Hydrogen Storage Engineering
CENTER OF EXCELLENCE

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SRNL
SAVANNAH RIVER NATIONAL LABORATORY

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Project ID# ST004

Overview

Timeline

- Start: February 1, 2009
- End: July 31, 2014
- 55% Complete (as of 3/31/12)

Budget

- Total Center Funding:
  - DOE Share: $ 36,232,765
  - Contractor Share: $ 3,591,709
  - FY ’11 Funding: $ 5,144,156
  - FY ’12 Funding: $ 5,930,000
- Prog. Mgmt. Funding
  - FY ’11: $ 400,000
  - FY ’12: $ 400,000

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

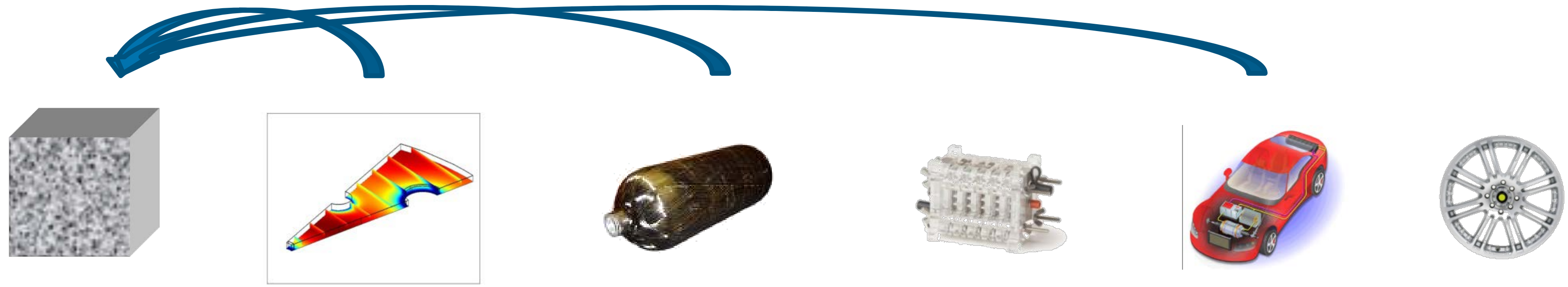
Partners

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
California Institute of Technology
Michigan
OSU Oregon State University
HRI UQTR
Ford
GM
United Technologies Research Center
BASF The Chemical Company
Lincoln Composites, A Member of Hexagon Composites Group

HSECoE

Why Perform Materials Development and System Engineering in Parallel?

continuous feedback with system design indicating 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

HSECoE Objectives

- **Develop materials based hydrogen storage systems for On-Board Hydrogen Storage for Light Duty Vehicles**
  - Develop **system models** that lend insight into overall fuel cycle efficiency.
  - Compile all relevant **materials data** for candidate storage media and define future data requirements.
  - Using systems engineering concepts, **design innovative system architectures** for **metal hydride, chemical, and sorption materials-based storage technologies** with the potential to meet DOE performance and cost targets.
  - Design components and experimental test fixtures to **evaluate the innovative storage devices** and subsystem design concepts, validate model predictions, and improve both component design and predictive capability.
  - Design, fabricate, test, and decommission **subscale prototype systems** of selected materials-based technologies.

Phased Approach

Phase I:
System Requirements & Novel Concepts

Phase II:
Novel Concept Modeling Design & Evaluation

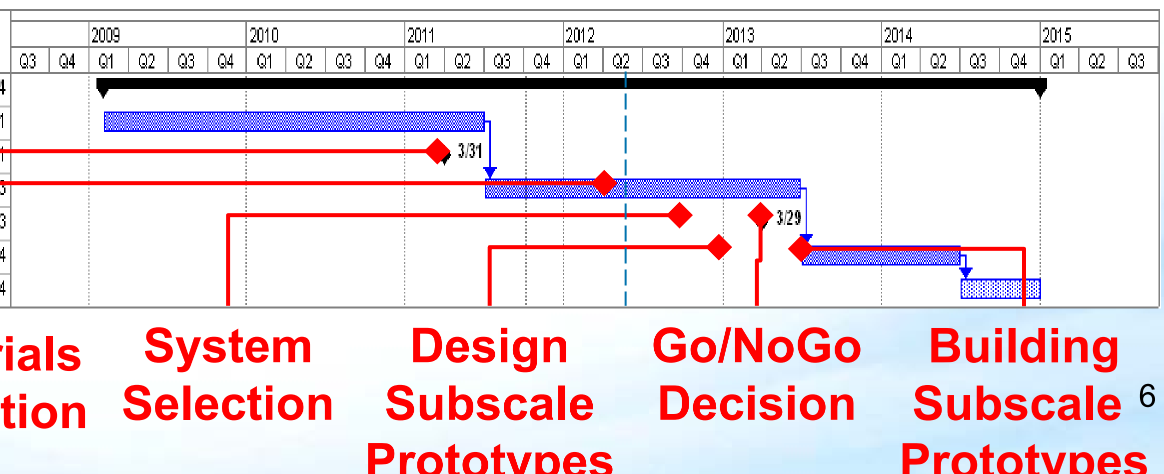
Phase III:
Sub-Scale Prototype Construction, Test and Evaluation

- **Where are 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?**
  - Component development
  - 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: 5.5 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, 2014 ⇨ *12/31/14?*

ID	Task Name	Start	Finish
1	**Hydrogen Storage Engineering Center of Excellence**	**Mon 2/2/09**	**Wed 12/31/14**
2	**Phase 1 System Requirements & Novel Concepts**	Mon 2/2/09	Thu 6/30/11
3	Phase 2 Go/No-Go	Thu 3/31/11	Thu 3/31/11
4	**Phase 2 Novel Concept Modeling, Design and Evaluation**	Fri 7/1/11	Fri 6/28/13
5	Phase 3 Go/No-Go	Fri 3/29/13	Fri 3/29/13
6	**Phase 3 Subscale Prototype Construction, Testing & Evaluation**	Mon 7/1/13	Mon 6/30/14
7	Phase 3 No Cost Extension	Tue 7/1/14	Wed 12/31/14

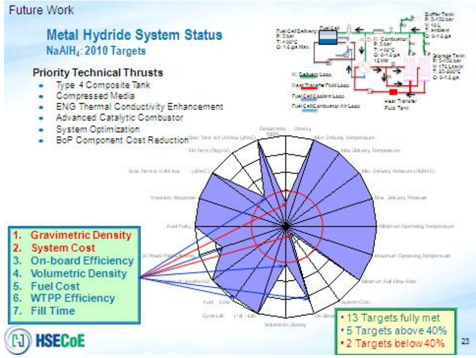


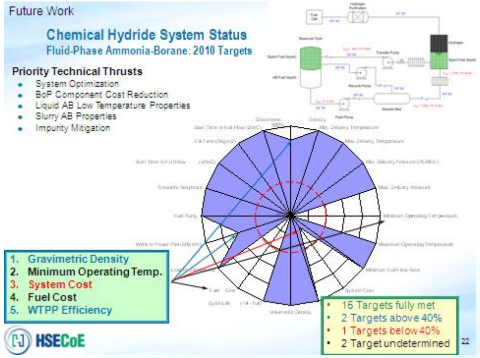
Phase 1-2 Transition

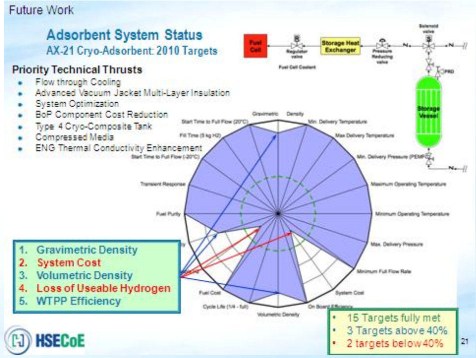
Overviewed Integrated System Model and its Role in Target Achievement

Prepared Summaries of Status for Metal Hydride, Chemical Hydride and Adsorbent Systems

- Current status vs targets
- Identification of critical technical barriers
- Identification of potential solutions to barriers
- Summary of projected system performance vs targets







Outcomes of Phase 1-2 Transition

- **Continued Work**

Adsorbent-Based Hydrogen Storage Systems

- Increasing compaction of the sorbent materials
- Demonstration of improved thermal conduction within the sorbent
- Thermal isolation of the inner storage bed.
- Flow through cooling designs must be accompanied with total cooling requirements

Liquid-Phase Chemical Hydrogen Storage Materials (including liquids, solutions and/or slurries)

- Development and validation of the critical components for baseline ammonia borane solutions
  - Thermal management within the reaction chamber,
  - Gas-liquid phase separations, and the
  - Hydrogen purification train be emphasized for the baseline ammonia borane solutions.
- Endothermic release material (e.g., AlH_3, alane) must be modeled

Outcomes of Phase 1-2 Transition

- **Discontinued Work**

Solid-Phase Chemical Hydrogen Storage Materials

- Material transport becomes a major challenge for this class of material.
- A reliable process for loading/unloading solids from the onboard storage vessel, nor transporting it through an onboard reactor, have been identified.

Work on Reversible Metal Hydrides

- Analyses for highly optimized vessel configurations that could adequately manage thermal and mass flow rates needed for reversible onboard hydrogen storage to meet the DOE performance targets imposed requirements **substantially exceeding the properties and behavior of any single, currently existing candidate hydride.**
- The necessary combination of gravimetric and volumetric capacities, reaction kinetics, thermodynamics properties, and reversibility have not been found simultaneously in any hydride investigated to date.
- Novel engineering solutions that will allow any currently known hydride, when incorporated into a complete system, have not been identified.

HSECoE Phase 3 Go/NoGo Milestones

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Phase 2 System Status

Chemical Hydrides

Target	Units	2015 DOE Goal (System)	Phase 1 HSECoE Baseline (System): Phase 1 HSECoE Baseline (Material) (3/31/2011)	Phase 1 HSECoE Basline (BOP only)	Phase 1 HSECoE Baseline (System)	Phase 2 HSECoE Go/No-Go Targets: Phase 2 HSECoE Targets (Material) (3/31/2013)	Phase 2 HSECoE Targets (BOP only)	Phase 2 HSECoE Targets (System)
Gravametric Capacity	kg H2/kg system	0.055	0.076	0.092	0.042	0.076	0.109	0.045
mass	*liters*	*102*			*133*			*124*
Volumetric Capacity	kg H2/L system	0.04	0.074	0.077	0.039	0.074	0.102	0.043
volume	*kg*	*140*			*144*			*130*
System Cost *	$/kWh net	6		25.6	25.6		25.6	25.6
	$	*480*						
Fuel Cost	$/gge at pump	2-6			?			45
Min Operating Temp	°C	-40			?			0
Max Operating Temp	°C	60			50			50
Min Delivery Temp	°C	-40			-40			-40
Max Delivery Temp	°C	85			85			85
Cycle Life	cycles	1500			1000			1000
Min Delivery Pressure	bar	5			5			5
Max Delivery Pressure	bar	12			12			12
Onboard Efficiency	%	90			97			97
Well to Power Plant Efficiency	%	60			37			37
System Fill Time	min	3.3			2.7			2.7
Min Full Flow Rate	(g/s/kW)	0.02			0.02			0.02
	g/s	*1.6*			*1.6*			*1.6*
Start Time to Full Flow (20°C)	sec	5			1			1
Start Time to Full Flow (-20°C)	sec	15			1			1
Transient Response	sec	0.75			0.49			0.49
Fuel Purity	%H2	99.97			99.97			99.99
Permeation, Toxicity, Safety	Scc/h	Meets or Exceeds Standards			s			s
Loss of Useable Hydrogen	(g/h)/kg H2 stored	0.05			0.1			0.1

System Desing Specifics

		Phase 1	Phase 2
LANL, PNNL, SRNL	Media	Liquid AB at 50wt%	Liquid AB at 65wt%
PNNL	Tank	Bladder Tank	Bladder Tank
LANL	Reactor	Flow Through Reactor	Flow Through Reactor
PNNL	System Design		
	BoP		
PNNL	Pumps	Feed/Recycle/Transfer Pumps	Feed/Recycle/Transfer Pumps
UTRC	Heat Exchanger		Heat Exchanger mass and volume cut
UTRC	GLS	Gas\Liquid Seperator	Gas\Liquid Seperator
UTRC	Purification	Purification	Hydrogen Purification mass and volume

