System Level Analysis of Hydrogen Storage Options

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Project ID: ST01

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

- FY16 DOE Funding: $480 K
- FY17 DOE Funding: $600 K

Partners/Interactions

- Hexagon Lincoln (HL), Materia, PNNL
- BMW, LLNL
- Ford, LANL
- ORNL
- Delivery Team, Hydrogen Interface Taskforce (H2IT)
- Strategic Analysis

Relevance and Impact

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 FY2017 work

- Demonstrated that 2-mm stainless steel (SS) liner is preferable to aluminum liner in cryo-compressed H_2 (CcH_2) storage systems for buses
- Compared to the baseline 350-bar compressed hydrogen (cH_2) tanks currently in use, 500-bar CcH_2 can achieve 66% improvement in gravimetric capacity, 132% increase in volumetric capacity, and 36% saving in carbon fiber (CF) composite
- Determined >7 d loss free dormancy with 95% full 500-bar CcH_2 tanks

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, national labs and others in obtaining data, and provide feedback
- Participate in meetings and communicate approach and results to foster consistency among DOE-sponsored analysis activities

FY2017 Tasks and Progress

1. Cryo-compressed H_2 Storage (FY2017 Q1)
   - Analyzed autofrettage process and liner fatigue using ABAQUS FE-SAFE
   - Conducted GCtool simulations of supercritical CcH_2 storage with off-board LH_2 pump and dormancy at different storage pressures and fill levels
2. Compressed H_2 storage (FY2017 Q2)
   - Setting up models for carbon fiber damage in impact tests
3. H_2 storage in sorbents (FY2017 Q3)
   - Update heat transfer model and absorption isotherms for compacted pellets
   - Revisit H_2 storage using high-pressure LH_2 pumps
4. H_2 storage in high-pressure metal hydrides (FY2017 Q4)
   - Revise analysis and publish paper on target material and transport properties

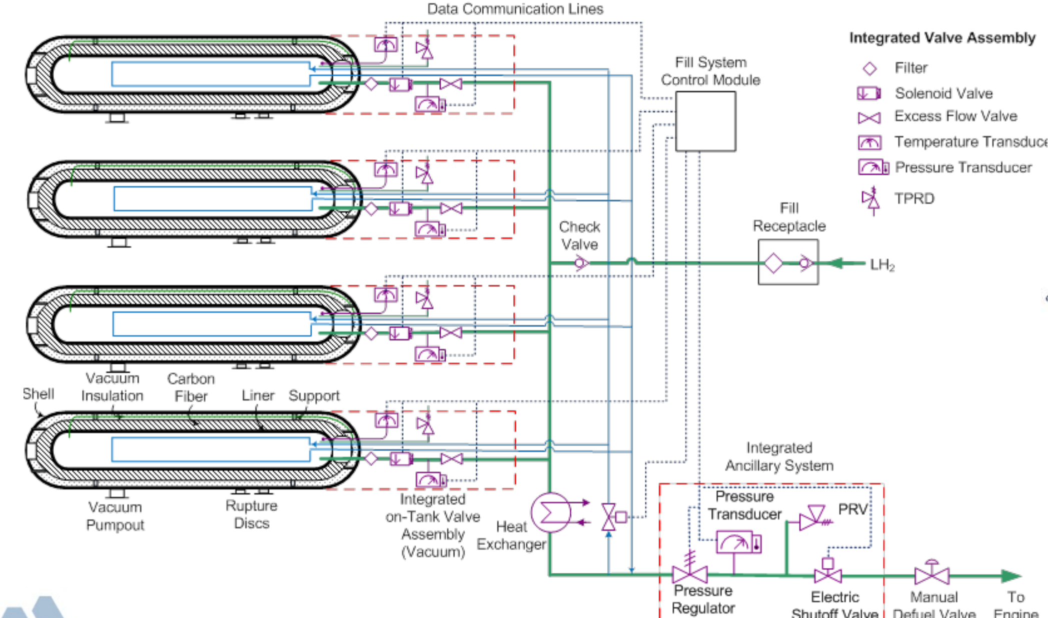
1	Conduct system analysis of CcH_2 storage for FC buses and garbage trucks with emphasis on dormancy, durability and capacity	12/16
2	Conduct ABAQUS simulations to determine reduction in CF usage and system cost with recent improvements in materials and designs, relative to the current benchmarks of 97 kg CF composite and 15 $/kWh for 5.6 kg usable H_2 at 700 bar.	03/17
3	Conduct system analysis for H_2 storage in sorbents utilizing data validated models for best-of-class framework materials relative to the 2020 system targets for gravimetric capacity (5.5 wt%), volumetric capacity (40 g/L), and WTE efficiency (60%).	06/17
4	Update system analysis for H_2 storage in high-pressure, low-enthalpy metal hydrides and determine material properties needed for meeting 2020 system targets for refueling rate (1.5 kg/min), gravimetric capacity (5.5 wt%), volumetric capacity (40 g/L), and WTE efficiency (60%).	09/17

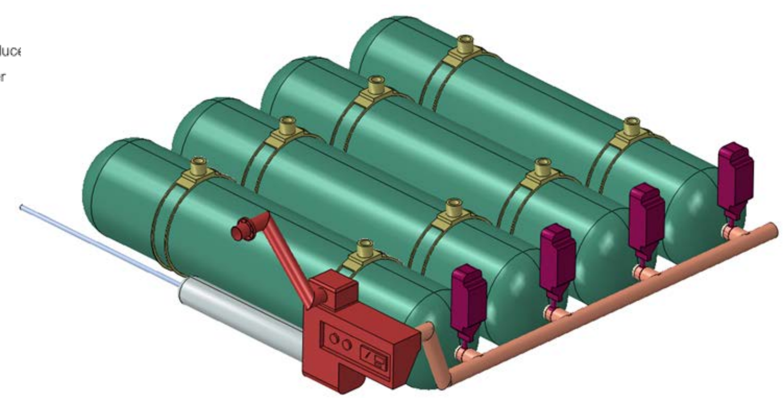
Cryo-Compressed (CcH_2) Hydrogen Storage for FC Buses

	Current Practice	Future Candidate
Storage Option	350-bar cH2	350-700-bar CcH_2
H_2 Tank	Type 3, T700 CF	Type 3, T700 CF
Liner	Aluminum	Aluminum or Stainless Steel
H_2 Storage Capacity	40 kg	40 kg
Number of Tanks	8	4
L/D	5	5
H_2 Density	24 kg/m^3	LH_2: 71 kg/m^3 at 20 K, 1 bar
Refueling Rate	5 kg/min	TBD

Issues to be addressed

1. Cryogenic liner behavior
2. CcH_2 system parameters
3. Operating pressures and temperatures
4. Realizable storage capacities
5. Loss-free dormancy





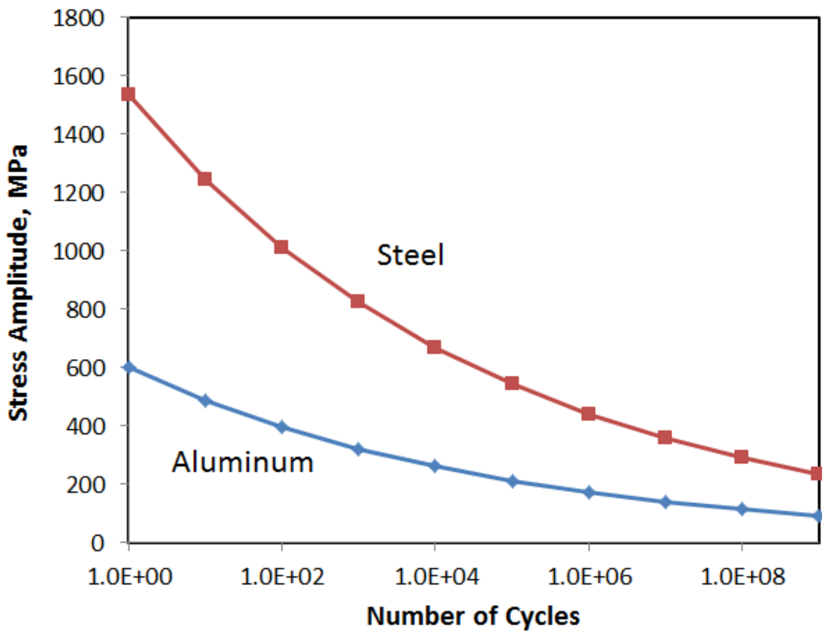
ABAQUS Analysis

ABAQUS WCM and FE-SAFE Models

- Autofrettage process to induce residual compressive stress in liner and increase the fatigue life of the composite tank
- Thermal stresses during service at cryogenic temperatures

Process and Material Options

- Autofrettage at ambient temperature or at cryogenic temperature
- Autofrettage (proof) pressure
- Minimum tank pressure to prevent separation
- Aluminum or stainless steel liners
- Fatigue SN curves* for aluminum (Al) and stainless steel (SS)



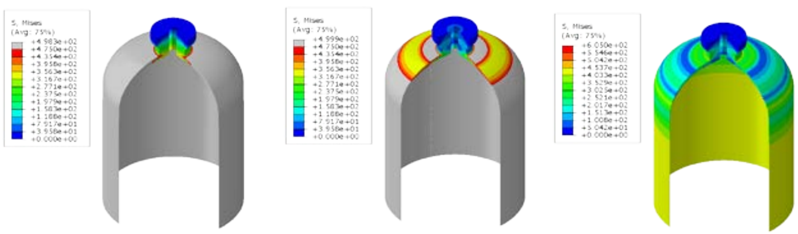
Applicable Codes and Standards

- SAE durability test cycles: 5500 for light duty vehicles, 15000 for commercial heavy duty vehicles

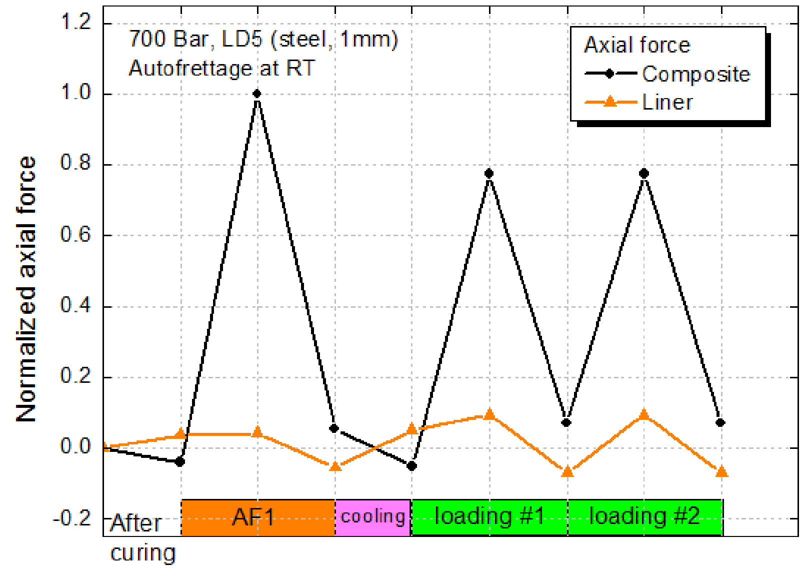
* Military Handbook, 2003, MIL-HDBK-5H, and Muralidharan UU, Manson SS, *ASME J. Eng. Mater. Technol.* 1988;110(1):55-58

Autofrettage Process – Axial Stresses

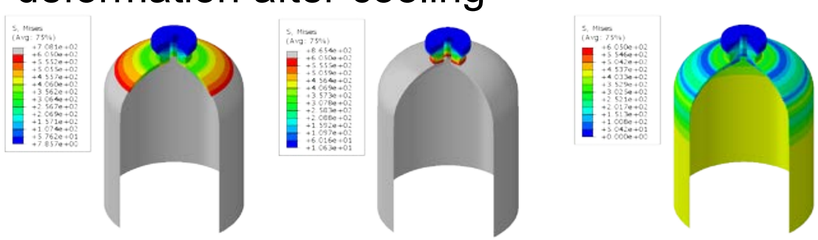
- Process option AF1: autofrettage at RT, then cool tank to service temperature
  - ➢ Liner is in compression after autofrettage, but thermal stress induced during cool-down places it in tension
  - ➢ Entire liner undergoes plastic deformation during loading (as expected)



