Advancement of Systems Designs and Key Engineering Technologies for Materials Based Hydrogen Storage

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United Technologies Research Center

DOE Hydrogen Program

Annual Merit Review
Washington, DC
May 11, 2011

HSECoE

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Project ID: ST006

Overview

- **Timeline**
  - Start: February 2009
  - End Phase 1: March 2011
  - End Phase 2: July 2013
  - End Phase 3 / Project: June 2014
  - Percent complete: 32% (spending)
- **Budget**
  - $6.86M Total Program
    - $5.32M DOE
    - $1.55M (22.5%) UTRC
  - FY10: $1.00M DOE
  - FY11: $950k DOE
- **Barriers***
  - A – J
  - A. System Weight & Volume
  - E. Charging / Discharging Rates
  - J. Thermal Management
- **Targets***
  - All
- **Partners**

Pacific Northwest National Laboratory, SRNL Savannah River National Laboratory, Los Alamos National Laboratory, Lincoln Composites (A Member of Hexagon Composites Group), HRI UQTR, GM, Ford, BASF The Chemical Company, OSU Oregon State University, JPL, California Institute of Technology, NREL National Renewable Energy Laboratory (Innovation for Our Energy Future), HSECoE, IEA HIA Task 22

* DOE EERE HFCIT Program Multi-year Plan for Storage

Objectives

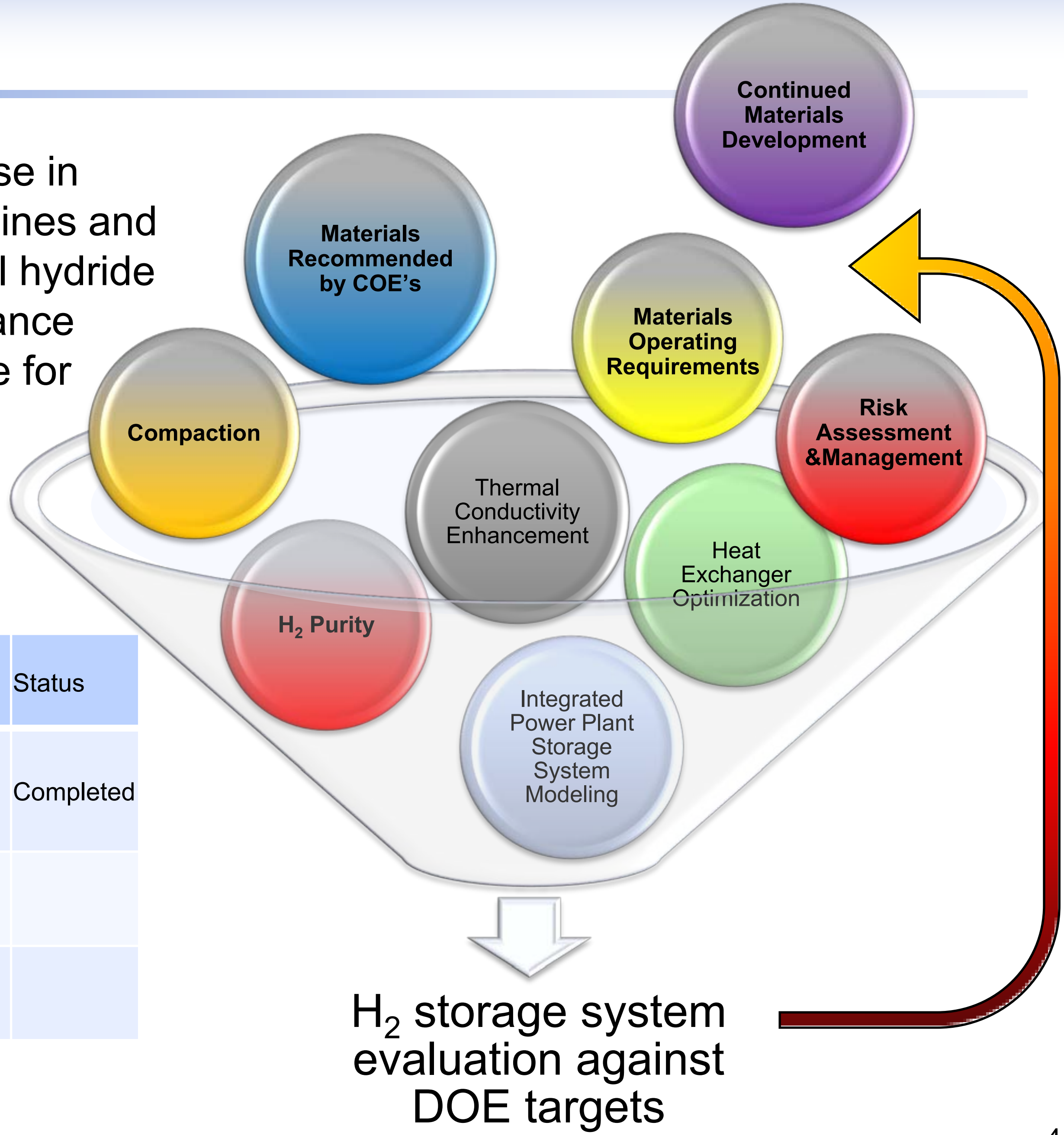
- Design of materials based vehicular hydrogen storage systems that will allow for a driving range of greater than 300 miles

Performance Measure	Units	2010	2015	Ultimate
System Gravimetric Capacity	g H_2 /kg system	45	55	75
System Volumetric Capacity	g H_2 /L system	28	40	70
System fill time (for 5 kg H_2)	minutes	4.2	3.3	2.5
Fuel Purity	% H_2	SAE J2719 guideline (99.97% dry basis)		

- Major project impact:
  - H_2 storage systems comparison on common basis for Go/No-Go decision:
    - Integrated Power Plant Storage System Modeling
  - Volumetric capacity (compaction)
  - System fill time (thermal conductivity, HX design)
  - Fuel purity (purification cartridge to remove NH_3)
  - Qualitative risk analysis (QLRA)

Approach

- Leverage in-house expertise in various engineering disciplines and prior experience with metal hydride system prototyping to advance materials based H_2 storage for automotive applications



Month/Year	Go/No-Go Decision	Status
Feb-11	Provide a system model for each material sub-class (metal hydrides, adsorption, chemical storage) which shows:	Completed
	● 4 of the DOE 2010 system storage targets are fully met	
	● Status of the remaining targets must be at least 40% of the target or higher	

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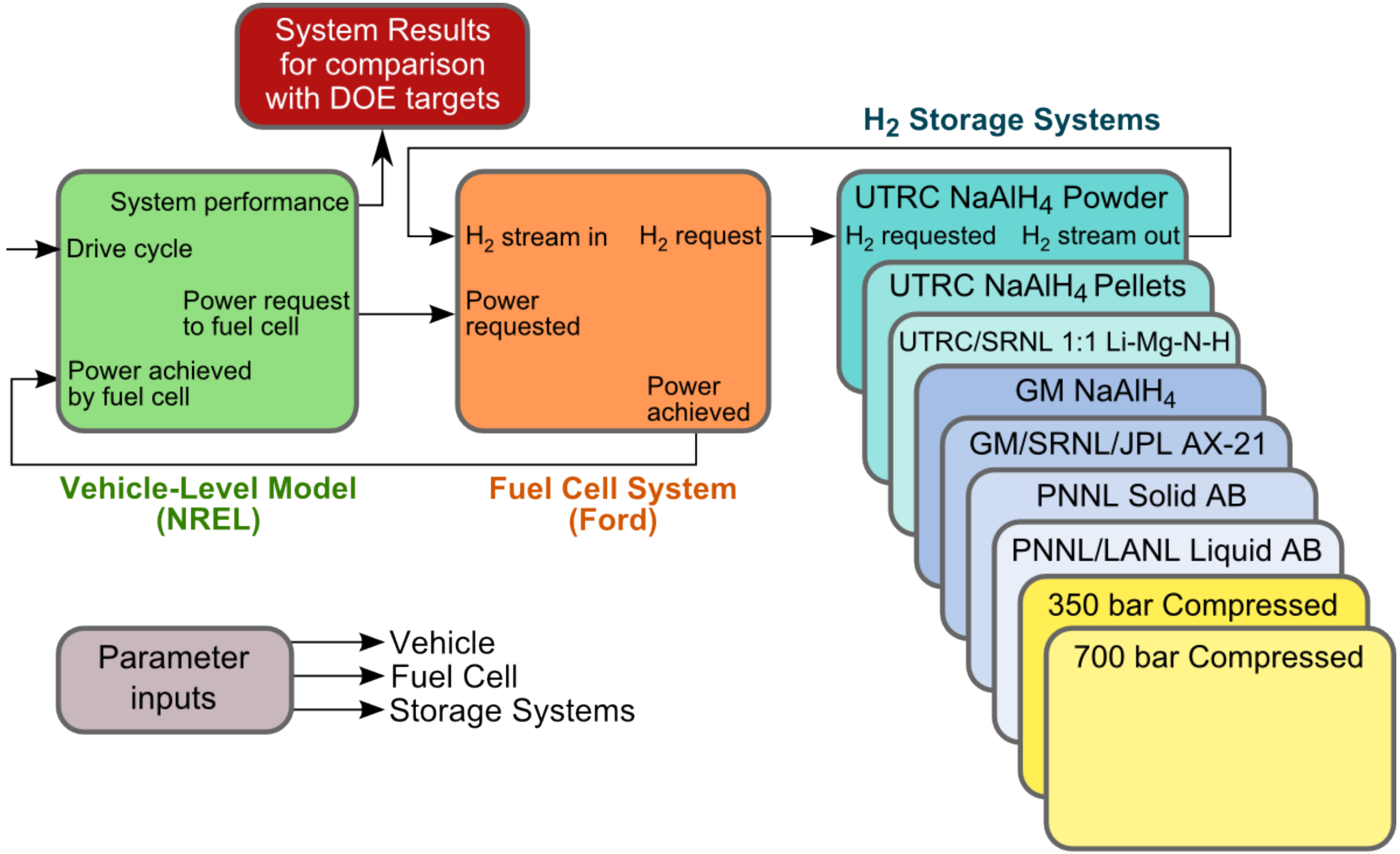
IPPSSM framework development



Quantitative comparison of H_2 storage systems on a common basis achieved by team effort

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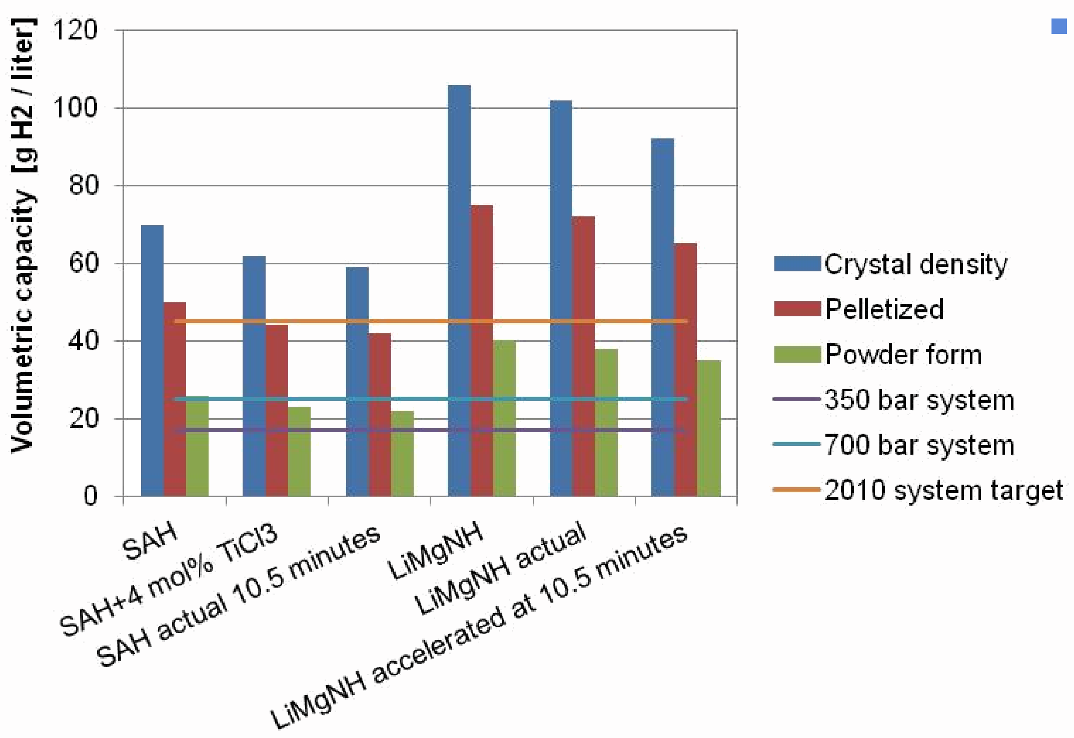
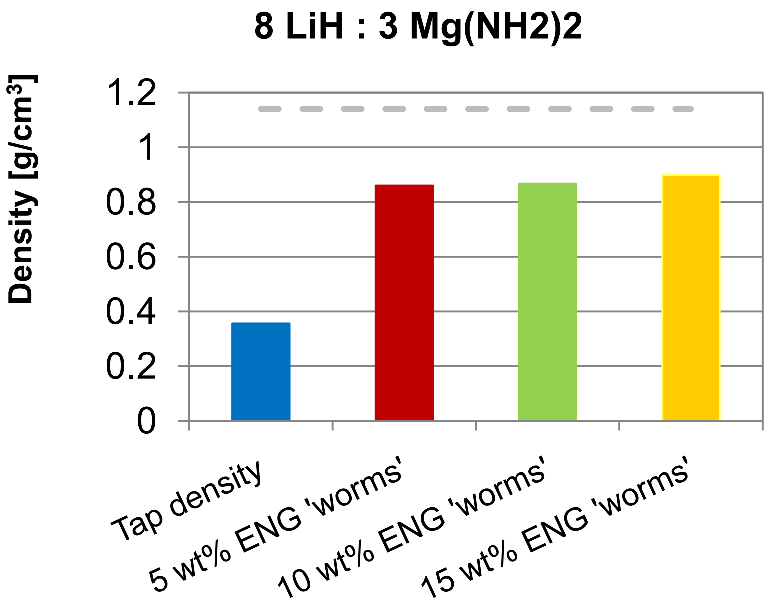
Compaction of (complex) metal hydrides



- Materials compacted:
  - $NaAlH_4$ (2010 AMR)
  - Li-Mg-N-H:



Address low volumetric capacity issue due to low powder density through compaction and higher capacity materials.

Li-Mg-N-H system requires binder (e.g. Expanded Natural Graphite (ENG)).

