System Level Analysis of Hydrogen Storage Options

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U.S. Department of Energy Hydrogen and Fuel Cells Program

2014 Annual Merit Review and Peer Evaluation Meeting

Washington, D.C.

June 16-20, 2014

Project ID: ST001

Overview

Timeline

- Project start date: Oct 2009
- Project end date: N/A
- Project continuation and direction determined annually by DOE

Barriers

- H_2 Storage Barriers Addressed:
  - A: System Weight and Volume
  - B: System Cost
  - C: Efficiency
  - E: Charging/Discharging Rates
  - J: Thermal Management
  - K: Life-Cycle Assessments

Budget

- FY13 DOE Funding: $480 K
- Planned FY14 DOE Funding: $480 K

Partners/Interactions

- Storage Systems Analysis Working Group (SSAWG)
- Hydrogen Storage Engineering Center of Excellence (HSECoE): SRNL, LANL
- Ford, PNNL, Tank OEMs
- Applied Nanotech Inc. (ANI)
- SA

Objectives and Relevance

Develop and use models to analyze the on-board and off-board performance of physical and material-based automotive hydrogen storage systems

- Conduct independent systems analysis for DOE to gauge the performance of H_2 storage systems
- Provide results to material developers for assessment against system performance targets and goals and help them focus on areas requiring improvements
- Provide inputs for independent analysis of costs of on-board systems.
- Identify interface issues and opportunities, and data needs for technology development
- Perform reverse engineering to define material properties needed to meet the system level targets

Impact of FY2014 work

- Determined potential reduction in carbon fiber (CF) requirement with advanced resins
- Demonstrated >30% reduction in CF requirement with cold H_2 storage
- Established sorbent properties needed to satisfy on-board and off-board storage system targets

Approach

- Develop thermodynamic and kinetic models of processes in physical, complex metal hydride, sorbent, and chemical H_2 storage systems
  - Address all aspects of on-board and off-board storage targets, including capacity, charge/discharge rates, emissions, and efficiencies
  - Perform finite-element analysis of compressed hydrogen storage tanks
  - Assess improvements needed in materials properties and system configurations to achieve storage targets
- Select model fidelity to resolve system-level issues
  - On-board system, off-board spent fuel regeneration, reverse engineering
  - Conduct trade-off analyses, and provide fundamental understanding of system/material behavior
  - Calibrate, validate, and evaluate models
- Work closely with DOE technology developers, HSECoE and others in obtaining data, and provide feedback
- Participate in SSAWG meetings and communicate approach and results to foster consistency among DOE-sponsored analysis activities

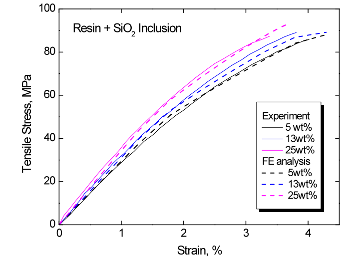
Summary: FY2014 Tasks and Accomplishments

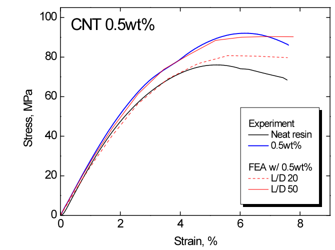
1. Physical storage
   – MultiMech simulations of advanced resins and composites
   – ABAQUS/Explicit simulations of fiber impact damage
   – On-board cold gas H_2 storage system and off-board WTT efficiency
2. H_2 storage in metal hydrides
   – Reverse engineering to determine material properties needed to meet system targets (low-temperature metal hydrides in FY2013)
   – High-temperature metal hydrides and unstable hydrides (Pending)
3. H_2 storage in sorbents
   – Reverse engineering to determine material properties needed to meet system targets
   – Off-board analysis for well-to-tank (WTT) efficiency
4. Chemical hydrogen storage
   – Reverse engineering to determine material properties needed to meet system targets (in progress)
   – Off-board analysis for well-to-engine efficiency (in progress)

Multiscale Modeling

MultiMech simulations to predict material properties of resins with nanoparticle additives (carbon nanotubes, SiO_2)

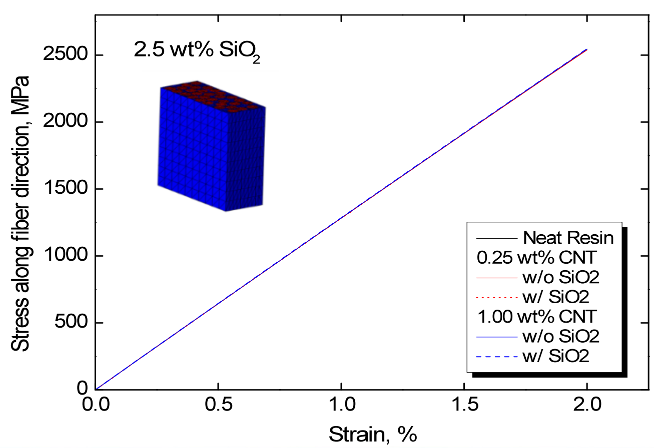
- Geometry, nanoparticle aspect ratio; Resin and particle properties: E,ρ,ν,α; Volume fractions
- Initial model validation: Epikote 828 resin containing up to 25 wt% nano-silica, Intl. Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012); and Applied Nanotech data (DOE AMR 2013) for resin with 0.5 wt% CNTs

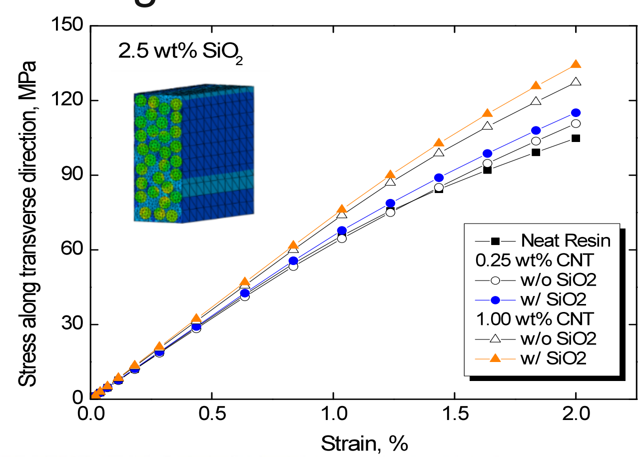




ABAQUS/*MultiMech* simulations of Toray T300 CF and ANI CNT/SiO_2 reinforced resins show small differences in axial stress (fiber dominated) but considerable improvement in transverse strength (matrix dominated);

- Resin additives may influence fiber/matrix interface load transfer efficiency and impact resistance more than composite strength

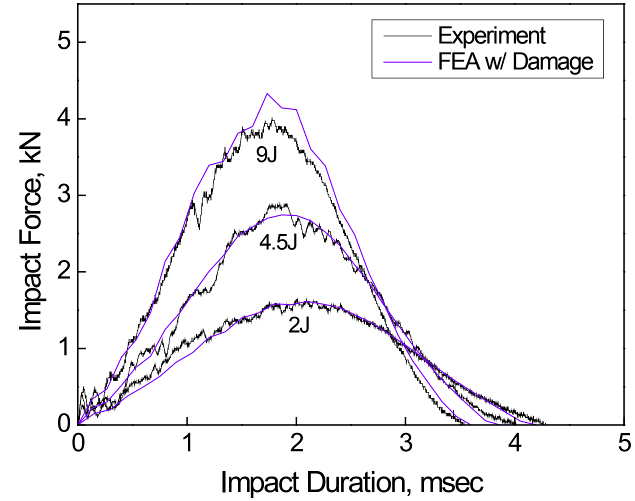




Impact Damage Analysis – Model Validation

Developed ABAQUS/Explicit model for CF composite damage due to physical impact

- Matrix cracking (occurs when transverse tension/compression, and shear stresses reach failure strength)
- Fiber breakage
- Delamination (more likely to occur between plies that have different fiber angles)
- Validated damage model with composite plate experiments*