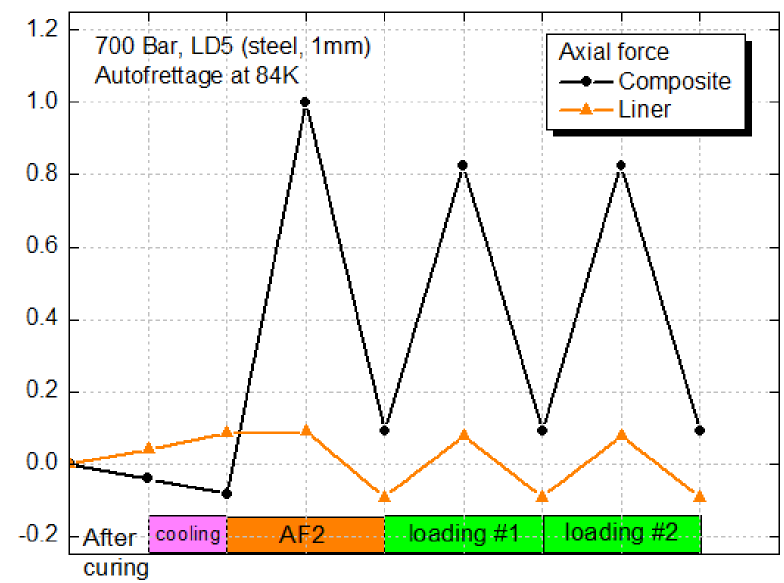
After proof loading After unloading After Cooling



- Process option AF2: cool tank to service temperature, then autofrettage
  - ➢ Liner is in tension after cool down, but in compression after autofrettage
  - ➢ The cylinder section has undergone plastic deformation after cooling

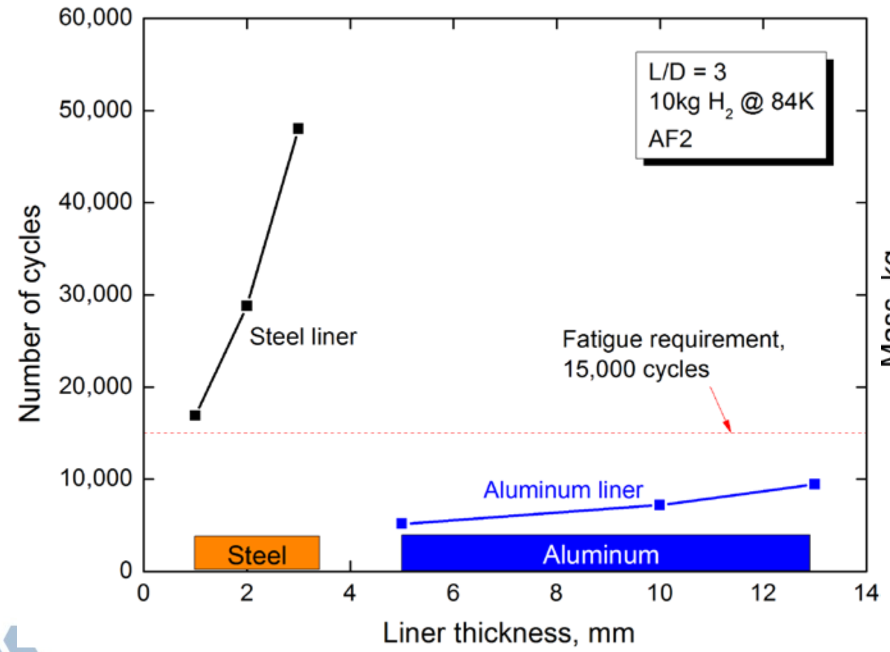


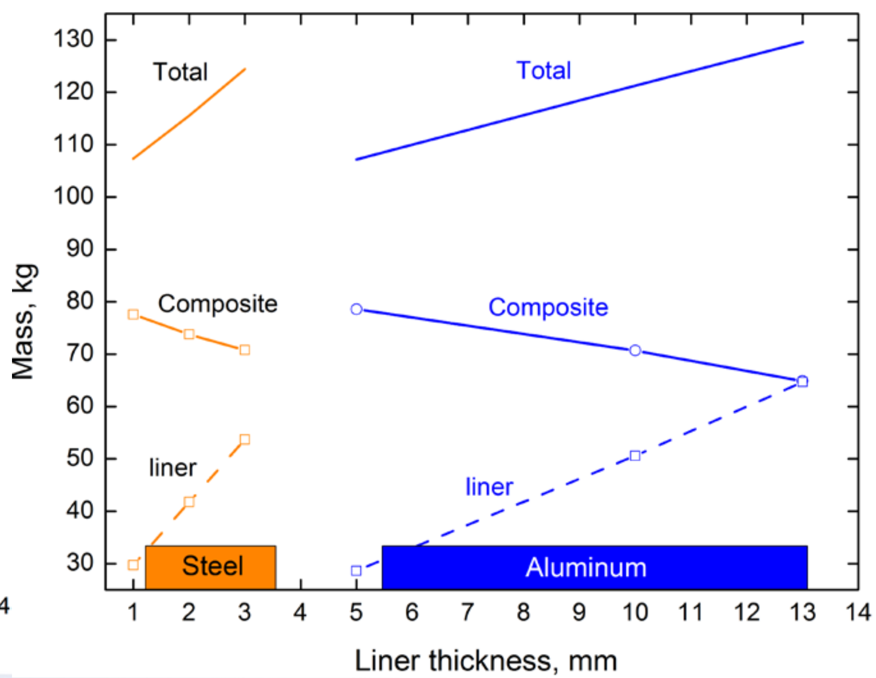
After cooling After proof loading After unloading



Fatigue Life: Aluminum vs. Steel

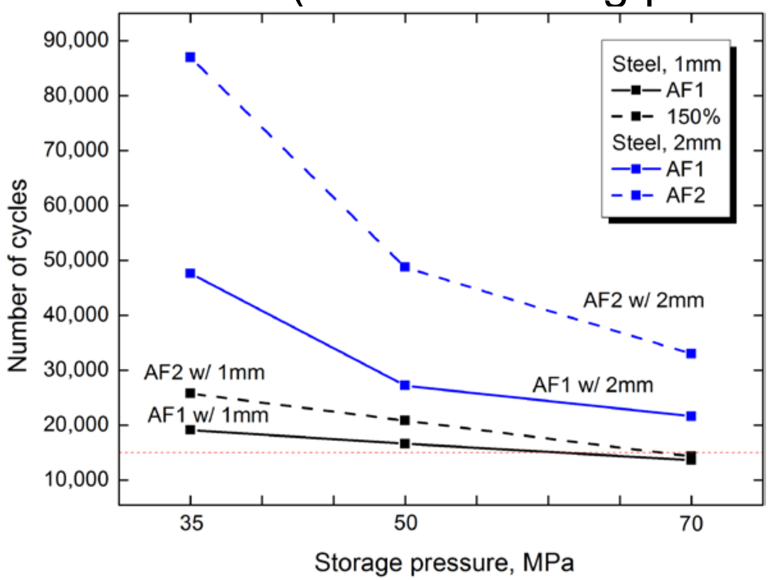
- 10-kg H_2 tanks with L/D = 3, nominal T = 84 K, P = 70 MPa, SF = 2.25
  - Autofrettage performed at 84 K
- **Steel liner meets fatigue life requirement with thickness as small as 1 mm**
  - 1 mm liner weighs 29.7 kg, about 28% of total tank weight
- **Aluminum liner fails before 15,000 cycles for thicknesses up to 13 mm (9500 cycles)**
  - Al liner weighs 64.7 kg, about 50% to total tank weight
  - Tank weight ~130 kg, 22 kg heavier than a 1-mm steel-lined tank

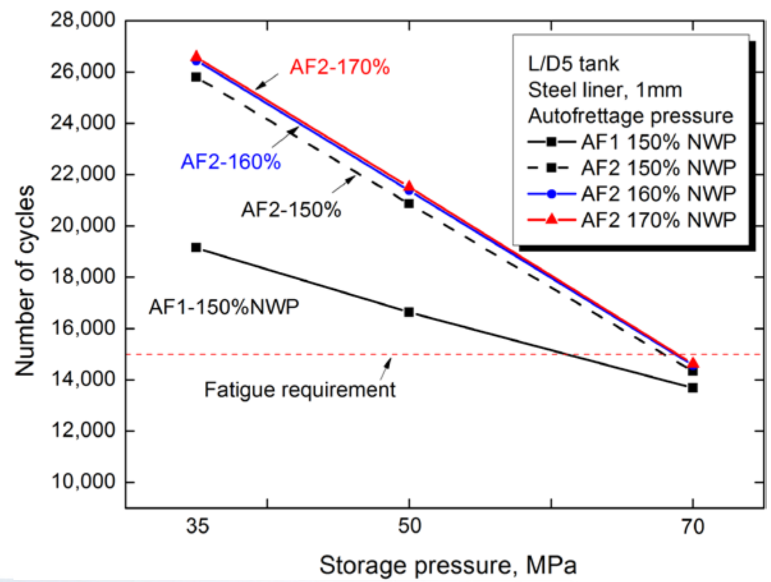




Fatigue Life: AF1 vs. AF2

- 10-kg H_2 tanks with L/D = 5, nominal T = 84 K, P = 35 – 70 MPa, SF = 2.25
- **Longer cycle life if autofrettage performed at cryogenic temperature (AF2)**
  – Improvement is more pronounced with thicker liner
  – **AF2 not necessary since AF1 can produce sufficient fatigue life**
- **Lower CF and liner material cost with 2-mm rather than 1-mm liner**
  – P = 50 MPa, Δ(CF) = - 4.0 kg, Δ(liner) = 15.0 kg, Δ(cost) = -$85
- Autofrettage performed at low temperature may be subjected to higher autofrettage pressure because yield stress and modulus of the metal are higher at lower temperature
  – Small enhancement in fatigue life by raising autofrettage to 170% NWP from 150% NWP (normal working pressure)





$29/kg CF (Strategic Analysis), $2/kg Al-6061 (commodity spot price)

Performance of CcH2 System for Fuel Cell Buses

GCtool model for CcH_2 storage: Ahluwalia, R. K. and Peng, J. K., Int. J. Hydrogen Energy, Vol. 33, Issue 17, pp. 4622-4633, Sep. 2008; Int. J. Hydrogen Energy, Feb. 2010, Vol. 35, 4171-4184, 2010; Int. J. Hydrogen Energy, Vol. 38, 13664-13672, 2013.

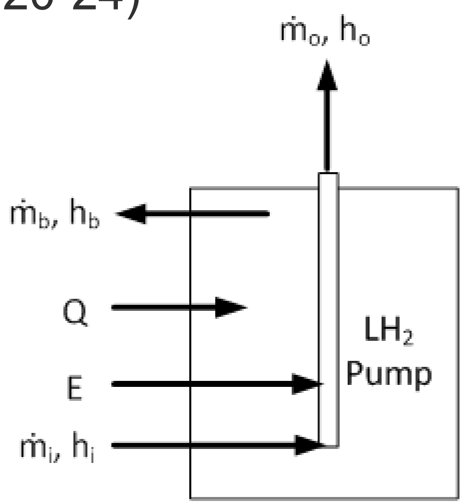
System Parameter	Reference Value[1]	Range[1]	Comment
Storage Pressure	500 bar	350-700 bar	Type-3 carbon fiber wound tank
Empty Pressure	5 bar	5-10 bar	Minimum delivery pressure set by FCS
Storage Volume[2]	4 x 169 L	4 x 155-183 L	40 kg usable H_2
Storage Temperature	107.9 K	93-123 K	Determined by LH_2 refueling and LH_2 pump efficiency
Discharge Temperature	47.1 K	47.1-49.5 K	Function of duty cycle, 1-3 day discharge time
Heat Rate	4 x 53 W	4 x 52-70 W	Repeat charge-discharge cycle
Refueling Rate	1.6 kg/min	5 kg/min target	Set by LH_2 pump capacity
Tank Aspect Ratio	L/D = 5	L/D = 3-5	
Liner Thickness	2-mm SS	9.5-15.2 mm Al	SAE J2579: 11,250 duty cycles; ABAQUS FE-SAFE Model
Autofrettage Pressure	1.5 x NWP		Same as proof pressure
Carbon Fiber Amount	4 x 64.2 kg	4 x 43.2-96.2 kg	T700 CF; SAE J2579: 2.25 Safety Factor; ABAQUS-WCM Model.
Insulation Thickness	7.4 mm	6.9-8.1 mm	10 W heat gain, MLVSI

