Hydrogen Storage Engineering
CENTER OF EXCELLENCE

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Savannah River National Laboratory
June 18, 2014

This presentation does not contain any proprietary, confidential or otherwise restricted information.

Project ID# ST004
SRNL-STI-2014-00176

Overview

Timeline

- Start: February 1, 2009
- End: June 30, 2015
- 90% Complete (as of 3/1/14)

Budget

- Total Center Funding:
  - DOE Share: $ 35,275,000
  - Cost Share: $ 3,322,000
  - FY ’13 Funding: $ 6,059,000
  - FY ’14 Funding: $3,138,000
- Prog. Mgmt. Funding
  - FY ’13: $ 300,000
  - FY ’14: $ 300,000

Barriers

A. System Weight and Volume
B. System Cost
C. Efficiency
D. Durability
E. Charging/Discharging Rates
G. Materials of Construction
H. Balance of Plant (BOP) Components
J. Thermal Management
K. System Life-Cycle Assessment
O. Hydrogen Boil-Off
P. Understanding Physi/Chemi-sorption
S. By-Product/Spent Material Removal

Partners

SRNL Savannah River National Laboratory
Pacific Northwest National Laboratory
Los Alamos National Laboratory
JPL Jet Propulsion Laboratory California Institute of Technology
NREL National Renewable Energy Laboratory
Michigan
OSU Oregon State University
HRI UQTR
Ford
GM
United Technologies Research Center
BASF The Chemical Company
Hexagon Lincoln

HSECoE Technical Objectives

Using systems engineering concepts, design innovative material-based hydrogen storage system architectures with the potential to meet DOE performance and cost targets.

- **Develop and validate system, engineering and design models** that lend insight into overall fuel cycle efficiency.
- Compile all relevant materials data for candidate storage media and **define required materials properties to meet the technical targets.**
- **Design, build and evaluate subscale prototype systems** to assess the innovative storage devices and subsystem design concepts, validate models, and improve both component design and predictive capability.

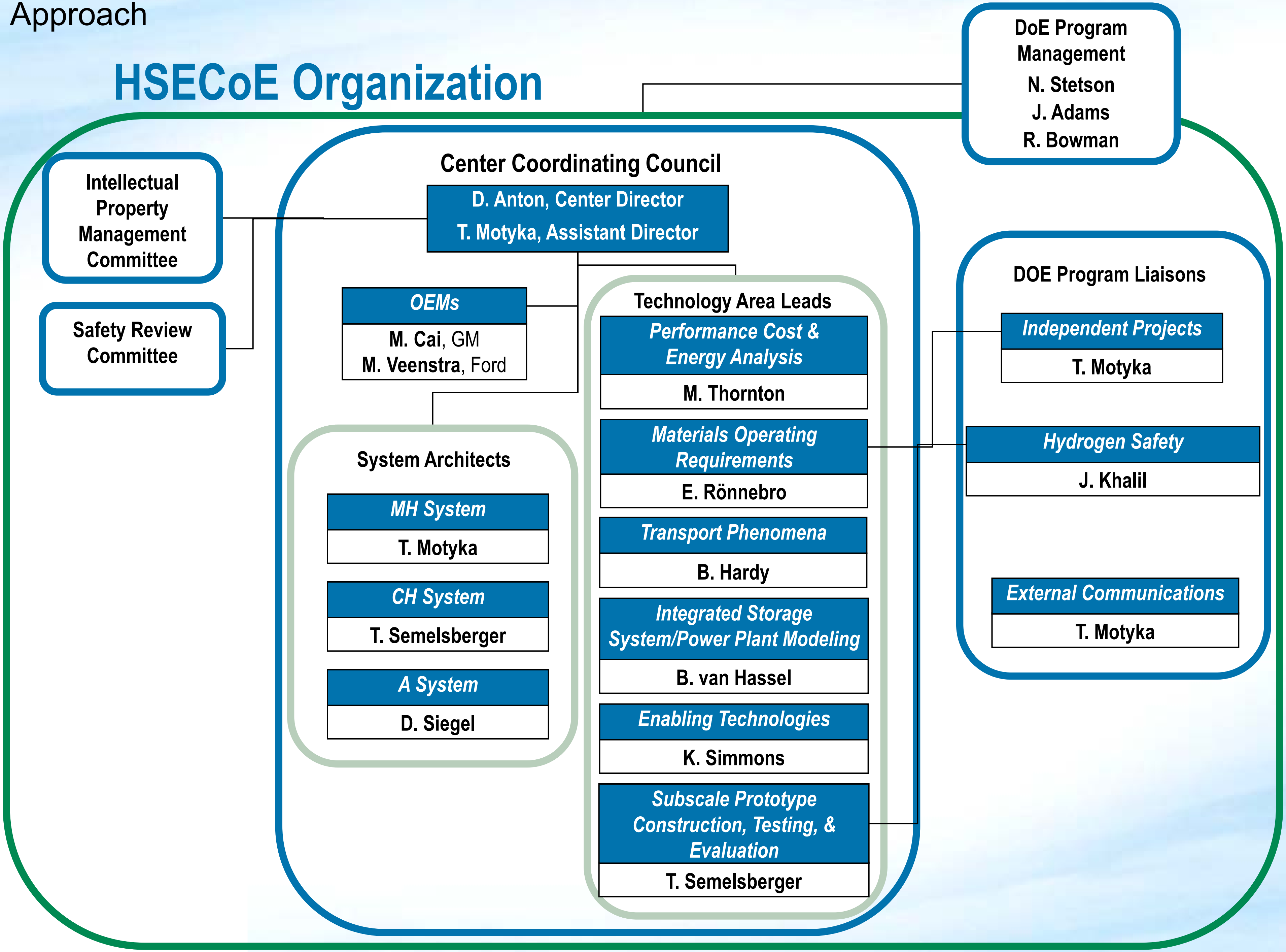
Why Perform Materials Development and System Engineering in Parallel?

continuous feedback with system design
through the integrated model
identifying materials requirements

Materials → Thermal Management → H_2 Storage BoP → Fuel Cell → Vehicle → Wheels

- Materials → Engineered Materials Properties
- Thermal Management → Heat Transfer Designs
- H_2 Storage BoP → BoP Component Requirements
- Fuel Cell, Vehicle, Wheels → What is Needed of the Hydrogen Storage Media & System

HSECoE Organization



DoE Program Management
N. Stetson
J. Adams
R. Bowman

Intellectual Property Management Committee

Safety Review Committee

Center Coordinating Council

D. Anton, Center Director
T. Motyka, Assistant Director

OEMs
M. Cai, GM
M. Veenstra, Ford

System Architects

System	Lead
MH System	T. Motyka
CH System	T. Semelsberger
A System	D. Siegel

Technology Area Leads

Area	Lead
Performance Cost & Energy Analysis	M. Thornton
Materials Operating Requirements	E. Rönnebro
Transport Phenomena	B. Hardy
Integrated Storage System/Power Plant Modeling	B. van Hassel
Enabling Technologies	K. Simmons
Subscale Prototype Construction, Testing, & Evaluation	T. Semelsberger

DOE Program Liaisons

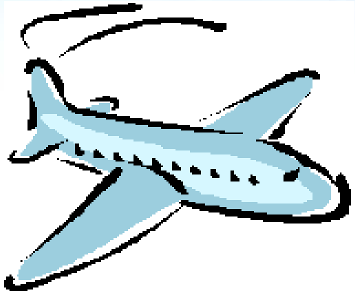
Liaison area	Liaison
Independent Projects	T. Motyka
Hydrogen Safety	J. Khalil
External Communications	T. Motyka

Technical Matrix

		System Architects	
		Adsorbent System *Siegel*	**Chemical Hydrogen Storage System** *Semelsberger*
Technology Areas	**Performance Modeling & Cost Analysis** *Thornton*	**Thornton** **Weimar**	**Thornton** **Weimar**
	Integrated Power Plant & Storage System Modeling *van Hassel*	**Tamburello**	**Brooks**
	Transport Phenomena *Hardy*	**Hardy** **Corgnali, Ortman,** **Drost**	**Brooks** **Semelsberger**
	Materials Operating Requirements *Rönnebro*	**Veenstra** **Siegel** **Chahine**	**Rönnebro** **Semelsberger**
	Enabling Technologies *Simmons*	**Simmons** **Newhouse**	**van Hassel** **Simmons** **Semelsberger**
	Subscale Prototype Demonstrations *Semelsberger*	**Chahine, Tamburello** **Sulic**	**Semelsberger**

Approach

Internal Communications



Annual F2F meetings (Sept.-Oct.)

AMR Pre-Meeting (May-June)

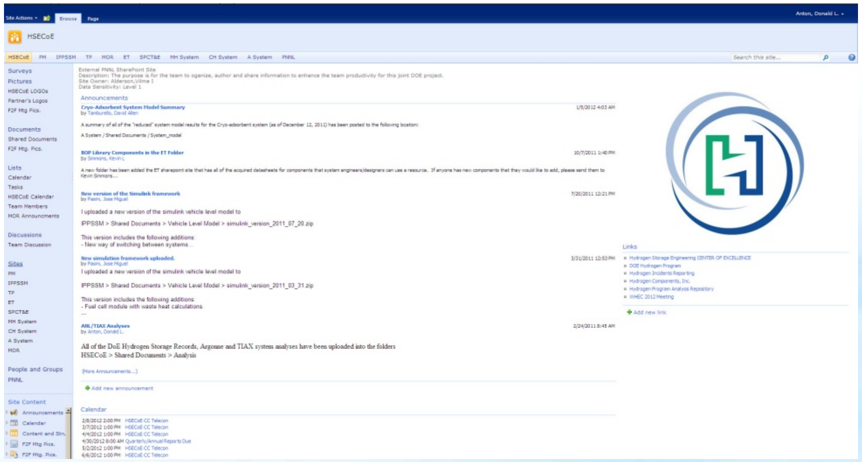
Tech Team Review F2F Meeting (Feb.-March)

Monthly System Architect Telecoms

Monthly Coordinating Council Telecoms

Semi-monthly technical team telecoms

SharePoint Site used extensively to share documents and data



External PNNL SharePoint Site
Description: The purpose is for the team to oganize, author and share information to enhance the team productivity for this joint DOE project.
Site Owner: Alderson,Vilma I
Data Sensitivity: Level 1

Announcements

Cryo-Adsorbent System Model Summary 1/5/2012 4:03 AM
by Tamburello, David Allen

A summary of all of the "reduced" system model results for the Cryo-adsorbent system (as of December 12, 2011) has been posted to the following location:

A System / Shared Documents / System_model

BOP Library Components in the ET Folder 10/7/2011 1:40 PM
by Simmons, Kevin L

A new folder has been added the ET sharepoint site that has all of the acquired datasheets for components that system engineers/designers can use a resource. If anyone has new components that they would like to add, please send them to Kevin Simmons...

New version of the Simulink framework 7/20/2011 12:21 PM
by Pasini, Jose Miguel

I uploaded a new version of the simulink vehicle level model to

IPPSSM > Shared Documents > Vehicle Level Model > simulink_version_2011_07_20.zip

This version includes the following additions:
- New way of switching between systems...

New simulation framework uploaded. 3/31/2011 12:53 PM
by Pasini, Jose Miguel

I uploaded a new version of the simulink vehicle level model to

IPPSSM > Shared Documents > Vehicle Level Model > simulink_version_2011_03_31.zip

This version includes the following additions:
- Fuel cell module with waste heat calculations.
...

ANL/TIAX Analyses 2/24/2011 8:45 AM
by Anton, Donald L.

All of the DoE Hydrogen Storage Records, Argonne and TIAX system analyses have been uploaded into the folders
HSECoE > Shared Documents > Analysis

(More Announcements...)

Add new announcement

Links
- Hydrogen Storage Engineering CENTER OF EXCELLENCE
- DOE Hydrogen Program
- Hydrogen Incidents Reporting
- Hydrogen Components, Inc.
- Hydrogen Program Analysis Repository
- WHEC 2012 Meeting

Calendar

2/8/2012 2:00 PM HSECoE CC Telecon
3/7/2012 1:00 PM HSECoE CC Telecon
4/4/2012 1:00 PM HSECoE CC Telecon
4/30/2012 8:00 AM Quarterly/Annual Reports Due
5/2/2012 1:00 PM HSECoE CC Telecon
6/6/2012 1:00 PM HSECoE CC Telecon

Phased Approach

Phase I:
System Requirements & Novel Concepts

Phase II:
Novel Concept Modeling Design & Evaluation

Phase III:
Sub-Scale Prototype Construction, Test and Evaluation

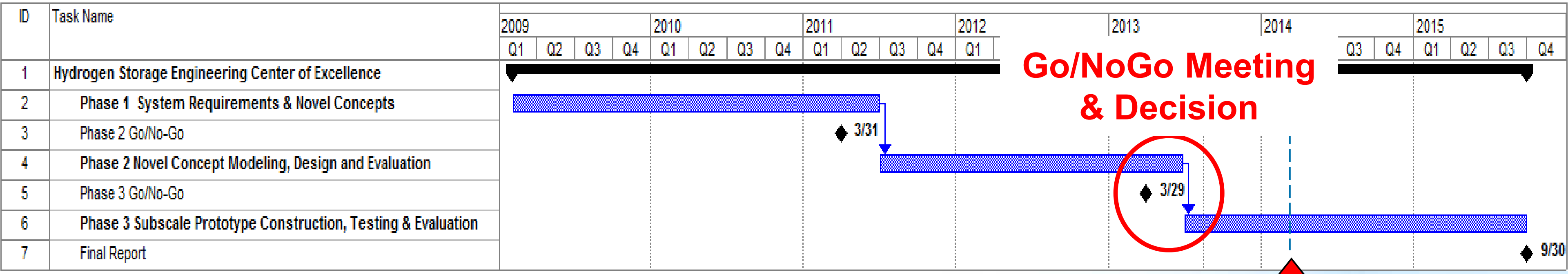
- **Where were we and where can we get to?**
  - Model Development
  - Benchmarking
  - Gap Identification
  - Projecting advances

- **How do we get there (closing the gaps) and how much further can we go?**
  - Novel Concepts
  - Concept Validation
  - Integration Testing
  - System Design

- **Put it all together and confirm claims.**
  - System Integration
  - System Assessments
  - Model Validation
  - Gap Analysis
  - Performance Projections

Important Dates

- Duration: 6.7 years
  - Phase 1 Start: Feb. 1, 2009
  - Phase 1-2 Transition: March 31, 2011
  - Phase 1 End: June 30, 2011
  - Phase 2 Start: July 1, 2011
  - Phase 3 Go/No-Go Determination: **March 31,2013**
  - *Phase 2 End:* **June 30, 2013**
  - Phase 3 Start: **July 1, 2013**
  - Completion Date: June 30, 2015



ID	Task Name
1	Hydrogen Storage Engineering Center of Excellence
2	Phase 1 System Requirements & Novel Concepts
3	Phase 2 Go/No-Go
4	Phase 2 Novel Concept Modeling, Design and Evaluation
5	Phase 3 Go/No-Go
6	Phase 3 Subscale Prototype Construction, Testing & Evaluation
7	Final Report

Go/NoGo Meeting & Decision

Here we are today.