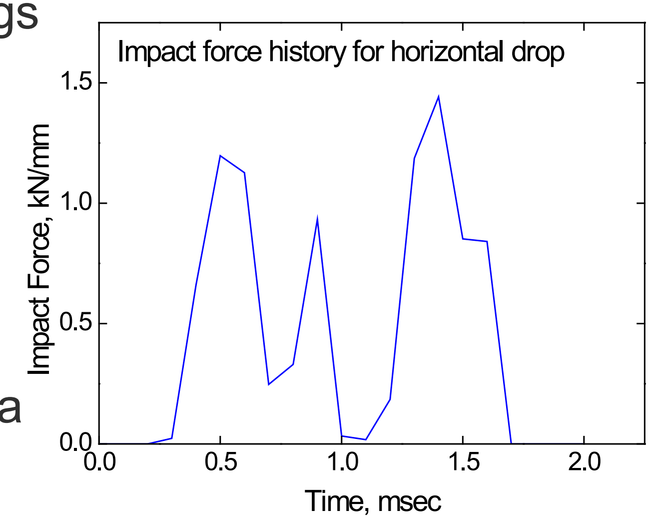
Drop test simulations per SAE J2579 from 1.8 m height: Type 4 tank with T700/Epoxy; 15^{o} helical and 90^{o} hoop filament windings

Key findings from horizontal drop simulations

- Surface matrix cracking (w/o glass fiber protection)
- No internal damage in matrix or fiber
- No delamination

Key findings from 45^{o} drop simulations

- Matrix damages through thickness near impact area 73 cc damage volume
- No fiber breakage or delamination



*H. S. Roh, "Monitoring the Impact and Buckling Behavior of Composite Structures using Fiber Optic Sensors," Korea Advanced Institute of Science and Technology, 1999.

Impact Resistance – Resin Property Enhancement

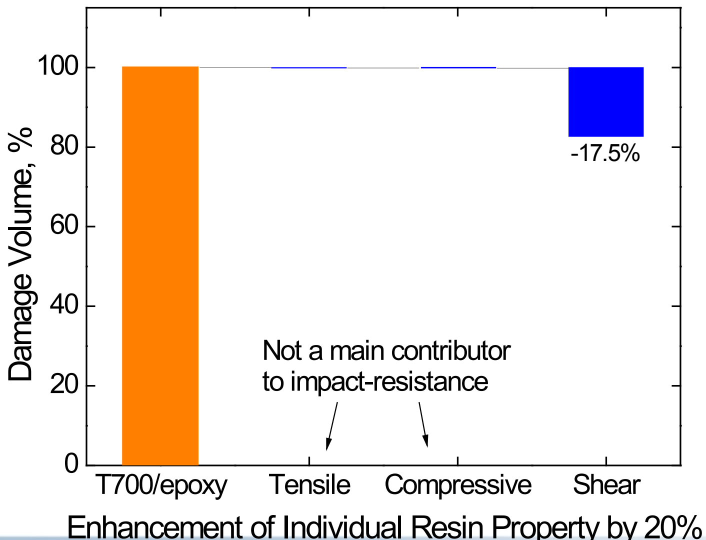
Conducted 45° drop test simulations to investigate the effect of matrix-dominant properties on impact resistance

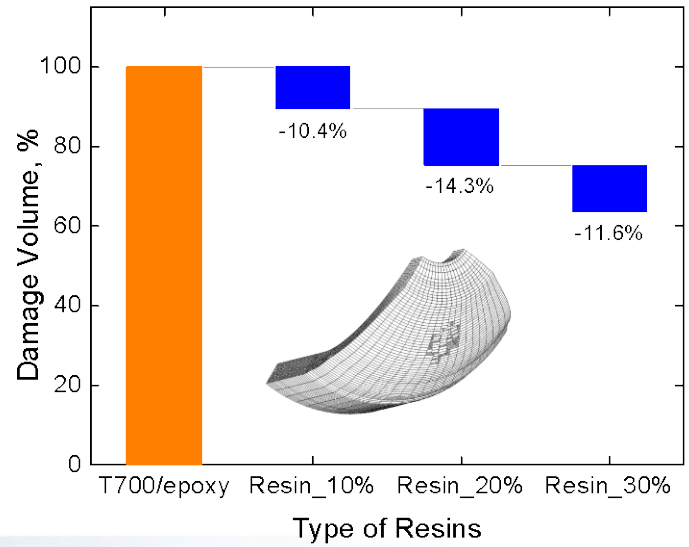
- Transverse tensile, transverse compressive, and shear strengths

Simulation results show that the impact damage resistance is highly correlated to the shear strength

- 17.5% reduction in damage volume with 20% enhancement in shear strength, small effects of transverse tensile and compressive strengths
- 35% reduction in damage volume with 30% enhancement in transverse tensile, transverse compressive, and shear strengths

ANI data for resins with 1% CNT and 0.25% SiO_2 show ~20% improvement in tensile, compressive and shear strengths over neat resins





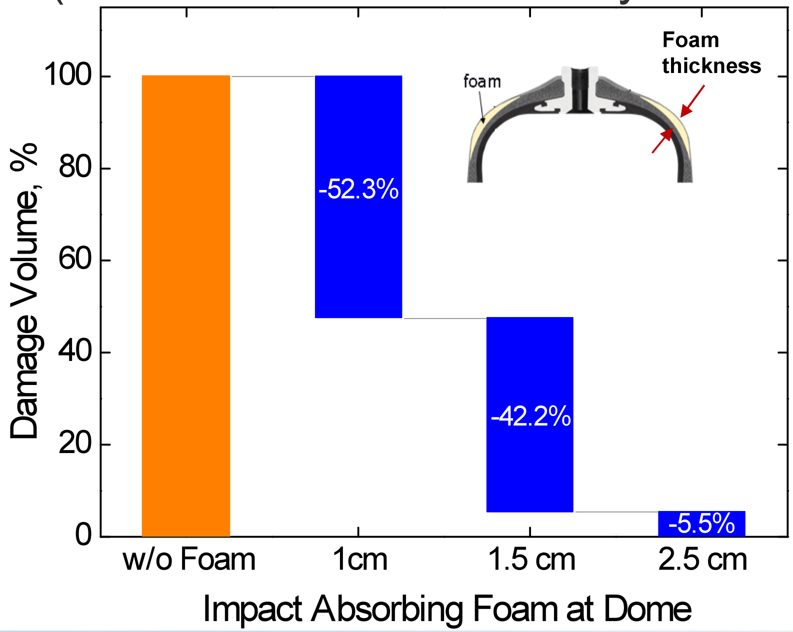
Impact Resistance – Foam

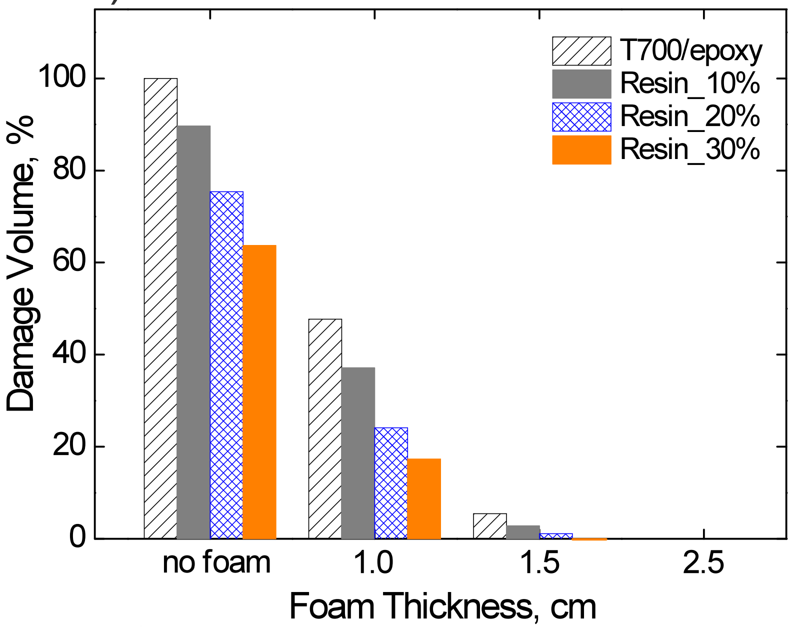
Simulations of 45° drop test show that use of foam material (EPS, EPP or PU*) between CF and glass fiber in dome can drastically reduce the impact damage

- 1 cm of PU foam can reduce the damage volume by 50%
- No damage predicted with 2.5 cm foam

Preliminary Conclusions

- Foam is needed to protect the dome.
- Advanced resins with improved mechanical properties can help in reducing the required foam thickness.
- Advanced resins may provide additional protection in areas without foam (near the boss and in the cylinder section).