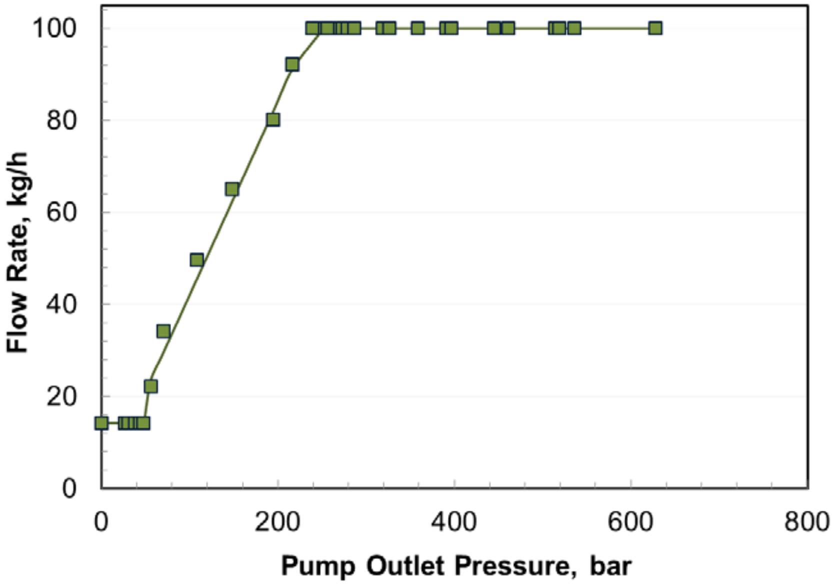
[1] Unless noted otherwise, results are for SS liner and high-efficiency LH_2 pump

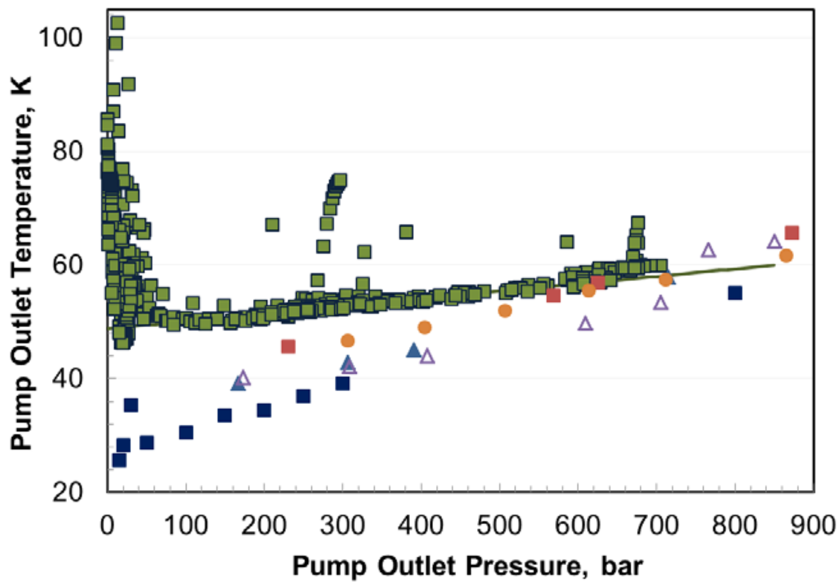
[2] Refers to gas (empty tank) volume

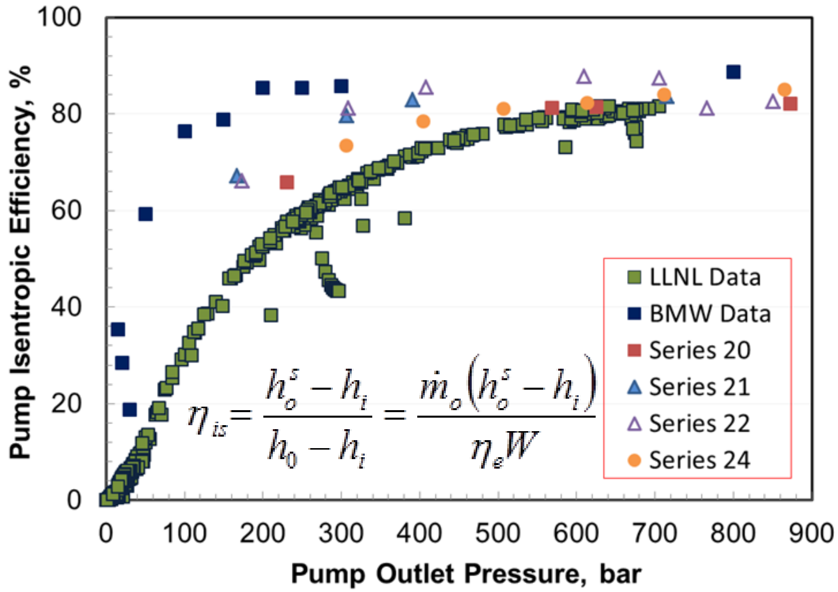
LH_2 Pump Performance

Data Sources: LLNL (880 bar pump), BMW (350 bar pump, high efficiency), Linde (Series 20-24)



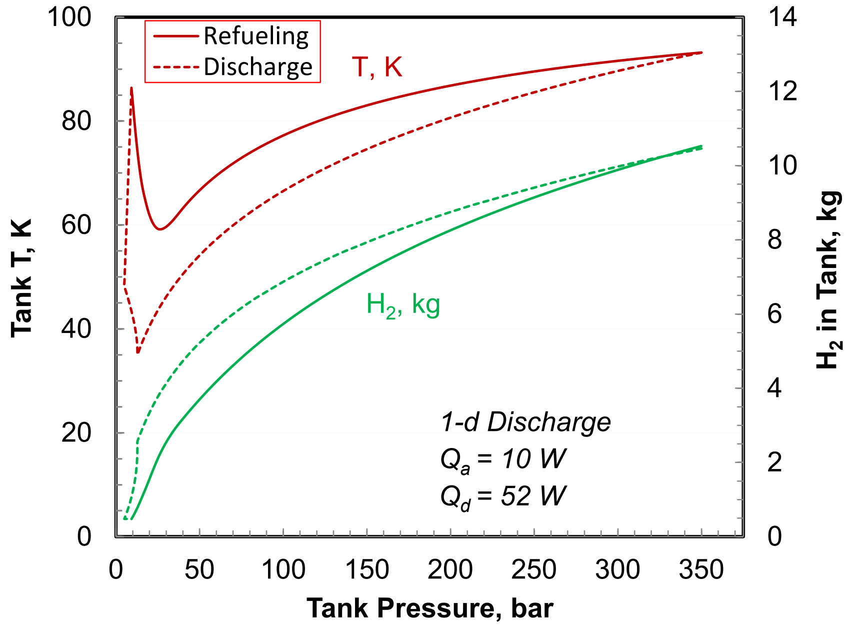






$$\eta_{is} = \frac{h_o^s - h_i}{h_0 - h_i} = \frac{\dot{m}_o\left(h_o^s - h_i\right)}{\eta_e W}$$

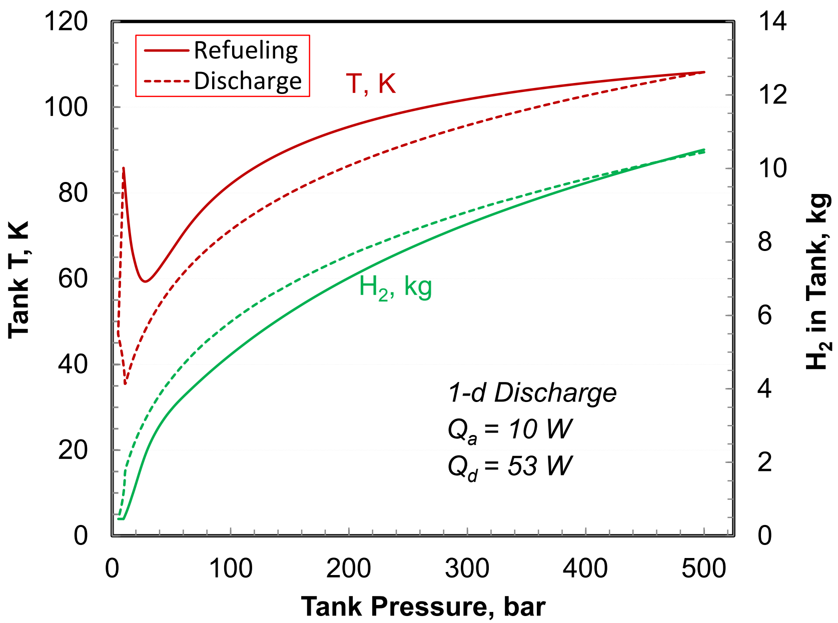
Repeat Charge-Discharge Cycle: 2-mm SS Liner, 350-700 bar

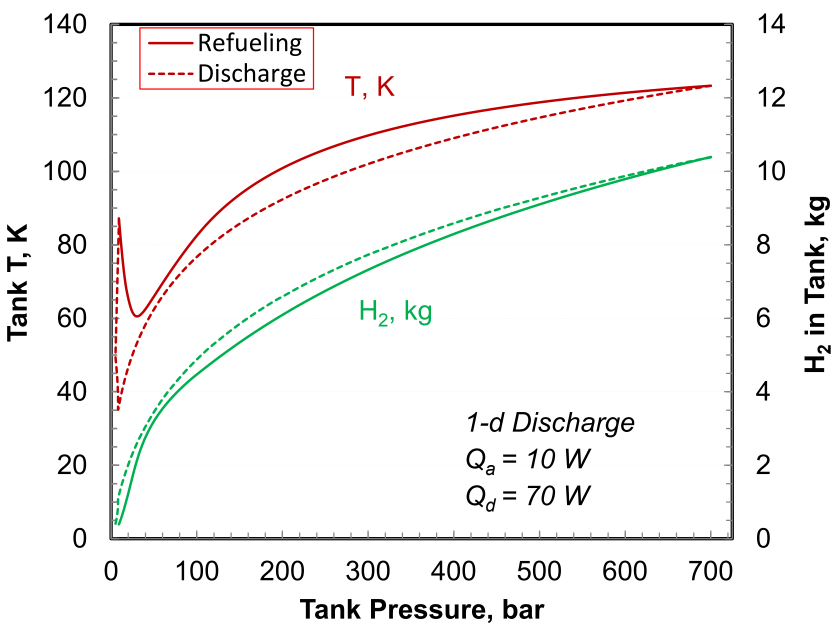


Supercritical CcH_2 storage: small heater or heat exchanger (HX) to prevent liquid formation

Volumetric capacity highest at intermediate P

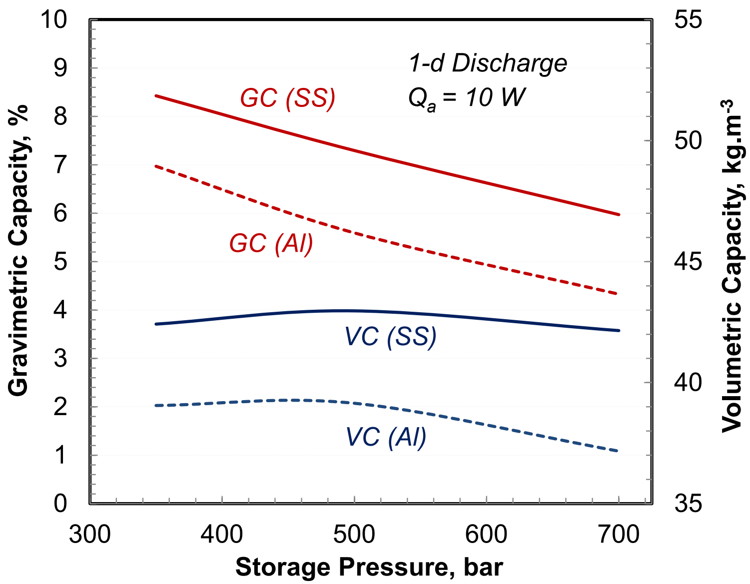
Storage Pressure	350 bar	500 bar	700 bar
Storage Temperature	93 K	108 K	123 K
Storage Density	57.4 g/L	61.9 g/L	67.0 g/L
Usable H_2	95.5%	95.6%	96.2%
Gravimetric Capacity	8.4%	7.3%	6.0%
Volumetric Capacity	42.4 g/L	43.0 g/L	42.2 g/L
Storage Volume	4x183 L	4x169 L	4x155 L

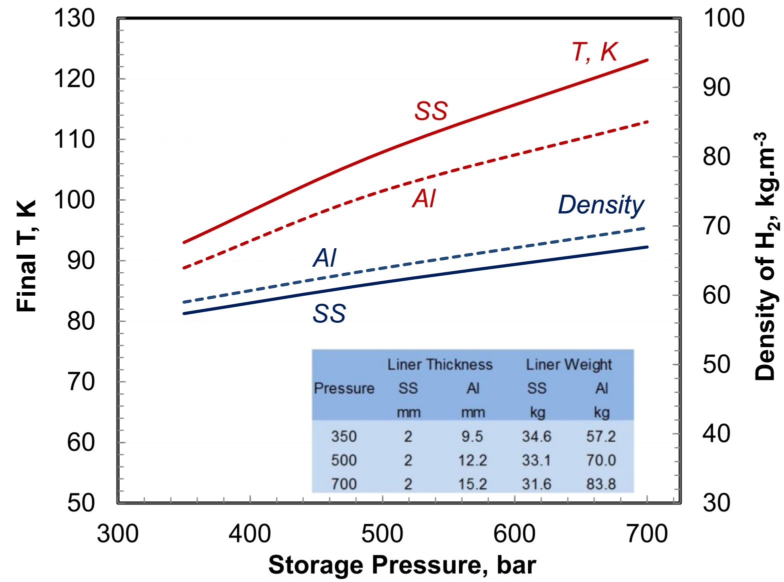




Storage Capacities: Stainless Steel vs. Aluminum Liner

In spite of higher material density and storage temperature, gravimetric and volumetric capacities are higher with stainless steel liner.