Phase 3 Go/NoGo Review Held

- **Where we are now?**
  - Phase 2 Spider Charts
  - Phase 2 SMART Milestone Status
  - Phase 2 Waterfall Charts
- **Why this demonstration will be valuable?**
  - Validate models
  - Materials Properties Requirements
  - Demonstrate Engineering Concepts
- **What will be demonstrated in Phase 3?**
  - Scale of test and justification
  - Specific designs/components (mass/volume/cost)
  - Design status/plan
- **How will it be demonstrated in Phase 3?**
  - Specific test plan for each target
  - What will be learned from each test
  - Test facility status/plan
  - Decommissioning plan
- **Who will participate and how?**
  - Partner's roles
  - Phase 3 Draft SMART Milestones
- **When will this come about?** *Planned Phase 3 Gantt chart*

Green text indicates deliverable to DOE

Phase 3 Go/NoGo Decisions

- ✓ **Complete a Unified Comprehensive Report of Metal Hydride System Efforts.**
- ✓ **Draw Down Chemical System Work to Systematic Conclusion**
- **Complete a Unified Comprehensive Report on Chemical System Efforts.**
- **Continue Phase 3 Demonstration Efforts of HexCell Adsorbent System to Validate Models**
- **Continue Phase 3 Demonstration Efforts of MATI Adsorbent System to Validate Models**
- **Complete a Unified Comprehensive Report of Adsorbent System Efforts.**
- **Make Models Generally Available to the Public**

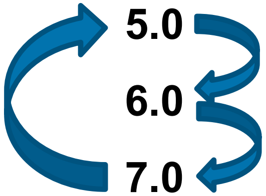
Phase 3 Task Structure

1.0 Design subscale prototype systems

2.0 Synthesize/modify materials

3.0 Complete test facilities

4.0 Fabricate/assemble prototype system



5.0 Evaluate prototype & assess performance

6.0 Compare to and refine models

7.0 Modify test apparatus/prototype

8.0 Decommission prototypes

9.0 Thermos bottle testing

10.0 Chemical system completion

11.0 Performance/cost model updates

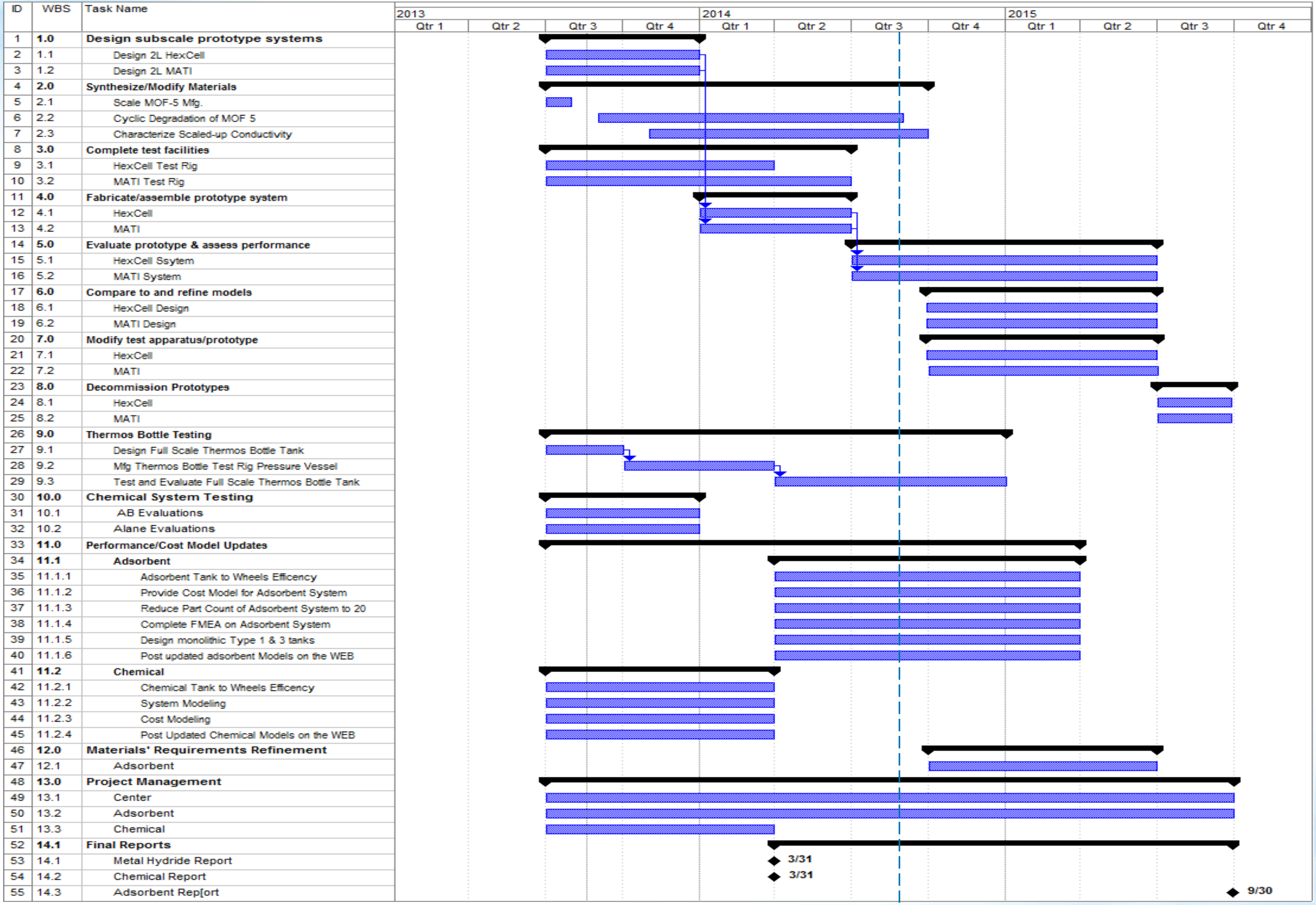
12.0 Materials' requirements refinement

13.0 Project management

14.0 Final Reports

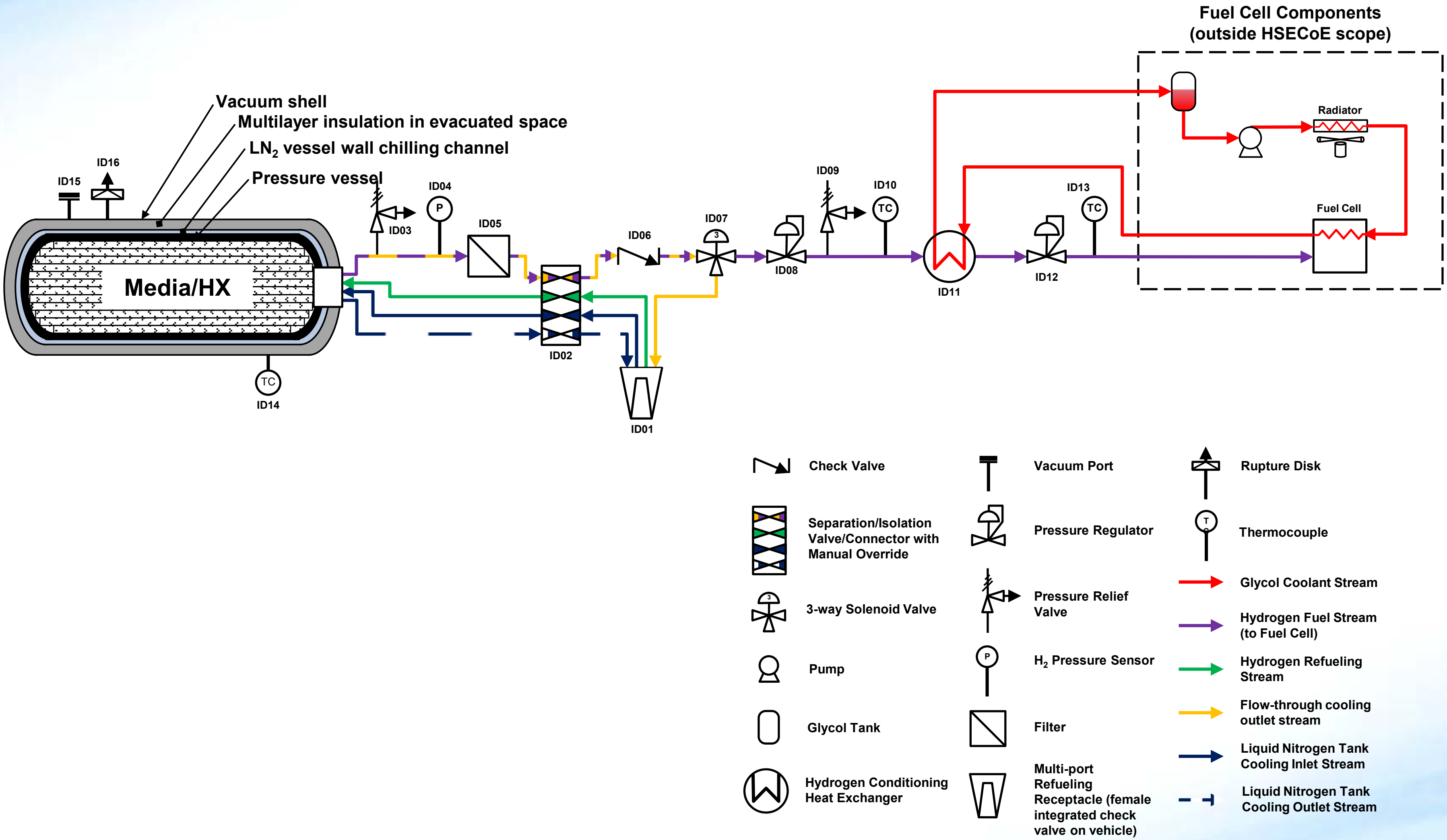
Approach

Phase 3 Gantt Chart

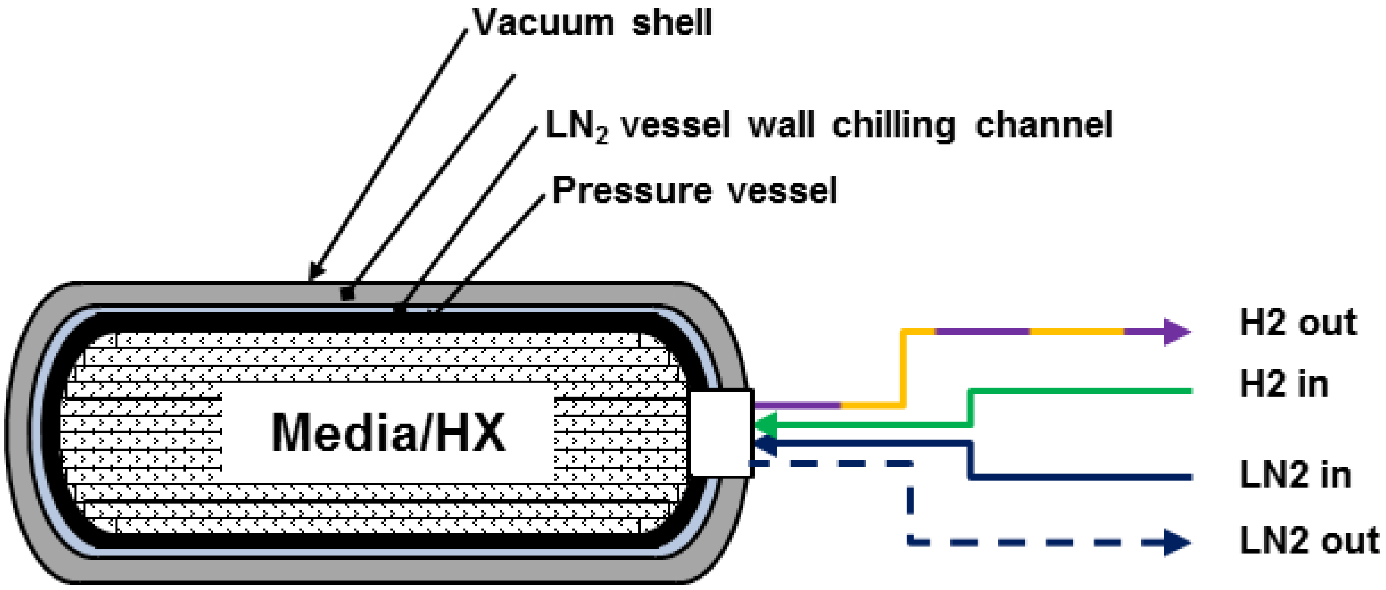


ID	WBS	Task Name
1	**1.0**	**Design subscale prototype systems**
2	1.1	Design 2L HexCell
3	1.2	Design 2L MATI
4	**2.0**	**Synthesize/Modify Materials**
5	2.1	Scale MOF-5 Mfg.
6	2.2	Cyclic Degradation of MOF 5
7	2.3	Characterize Scaled-up Conductivity
8	**3.0**	**Complete test facilities**
9	3.1	HexCell Test Rig
10	3.2	MATI Test Rig
11	**4.0**	**Fabricate/assemble prototype system**
12	4.1	HexCell
13	4.2	MATI
14	**5.0**	**Evaluate prototype & assess performance**
15	5.1	HexCell Ssytem
16	5.2	MATI System
17	**6.0**	**Compare to and refine models**
18	6.1	HexCell Design
19	6.2	MATI Design
20	**7.0**	**Modify test apparatus/prototype**
21	7.1	HexCell
22	7.2	MATI
23	**8.0**	**Decommission Prototypes**
24	8.1	HexCell
25	8.2	MATI
26	**9.0**	**Thermos Bottle Testing**
27	9.1	Design Full Scale Thermos Bottle Tank
28	9.2	Mfg Thermos Bottle Test Rig Pressure Vessel
29	9.3	Test and Evaluate Full Scale Thermos Bottle Tank
30	**10.0**	**Chemical System Testing**
31	10.1	AB Evaluations
32	10.2	Alane Evaluations
33	**11.0**	**Performance/Cost Model Updates**
34	**11.1**	**Adsorbent**
35	11.1.1	Adsorbent Tank to Wheels Efficency
36	11.1.2	Provide Cost Model for Adsorbent System
37	11.1.3	Reduce Part Count of Adsorbent System to 20
38	11.1.4	Complete FMEA on Adsorbent System
39	11.1.5	Design monolithic Type 1 & 3 tanks
40	11.1.6	Post updated adsorbent Models on the WEB
41	**11.2**	**Chemical**
42	11.2.1	Chemical Tank to Wheels Efficency
43	11.2.2	System Modeling
44	11.2.3	Cost Modeling
45	11.2.4	Post Updated Chemical Models on the WEB
46	**12.0**	**Materials' Requirements Refinement**
47	12.1	Adsorbent
48	**13.0**	**Project Management**
49	13.1	Center
50	13.2	Adsorbent
51	13.3	Chemical
52	**14.1**	**Final Reports**
53	14.1	Metal Hydride Report
54	14.2	Chemical Report
55	14.3	Adsorbent Rep[ort

Adsorbent System Overview



Adsorbent System Overview



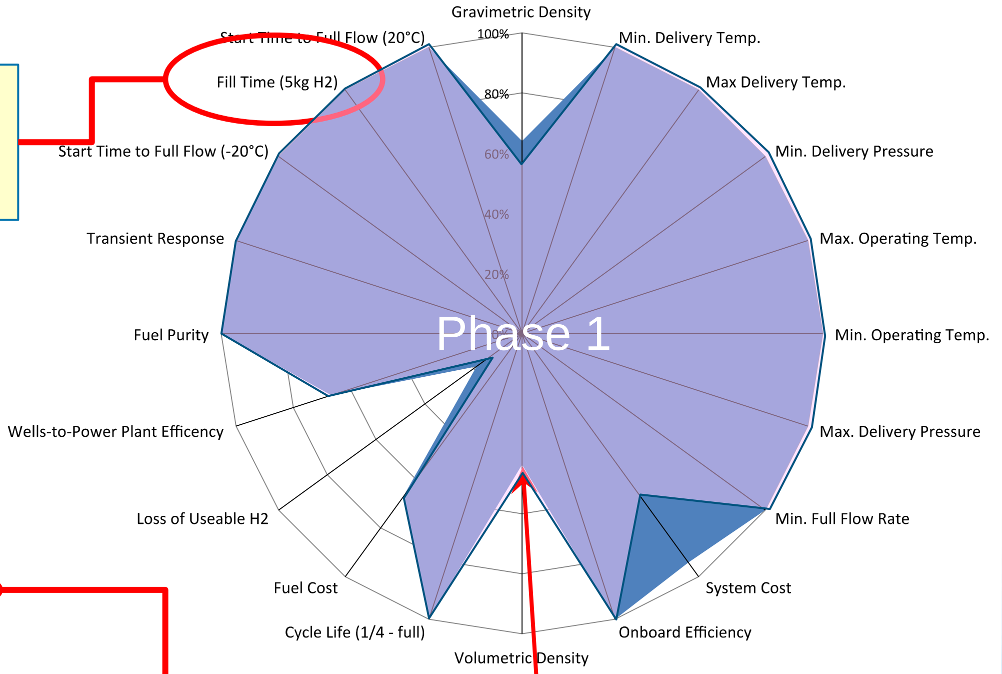
Accomplishment

Adsorbent System

Media: MOF-5
P: 5-60 bar – Type I Al Pressure Vessel
T: 80-160K - MLVI

HexCell Heat Exchanger

Fill time targets achieved due to advanced heat exchanger designs



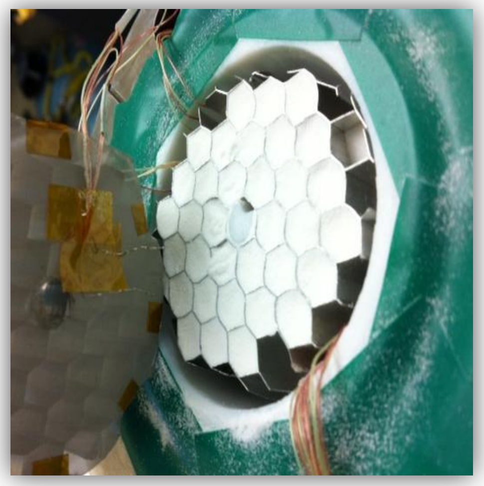
Technical Hurdles

Gravimetric Capacity – BoP Mass
System Cost – BoP cost
Volumetric Capacity – Media Density
Fuel Cost – LN2 Chilled H_2
Loss of Useable H_2 - Insulation
Well to Power Plant Efficiency – LN2 chilled H_2