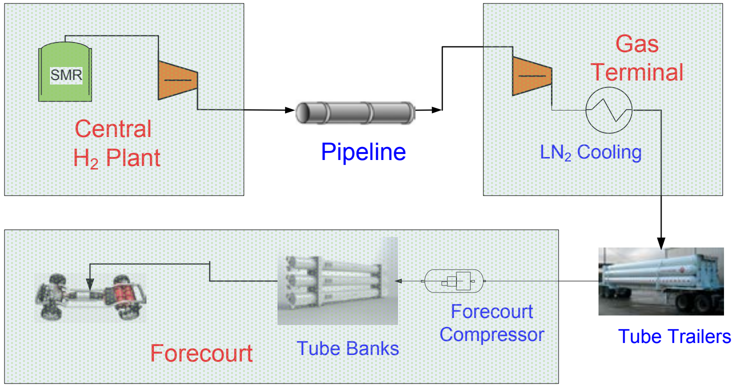




*Expanded polystyrene, expanded polypropylene, polyurethane

H_2 Storage as Cold Gas

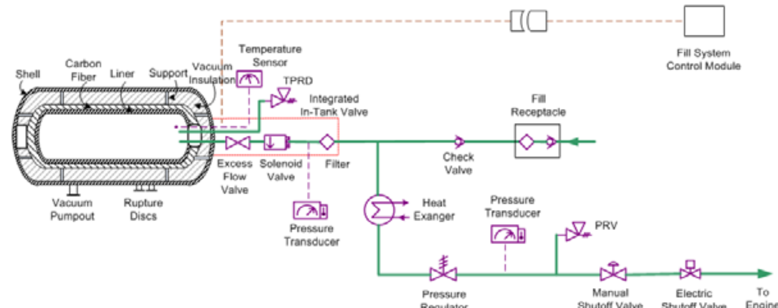
Production and Delivery Pathway: H_2 produced by SMR, transmitted via pipeline to gas terminal at city gate, MD Paster, RK Ahluwalia, G Berry, A Elgowainy, S Lasher, K McKenney, and M Gardiner, IJHE 36 (2011) 14534-14551



- Compressed to 340 bar at gas terminal, cooled nominally to 90 K* using LN_2 and transported to forecourt by insulated Type 3 tube trailers
- Compressed to 1.35X nominal storage pressure and stored in insulated Type 3 or Type 1 tube banks at forecourt

On-board Storage System: Pressure Vessel: Type 3 (Al 6061-T6 alloy) or Type 4 (HDPE liner), fatigue analysis of auto-fretaged Type 3 vessel with temperature cycling

- Heat Transfer: Vacuum MLSI*, aluminized Mylar® sheets with Dacron® spacers
- Shell: 3-mm Al shell
- BOP: Adapted from compressed and cryo-compressed H_2 systems, includes cryogenic valves and heat exchanger
- Operating Conditions: Storage T determined as function of storage P, heat transfer rate (5 W) and time between refueling (10 days), 5.6 kg usable H_2 at10 bar empty tank P
- Carbon Fiber Composite: Netting analysis of geodesic winding, calibration factors from ABAQUS

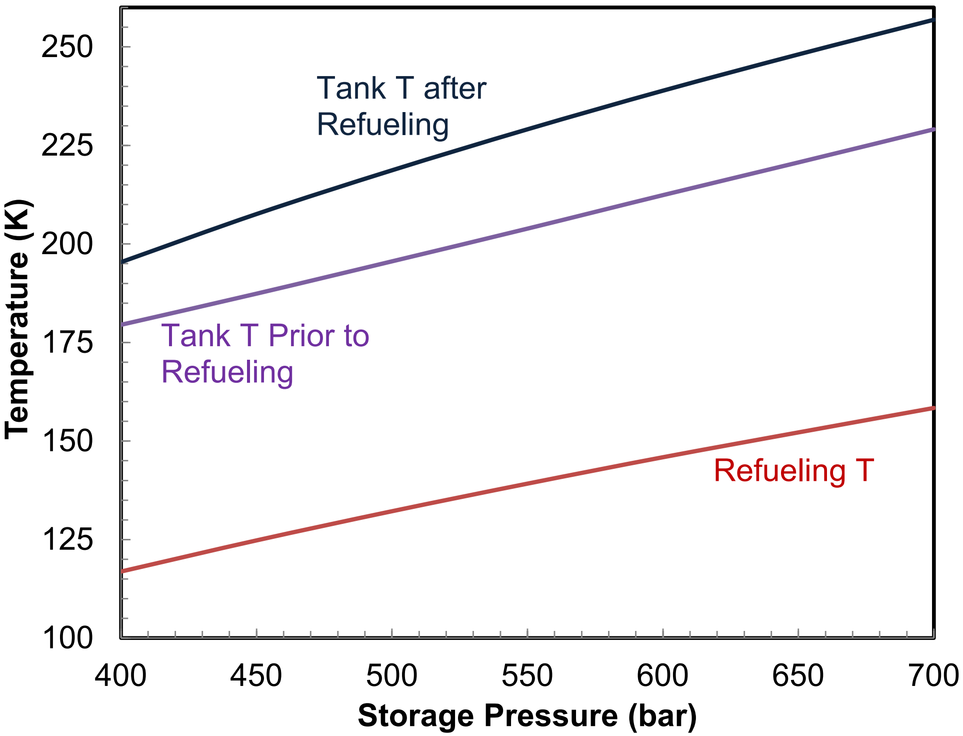


*83 K actual temperature to account for heat gain in off-board storage tanks

Operating Temperatures

Storage temperature is a function of the storage pressure

- Refueling T: Temperature of cold gas at 90 K and 340 bar in tube trailer compressed to 1.35X storage pressure, 65% isentropic efficiency, single stage (intercooling not available)
- Tank T prior to refueling: Thermodynamic model accounting for 5.6 kg H_2 discharged from the tank at varying P and T, 50 W-day heat gain from the ambient
- Tank T after refueling: Modeled temperature accounting for PV work and 5.6 kg H_2 charged in to the tank at refueling gas P and T, gas in tank isothermal with liner and CF composite
- Iteration to determine tank temperatures after refueling and after discharge
- At 400 bar, temperatures above the HDPE glass transition temperature but below the ductile to fragile transition temperature



T_g: Glass transition temperature; T_{df}: Ductile/fragile transition temperature

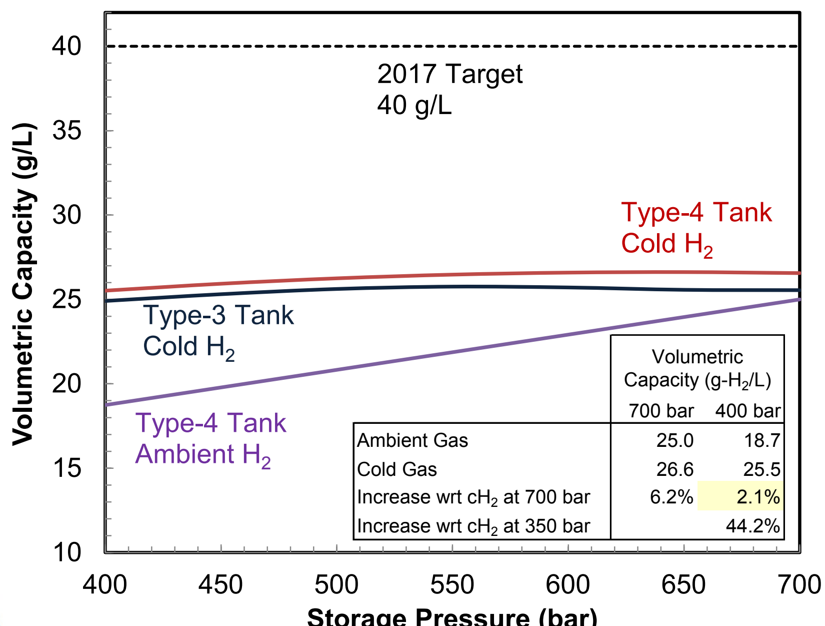
Volumetric and Gravimetric Capacities

Volumetric capacity of the cold gas option* is nearly independent of the storage P and is 2-6% higher than 25 g/L for the baseline ambient-T 700-bar cH_2 system