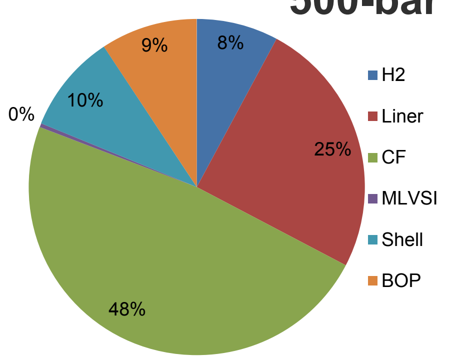




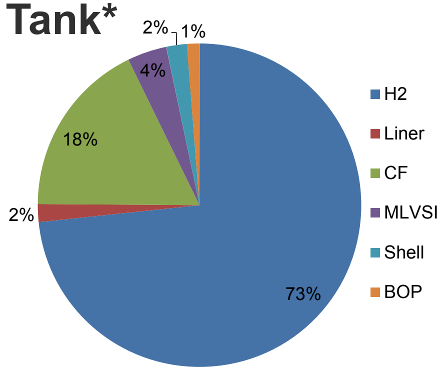
Pressure	Liner Thickness SS mm	Liner Thickness Al mm	Liner Weight SS kg	Liner Weight Al kg
350	2	9.5	34.6	57.2
500	2	12.2	33.1	70.0
700	2	15.2	31.6	83.8

At 500 bar, CF composite and SS liner account for 73% of the tank* weight, the volumetric efficiency is 73%.

500-bar Tank*

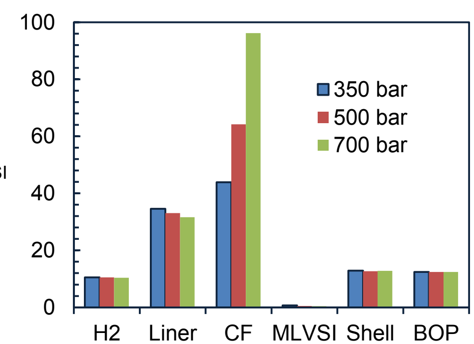


Weight Distribution

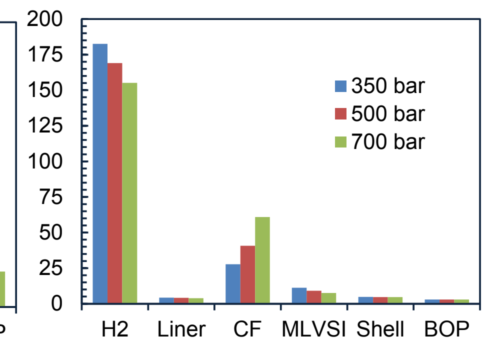


Volume Distribution

Effect of Pressure on Weight and Volume



Weight (kg)



Volume (L)

[1]Includes components associated with each tank, excludes components common to all tanks

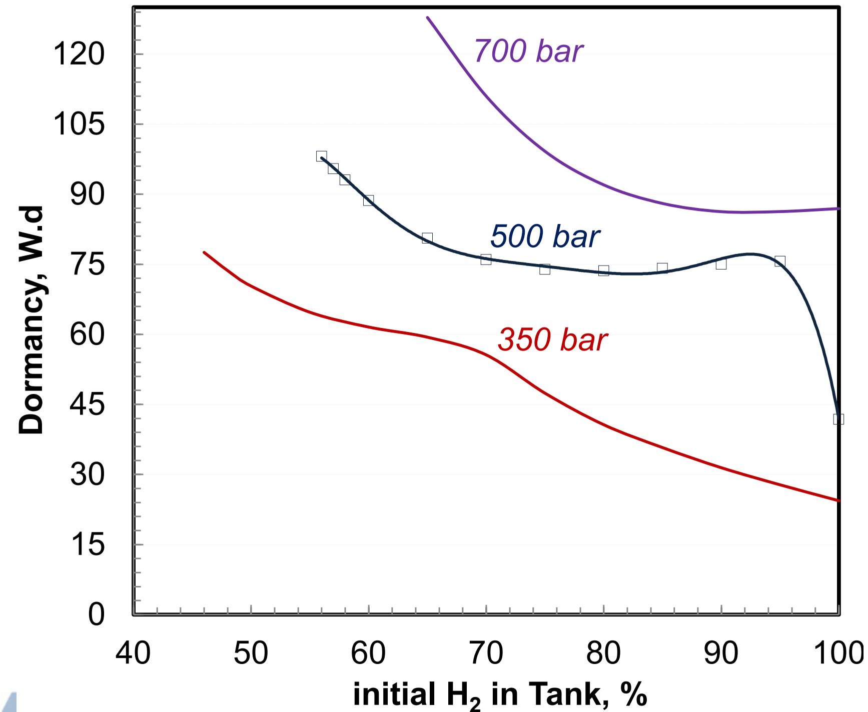
Dormancy

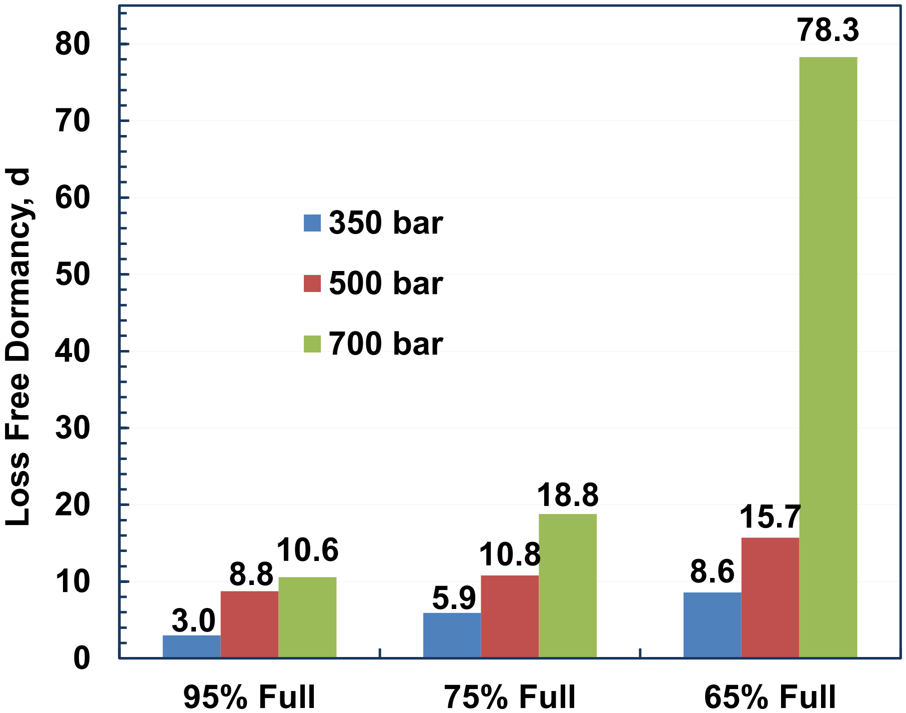
>7-d dormancy for 95% full tank at 500-bar storage pressure

- Increase in dormancy with storage pressure also depends on amount of H_2 stored; 700 vs. 350 bar: 3.5x at 95% full, 9x at 65% full

Simulation parameters

- Pressure relief valve (PRV) set point: 1.25 X normal working pressure
- Initial tank temperature function of prevailing tank pressure
- Heat gain function of tank temperature
- Para-to-ortho conversion





Summary and Evaluation

Liner material of choice: SS for CcH_2 and Al for Type-3 350-bar, RT cH_2 storage

- LH_2 pump efficiency impacts off-board H_2 loss and recovery more than the storage temperature and gravimetric/volumetric efficiency
- 5 kg/min H_2 refueling rate for FC buses requires a LH_2 pump that has 3 times the capacity of the pump tested at LLNL
- 66% (64%) increase in gravimetric capacity, 132% (74%) increase in volumetric capacity, and 36% (64%) saving in CF composite for FC buses (LDVs)

	Fuel Cell Bus				**Fuel Cell LDV**	
Storage Method	CcH_2	CcH_2	CcH_2	cH2	CcH_2	cH2
Storage Pressure	500 bar	500 bar	500 bar	350 bar	500 bar	700 bar
Usable H_2	4 x 10 kg	4 x 10 kg	4 x 10 kg	8 x 5 kg	1 x 5.6 kg	1 x 5.6 kg
Liner	2-mm SS	12.2 mm Al	2-mm SS	7.1 mm-Al	2-mm SS	5-mm HDPE
LH_2 Pump Efficiency	High	High	Low		High	
Storage Temperature	107.9 K	101.5 K	115.8 K	288 K	102.3 K	288 K
Storage Density	61.9 kg/m^3	63.9 kg/m^3	59.5 kg/m^3	24 kg/m^3	63.6 kg/m^3	40.2 kg/m^3
Usable Hydrogen	95.6%	95.6%	95.5%	96.1%	98.3%	95.8%
Gravimetric Capacity	7.3%	5.6%	7.1%	4.4%	6.9%	4.2%
Volumetric Capacity	43.0 kg/m^3	39.2 kg/m^3	41.4 kg/m^3	18.5 kg/m^3	42.7 kg/m^3	24.6 kg/m^3
CF Composite	4 x 64.2 kg	4 x 70.3 kg	4 x 66.9 kg	8 x 50 kg	1 x 34.5 kg	1 x 96 kg
Dormancy						
95% Full	8.8 d	9.3 d	9.3 d	NA	9.4 d	NA
75% Full	10.8 d	12.5 d	12.0 d	NA	11.2 d	NA
60% Full	23.9 d	26.2 d	35.0 d	NA	23.1 d	NA

Updated 700-bar cH_2 System

Updated system physical parameters

- Ambient temperature: consistent with SAE regulations (15°C vs. 20°C), 1.1% saving in CF
- Tank empty pressure: 1 (20 bar) or 2-stage (10-15 bar) pressure regulator and supply pressure effect, 1.1-2.1% saving in CF
- Tank design: conventional (Conv.) vs. alternate (Alt.) design similar to Mirai tank, 4.9% saving in CF

	A	B	C	D	E	F
Empty pressure, bar	20(1)	20	15(2)	10(3)	15	10
Ambient temperature, °C	20	15	15	15	15	15
Tank design	Conv.	Conv.	Conv.	Conv.	Alt.(4)	Alt.
CF composite, kg	97	95.9	94.9	93.9	90.3	89.3
Gravimetric capacity, wt%	4.19	4.23	4.26	4.29	4.41	4.45
Volumetric capacity, g-H_2/L	24.38	24.64	24.88	25.13	25.23	25.48

(1) Quantum 1 or 2-stage pressure regulator

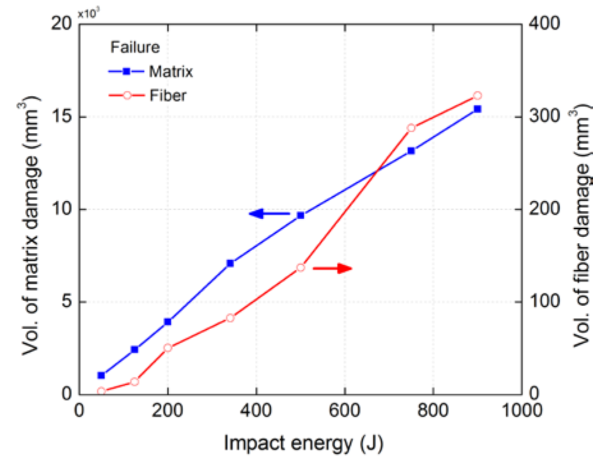
(2) Aerodyne Controls 2-stage pressure regulator