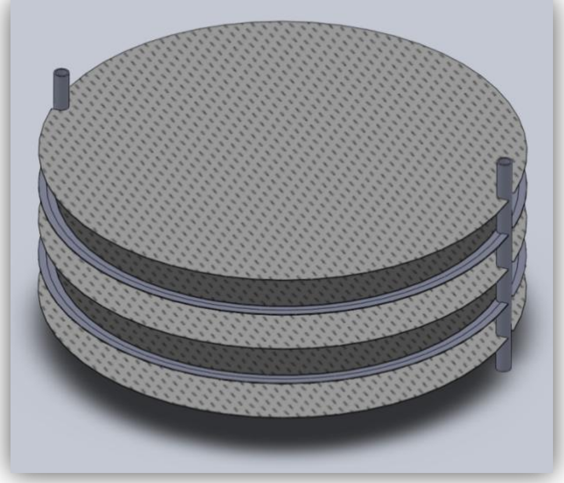
Further work needed to approach volumetric target

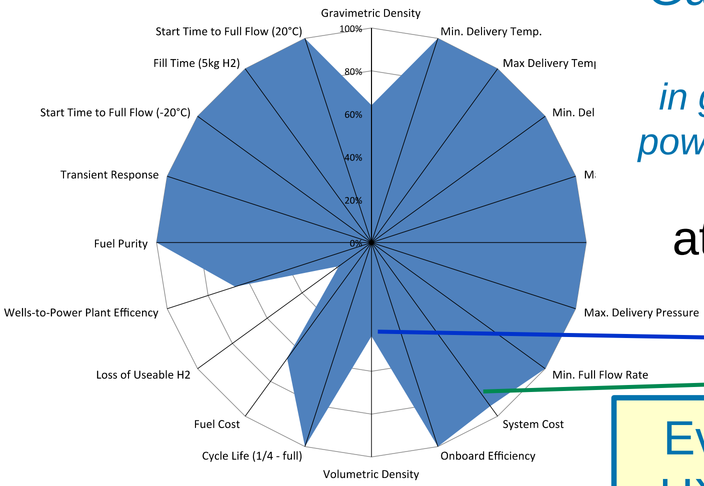
Adsorbent Heat Exchanger Types

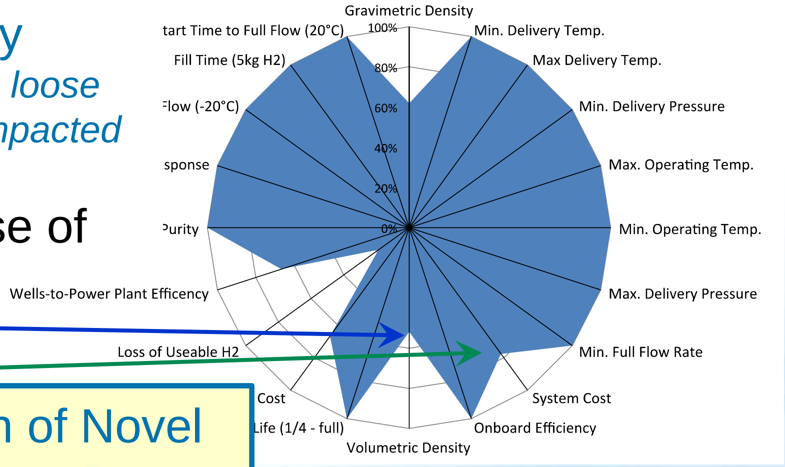
HexCell



MATI







Gain Volumetric Density

in going from loose powder to compacted pucks

at expense of

Cost

Evaluation of Novel HX Design to Prove Efficacy & Utility

Approach

HSECoE Adsorbent System S*M*A*R*T Milestones

Addsorbent System						
Component	Partner	Proposed SMART Milestones	Due Date	Modified Date	Status	Reason
Adsorbent Media	Ford/UM/BASF	Conduct a scale-up of the MOF-5 manufacturing process to deliver > 9 kg of material while maintaining performance, as measured by surface area and particle size, to within 10% of lab-scale procedure.	12/31/201	Adsorbent Media		
Adsorbent Media	Ford/UM/BASF	Evaluate MOF-5 degradation beyond 300 cycles based on maximum allowable impurity levels as stated in SAE J2719 and report on the ability to mitigate to less than 10%.	9/30/2014			
Adsorbent Media	LANL	Perform a minimum of 10 heat capacity or thermal conductivity measurments at temperatures ranging from 70-200K on compacted MOF-5 samples preapred by Ford and to support validating system models and system level designs.	9/30/2014			
MATI HX	OSU	Design a 2L adsorbent subscale prototype utilizing a MATI thermal management system having 54 g available hydrogen, internal densities of 0.10g/g gravimetric, and 27g/L volumetric.	12/31/201	MATI System		
MATI Prototype	SRNL	Design and construct a hydrogen cryo-adsorbent test station capable of evaluating the performance of a two liter cryo-adsorbent prototype between 80-160K and which would meet all of the performance metrics for the DoE Technical Targets for On-Board Hydrogen Storage Systems.	9/30/2014			
MATI HX	OSU	Demonstrate performance of subscale system evaluations and model validation of a 2L adsorbent system utilizing a MATI thermal management system having 54 g available hydrogen, internal densities of 0.10g/g gravimetric, and 27 g/L volumetric.	6/30/2015			
MATI Prototype	SRNL	Demonstrate a two liter hydrogen adsorption system containing a MATI internal heat exchanger provided by Oregon State University characterizing its performance against each of the sixteen performance DoE Technical Targets for On-Board Hydrogen Storage Systems.	9/30/2015			
HexCell HX	SRNL/UQTR	Design a 2L adsorbent subscale prototype utilizing a HexCell heat exchanger having 46g avialable hydrogen, internal densities of 0.13g/g gravimetric, and 23.4g/L volumetric.	12/31/2013	HexCell System		
HexCell Prototype	SRNL/UQTR	Demonstrate performance of subscale system evaluations and model validation of a 2L adsorbent system utilizing a HexCell heat exchanger having 46g avialable hydrogen, internal densities of 0.13g/g gravimetric, and 23.4g/L volumetric.	6/30/2015			
Pressure Vessel	Hexagon-Lincoln	**Design and manufacture a baseline, separable Type 1 tank** in accordance with size (2L - 6L), pressure (100 bar service pressure), operating temperatures (80K – 160K) and interfaces specified by HSECoE team members, and with a 10% reduction in weight per unit volume compared with the Type 1 tank tested in Phase 2.	12/31/13	Pressure Vessel		
Pressure Vessel Cooling	PNNL / Hexagon-Lincoln	Evaluate the thermal-mechanical stresses in the thermos bottle concept during refueling considering a fatigue life of 1500 cycles. Identify any necessary design criteria to avoid failure of the pressure vessel under combined thermal-mechanical loading. Design a scale thermos bottle tank using LN2 cooling having a cooling rate capable of meeting the DoE technical targets for refueling from 160K to 77K in 4.2 mins and meet any necessary fatigue design criteria.	9/30/2014			
Pressure Vessel	Hexagon-Lincoln	Design alternate tank configurations, such as monolithic Type 1, Type 3 with suitable cryogenic liner, and Type 4 with suitable cryogenic liner, that can operate at 100 bar service pressure, at temperatures of 80K – 160K, and offer a further 10% reduction in weight compared with the Phase 3 baseline Type 1 tank, and are consistent with safety requirements established by industry for hydrogen fuel containers.	3/31/2015			
Pressure Vessel Cooling	PNNL /Hexagon-Lincoln	Hexagon-Lincoln will fabricate and PNNL will demonstrate a minimum one liter scale thermos bottle tank. With this device they will measure the transient heat loss for dormancy and demonstrate the LN2 thermos bottle tank cooling concept. This experiment will be scaled to the full size 5.6 kgH2 size and shown experimentally to meet the DoE technical targets for dormancy and refueling time.	6/30/2015			
Particualte Filter	UTRC	Demonstrate a particulate filter for a cryo-adsorbent bed passing less than 1mg/L and 10mm diameter (SAE J2719 guideline).	3/31/2014	Particulate Filter		
System Modeling	NREL	Prepare a report on the impact of system design changes on the tank to wheels efficincy and document progress relative to a 300 mile range for adsorbent systems.	9/30/2014	System Modeling		
System Modeling	NREL/SRNL/PNNL/ Ford/UTRC	Update the cryo-adsorbent system model with Phase 3 performance data, integrate into the framework; document and release models to the public.	9/30/2014			
system Modeling	Ford/UM/BASF	Complete the failure mode and effects analysis (FMEA) associated with real-world operating conditions for a MOF-5-based system, for both HexCell and MATI concepts based on the Phase 3 test results. Report on the ability to reduce the risk priority numbers (RPN) from the phase 2 peak/mean and identify key failure modes.	6/30/2015			
System Modeling	GM	Attend Center F2F meetings and submit a letter memo indicatingtechnical or programitic areas the Center should be pursuing with more emphasis. Actively participate in Center Coordinting Coucnil Telecoms. Actively participate in testing and evaluation of models to be published on the WEB.	6/30/2015			

🟩 Complete
On Schedule
🟥 Behind Schedule

Accomplishment

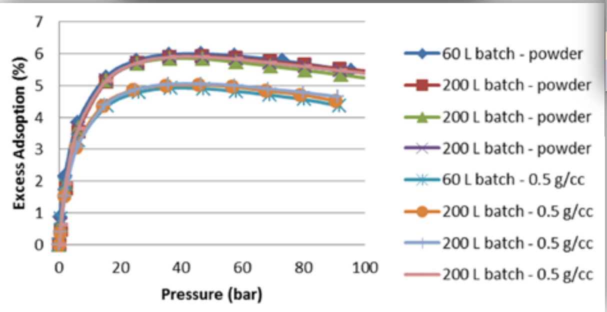
Adsorbent Media Preparation

Conduct a scale-up of the MOF-5 manufacturing process to deliver > 9 kg of material while maintaining performance, as measured by surface area and particle size, to within 10% of lab-scale procedure.

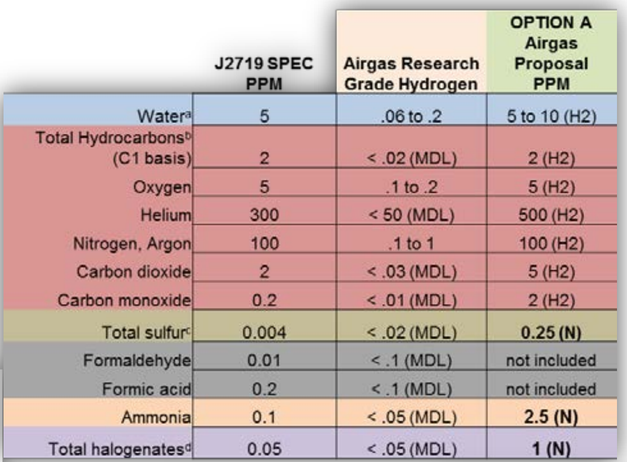
Evaluate MOF-5 degradation beyond 300 cycles based on maximum allowable impurity levels as stated in SAE J2719 and report on the ability to mitigate to less than 10%.

Perform a minimum of 10 heat capacity or thermal conductivity measurments at temperatures ranging from 70-200K on compacted MOF-5 samples preapred by Ford and to support validating system models and system level designs.

10 kg of MOF-5 Received and Characterized

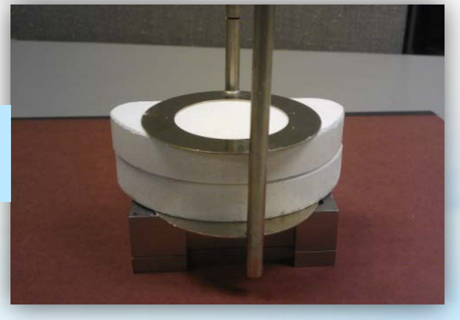


Hydrogen Impurity Concentrations Selected



	J2719 SPEC PPM	Airgas Research Grade Hydrogen	OPTION A Airgas Proposal PPM
Water[a]	5	.06 to .2	5 to 10 (H2)
Total Hydrocarbons[b] (C1 basis)	2	< .02 (MDL)	2 (H2)
Oxygen	5	.1 to .2	5 (H2)
Helium	300	< 50 (MDL)	500 (H2)
Nitrogen, Argon	100	.1 to 1	100 (H2)
Carbon dioxide	2	< .03 (MDL)	5 (H2)
Carbon monoxide	0.2	< .01 (MDL)	2 (H2)
Total sulfur[c]	0.004	< .02 (MDL)	**0.25 (N)**
Formaldehyde	0.01	< .1 (MDL)	not included
Formic acid	0.2	< .1 (MDL)	not included
Ammonia	0.1	< .05 (MDL)	**2.5 (N)**
Total halogenates[d]	0.05	< .05 (MDL)	**1 (N)**

MATI Half-Pucks Fabricated

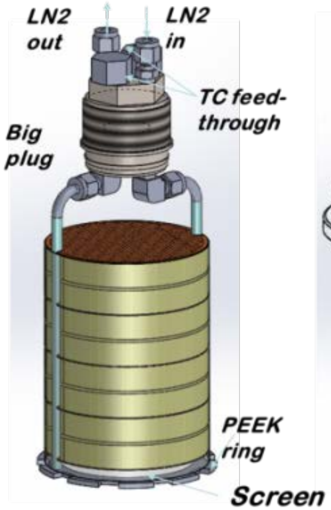


Cryogenic thermal conductivity apparatus upgraded for Powder Testing

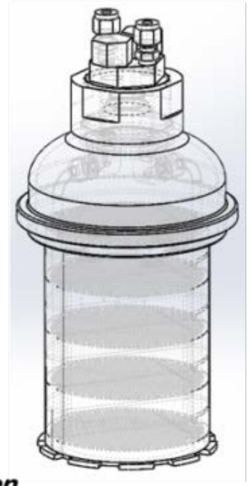
MATI Heat Exchanger & Test Systems

Design a 2L adsorbent subscale prototype utilizing a MATI thermal management system having 54 g available hydrogen, internal densities of 0.10g/g gravimetric, and 27g/L volumetric.
Design and construct a hydrogen cryo-adsorbent test station capable of evaluating the performance of a two liter cryo-adsorbent prototype between 80-160K and which would meet all of the performance metrics for the DoE Technical Targets for On-Board Hydrogen Storage Systems.
Demonstrate performance of subscale system evaluations and model validation of a 2L adsorbent system utilizing a MATI thermal management system having 54 g available hydrogen, internal densities of 0.10g/g gravimetric, and 27 g/L volumetric.
Demonstrate a two liter hydrogen adsorption system containing a MATI internal heat exchanger provided by Oregon State University characterizing its performance against each of the sixteen performance DoE Technical Targets for On-Board Hydrogen Storage Systems.

MATI System Design Completed



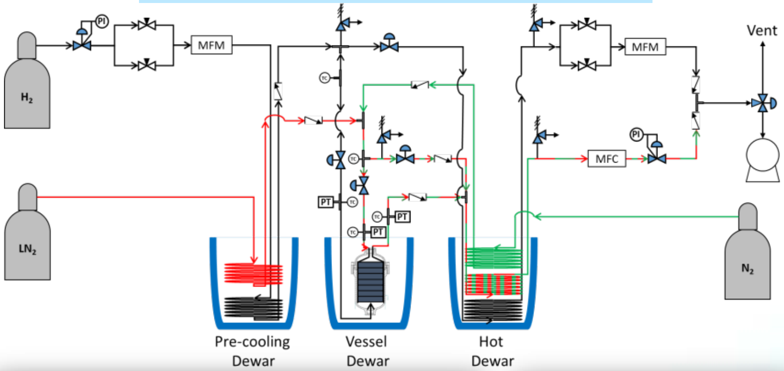
MATI connected to the Plug



Dome threaded onto the Plug

Housing attached to the dome

MATI Test Station Design

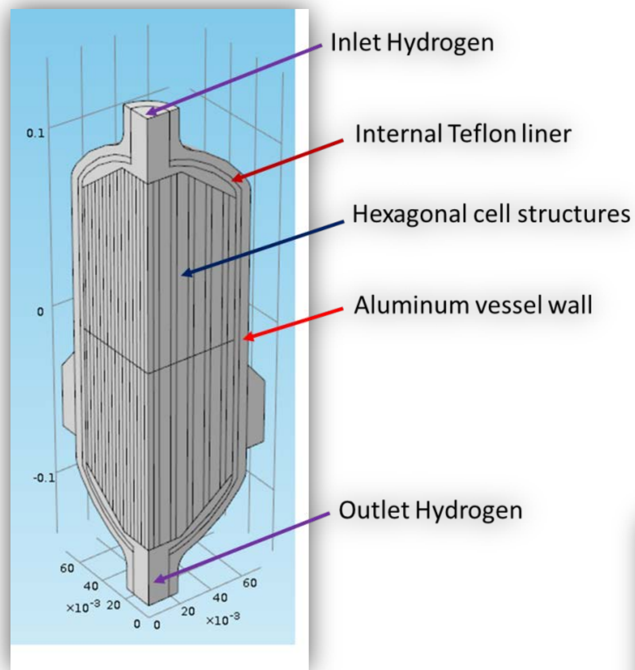


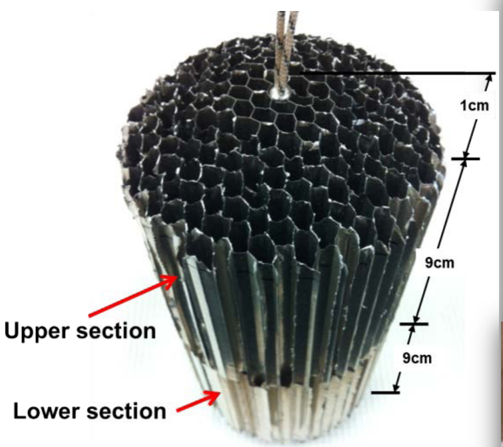
Accomplishment

HexCell Heat Exchanger & Test System

Design a 2L adsorbent subscale prototype utilizing a HexCell heat exchanger having 46g avialable hydrogen, internal densities of 0.13g/g gravimetric, and 23.4g/L volumetric.
Demonstrate performance of subscale system evaluations and model validation of a 2L adsorbent system utilizing a HexCell heat exchanger having 46g avialable hydrogen, internal densities of 0.13g/g gravimetric, and 23.4g/L volumetric.