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Phase 2 System Status

Adsorbants

Target	Units	2017 DOE Goal (System)	Phase 1 HSECoE Baseline (System): Phase 1 HSECoE Baseline (Material) (3/31/2011)	Phase 1 HSECoE Basline (BOP only)	Phase 1 HSECoE Baseline (System)	Phase 2 HSECoE Go/No-Go Targets: Phase 2 HSECoE Targets (Material) (3/31/2013)	Phase 2 HSECoE Targets (BOP only)	Phase 2 HSECoE Targets (System)
Gravametric Capacity	kg H2/kg system	0.055	0.15	0.05	0.038	0.15	0.05	0.045
mass	*kg*	*102*			*147*			*124*
Volumetric Capacity	kg H2/L system	0.04	0.042	0.043	0.022	0.045	0.074	0.028
Volumetric	*liters*	*140*			*255*			*200*
System Cost	$/kWh net	6	3.5	15.0	18.5	3.5	10.3	13.8
	$	*1,119*			*3,450*			*2,573*
Fuel Cost	$/gge at pump	2-6			4.89			4.89
Min Operating Temp	°C	-40			-30			-40
Max Operating Temp	°C	60			50			60
Min Delivery Temp	°C	-40			-40			-40
Max Delivery Temp	°C	85			85			85
Cycle Life	Cycles	1500			1000			1500
Min Delivery Pressure	bar	5			5			5
Max Delivery Pressure	bar	12			12			12
Onboard Efficiency	%	90			96			92
Well to Power Plant Efficiency	%	60			40.1			40.1
System Fill Time	min	3.3			3.3			3.3
Min Full Flow Rate	(g/s/kW)	0.02			0.02			0.02
	g/s	*1.6*			*1.6*			*1.6*
Start Time to Full Flow (20°C)	sec	5			5			5
Start Time to Full Flow (-20°C)	sec	15			15			15
Transient Response	sec	0.75			0.75			0.75
Fuel Purity	%H2	99.97			99.97			99.99
Permeation, Toxicity, Safety	Scc/h	Meets or Exceeds Standards			s			s
Loss of Useable Hydrogen	(g/h)/kg H2 stored	0.05			0.44			0.44

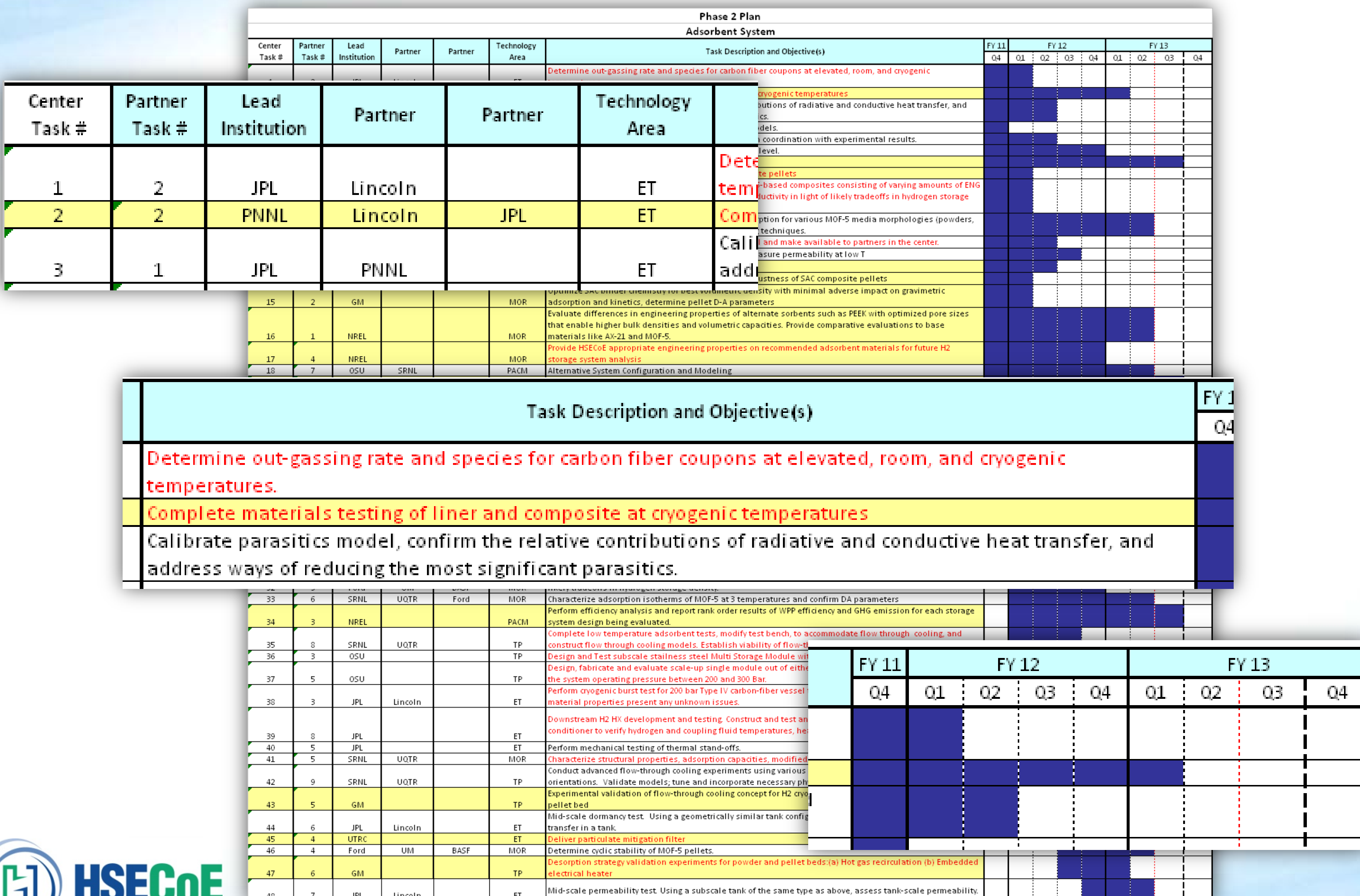
System Desing Specifics

		Phase 1	Phase 2
JPL	Insultation	MLVJ Insulation	MLVJ Insulation
LC	Tank	Type III 200 bar tank	Type IV 150 bar tank
Ford	Media	Uncompacted Super Activated Carbon	Compacted MOF-5 w/ density 0.3
SRNL, GM	Internal HX	Flow thorugh Cooling	Flow thorugh Cooling
SRNL,OSU	External HX	PEMFC Fluid Coupled HX Loop	PEMFC Fluid Coupled HX Loop
	Initial Conditions		Initial conditions: 140 bar, 80 K
	H2 input		Final/Refill conditions: ~3 bar, ~160

HSECoE

Approach

Phase 2 Gantt Chart

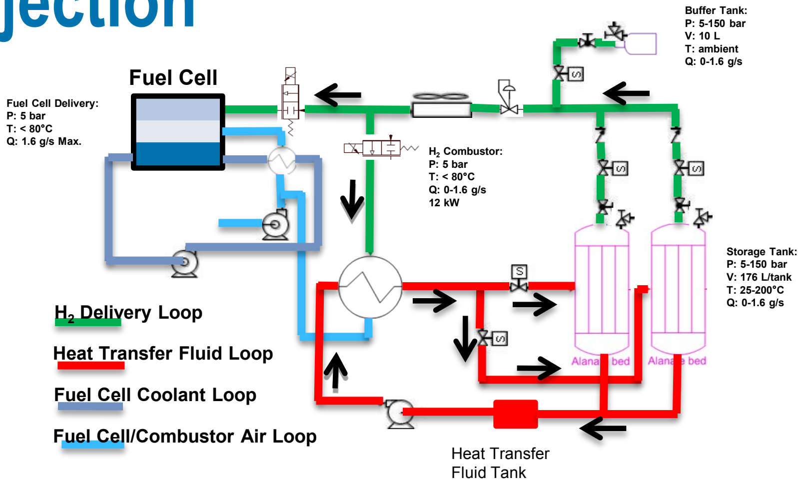


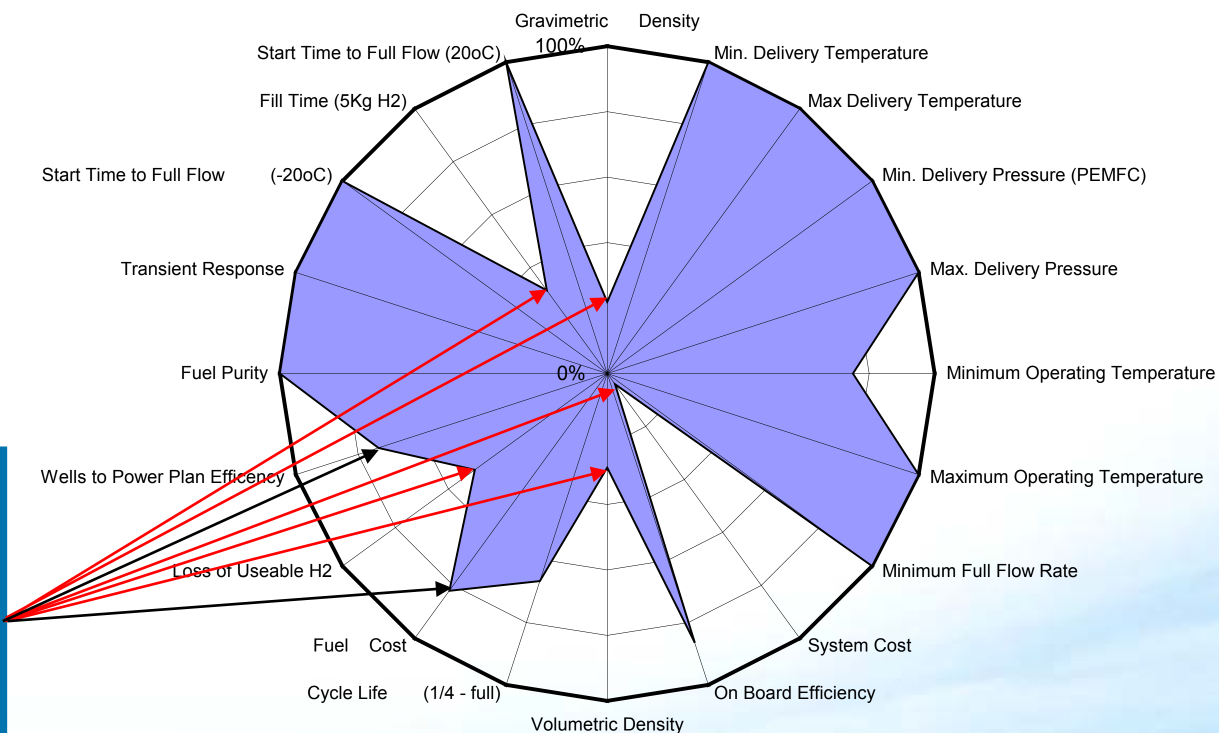
HSECoE

P1/2 Metal Hydride System Projection

2017 Targets

- Dual Vessel Sodium Alanate Design (w. 4 mol%$TiCl_3$ & 5 wt% ENG)
- GM1 Design: fin and tube heat exchanger optimized to meet 10.5 min refueling time at the expense of wt %
- 2 Type 3 composite tanks with SS liners
- System includes a 10 l buffer tank and a 12 kW H_2 combustor





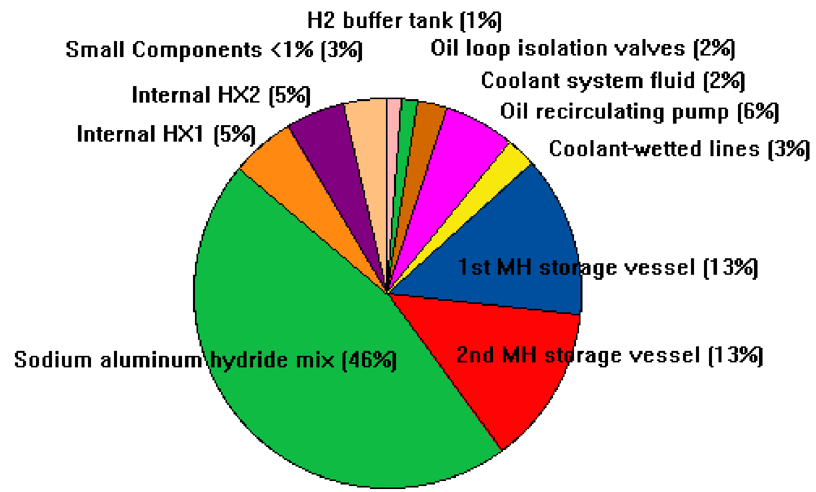
1. **Gravimetric Density**
2. **System Cost**
3. **Onboard Efficiency**
4. **Volumetric Density**
5. **Fill Time**
6. Fuel Cost

