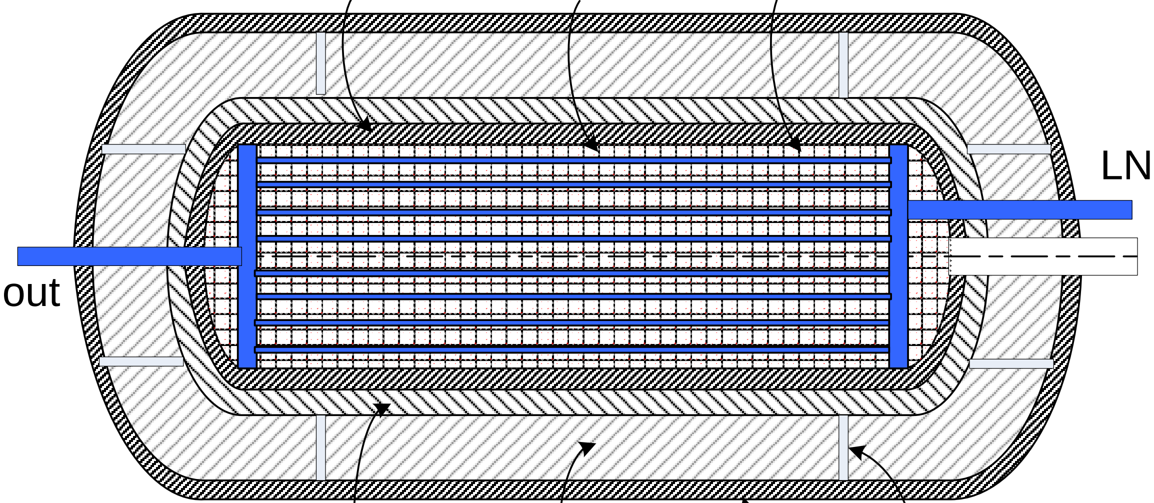
High-Pressure, Low-Temperature Storage of Hydrogen on Activated Carbon

- Determine the volumetric and gravimetric capacity of AC storage systems at low temperatures (77-150 K) and high pressures (P > 100 bar).
  - Compare amounts of H_2 adsorbed on AC and in void space.
  - Evaluate the heating and cooling requirements for the AC tank and how they may be accomplished.
  - Characterize dormancy and boil-off losses.
  - Estimate energy consumed in storing hydrogen.
- Determine the attributes of an advanced AC sorbent that can help meet the 2005 targets of 4.5 wt% H_2 and 36 kg H_2/m^3 (1.2 kWh/L).