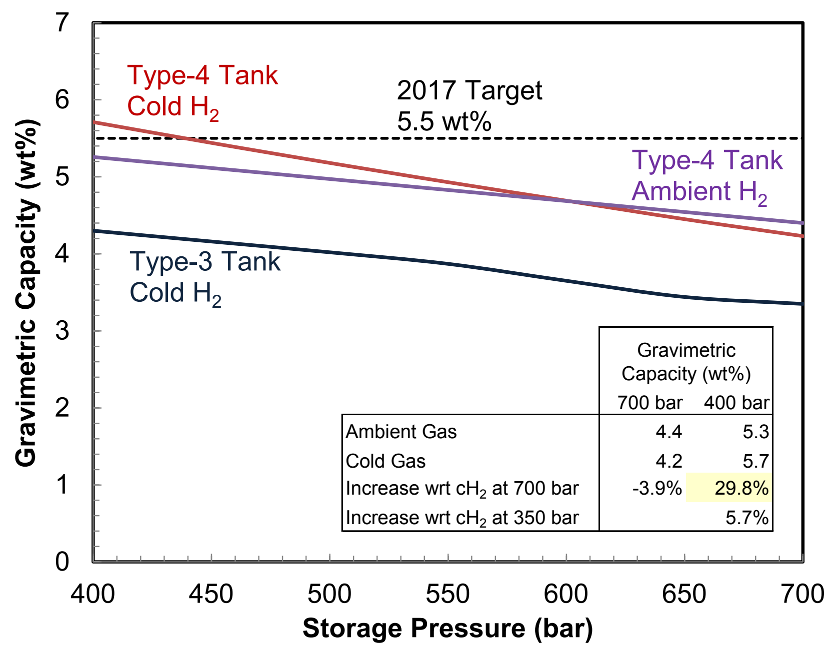
- Compared to the baseline system, higher gain in V-capacity at lower storage P
- Small difference in V-capacities of Type-3 and Type-4 vessels storing cold gas

May be possible to meet the 5.5-wt% 2017 gravimetric capacity target with cold H_2 storage in Type-4 tanks* at storage P below 450 bar*.

- Type 4 tanks always lighter than Type-3 tanks
- Higher gravimetric capacity for Type 4 tanks storing cold H_2 than Type 4 tanks storing ambient H_2 at pressures below 600 bar



	Volumetric Capacity (g-H_2/L) 700 bar	400 bar
Ambient Gas	25.0	18.7
Cold Gas	26.6	25.5
Increase wrt cH_2 at 700 bar	6.2%	2.1%
Increase wrt cH_2 at 350 bar		44.2%



	Gravimetric Capacity (wt%) 700 bar	400 bar
Ambient Gas	4.4	5.3
Cold Gas	4.2	5.7
Increase wrt cH_2 at 700 bar	-3.9%	29.8%
Increase wrt cH_2 at 350 bar		5.7%

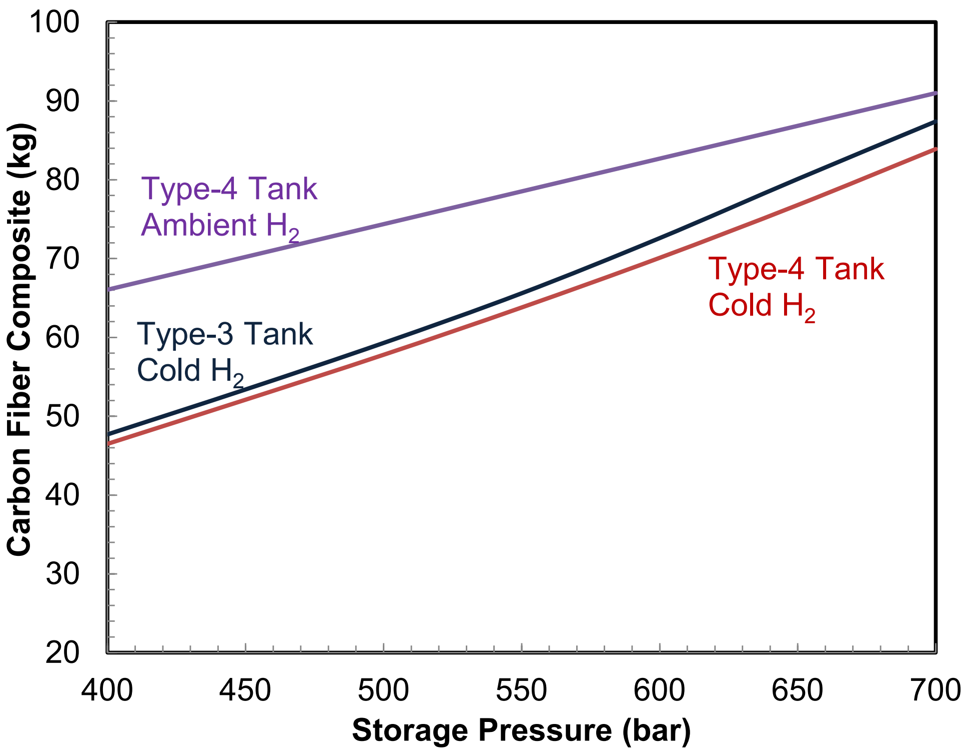
*Fixed 90 K tube trailer temperature

Carbon Fiber Composite Requirement

Nearly 50% reduction in CF composite (from 91 kg in baseline 700 bar Type-4 tank) is possible by storing cold gas (fixed 90 K nominal tube trailer temperature) at 400 bar*.

- Small difference in CF composite requirements for Type-3 and Type-4 tanks storing cold gas
- Projected composite usage based on fiber strengths that are independent of storage temperature and translation efficiencies that only depend on storage pressure

	Carbon Fiber Composite (kg) 700 bar	Carbon Fiber Composite (kg) 400 bar
Ambient Gas	91.0	66.1
Cold Gas	83.9	46.5
Saving wrt cH_2 at 700 bar	9%	48.9%
Saving wrt cH_2 at 350 bar		24.9%



*HDPE may not be suitable for service at the corresponding service temperatures.