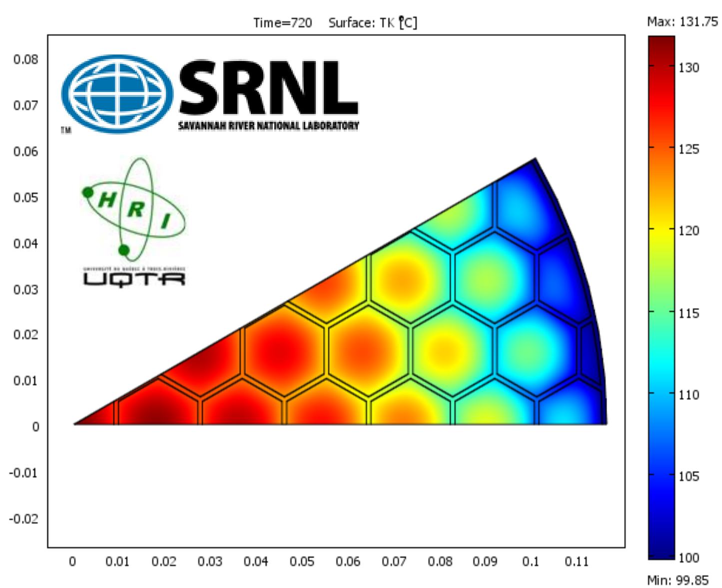
MH Barriers and Approaches

- **Gravimetric & Volumetric Density**
  - **New materials discovery**
  - **Improved Tank Design**
  - **Low mass BoP Components**
  - **Improved Internal HX**
    - Media Thermal Conductivity
    - Internal HX Design

MH System Gravimetric BOP

System mass 457.5 kg





Improved Internal HX Concept

$NaAlH_4$ systems

as-milled

discharged

Compacted Media

MH Barriers and Approaches

- **Fill Time**
  - Improved Internal HX
  - Enhanced Media Thermal Conductivity

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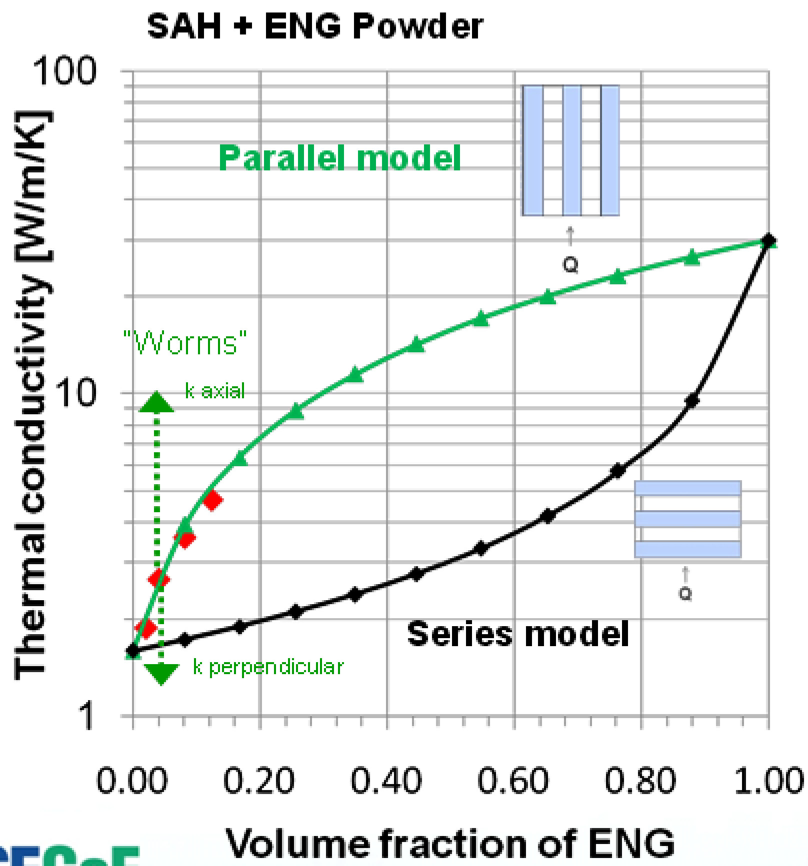

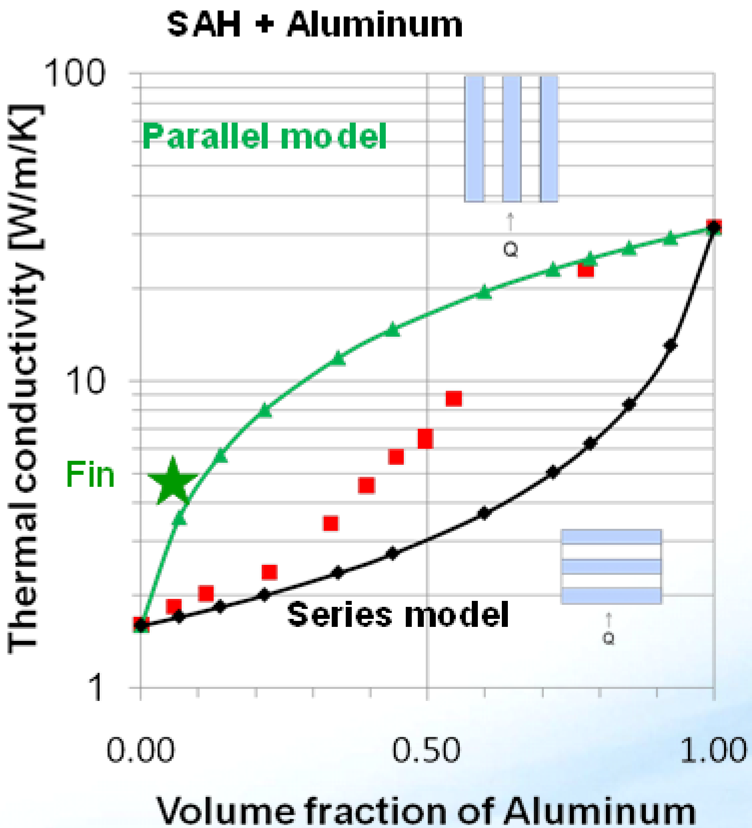

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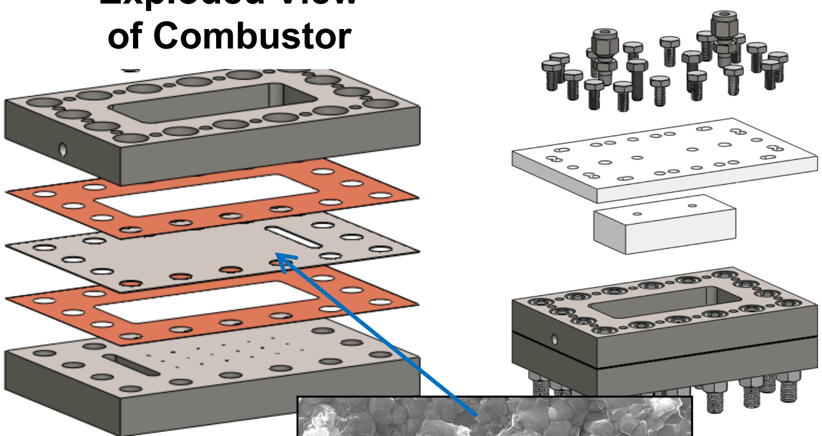
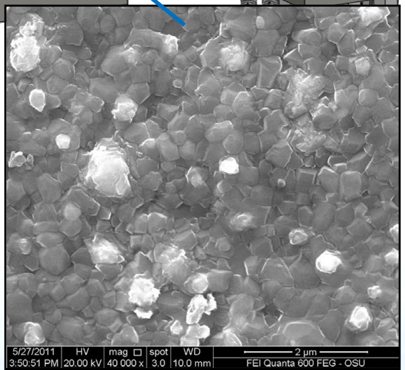
MH Barriers and Approach

- **On Board Efficiency**
  - Improved Catalytic Combustor

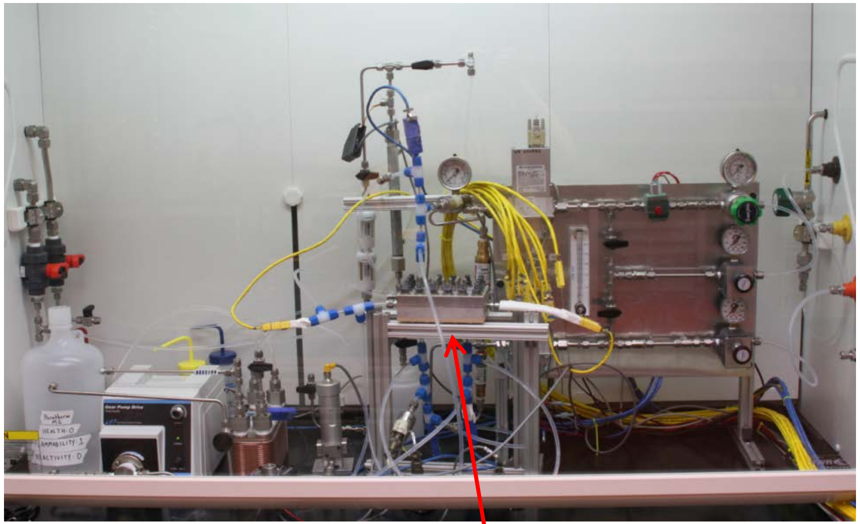
Microchannel Catalytic Combustor >96%Efficency

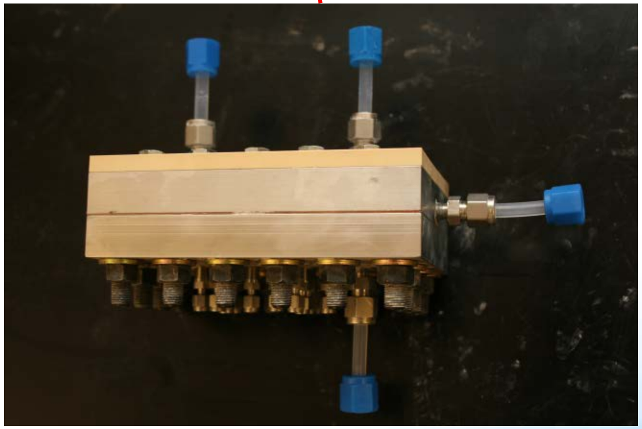
Exploded View of Combustor





Wet Deposited Pt Catalyst





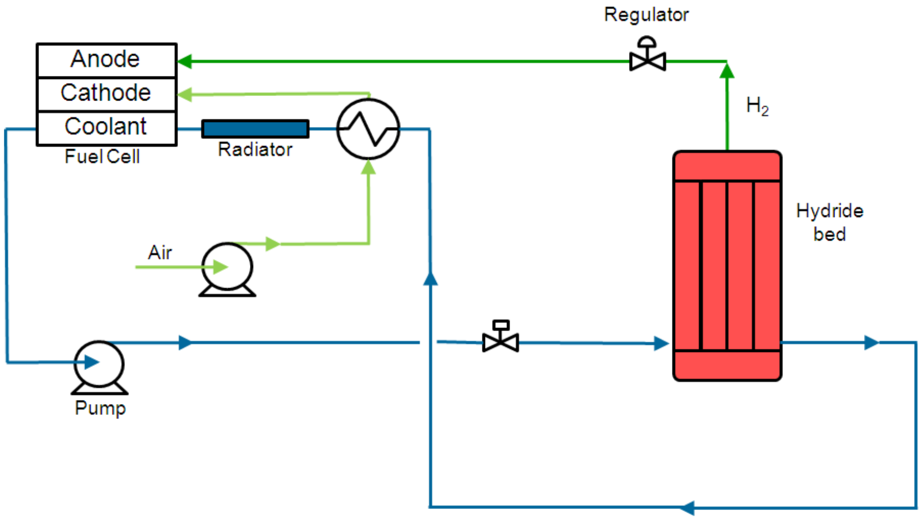
Assembled Experimental Facility

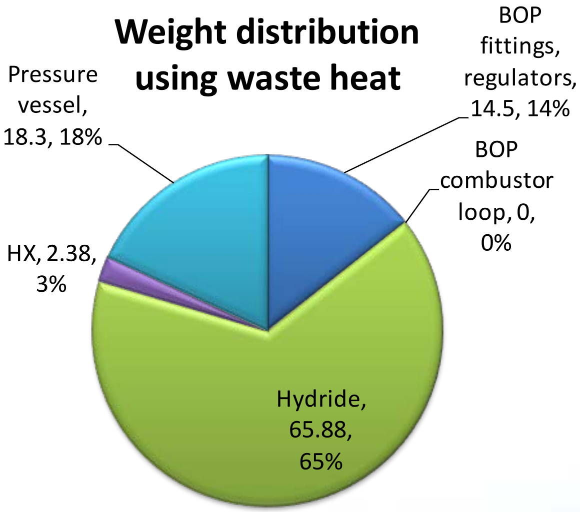
V. Narayanan, D. Haley, M. Ghazvini & K. Drost

