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

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United Technologies Research Center

DOE Hydrogen Program

HSECoE

United Technologies Research Center

Annual Merit Review
Washington, DC
May 11, 2011

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

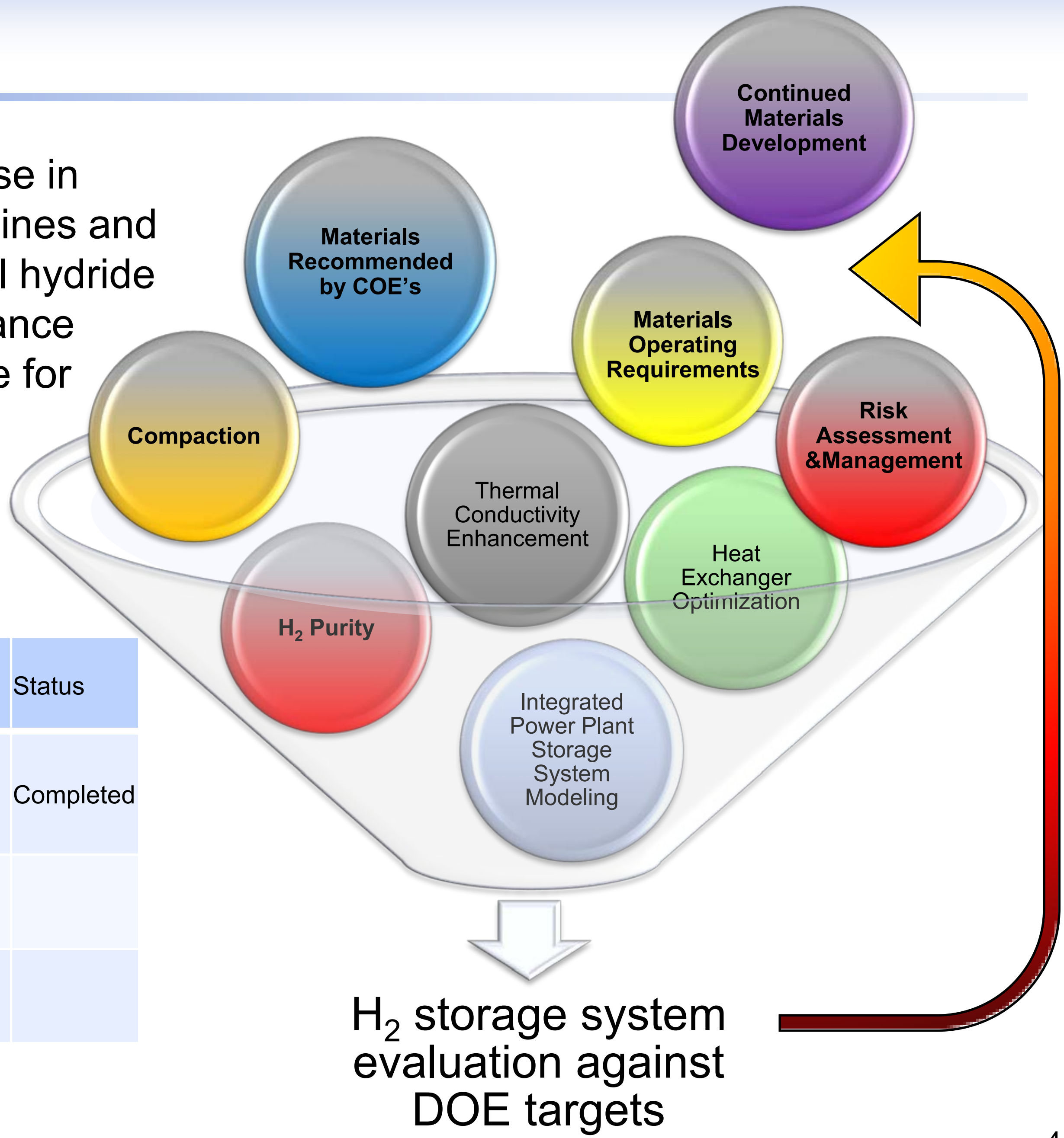
- Design of materials based vehicular hydrogen storage systems that will allow for a driving range of greater than 300 miles

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)

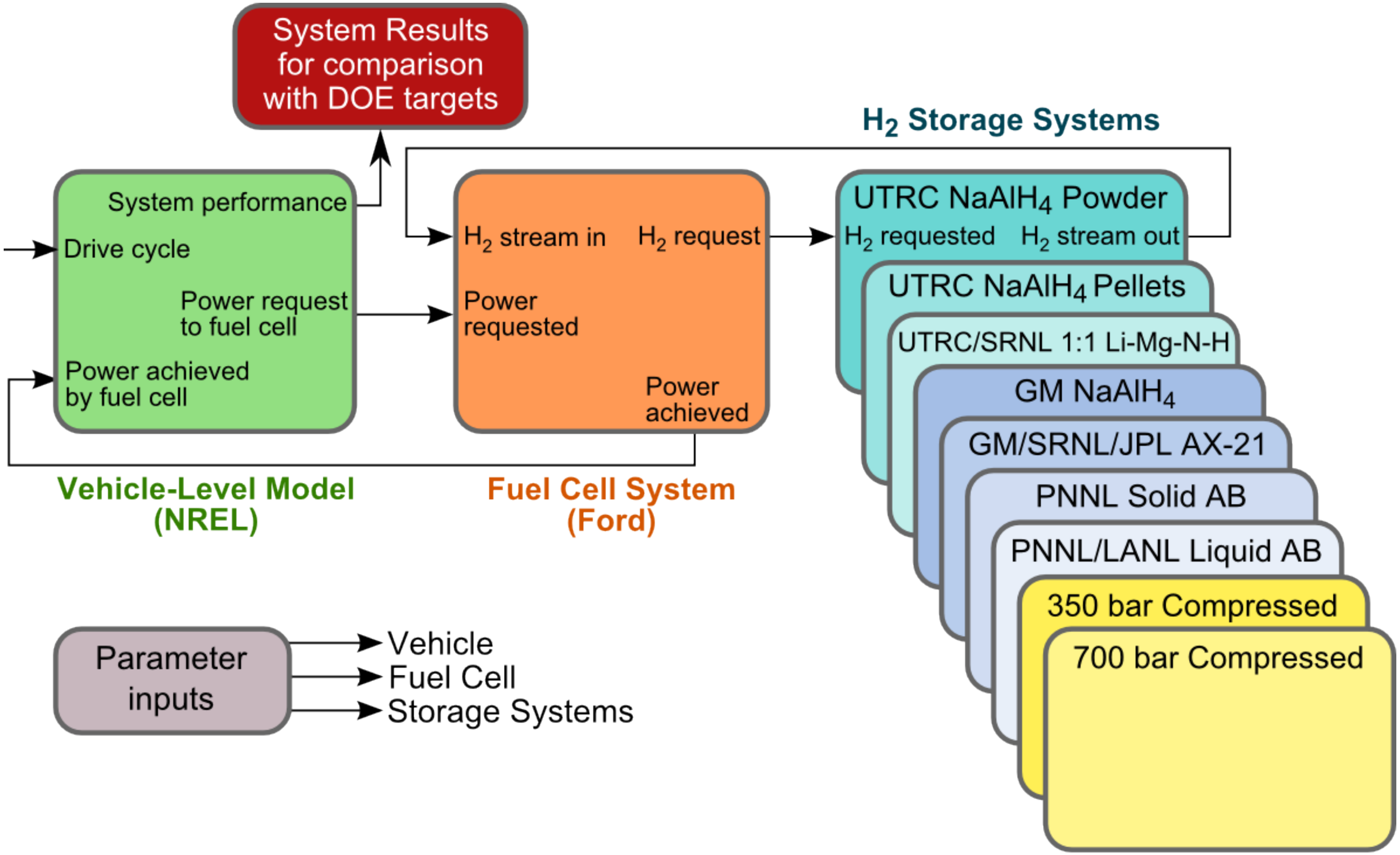
Approach

- 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



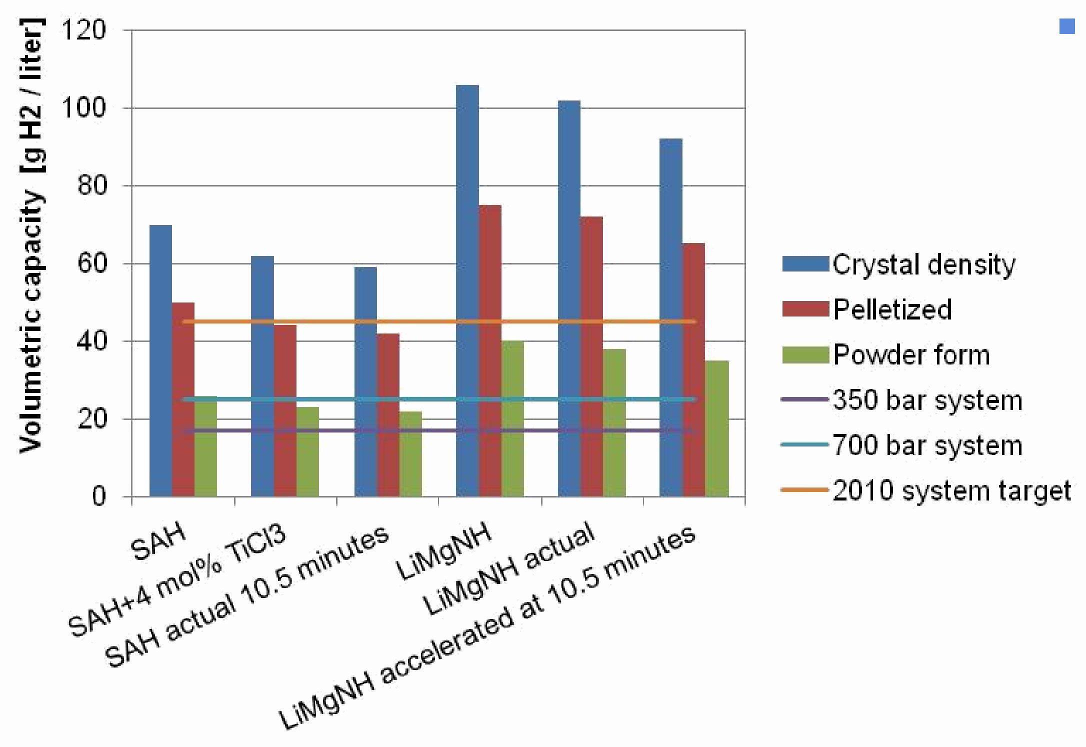
Month/Year	Go/No-Go Decision	Status
Feb-11	Provide a system model for each material sub-class (metal hydrides, adsorption, chemical storage) which shows:	Completed
	● 4 of the DOE 2010 system storage targets are fully met	
	● Status of the remaining targets must be at least 40% of the target or higher	

IPPSSM framework development

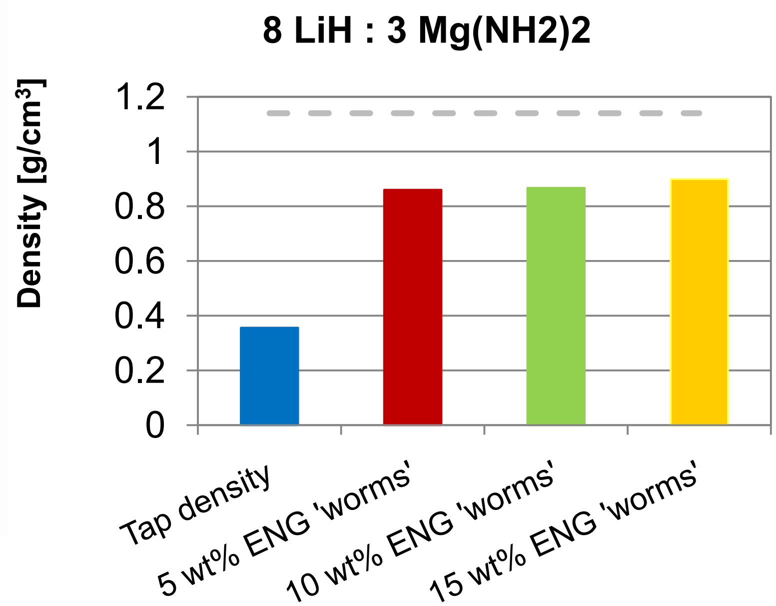


Quantitative comparison of H_2 storage systems on a common basis achieved by team effort