AC H_2 Storage System

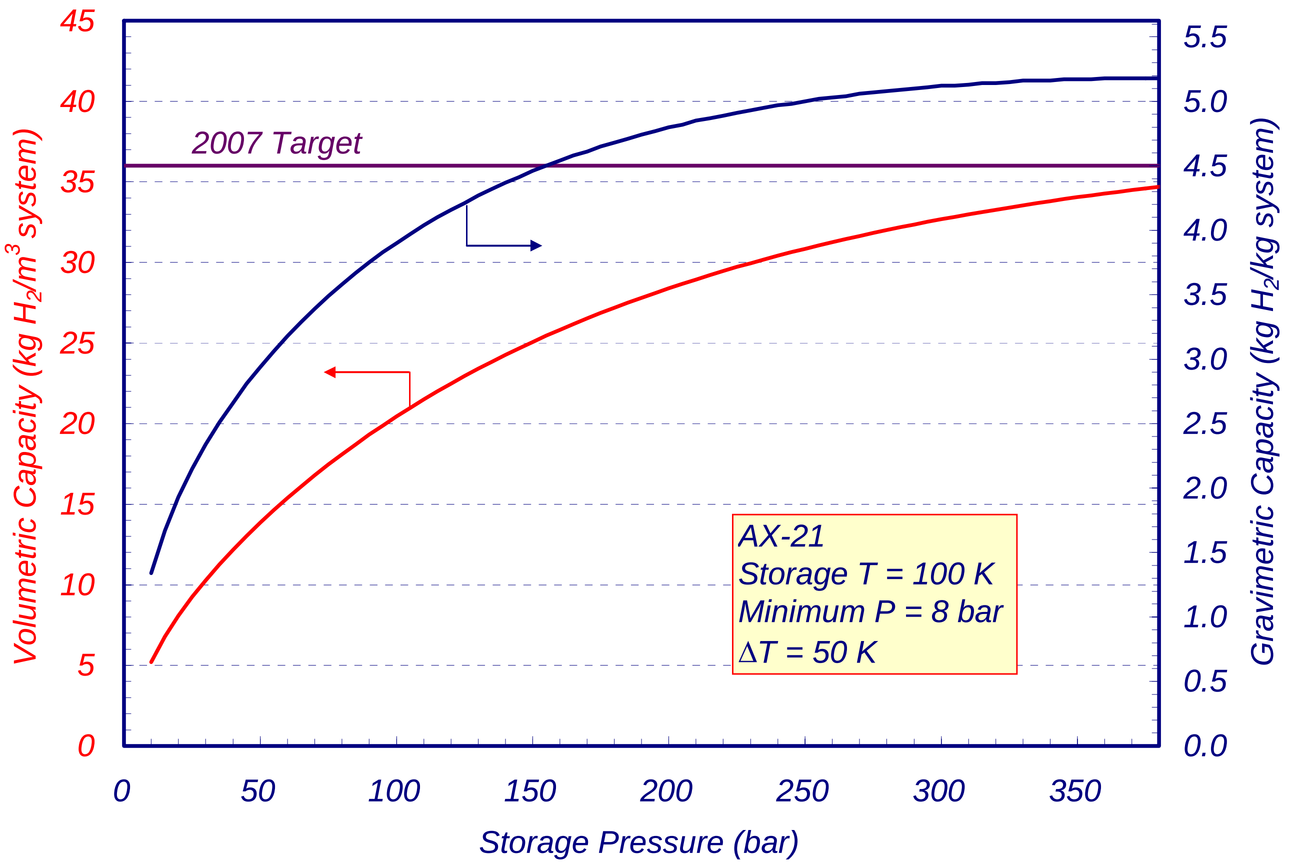
Thermally insulated, filament wound carbon fiber/epoxy PV

- Super AC powder medium
- Metal foam support
- In-tank HX and manifolds
- Al liner
- Carbon fiber
- Multi-layer vacuum insulation
- Al shell
- Miscellaneous



Storage Capacity of AC System at 100 K

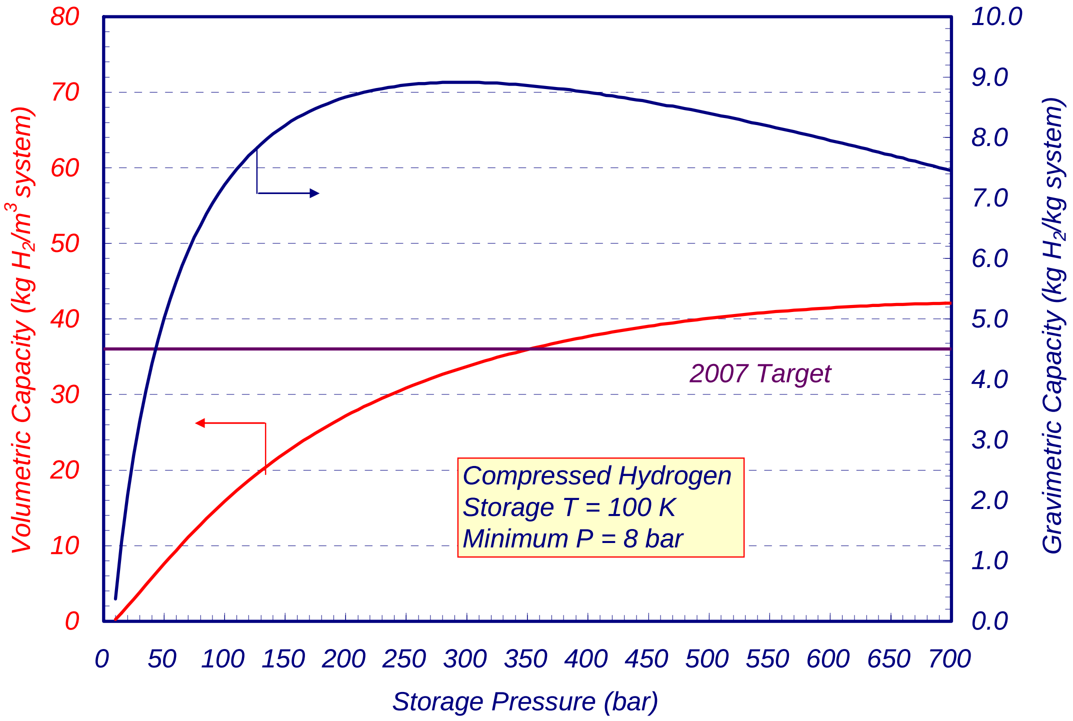
- At 100 K, the storage capacity of AC system is >4.5 wt% for P >150 bar and approaches 36 kg/m^3 at P = 380 bar.
- Need to increase sorption capacity of AX-21 by 61-82% and bulk density by ~100% to satisfy targets at 100 K and 100 bar.