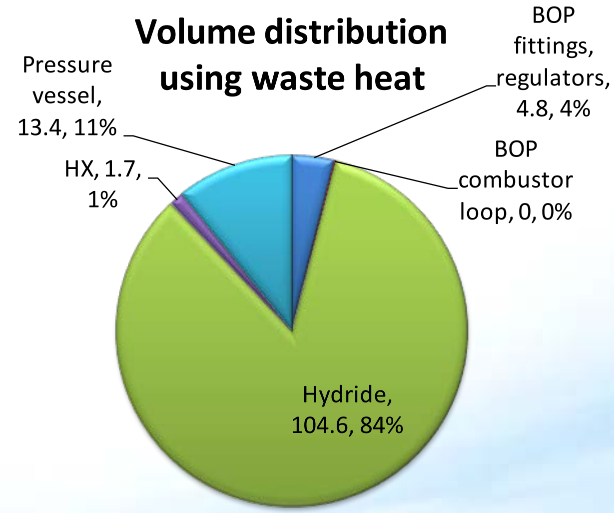
Accomplishment

Metal Hydride System 1: Use Waste Heat Only

- Attributes
  - Very simple system.
  - Fuel cell waste heat stream used
  - No separate buffer tank: use H_2 in pores.
- Media Characteristics
  - $\Delta H = 27$ kJ/mol-H_2 ($T_{5\ bar} = 20.7\ ^oC$)
  - 11 wt.% material capacity
- Results
  - Satisfies all targets.
  - On-board efficiency: ~100%
  - System: 101 kg, 124 liters



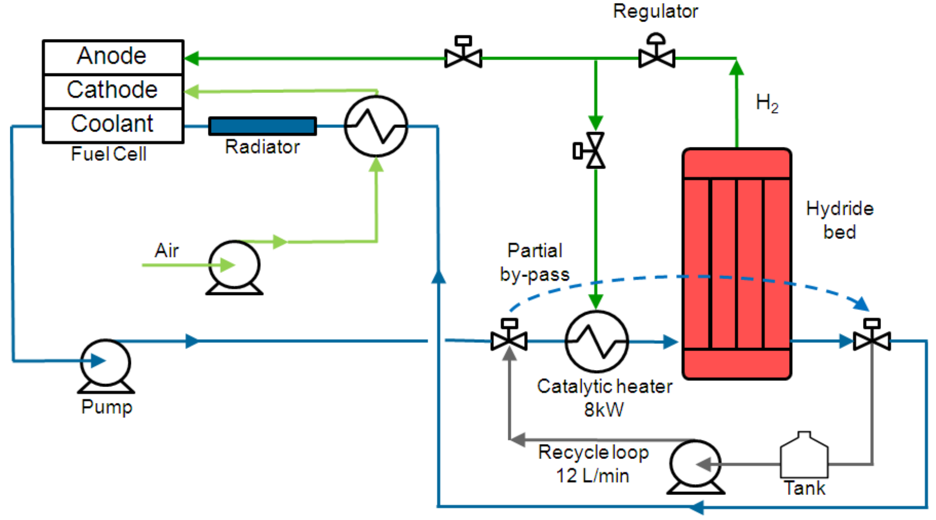


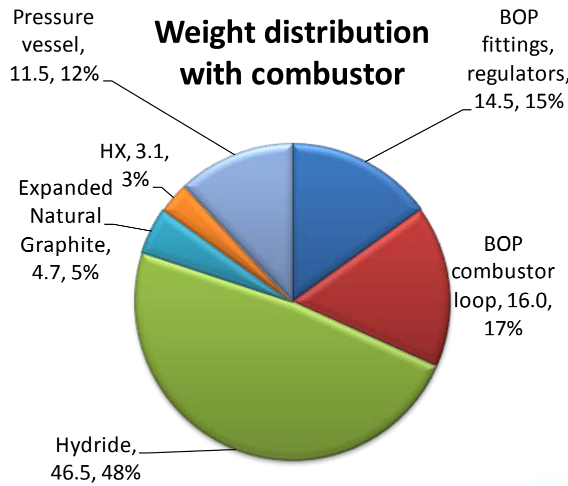


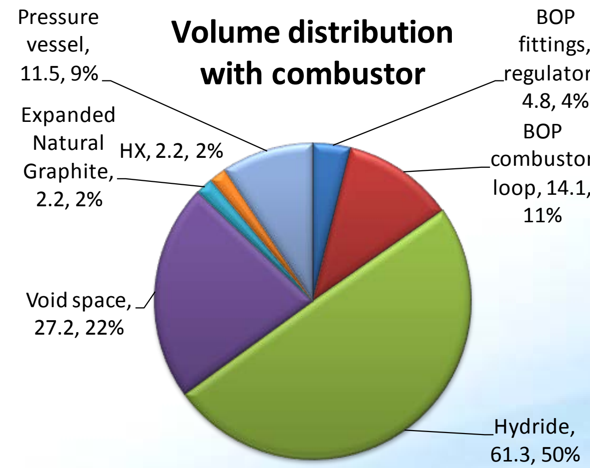
Accomplishment

Metal Hydride System 2: Combust Some H_2

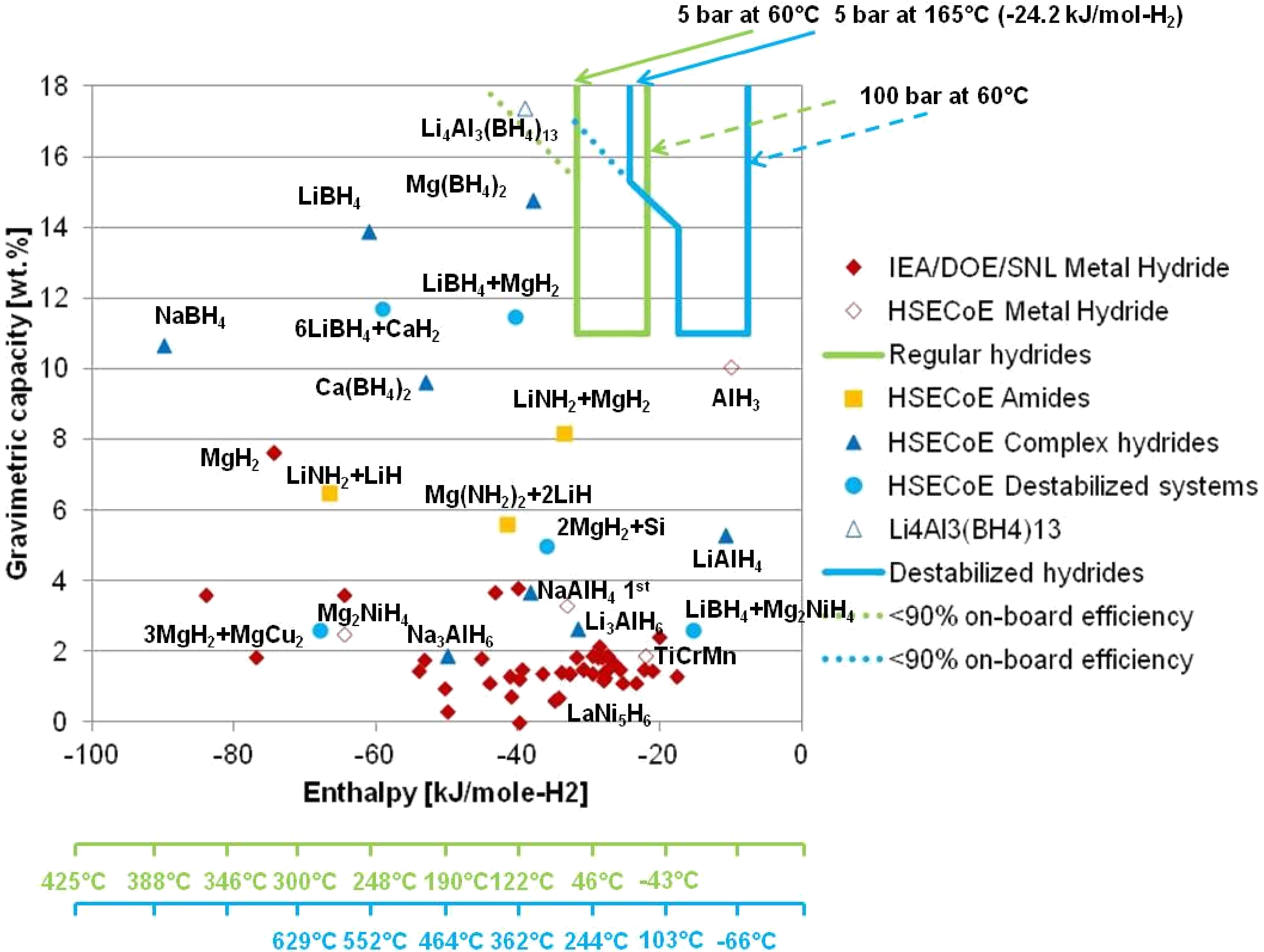
- Attributes
  - Mix of fuel cell coolant and recycled fluid used for warm-up and to maintain T_{tank}.
  - No separate buffer tank: use H_2 in pores.
- Media Characteristics
  - ΔH = -40 kJ/mol-H_2 ($T_{5\ bar}$ = 122.8 °C)
  - 17 wt.% pure material capacity
- Results
  - Satisfies all targets except on-board system efficiency.
  - On-board efficiency: ~81%
  - System: 103 kg, 126 liters
  - Operating at 130°C delivers 5.4 kg-H_2 (delivered + combusted: 6.6 kg-H_2)







Gravimetric Capacity vs. Enthalpy



MH System Conclusions

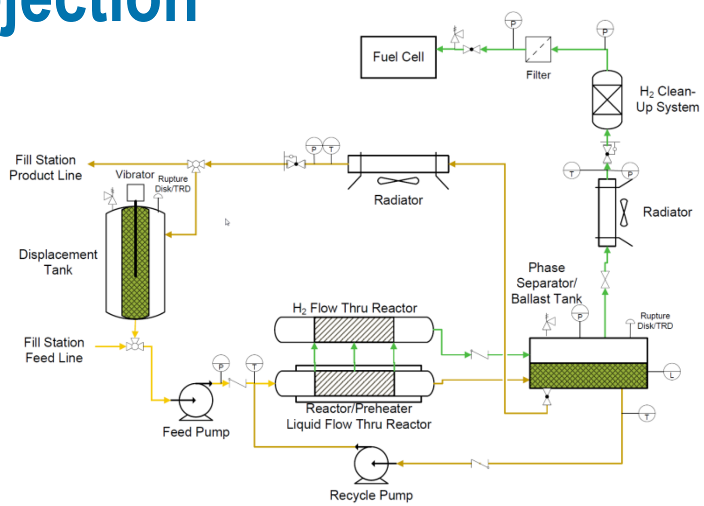
- **A material will need reasonably fast charging kinetics (3-8X better than SAH), at moderate pressures (< 100 bar).**
- **Any additional hydrogen capacity (1 to 1.5 wt%) gained by using higher pressure, hybrid tanks would be negated by the additional weight associated with the additional carbon fiber needed to reinforce the tank walls.**
- **For many material densities (>800 kg/m^3) – the volumetric target can be easily met if the gravimetric target is met**
- **A minimum material H_2 capacity to meet the DOE 2017 Targets is 10 to 11 w/o (with no hydrogen combusted i.e. $\Delta H < 27$ kJ/mol-H_2).**
- **For materials with a higher ΔH (some H_2 combustion required i.e. $\Delta H > 30$ kJ/mol-H_2) a minimum material capacity would need to be 15 to 16 w/o.**