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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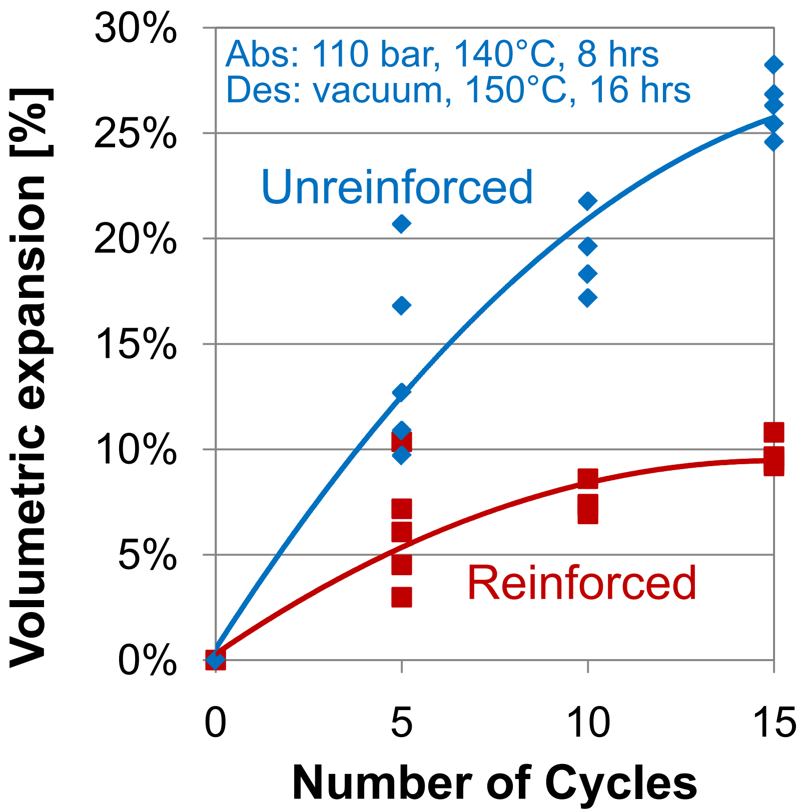
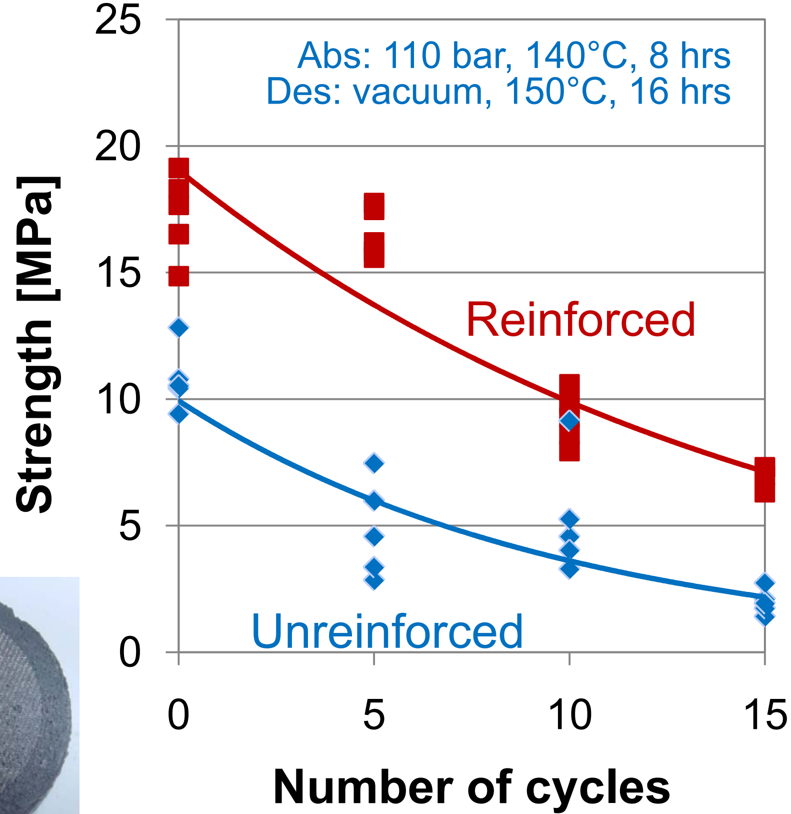
Stabilization of $NaAlH_4$ (SAH) pellets





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

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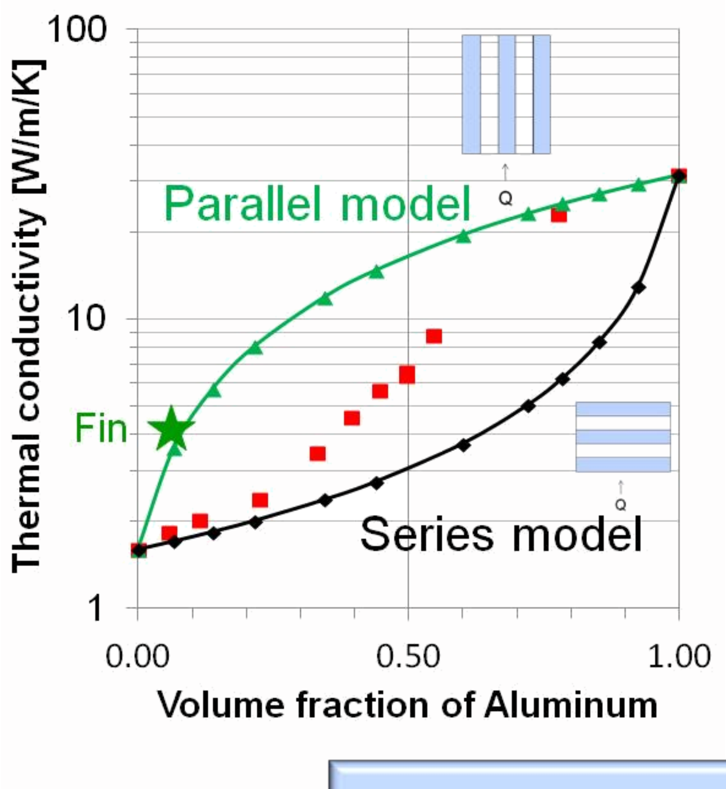
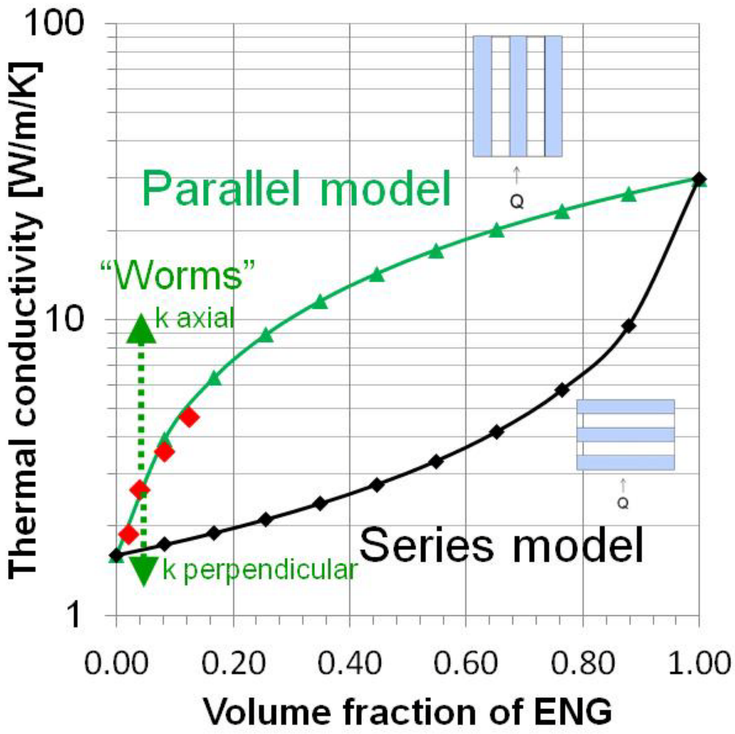
Thermal conductivity enhancement

- 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

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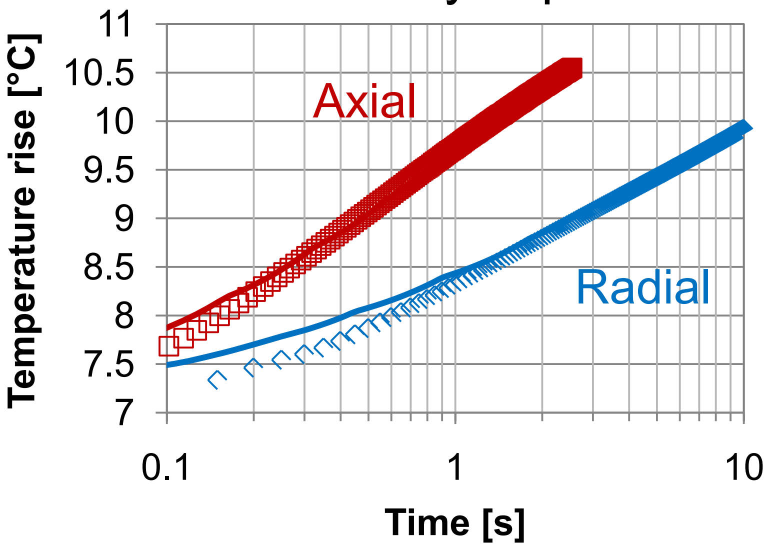
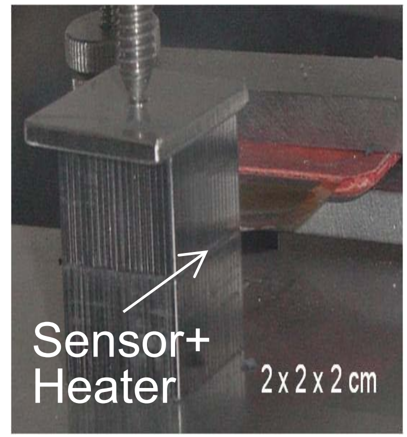
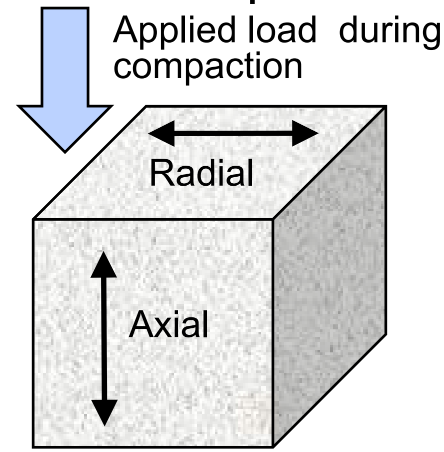
Thermal conductivity anisotropy with ENG 'worms'

- Thermal conductivity experiment

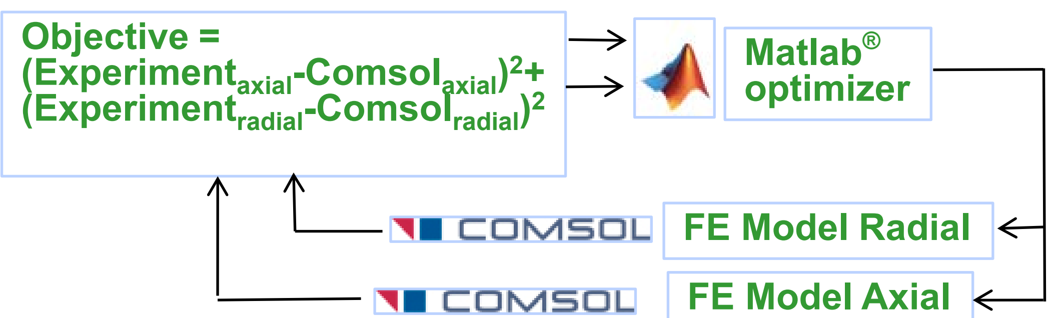


- COMSOL™ model development





- 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

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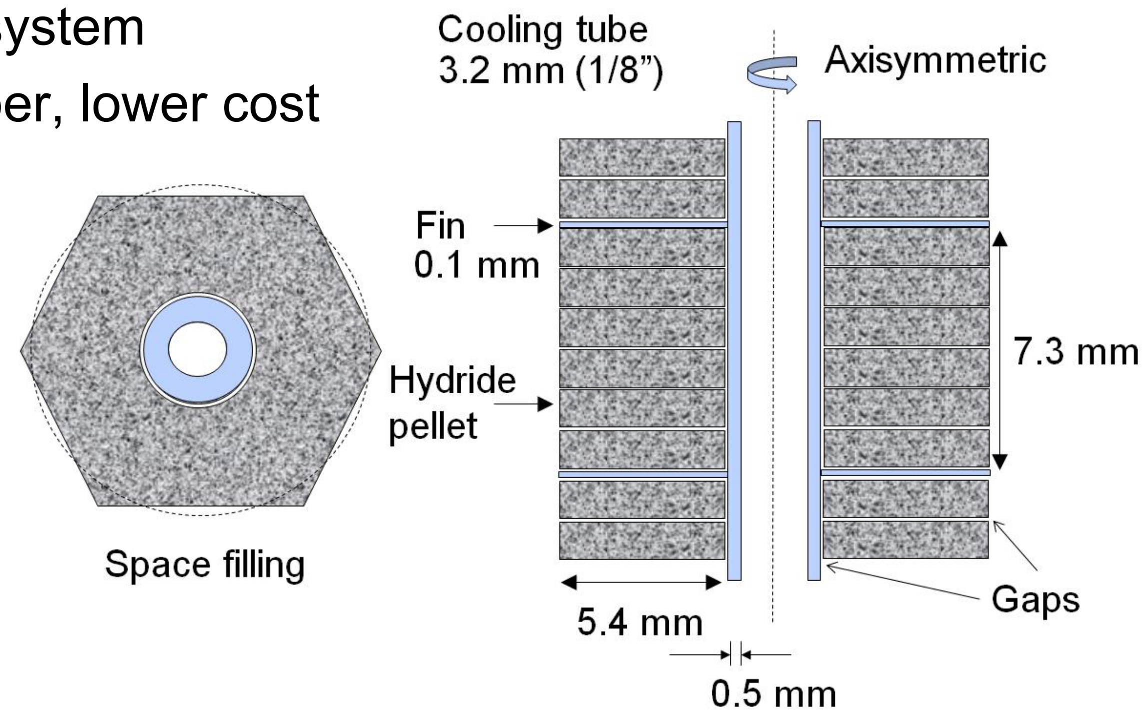
Induce high thermal conductivity towards the heat exchanger tube