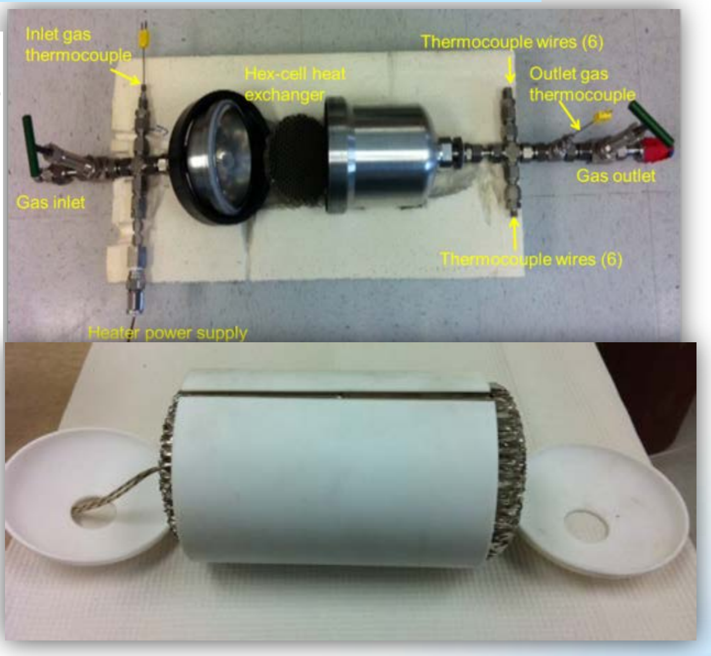
HexCell 2L System Design

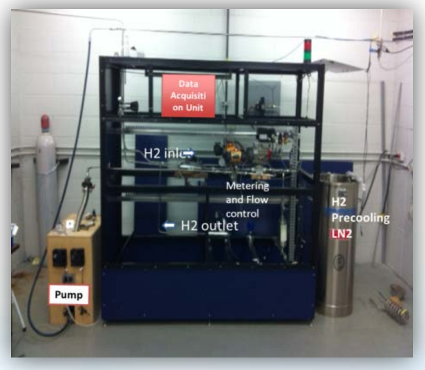




Heating cartridge is 18cm long

HexCell 2L System Assembly





HexCell 2L Test System

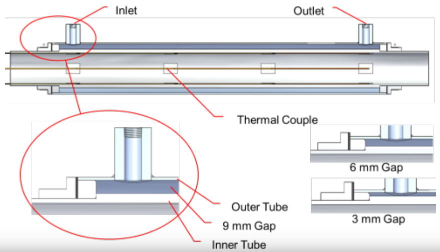
Pressure Vessel Demonstration

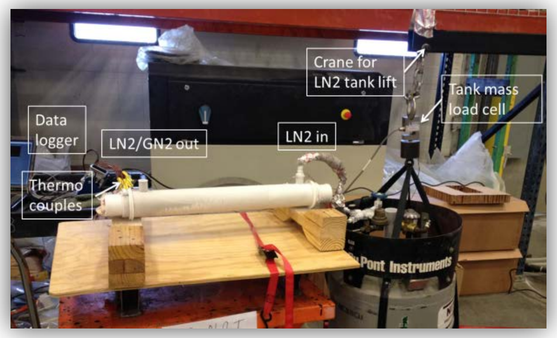
Evaluate the thermal-mechanical stresses in the thermos bottle concept during refueling considering a fatigue life of 1500 cycles. Identify any necessary design criteria to avoid failure of the pressure vessel under combined thermal-mechanical loading. Design a scale thermos bottle tank using LN2 cooling having a cooling rate capable of meeting the DoE technical targets for refueling from 160K to 77K in 4.2 mins and meet any necessary fatigue design criteria.

Design alternate tank configurations, such as monolithic Type 1, Type 3 with suitable cryogenic liner, and Type 4 with suitable cryogenic liner, that can operate at 100 bar service pressure, at temperatures of 80K – 160K, and offer a further 10% reduction in weight compared with the Phase 3 baseline Type 1 tank, and are consistent with safety requirements established by industry for hydrogen fuel containers.

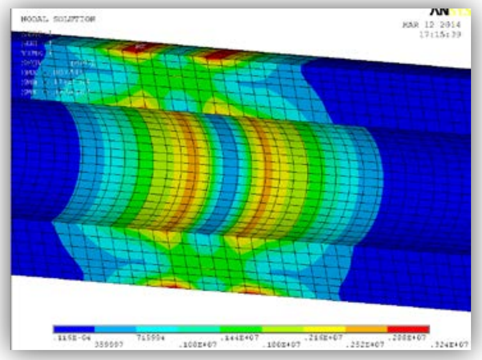
Hexagon-Lincoln will fabricate and PNNL will demonstrate a minimum one liter scale thermos bottle tank. With this device they will measure the transient heat loss for dormancy and demonstrate the LN2 thermos bottle tank cooling concept. This experiment will be scaled to the full size 5.6 kgH2 size and shown experimentally to meet the DoE technical targets for dormancy and refueling time.

Tank Cooling Design and Test Apparatus



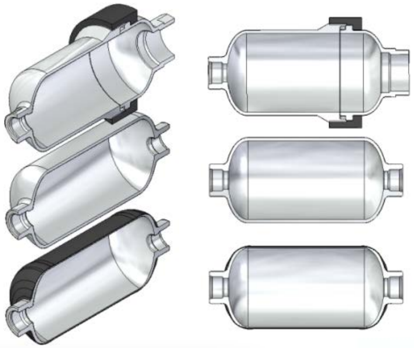


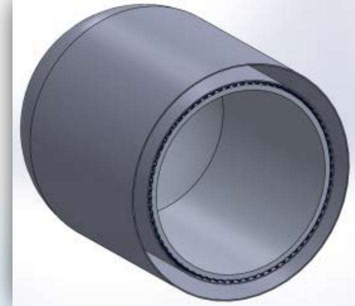
Thermal and Fatigue Stress Calculated



Peak thermal stress is 3.2 MPa (von Mises). Fatigue strength of 100 MPa is required for 5000 cycle life.

Alternate Tank Configurations



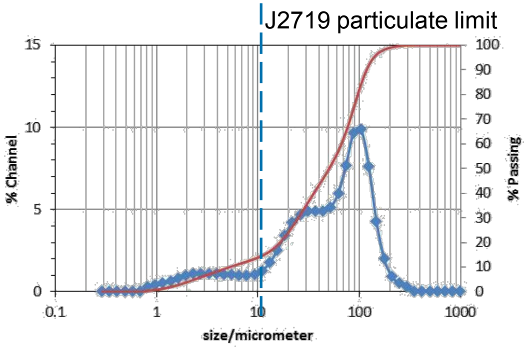


Thermos® Bottle Tank Design

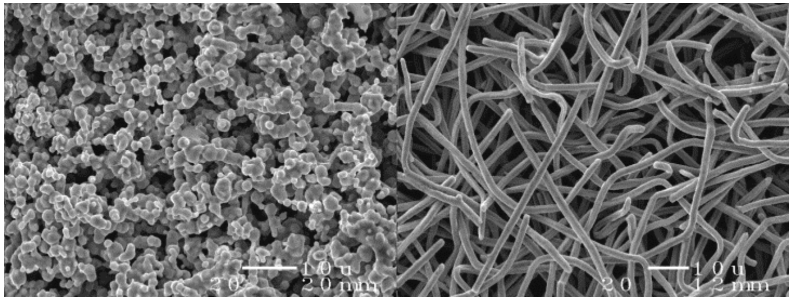
Particle Filter Demonstration

Demonstrate a particulate filter for a cryo-adsorbent bed passing less than 1mg/L and 10mm diameter (SAE J2719 guideline.

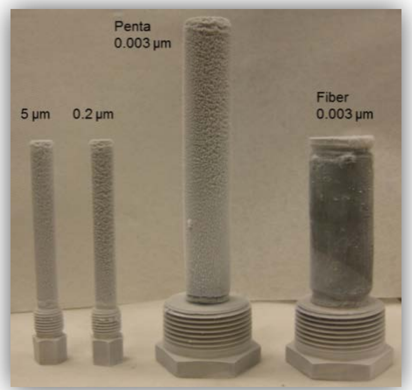
MOF-5 particle size distribution



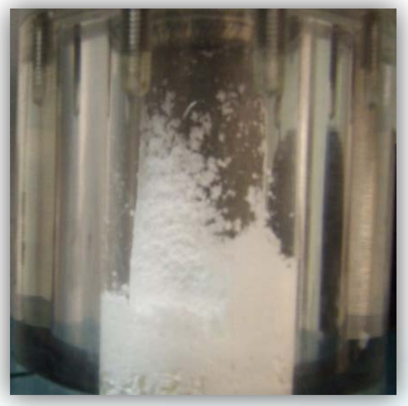
Both particle and fiber filters evaluated



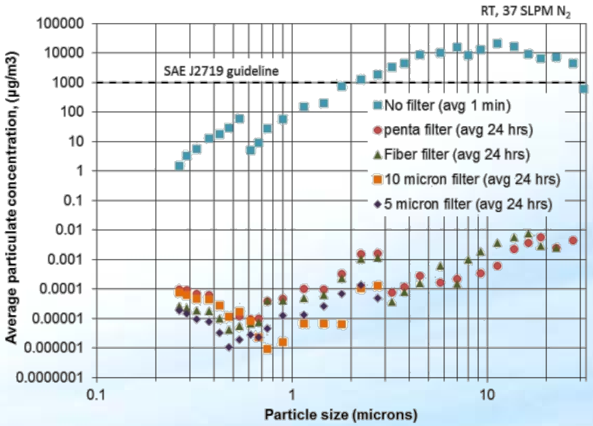
All filters survive LN2 thermal shock testing



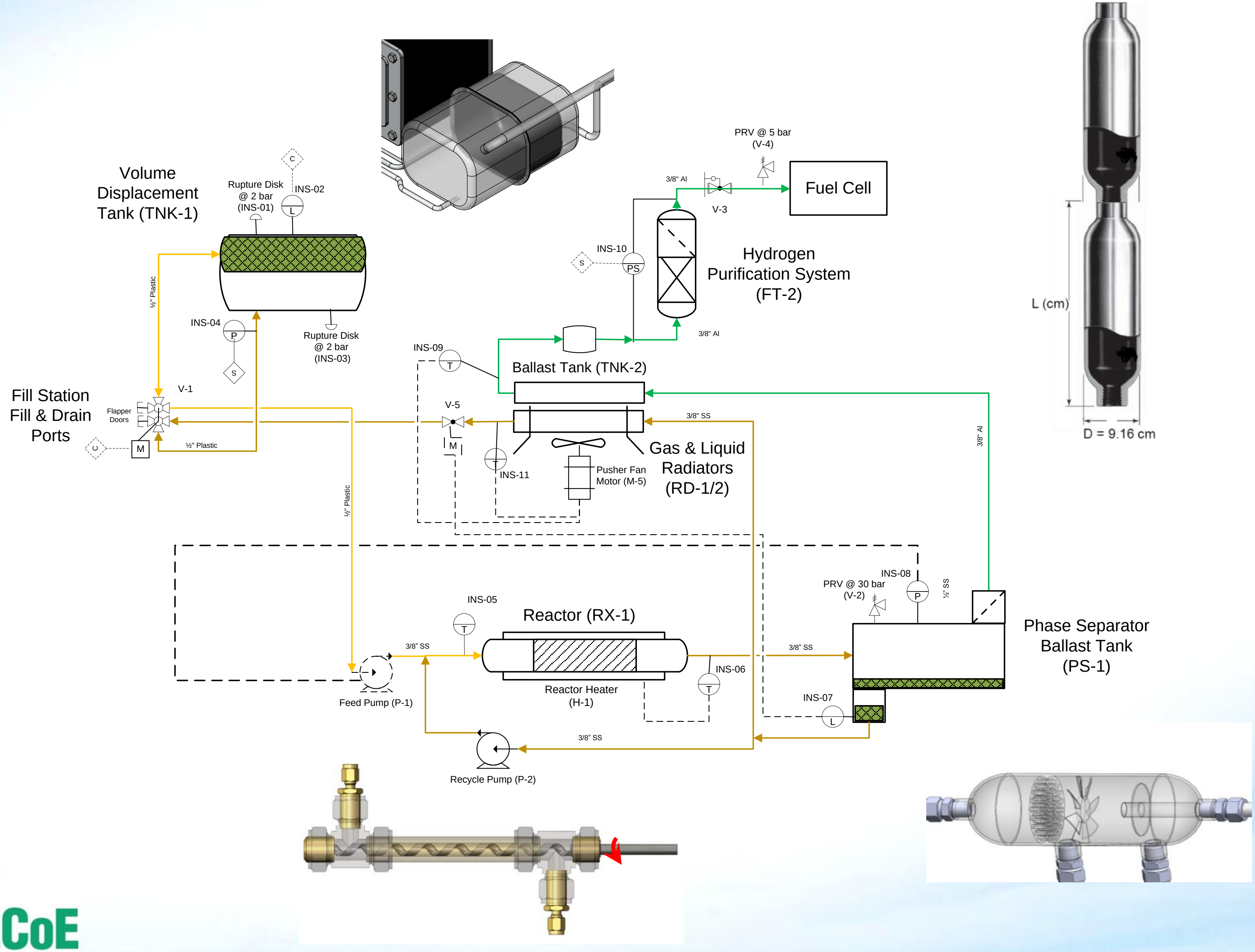
Filter caking after 20 slpm N_2 fluidized MOF-5