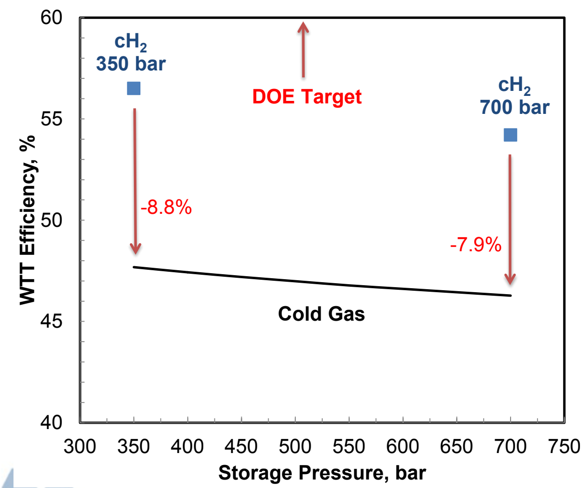
Summary: Cold Gas Storage

Off-board analysis using FCHtool and H2A

- WTT efficiency <50%, 8-9% less than 350 and 700-bar cH_2 options

Advantages/disadvantages relative to cH_2 storage at 700 bar

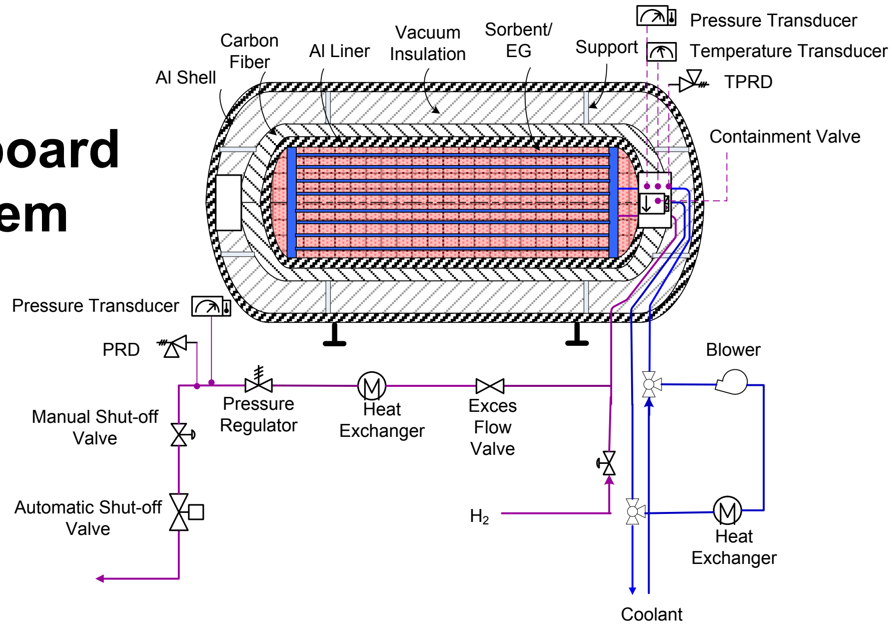
- ~50% saving in carbon fiber composite
- ~30% increase in gravimetric capacity if Type 4 tank can be used
- Small (2%) increase in volumetric capacity
- 13% lower WTT efficiency
- Operating temperatures below the HDPE ductile/fragile temperature
- Vacuum superinsulation required
- Off-board issues related to cryogenic cooling and insulated Type 3 vessels for trailer tubes and cascade storage



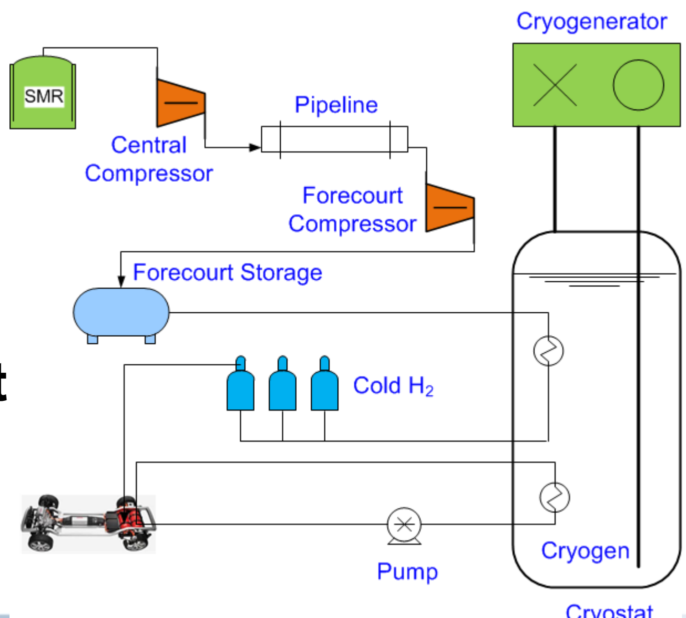
	Units	Ambient cH_2		Cold Gas	2017 Targets
Storage Pressure	bars	350	700	400	
Storage Temperature	K	288	288	195	
H_2 Storage Density	g/L	24.0	40.2	36.4	
Carbon Fiber Composite	kg	61.9	91.0	46.5	
Gravimetric Capacity	wt%	5.4	4.4	5.7	5.5
Volumetric Capacity	g-H_2/L	17.7	25.0	25.5	40.0
Cost at High-Volume Manufacturing	$/kWh	13.0	17.0	TBD	12.0
WTT Efficiency	%	56.5	54.2	47.4	60.0

Hydrogen Storage in Sorbents: Reverse Engineering

On-board System



Forecourt



Key System Requirements

Storage Medium

- 5.6 kg recoverable H_2
- 5-bar minimum delivery P
- Structured Sorbent

Type-3 Containment Vessel

- 2.25 safety factor
- 5,500 P and T cycles
- Toray 2550 MPa CF
- Al 6061-T6 alloy liner

Heat Transfer System

- 1.5 kg/min H_2 refueling rate
- 1.6 g/s H_2 min full flow rate
- MLVSI for 5 W heat in-leakage

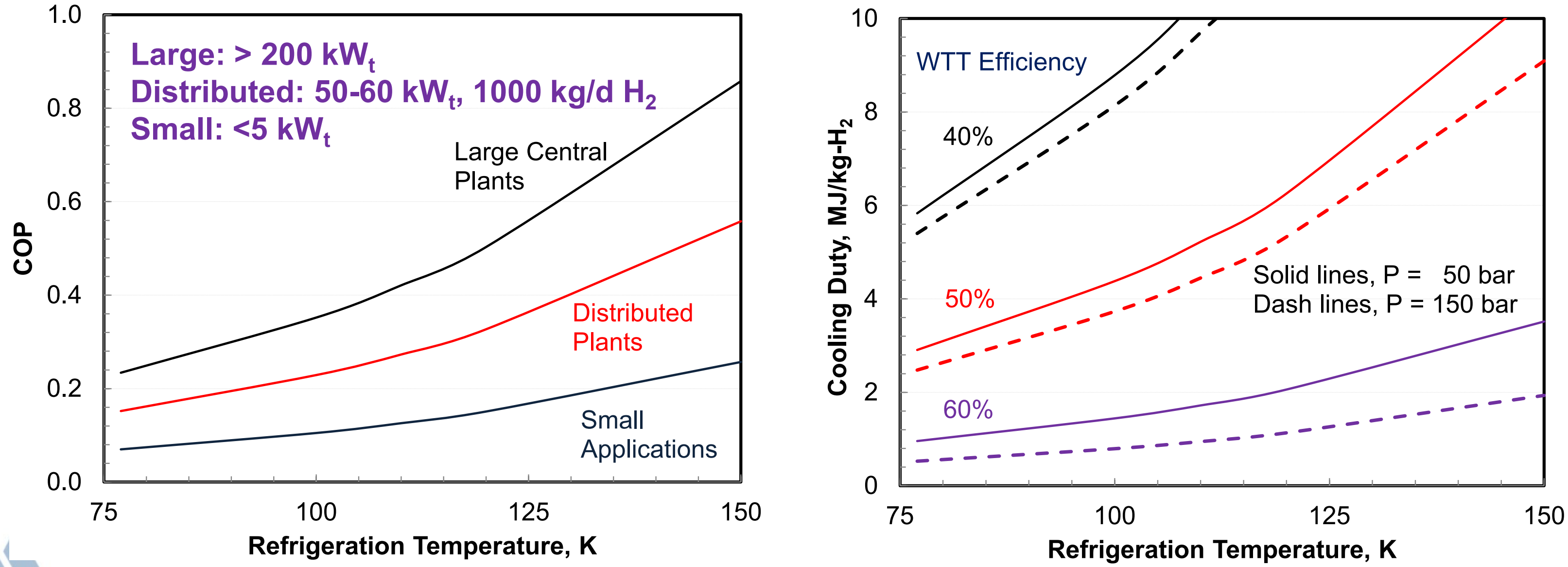
Well-to-Tank Efficiency

Developed an empirical correlation for coefficient-of-performance (COP) of cryogenic systems as a function of refrigeration temperature and plant size

- Literature data for H_2 liquefaction (20 K), LN2 (77 K), LNG (110 K), VLT (180-200 K), and commercial refrigerated storage (230-275 K)
- Three plant sizes: medium size (50-60 kW_t) for 1000 kg/d H_2 stations

Analyzed central H_2 production pathway with pipeline delivery and determined the allowable cooling duty (Q_c) as function of coolant temperature (T_c) and target WTT efficiency (η_{WTT})