Heat exchanger optimization for fast refueling

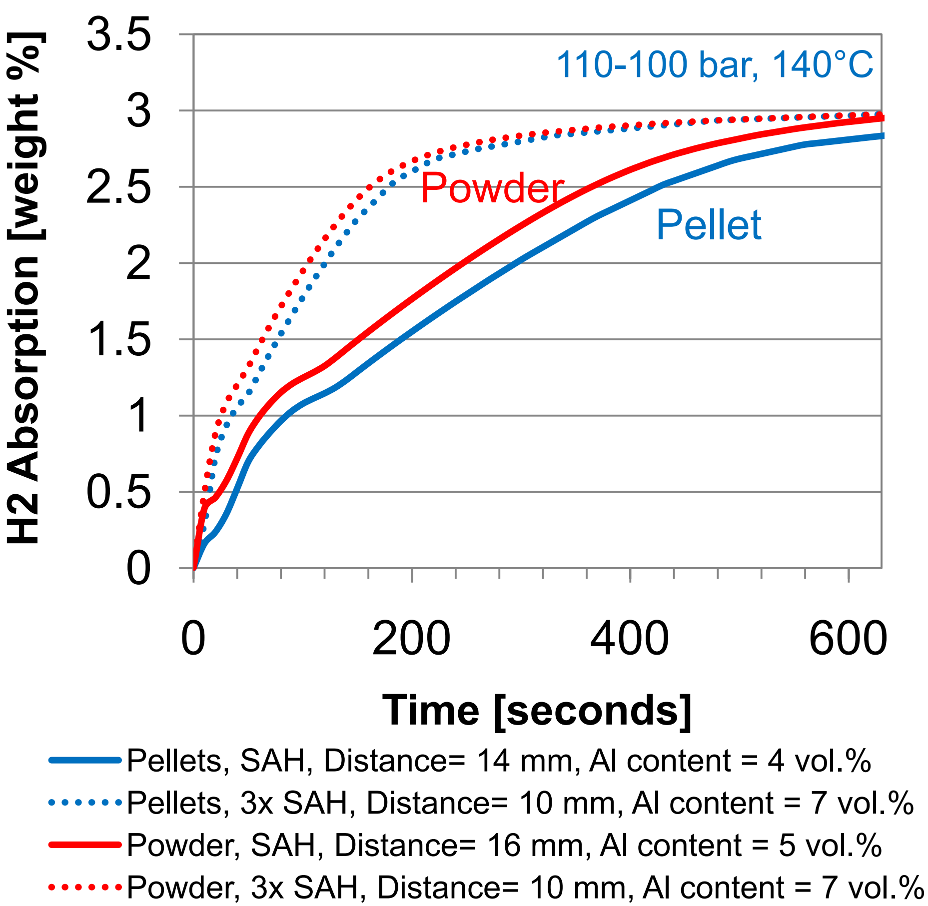
- Refueling time target 10.5 minutes (40% of DOE 2010 target)
- 90% of materials capacity (SAH) equals 3.06 wt.%
- T_{max}=170°C
- PH_2=100 bar:
  - Low pressure system
  - Less carbon fiber, lower cost

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

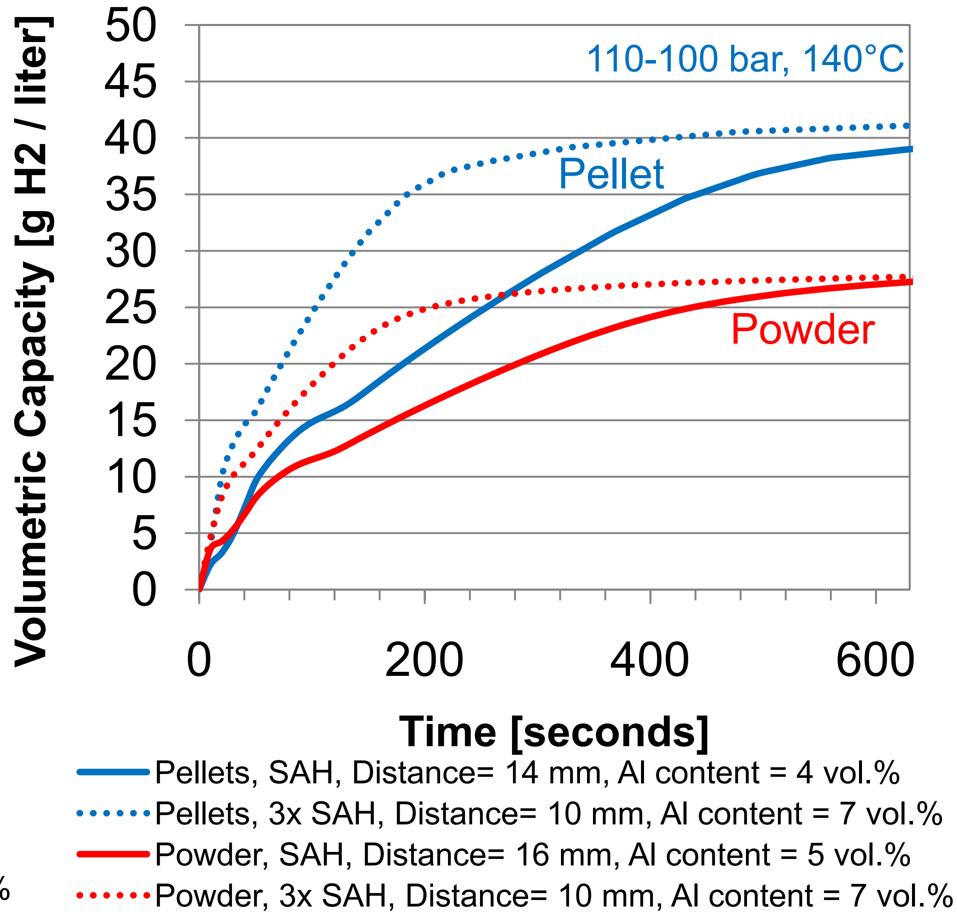


Performance modeling (COMSOL™)

- 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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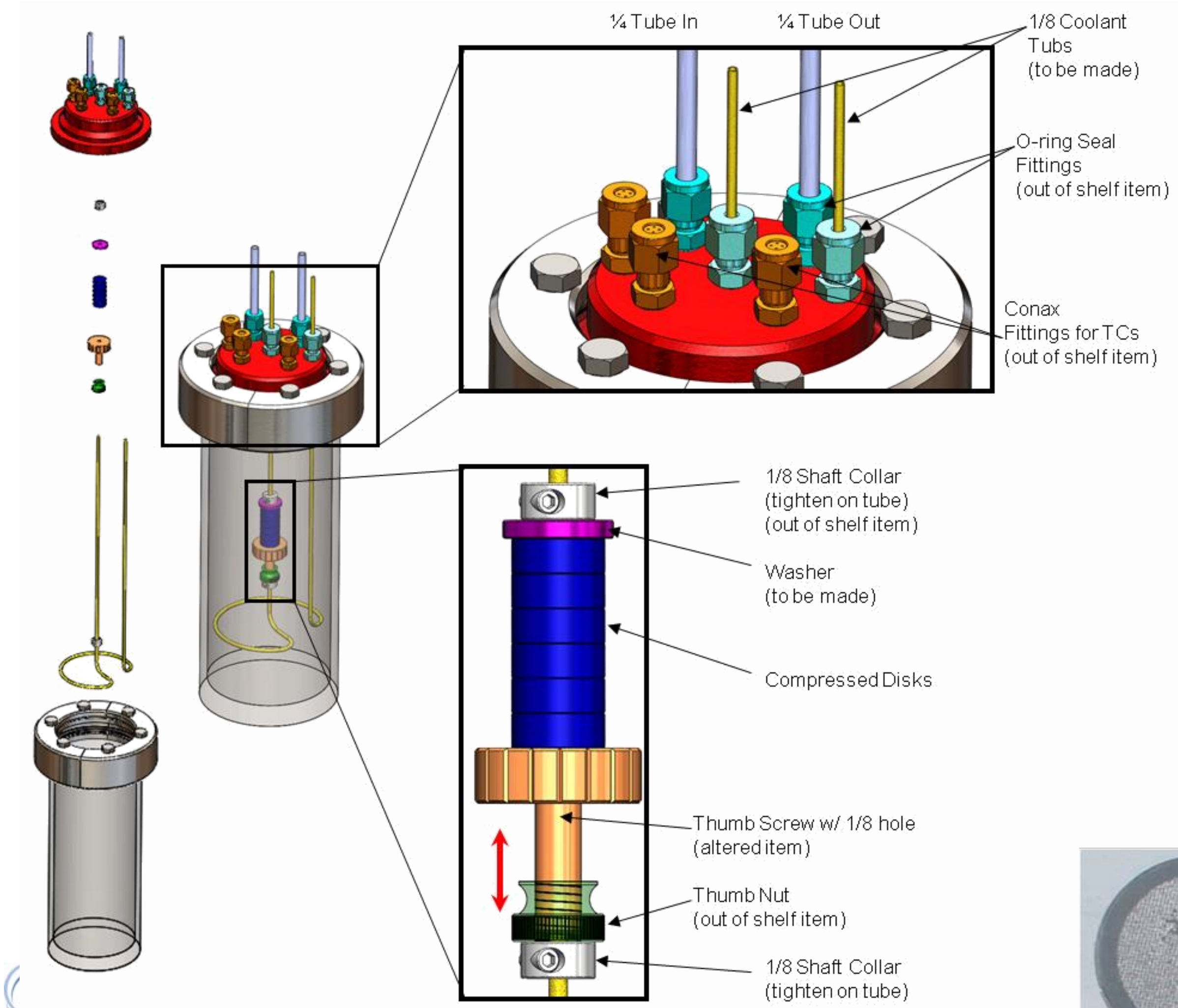
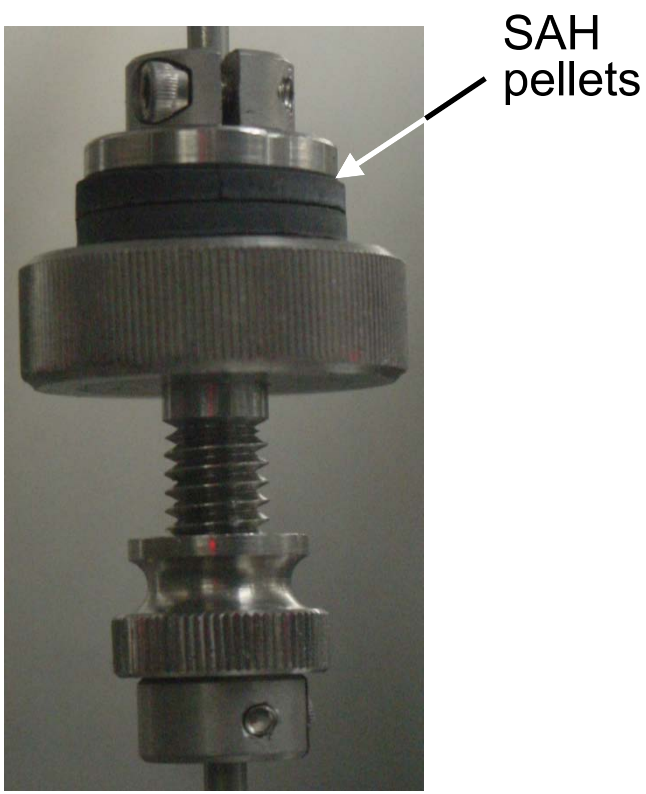
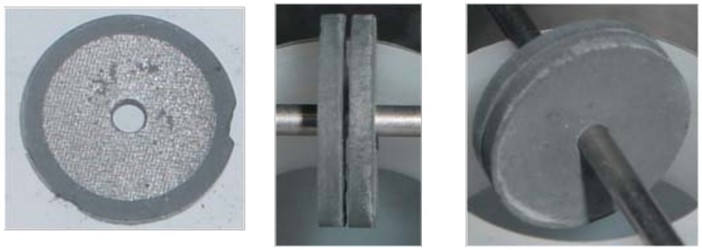
Concept evaluation (Lab-scale)

- Integration with HX



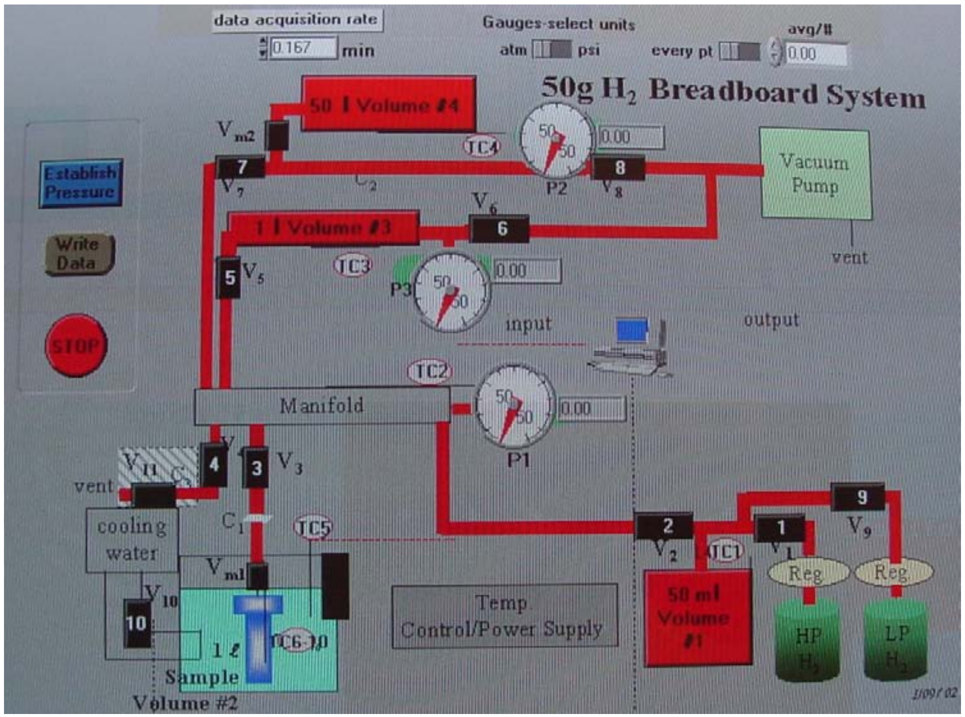
- SAH pellets around HX tube



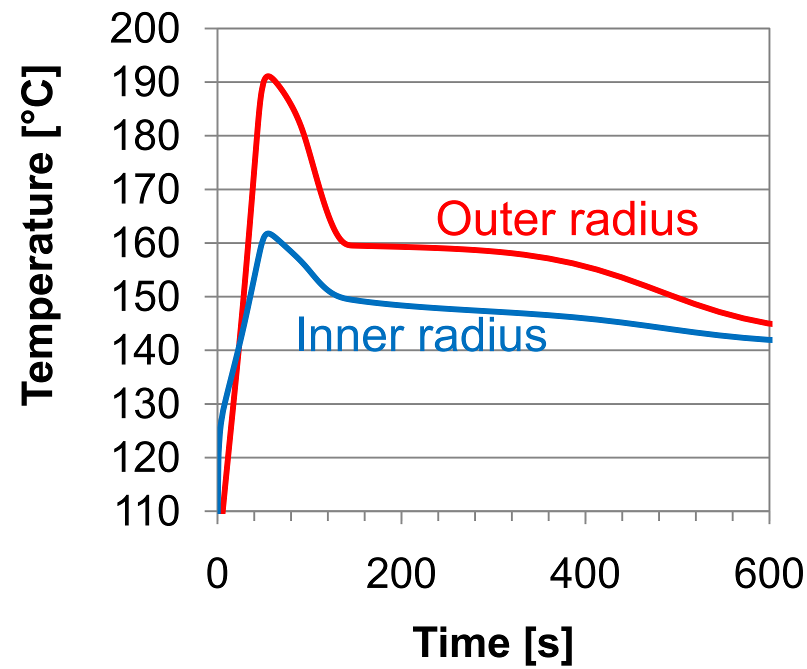


Concept evaluation (Lab-scale)