All filters reduce particle entrainment to below J2719 guidelines



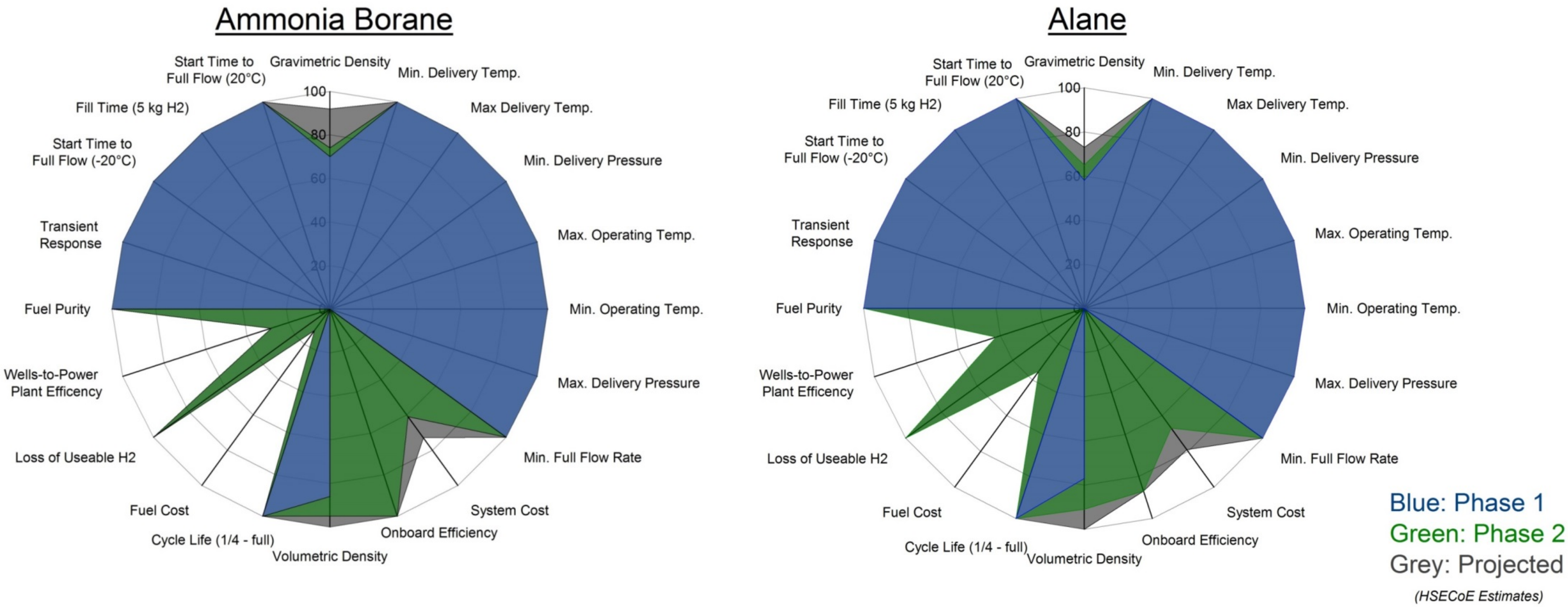
Chemical System Overview



Accomplishment

Chemical System

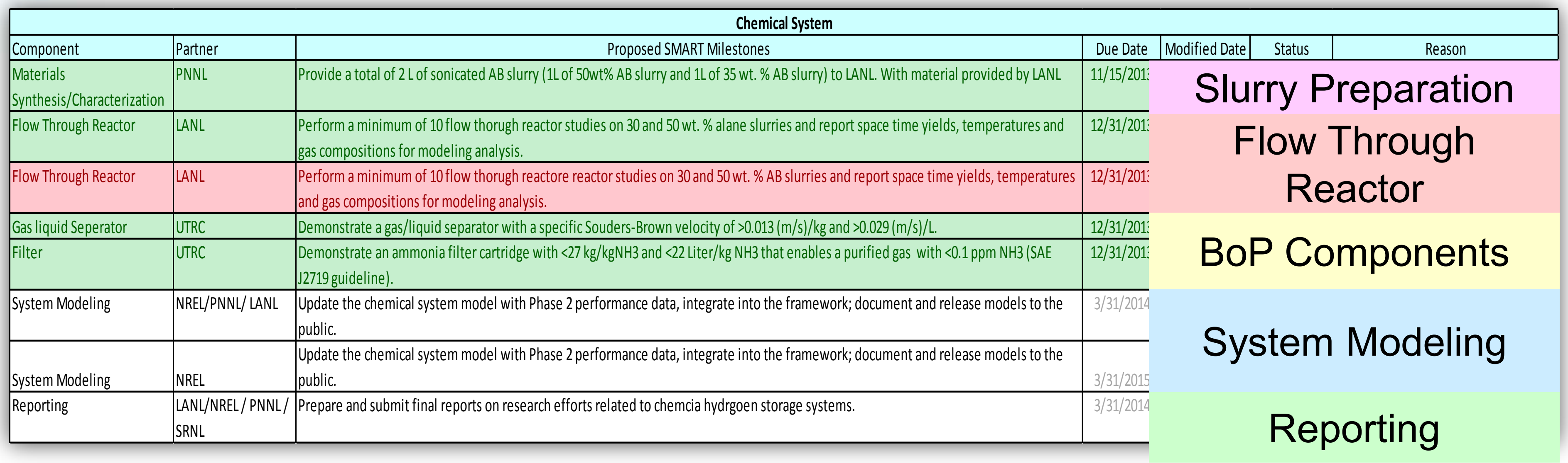
50 wt.% slurries



Technical Hurdles:
Fuel Cost, System Cost, WTPP, Gravimetric Density

Fuel Cost, System Cost, WTPP, On-board Efficiency, Gravimetric Density

Chemical Hydrogen Milestones



Chemical System						
Component	Partner	Proposed SMART Milestones	Due Date	Modified Date	Status	Reason
Materials Synthesis/Characterization	PNNL	Provide a total of 2 L of sonicated AB slurry (1L of 50wt% AB slurry and 1L of 35 wt. % AB slurry) to LANL. With material provided by LANL	11/15/201			
Flow Through Reactor	LANL	Perform a minimum of 10 flow thorugh reactor studies on 30 and 50 wt. % alane slurries and report space time yields, temperatures and gas compositions for modeling analysis.	12/31/201			
Flow Through Reactor	LANL	Perform a minimum of 10 flow thorugh reactore reactor studies on 30 and 50 wt. % AB slurries and report space time yields, temperatures and gas compositions for modeling analysis.	12/31/201			
Gas liquid Seperator	UTRC	Demonstrate a gas/liquid separator with a specific Souders-Brown velocity of >0.013 (m/s)/kg and >0.029 (m/s)/L.	12/31/201			
Filter	UTRC	Demonstrate an ammonia filter cartridge with <27 kg/kgNH3 and <22 Liter/kg NH3 that enables a purified gas with <0.1 ppm NH3 (SAE J2719 guideline).	12/31/201			
System Modeling	NREL/PNNL/ LANL	Update the chemical system model with Phase 2 performance data, integrate into the framework; document and release models to the public.	3/31/2014			
System Modeling	NREL	Update the chemical system model with Phase 2 performance data, integrate into the framework; document and release models to the public.	3/31/2015			
Reporting	LANL/NREL / PNNL / SRNL	Prepare and submit final reports on research efforts related to chemcia hydrgoen storage systems.	3/31/2014			

Slurry Preparation

Flow Through Reactor

BoP Components

System Modeling

Reporting

Complete
On Schedule
Incomplete

Accomplishment

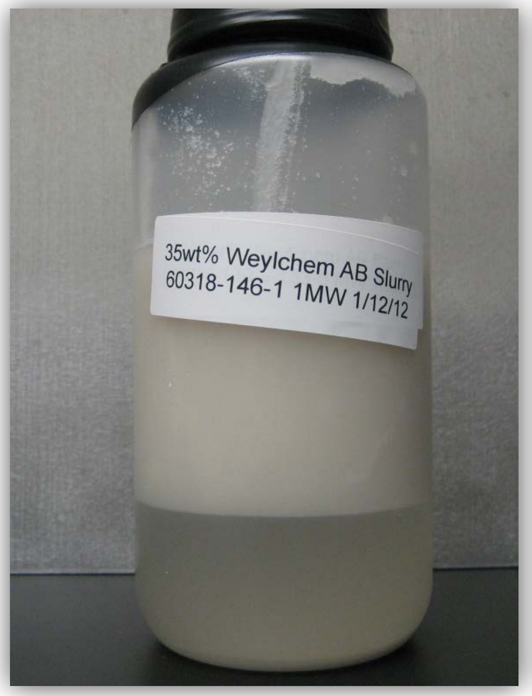
Chemical Hydrogen Media Preparation

Provide a total of 2 L of sonicated AB slurry (1L of 50wt% AB slurry and 1L of 35 wt. % AB slurry) to LANL. With material provided by LANL

One Liter 35wt% AB in silicon oil

One Liter 50wt% AB in silicon oil

60wt% AlH_3 Slurry Successfully Demonstrated

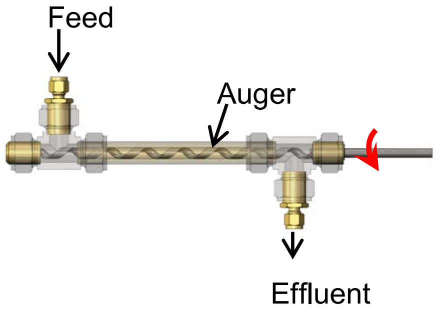


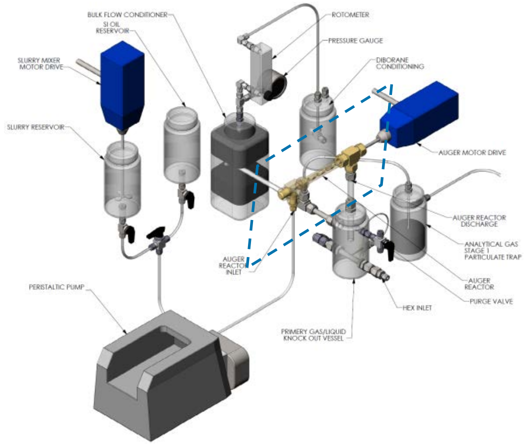
Chemical Hydrogen Media Preparation

Perform a minimum of 10 **flow thorugh reactor studies on 30 and 50 wt. % alane slurries** and report space time yields, temperatures and gas compositions for modeling analysis.

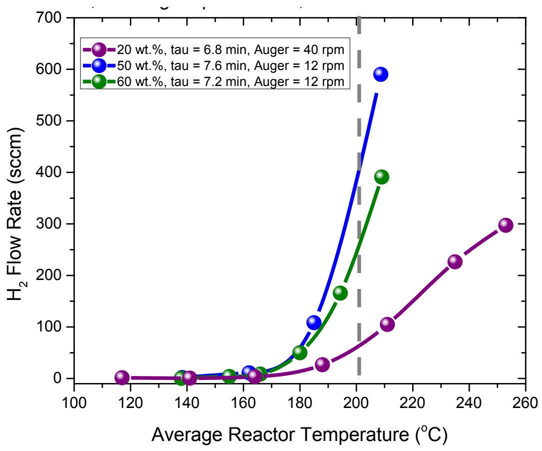
Perform a minimum of 10 **flow thorugh reactore reactor studies on 30 and 50 wt. % AB slurries** and report space time yields, temperatures and gas compositions for modeling analysis.

Flow Through Reactor Experiments

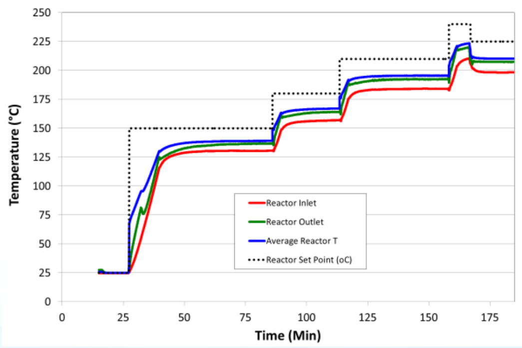




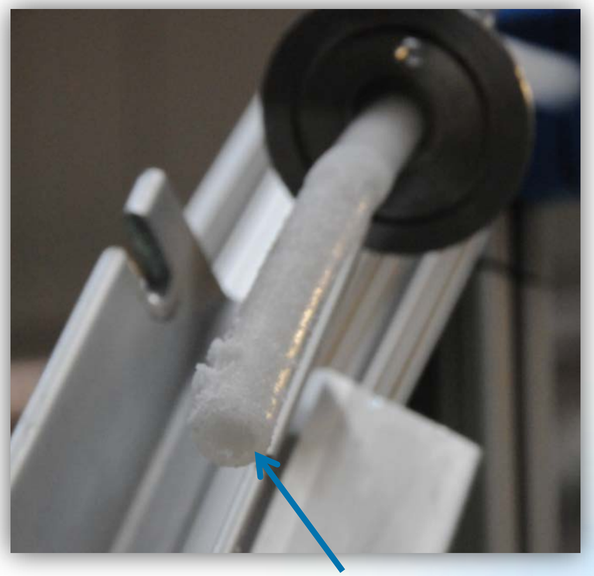
20-50 wt.% AlH_3 Successfully Slurries Tested



60 wt.% AlH_3 in MPF



50% AB Slurry Clogged in Pumps and Lines

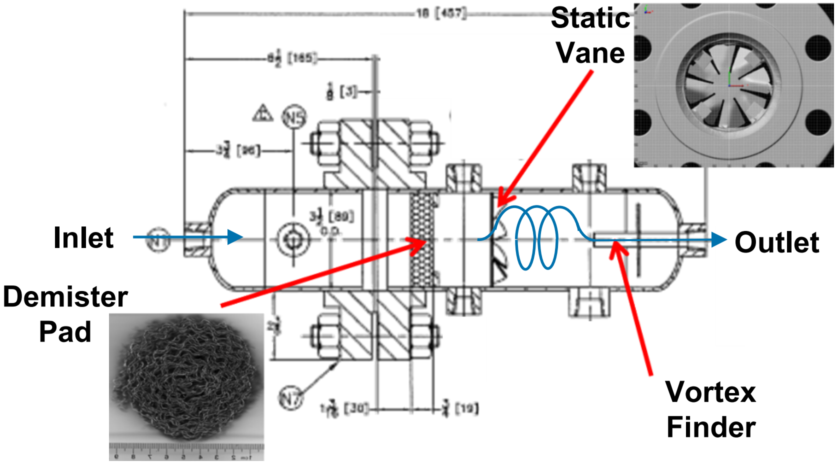


Viscous AB filled the ½ in Teflon tubing

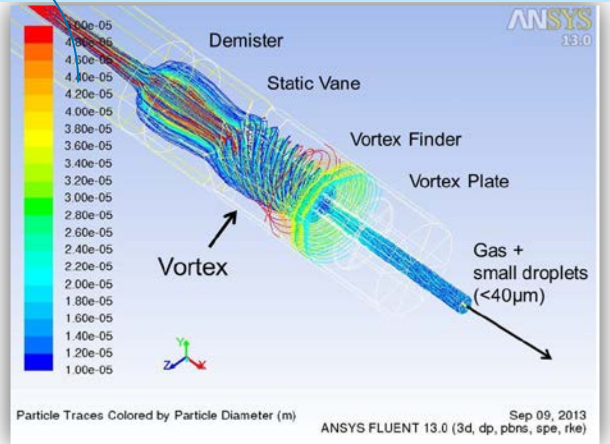
Chemical Hydrogen BoP Components

Demonstrate a gas/liquid separator with a specific Souders-Brown velocity of >0.013 (m/s)/kg and >0.029 (m/s)/L.
Demonstrate an ammonia filter cartridge with <27 kg/kgNH3 and <22 Liter/kg NH3 that enables a purified gas with <0.1 ppm NH3 (SAE J2719 guideline).

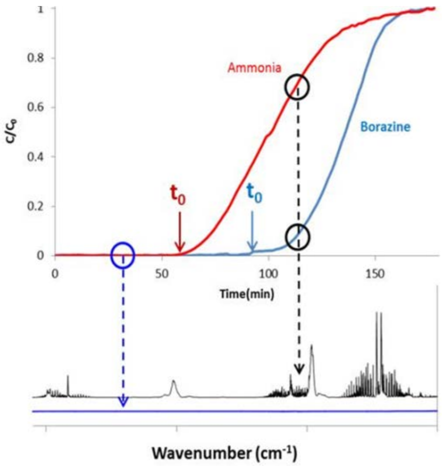
GLS Designed and Evaluated



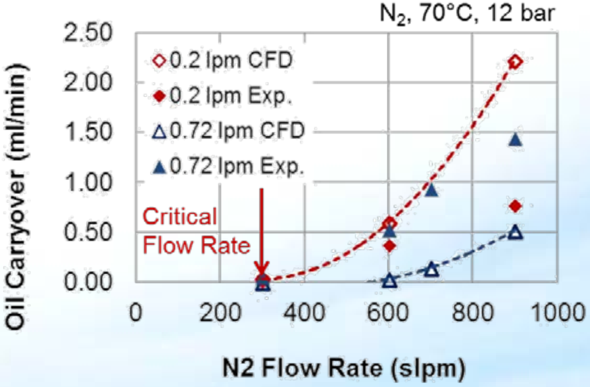
Fluent model predicts droplet size and location



Ammonia and Borazine Filters Effectively Eliminate Gas Contamination



GLS shown to Effectively Eliminate oil Carryover Under Operational Conditions

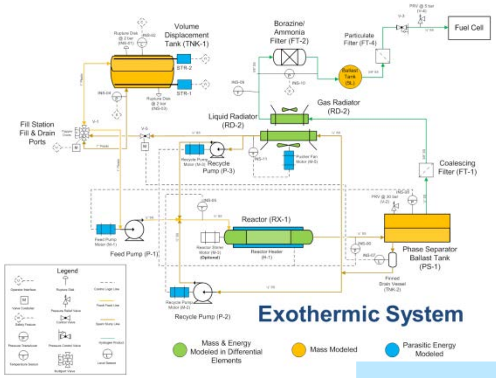


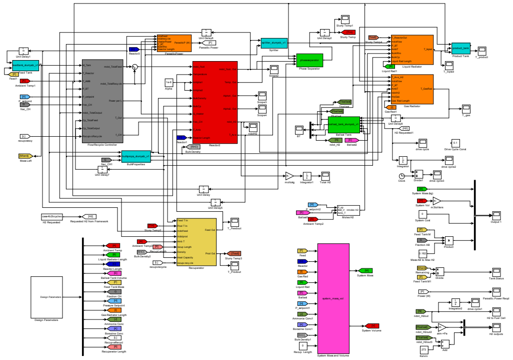
Accomplishment

Chemical Hydrogen System Modeling

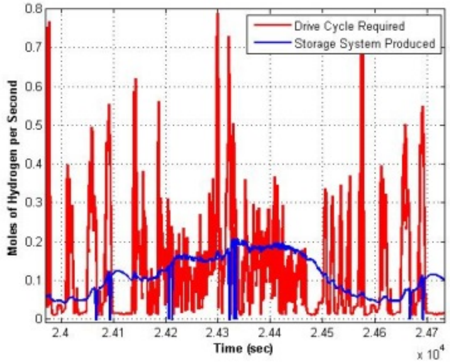
Update the chemical system model with Phase 2 performance data, integrate into the framework; document and release models to the public.