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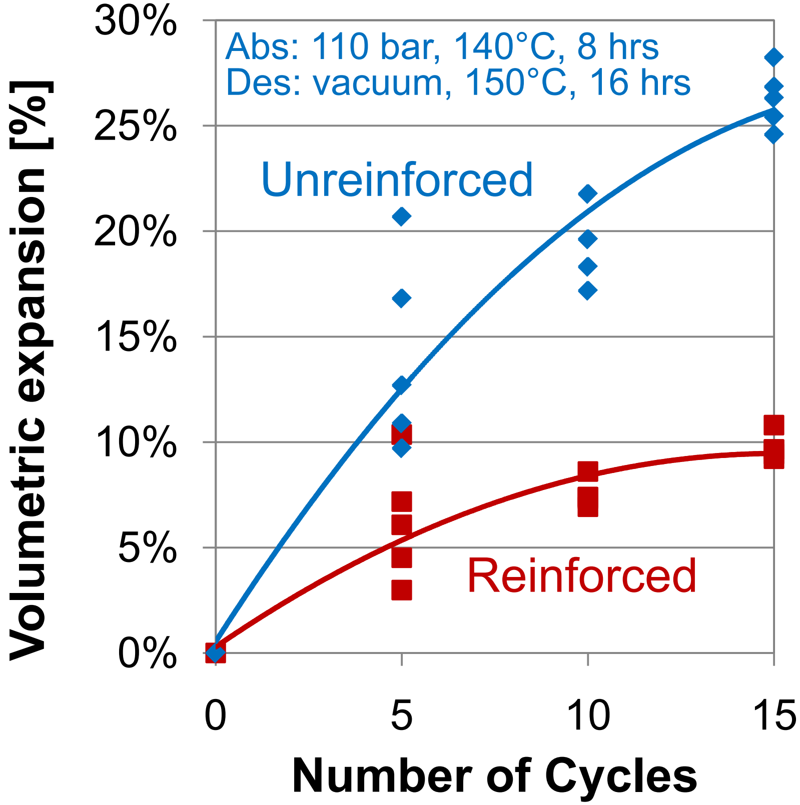
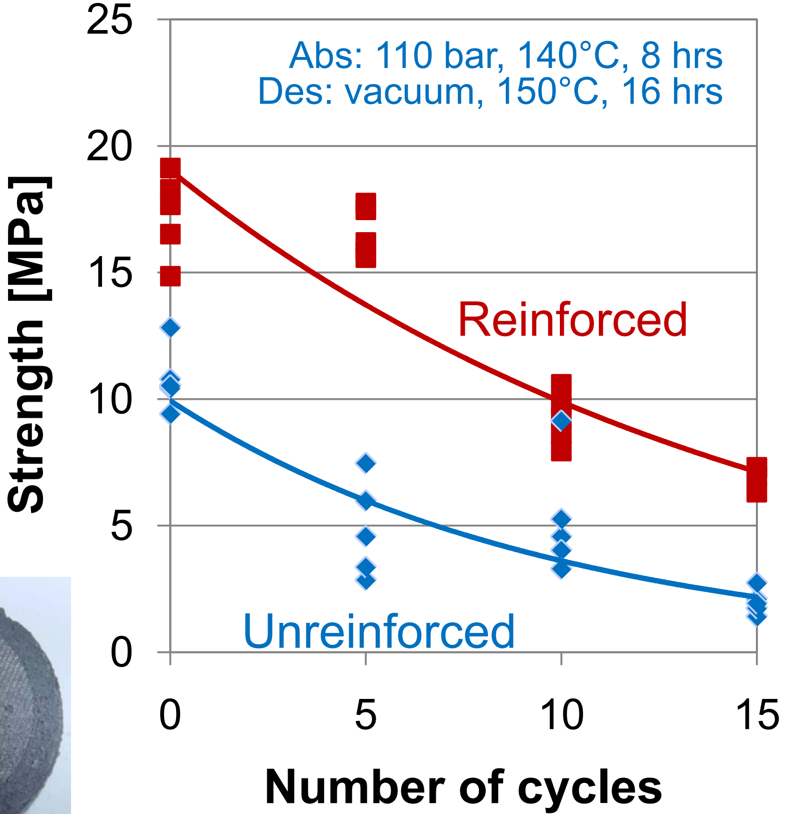
Stabilization of $NaAlH_4$ (SAH) pellets





Mesh reinforcement reduces volumetric expansion and yields stronger pellets after absorption/desorption cycles but DOE target is 1,500 cycles

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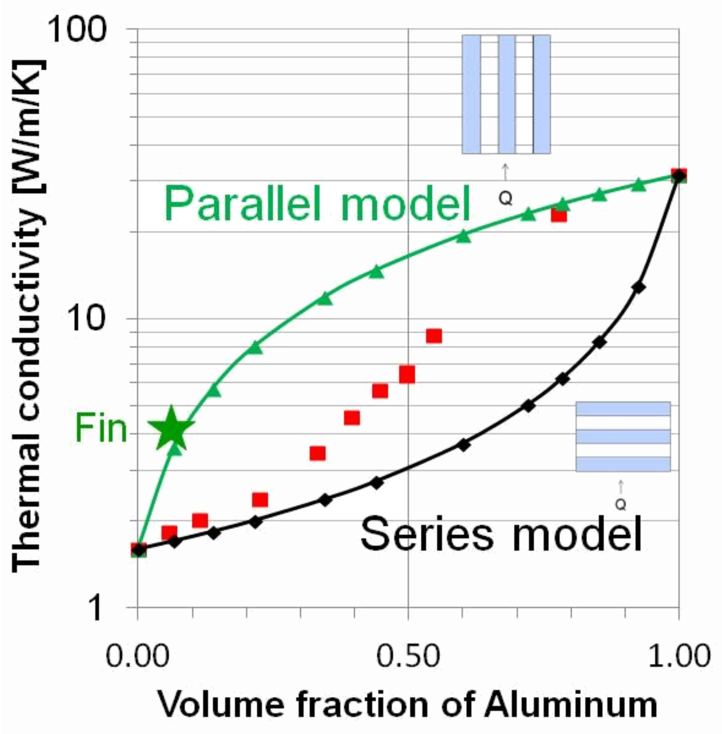
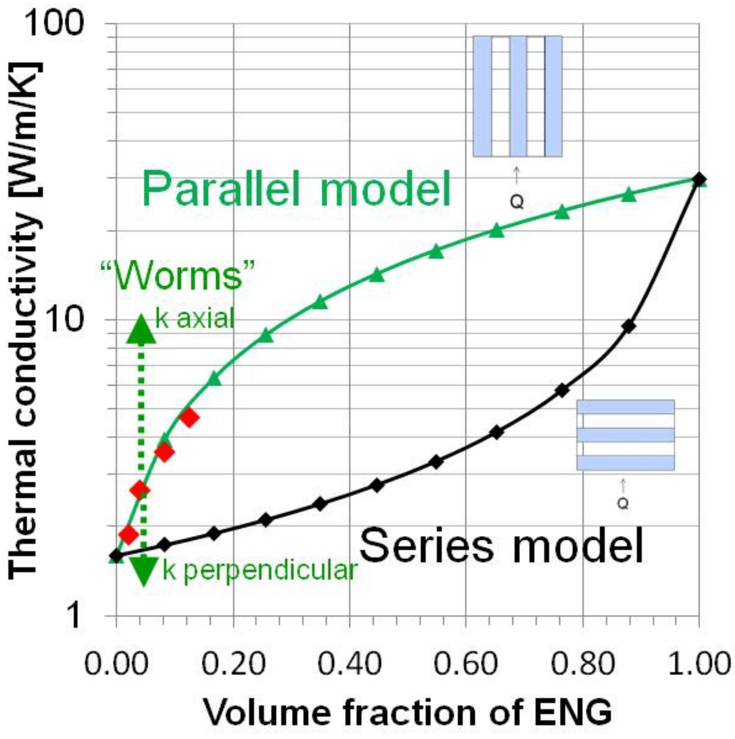
Thermal conductivity enhancement

- Fast refueling time with SAH requires an effective bed thermal conductivity of 4-8 W/m/K



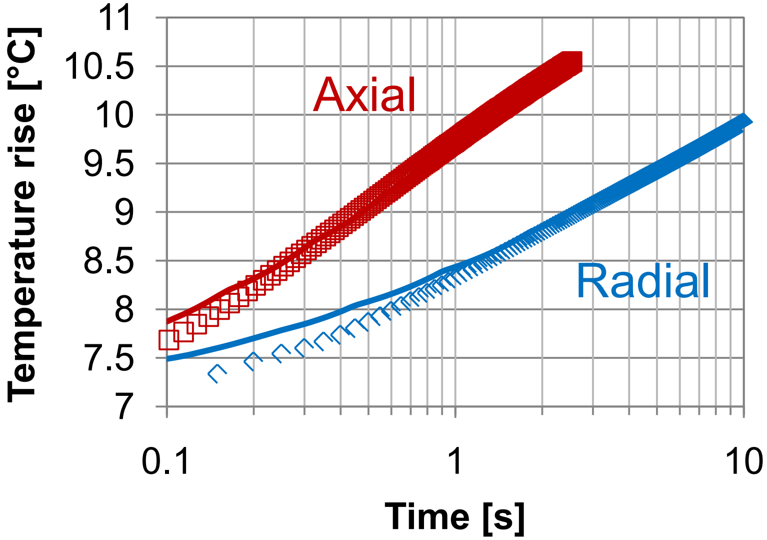
- Compaction of SAH without additives is not sufficient (AMR 2010)



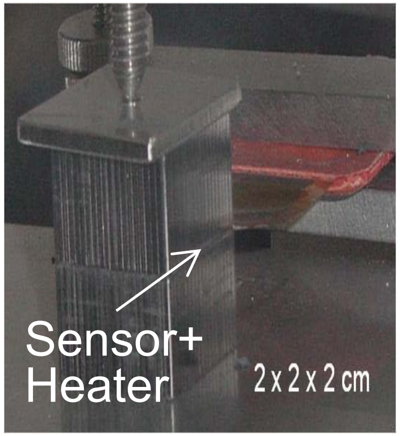
Aluminum powder is ineffective; Use aluminum fins.
Expanded Natural Graphite can be effective when used as 'worms' causing thermal conductivity anisotropy

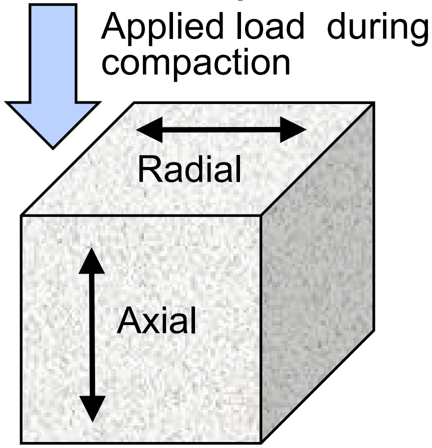
Thermal conductivity anisotropy with ENG 'worms'

- Thermal conductivity experiment

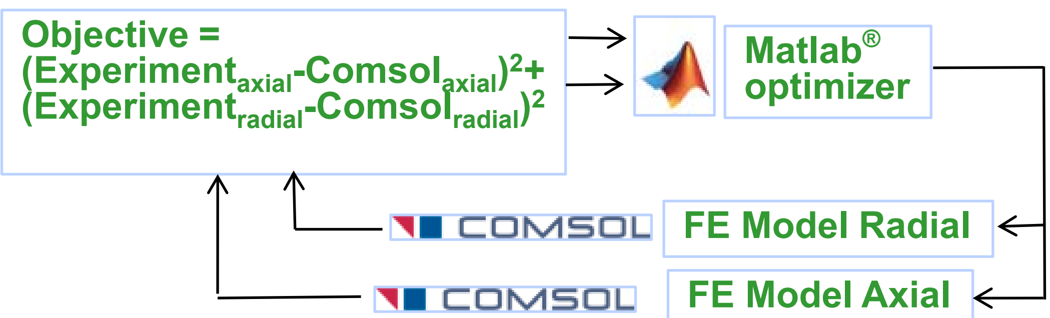


- COMSOL™ model development





- Fit to experimental data



- Results for 8 LiH : 3 $Mg(NH_2)_2$

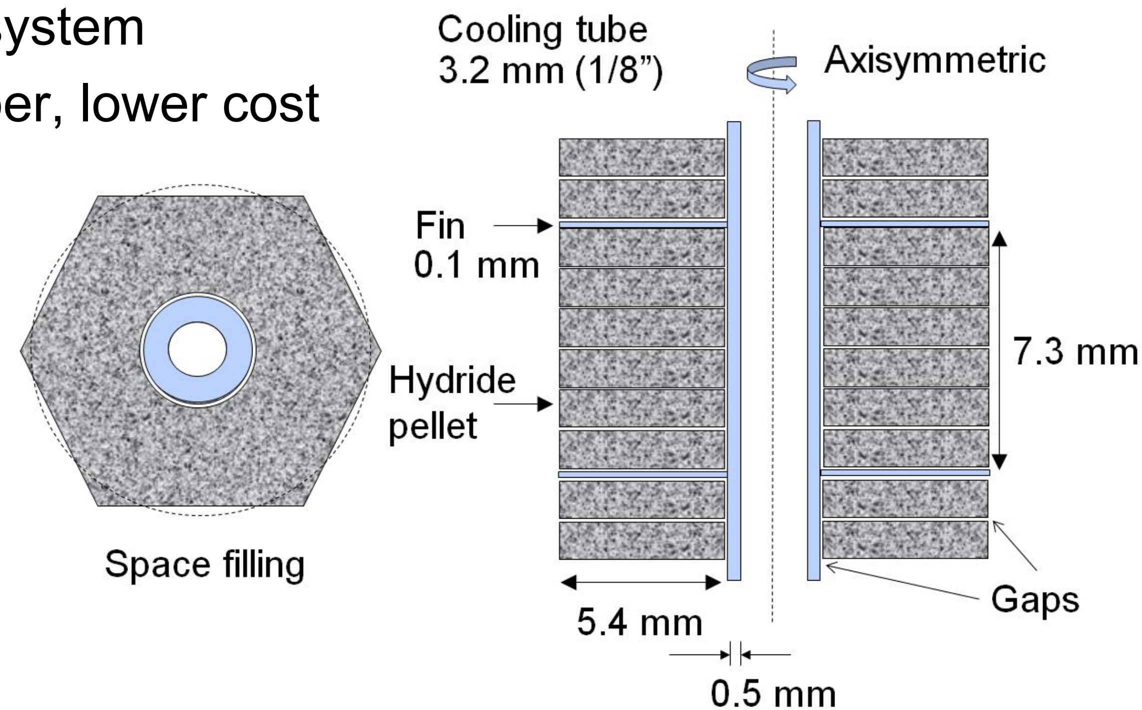
	ENG wt.%	k radial [W/m/K]	k axial [W/m/K]
SAH	5	10.8	1.54
LiMgNH	5	1.56	1.13
LiMgNH	10	2.64	1.95
LiMgNH	15	11.6	0.75

Induce high thermal conductivity towards the heat exchanger tube

Heat exchanger optimization for fast refueling

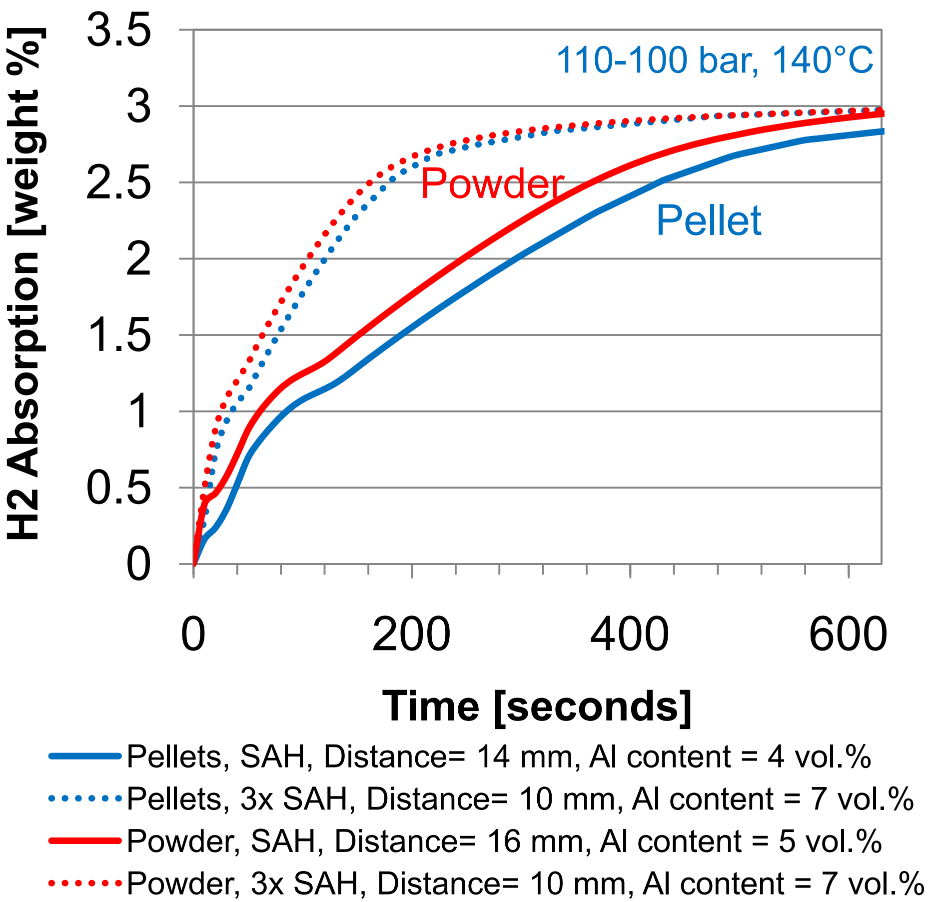
- Refueling time target 10.5 minutes (40% of DOE 2010 target)
- 90% of materials capacity (SAH) equals 3.06 wt.%
- T_{max}=170°C
- PH_2=100 bar:
  - Low pressure system
  - Less carbon fiber, lower cost

Determined minimum HX mass inside SAH bed that would allow 90% of H_2 storage capacity in 10.5 minutes.