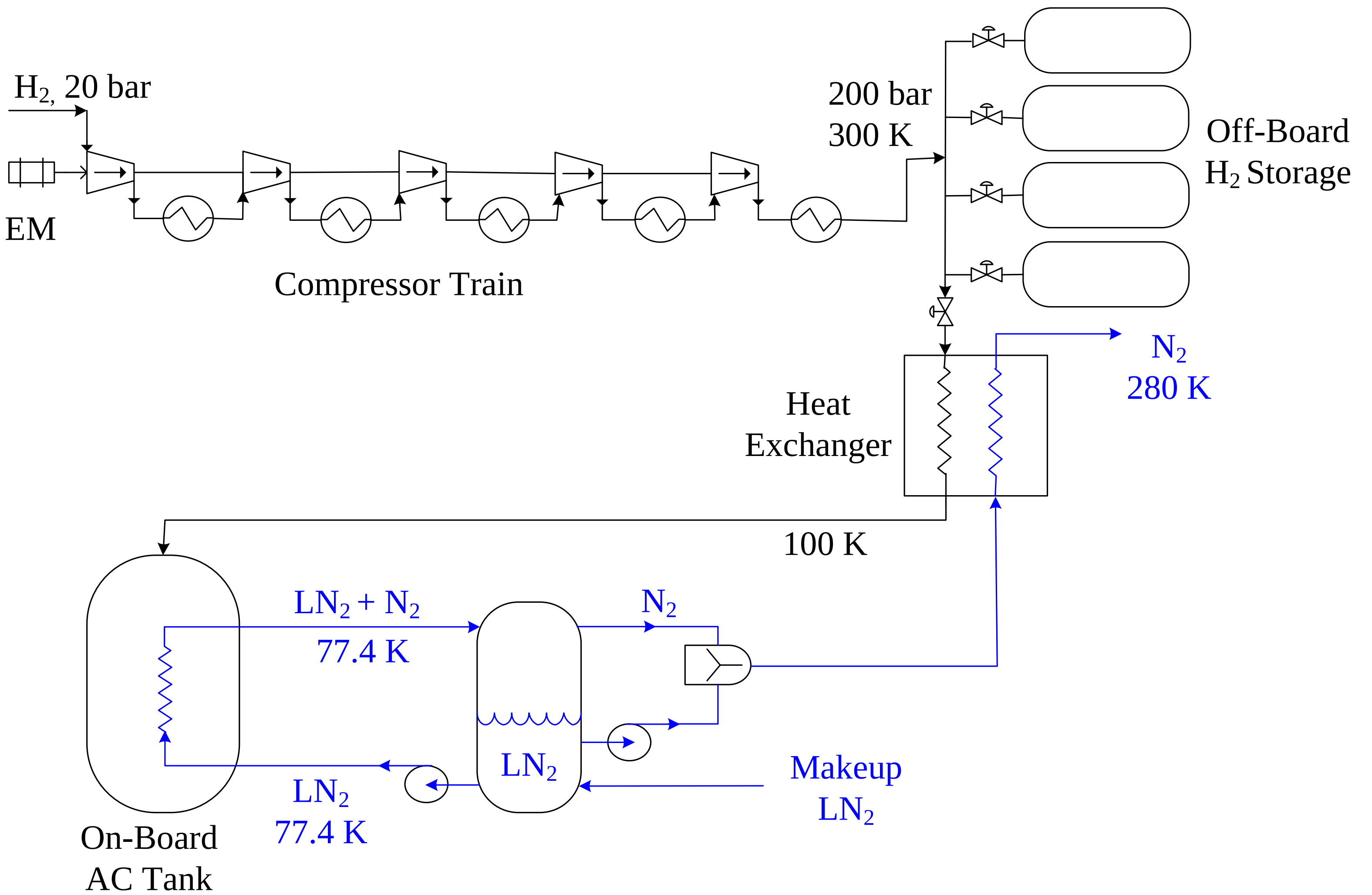
Storage Capacity of Cryo-cH2 System at 100 K

Assumption: No on-board heat transfer system needed because the tank is charged with H_2 subcooled to about 70 K.