(3) JTEKT 2-stage pressure regulator in Toyota Mirai, empty pressure unknown

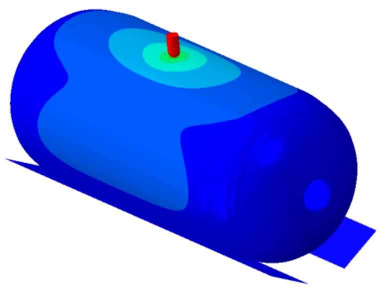
(4) Similar in design to the storage tank used in Toyota Mirai

Preliminary ABAQUS Impact Damage Analysis Results

- Deformation extends as far as the dome region for energy as low as 50 J
- For impact energy E < 200 J, fiber damage occurs only in the outer layers (GF/epoxy)
- For E > 340 J, fibers in the inner composite layers (CF/GF/epoxy) are also damaged
- Matrix is damaged before fibers and matrix damage occurs throughout the thickness of the composite
- The damage volume is >50X higher in matrix than in fiber



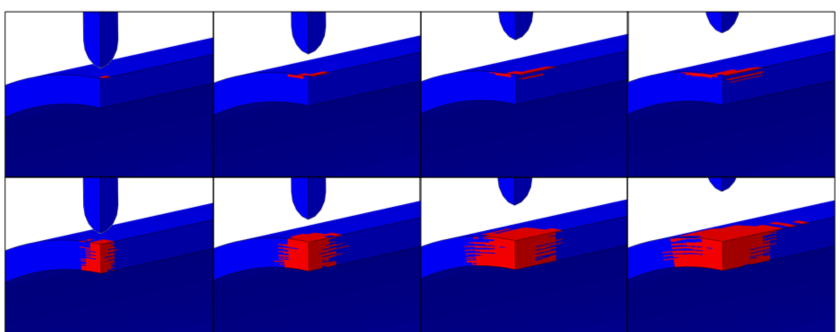
Deformation at 50 J impact



50 J 200 J 500 J 900 J

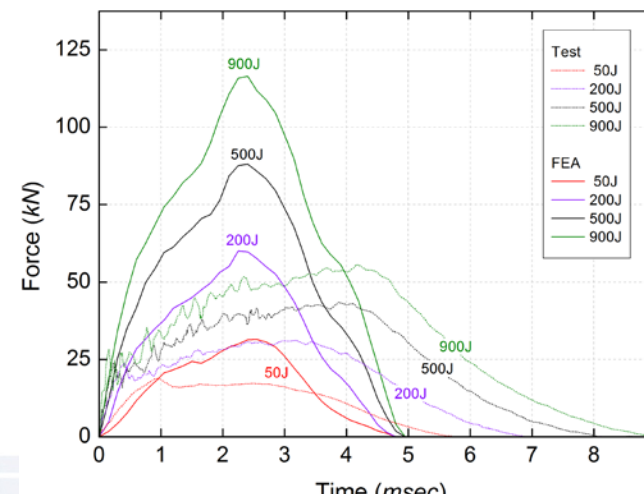
Fiber damage

Matrix damage



Impact Load History

Compared to test data*, the peak force is ~2X higher, but the measured and modeled areas under the curves are in good agreement. The FE models will be improved to include the effects of layers delamination, void content in laminate, and resin crushing.

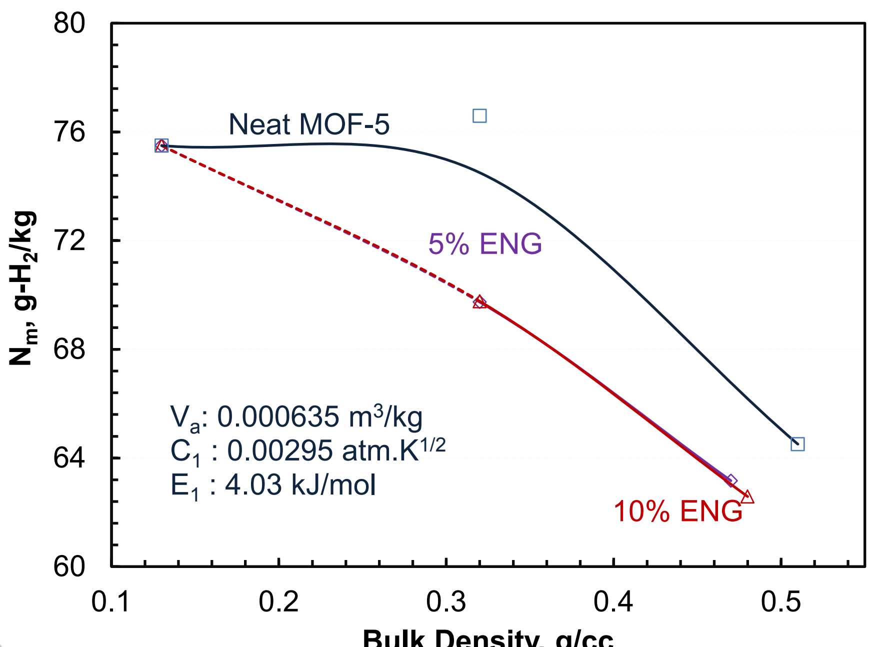


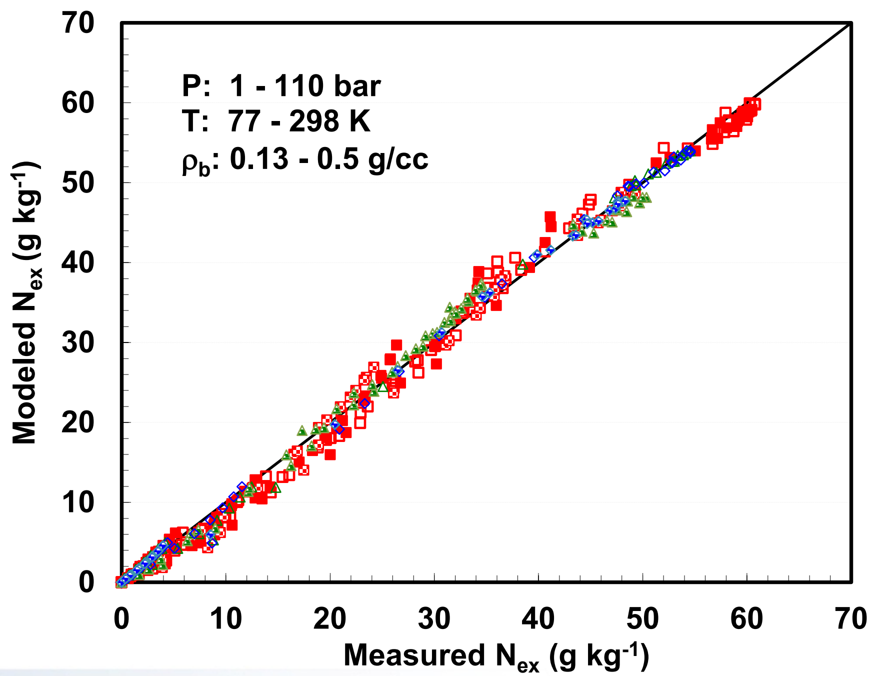
* Norm Newhouse, Hexagon Lincoln, private communication

Adsorption Isotherms for Pellets

Single-Langmuir equation can correlate Ford/UM excess H_2 uptake (N_{ex}) data for MOF-5 powder and pellets (0.13-0.5 g/cc bulk density) with 0-10 wt% expanded natural graphite (ENG) at 77-298 K, 1-110 bar

- M. Veenstra, et al, Ford/BASF-SE/UM Activities in Support of the HSECoE, ST010, AMR 2013, 2014. and 2015
- Same adsorption parameters (ΔH^0, ΔS^o, V_a), but sorption capacity parameter (N_m, g-H_2/kg-sorbent) depends on bulk density and ENG weight fraction.
- Up to 15% decrease in N_m with compaction to 0.5 g/cc bulk density; N_m can further decrease by 6% with addition of 5-10 wt% ENG



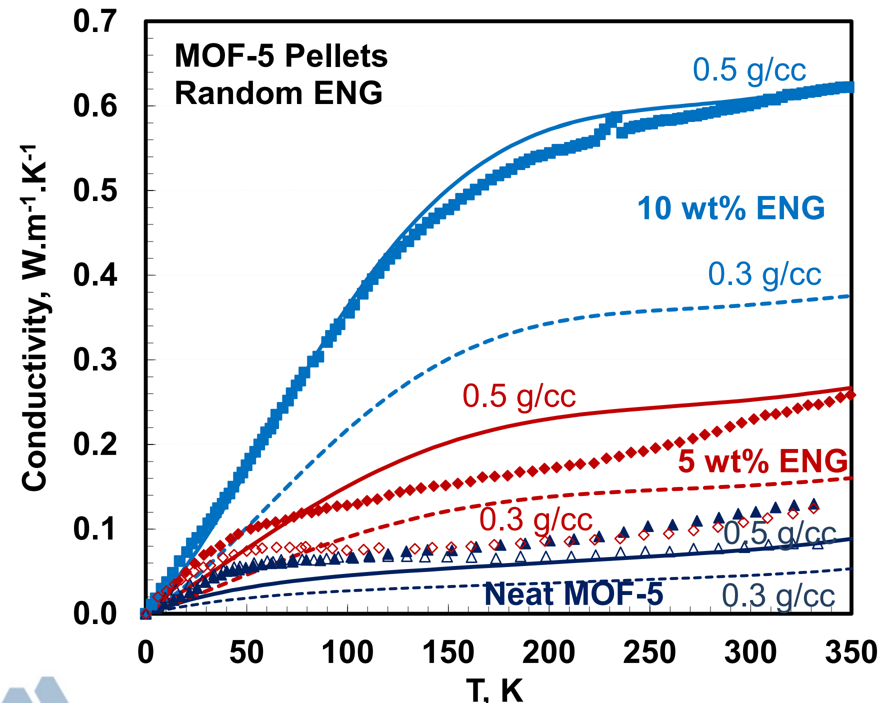


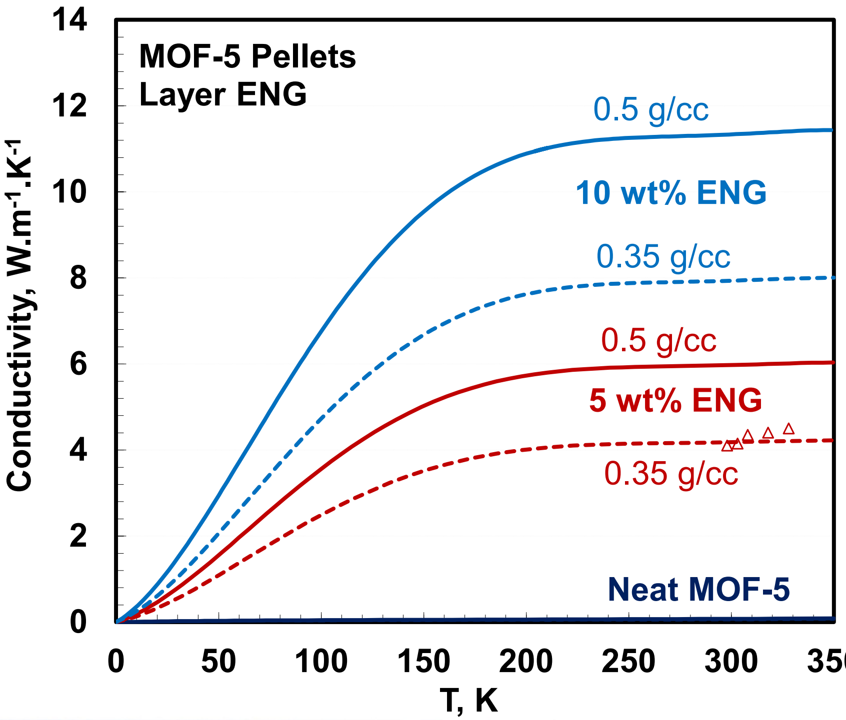
J. J. Purewal, et. al., IJHE 37 (2012) 2723-2727