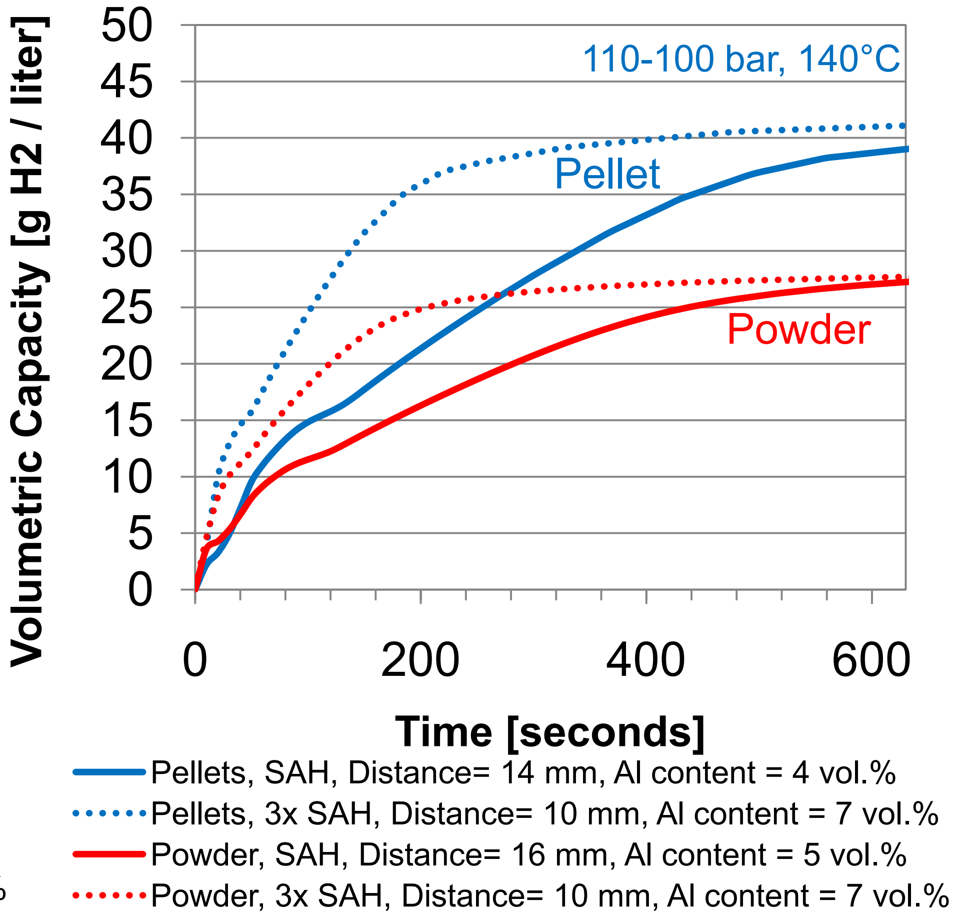


Performance modeling (COMSOL™)

- Gravimetric capacity



- Volumetric capacity



Pelletized SAH kinetics (updated) in combination with HX design enables 90% of storage capacity in 10.5 minutes.

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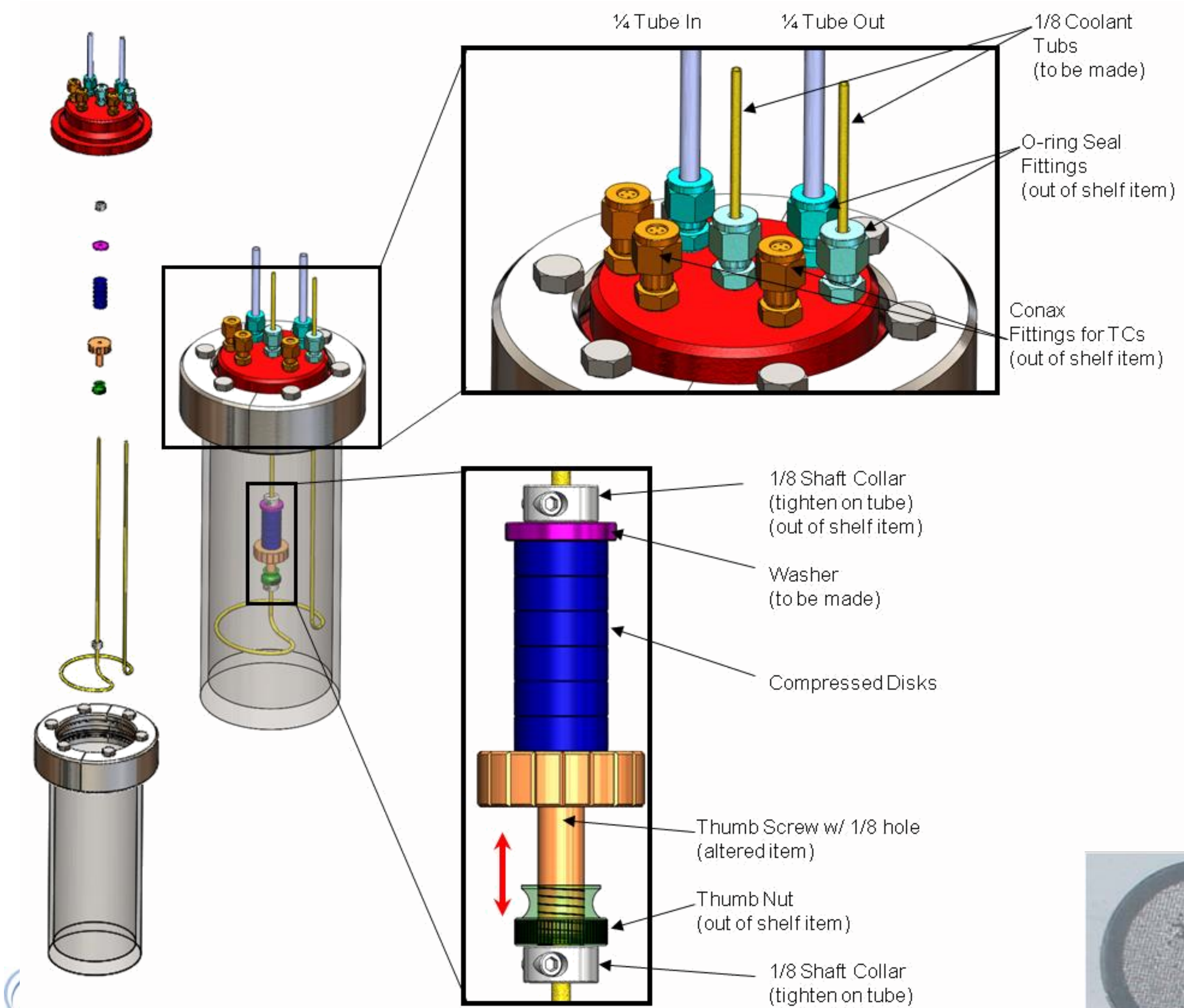
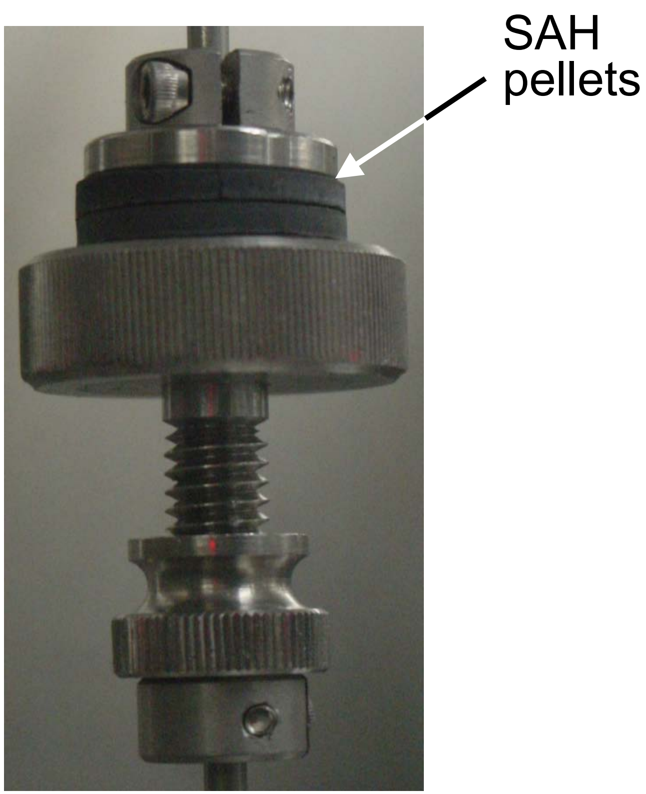
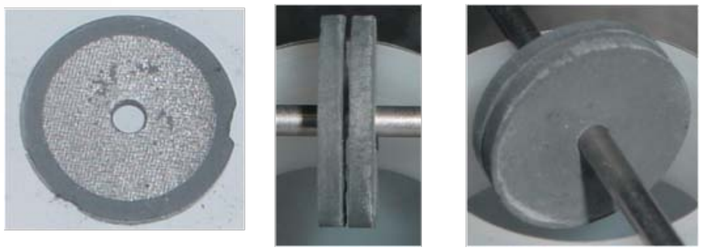
Concept evaluation (Lab-scale)

- Integration with HX
- SAH pellets around HX tube

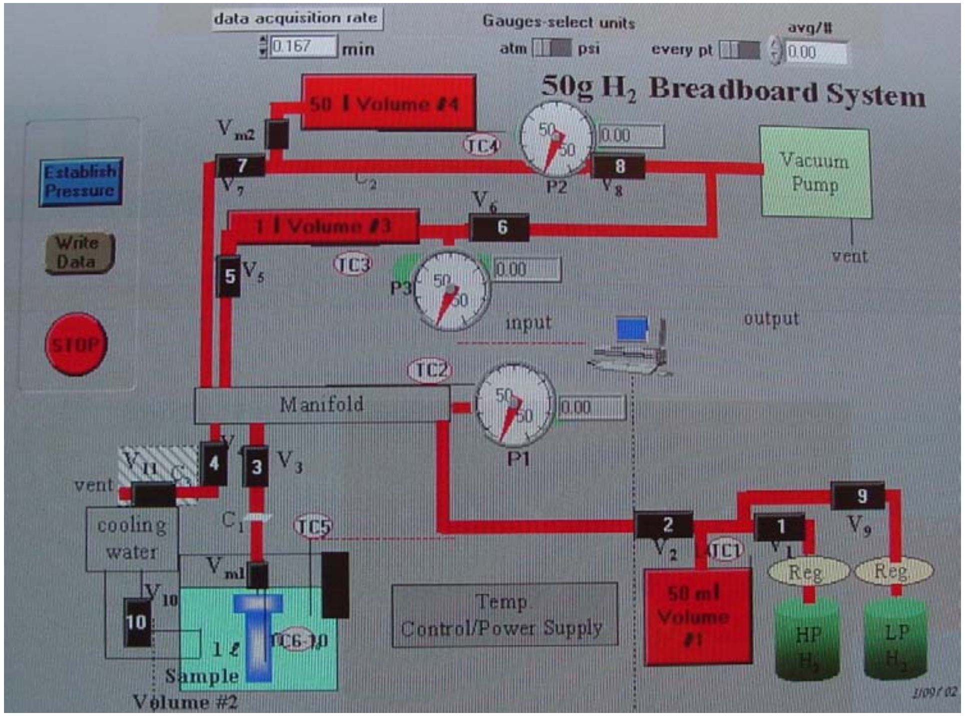




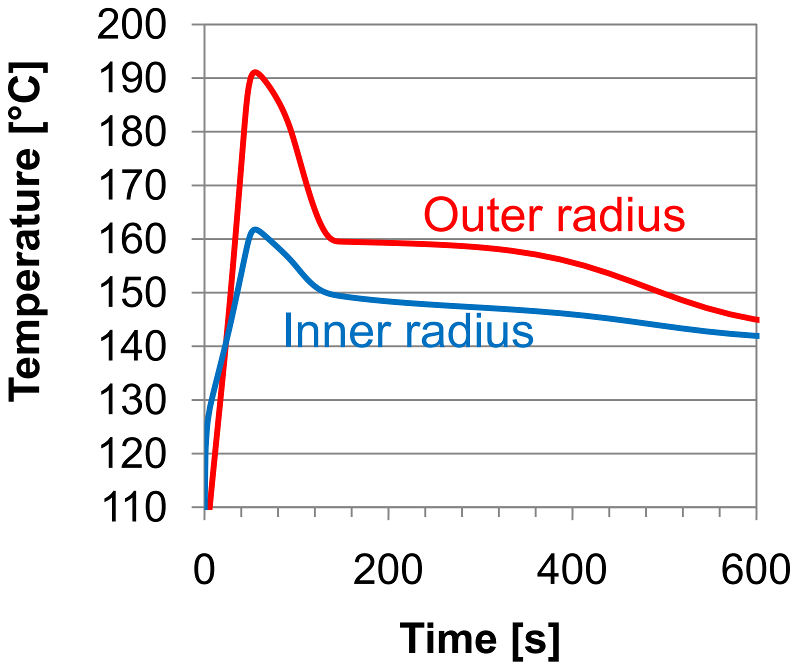


Concept evaluation (Lab-scale)

- Repaired/Modified PCT control system



- Adjusted COMSOL™ model with updated kinetics and axi-symmetry of test article

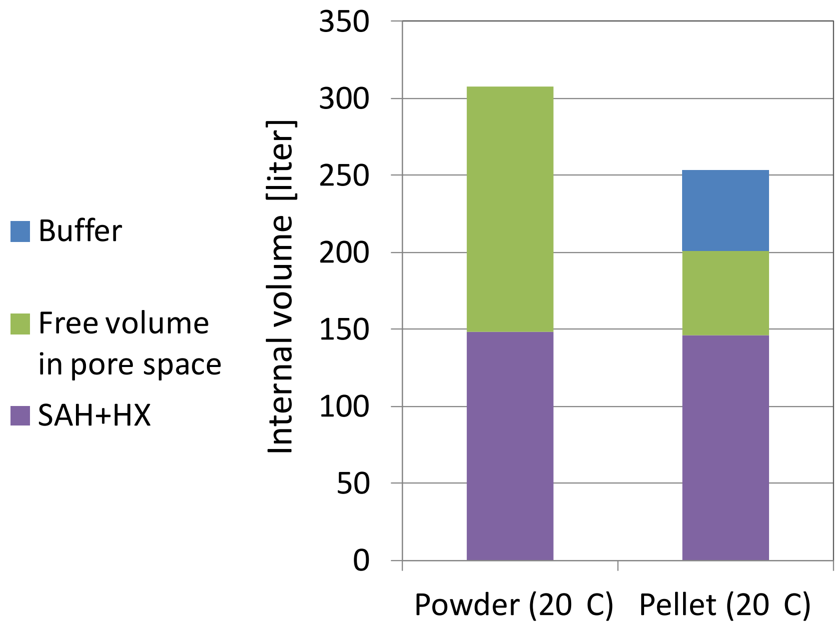


Validate key components and concepts at an appropriate scale for Phase 2

Framework results

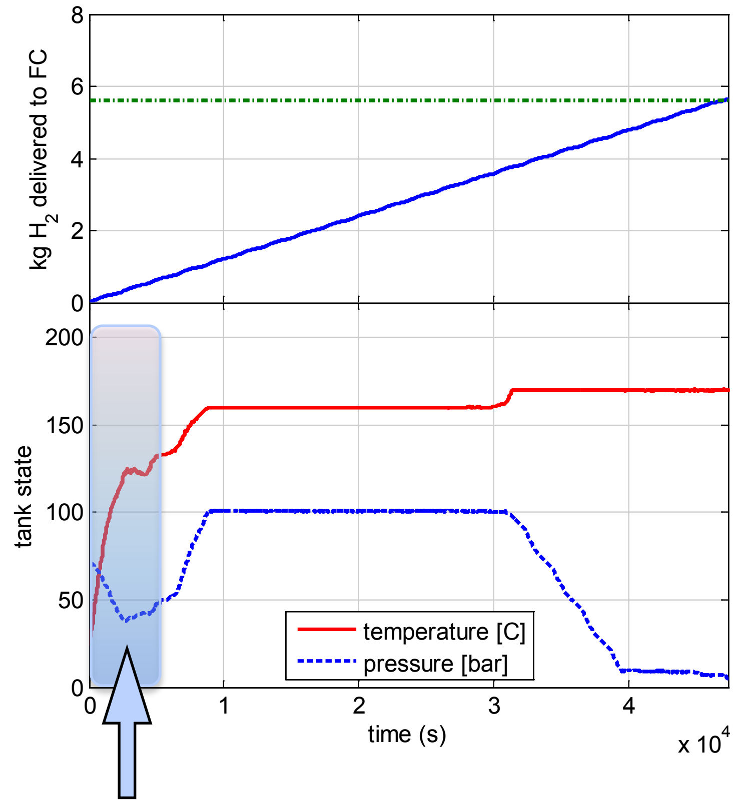
$NaAlH_4$ powder and compacted pellets systems

- Maximum operating temperature: 170°C
- System starts at 20°C and delivers 5.6 kg H_2 to fuel cell
- Back-to-back EPA Fuel Economy test drive cycles
- Pressure drops during heat-up as gas in voids is sent to combustor to bring the system to operating temperature.