Accomplishment

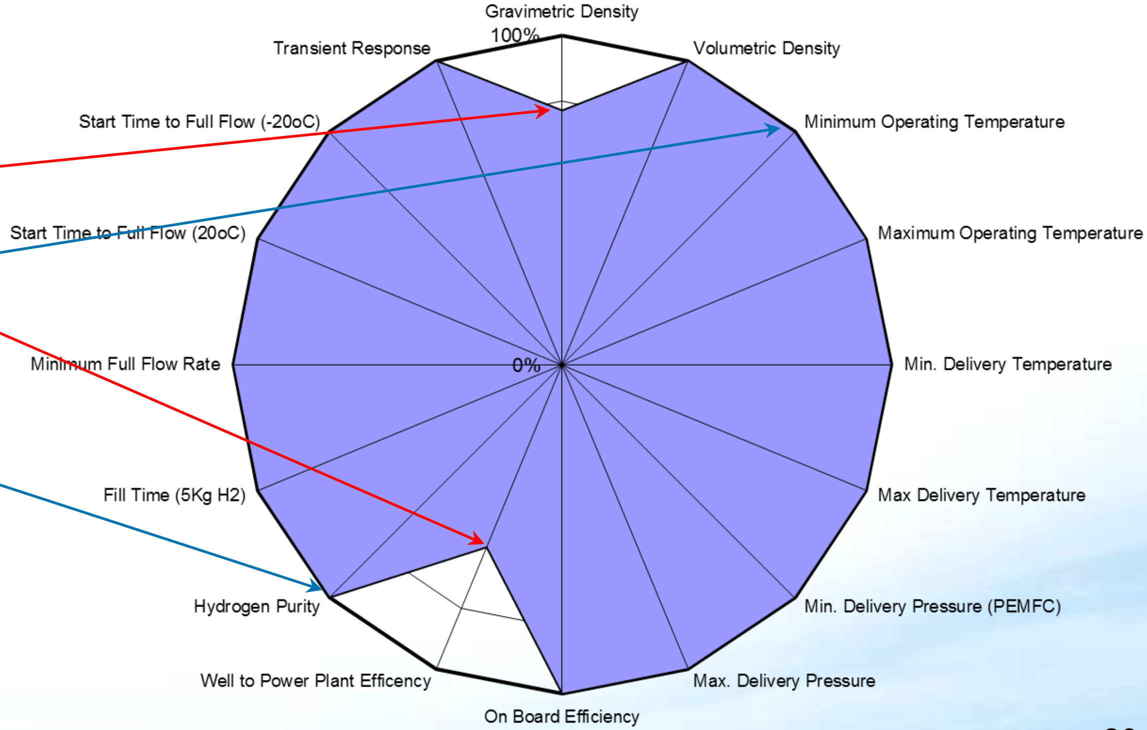
Chemical Hydride System Projection

2017 Targets

- **Media Type: Fluid Phase Ammonia Borane**
- **Composition: 50wt.% AB in BMIMCl (1-n-butyl-3-methylimidazolium chloride)**
- **Products: Similar rheological properties to reactants**



1. Gravimetric Density
2. On-Board Efficiency
3. Min. Op. Temperature?
4. *Fuel Cost*
5. System Cost
6. H_2 Purity ?

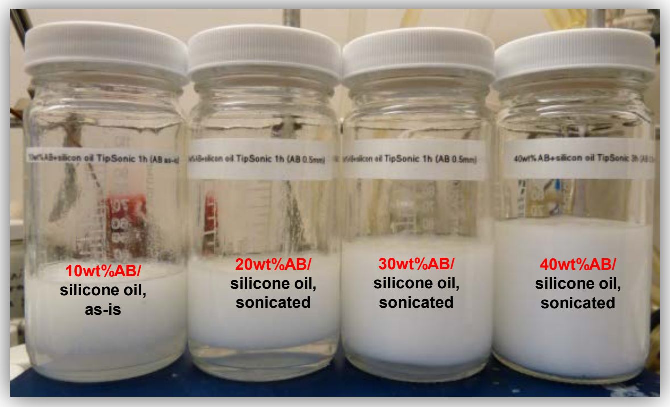


Chemical Hydride Barriers and Approaches

- **Gravimetric Density**
  - Improved Solvent/Slurry to Achieve Higher Density Loading
- **Minimum Operating Temperature**
  - Identify Viscosity vs. Temperature
- **System Cost**
  - Low Cost Solvent/Slurry

Slurry AB Kinetics Measurement

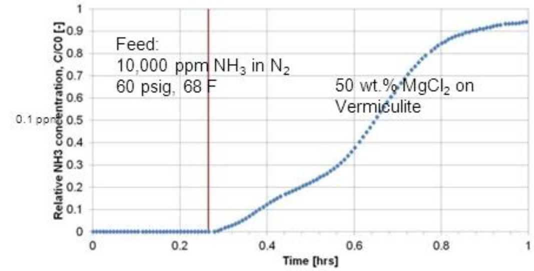
Slurry AB Development

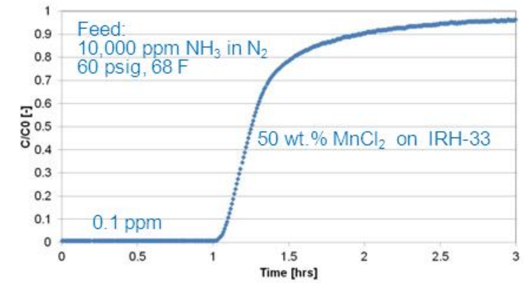


Slurry AB Viscosity Measurement

Chemical Hydride Barriers and Approaches

- **Hydrogen Purity**
  - Improved Solvent/Slurry
  - Improved Chemical Trapping
  - Good Thermal Control



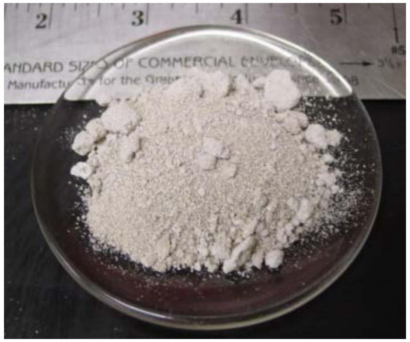


Impurities Trap Development

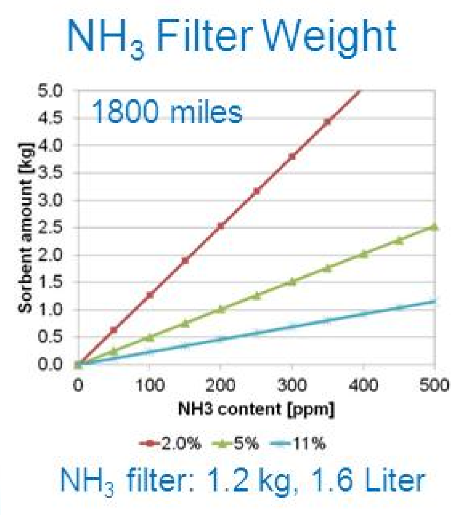
United Technologies Research Center

Metal Chloride on Porous Supports

Activated Carbon



Vermiculite



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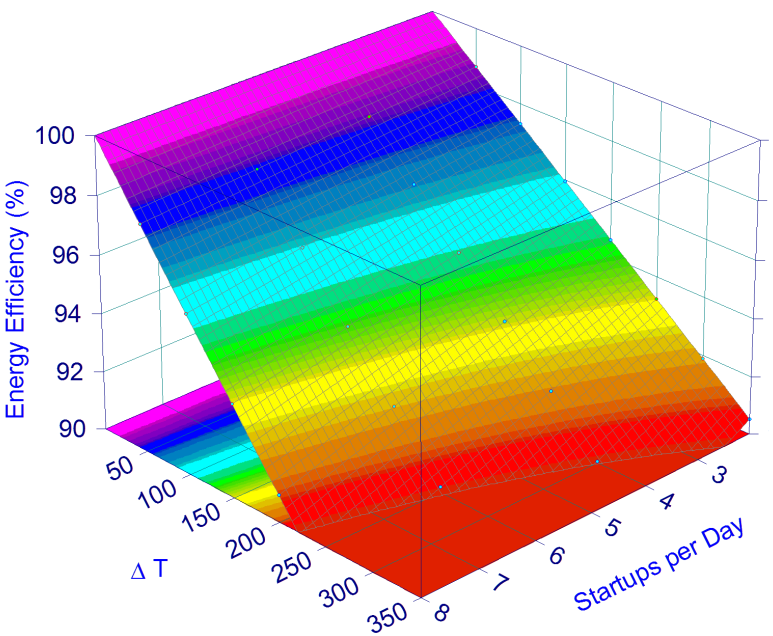
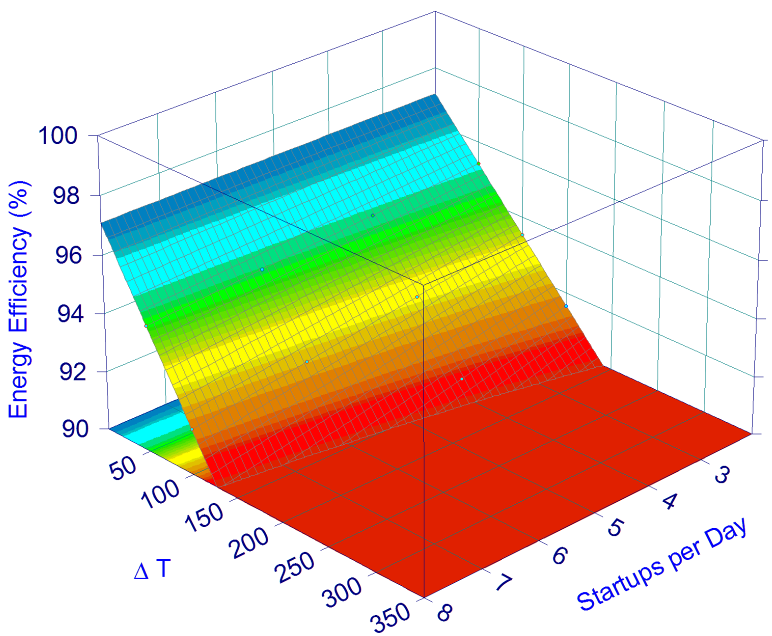
Chemical Hydride Barriers and Approaches

- **On-Board Efficiency**
  - Endothermic vs. Exothermic
  - Daily Utilization

AB Energy Efficiency Calculations as a Function of the Number of Startups and Delta T for a SS Reactor Mass of 5 kg (Total Mass of H2 = 5.6kg)
Includes Energy for Reactor Startup and Energy to Heat Fluid



Alane Energy Efficiency Calculations as a Function of the Number of Startups and Delta T for a SS Reactor Mass of 5 kg (Total Mass of H2 = 5.6kg)
Includes Energy for Reactor Startup, Energy to Heat Fluid and ΔH_{rxn}

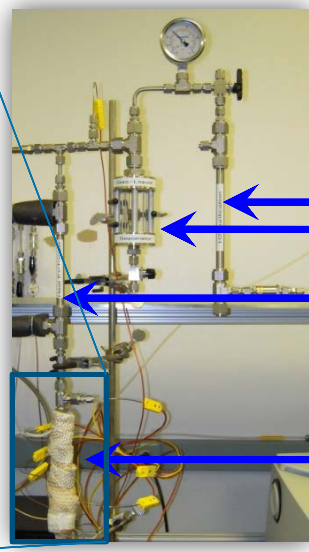


T. Semelsberger, K. Brooks

Chemical Hydride Component
Flow Through Reactor Validation Experiments

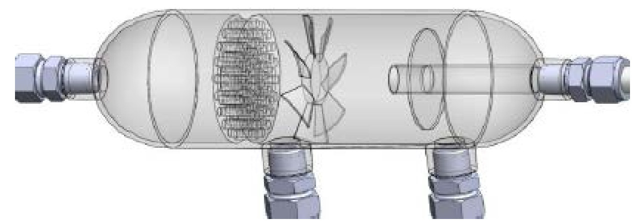
Fluid AB Flow Through Reactors & Test Facility

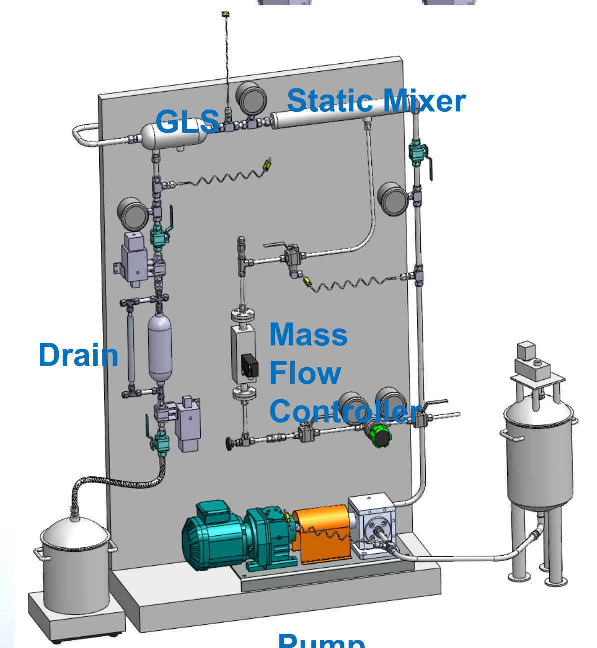
Los Alamos NATIONAL LABORATORY EST. 1943