- 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

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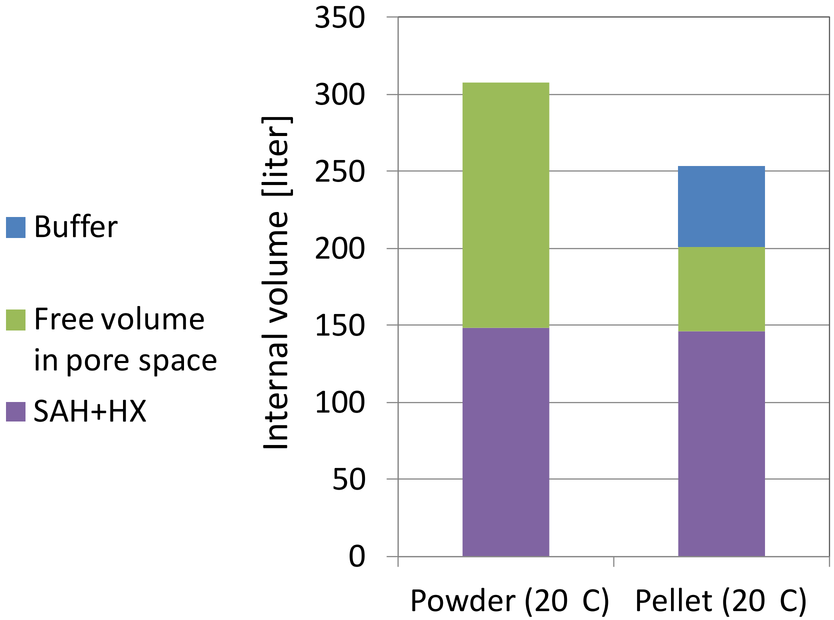
Framework results

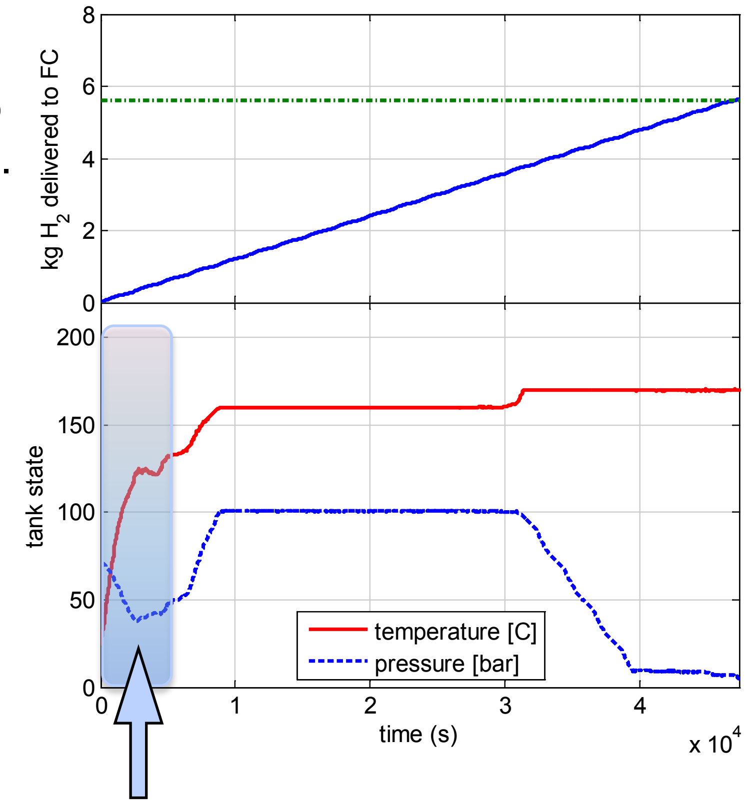
$NaAlH_4$ powder and compacted pellets systems

- 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

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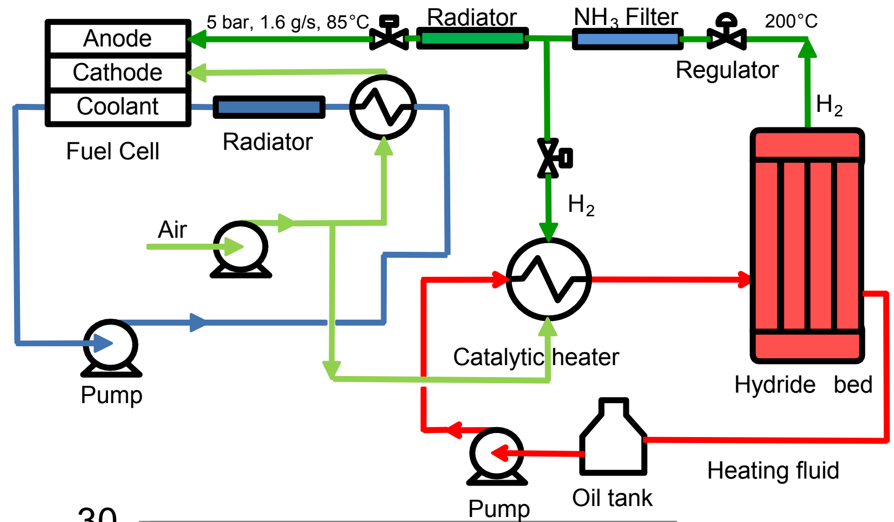
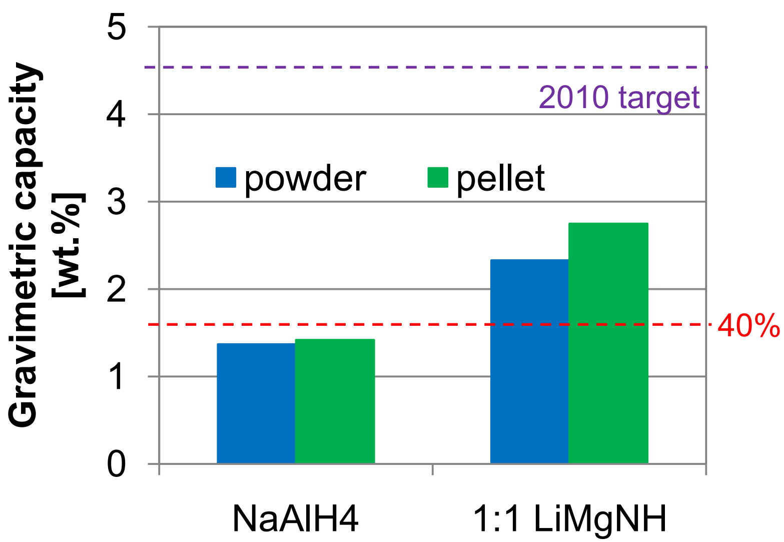
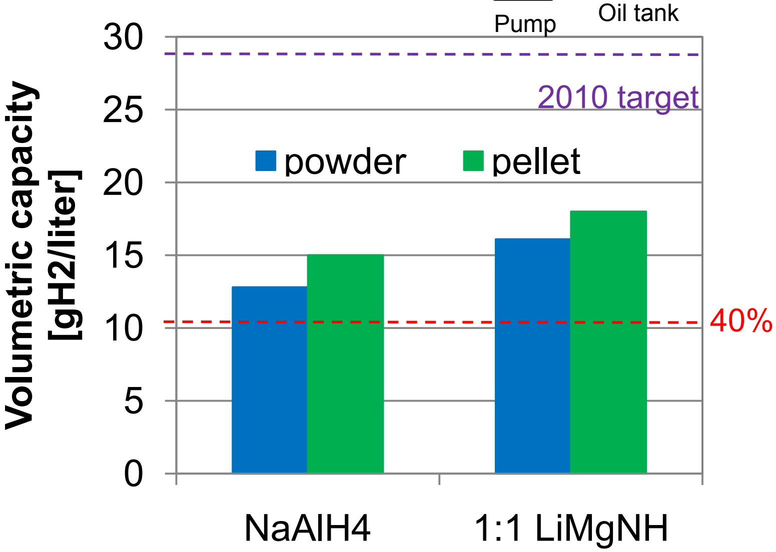
H_2 buffer requirement for startup limits benefits of compaction

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







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

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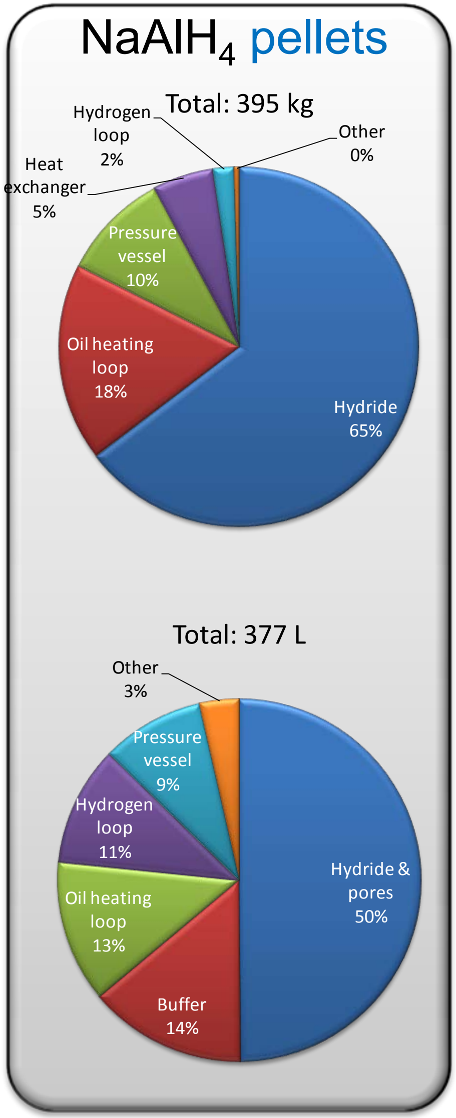
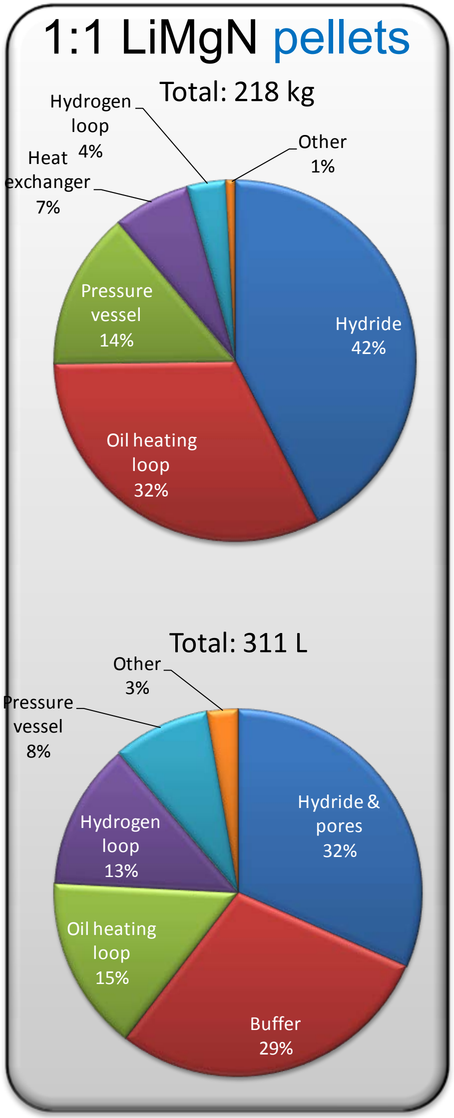
Framework results

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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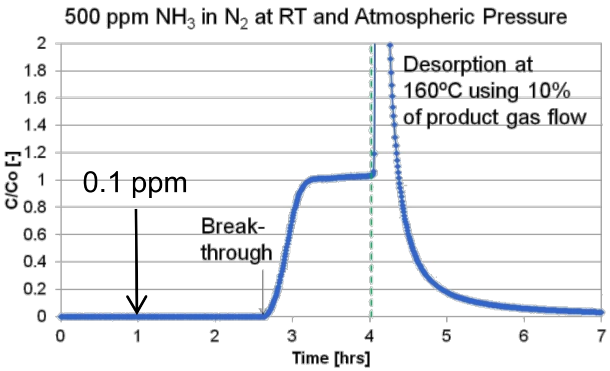
Enabling technology: H_2 quality

- 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

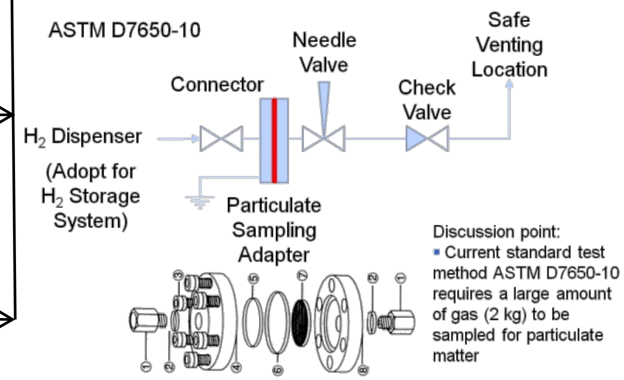
Ammonia adsorbent (UTRC)