Buffer size can be reduced by 30% if buffer at 20°C instead of 140°C

$NaAlH_4$ powder system running Fuel Economy Test drive cycles

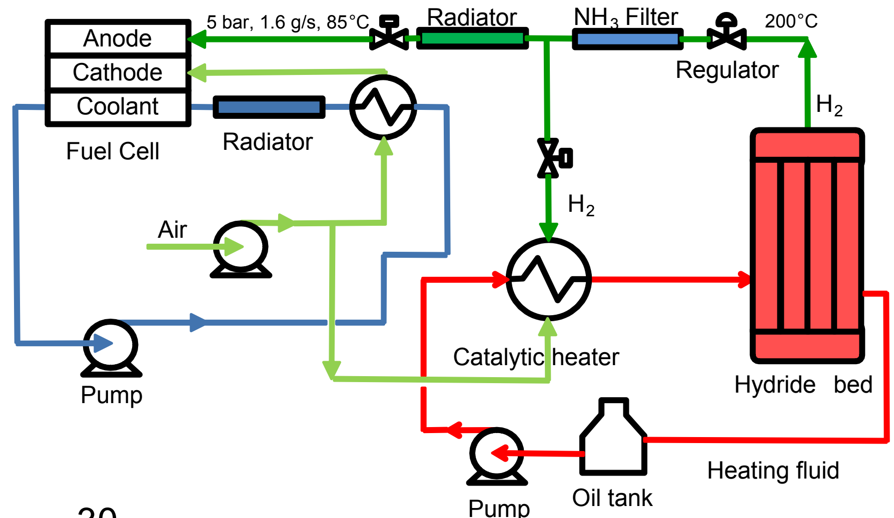


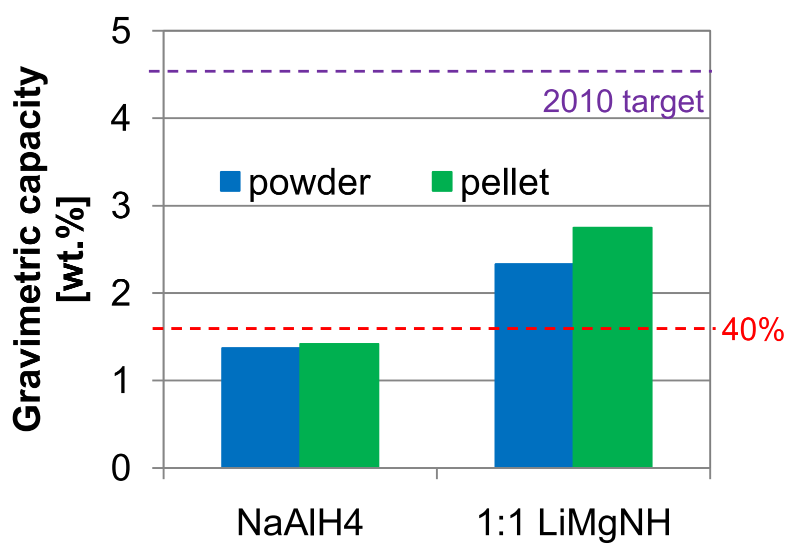
Initial pressure drop: H_2 gas in voids is sent to combustor to heat up the system

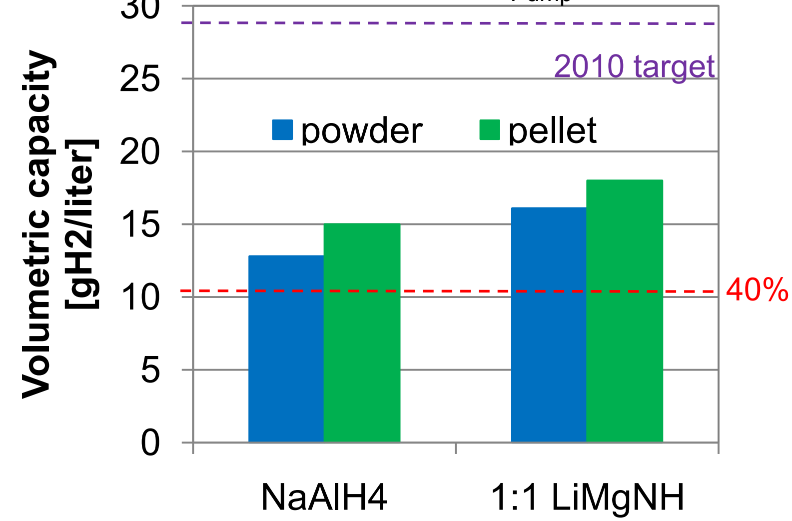
H_2 buffer requirement for startup limits benefits of compaction

Framework results

	Form	Amount [kg]	Buffer Volume [Liter]
$NaAlH_4$ 3.1 wt.% in 10.5 min.	Powder	243	-
	Pellet	255	53
1:1 LiMgNH 7 wt.%	Powder	92	90
	Pellet	93	90







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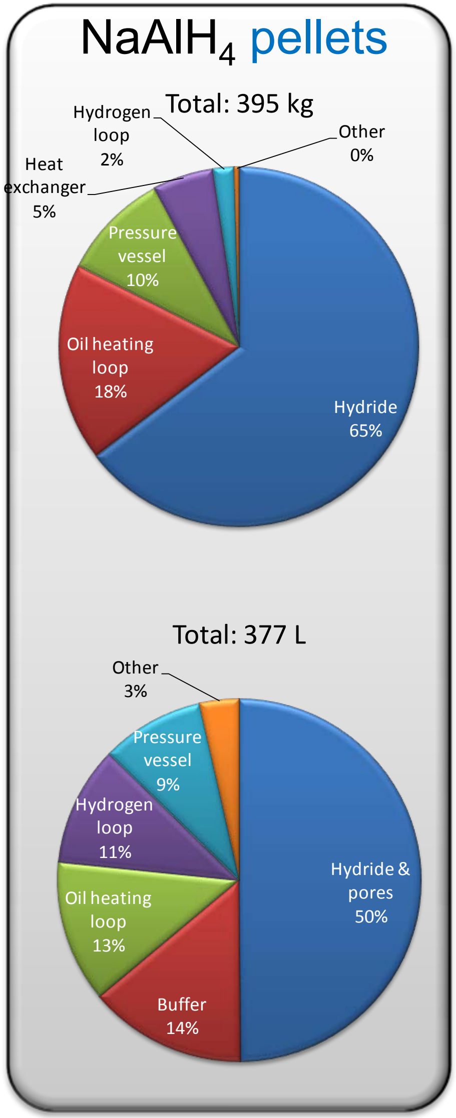
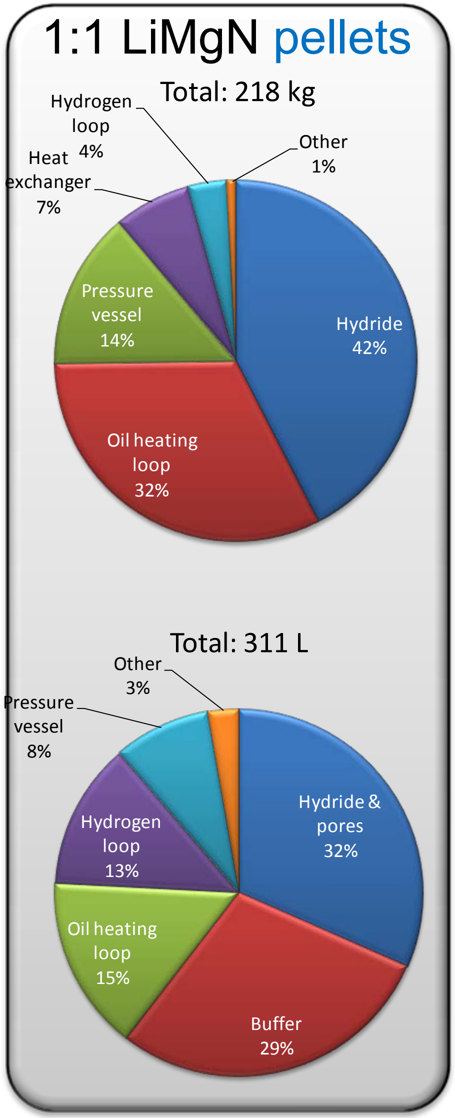
Considered (complex) metal hydride systems are heavy and occupy a large volume

Framework results

Weight and volume*: main contributors

- Effect of increased capacity:
  - BOP weight and volume become increasingly important when using a higher capacity material.
- Guidance:
  - BOP weight and volume reduction important when using higher capacity material
  - Make buffer tank separate from hydride storage system





* Using BOP components library developed by PNL

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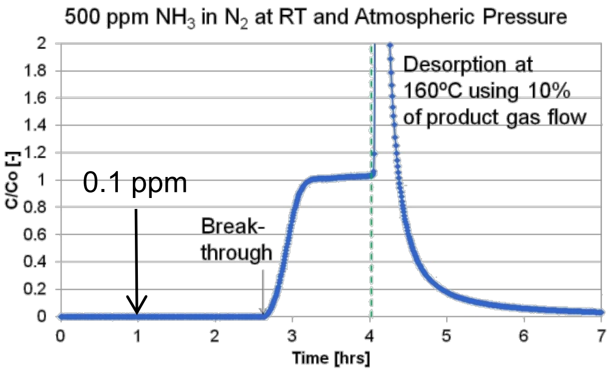
Enabling technology: H_2 quality

- Objective: Develop system methods to improve discharged hydrogen purity / quality for acceptable PEM fuel cell durability (SAE J2719 APR2008 guideline)



Adsorbents

AX21

Particulates: <10µm, <1µg/l, ASTM D7650

Complex metal hydrides

LiMgNH

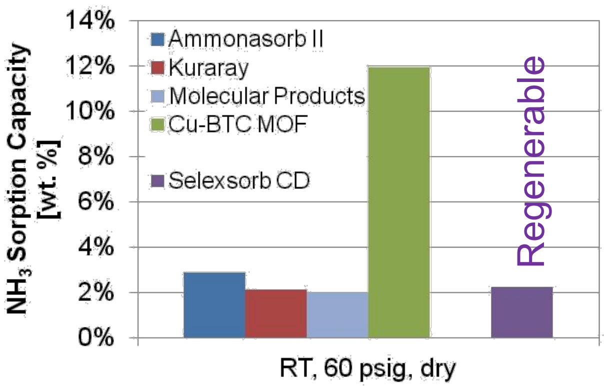
Ammonia adsorbent (UTRC)

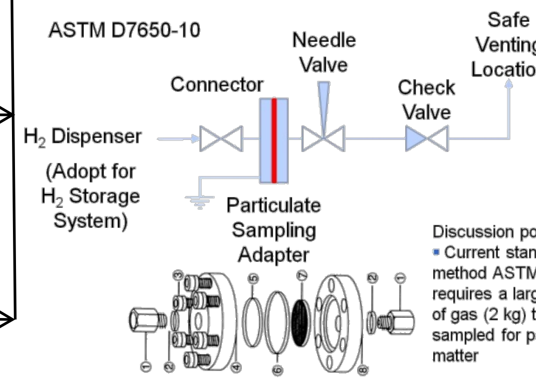
AB

Chemical hydrides

AB

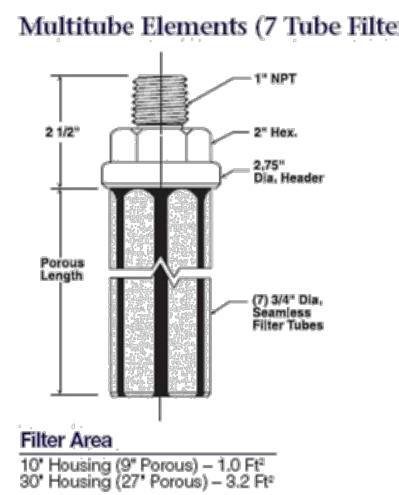
Quantification: Ammonia, Diborane, Borazine, Solvents (LANL, PNL)





Discussion point:
- Current standard test method ASTM D7650-10 requires a large amount of gas (2 kg) to be sampled for particulate matter

Consensus Concentration [ppm]			
	Borazine	Diborane	Ammonia
AB	1000	-	619



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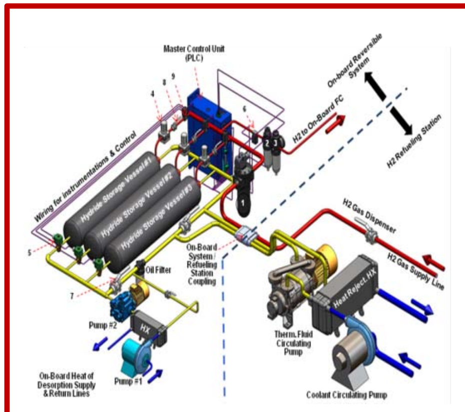
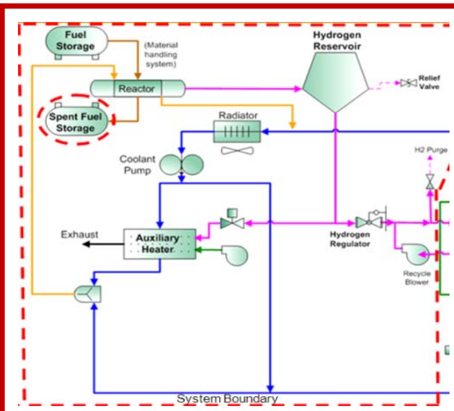
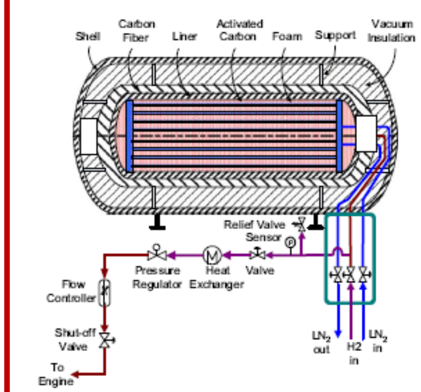
Qualitative risk analysis (QLRA)

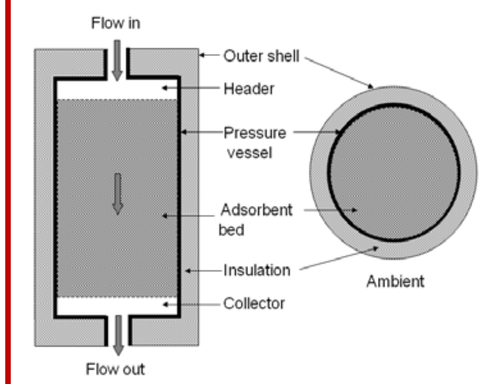
Objective: *Identify the critical risks, failure modes and technical challenges of three H_2 storage systems.*

On-board sodium alanate system (UTRC)	Off-board solid AB system (PNNL)	On-board cryo-adsorption system (ANL)	On-board cryo-adsorption system (GM)









Examples of Critical Risks, Failure Modes and Technical Challenges

Risk: Potential for dust explosion in air (wet/dry). Also, fire and/or explosion of released H_2 gas. Failure mechanism: accidental rupture of storage vessel upon collision.	Risk: Runaway chemical reaction during AB thermolysis. Failure mechanism: Loss of thermolysis exothermic heat removal capability.	Risk: Loss of vacuum insulation enhances heat influx through the tank wall causing boil off of stored H_2, pressurizing the storage tank, loss of H_2 inventory via PRD venting and potential for tank failure by overpressurization if PRD venting rate is not sufficient. Note: Loss of H_2 via PRD venting and permeation through the tank wall reduce the mass of stored H_2 available to feed the on-board fuel cells. Failure mechanism: Stored H_2 gradually permeates / diffuses to the vacuum insulation gap leading to pressurizing the gap with H_2.
Risk: material reactivity with water and subsequent fire and vessel failure by overpressurization. Failure mechanism: water intrusion in-vessel.	Risk: Release of toxic gases (diborane and borazine) during solid AB thermolysis. Failure mechanism: Rupture of the on-board spent fuel tank or pipe leaks from the system.	

Safety categorization of H_2 storage media

Objective: *develop a framework for safety categorization of H_2 storage media for on-board vehicular applications.*

- The storage media can be solid, liquid, or slurry and include: Metal hydrides, chemical hydrides and adsorbents
- Categorization is based on risk assessment of:
  Material reactivity, pyrophoricity, sensitivity to mechanical impact, toxicity, chemical stability, ability to cause runaway chemical reaction, on-board vehicular use & handling and off-board regeneration/recycling.
- Material risk includes adverse impact on human safety, health and environment impact.
- Four categories of material risk: Green, Yellow, Orange and Red.