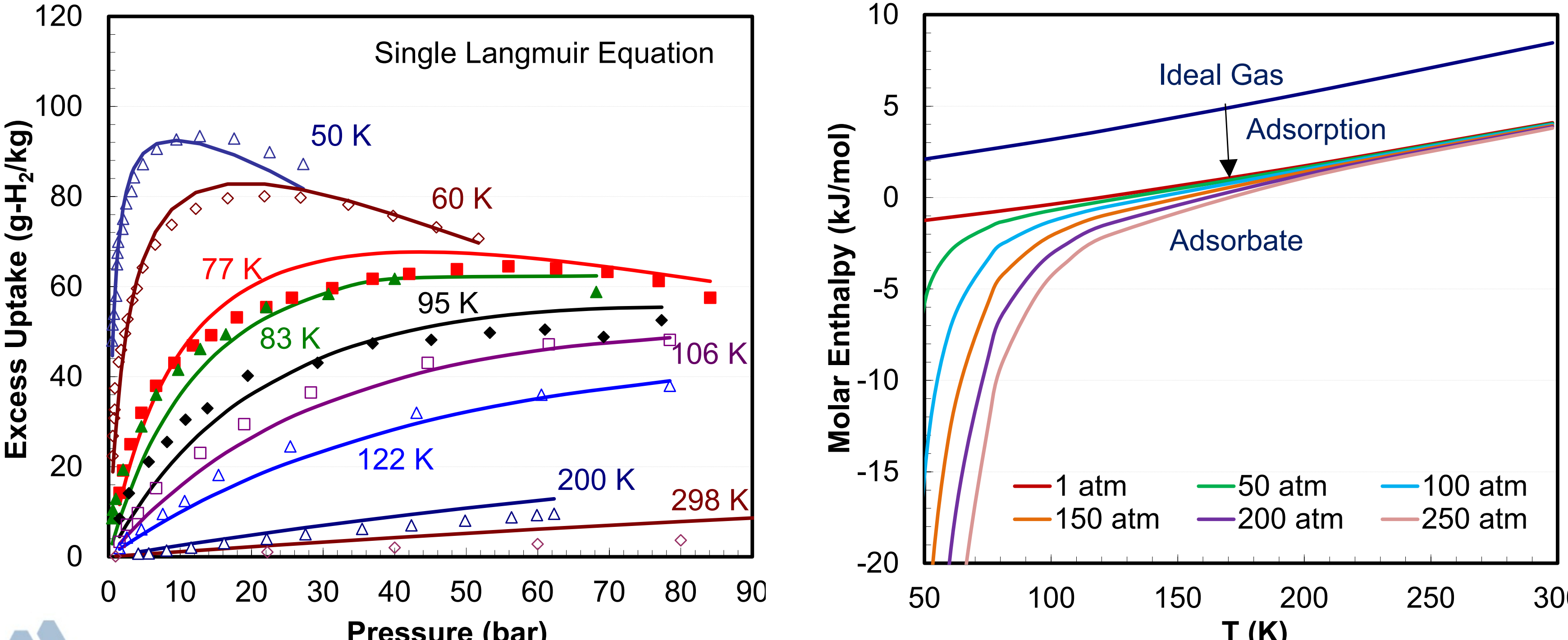
- At 77 K, >4-fold reduction in Q_c if η_{WTT} raised from 40% to 60%
- For 50% η_{WTT}, >3-fold increase in Q_c if T_c raised from 77 K to 150 K



Adsorption Isotherms

Single-Langmuir equation (Stadie, 2013) chosen for reverse engineering as it has only 4 parameters and can adequately fit the available data for H_2 adsorption on MOF-5 powder at 60-300 K (W. Zhou, J. Phys. Chem. C 2007, 111, 16131-16137)

- N_m: Sorption capacity (g-H_2/kg-sorbent), measure of active sites
- ΔH^o: Enthalpy change on adsorption, 3.1 kJ/mol for MOF-5, related to isosteric heat of adsorption
- ΔS^o: Entropy change, 66.5 J/mol.K, varies slightly with temperature
- V_a: Adsorption volume, 0.012 m^2/kg, a fitted parameter

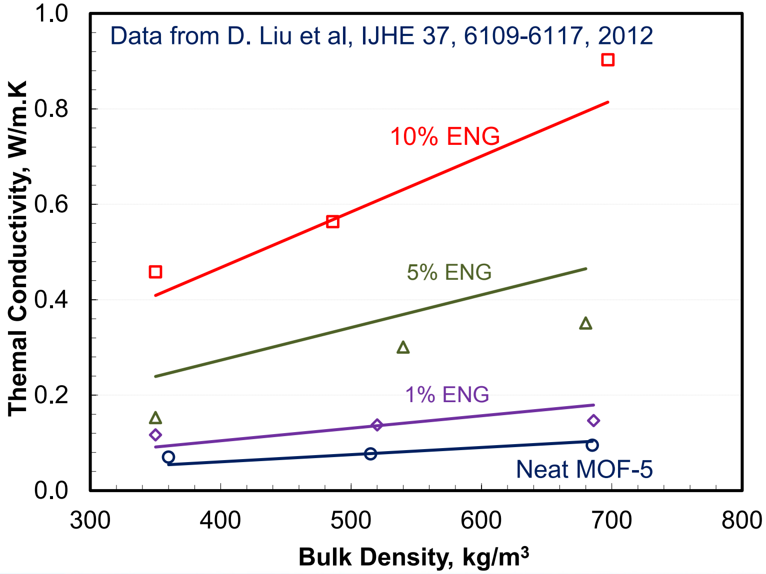


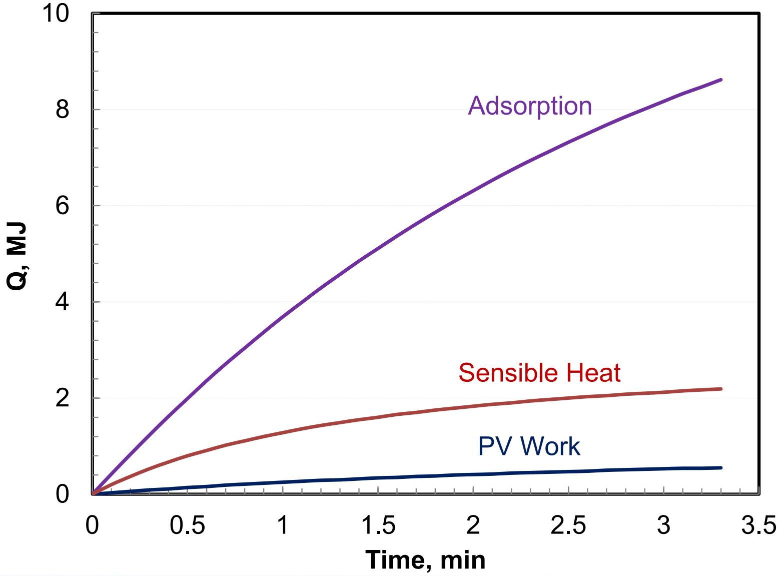
N Stadie, Synthesis and Thermodynamic Properties of Physisorptive Energy Storage Materials, PhD Thesis, Caltech, 2013

Medium Thermal Conductivity and Refueling Dynamics

Expanded natural graphite (ENG) and sorbent compacts for conductivity enhancement and bulk density improvement

- Thermal conductivity is a function of the graphite to sorbent powder weight ratio and the fill factor*, Data from D. Liu et al, IJHE 37, 6109-6117, 2012
- Target ε determined by sorbent bulk density needed to satisfy the volumetric capacity target
- Tube spacing determined by the required rate of heat removal (55 kW avg.) during refueling (25 g/s) rather than heat supply during discharge (1.6 g/s)
- Cooling load for refueling at 100 bar, ΔH^o = 5 kJ/mol
  Off-board: 2.2 MJ/kg-H_2; on-board: 2.0 MJ/kg-H_2





*AR Sanchez, HP Klein, and M Groll, Int. J. Hydrogen Energy 28 (2003) 313-327

Reference Sorbent Targets

A parametric optimization study was conducted to determine the minimum peak excess adsorption (at the reference LN_2 temperature), and the bulk density and T swing, needed to meet the system weight and volume targets with constraints on WTT efficiency, refueling time, and minimum full flow rate of H_2.