- May simultaneously meet the 2007 targets of 4.5 wt% and 36 kg/m^3 at P > 355 bar.
- May meet the 2010 target of 6 wt% but not the 45 kg/m^3 target.
- 8.9 wt% peak gravimetric capacity at 300 bar.



H_2 Refueling System



LN2 Production

- Linde-Hampson system: Joule-Thompson valve only
- Claude system: J-T valve and an expander
- Cascade system: Precooling with multiple refrigeration systems (NH_3, C_2H_4, CH_4)

Air Liquefaction System	Liquid Yield	Work per unit mass liquefied	Figure of Merit
	%	kWh/kg	%
Ideal reversible system	1.000	0.199	1.000
Linde-Hampson system	0.061*	2.868	0.070
Pre-cooled Linde-Hampson system	0.158*	1.550	0.129
Linde dual-pressure system	0.032*	1.764	0.113
Pre-cooled Linde dual-pressure system		0.995	0.201
Claude system	0.189*	0.995	0.201
Heylandt system	0.301*	0.924	0.216
Cascade system		0.904	0.221
Cosmodyne ASPEN A1000		0.970	0.205

Ref: R Barron, “Cryogenic Systems,” McGraw-Hill Book Company, New York, 1966

Electric Energy Consumed in Refueling

- Five-stage hydrogen compressor with intercooling
  - 70% stage, 97% mechanical, 90% motor efficiency
- Off-site LN2 production from liquefaction of air

Cooling Duty	MJ/kg H_2	5.9
H_2 Pre-cooler	MJ/kg H_2	2.9
Tank Refueling	MJ/kg H_2	3.0
LN2 Boil-Off	kg/kg H_2	14.3
Electrical Energy	kWh/kg H_2	14.3
H_2 Compression	kWh/kg H_2	1.4
LN_2 Production	kWh/kg H_2	12.9

- Option 1: On-site production of LN2 in a closed loop
- Option 2: Cryogenic refrigeration at LN2 temperature

Preliminary Assessment of Alternate Cooling Schemes

- Option 1: Cool cH2 at 200 bar to 100 K at fueling site
- Option 2: Off-site cryo-cH2 + on-site LN2 for cooling tank
- Option 3: On-site LN2 production for cooling H_2 + tank
- Cryo-cH2 storage: 7-stage H_2 compression to 450 bar and cooling to 70 K

	Electric Energy Consumption (kWh/kg H_2)			
	H_2 Compression	H_2 Cryogenics	LN2 Production	Total
EAC-2007				
Reference: LN2 cooling	1.4		12.9	14.3
Cryo-cH2 + LN2	1.4	3.1	13.7	18.2
Cryo-cH2 + on-site LN2	1.4	3.1	4.1	8.6
On-site LN2 cooling	1.4		8.0	9.4
Cryo-cH2 storage	2.0	3.6		5.6

Assumption: On-site LN2 plant can achieve a FOM of 0.35

Fuel Cycle Efficiencies of Hydrogen Storage Options

Simple but consistent method of calculating WTT efficiency

- Chemical hydrogen storage with off-board regeneration
- Hydrogen carrier different than on-board storage method

Issued a paper that defines efficiency and presents data

- Specific energy for converting (energy) feedstocks to (process) fuels
- Specific energy for producing, distributing and storing H_2
- H_2 losses during transportation, off-board storage, in dispensing and on-board vehicle
- Spreadsheet based tool being written