Safety Categories of Storage Media	Classification Criteria
GREEN	Material's chemistry is green, i.e., causes no risks to human health and/or the environment. Qualifying features: 1) No release of toxic chemicals during its manufacturing, on-board vehicular use or regeneration/recycling. 2) Material is chemically stable, i.e., nonpyrophoric, non-water reactive. 3) Non-corrosive and no material compatibility concerns. 4) Not sensitive to mechanical impact.
YELLOW	Low-to-moderate-risk material. Qualifying features: 1) Material may release very low concentrations of toxic chemicals during its manufacturing, use or regeneration/recycling. Releases are of no harm to humans and/or the environment. 2) Risk can be eliminated through risk mitigation. Examples: • Material's pyrophoricity and water reactivity can be eliminated by powder compaction. • Material's temperature sensitivity can be eliminated by stabilizing the material using additives with green chemistry features.
ORANGE	High-risk material. Qualifying features: 1) Material releases high concentrations of toxic chemical during its manufacturing, use or regeneration/recycling. Releases are harmful to human health and/or the environment. 2) Risk may be eliminated/reduced through risk mitigation but cost would be high, process is complex, additives are of non-green chemistry, additives adversely impact the volumetric and/or gravimetric storage capacity.
RED	Material's risk is unacceptable to human health and/or the environment. Qualifying features: 1) Material may release unacceptably high concentrations of toxic chemicals during its manufacturing, use or regeneration/recycling. Releases are harmful to human health and/or the environment. 2) Risk cannot be eliminated through risk mitigation. Examples: • Material's pyrophoricity and water reactivity cannot be eliminated by powder compaction. • Material's temperature sensitivity cannot be eliminated by stabilizing the material using additives with green chemistry features. • Material may cause a runaway chemical reaction.

Phase-II risk analysis activities

- *Perform failure modes and effects analysis (FMEA) to rank material and system risks based on the probability of occurrence and severity of consequences.*
- *Populate the safety categorization framework.*

Collaborations

- *Continue to incorporate risk insights from UTRC materials reactivity contract.*
- *Continue to incorporate quantitative insights from SNL and SRNL reactivity contracts.*

FY11 and FY12 Plan

	FY11			FY12		
	2Q	3Q	4Q	1Q	2Q	3Q
Go/No-Go meeting for Phase 1 to Phase 2 transition	★					
Design FMEA of H_2 storage systems: improve levels of quantitative risk assessment	■	■	■	■	■	■
Improve understanding of DOT requirements		■	■			
Framework maintenance and support and updating models	■	■	■	■	■	■
LiMgNH system implementation in Framework	■					
Enable sensitivity studies with Framework		■	■	■	■	■
Address data gaps in material properties	■	■	■	■	■	■
Further develop internal mesh reinforcement path of compacted hydrides	■	■	■			
Evaluation hydride pellet / HX tube concept	■	■	■			
Screen NH_3 sorbent with higher capacity that is regenerable		■	■			
Fabricate and evaluate test article for impurity mitigation		■	■	■	■	
Evaluate particulate mitigation strategies		■	■	■	■	■
Prioritize tasks after DOE's review of Go/No-Go presentation materials		★				
Solid transport quantification with surrogate material	■					
Gas/liquid separation design for liquid chemical hydride system		■	■			
Engineer specialty components and their evaluation		■	■	■	■	■
Support material and system selection of best technology for Phase 3						★

Summary

Relevance: Design of materials based vehicular hydrogen storage systems that will allow for a driving range of greater than 300 miles

Approach: Leverage in-house expertise in various engineering disciplines and prior experience with metal hydride system prototyping to advance materials based H_2 storage for automotive applications

Technical Accomplishments and Progress:

- Simulink framework generated a quantitative comparison of all three hydrogen storage systems on a common basis for the Go/No-Go decision.
- Compaction know-how transferred from SAH to LiMgNH system; Identified need for binder; SAH pellet stabilization with internal mesh demonstrated.
- Additives evaluated for thermal conductivity enhancement; introduced preferred thermal conductivity enhancement towards HX tube (anisotropy)
- Designed heat exchanger with minimal weight for fast refueling of SAH tank
- Revitalized PCT for evaluating concept of SAH pellet integration with HX tube
- Screened ammonia sorbents and particulate filter to enable sufficient H_2 purity
- Qualitative risk assessment of all three H_2 storage systems

Collaboration: Simulink framework recognized as successful effort of HSECoE as it enabled a team effort and yielded results at a critical time (Go/No-Go)

Future Work: Work towards milestones and next phase Go/No-Go decision

Acknowledgements

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Technical Back-Up Slides

Center structure – roles & collaborations

Hydrogen Storage Engineering Center of Excellence

D. Anton, SRNL
T. Motyka, SRNL

Materials Operating Requirements
D. Herling, PNNL
- Materials Centers of Excellence Collaboration – SRNL, LANL, NREL
- **Reactivity & Compatibility – UTRC**
- Adsorption Properties – UQTR
- **Metal Hydride Properties – SRNL**
- Chemical Hydride Properties – LANL
- Media Structure - GM

Transport Phenomena
B. Hardy, SRNL
- **Bulk Materials Handling – PNNL**
- Mass Transport – SRNL
- Thermal Transport – SRNL

Enabling Technologies
J. Reiter, JPL
- Thermal Insulation – JPL
- **Hydrogen Purity – UTRC**
- Sensors – LANL
- **Thermal Devices - OSU**
- Pressure Vessels - PNNL

Performance Analysis
M. Thornton, NREL
- Vehicle Requirements– NREL
- Tank-to-Wheels Analysis – NREL
- **Forecourt Requirements - UTRC**
- Manufacturing & Cost Analysis - PNNL

Integrated Power Plant / Storage System Modeling
B.A. van Hassel, UTRC
- Off-Board Rechargeable - PNNL
- On-Board Rechargeable – GM
- Power Plant – Ford

Subscale Prototype Construction, Testing & Evaluation
T. Semelsberger, LANL
- **Risk Assessment & Mitigation – UTRC**
- **System Design Concepts and Integration - LANL**
- Design Optimization & Subscale Systems – LANL, SRNL, UQTR
- Fabricate Subscale Systems Components – SRNL, LANL
- Assemble & Evaluate subscale Systems – LANL, JPL, UQTR

Leading / Project Tasks
Additional Project Tasks
Supporting

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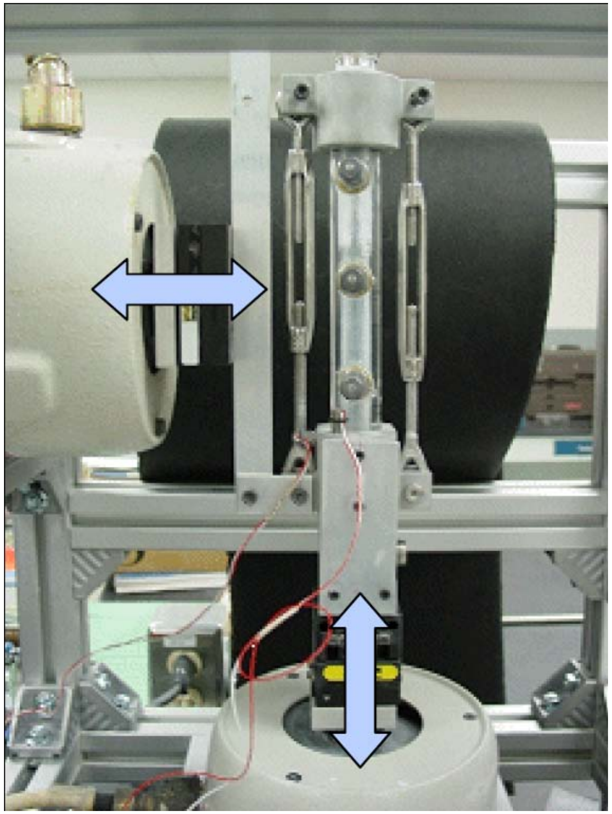
Vibration packing

Objective: Evaluate whether vibration packing of adsorbent material like AX21/Maxsorb can improve density from 0.3 g/cm^3 to 0.6 g/cm^3 without binder additions

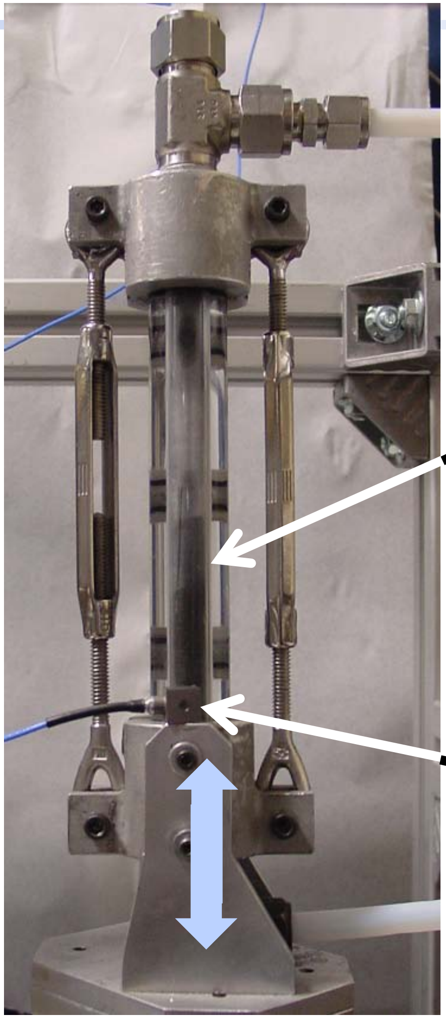
Expectations for packing density:

Model	Description	Packing density
Dense regular packing	Monodisperse spheres	0.7405
Random close packing	Bimodal particle size distribution	0.75-0.68
Random close packing	E.g. the bed vibrated	0.641-0.625
Random loose packing		0.58

Vibration packing principle



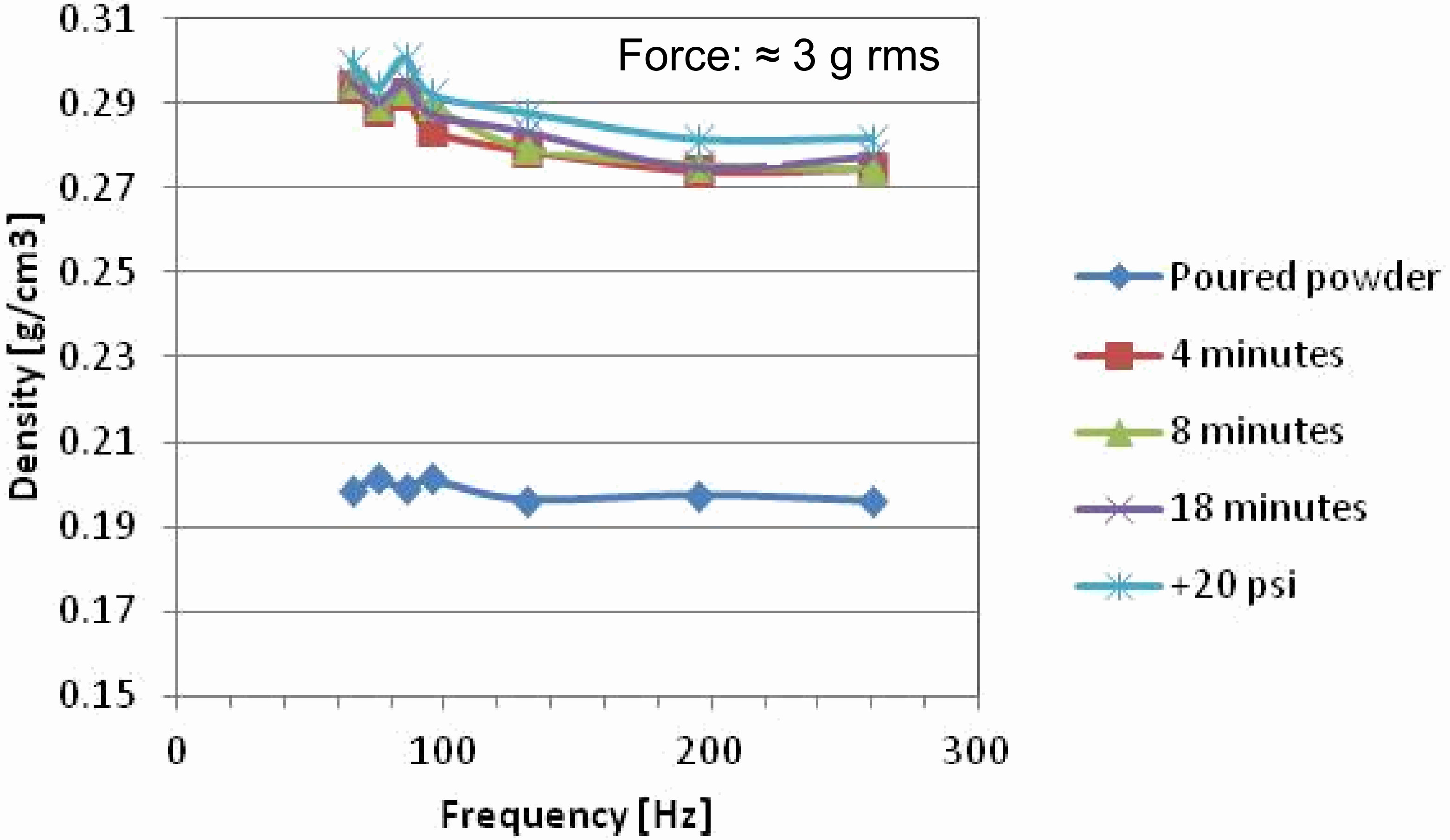
Shakers
in two directions



Maxsorb

Accelero-
meter

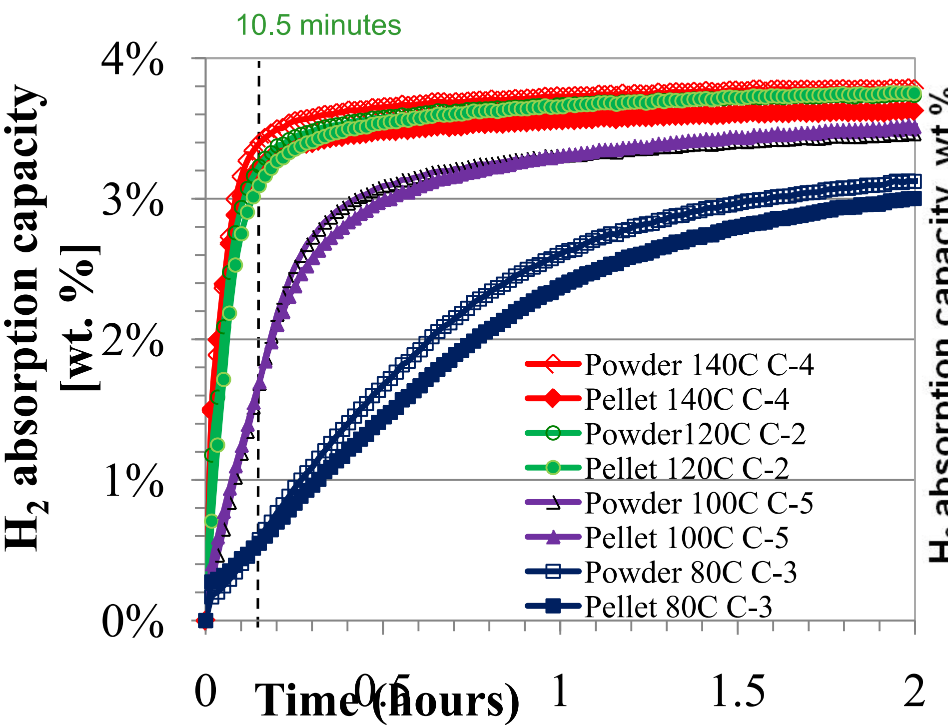
Time and frequency dependence



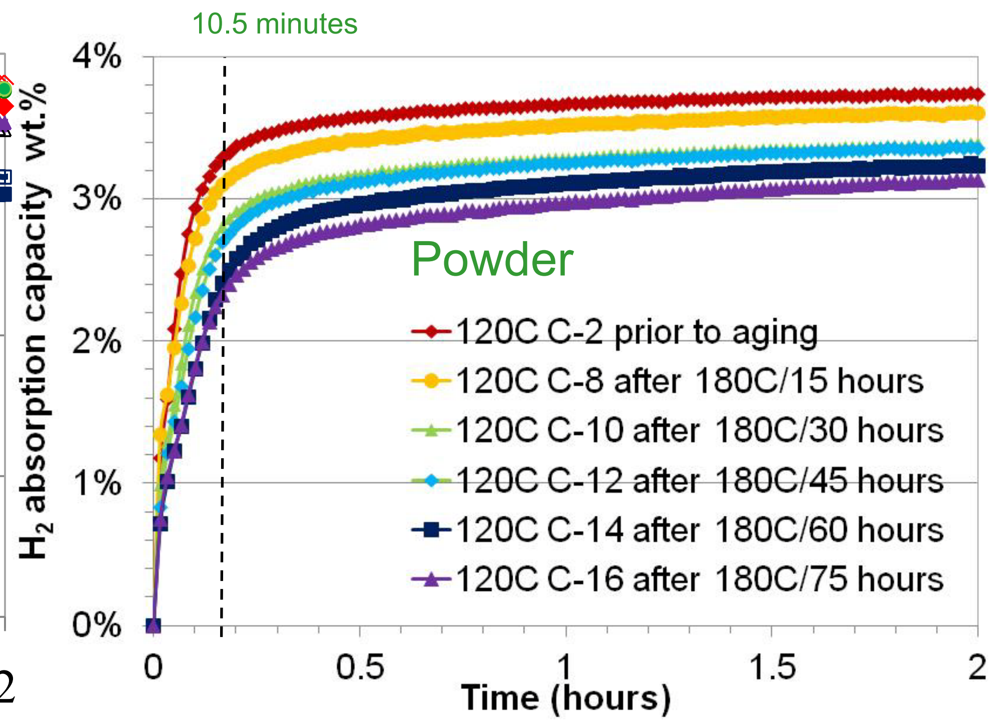
Vibration packing did not improve density of AX21/Maxsorb above 0.3 g/cm^3. AX21/Maxsorb needs to be kept under compression to yield 0.6 g/cm^3.