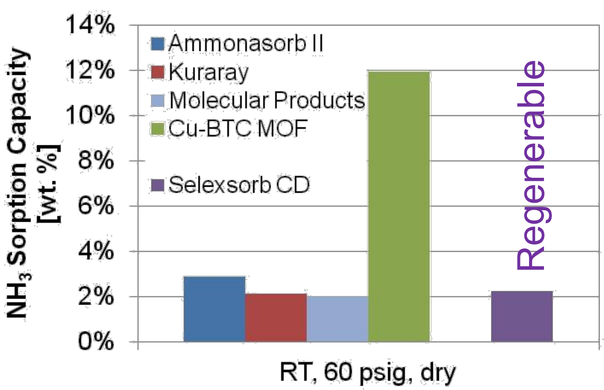
AB

Chemical hydrides

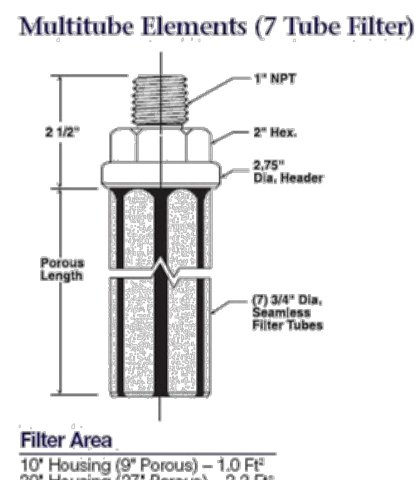
AB

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





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



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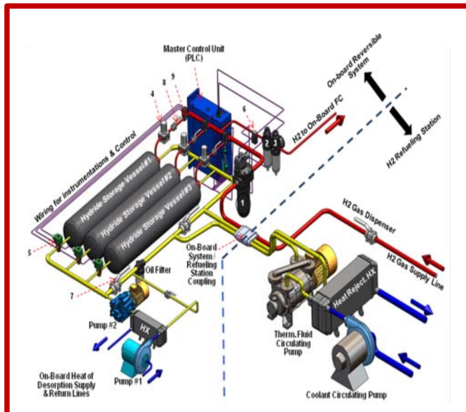
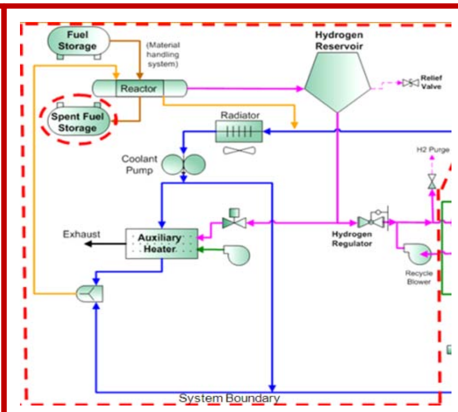
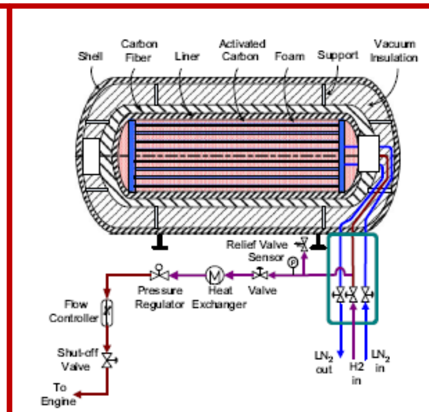
Qualitative risk analysis (QLRA)

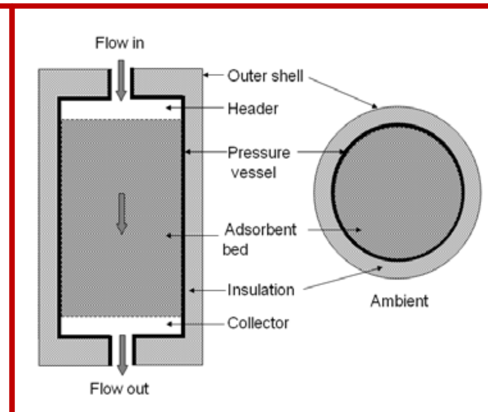
Objective: *Identify the critical risks, failure modes and technical challenges of three H_2 storage systems.*

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

On-board sodium alanate system (UTRC)

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: material reactivity with water and subsequent fire and vessel failure by overpressurization.

Failure mechanism: water intrusion in-vessel.

Off-board solid AB system (PNNL)

Risk: Runaway chemical reaction during AB thermolysis.

Failure mechanism: Loss of thermolysis exothermic heat removal capability.

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.

On-board cryo-adsorption systems

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.

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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

Acknowledgement: This material is based upon work supported by the U.S. Department of Energy under Contract No. DE-FC36-09GO19006.

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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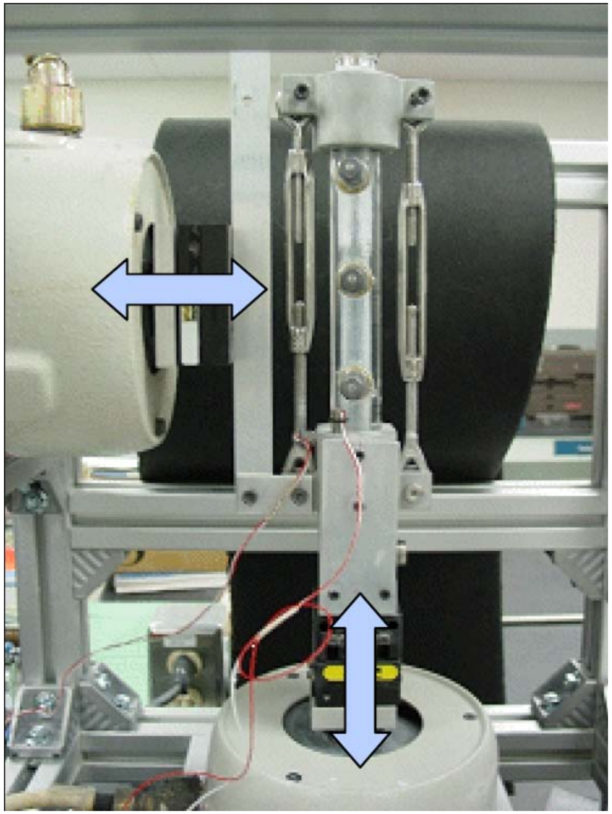
Vibration packing

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

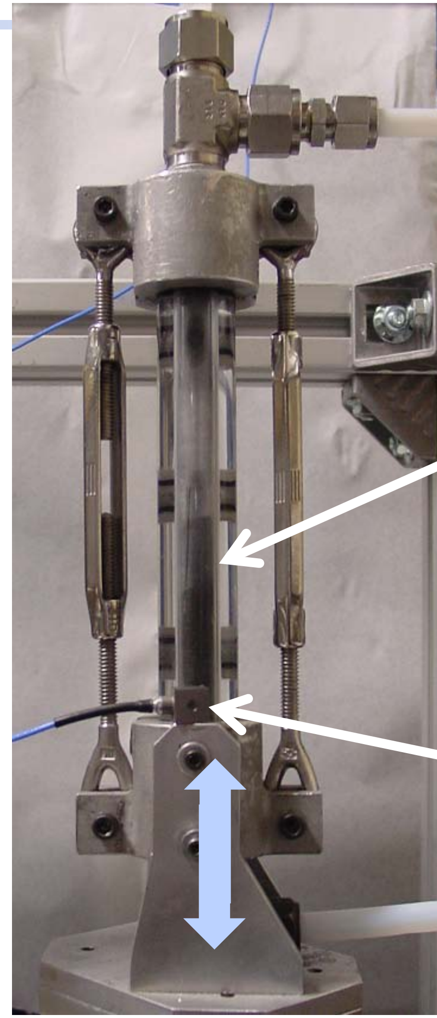
Expectations for packing density:

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

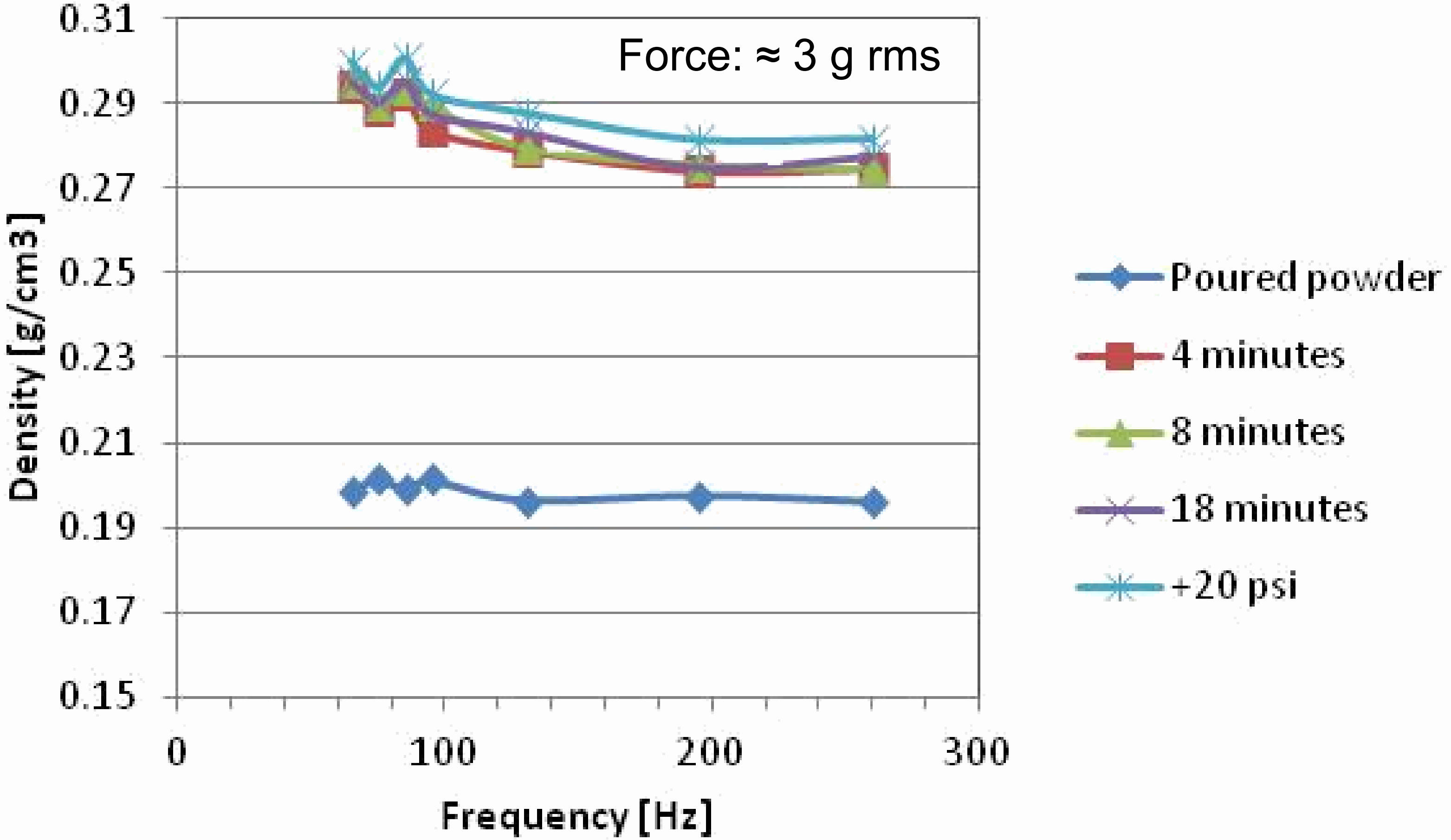
Vibration packing principle



Shakers
in two directions



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.

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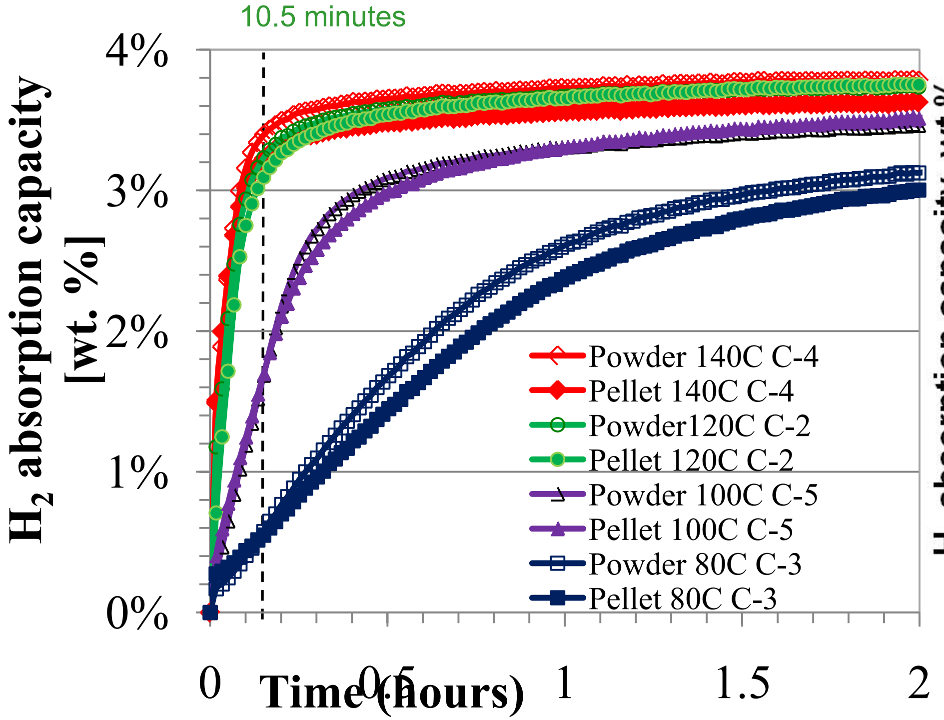
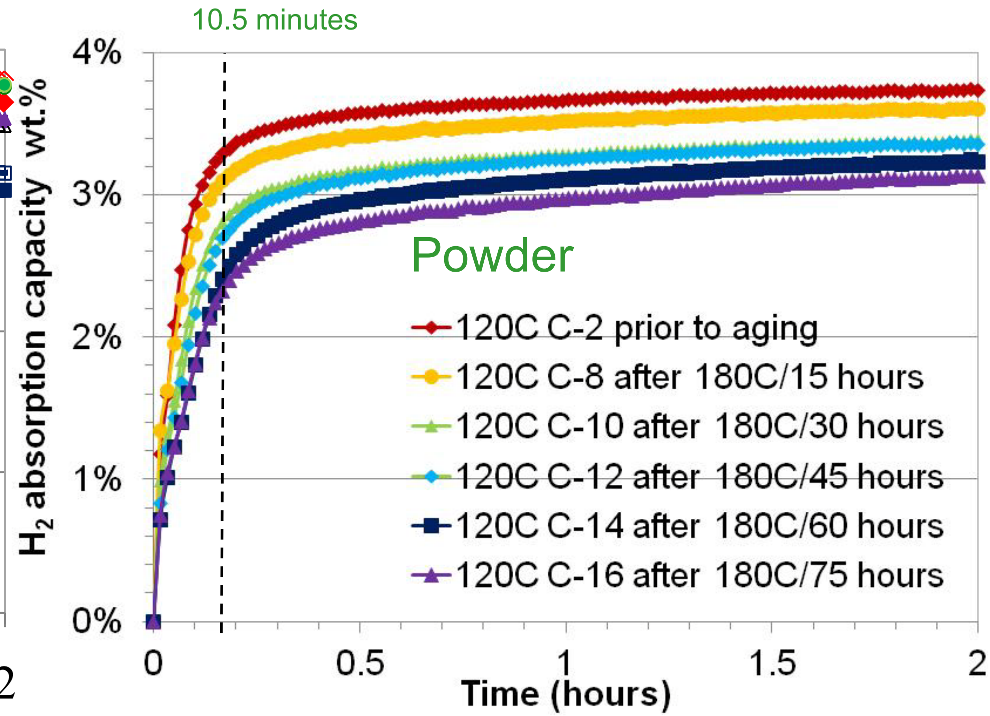
Kinetics of $NaAlH_4$ + 4 mol% $TiCl_3$ remeasured