Medium Thermal Conductivity

Heat transfer model for ENG and sorbent compacts

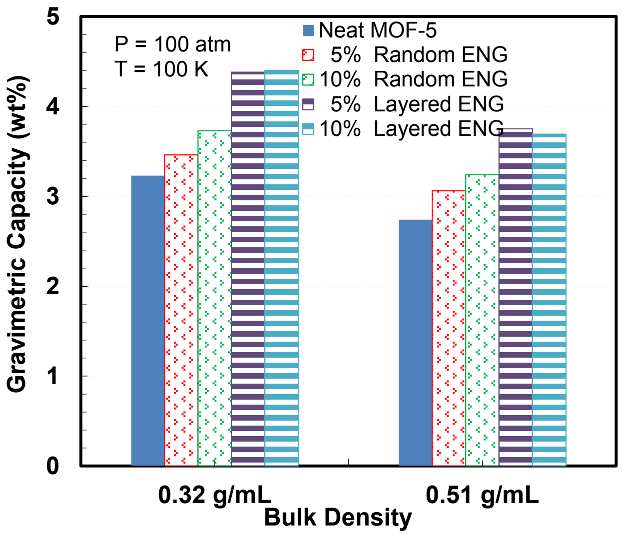
- M. Veenstra, et al, Ford/BASF-SE/UM Activities in Support of the HSECoE, ST010, AMR 2013, 2014. and 2015
- Thermal conductivity (λ_{eff}) is a function of the graphite to sorbent powder weight ratio and the fill factor[1]
- Series-parallel resistance model for heat transfer in random ENG structures
- Parallel resistance model for heat transfer in layered ENG structures
- Anisotropic conductivity model for heat transfer in layered ENG structures with source terms[2]

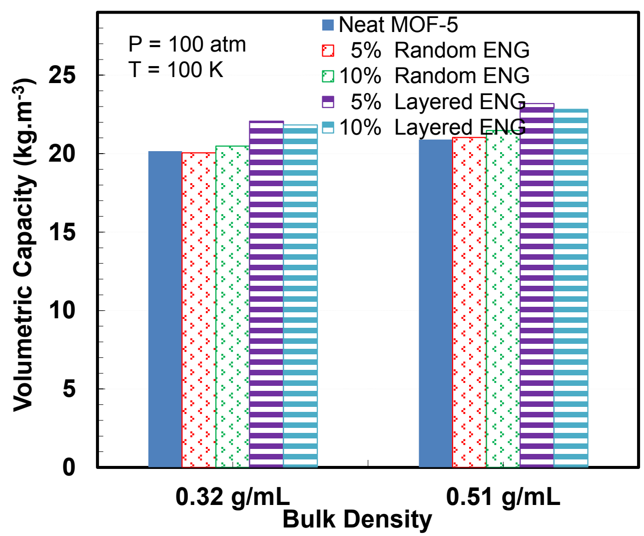




1) D. Liu, et. al., IJHE 37 (2012) 6109-6117. 2) Y. Ming, et. al., IJHMT 82 (2015) 250-258

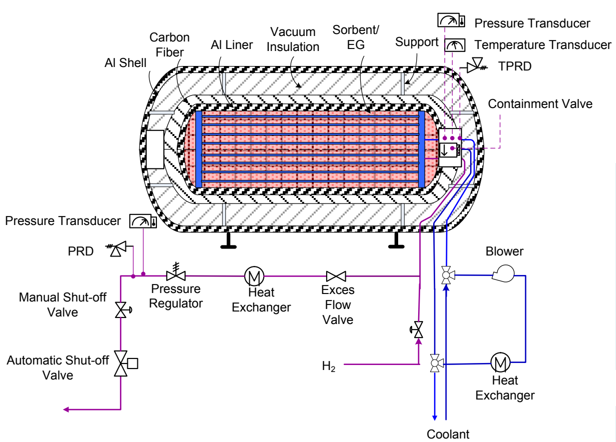
Performance of Sorbent H_2 Storage System: PRELIMINARY RESULTS





Study 1: 100 K Storage Temperature

- Addition of 5-wt% layered ENG to compacted MOF-5 improves gravimetric capacity by 35.6% and volumetric capacity by 9.4%



- >25% smaller target uptake with improved thermal conductivity[1], lower ENG weight fraction, and more compact HX

Study 2: Reverse Engineering Update

	Material Targets 2014	Material Targets 2017	Comments
Operating Pressures and Temperatures			
Storage Pressure (P)	100 bar	100 bar	
Storage Temperature (T)	155 K	155 K	20 K above coolant T
Discharge Pressure (P_d)	5 bar	5 bar	In addition to P swing, 60-K
Temperature Swing (ΔT)	60 K	60 K	ΔT allowed for 95% usable H_2
Off-board Coolant T (T_f)	135 K	135 K	55% WTT efficiency
Material Properties			
Peak Excess Uptake	190 g-H_2.kg^{-1}	**150 g-H_2.kg^{-1}**	5.5 wt% gravimetric capacity
at 77 K			E_1 = 5 KJ.mol^{-1}
Excess Uptake at Storage	120 g-H_2.kg^{-1}	**90 g-H_2.kg^{-1}**	V_a = 0.0125 m^3.kg^{-1}
P and T			C_1 = 0.0053 atm.K$^{0.5}$
Medium Bulk Density	500 kg.m^{-3}	**530 kg.m^{-3}**	40 g.L^{-1} volumetric capacity
Bed Thermal Conductivity	1 W.m^{-1}.K^{-1}	**5.5 W.m^{-1}.K^{-1}**	
Added ENG	20-wt% Random	**5-wt% Layered**	

1) Thermal conductivity Includes contribution of H_2 in pores, T. Semelsberger, et. al., IJHE 41 (2016) 4690-4702

FY2017 Collaborations

Cryo-Compressed Hydrogen	LLNL, BMW: LH_2 pumps, fatigue behavior of metal liners, supercritical hydrogen storage, vacuum insulation, model validation
Compressed Hydrogen Storage	PNNL Team: 700-bar tank performance (ST101) Ford: Alternate tank design concepts Hexagon Lincoln (HL): Impact damage in Type 4 tanks Materia: Low-void resins
Sorbents	Ford, LANL: Material properties of sorbents, reverse engineering, acceptability envelope
Metal Hydrides	ORNL: reverse engineering of high-pressure metal hydrides, acceptability envelope
Off-Board Fuel Cycle Efficiency	ANL (H2A Group), ANL (HDSAM), H2IT Taskforce
Off-Board Cost	ANL (H2A Group), ANL (HDSAM), H2IT Taskforce
On-Board Cost	Strategic Analysis Inc (SA)

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

Proposed Future Work

Physical Storage

- Validate ABAQUS model against cryogenic burst test data for cold gas storage (PNNL collaboration)
- MultiMech/ABAQUS simulation of CF composite performance degradation due to void defects, fatigue performance due to crack initiation and growth (Materia/Spencer Composite collaboration)
- Validate impact damage model and calibrate fatigue model against room temperature tank data (PNNL/HL collaboration)
- Support on-going tank projects (graded CF structure, conformable design, improved composites, low-cost glass fibers)
- Independently identify potential of cryo-cH_2 systems in fleet applications (such as buses and waste trucks) with particular focus on dormancy

Material Based Storage

- Analyze system performance with compacted sorbents using HSECoE data for materials and prototypes
- Expand system analysis of hydrogen storage in high-pressure metal hydrides
- Provide system-level support to new projects on material discovery projects, as requested

Document models and publish papers in IJHE

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:	Demonstrated that 2-mm stainless steel (SS) liner is preferable to aluminum liner in cryo-compressed H_2 (CcH_2) storage systems for buses Showed that compared to the baseline 350-bar cH_2 tanks currently in use, 500-bar CcH_2 can achieve 66% improvement in gravimetric capacity, 132% increase in volumetric capacity, and 36% saving in carbon fiber composite (CF) Determined >7-d loss free dormancy with 95% full 500-bar CcH_2 tanks
Collaborations:	Ford, HL, LANL, LLNL, Materia, ORNL, PNNL, SA
Future Work:	Propose, analyze and validate methods of reducing cost of CF wound storage tanks Validate models for heat transfer and H_2 uptake models in compacted sorbents, high-pressure metal hydrides Provide system-level support to new material discovery projects

Reviewer Comments

Generally favorable reviews with the following comments/recommendations

- Reverse engineering approach to provide guidance about storage solutions for different vehicle platforms that could be considered for hydrogen delivery
- Assessment of high pressure MHs needs more emphasis on thermal management and in-depth comparison of Type 3 versus Type 4 hydride-based tanks
- Include some sensitivity analyses of key parameters is recommended
- The team should keep up efforts to publish results in a timely fashion

FY17 work scope consistent with above recommendations

√ ANL is providing information and support to the Hydrogen Interface Taskforce for detailed holistic hydrogen pathway analysis

√ We plan to include detailed analysis of thermal management for charging high-pressure MH tanks, in-depth comparison of Type III v. Type IV tanks, and estimates of economic value of hydride system relative to 700-bar cH2 system

√ Sensitivity analyses of key parameters were included in recent reverse engineering work

√ We plan to publish the work on system analysis of cryo-compressed hydrogen storage and ABAQUS analysis of impact damage in Type IV tanks in 2017.

Technical Back-Up Slides

Publications and Presentations

Journal Publications

R.K. Ahluwalia, J.K. Peng, and T.Q. Hua, "Chemical Hydrogen Storage Material Requirements for Automotive Fuel Cell Systems," In preparation for submission to International Journal of Hydrogen Energy. 2017.

R.K. Ahluwalia, J.K. Peng, and N. T. Stetson, "Characteristics of Low-Enthalpy Metal Hydrides for On-Board High-Pressure Hydrogen Storage Applications," In preparation for submission to International Journal of Hydrogen Energy. 2017.

T.Q. Hua, H.S. Rho, R.K. Ahluwalia "Performance of Type-IV Compressed Hydrogen Storage System," In preparation for submission to International Journal of Hydrogen Energy. 2017.

Book Chapters

R.K. Ahluwalia, J.K. Peng, and T.Q. Hua, "Cryo-Compressed Hydrogen Storage," Chapter 5 in Compendium of Hydrogen Energy, Vol 2: Hydrogen Storage, Distribution and Infrastructure, R. Gupta, A. Basile, T. N. Veziroglu (Editors), Woodhead Publishing, 2016, 119-144.

R.K. Ahluwalia and T.Q. Hua, "Pressurized Systems," Chapter 15 in Data, Facts and Figures on Fuel Cells, Detlef Stolten and Remzi and Nancy Garland (Editors), Wiley-VCH, 2016, 143-148.

R.K. Ahluwalia and T.Q. Hua, "Onboard Safety," Chapter 18 in Fuel Cells Data, Facts and Figures, Detlef Stolten and Remzi Samsun and Nancy Garland (Editors), Wiley-VCH, 2016, 177-182.