Kinetics of $NaAlH_4$ + 4 mol% $TiCl_3$ remeasured

- H_2 Absorption Rate



- Capacity loss upon aging at 180°C, 110-100 bar H_2 partial pressure



SAH + 4 mol% $TiCl_3$ has considerably higher kinetics than Prototype 2 material.
Consider 170°C upper limit for SAH to avoid capacity loss

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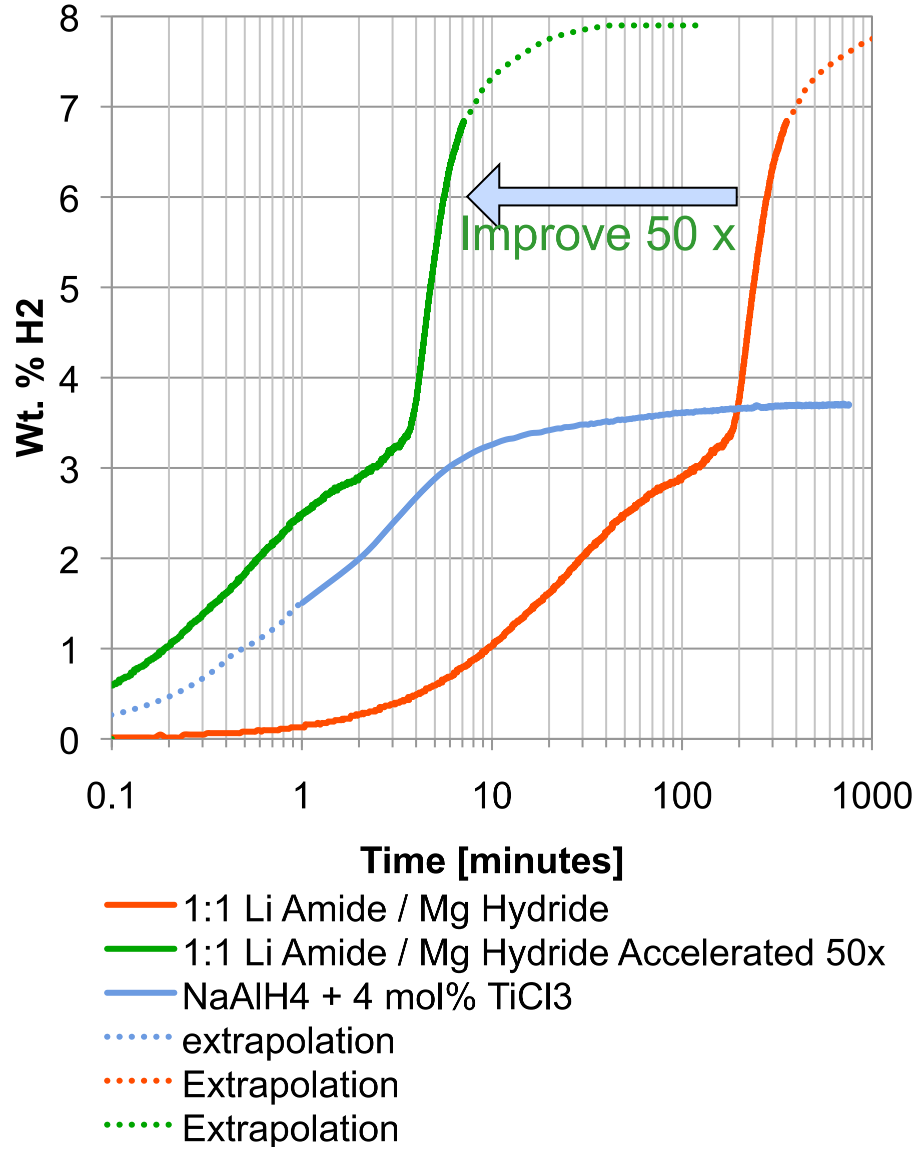
Kinetics and heat transfer for LiMgNH system

- Requirement
  - A fast system fill time

	System Fill Time [min]
2010	4.2
2015	3.3
Ultimate	2.5

  - Enablers:
    - Kinetics yields 90% of materials capacity at targeted fill time
    - Not reduced by compaction
    - (Complex) metal hydride bed effective thermal conductivity 4-8 W/m/K



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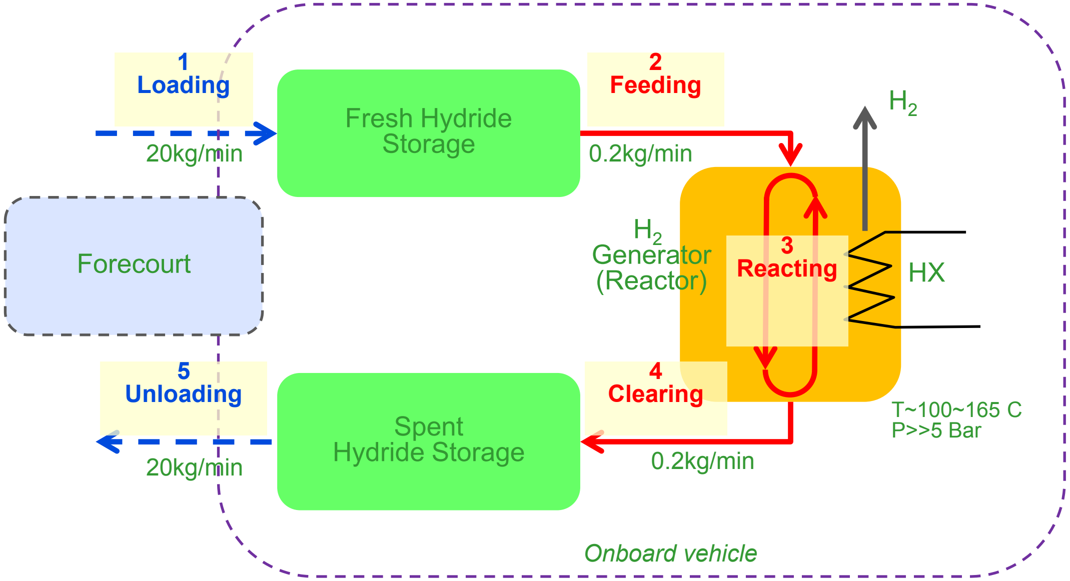
Solid hydride transport: requirements and concepts

- **Objectives:**
  - Functionally demonstrate solid hydride transport
  - Identify key challenges to on board bulk material handling
  - Support March 2011 go/no-go decision (BMH)
- **Scope:**
  - Material: surrogate representative of solid candidate fuels
  - Engineering forms: powder and encapsulated pellets
  - Through reactor and fuel tanks
- **Evaluation metric**
  - Distance over which the material is transported
  - Elevation that one needs to be able to achieve
  - Section with curvature and hot zone
  - Rate at which the material is transported
  - Absolute pressure and/or pressure difference
  - Scalability



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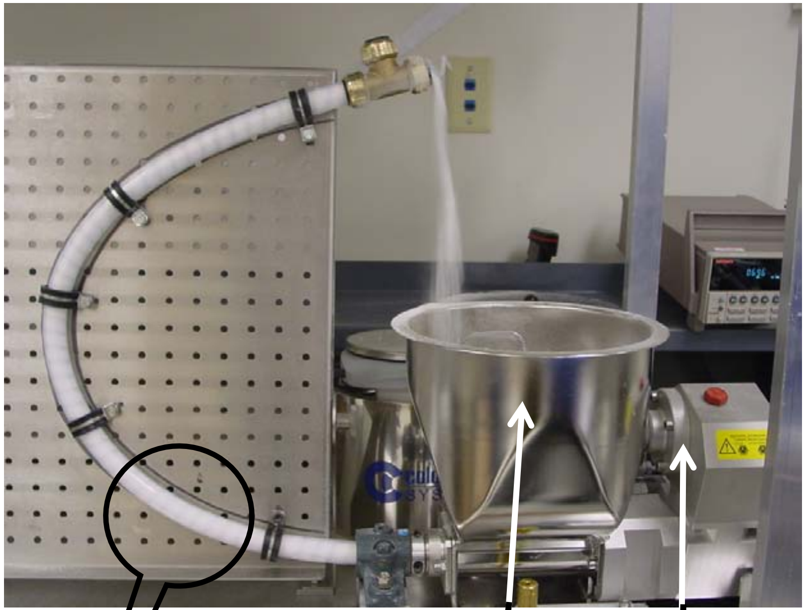
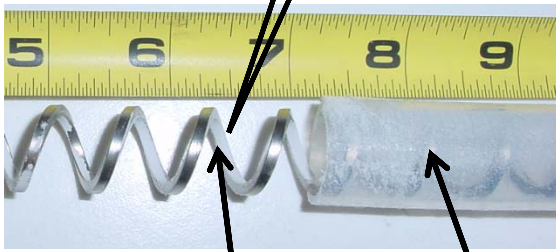
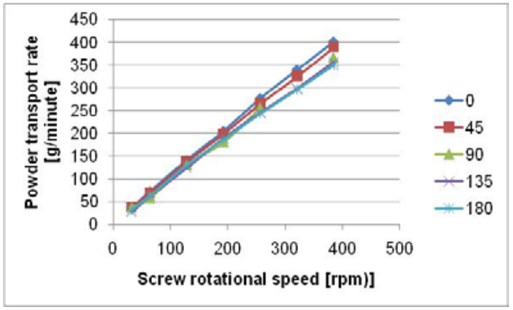
Solid hydride transport: experiment with flexible screw

- Flexible rectangular coil screw as primary propulsion element
- Teflon outer tube and inner core forming an annular passage to minimize flow back
- Curved material passage to mimic for reactor
- Low speed feeding and metering by variable speed drive (up to 600 rpm of screw speed)
- *Microthene G polyolefin powders* (50 mesh) used as surrogated material for Ammonia Borane

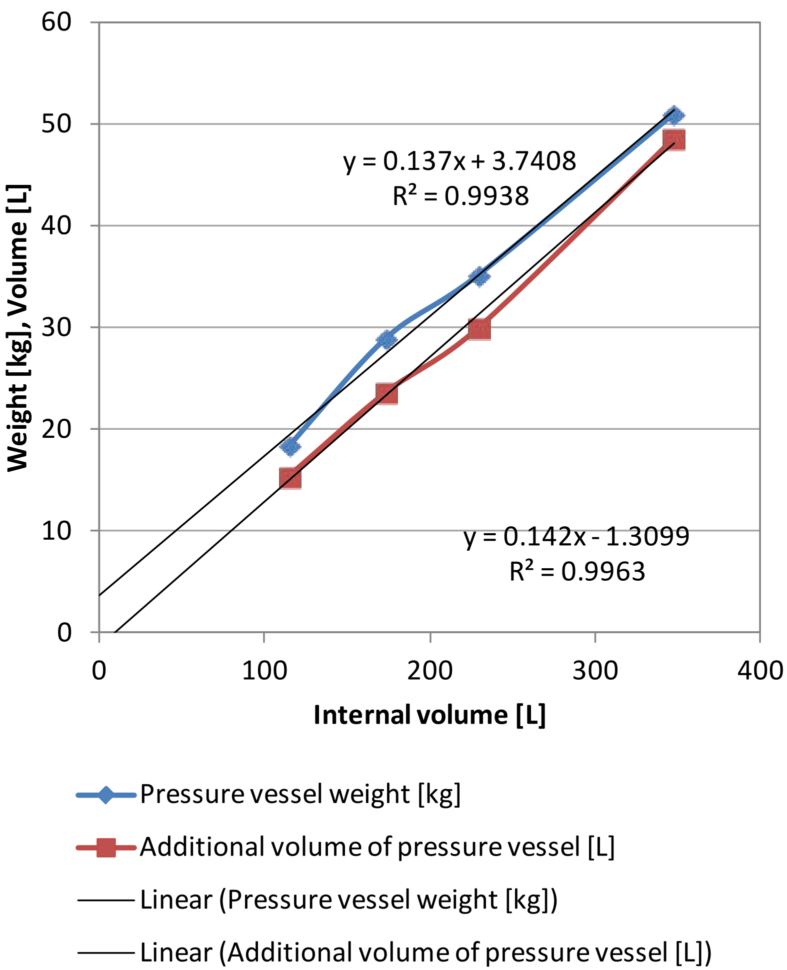






Weight & volume correlation for 100 bar pressure vessels

- To quickly obtain weight and volume of a Type IV pressure vessel, Lincoln Composites provided some cases for different internal volumes at 100 bar.
  - Type IV tank.
  - Rated for 100 bar (2.25 FS)
- A simple linear correlation is used to determine the additional weight and volume due to the pressure vessel at intermediate points.



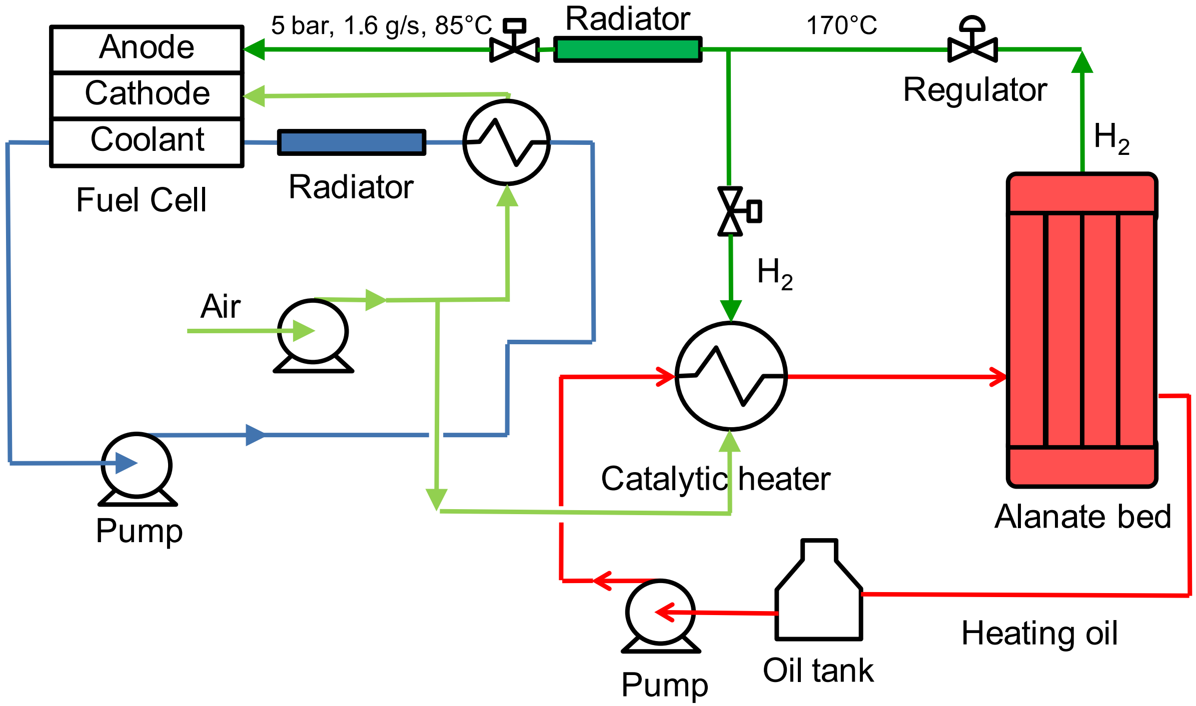
Drive cycles & test conditions for use in the framework

Case	Test Schedule	Cycles	Description	Test Temp (°F)	Distance per cycle (miles)	Duration per cycle (minutes)	Top Speed (mph)	Average Speed (mph)	Max. Acc. (mph /sec)	Stops	Idle	Avg. H2 Flow (g/s)*	Peak H2 Flow (g/s)*	Expected Usage
1	**Ambient Drive Cycle** - Repeat the EPA FE cycles from full to empty and adjust for 5 cycle post-2008	UDDS	Low speeds in stop-and-go urban traffic	75 (24 C)	7.5	22.8	56.7	19.6	3.3	17	19%	0.09	0.69	**1. Establish baseline fuel economy (adjust for the 5 cycle based on the average from the cycles) 2. Establish vehicle attributes 3. Utilize for storage sizing**
		HWFET	Free-flow traffic at highway speeds	75 (24 C)	10.26	12.75	60	48.3	3.2	0	0%	0.15	0.56	
2	**Aggressive Drive Cycle** - Repeat from full to empty	US06	Higher speeds; harder acceleration & braking	75 (24 C)	8	9.9	80	48.4	8.46	4	7%	0.20	1.60	**Confirm fast transient response capability – adjust if system does not perform function**
3	**Cold Drive Cycle** - Repeat from full to empty	FTP-75 (cold)	FTP-75 at colder ambient temperature	-4 (-20 C)	11.04	31.2	56	21.1	3.3	23	18%	0.07	0.66	**1. Cold start criteria 2. Confirm cold ambient capability – adjust if system does not perform function**
4	**Hot Drive Cycle** - Repeat from full to empty	SC03	AC use under hot ambient conditions	95 (35 C)	3.6	9.9	54.8	21.2	5.1	5	19%	0.09	0.97	**Confirm hot ambient capability - adjust if system does not perform function**
5	**Dormancy Test**	n/a	Static test to evaluate the stability of the storage system	95 (35 C)	0	31 days	0	0	0	100%	100%			**Confirm loss of useable H2 target**

*Based on NREL simulation with compact vehicle, 5.6 kg usable H2, 80 kW fuel cell with a 20 kW battery

$NaAlH_4$ (uncompacted powder) system diagram

- 243 kg hydride needed to deliver 5.6 kg to the fuel cell.
- System: 410 kg, 438 liters = 1.37 wt%, 13 g-H_2/L
- No separate buffer tank. All gas comes from the pores.