- 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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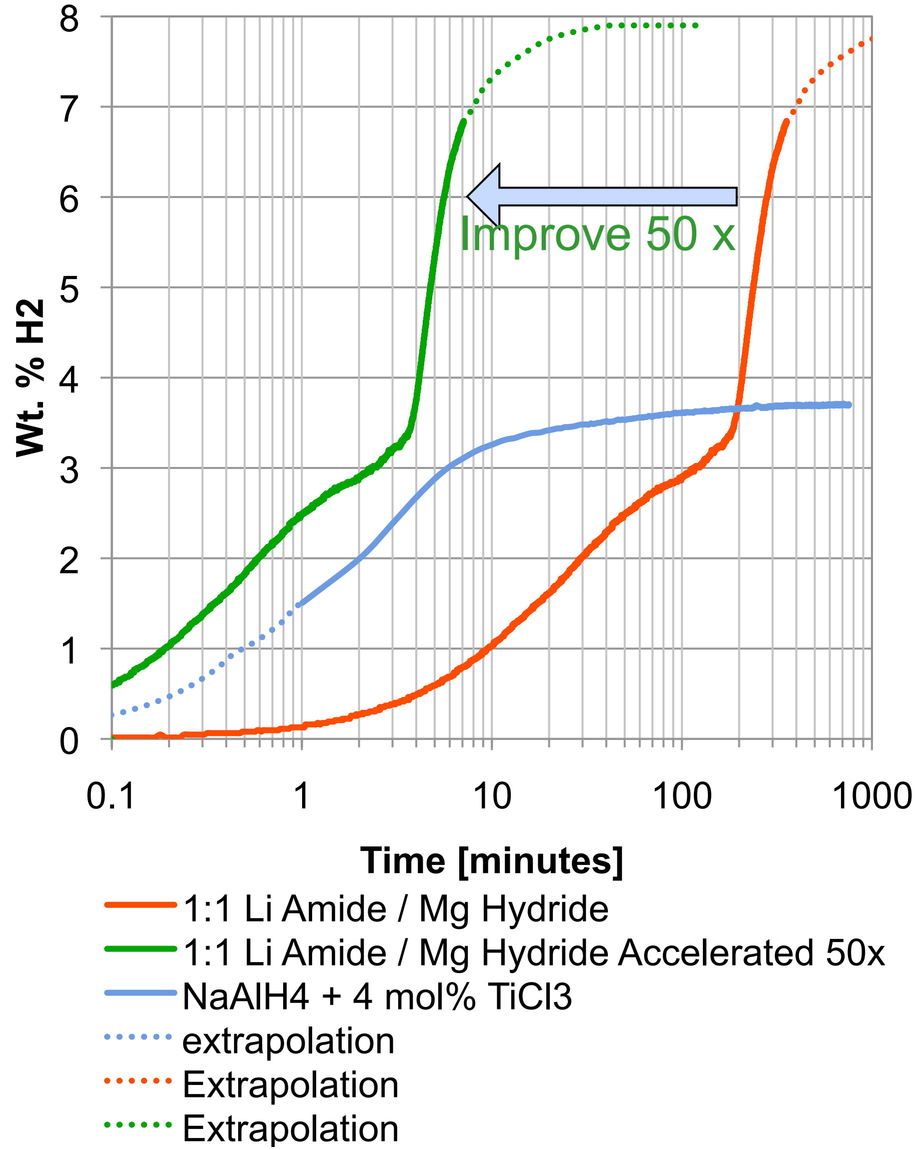
Kinetics and heat transfer for LiMgNH system

- 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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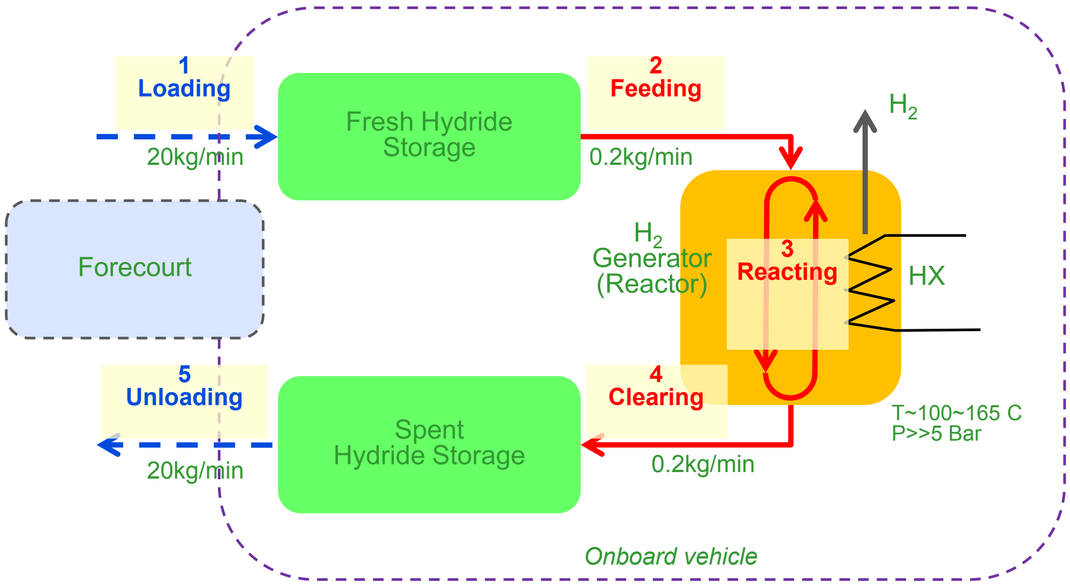
Solid hydride transport: requirements and concepts

- **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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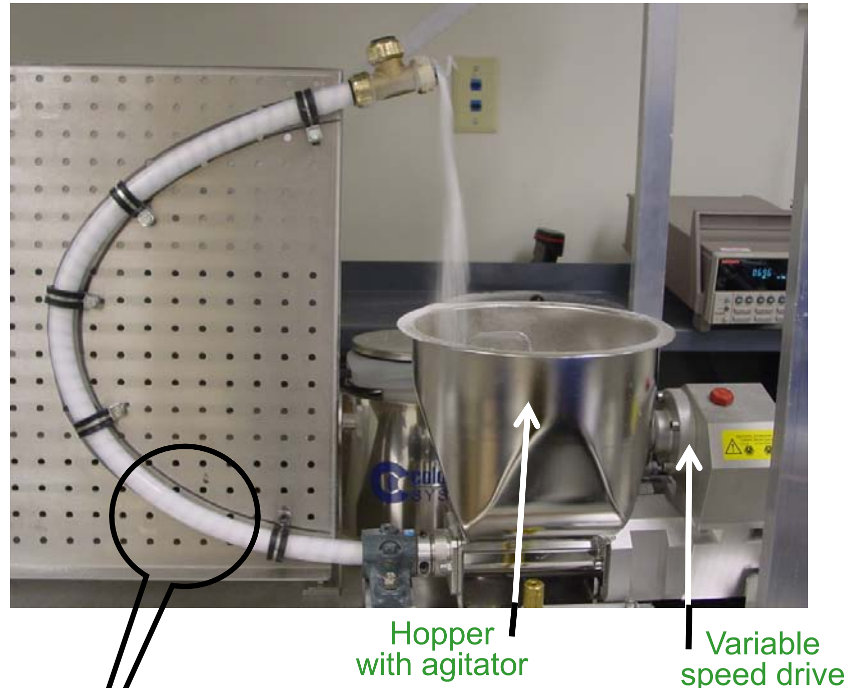
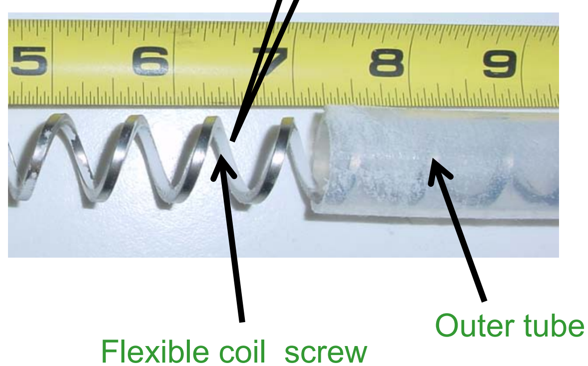
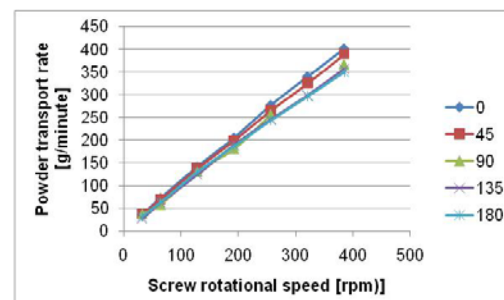
Solid hydride transport: experiment with flexible screw

- 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







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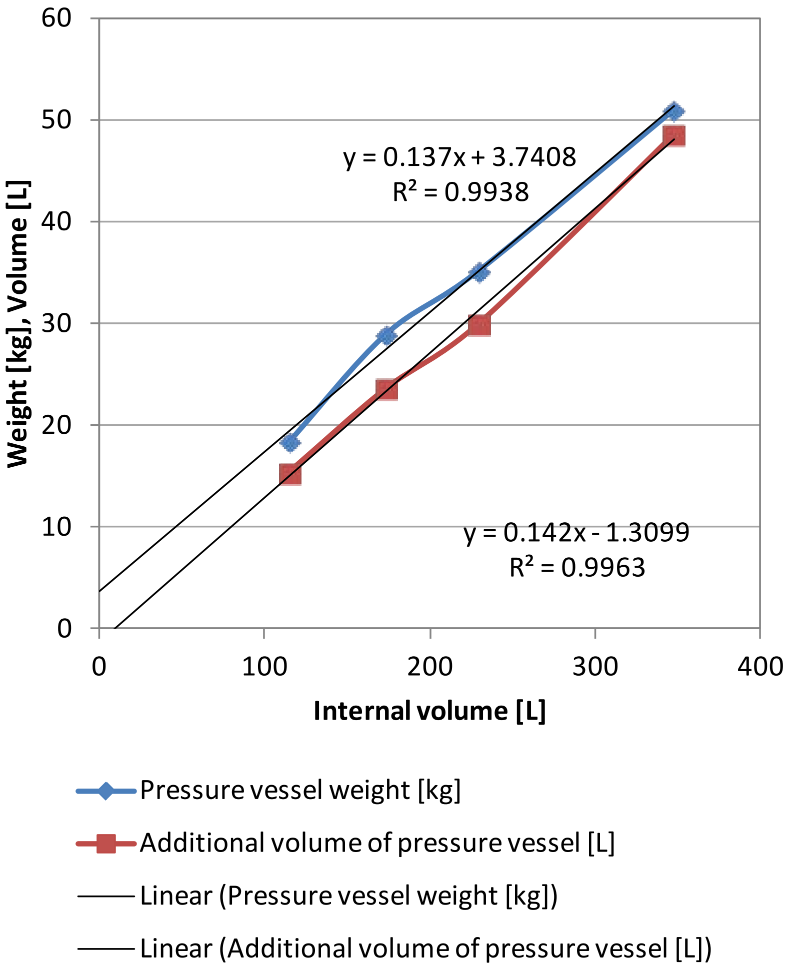
Weight & volume correlation for 100 bar pressure vessels

- 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.