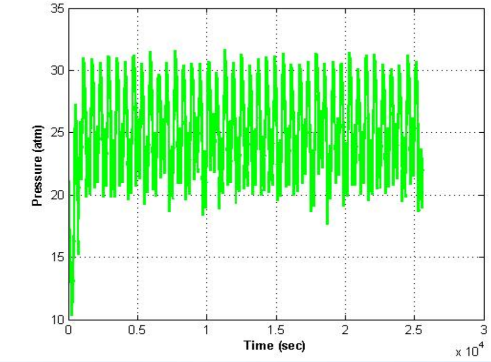
P&ID Translated to Simulink



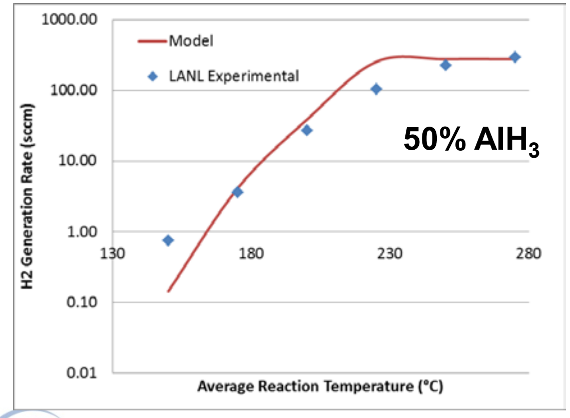


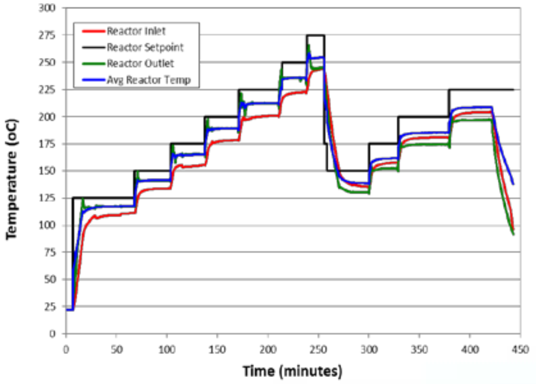
System Models Show Continuous Hydrogen Feed from Ballast Tank





Thermal Models Match to Experimental Results



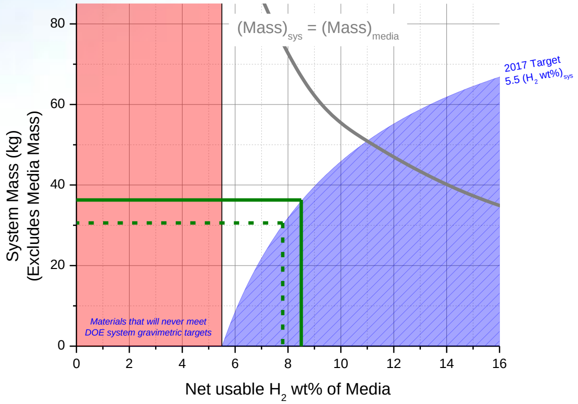


Accomplishment

Chemical Hydrogen Material Properties

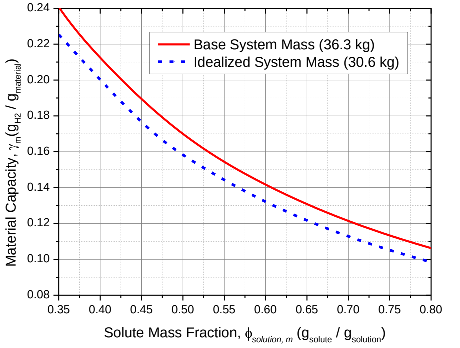
Media Gravimetric Density

Plot of Available System Mass as a Function of Net Usable H_2 wt%



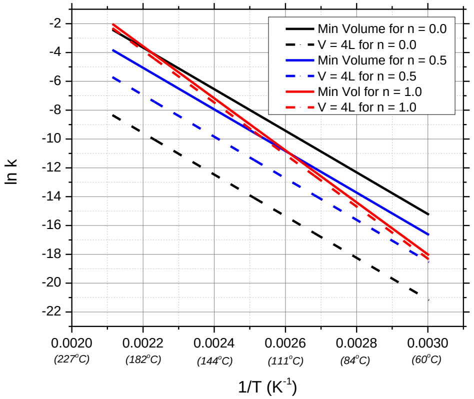
Slurry Gravimetric Density

Plot of solute mass fractions and material capacities required for a base system mass of 36.3 kg and an idealized system mass of 30.6 kg

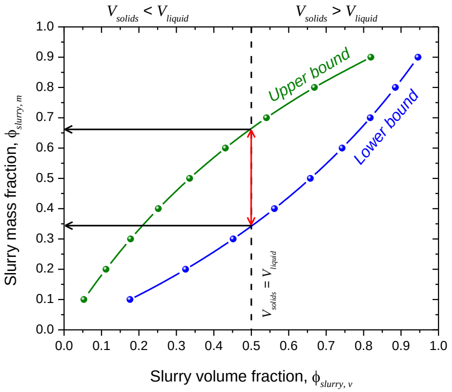


Slurry Kinetics

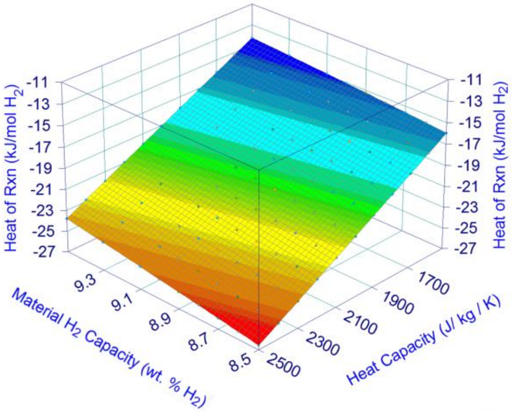
Arrhenius plots showing the desirable ranges of activation energies (kcal/mol K) and preexponential factors as a function of reaction order



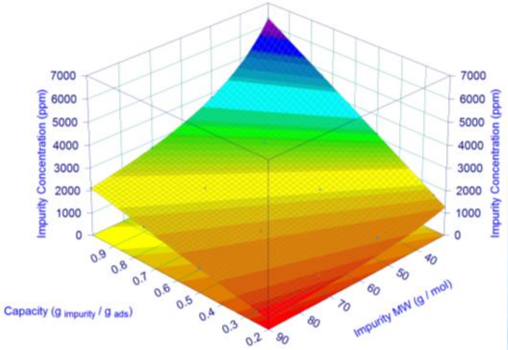
Slurry Mass/Volume Fraction



Enthalpy of Reaction



Impurities



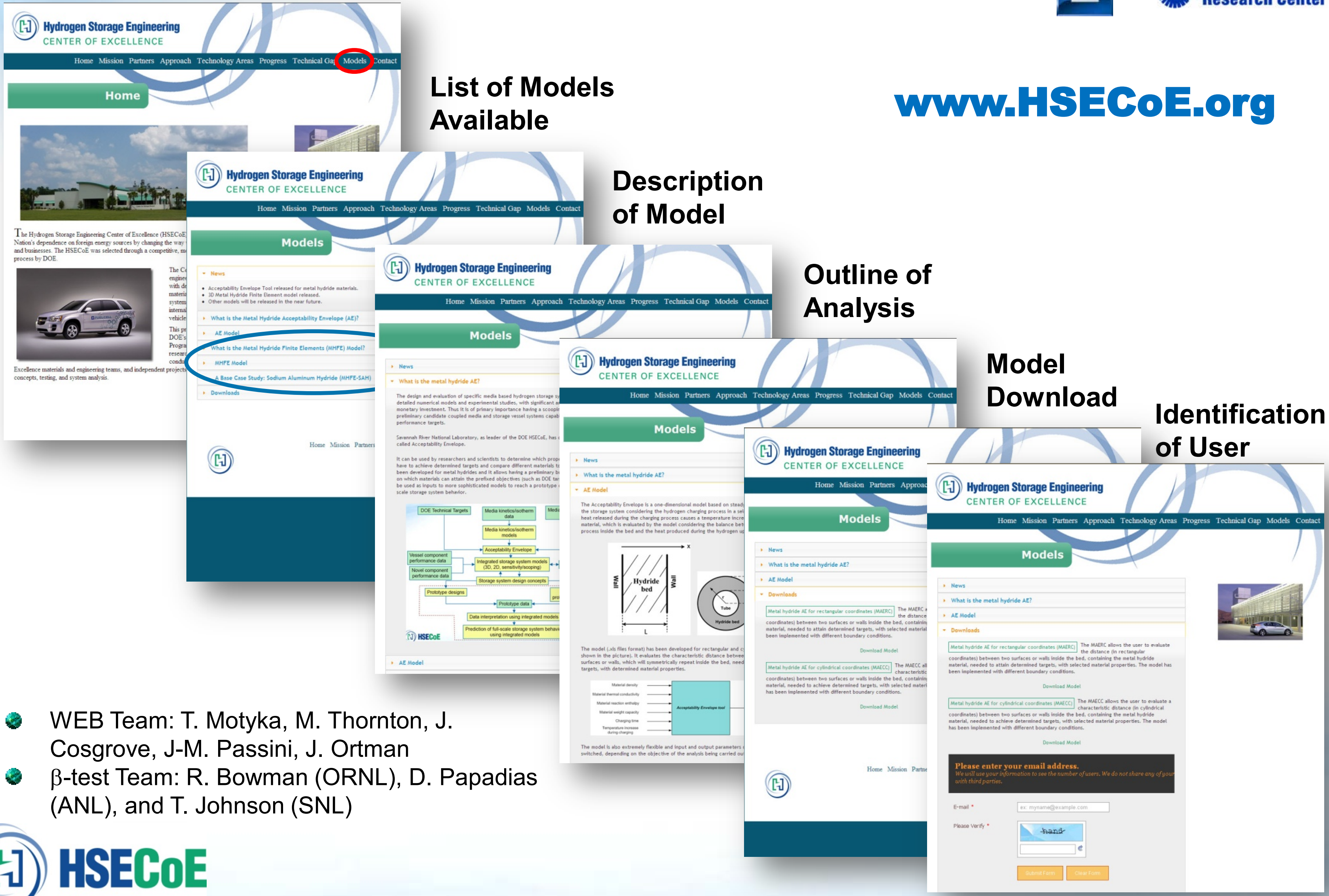
Accomplishment

Required Materials Properties

Parameter	Symbol	Units	Range*	Influence
Minimum Material capacity (liquids)	γ_{mat}	$g_{H2} / g_{material}$	**~ 0.078 (*0.085*)†**	**System**
Minimum Material capacity (solutions)	γ_{mat}	$g_{H2} / g_{material}$	**~ 0.098 (*0.106*)†**	**System**
Minimum Material capacity (slurries)	γ_{mat}	$g_{H2} / g_{material}$	**~ 0.112 (*0.121*)†**	**System**
Kinetics: Activation Energy	E_a	**kcal / mol**	**28–36**	**Reactor and Shelf life**
Kinetics: Preexponential Factor	A		**$4 \times 10^{9} – 1 \times 10^{16}$**	
Endothermic Heat of Reaction	ΔH_{rxn}	**kJ / mol H_2**	**≤ +17 (*15*)†**	**On-board efficiency**
Exothermic Heat of Reaction	ΔH_{rxn}	**kJ / mol H_2**	**≤ -27**	
Maximum Reactor Outlet Temperature	T_{outlet}	**°C**	**250**	**Heat Exchanger**
Impurities Concentration	y_i	**ppm**	**No *a priori* estimates can be quantified**	**Purification**
Media H_2 Density	$(\gamma_{mat}) (\phi_m)(\rho_{mat})$	**kg H_2 / L**	**≥ 0.07**	**Tank size System**
Regen Efficiency	η_{regen}	**%**	**≥ 66.6%**	**Well-to-Power Plant Efficiency**
Viscosity	η	**cP**	**≤ 1500**	**Fill time Pump size On-board efficiency**

Accomplishment

WEB Site Models Added



List of Models Available

Description of Model

Outline of Analysis

Model Download

Identification of User

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Hydrogen Storage Engineering
CENTER OF EXCELLENCE

Home Mission Partners Approach Technology Areas Progress Technical Gap Models Contact

Models

- News
  - Acceptability Envelope Tool released for metal hydride materials.
  - 3D Metal Hydride Finite Element model released.
  - Other models will be released in the near future.
- What is the Metal Hydride Acceptability Envelope (AE)?
  - AE Model
- What is the Metal Hydride Finite Elements (MHFE) Model?
  - MHFE Model
  - A Base Case Study: Sodium Aluminum Hydride (MHFE-SAH)
- Downloads

Models

- News
- What is the metal hydride AE?
- AE Model
- Downloads

Metal hydride AE for rectangular coordinates (MAERC) The MAERC allows the user to evaluate the distance (in rectangular coordinates) between two surfaces or walls inside the bed, containing the metal hydride material, needed to attain determined targets, with selected material properties. The model has been implemented with different boundary conditions.

Download Model

Metal hydride AE for cylindrical coordinates (MAECC) The MAECC allows the user to evaluate a characteristic distance (in cylindrical coordinates) between two surfaces or walls inside the bed, containing the metal hydride material, needed to achieve determined targets, with selected material properties. The model has been implemented with different boundary conditions.

Download Model

Please enter your email address.
We will use your information to see the number of users. We do not share any of your with third parties.

E-mail * ex: myname@example.com

Please Verify * hand

- WEB Team: T. Motyka, M. Thornton, J. Cosgrove, J-M. Passini, J. Ortman
- β-test Team: R. Bowman (ORNL), D. Papadias (ANL), and T. Johnson (SNL)

Accomplishment

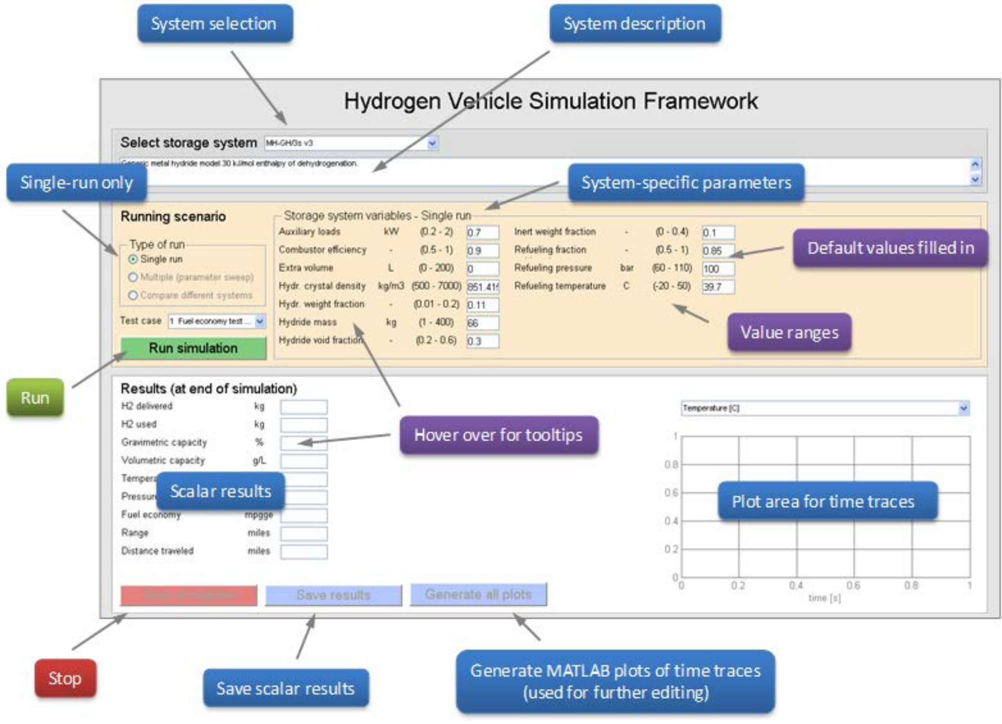
SRNL
SAVANNAH RIVER NATIONAL LABORATORY

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

GM

United Technologies Research Center

WEB Site Models Added



Hydrogen Vehicle Simulation Framework

Select storage system: MH-GH/3s v3

Generic metal hydride model 30 kJ/mol enthalpy of dehydrogenation.

Running scenario

Type of run
● Single run
○ Multiple (parameter sweep)
○ Compare different systems

Test case: 1 Fuel economy test ...