Adapted from the GM alanate system diagram

$NaAlH_4$ powder system: Case 1 for sizing

- Main parameters

Usable H_2	5.6	kg
Total weight	410.2	kg
Total volume	438	L
Gravimetric capacity	1.37%	
Volumetric capacity	12.8	g/L

- Material (pelletized)

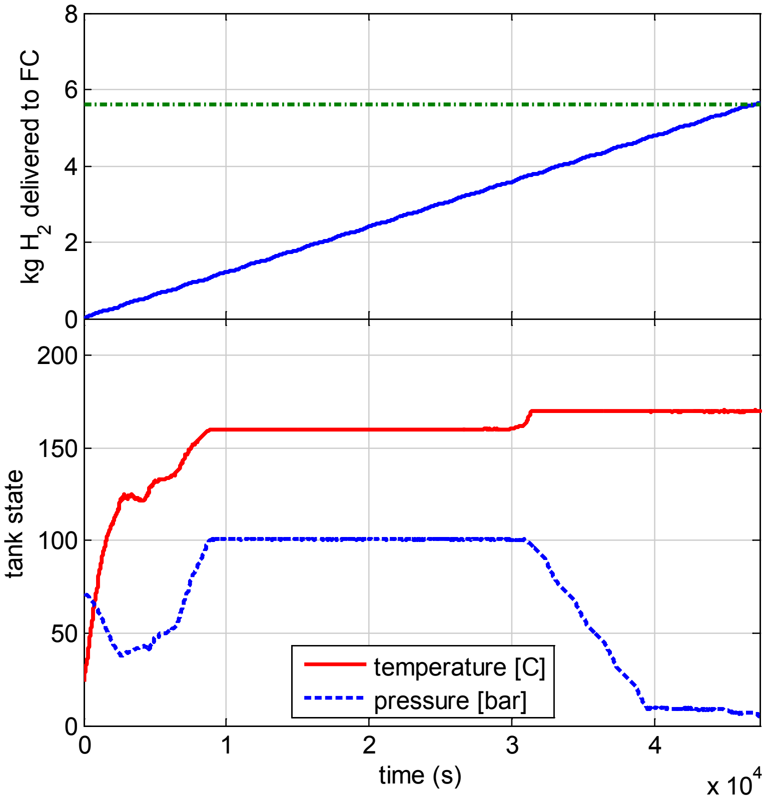
Gravimetric capacity	3.1%
Porosity	56%

- Weights

Material	243	kg
Heat exchanger	41.6	kg
Pressure vessel (additional)	45.8	kg
Heat transfer fluid loop	70.53	kg
Hydrogen loop	7.61	kg
Isolation valve	1.65	kg

- Volumes

Tank internal volume	307	L
Pressure vessel (additional)	42.3	L
Heat transfer fluid loop	47.7	L
Hydrogen loop	40.2	L
Isolation valve	0.26	L



- Other targets

On-board efficiency	70%
Cold/hot cases	OK
Dormancy	N/A
Delivery temperature	< 85C
Min delivery pressure	5 bar
Min full flow rate	1.6 g/s

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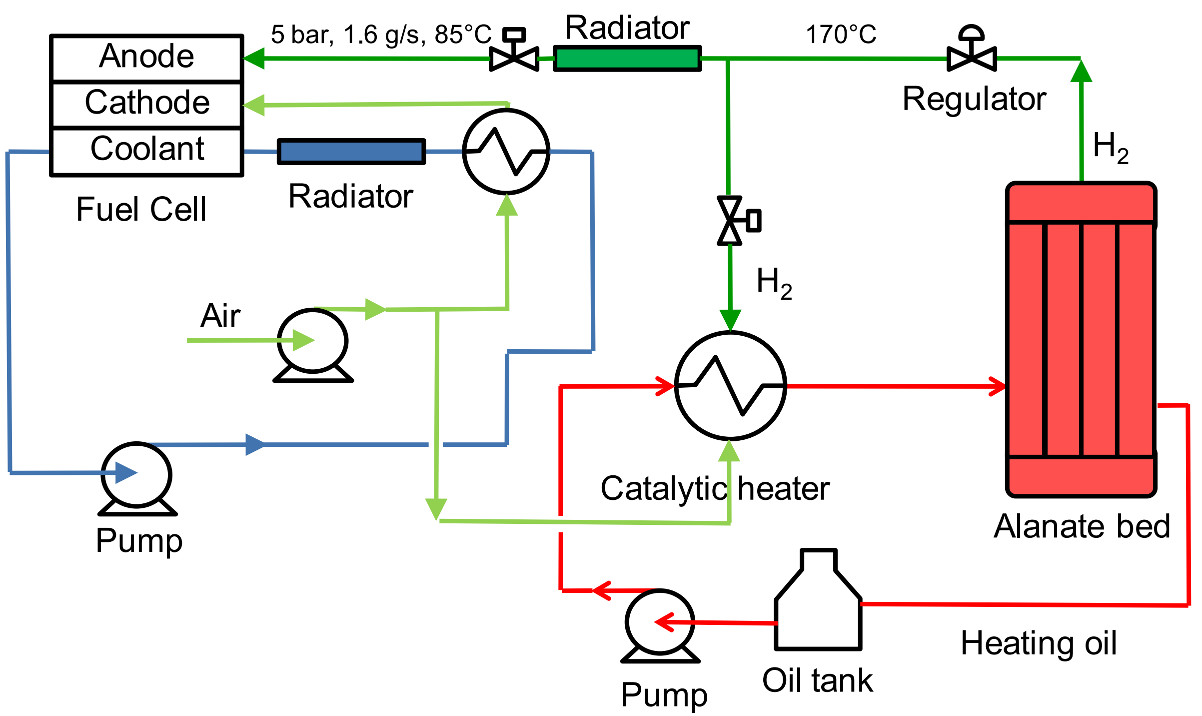
$NaAlH_4$ (compacted pellets) system diagram

- 255 kg hydride needed to deliver 5.6 kg to the fuel cell.
- System: 395 kg, 377 liters = 1.42 wt%, 15 g-H_2/L
- No separate buffer tank: additional 53 L in-tank provided.



Adapted from the GM alanate system diagram

$NaAlH_4$ compacted system: Case 1 for sizing

- Main parameters

Usable H_2	5.6	kg
Total weight	394.8	kg
Total volume	376.6	L
Gravimetric capacity	1.42%	
Volumetric capacity	15	g/L

- Material (pelletized)

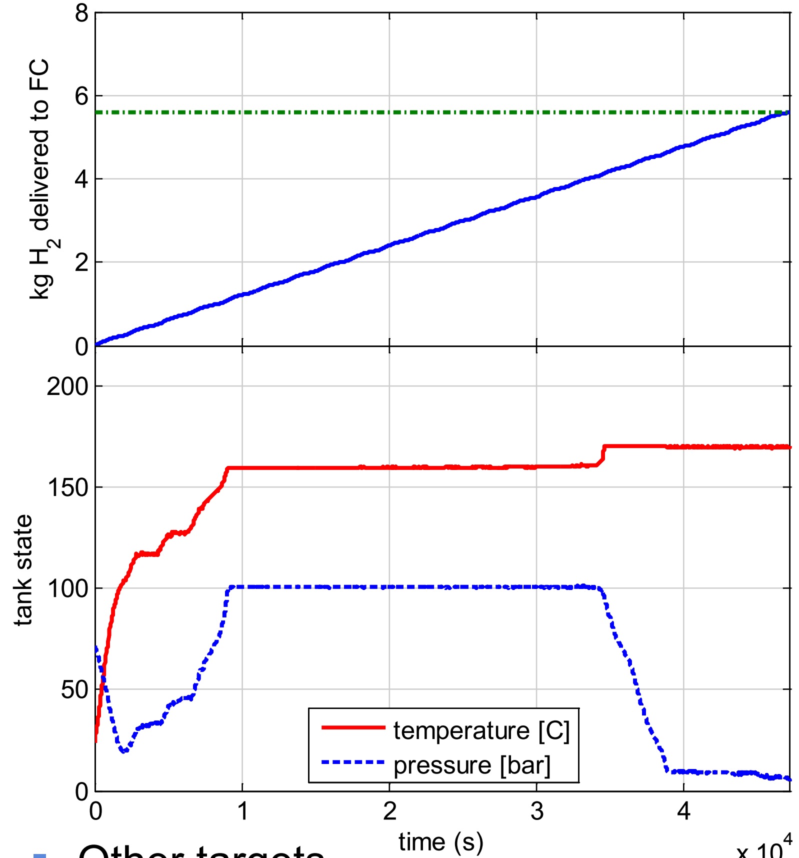
Gravimetric capacity	3.1%	
Porosity	29%	

- Weights

Material	255	kg
Heat exchanger	21.5	kg
Pressure vessel (additional)	38.5	kg
Heat transfer fluid loop	70.53	kg
Hydrogen loop	7.61	kg
Isolation valve	1.65	kg

- Volumes

Tank internal volume	253.7	L
Pressure vessel (additional)	34.7	L
Heat transfer fluid loop	47.7	L
Hydrogen loop	40.2	L
Isolation valve	0.26	L



- Other targets

On-board efficiency	69%
Cold/hot cases	OK
Dormancy	N/A
Delivery temperature	< 85C
Min delivery pressure	5 bar
Min full flow rate	1.6 g/s

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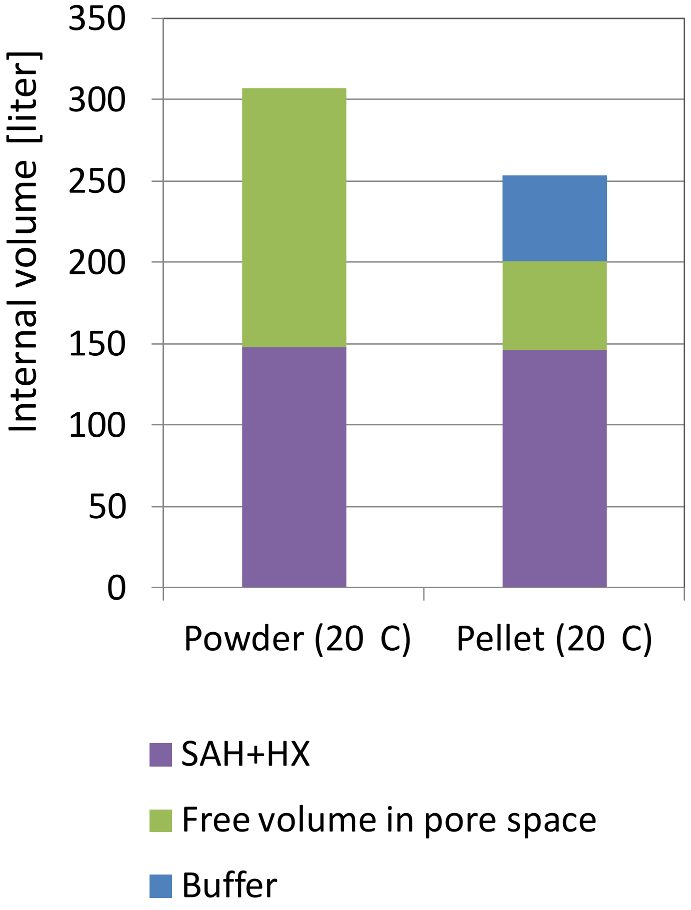
Comparison of $NaAlH_4$ powder and compacted pellets systems

- There is a trade-off in compacting the material.
  - A reduction in pore volume can be effective up to a point.
  - Further compaction results in insufficient gas initially to heat the system to operating conditions → additional buffer space must be provided.



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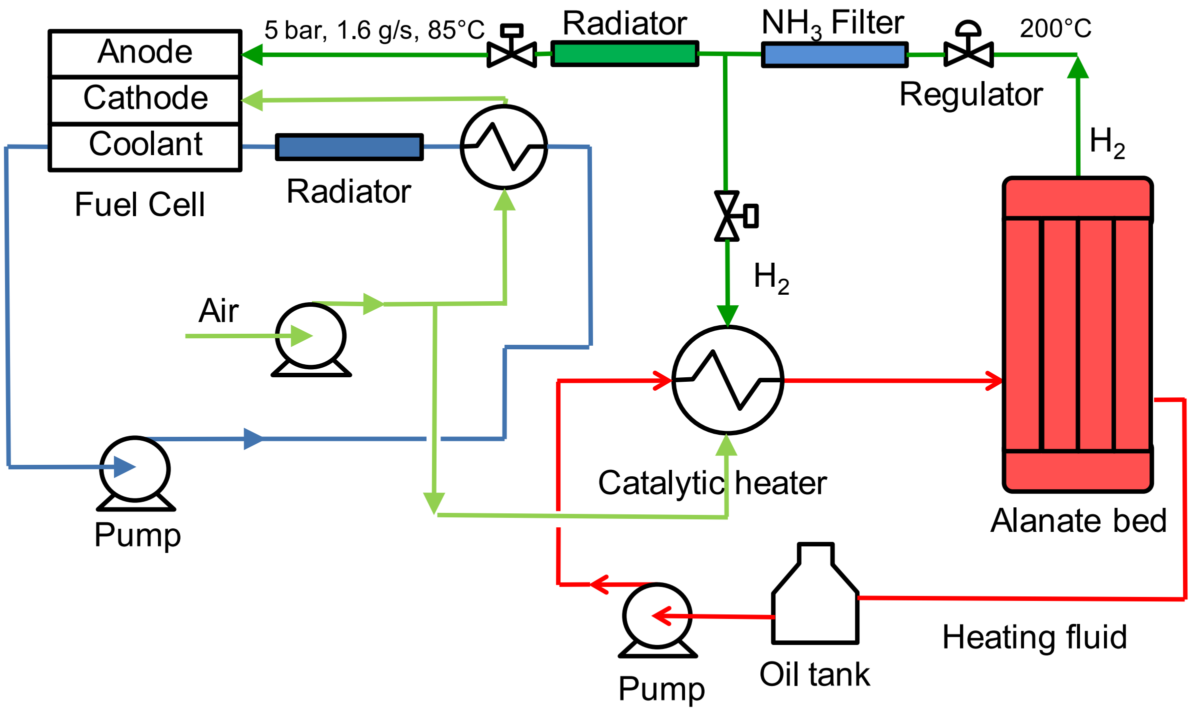
1:1 Li-Mg-N-H (uncompacted powder) system

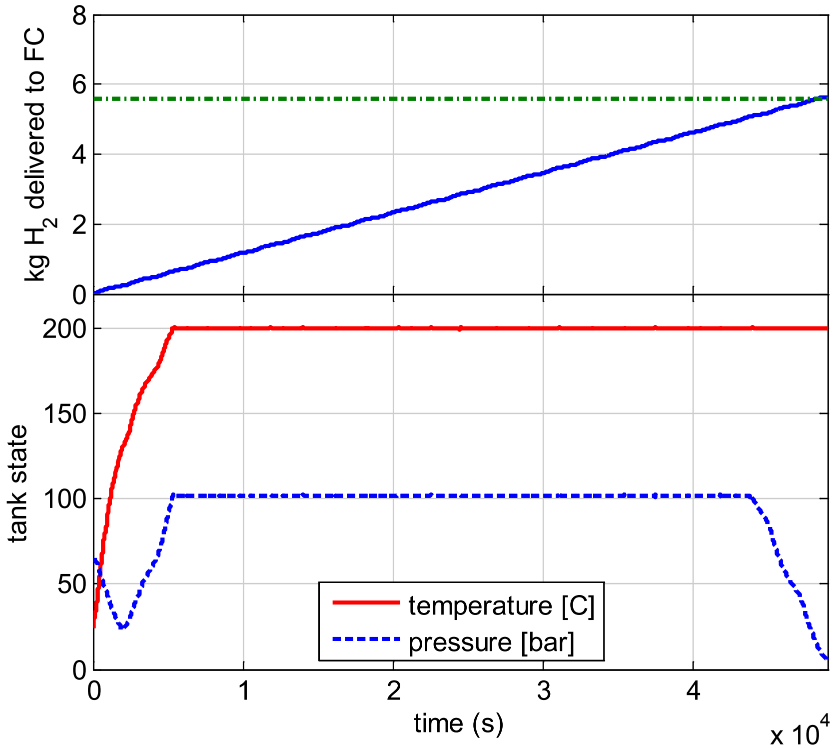
- 92 kg hydride needed to deliver 5.6 kg to the fuel cell.
- System: 240 kg, 348 liters = 2.33 wt%, 16.1 g-H_2/L
- No separate buffer tank: additional 90 L in-tank provided for cold start.