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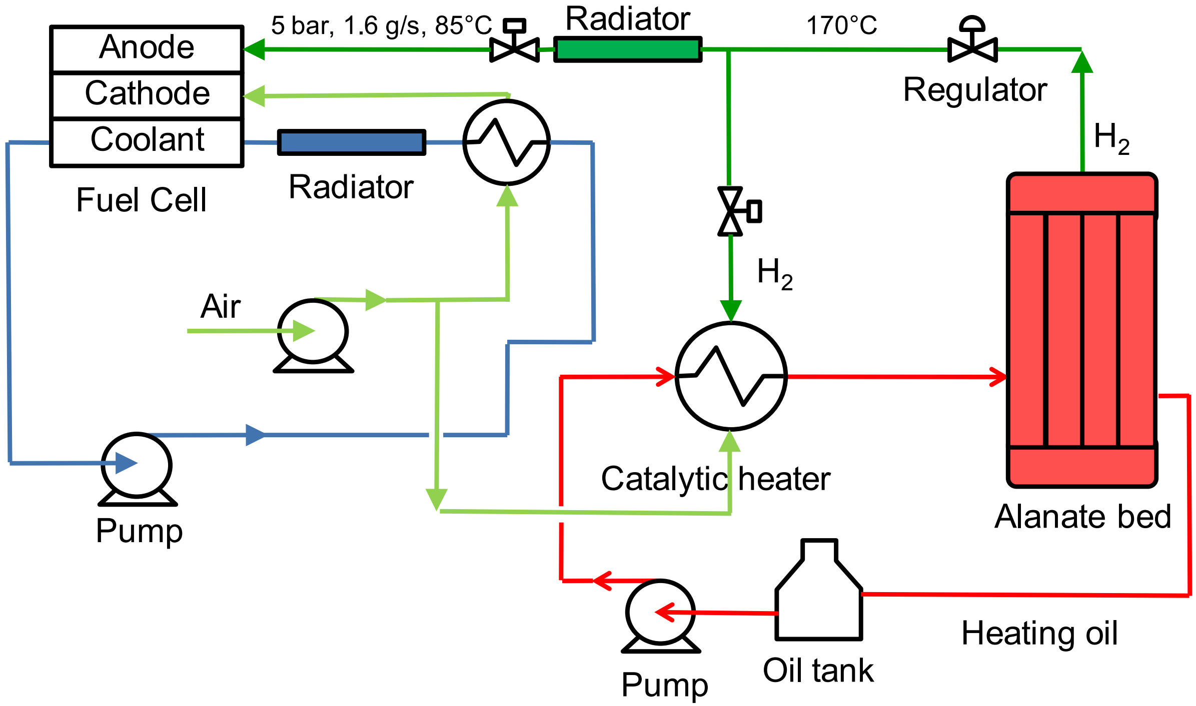
Drive cycles & test conditions for use in the framework

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)

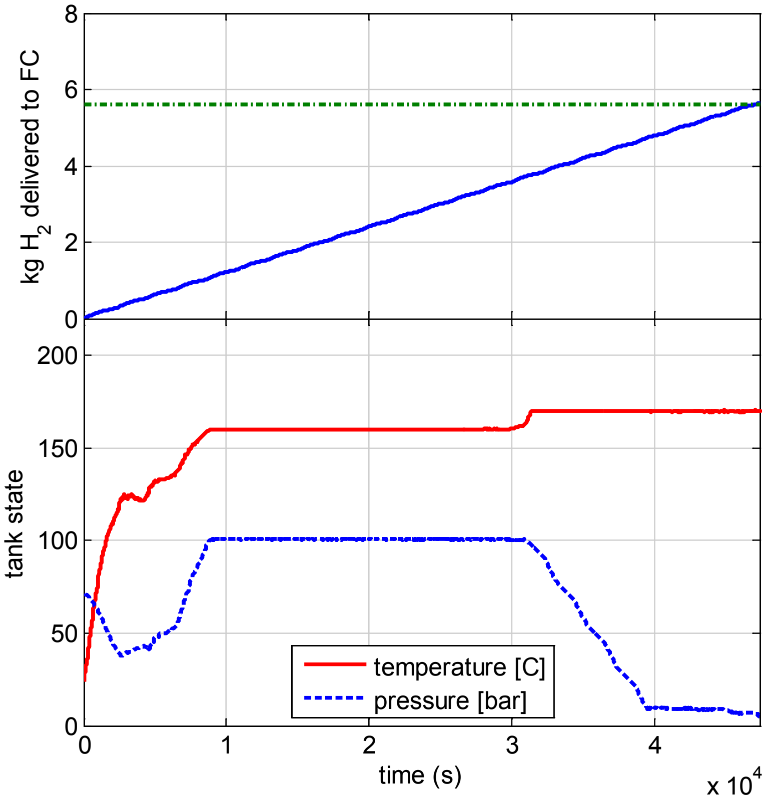
Gravimetric capacity	3.1%
Porosity	56%

- 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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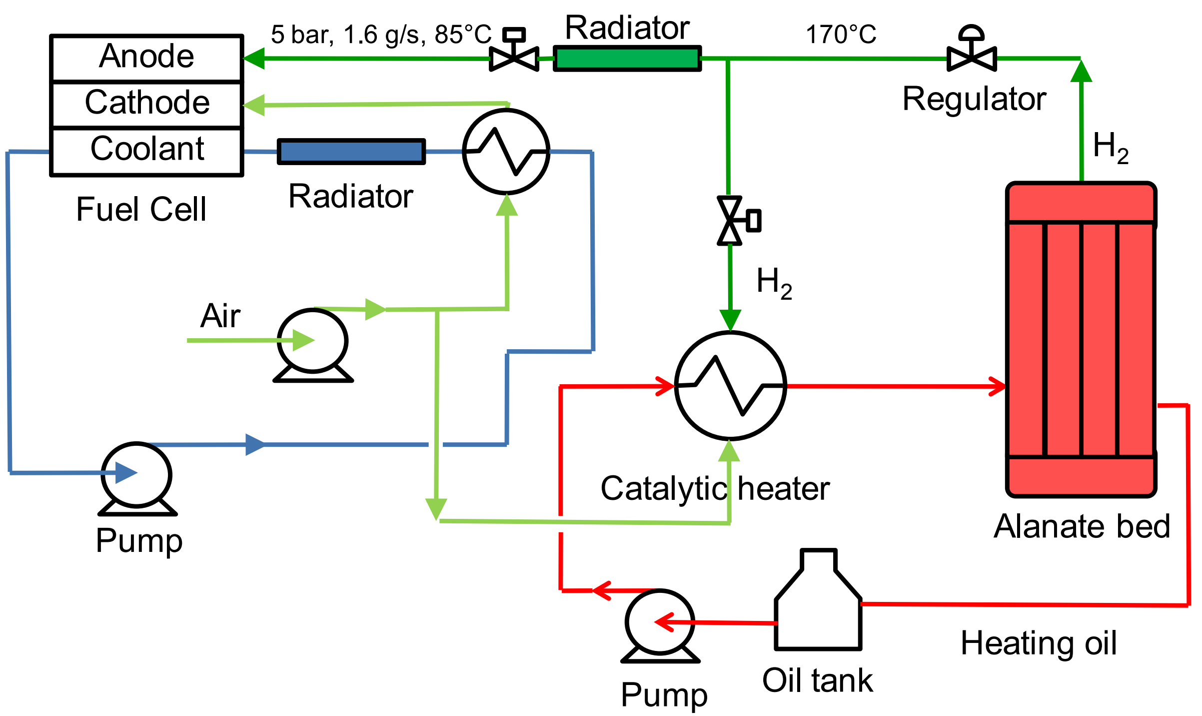
$NaAlH_4$ (compacted pellets) system diagram

- 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

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$NaAlH_4$ 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)**

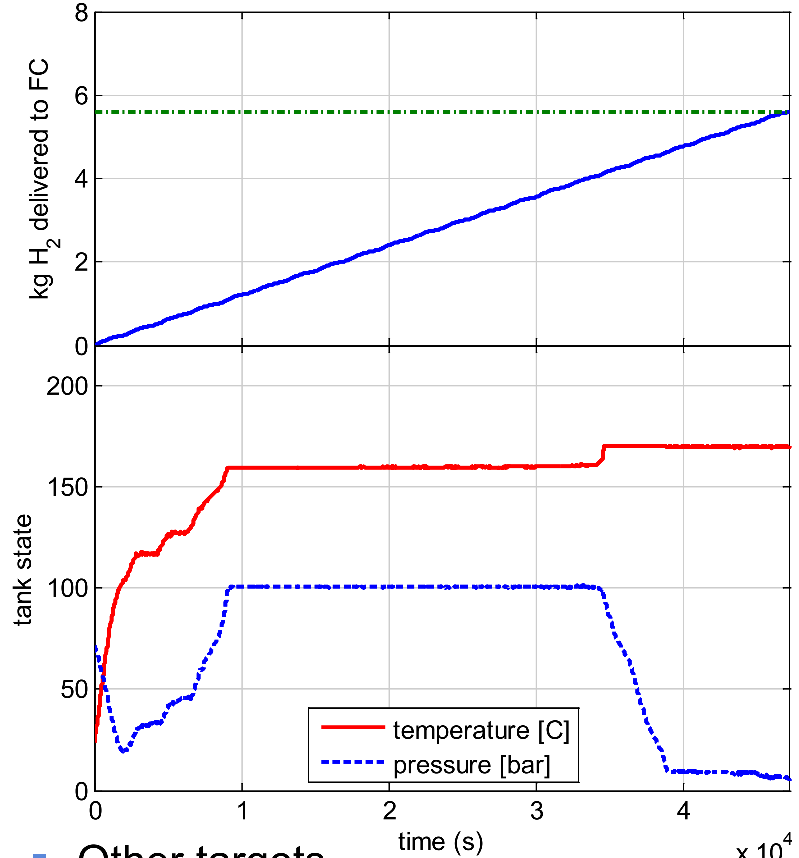
Gravimetric capacity	3.1%
Porosity	29%

- **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

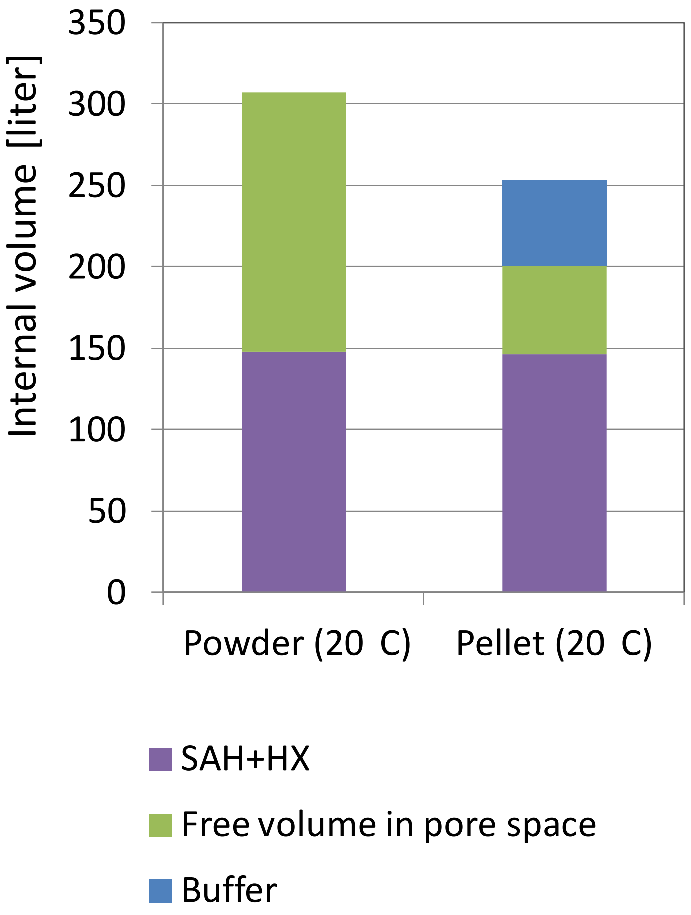


- **Other targets**

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

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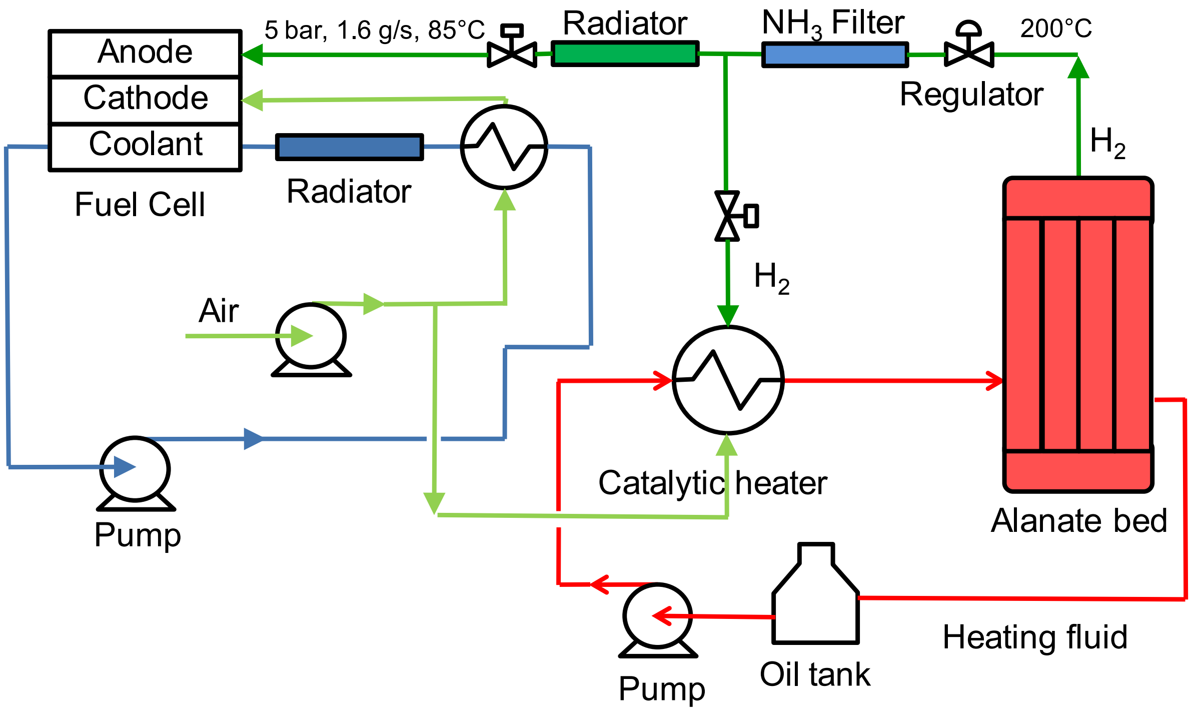
1:1 Li-Mg-N-H (uncompacted powder) system

- 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)