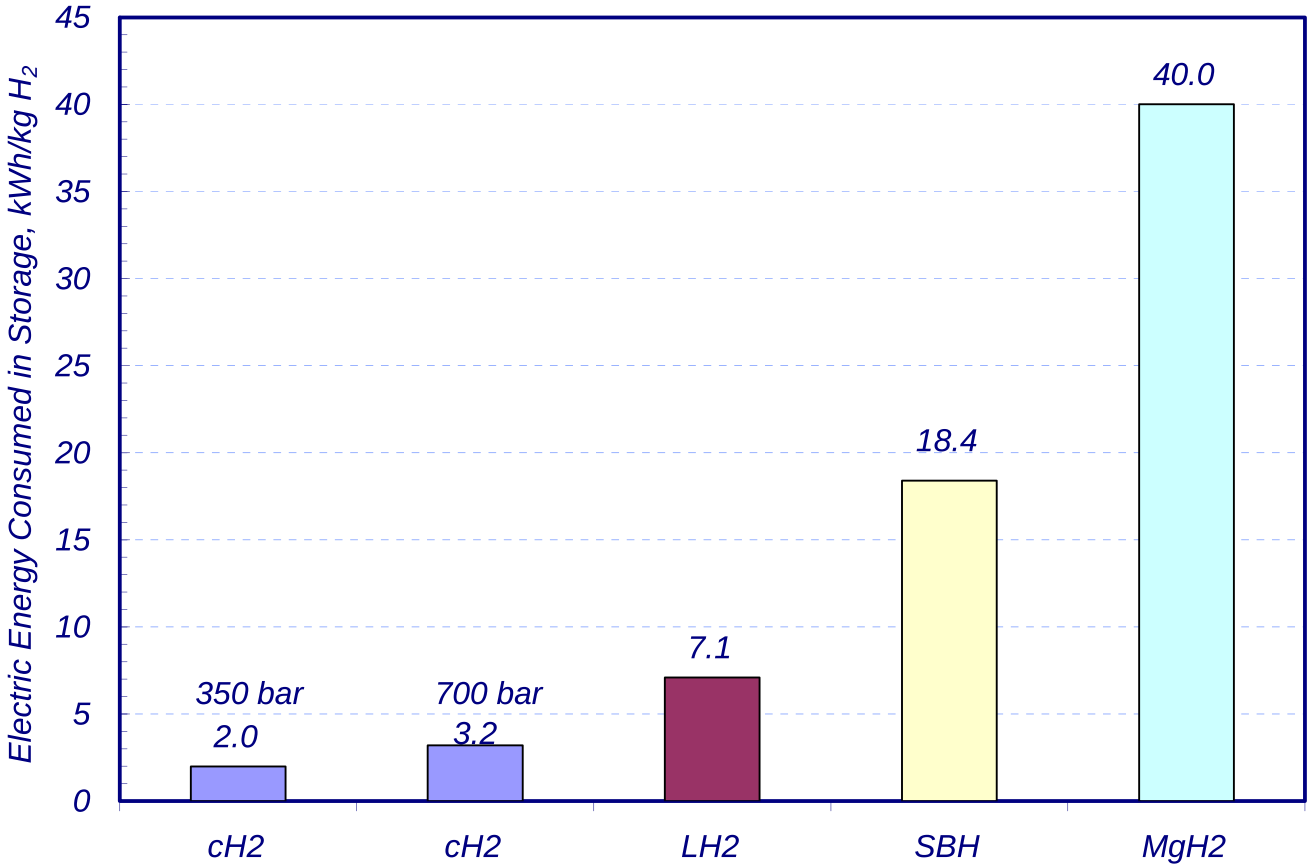
WTT Efficiency of Different Storage Options

Considered centralized production of H_2 by SMR+PSA, 73% efficiency

1. Compressed hydrogen at 350 or 700 bar
   - Distribution by tube trailers for 1% market share
   - Distribution by pipelines for 50% market
2. Liquid hydrogen storage option
   - Liquefaction plant at production site, >200,000 kg/d capacity
   - Delivery truck capacity: 400 kg (1% market), 4000 kg (10% market)
3. MgH_2 slurry
   - Electricity consumed mainly by LTF-SOM process at 1150^{o}C
   - BU 2005 data: 3-V cell voltage (~1-V dissoc. potential with H_2), 100% current eff., 6.7 kWh/kg Mg (SafeH_2 quoted 10 kWh/kg)
4. SBH system
   - Electricity consumed mainly by H-assisted NaOH electrolysis
   - MCEL data: 1.2-V cell voltage (~1.07-V theoretical with H_2), 100% current eff., 1.6 kWh/kg Na (MCEL quoted 1.8 kWh/kg)