Storage system variables - Single run

Auxiliary loads	kW	(0.2 - 2)	0.7
Combustor efficiency	-	(0.5 - 1)	0.9
Extra volume	L	(0 - 200)	0
Hydr. crystal density	kg/m3	(500 - 7000)	851.41
Hydr. weight fraction	-	(0.01 - 0.2)	0.11
Hydride mass	kg	(1 - 400)	66
Hydride void fraction	-	(0.2 - 0.6)	0.3
Inert weight fraction	-	(0 - 0.4)	0.1
Refueling fraction	-	(0.5 - 1)	0.85
Refueling pressure	bar	(60 - 110)	100
Refueling temperature	C	(-20 - 50)	39.7

Results (at end of simulation)

H2 delivered	kg
H2 used	kg
Gravimetric capacity	%
Volumetric capacity	g/L
Tempera	
Pressur	
Fuel economy	mpgge
Range	miles
Distance traveled	miles

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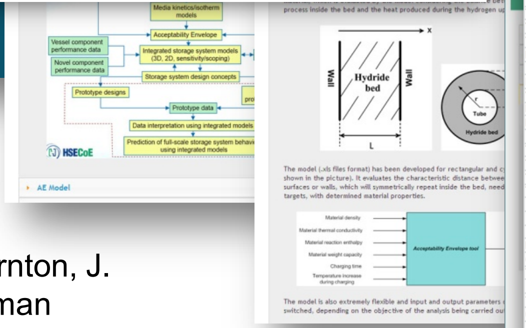
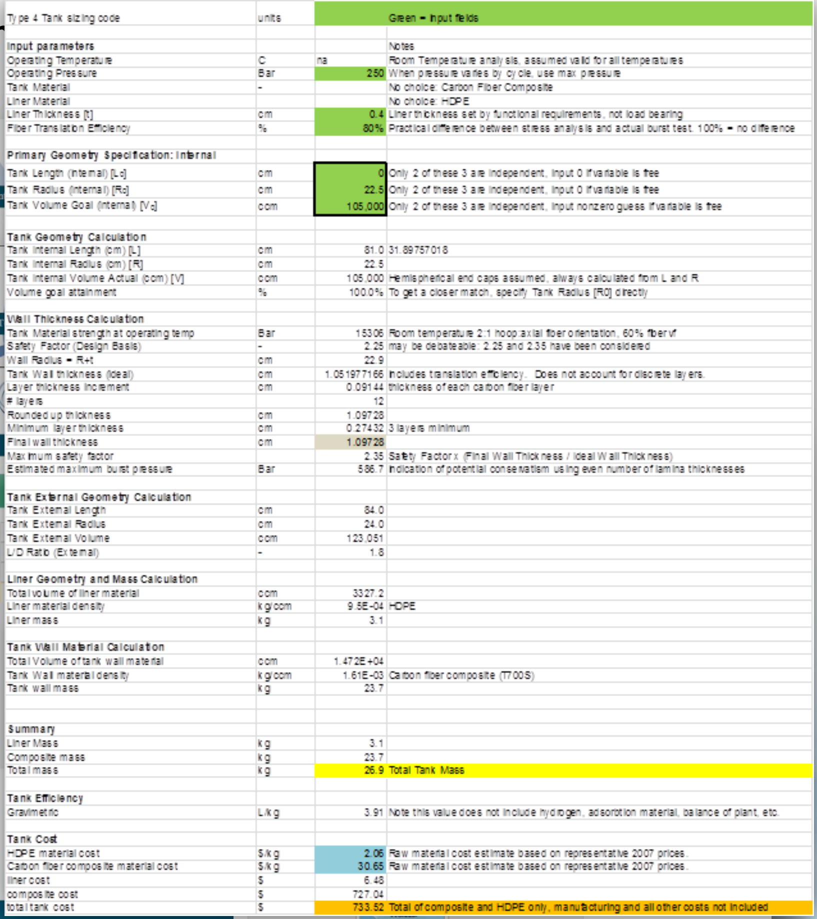




Type 4 Tank sizing code	units		Green = input fields
Input parameters			Notes
Operating Temperature	C	na	Room Temperature analysis, assumed valid for all temperatures
Operating Pressure	Bar	250	When pressure varies by cycle, use max pressure
Tank Material	-		No choice: Carbon Fiber Composite
Liner Material			No choice: HDPE
Liner Thickness [t]	cm	0.4	Liner thickness set by functional requirements, not load bearing
Fiber Translation Efficiency	%	80%	Practical difference between stress analysis and actual burst test. 100% = no difference
Primary Geometry Specification: Internal			
Tank Length (internal) [L_0]	cm	0	Only 2 of these 3 are independent, input 0 if variable is free
Tank Radius (internal) [R_0]	cm	22.5	Only 2 of these 3 are independent, input 0 if variable is free
Tank Volume Goal (internal) [V_0]	ccm	105,000	Only 2 of these 3 are independent, input nonzero guess if variable is free
Tank Geometry Calculation			
Tank Internal Length (cm) [L]	cm	81.0	31.89757018
Tank Internal Radius (cm) [R]	cm	22.5	
Tank Internal Volume Actual (ccm) [V]	ccm	105,000	Hemispherical end caps assumed, always calculated from L and R
Volume goal attainment	%	100.0%	To get a closer match, specify Tank Radius [R0] directly
Wall Thickness Calculation			
Tank Material strength at operating temp	Bar	15306	Room temperature 2:1 hoop:axial fiber orientation, 60% fiber vf
Safety Factor (Design Basis)	-	2.25	may be debateable: 2.25 and 2.35 have been considered
Wall Radius = R+t	cm	22.9	
Tank Wall thickness (ideal)	cm	1.051977166	Includes translation efficiency. Does not account for discrete layers.
Layer thickness increment	cm	0.09144	thickness of each carbon fiber layer
# layers		12	
Rounded up thickness	cm	1.09728	
Minimum layer thickness	cm	0.27432	3 layers minimum
Final wall thickness	cm	1.09728	
Maximum safety factor		2.35	Safety Factor x (Final Wall Thickness / Ideal Wall Thickness)
Estimated maximum burst pressure	Bar	586.7	Indication of potential conservatism using even number of lamina thicknesses
Tank External Geometry Calculation			
Tank External Length	cm	84.0	
Tank External Radius	cm	24.0	
Tank External Volume	ccm	123,051	
L/D Ratio (External)	-	1.8	
Liner Geometry and Mass Calculation			
Total volume of liner material	ccm	3327.2	
Liner material density	kg/ccm	9.5E-04	HDPE
Liner mass	kg	3.1	
Tank Wall Material Calculation			
Total Volume of tank wall material	ccm	1.472E+04	
Tank Wall material density	kg/ccm	1.61E-03	Carbon fiber composite (T700S)
Tank wall mass	kg	23.7	
Summary			
Liner Mass	kg	3.1	
Composite mass	kg	23.7	
Total mass	kg	26.9	Total Tank Mass
Tank Efficiency			
Gravimetric	L/kg	3.91	Note this value does not include hydrogen, adsorption material, balance of plant, etc.
Tank Cost			
HDPE material cost	$/kg	2.06	Raw material cost estimate based on representative 2007 prices.
Carbon fiber composite material cost	$/kg	30.65	Raw material cost estimate based on representative 2007 prices.
liner cost	$	6.48	
composite cost	$	727.04	
total tank cost	$	733.52	Total of composite and HDPE only, manufacturing and all other costs not included

- WEB Team: T. Motyka, M. Thornton, J. Cosgrove, J-M. Passini, J. Ortman
- β-test Team: R. Bowman (ORNL), D. Papadias (ANL), and T. Johnson (SNL)

HSECoE

Models on the WEB Schedule

MH Acceptability Envelope	**Hardy/SRNL**	**complete**
MH Finite Element Model	**Hardy/SRNL**	**complete**
Tank Volume/Cost Model	**Simmons/PNNL**	**complete**
MH Framework Model	**Pasini/UTRC**	**complete**
CH Framework Model	**Brooks/PNNL**	**6/2014**
AD Framework Model	**Tamburello/SRNL**	**9/2014**
AD Finite Element Model	**Hardy/SRNL**	**3/2015**

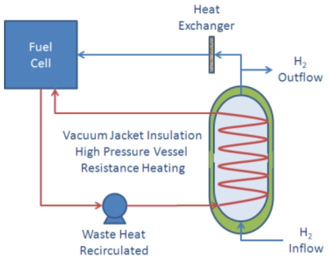
Where are we going in Phase 3: Technology Readiness Levels

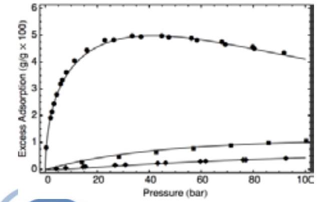
Materials Based Hydrogen Storage Systems for Automotive Applications

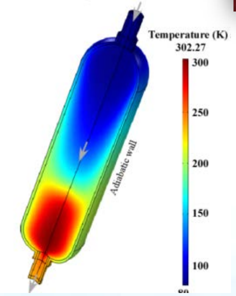
Materials CoEs

HSECoE

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Basic Technology Research		Research to Prove Feasibility	Technology Development		Technology Demonstration	System Commissioning		System Operation
Basic Principals	**Concept Formulation**	**Characteristic Proof of Concept**	**System Validation in Laboratory Environment**	**System Validation in Relevant Environment**	**Pilot Scale System Validation**	**Full Scale System Validation**	**Actual System Qualification**	**Actual System Operation**







Where are we going in Phase 3: Technology Readiness Levels

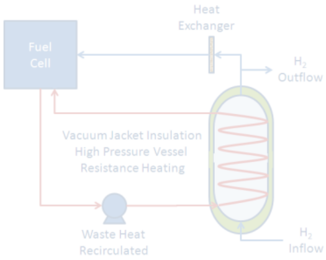
Materials Base orage Systems
for Aut ations

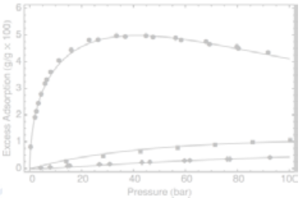
Materials CoEs

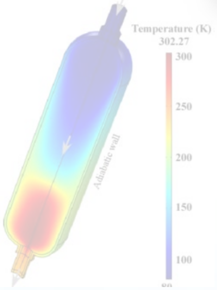
HSECoE

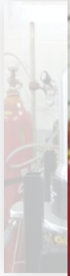
TRL 4
System Validation in Laboratory Environment

TRL 1	TRL 2	TRL 3			L 6	TRL 7	TRL 8	TRL 9
Basic Technology Research		Research to Prove Feasibility			nology nstration	System Commissioning		System Operation
Basic Principals	Concept Formulation	Characteristic Proof of Concept	System Validation in Laboratory Envi	System Validation in Relevant	Pilot Scale System Validation	Full Scale System Validation	Actual System Qualification	Actual System Operation





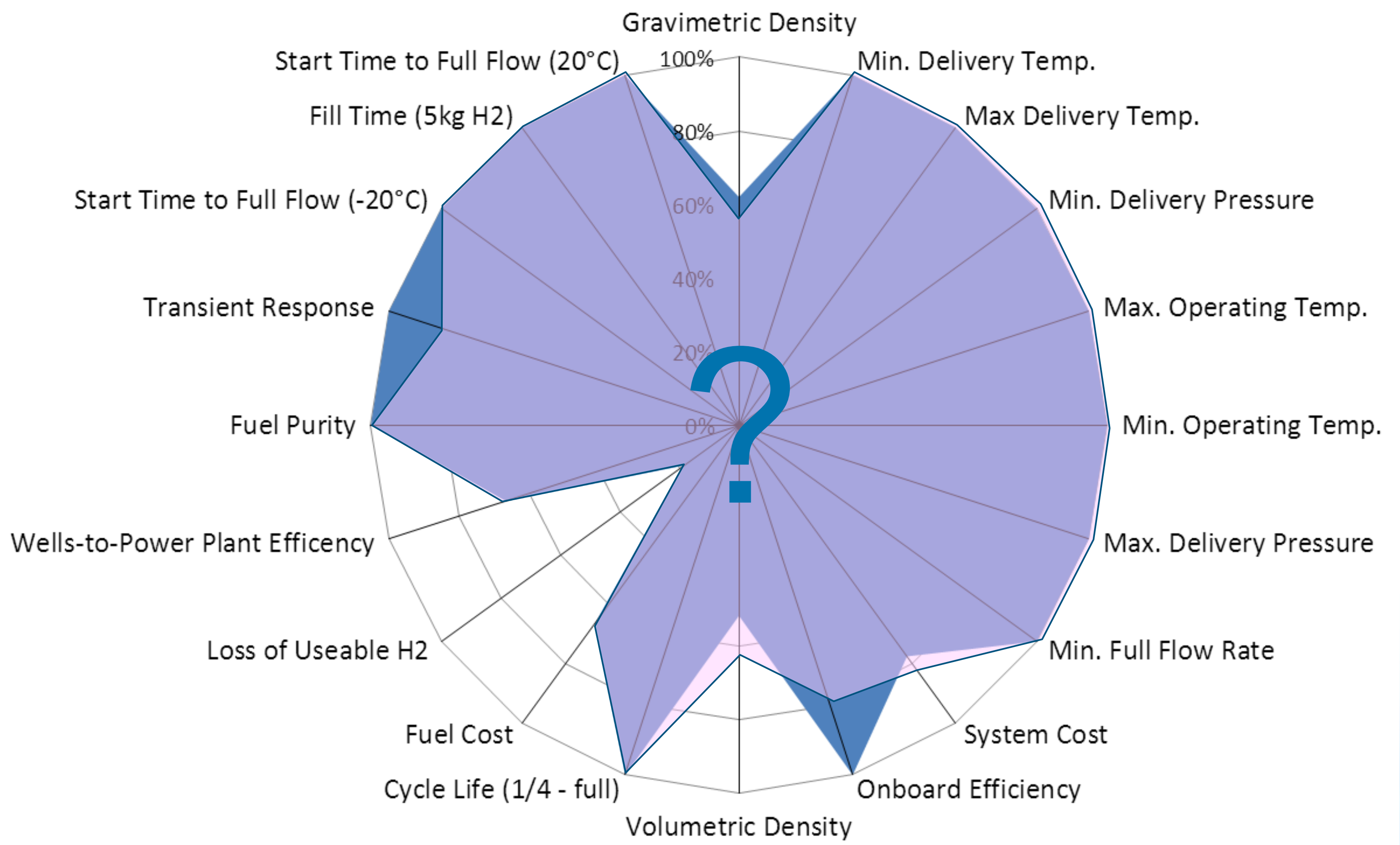




Preliminary vs. Demonstrated Spider Chart

Why Phase 3 demonstration is critical in model validation

MATI Adsorbent Storage System (2012)



LANDMARK Innovations

What has the Center done to change the way we look at hydrogen storage?

- **Overall**
  - Technical target prioritization
  - Development of models which integrate the storage system, fuel cell and vehicle drive cycles
- **Metal Hydrides**
  - Acceptability envelope
  - Microchannel catalytic burner
- **Chemical Hydrogen Storage**
  - Storage material requirements
  - Auger reactor for slurries and helical reactor for neat liquids
  - Demonstrated 60wt.% alane slurry reactor
- **Adsorbents**
  - LN2 tank cooling strategy
  - Low cost HX Flow Through Design
  - Combined MOF Compaction/ Augmentation
  - Microchannel HX in compacted media design

Technical Lessons Learned

Metal Hydride System: *End of Phase 1*

- **Parallel materials development effort needed**
- **Less effort should have been spent on evaluating and down selecting candidate materials during Phase 1**
- **Efforts should have been focused on radically improve the efficiency and design of heat exchangers and other BoP components.**

Adsorbent System

- **Heat and mass transfer modeling necessary to understand system**
- **Model validation necessary to fine tune models and gain confidence in model accuracy**
- **Forecourt concerns which impact fuel cost are important, and should have been included in analyses**
- **Prioritizing technical targets important in evaluating approaches to their mitigation**

Technical Lessons Learned

Chemical Hydrogen Storage

- **System volumetric capacity is a key benefit with chemical hydrogen storage materials.**
- **AB slurries are unusable in a silicon oil due to coagulating of AB**
- **Neat liquid phase chemical hydrogen storage materials around 8 wt. % hydrogen required to meet DoE 2017 targets.**
- **Solid or slurry phase chemical hydrogen materials requiring off-board regeneration are unlikely commercial candidates without innovations in materials handling and system durability.**
- **Compact and inexpensive reactor designs accommodating gas evolution two phase flow will require additional development.**
- **It is very difficult to validated chemical hydrogen storage system models because the complexity of the physical phenomena.**

Lessons Learned Programmatically

- **Organize the team functionally to distribute responsibility and gain ownership by the members.**
  - Assignment of Technology Area Leads to lead model development in Phase 1
  - Assignment of System Architects to move system concept forward into Phase 2
- **Set up clear communications networks to facilitate data and information flow.**
  - IP Agreement
  - F2F Meetings
  - SharePoint Site
  - Monthly Telecons
  - Safety and risk issues discussed regularly

Lessons Learned Programmatically (cont.)

- **Milestones**
  - Negotiate clear milestones with partners for each individual tasks needing to be accomplished and track milestone accomplishment.
  - **Facilitate discussion and face to face meetings early after identifying milestone may be in jeopardy to correct situation**
  - Down select from multiple technical approaches as soon as possible
  - Readjust partner responsibility after down select decisions
- **Perform FMEA early and often to stimulate nonlinear thinking**
- **Disseminate findings in a manner that the stakeholders can understand and use.**
- **Judiciously evaluate and selectively implement stakeholder guidance**

Reviewers Comments

“This is a very successful and well run project that should not end in 2014.”

“If the DOE Hydrogen and Fuel Cells Program is going to keep funding research on hydrogen storage, it should consider a “reinvention” of the HSECoE into a new entity that keeps the core HSECoE capabilities intact”

- **The program has been extended to run through fiscal year 2015 with current funding.**

“DOE and the Center should carefully discuss the scope of Phase III activities.”