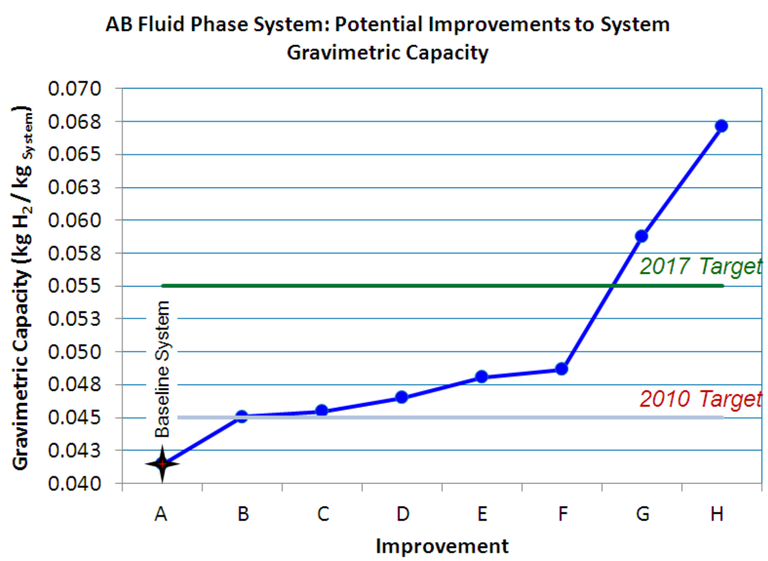
Gas/Liquid Separator Test Facility

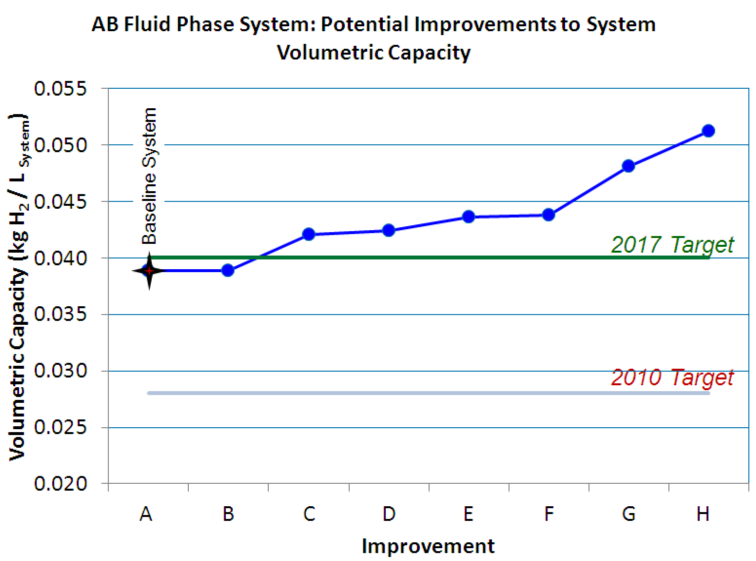
United Technologies Research Center





CH Projections of Progress





Step	Description
A	Phase 1 Baseline: 50:50 Fluid composition
B	Change from steel shell ballast tank to aluminum
C	Reduce HX from 76 kW to 38 kW
D	Reduce H_2 Wetted Tubing
E	Low Mass Borazine Scrubber
F	Low Mass Ammonia Scrubber
G	Increase AB loading from 50 to 65 wt. %
H	Increase AB loading from 65 to 80 wt. %

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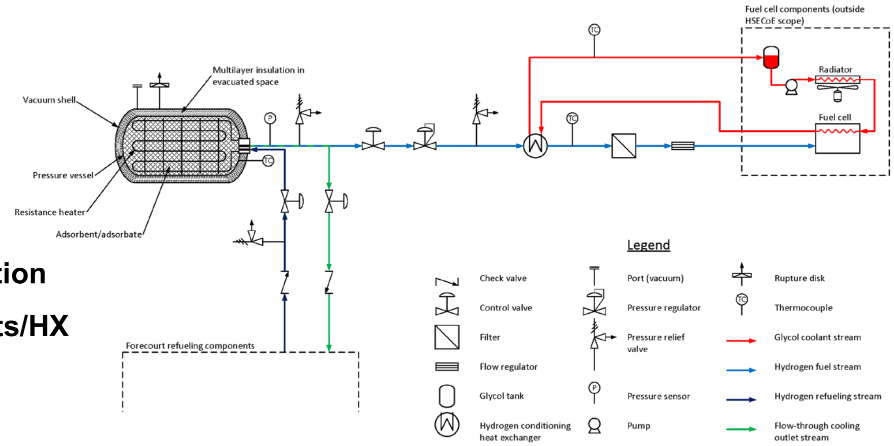
Accomplishment

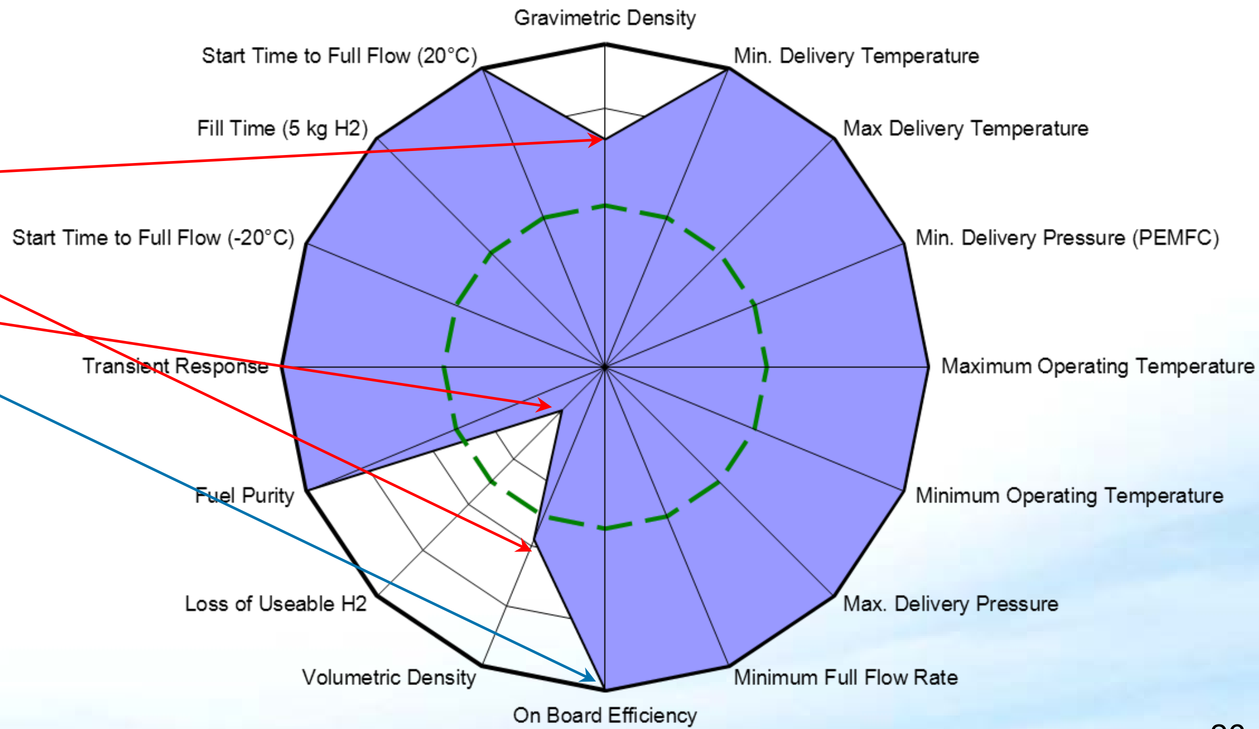
Adsorbent System Projection

2017 Targets

- **2000 bar AX-21, no thermal enhancement, 80 K initial fill**
- **Type 3 CF/Al lined pressure vessel, 6 mm liner, 200 bar**
- **Double-wall 60-layer MLVI jacket design, 5W heat leak @ 80 K**
- **Porous-bed "flow-through" cooling/fueling design for adsorption**
- **Desorption heat via tank-integral electrical resistance elements/HX**



1. Gravimetric Density
2. Volumetric Density
3. System Cost
4. Loss of Usable H_2
5. On-Board Efficiency



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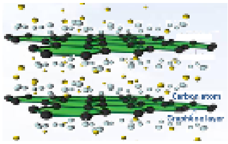
Adsorbent Barriers and Approaches

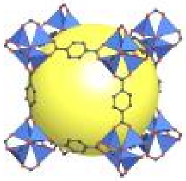
- **Gravimetric Density**
  - Media
  - Media Compaction
  - Type 3 & 4 Tank Development
  - Advanced HX Design
    - Modular Tank Insert
    - Flow

Type IV Cryogenic Pressure Vessel Manufacturing

LINCOLN COMPOSITES
A Member of Hexagon Composites Group



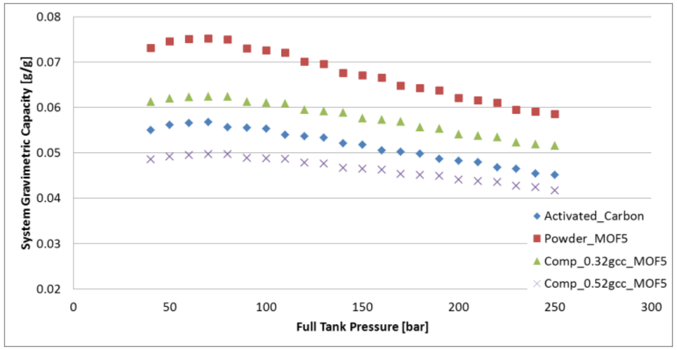
Activated Carbon



MOF-5

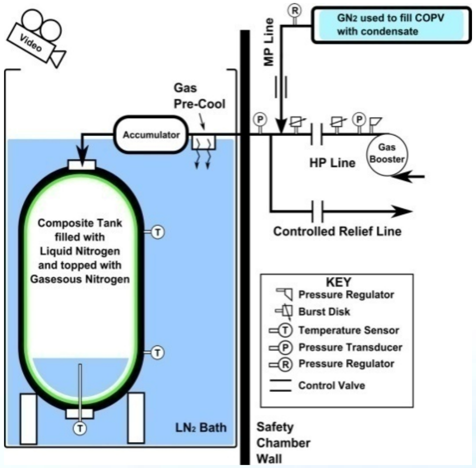
Ford

SRNL



Cryogenic Tank Burst Facility

JPL
Jet Propulsion Laboratory
California Institute of Technology



Cryogenic Materials Testing

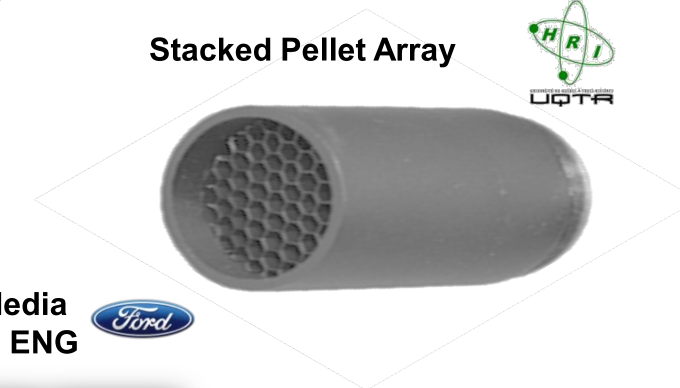
Pacific Northwest NATIONAL LABORATORY

HSECoE

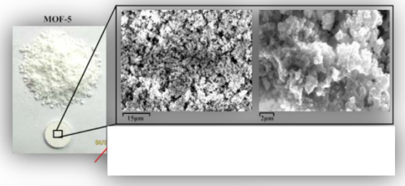
Adsorbent Barriers and Approaches

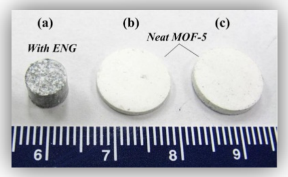
- **Volumetric Density**
  - Media Compaction
  - Advanced HX Design
    - Modular Tank Insert
    - Flow Through Cooling
    - Hexagonal Pellet Array