- Study parameters: 77-200 K off-board coolant temperature; $T_s - T_c = 20$ K
- Temperature swing for 95% usable H_2
- Fixed sorbent parameters: ΔH^o, ΔS^o, V_a
- Fixed ENG to sorbent weight ratio (20%)

Independent Variables	Related Variables	Reference Values	Constraints
Material Properties			
Excess Uptake at 77 K	ΔH^o = 5 kJ/mol	190 g-H_2/kg-sorbent	5.5 wt% gravimetric capacity
Fill Ratio	Bulk Density	67% bed porosity	40 g/L volumetric capacity
		420 kg/m^3 sorbent bulk density	
	Thermal Conductivity	1 W/m.K bed conductivity	
Operating Temperatures			
Off-board Coolant	WTT Efficiency	135 K	>55% WTT efficiency
Storage Temperature		155 K	
Temperature Swing	Usable H_2	60 K	95% usable H_2
System Variables			
Mass of Sorbent	Mass of Expanded	42 kg sorbent	5.6 kg usable H_2
	Graphite	8.4 kg ENG	
HX Tube Spacing	Number of HX Tubes	$r_2/r_1 = 3.4$	1.5 kg/min refueling rate
		112 U tubes	

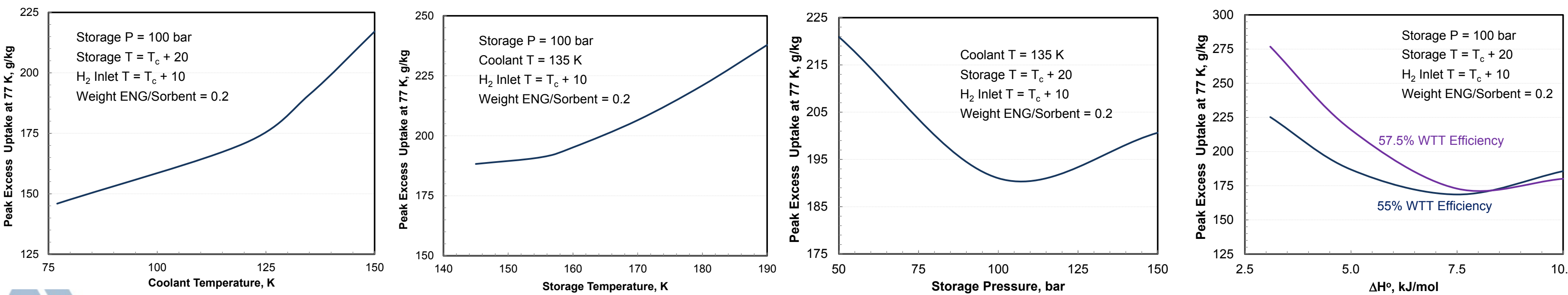
Sensitivity Study

Promising sorbent should have >120 g-H_2/kg excess sorption capacity at 150 K or higher T and 100 bar P, when compacted to 420 kg/m^3 bulk density and mixed with 10-20% ENG (or other conductivity enhancement materials)

- Uptake target can be lower at lower coolant T, but T_c > 135 K needed for >55% WTT efficiency. Also, the lower the T_c, the larger are the on-board and off-board cooling loads.
- Slight decrease in uptake target if the storage temperature is lowered to 145 K, but heavier heat exchanger and lower WTT efficiency.
- For the reference conditions, the uptake target is lowest at 100 bar storage P: compromise between gas density, uptake, temperature swing, and weights of liner and CF.
- Possible to further improve system performance (lower uptake target) by trading-off weights of heat exchanger tubes and conduction enhancement additives. Adsorbents with ΔH^o >7.5 kJ/mol are especially appealing.

Storage temperatures below 150 K not needed, actually counterproductive

Advantageous to reduce the storage pressure to 50 bar



FY2014 Collaborations

Physical Storage	Applied Nanotech, Ford, Hexagon Lincoln Composites, PNNL, SA
Metal Hydrides	HSECoE: SRNL, UTRC
Sorbents	HSECoE: SRNL, UM
Chemical Hydrogen	HSRCoE: LANL, PNNL
GHG Emissions	ANL (GREET)
Off-Board Spent Fuel Regeneration	TBD
Off-Board Cost	ANL (H2A Group), ANL (HDSAM), SA
On-Board Cost	SA
SSAWG	DOE, HSECoE (LANL, PNNL, SRNL, UTRC), OEMs,Tank Manufactures, SA

– Argonne develops the storage system configuration, determines performance, identifies and sizes components, and provides this information to SA for manufacturing cost studies

Future Work

Physical Storage

- MultiMech simulation and validation of CNT/SiO_2 reinforced resins and composites (Applied Nanotech collaboration)
- Validate finite element model against experimental and field data for cold gas storage (collaboration with PNNL led project)
- Further develop and calibrate models for damage tolerance including effects of resin mechanical properties
- Calibrate ABAQUS model for CNG storage conditions (SA collaboration)
- Compare and calibrate results for compressed gas storage (PNNL, Ford collaboration)

Material Based Storage

- Reverse engineering to determine material targets for higher-temperature metal hydrides that need on-board burner
- Hydrogen storage in unstable metal hydrides
- Reverse engineering to develop material properties for chemical storage systems that require off-board regeneration (LANL and PNNL collaboration)
- Provide system-level support to new projects on material discovery

Document models and publish papers on material properties in IJHE

Reviewer Comments

Generally favorable reviews with the following comments/recommendations

- Validation of CF designs may require more than coupon testing – possibly standards-based qualification testing.
- Include recommendations for future improvements to hydrogen storage systems by conducting sensitivity analysis with the models.
- Little or no progress was described for sorbent and off-board regeneration tasks
- Coordinate assumptions and efforts and compare results with HSECoE to avoid duplication.
- Should not continue work on high temperature metal hydrides especially for automotive applications.

FY14 work scope consistent with above recommendations

√ Validating ABAQUS models with Lincoln ring and tank burst tests, modelling SAE J2579 standards-based drop tests.

√ Conducted sensitivity analysis for sorbent systems with recommendations for excess uptake, temperature and pressure.

√ Completed reverse engineering of sorbent systems. CBN regeneration by $MeOH/NaAlH_4$ and formic acid digestion/reduction methods was described in backup slides.

√ Held SSAWG meeting to compare assumptions and results with HSECoE.

Project Summary

Relevance:	Independent analysis to evaluate on-board and off-board performance of materials and systems
Approach:	Develop and validate physical, thermodynamic and kinetic models of processes in physical and material-based systems Address all aspects of on-board and off-board targets including capacities, rates and efficiencies
Progress:	Determined optimum storage pressure for cold gas storage that can achieve >30% reduction in CF compared to ambient temperature 700-bar tanks Evaluated the penalty (13%) in off-board WTT efficiency for cold gas option Performed reverse engineering to determine material properties of adsorbents: sorption capacity, enthalpy of adsorption, storage and operating temperatures, and heat transfer Reverse engineering in progress to determine properties of chemical storage materials: H-capacity, thermodynamics, chemical kinetics, and operating temperatures, and heat transfer
Collaborations:	SSAWG, HSECoE, ANI, Ford, LANL, PNNL, SA, SRNL
Future Work:	Propose, analyze and validate methods of reducing cost of CF wound storage tanks Reverse engineering to establish material targets for metal hydrides, sorbents, and chemical storage

Technical Back-Up Slides

Publications and Presentations

Journal Publications

H.S. Roh, T.Q. Hua, and R.K. Ahluwalia, "Optimization of Carbon Fiber Usage in Type-4 Hydrogen Storage Tanks for Fuel Cell Automobiles," International Journal of Hydrogen Energy. 38 (2013) 12795-12802.

J.K. Peng and R.K. Ahluwalia, "Enhanced Dormancy due to Para-to-Ortho Hydrogen Conversion in Insulated Cryogenic Pressure Vessels for Automotive Applications," International Journal of Hydrogen Energy, 38 (2013) 13664-13672.