- **Phase III planning and consultation with DoE was extensive with the ultimate decision made to focus efforts on the adsorption system utilizing the two heat exchanger systems which show the most promise and diversity in approaching the technical targets.**

“A clear and detailed statement of the specific technical challenges and plans for addressing those challenges should be included in the plans for the Phase III effort.”

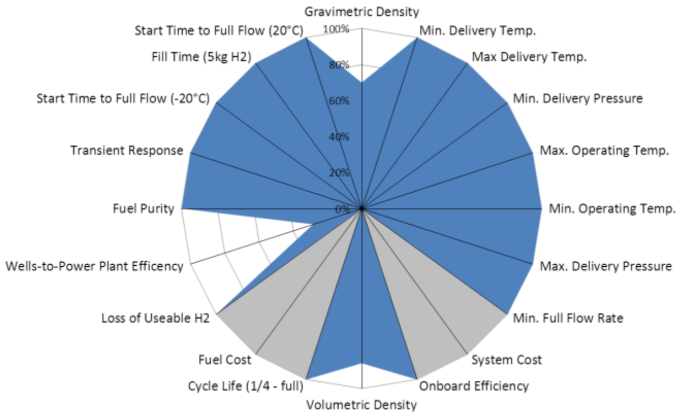
- **A clearer and more concise description of the technical hurdles and approaches has been given in this and the following partner contributions.**

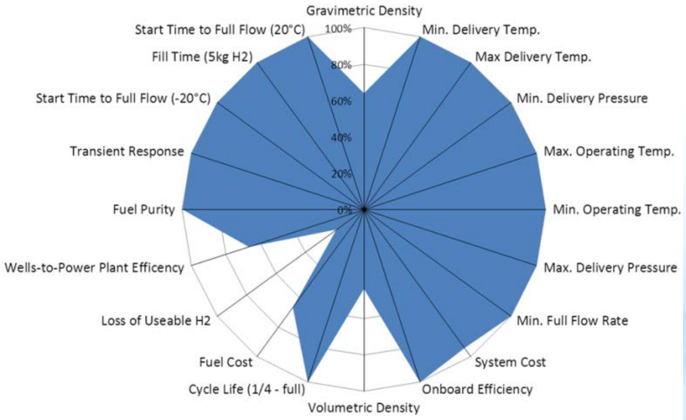
“The signature problem that may ultimately limit overall project success is that no single material that meets all of the DOE targets has been identified. Consequently, engineering systems based on sub-optimal materials are being developed.”

- **It is the objective of the HSECoE to model, design and build the best systems with the materials available and to project what materials characteristics are needed to achieve the all of the DoE technical targets.**

Summary

- **Chemical Systems**
  - Limited in gravimetric density and efficiency due to materials limitations.
  - AB Slurry could not be pumped while Alane slurry was successfully demonstrated using a auger flow through reactor.
  - High fuel cost resulting from recycle inefficiencies limits potential for Chemical Hydrogen Storage materials.
- **Adsorption Systems**
  - Volumetric density addressed with microchannel MATI HX Design
  - Charge time addressed with flow through cooling and independent LN2 tank cooling
  - Low pressure adsorption systems hold best opportunity to meet DoE Technical Targets.

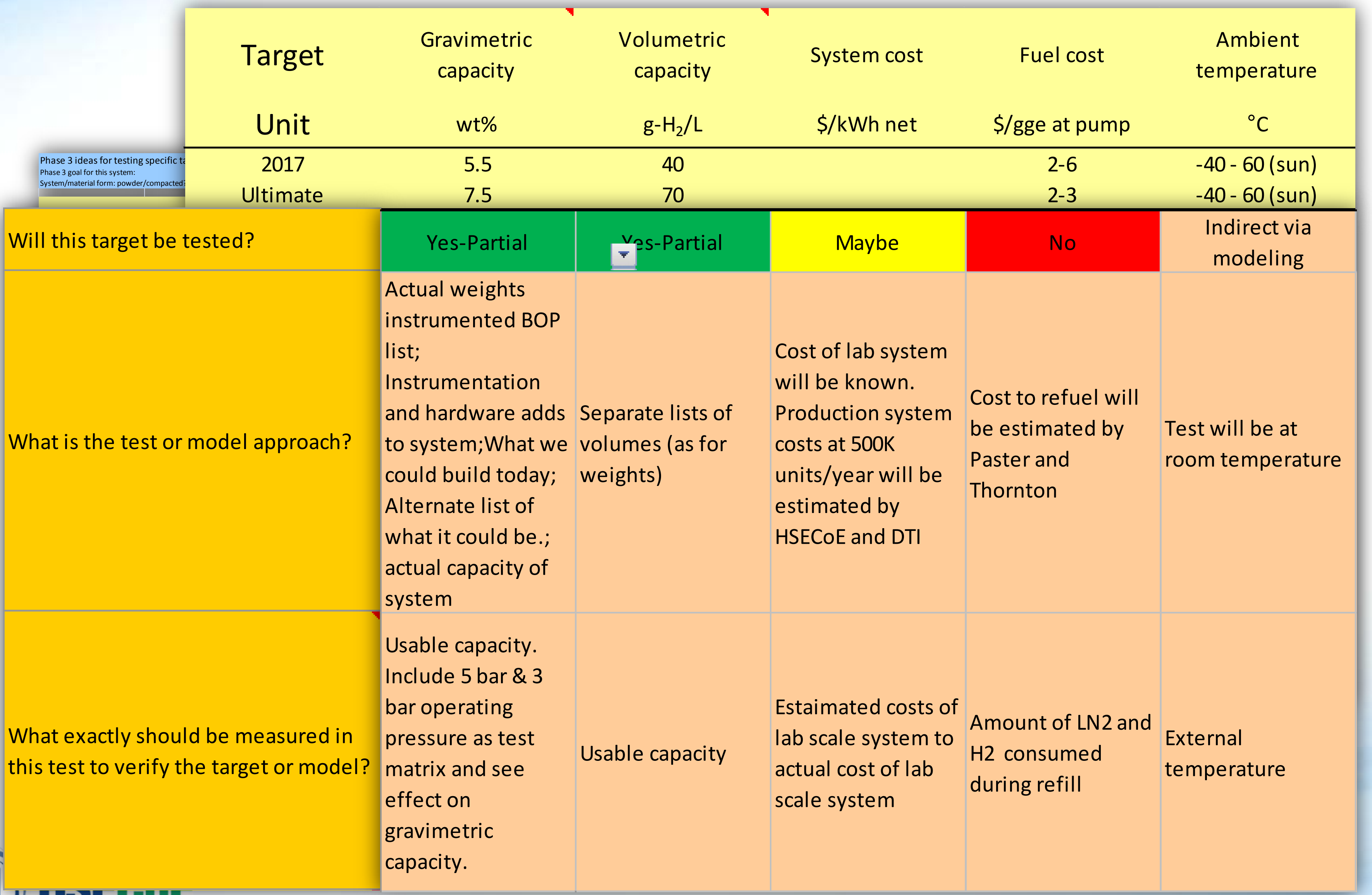

Chemical System


Adsorbent System

Technical Back-Up Slides

Accomplishment

System Test Matrixes

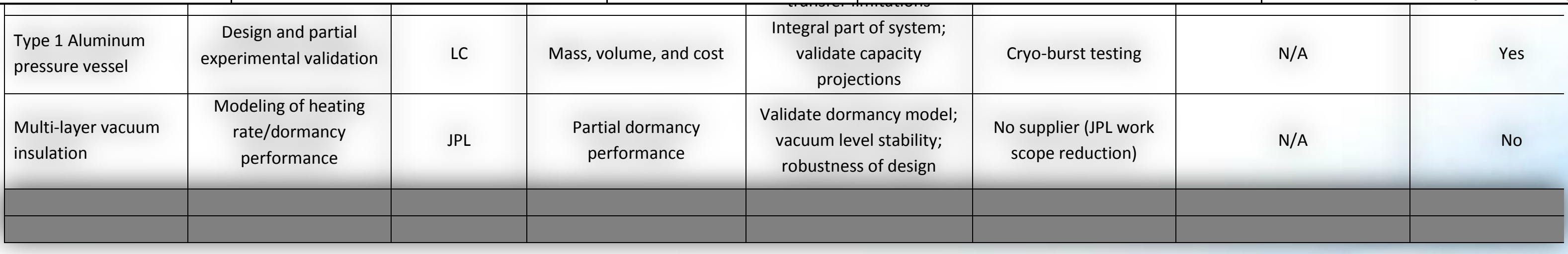


Phase 3 ideas for testing specific ta
Phase 3 goal for this system:
System/material form: powder/compacted

Target	Gravimetric capacity	Volumetric capacity	System cost	Fuel cost	Ambient temperature
Unit	wt%	g-H_2/L	$/kWh net	$/gge at pump	°C
2017	5.5	40		2-6	-40 - 60 (sun)
Ultimate	7.5	70		2-3	-40 - 60 (sun)
Will this target be tested?	Yes-Partial	Yes-Partial	Maybe	No	Indirect via modeling
What is the test or model approach?	Actual weights instrumented BOP list; Instrumentation and hardware adds to system;What we could build today; Alternate list of what it could be.; actual capacity of system	Separate lists of volumes (as for weights)	Cost of lab system will be known. Production system costs at 500K units/year will be estimated by HSECoE and DTI	Cost to refuel will be estimated by Paster and Thornton	Test will be at room temperature
What exactly should be measured in this test to verify the target or model?	Usable capacity. Include 5 bar & 3 bar operating pressure as test matrix and see effect on gravimetric capacity.	Usable capacity	Estaimated costs of lab scale system to actual cost of lab scale system	Amount of LN2 and H2 consumed during refill	External temperature

System Component Specification

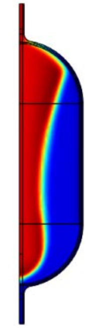
Component	Assumed Validation in Phase II		Responsible Design Organization	What can be validated with modeling rather than experimental work?
Internal Heat Exchanger: **HexCell Resistance Heater with Flow-Through Cooling**	Modeling and partial experimental validation of individual components/capabilities	SRNL / UQTR	1st-order thermal behavior (already completed).	Simple, low-cost design; Verify capability for rapid cooling: dynamic behavior (such as channeling) can only be evaluated experimentally
Cryo-Adsorbent Material: **Powder MOF-5**	Modeling and experimental validation	SRNL / UQTR / Ford (BASF)	Theoretical H2 uptake; heat transfer (partial)	Integral part of system; validate capacity projections; Quantify effects due to bed inhomogeneities (non-uniform packing)



Type 1 Aluminum pressure vessel	Design and partial experimental validation	LC	Mass, volume, and cost	Integral part of system; validate capacity projections	Cryo-burst testing	N/A	Yes
Multi-layer vacuum insulation	Modeling of heating rate/dormancy performance	JPL	Partial dormancy performance	Validate dormancy model; vacuum level stability; robustness of design	No supplier (JPL work scope reduction)	N/A	No

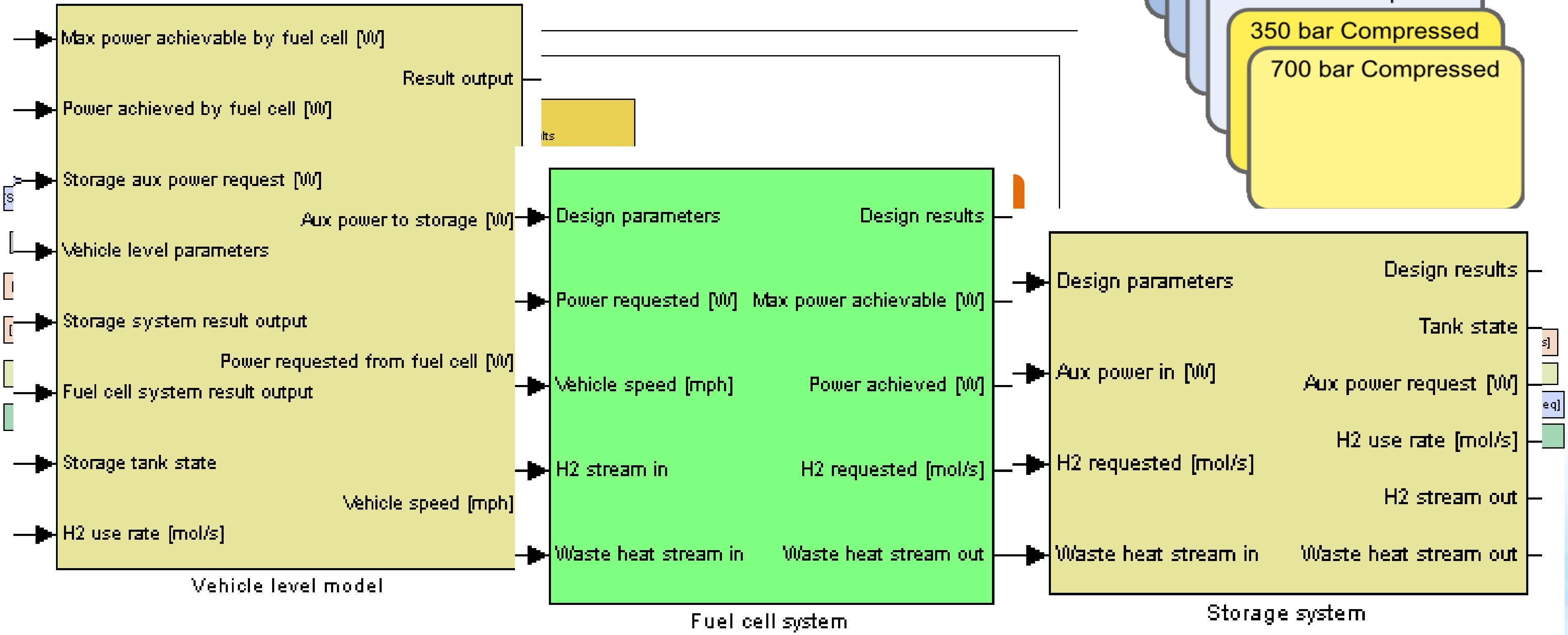
Integrated Model Framework

$$n_{ex} = n_{\max} \exp\left[-\left[\frac{RT}{\alpha + \beta T} \right]^2 \ln^2\left(\frac{P_0}{P} \right) \right] - \rho_g V_a$$



SRNL 200 bar
AX-21
Flow-Through

- UTRC $NaAlH_4$ Powder
  - H_2 requested
  - H_2 stream out
- UTRC $NaAlH_4$ Pellets
- UTRC/SRNL 1:1 Li-Mg-N-H
- GM $NaAlH_4$
- GM/SRNL/JPL AX-21
- PNNL Solid AB
- PNNL/LANL Liquid AB
- 350 bar Compressed
- 700 bar Compressed



Addressing DOE's Technical Targets

Target	2017 Value	Units	Measurement	Additional_Measurements
Gravimetric Capacity	0.055	g_{H2} / g_{sys}	Total Mass of Gas Stored	Total Mass of System (all equipment, tubing, tank, etc.)
Volumetric Capacity	40	g_{H2} / L_{sys}	Total Mass of Gas Stored	Total Volume of System (all equipment, tubing, tank, etc.)
System Cost	12	$/kWh	Total Mass of Gas Stored	Total cost of the full experimental set-up
Fuel Cost	2-6	$/gge	Not Measured at SRNL/OSU	
Ambient Temperature	-40 - 60 (sun)	°C	Room Temperature	
Min/Max Delivery Temperature	-40 - 85	°C	H_2 Outlet Temperature	
Operational cycle life (1/4 tank to full)	1500	cycles	Not Measured at SRNL/OSU	
Min/Max Delivery Pressure	5 / 12 bar	bar	H_2 Outlet Pressure	
On-board efficiency	90	%	Energy used to release the hydrogen (converted into H_2)	
Wells-to-Power Plant Efficiency	60	%	Energy used to refuel / reload the hydrogen (converted into H_2)	
System Fill Rate	1.5	kg_{H2} / min	Time to completely fill the tank (function of operating conditions)	Scaling this to our 2-Liter tank, it would only be a 4 second fill for the ~100 grams of H2
Min Full Flow Rate	0.02	(g/s)/kW	Not Measured at SRNL/OSU	
Start time to full flow rate (20 °C)	5	s	H_2 Flow Rate?	Time to achieve full flow rate at start-up (no "hold time" listed)
Start time to full flow rate (-20 °C)	15	s	Not Measured at SRNL/OSU	
Transient Response (10%-90% & 90%-0%)	0.75	s	H_2 Flow Rate?	Time to achieve desired response in flow rate ("driving" response to rapidly accelerate and stop)
Fuel Purity (SAE J2719 & ISO/PDTS 14687-2)	99.97	%H_2	Gas composition (via mass spec or RGA)	
Permeation & Leakage		Scch/h	Not Measured at SRNL/OSU	
Toxicity			Not Measured at SRNL/OSU	Dust cloud ignition at BASF and/or UTRC
Safety			Not Measured	Design for applicable safety standards
Loss of usable H_2	0.05	(g/h)/$kg_{H2,stored}$	Not Measured at SRNL/OSU	Simplified thermos bottle + MLVI system TBD