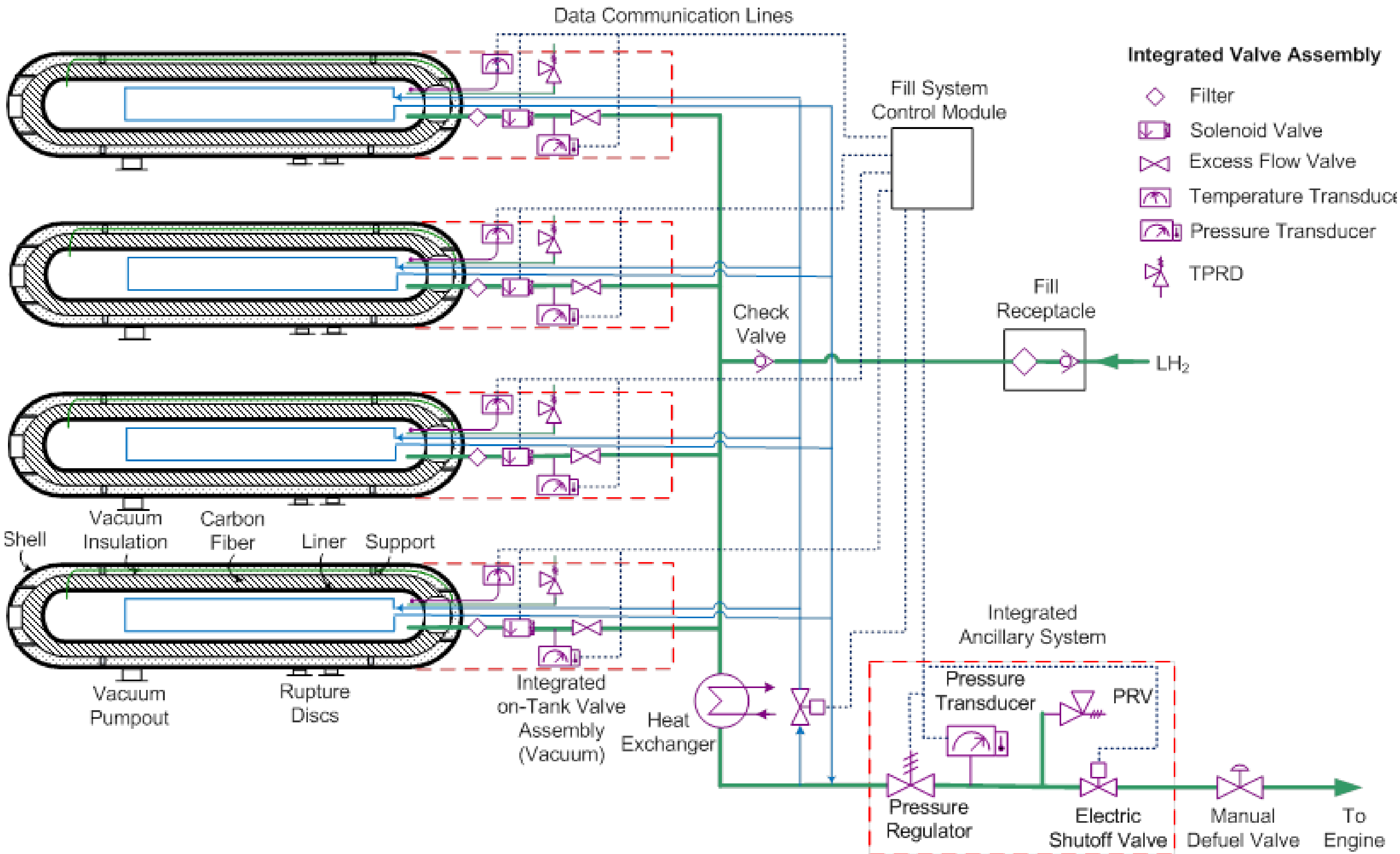
R.K. Ahluwalia, J.K. Peng, and T.Q. Hua, "Implementing Hydrogen Storage Based on Metal Hydrides," Chapter 32 in Hydrogen Science and Engineering, Materials, Processes, Systems and Technology, Vol 2, Detlef Stolten and Bernd Emonts (Editors), Wiley-VCH, 2016, 791-808.

Presentations

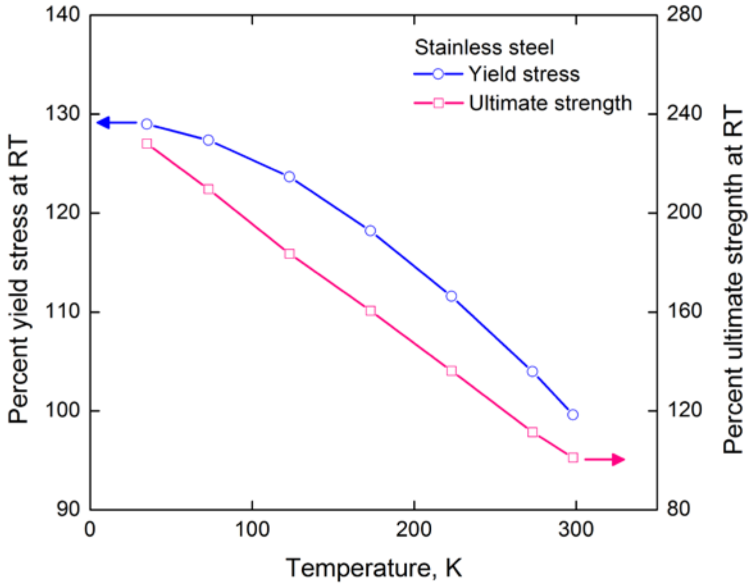
N.T. Stetson, R.K. Ahluwalia, J.K. Peng, and G. Ordaz, "Characteristics of Low-Enthalpy Metal Hydrides Favorable for High-Pressure Hydrogen Storage Applications," 15th International Symposium on Metal-Hydrogen Systems, MH2016, Interlaken, Switzerland, August 7-12, 2016.

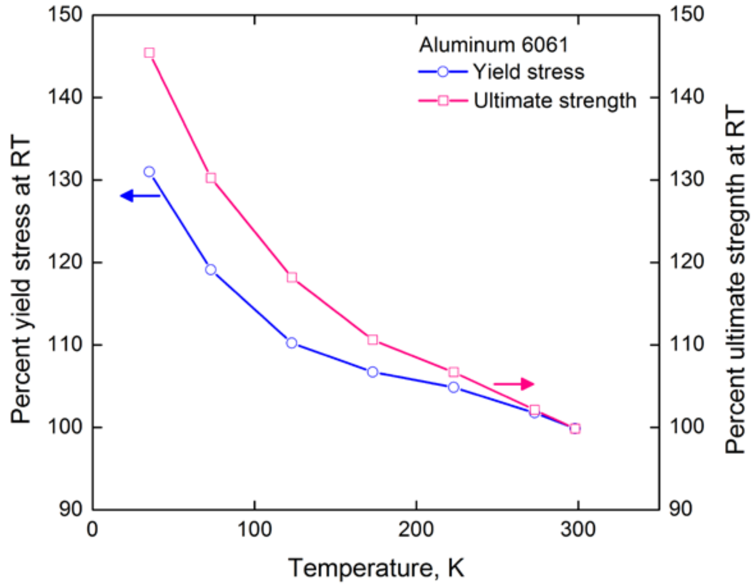
R.K. Ahluwalia, T.Q. Hua, J.K. Peng, and H.S. Roh, "System Level Analysis of Hydrogen Storage Options," Hydrogen Storage Tech Team Meeting, Southfield, MI, January 9, 2017.

Schematic of CcH_2 Storage System for Buses



Yield Stress and Ultimate Strength

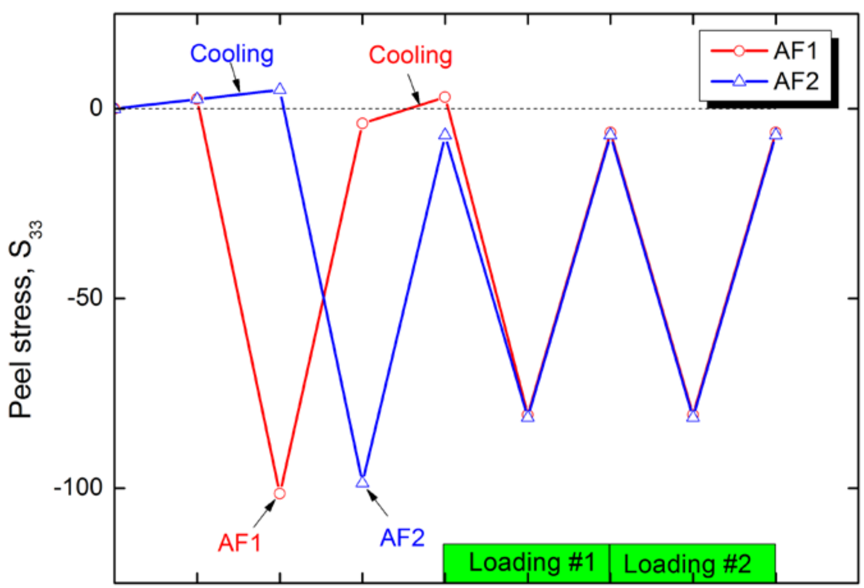


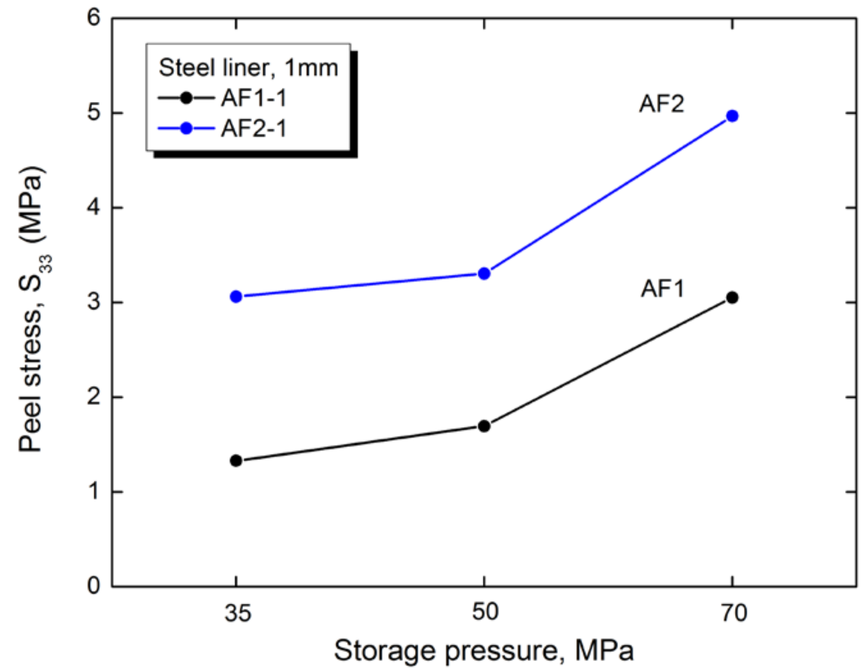


	Yield stress (MPa)		Strength (MPa)	
	84K	298K	84K	298K
Aluminum	335	282	433	333
Steel	605	475	1079	515

Peel Stress

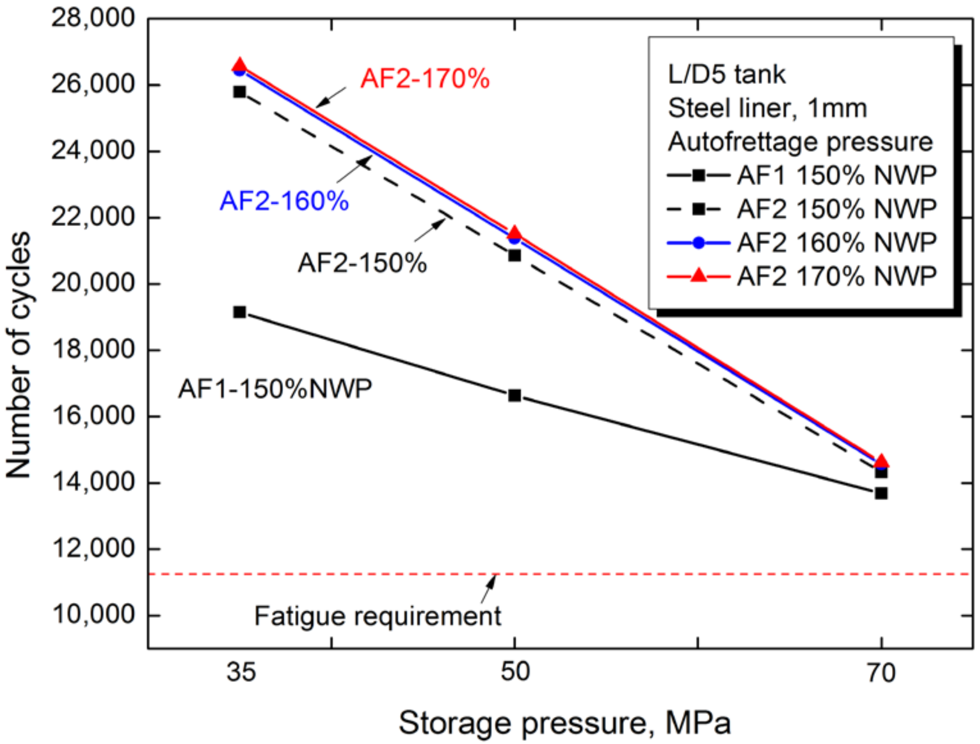
- During cool down to cryogenic temperature, tensile (peel) stress is induced at the liner/CF interface due to mismatch in CTE
    - Lower peel stress if autofrettage is performed at RT
- For a 70 MPa tank, internal pressure must be maintained at >5 MPa during cool down to prevent liner debonding from composite
- Results shown are for the tank cylinder section, gaps developed during cool down (unpressurized tank) are larger in the dome than in the cylinder