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Insulated Tanks for On-board and Off-board Storage

ASTM or UL Test	HDPE Property	Value
D 696	Coefficient of thermal expansion (10^{-5} m/m/°C)	-12
	Specific heat (kJ/kg-K at 25°C)	2.2 - 2.3
D 792	Density (kg/m^3)	950
	Glass transition temperature (°C)	-110
	Ductile/fragile temperature (°C)	-70
D 3418	Melting temperature (°C)	120 - 130
	Maximum operating temperature (°C)	82

Trailer tubes

- Temperatures too low for Type 4
- Trailer payload capacity favors Type 3 over Type 1

On-board fuel tank

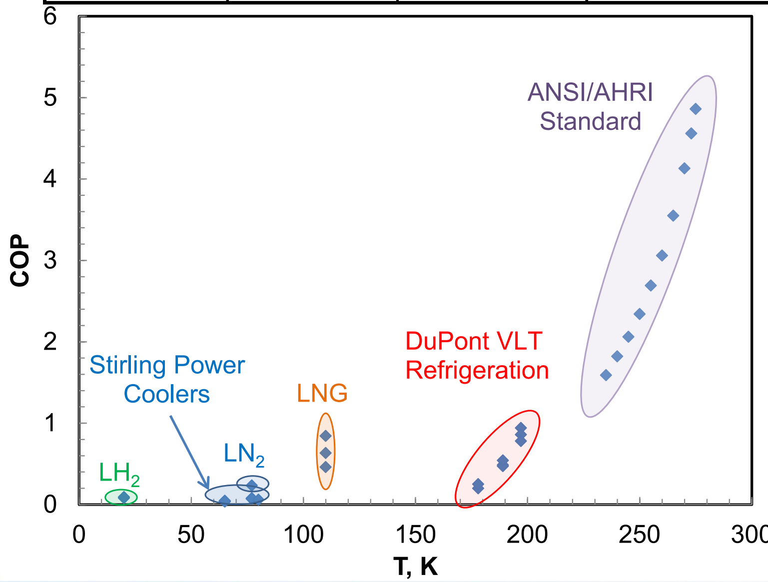
- Type 4 preferable to Type 3 because of lower weight and cost
- Type 4 possible if operating temperatures remain above 200 K

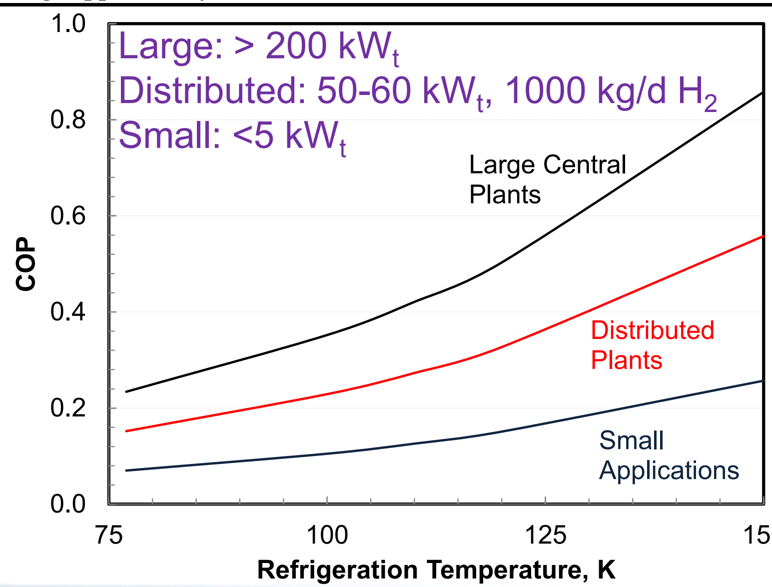
Tube banks at station

- Type 1 may cost less than Type 3

Coefficient of Performance (COP) of Cryogenic Systems

Refrigeration System	T, K	Capacity, kW_t	COP	Comments
LH_2	20	200	0.081	Linde Ingolstadt (1992), 13.6 kWh/kg, 4.4 t/d
	20	225	0.092	Linde Leuna (2007), 11.9 kWh/kg, 4.9 t/d
LN_2	65	0.5 - 2.5	0.037 - 0.046	Stirling Power Cooler, Stirling Cryogenics
	77	0.8 - 7.3	0.070 - 0.077	Stirling Power Cooler, Stirling Cryogenics
	77	24000	0.234	Large air separation plant, 0.5 kWh/kg, 4860 t/d
LNG	110	17000	0.46 - 0.632	Kanfa Aragon N_2 expander cycle, 0.4-0.55 kWh/kg, 3000 t/d
	110	17000	0.843	Aragon Dual Cascade mixed refrigerant, 0.3 kWh/kg, 3000 t/d
VLT: R-503	178 - 197	0.2 - 1.9	0.2 - 0.94	VLT refrigeration, DuPont, ozone depleter, higher capacity than R-13
VLT: R-13	178 - 197	0.1 - 1.2	0.25 - 0.78	DuPont, ozone depleter, to be phased out
VLT: HFC-23	189 - 197	0.1 - 1.6	0.86	Freon 23, CFC free, 10% higher energy consumption than R-503
Commercial Refrigerated Storage	230 - 245	5	1.59 - 2.06	ANSI / AHRI standard refrigerated storage contaniners, cabinets
	250 - 260	5	2.34 - 3.06	ANSI/AHRI Standard 1210
	265 - 275	5	3.55 - 4.86	Ratings approved by ANSI in Jan 2011



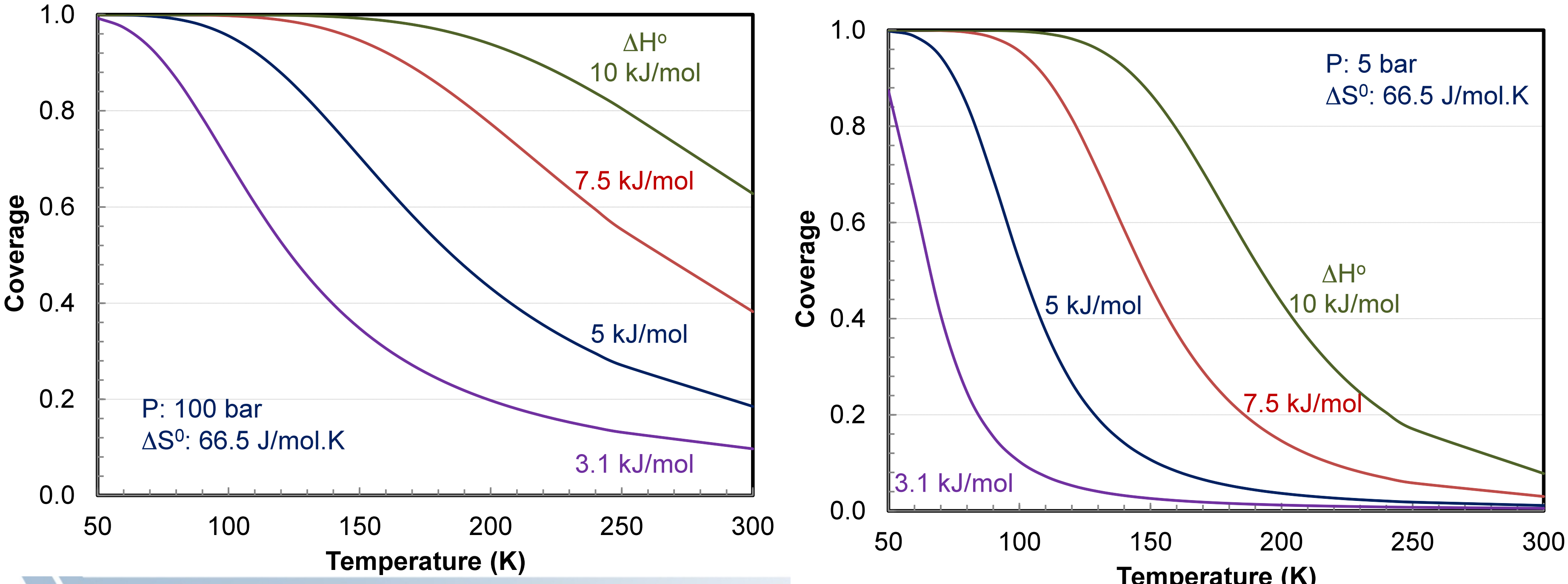


COP (ratio of heat removed to input electrical energy) is a function of refrigeration T and plant size

Advanced Sorbents

Advanced micro-porous adorbents with high specific area (sites) and ΔHº > 5 kJ/mol as well as low storage temperatures with sufficient temperature swings are needed.

- Storage temperature depends on ΔH^0. Temperature below 150 K not needed if ΔH^0 > 7.5 kJ/mol.
- Pressure swing alone may not be sufficient for >90% usable H_2. Materials with ΔH^0 > 7.5 kJ/mol will require temperature swing.



Summary: Sorbents

The promising sorbent should have >120 g-H_2 /kg excess sorption capacity at 150 K or higher temperature and 100 bar pressure, when compacted to 420 kg/m^3 bulk density and mixed with 10-20% expanded natural graphite (or other conductivity enhancement materials)