Gravimetric improvement is driven by the material.
Volumetric improvement is marginal due to need for extra volume for cold start.

1:1 Li-Mg-N-H powder Case 1 for sizing

- Main parameters
  - Usable H2 — 5.6 kg
  - Total weight — 240 kg
  - Total volume — 348 L
  - Gravimetric capacity — 2.33%
  - Volumetric capacity — 16.1 g/L
- Material (pelletized)
  - Gravimetric capacity — 7.5%
  - Porosity — 50%
- Weights
  - Material — 92 kg
  - Heat exchanger — 32 kg
  - Pressure vessel (additional) — 35 kg
  - Heat transfer fluid loop — 70.5 kg
  - Hydrogen loop — 7.6 kg
  - Isolation valve — 1.65 kg
- Volumes
  - Tank internal volume — 229 L
  - Pressure vessel (additional) — 31.1 L
  - Heat transfer fluid loop — 47.7 L
  - Hydrogen loop — 40.2 L
  - Isolation valve — 0.26 L



- Other targets
  - On-board efficiency — 75%
  - Cold/hot cases — OK
  - Dormancy — N/A
  - Delivery temperature — < 85C
  - Min delivery pressure — 5 bar
  - Min full flow rate — 1.6 g/s

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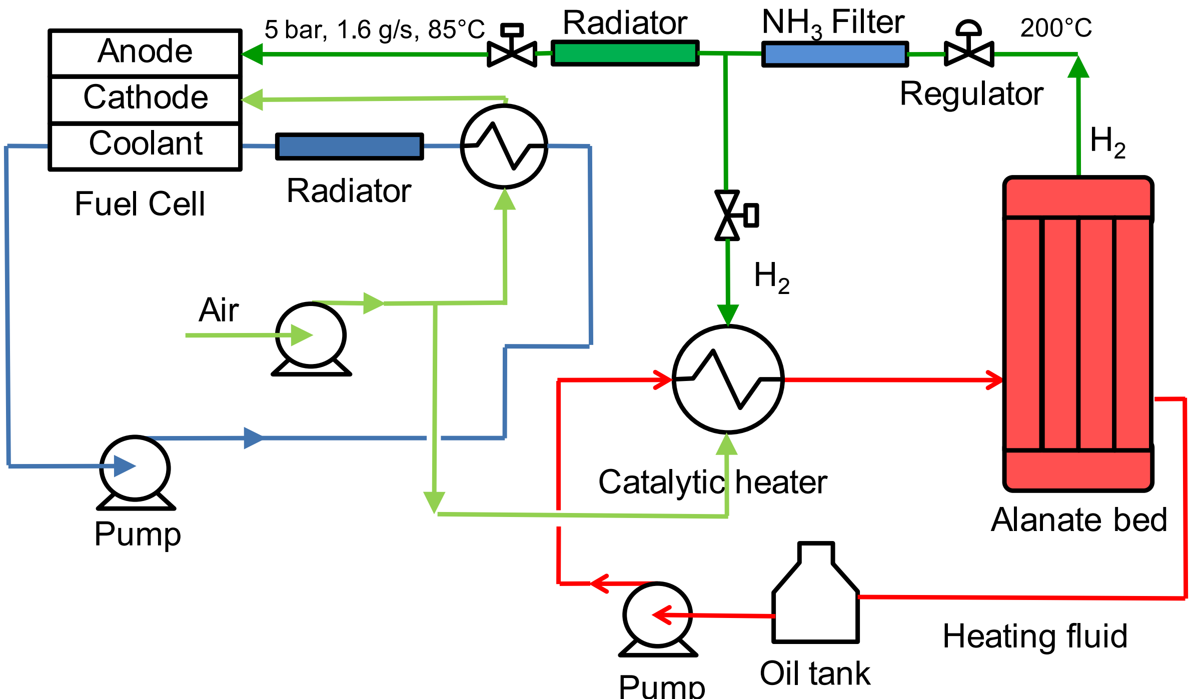
1:1 Li-Mg-N-H (compacted pellets) system

- 92.5 kg hydride needed to deliver 5.6 kg to the fuel cell.
- System: 218 kg, 311 liters = 2.75 wt%, 18 g-H_2/L
- No separate buffer tank: additional 90 L in-tank provided for cold start.



Gravimetric improvement is driven by the material.
Volumetric improvement is marginal due to need for extra volume.

- In-tank buffer is inefficient for this case: a separate buffer with colder H_2 may be more effective.

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1:1 Li-Mg-N-H compacted Case 1 for sizing

- Main parameters

Usable H2	5.6	kg
Total weight	218	kg
Total volume	311	L
Gravimetric capacity	2.75%	
Volumetric capacity	18	g/L

- Material (pelletized)

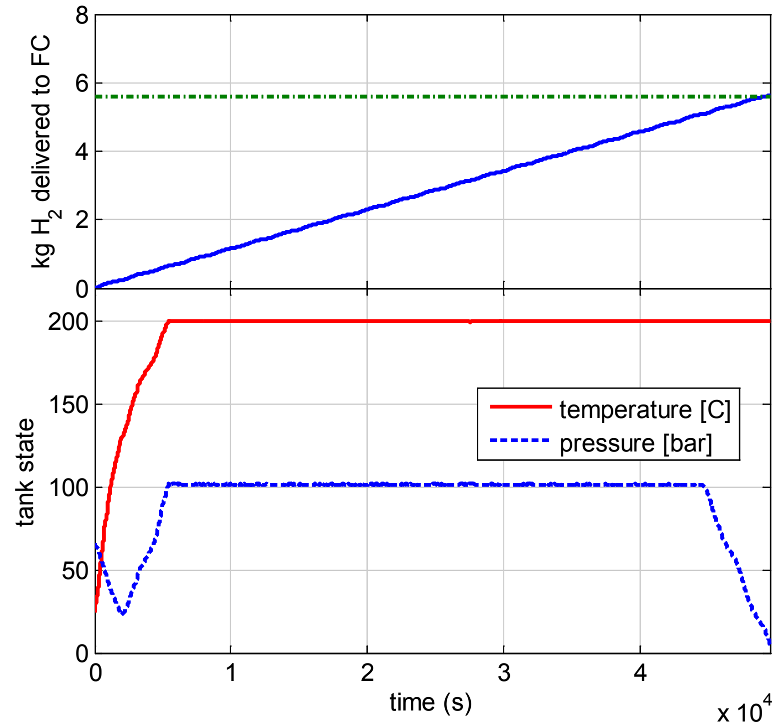
Gravimetric capacity	7.5%
Porosity	25%

- Weights

Material	92.5	kg
Heat exchanger	15	kg
Pressure vessel (additional)	30.7	kg
Heat transfer fluid loop	70.53	kg
Hydrogen loop	7.61	kg
Isolation valve	1.65	kg

- Volumes

Tank internal volume	196	L
Pressure vessel (additional)	26.7	L
Heat transfer fluid loop	47.7	L
Hydrogen loop	40.2	L
Isolation valve	0.26	L



- Other targets

On-board efficiency	75%
Cold/hot cases	OK
Dormancy	N/A
Delivery temperature	< 85C
Min delivery pressure	5 bar
Min full flow rate	1.6 g/s

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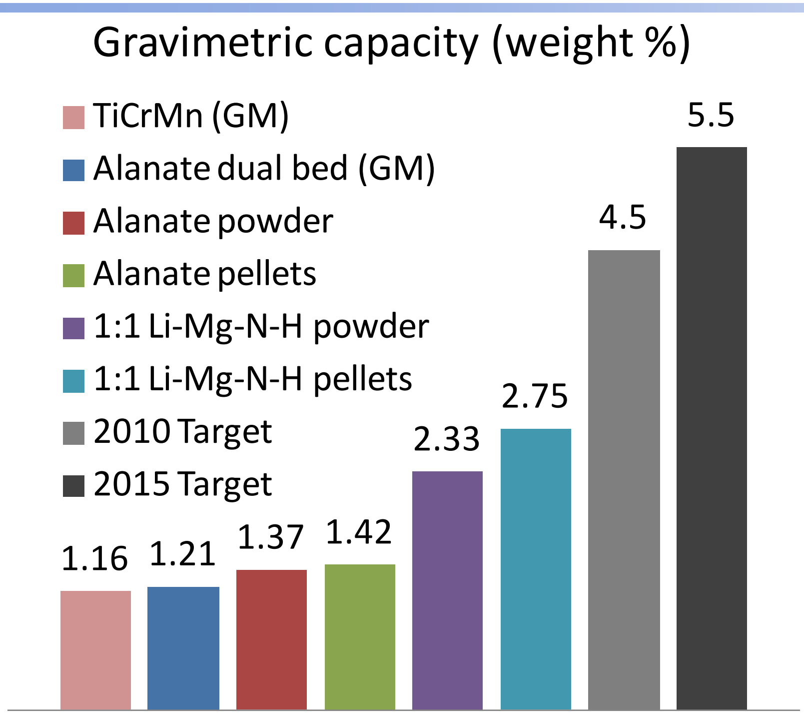
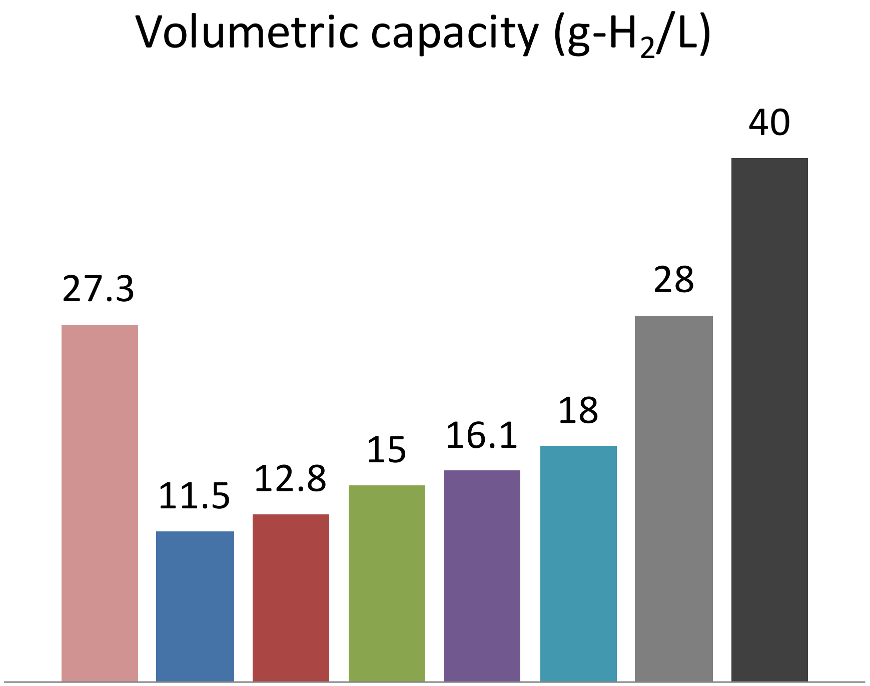
Capacity comparison summary



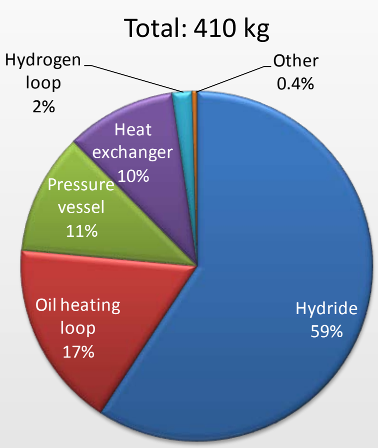


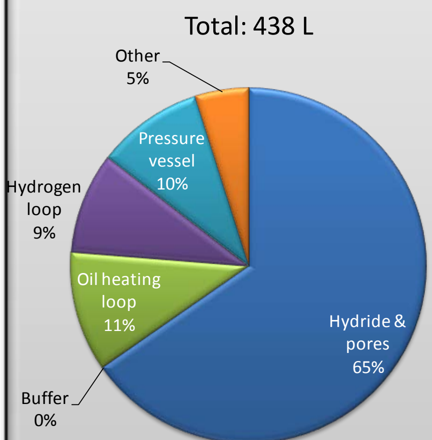
- Independent alanate powder system analyses (GM & UTRC) give comparable results. The difference in gravimetric capacity is due to the pressure vessel assumption: Composite tank + Steel liner (GM) vs Type IV (UTRC).

- Most promising is the 1:1 Li-Mg-N-H compacted system:
  - Gravimetric capacity: 61% of 2010 target, 50% of 2015 target
  - Volumetric capacity: 64% of 2010 target, 45% of 2015 target

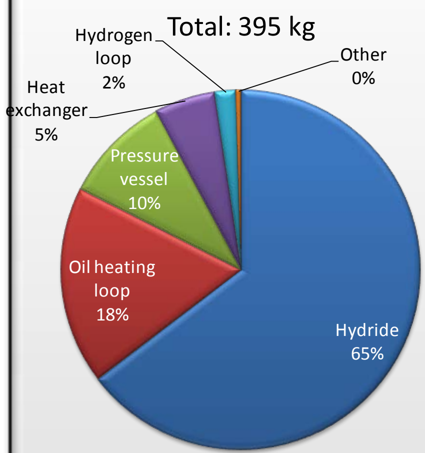
Weight and volume: main contributors

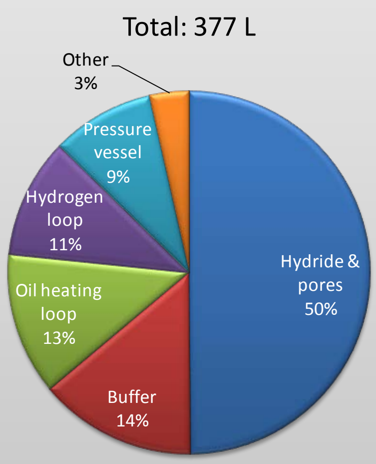
$NaAlH_4$ powder



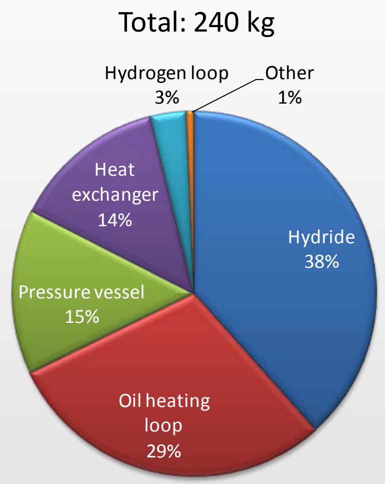


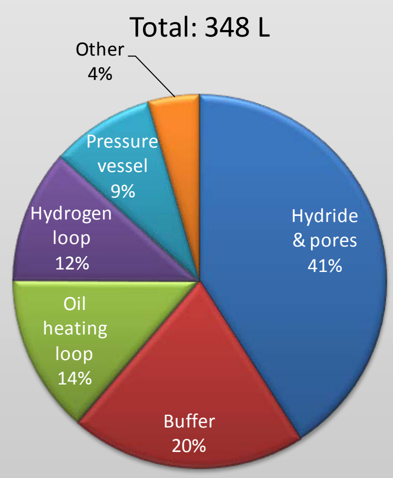
$NaAlH_4$ pellets





1:1 LiMgN powder





1:1 LiMgN pellets