Stacked Pellet Array

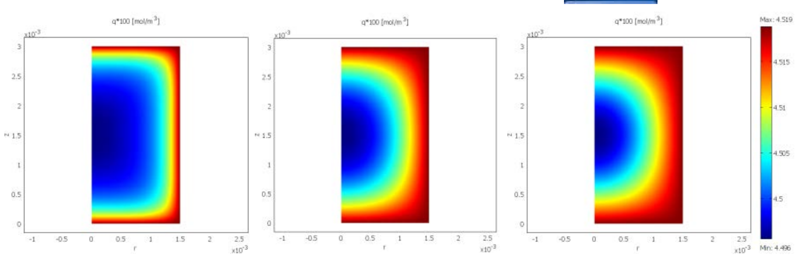


Compacted Media Incorporating ENG

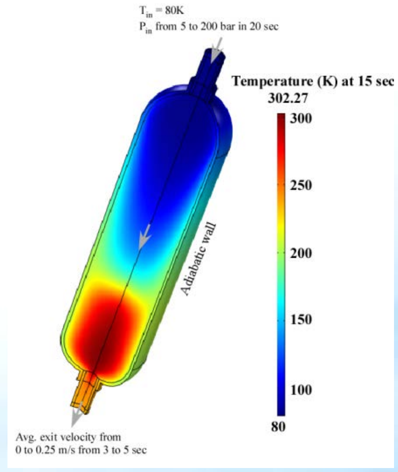




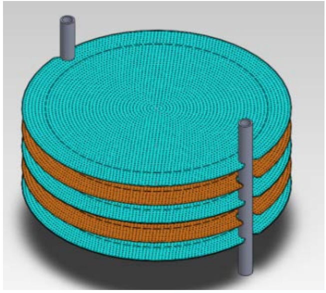
Pellet Thermal Modeling

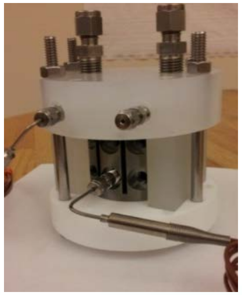


Flow Through Cooling



Modular Tank Insert

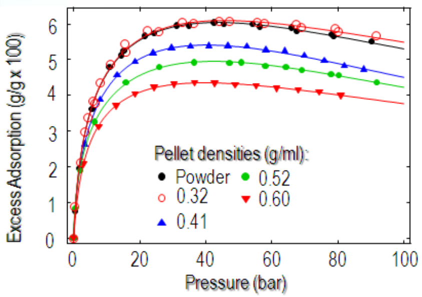


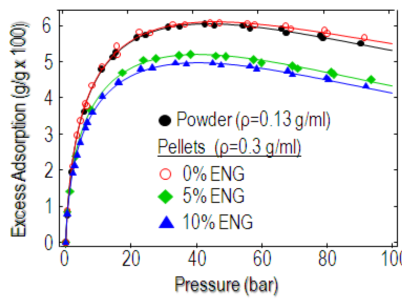


Cryogenic Adsorbent Component Test System

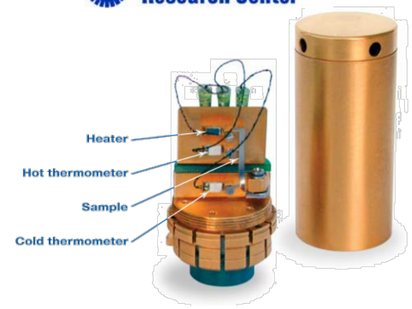
Adsorbent Materials Characterization

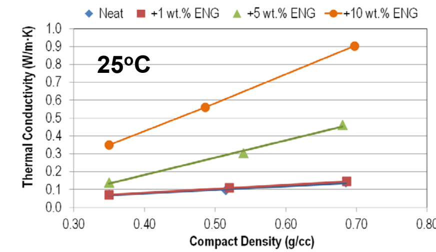
MOF-5 Excess Adsorption Measurements

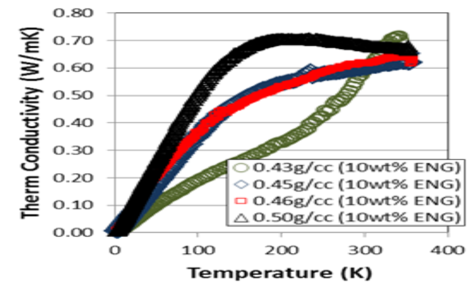




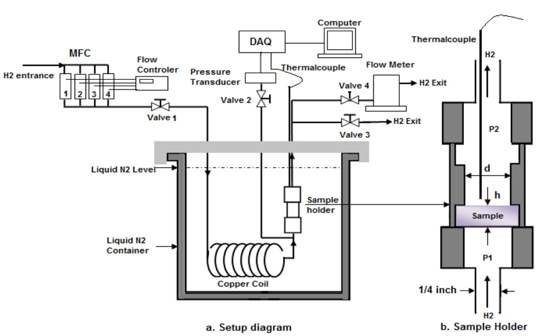
MOF-5 Thermal Conductivity Measurements

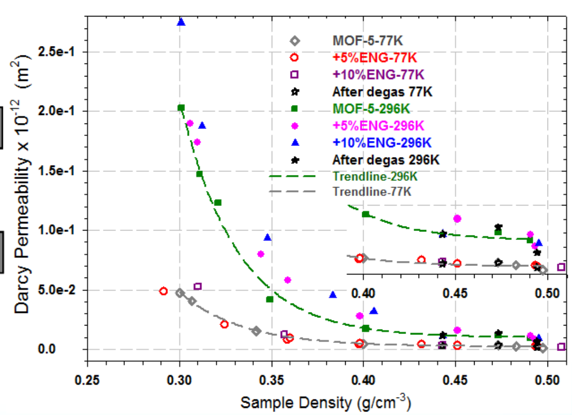


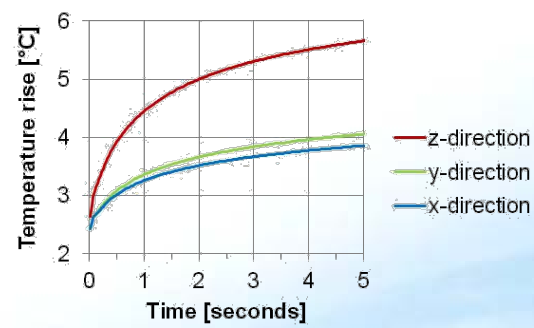




MOF-5 Cryogenic Permeability Measurements







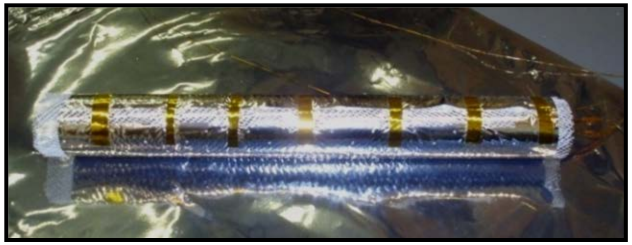
parameter	95% confidence interval	Unit
kX	3.32 < 3.45 < 3.58	W/m/K
kY	1.44 < 1.49 < 1.55	W/m/K
kZ	0.280 < 0.286 < 0.292	W/m/K
C_p	1395 < 1438 < 1484	J/kg/K

Adsorbent Barriers and Approaches

- **Loss of Usable H_2**
  - **Reducing Parasitic Load**
    - Improved thermal isolation
    - Utilizing Vented Hydrogen

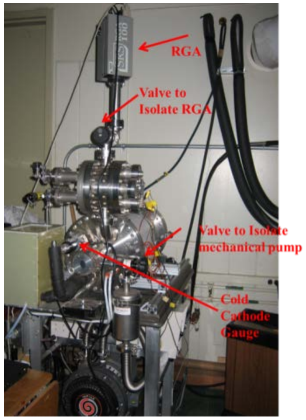
MLVI Development

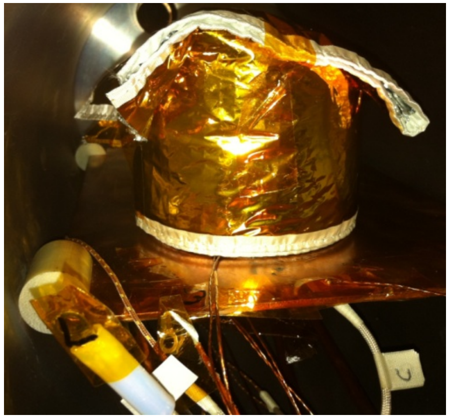
Jet Propulsion Laboratory
California Institute of Technology



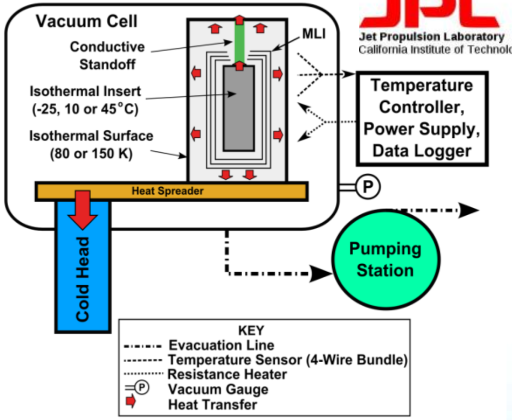
Cryogenic Vacuum Outgassing

Jet Propulsion Laboratory
California Institute of Technology

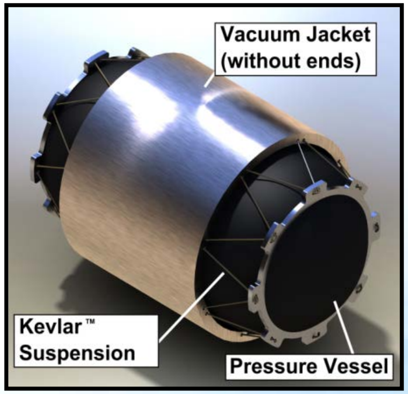




Heat Leak Evaluations



Kevlar™-suspended tank Vacuum shell



Jet Propulsion Laboratory
California Institute of Technology

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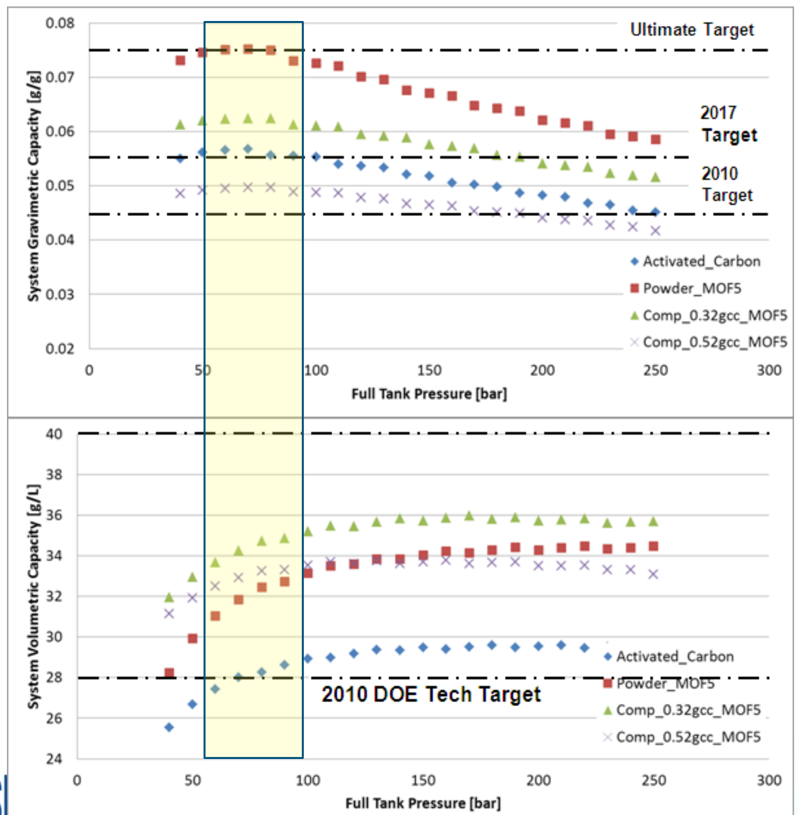
Adsorbent Barriers and Approaches