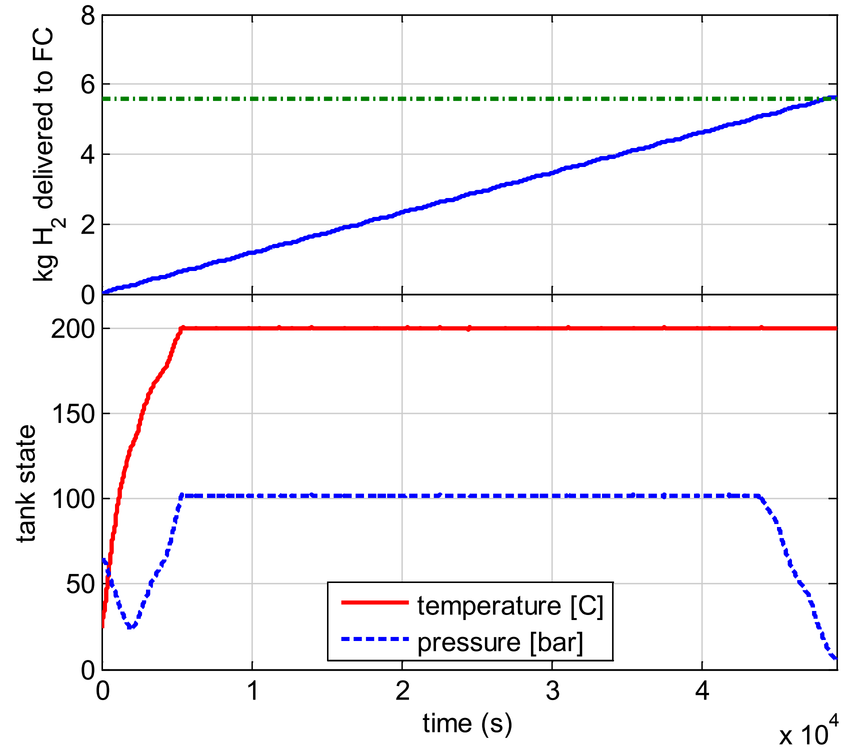
Gravimetric capacity	7.5%
Porosity	50%

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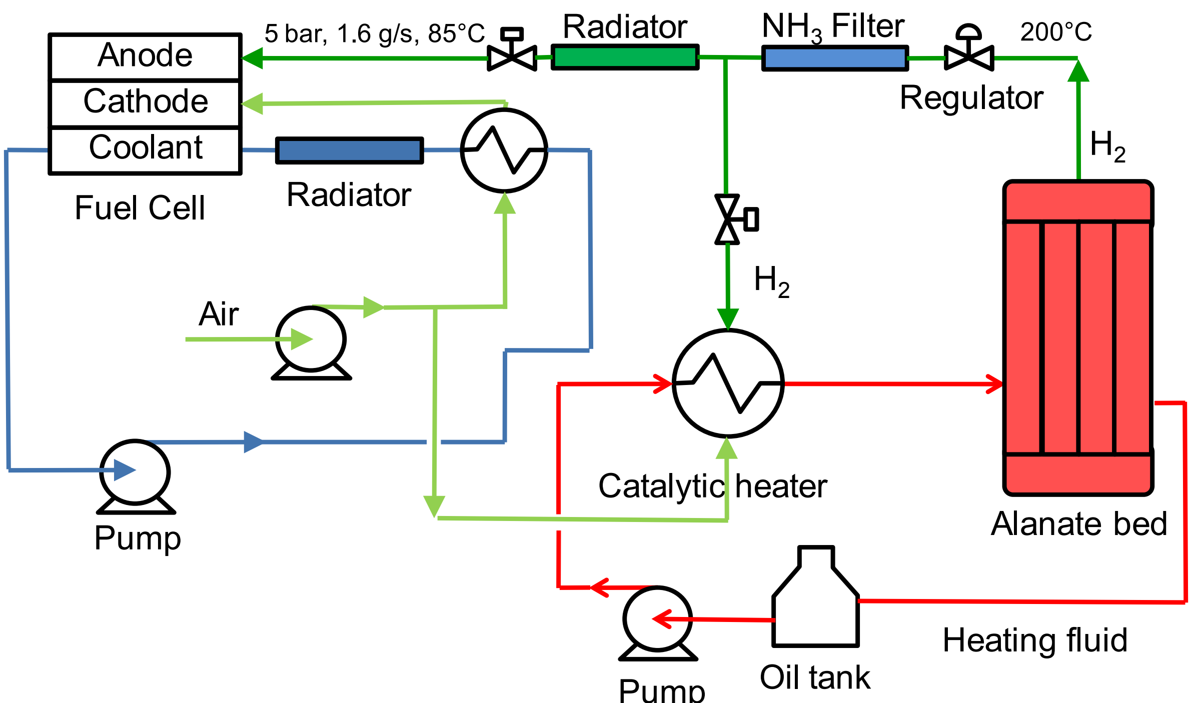
1:1 Li-Mg-N-H (compacted pellets) system

- 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.

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)

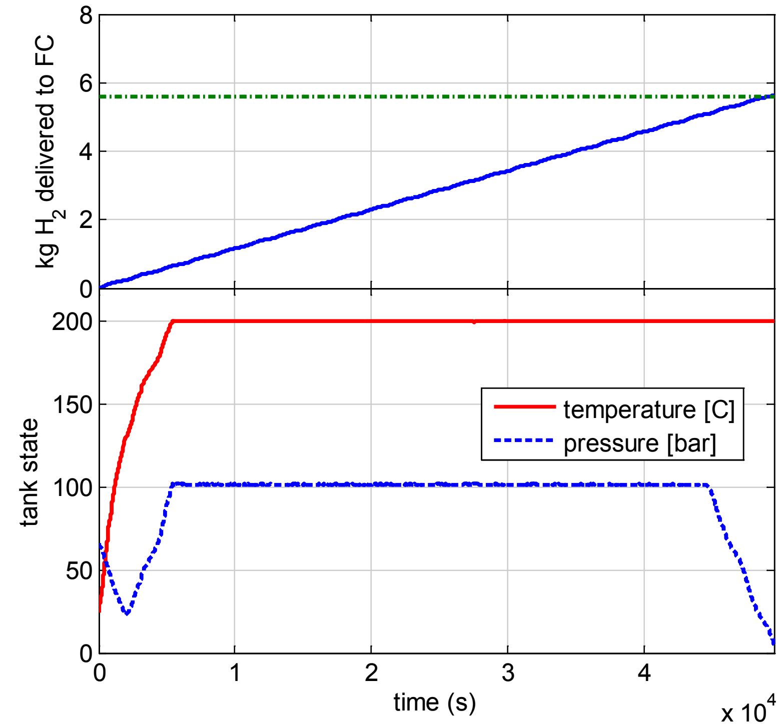
Gravimetric capacity	7.5%
Porosity	25%

- 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

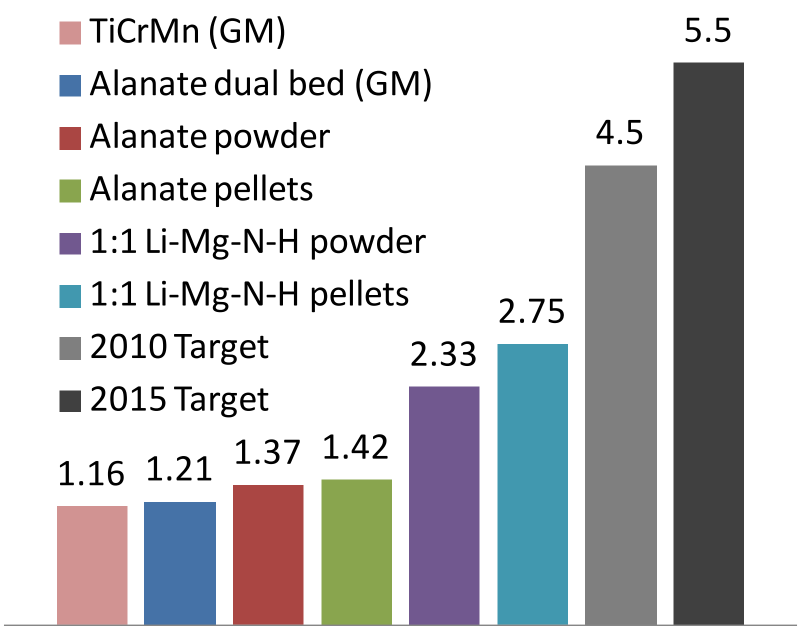


- Other targets

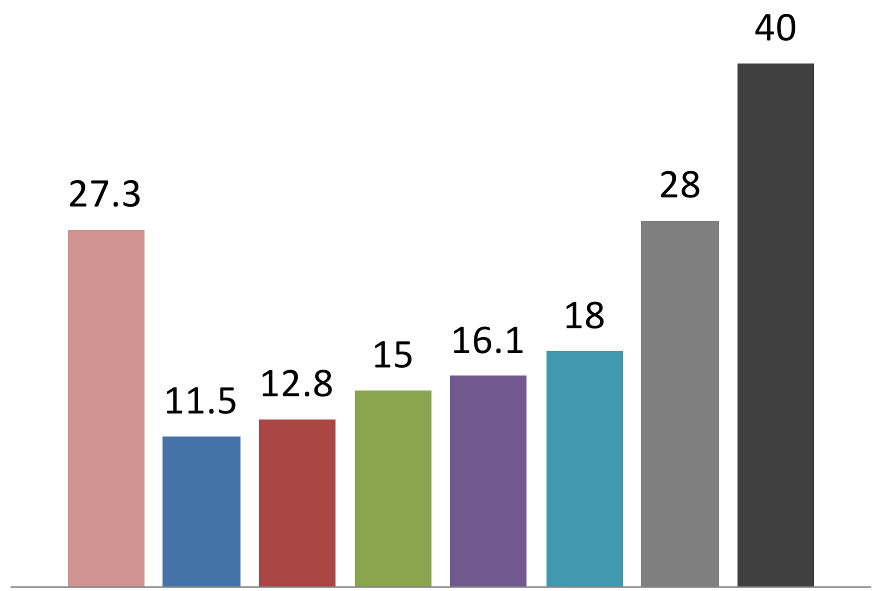
On-board efficiency	75%
Cold/hot cases	OK
Dormancy	N/A
Delivery temperature	< 85C
Min delivery pressure	5 bar
Min full flow rate	1.6 g/s

Capacity comparison summary

Gravimetric capacity (weight %)



Volumetric capacity (g-H_2/L)

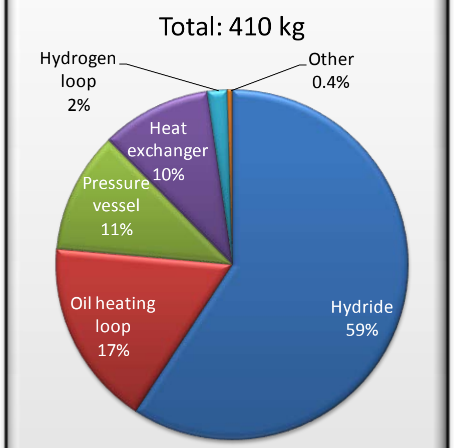


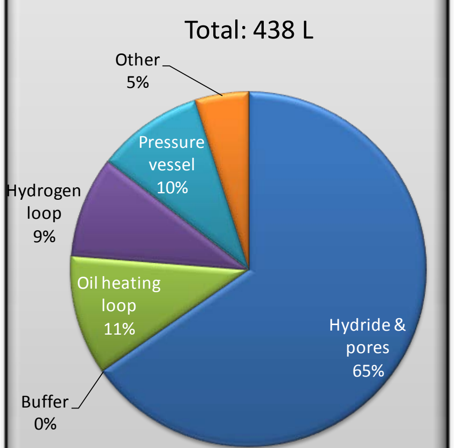
- Independent alanate powder system analyses (GM & UTRC) give comparable results. The difference in gravimetric capacity is due to the pressure vessel assumption: Composite tank + Steel liner (GM) vs Type IV (UTRC).

- 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

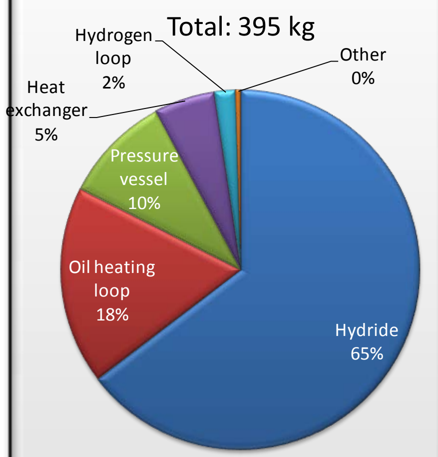
Weight and volume: main contributors

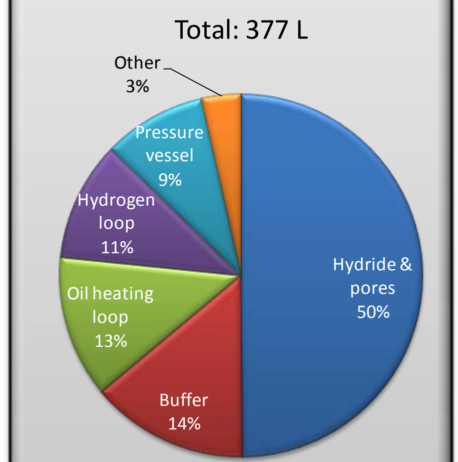
$NaAlH_4$ powder



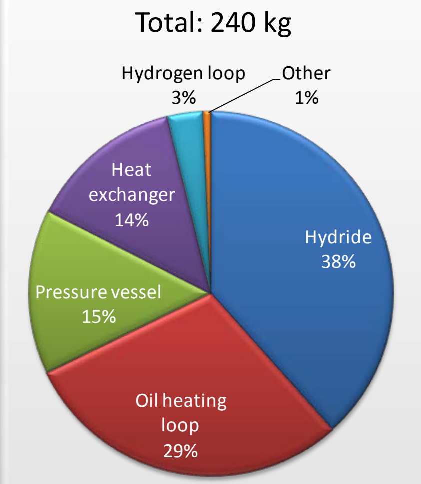


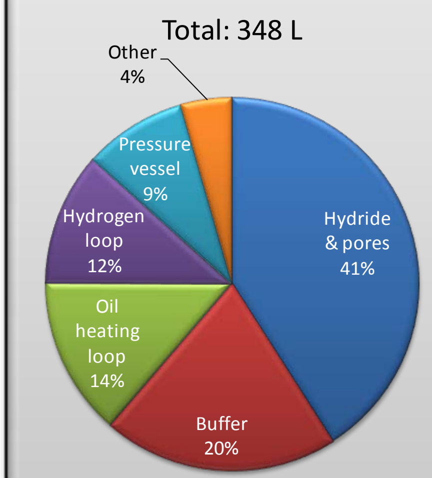
$NaAlH_4$ pellets





1:1 LiMgN powder





1:1 LiMgN pellets