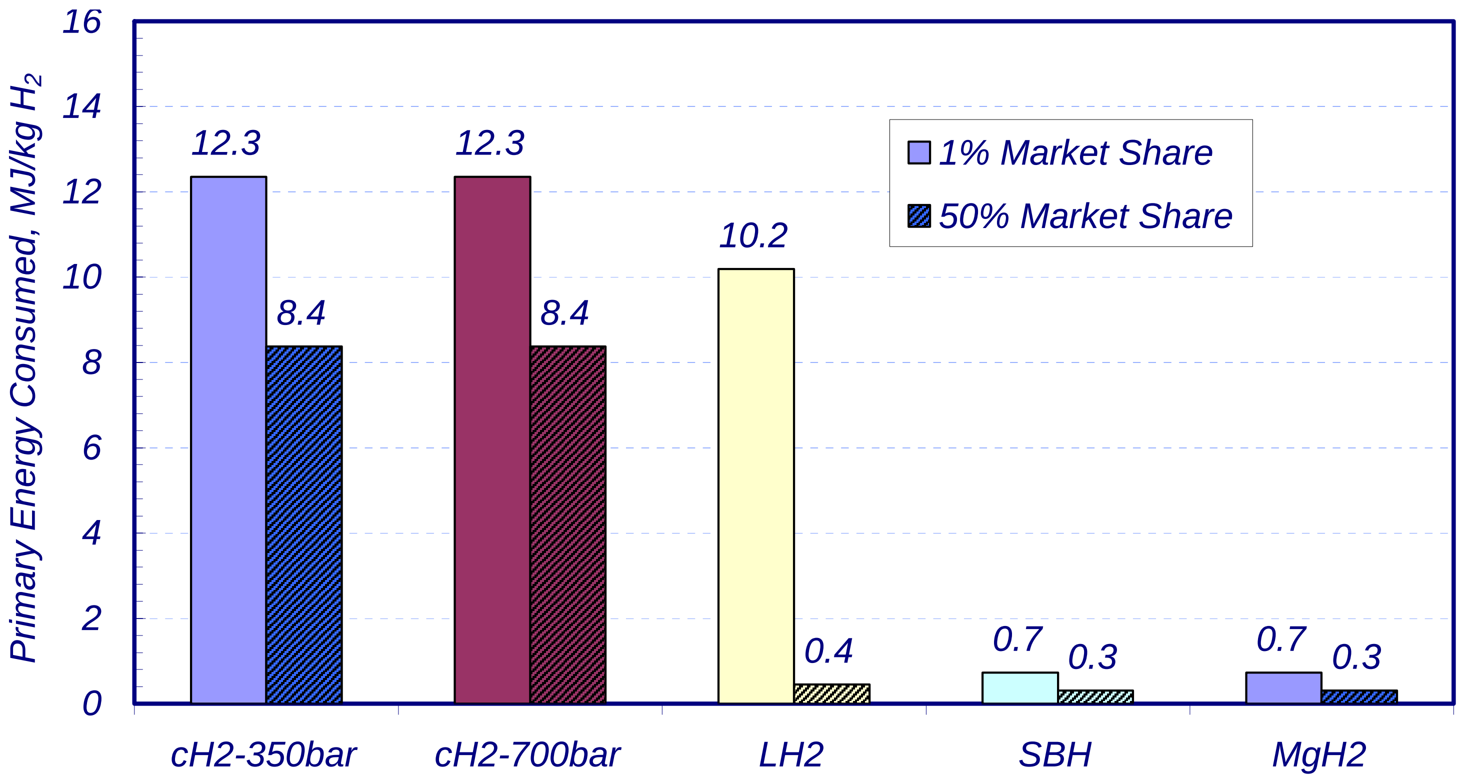
Electric Energy Consumed in Storage/Regeneration Step (Preliminary Results)

- May not be possible to achieve 0.451 FOM for LH_2 production
- Theoretical minimum for SBH by NaOH route: 16.4 kWh/kg H_2
- Theoretical minimum for MgH_2 by SOM: 18.7 kWh/kg H_2