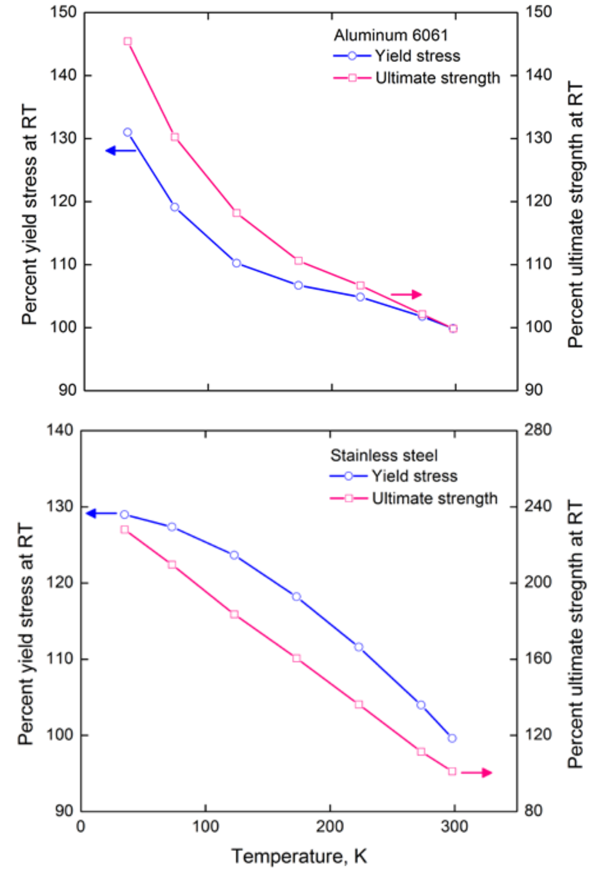




Autofrettage Pressure

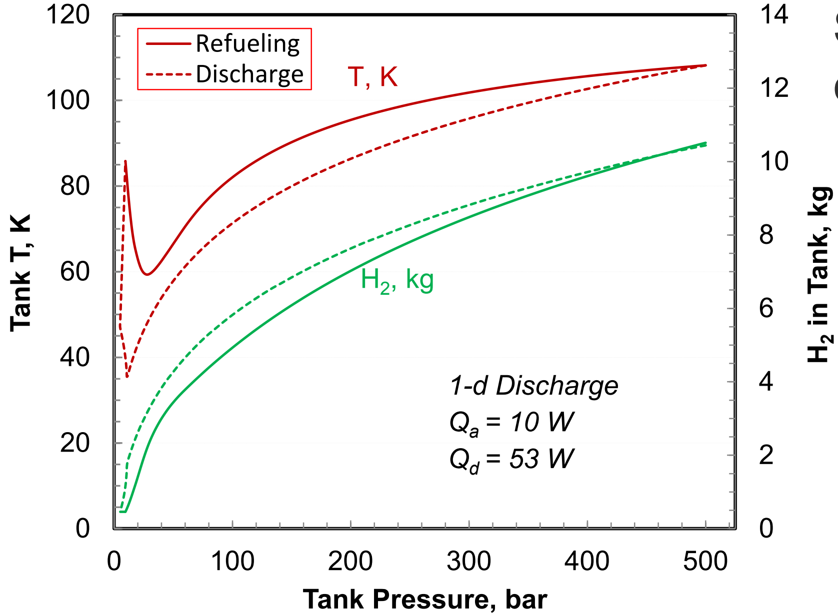
- For pressure vessels, autofrettage pressure typically corresponds to proof pressure (150% NWP)
- Autofrettage performed at low temperature may be subjected to higher autofrettage pressure because yield stress and modulus of the metal are higher at lower temperature
  - Small enhancement in fatigue life by raising autofrettage to 170% NWP





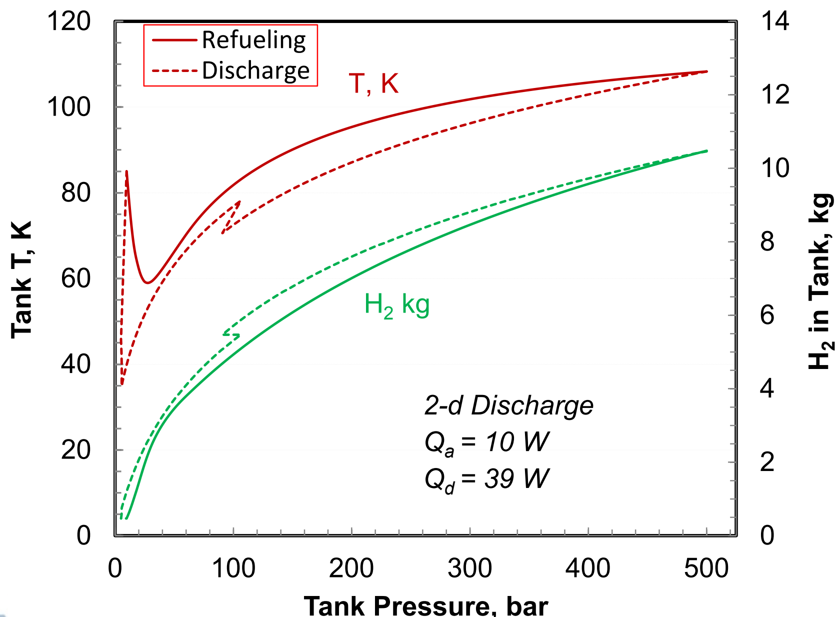
* MIL-HDBK-5H, Metallic materials and elements for aerospace vehicle structures, 1998

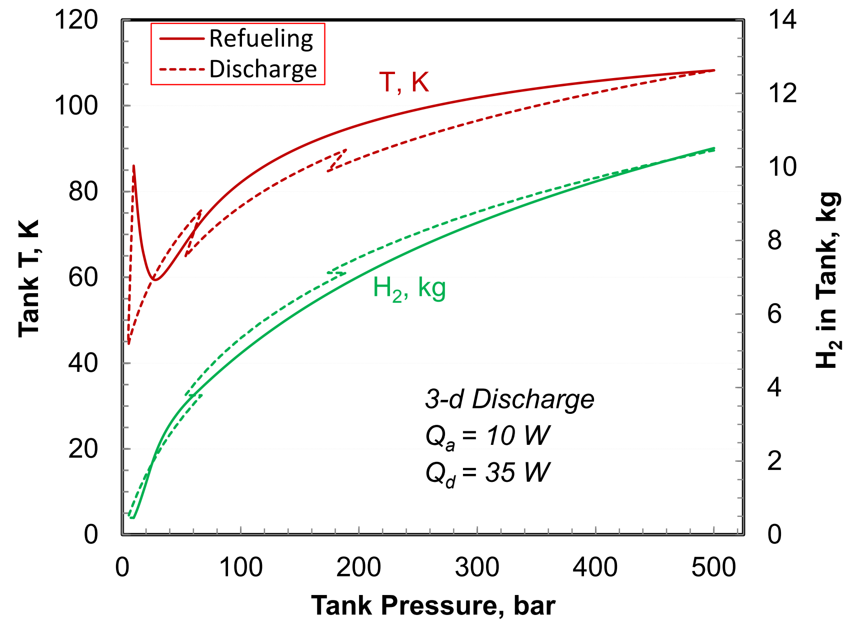
3. Repeat Charge-Discharge Cycle: 2-mm SS Liner, 500 bar



Supercritical CcH_2 storage: small heater or HX to prevent liquid formation

Storage Pressure	500 bar
Storage Temperature	108 K
Storage Density	61.9 g/L
Usable H_2	95.6%
Gravimetric Capacity	7.3%
Volumetric Capacity	43.0 g/L



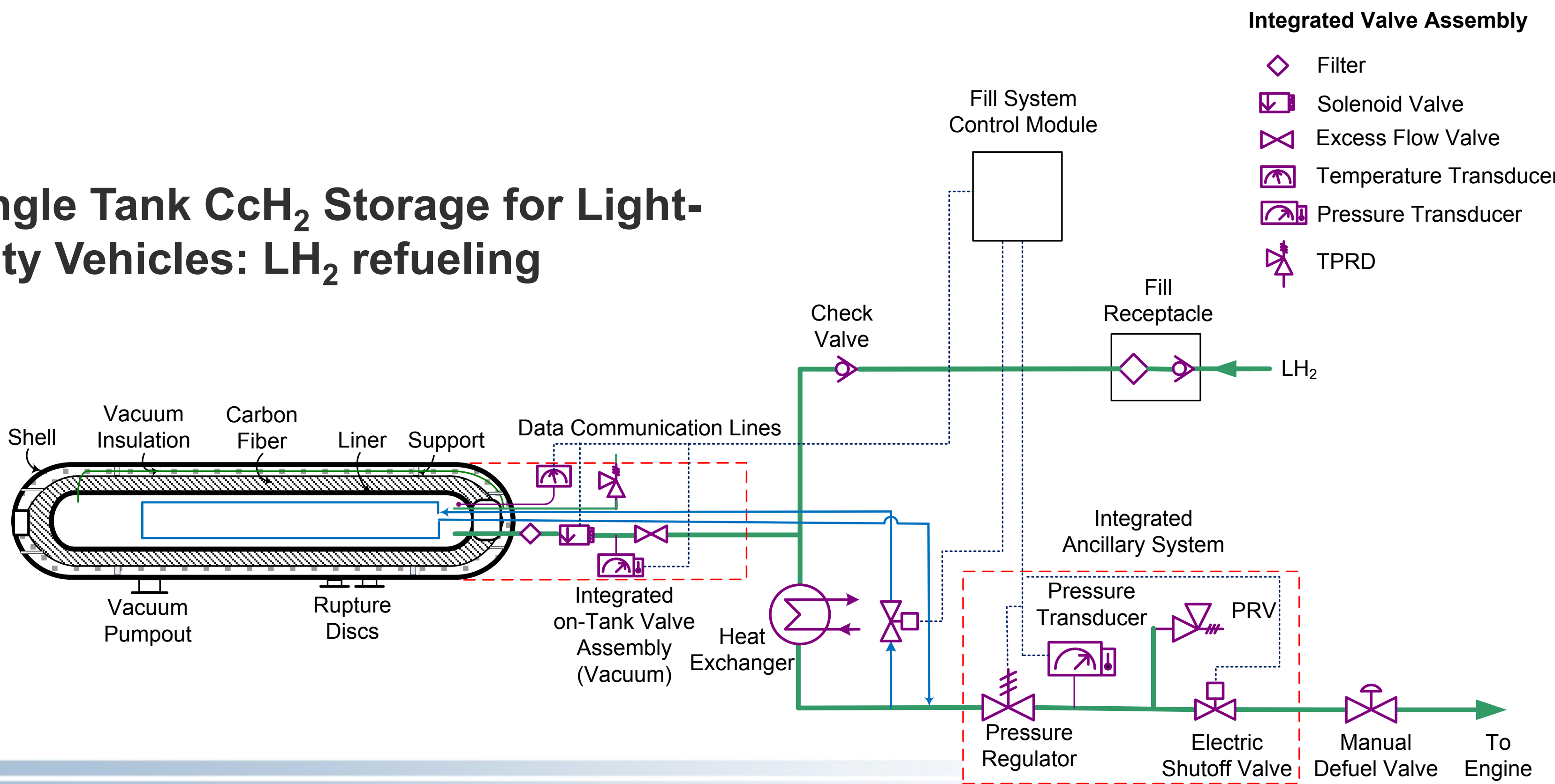


Remaining Work

Issues needing further investigation

- Effect of empty tank pressure on usable capacity
- ABAQUS fatigue modeling for combined pressure and temperature cycling
- In-tank heaters or heat exchangers, refueling receptacle and nozzle for 700-bar system
- Possible credit for using LH_2 to reduce radiator and AC loads
- CcH_2 system for light-duty vehicles (5.6 kg)

Single Tank CcH_2 Storage for Light-Duty Vehicles: LH_2 refueling



Impact Damage Analysis

Model tank damage (CF/GF composite) due to physical impact

- Transient behaviors of impact force and composite displacement
- Damage model includes fiber and matrix damage
- Horizontal and 45^o drop tests (future work)
- Burst pressure after impact (degradation of tank safety factor, ongoing)
- Overwrap design to reduce impact damage (future work)

Validate FE damage model of Type IV tank with Hexagon Lincoln data

- 54-L tanks, 883 mm long, 350 mm OD, wound with CF and GF (0.9:1 ratio)
- 50 to 900 J impact energies, 24-mm hemisphere tip impactor
- Data includes force history and burst pressure

As a first step, the tank was modeled with ABAQUS to determine the failure strain at burst without impact damage