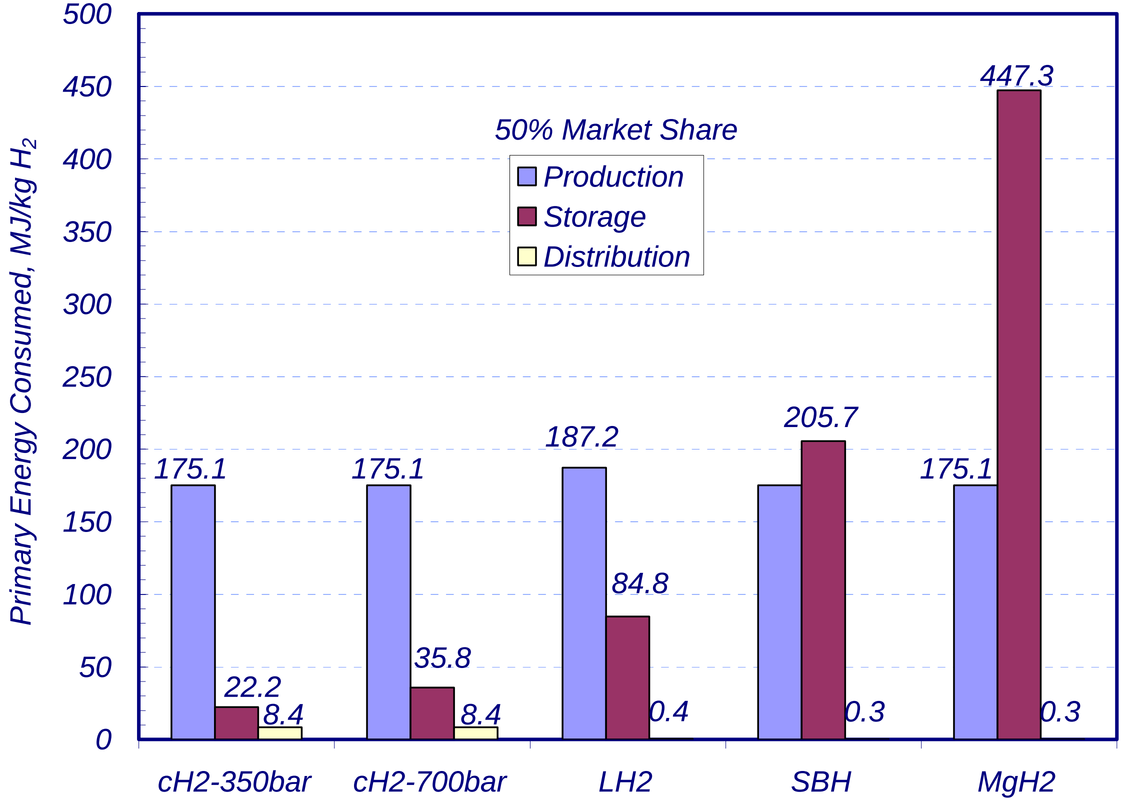
Primary Energy Consumed in Distribution Step

- In 50% market scenario, energy consumed in distribution of LH_2 and chemical hydrides is small.
- 8-12 MJ/kg H_2 consumed in truck/pipeline delivery of cH_2
  - 34.8% efficiency for 2015 U.S. electric grid
- About 10 MJ/kg H_2 consumed in delivering LH_2 in 1% scenario



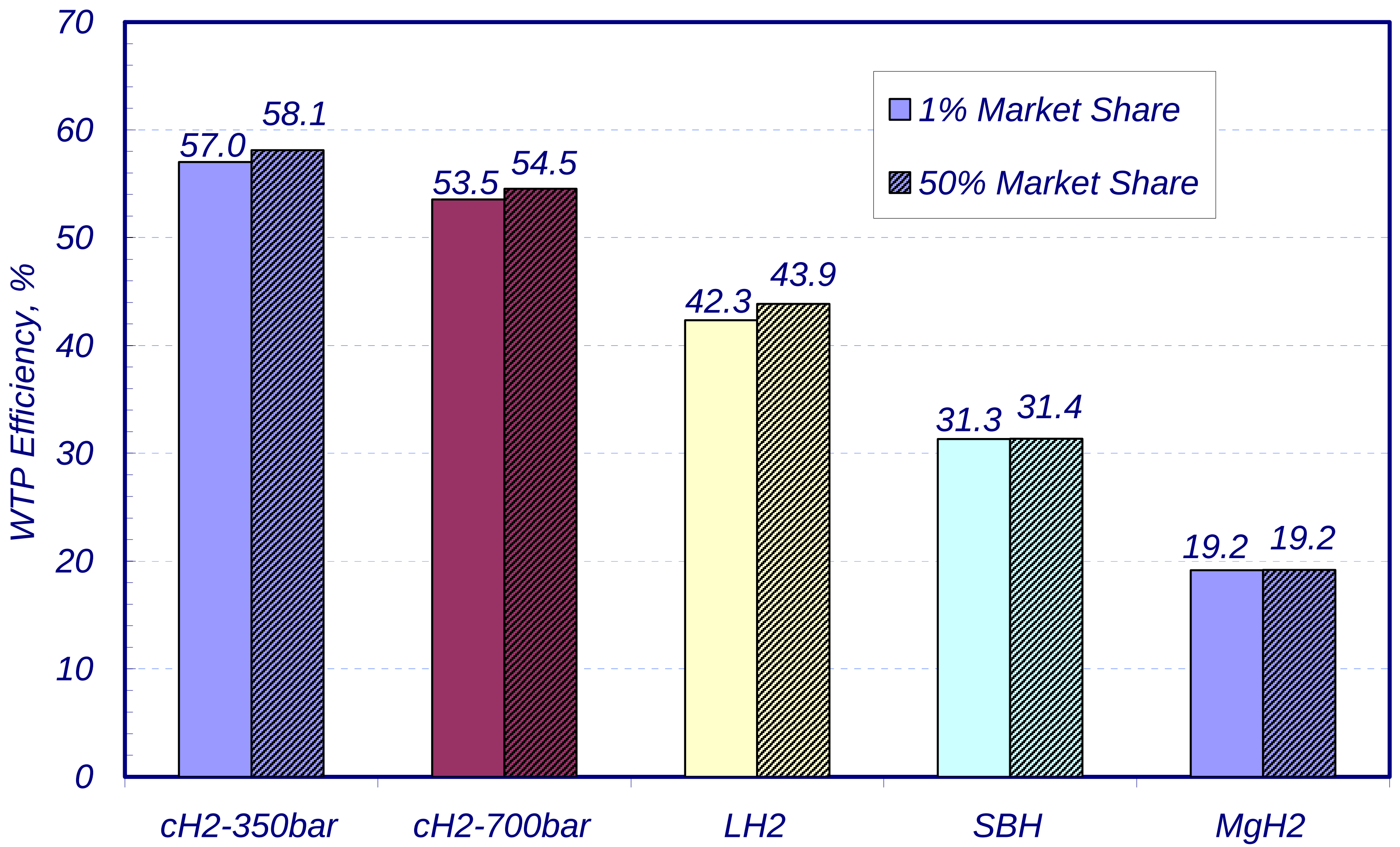
Primary Energy Consumed in Production, Distribution and Delivery Steps

- cH_2 option: Storage & distribution require 18-26% of energy consumed in production
- LH_2: Liquefaction requires 40% of energy consumed in production
- SBH: Energy consumed in storage & production steps about equal
- MgH_2: Regeneration requires >2.2 times energy consumed in production



Preliminary Fuel Cycle Efficiency

- Differences in efficiency are mainly due to the energy consumed in storage/regeneration steps.



Future Work

Continue to work with DOE contractors and COE to model and analyze various developmental hydrogen storage systems.

Metal Hydrides

- PCT deconvolution module
- Module to derive kinetic constants from experimental data

Carbon Storage

- Extend work to nanocarbons

Cryo-Compressed Hydrogen

- Support DOE in go no-go decision

Chemical Hydrogen

- Evaluate regeneration energy consumption and fuel cycle efficiencies of candidate materials and processes
- Develop CHTool to help scientist evaluate how well their material can perform in a full scale on-board system to satisfy DOE's storage targets (kinetics, energetics, thermodynamics)

Storage System Parameters

Super AC powder medium

- AX-21: 2800 m^2/g, 300 kg/m^3, 0.1 W/m.K

Metal foam support

- 2-wt% Al 2024, 2.4 W/m.K

In-tank HX and manifolds

- Al 2024 construction
- 9.5-mm OD, 1.2-mm thick tubes
- 0.9-mm thick tube sheets

2-mm thick Al alloy liner

T700S carbon fiber

- 68%CF+32%resin, 1600 kg/m^3
- 2550 MPa tensile strength
- Fiber translation: 70% at 700 bar, 85% at 350 bar
- 2.25 SF

MLVSI

- Aluminized mylar sheets with Dacron spacer, 70 layers/in.
- 59.3 kg/m^3
- 10^{-5} torr
- 5.2×10^{-4} W/m.K
- 1 W heat transfer

3-mm thick Al alloy shell

System

- L/D = 2, 3:1 oblate ellipsoid head
- Misc.: pipes, PR, RV, insulation supports, etc., 20 kg, 10 L
- LN2 cooling
- H_2 refueled at +100 bar, tank T
- 5.6 kg recoverable H_2 capacity
- 0.5-2 kg/min H_2 refueling rate