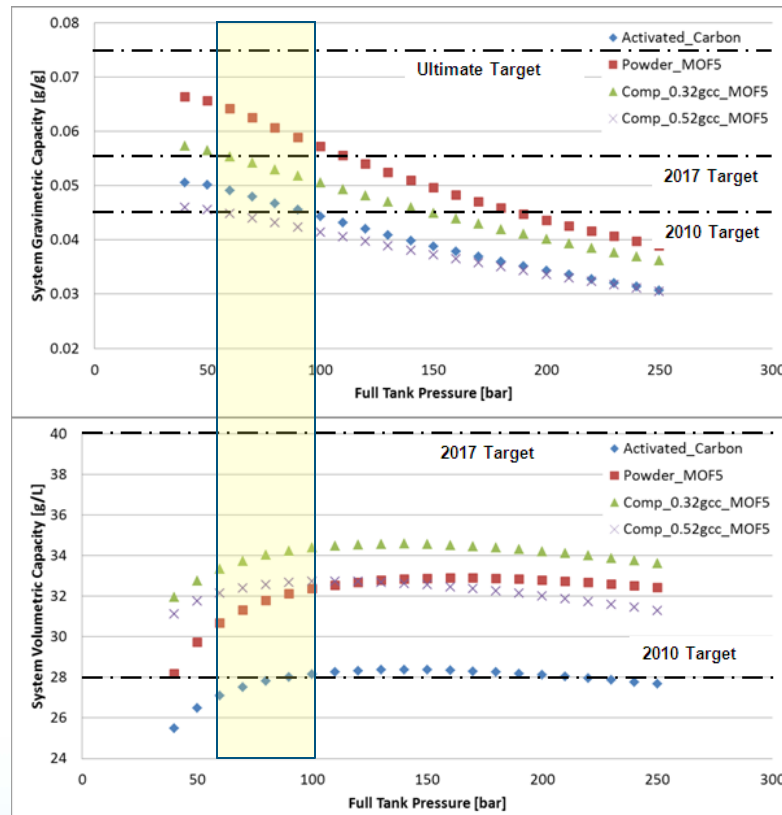
- **On-Board Efficiency**
  - Low Pressure Design

- **Flow-through cooling for refueling**
- **Resistance heater for desorption**
- **40K < $T_{operating}$ < 120K**

Composite Type III Tank

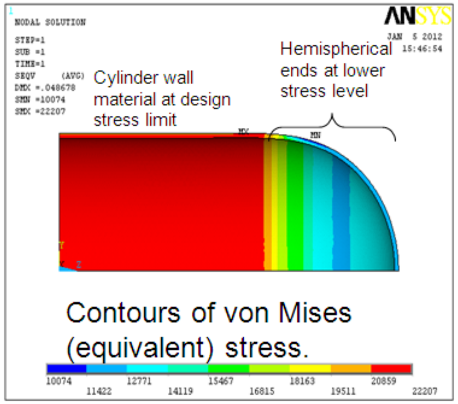


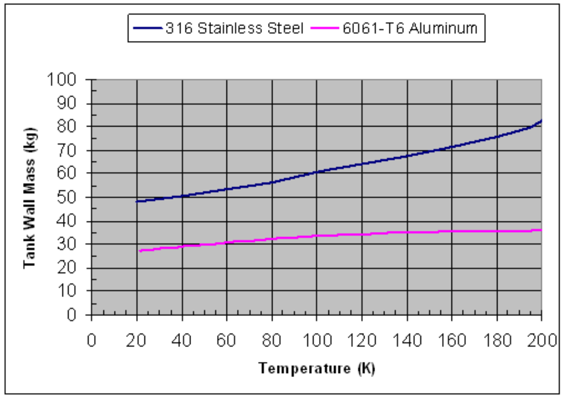
Aluminum Type I Tank



Adsorbent Barriers and Approaches

- **System Cost**
  - Low Pressure Type I Tank
  - Low cost BoP component identification



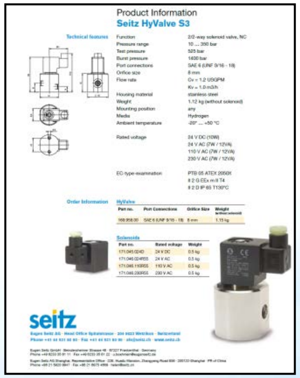


MOF-5 Cost Analysis

Oct. 2011

	Production Amount					
	1,000	10,000	30,000	80,000	130,000	500,000
Total Costs	16,687	7,051	5,176	4,113	3,690	2,871
$/kWh						15.4

Item	1,000	10,000	30,000	80,000	130,000	500,000
Tanks	1,837	1,578	1,470	1,381	1,340	1,308
Media	6,820	1,834	1,026	642	520	321
Media Cost/kg	367	99	55	34	28	17
Balance of Plant	5,136	2,426	1,804	1,426	1,264	980
Assembly	2,894	1,213	875	664	567	261



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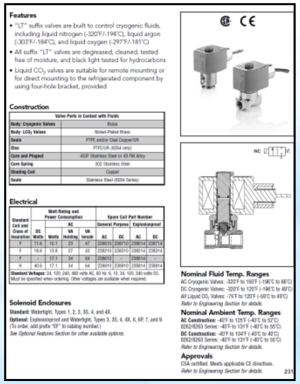

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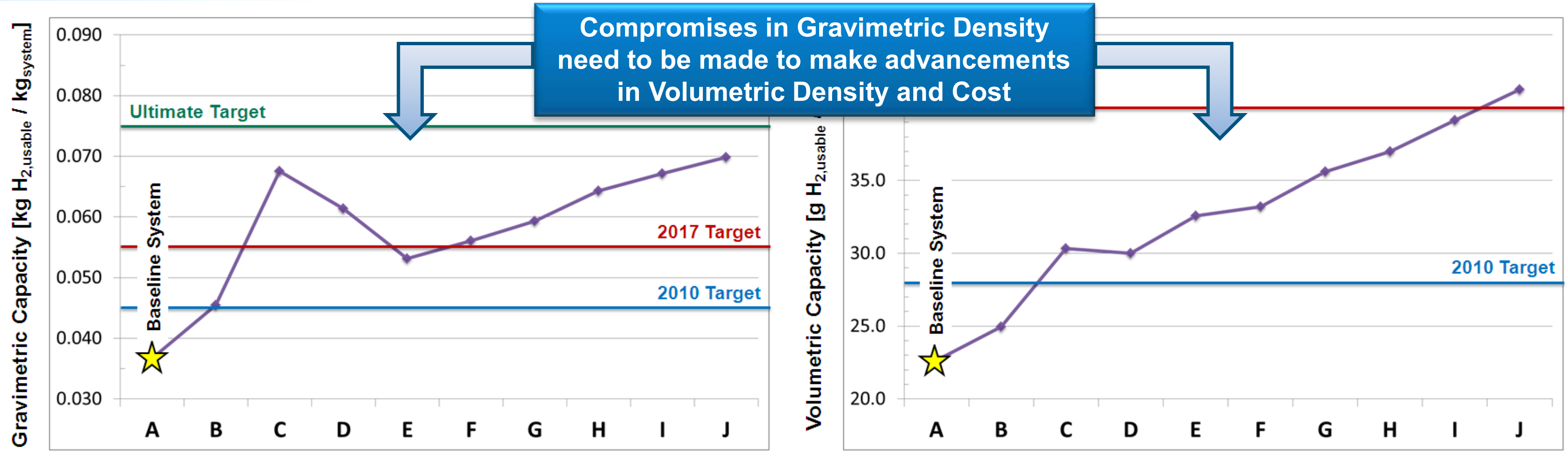
Adsorbent System Projection of Progress



Step	Description
A	Phase 1 Baseline – Activated Carbon in a Composite Tank; Flow-Through Cooling with a Resistance Heater; Full Conditions of 80 K, 200 bar
B	Change Material to Powdered MOF-5
C	Change Full Tank Conditions to 40 K, 60 bar
D	Change Tank to Type I Aluminum (lower cost)
E	Change to Compacted MOF-5 (0.32 g/cc)
F	Increase Compacted MOF-5 thermal conductivity by an order of magnitude
G	Change from Flow-Through Cooling with a Resistance Heater to the M.A.T.I.
H	Reduce mass and volume of BOP components by 25%
I	Improve material capacity by 10%
J	Improve material capacity by 20%

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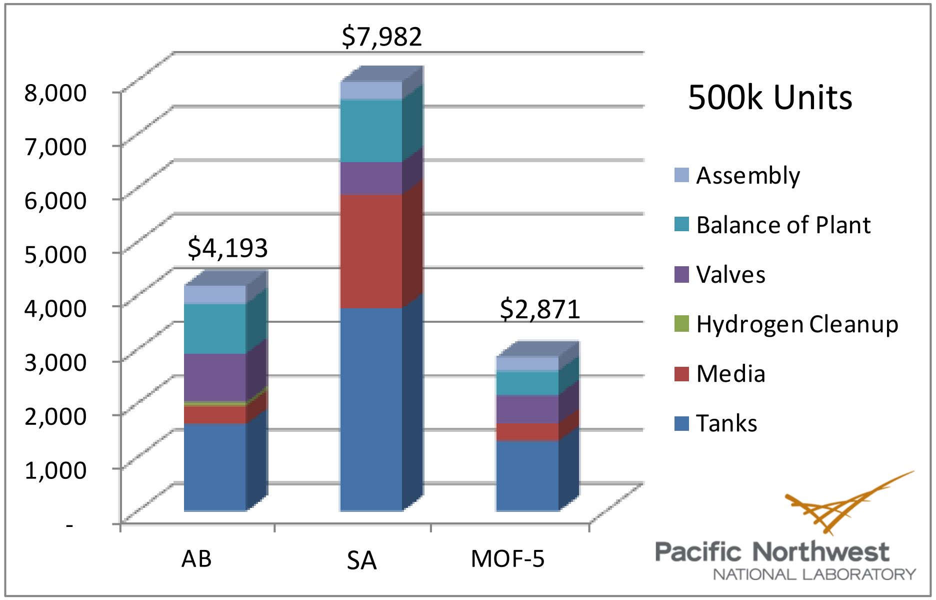
Initial System Cost Projections

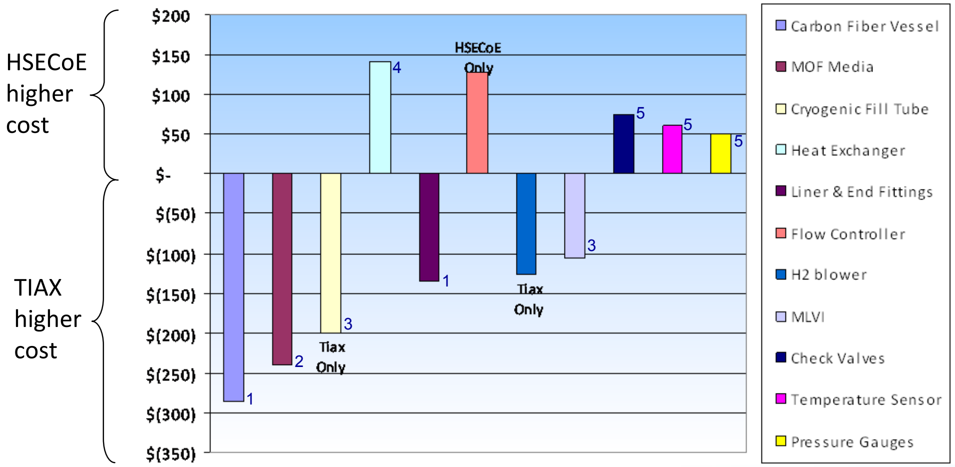
- Developing bill-of-materials for various storage systems
- Assessed industry available parts with appropriate capabilities for system conditions
- Reviewed quotes from distributors and manufactures for different quantity levels
- Evaluated progress ratio models based on production level and volume
- Compared costs with direct material models and other benchmarks

HSECoE System Comparison ($/System)



$23/kWh **$43/kWh** **$15/kWh**

MOF System Cost Comparison



Comments / Observations

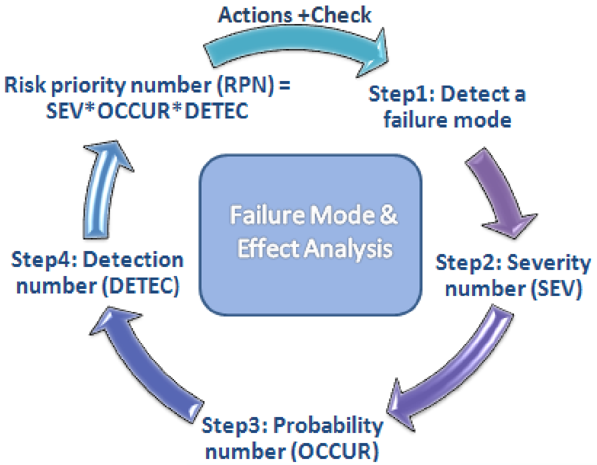
1. Further analysis is required to evaluate pressure vessel cost (fiber and liner)
2. MOF media difference is expected (MOF-177 with Tiax vs MOF-5 with HSECoE
3. The insulation criteria for the fill tube and MLVI needs confirmation
4. Heat exchanger details needs to be expanded into individual items
5. The main difference is related to the number of parts assumed in the system

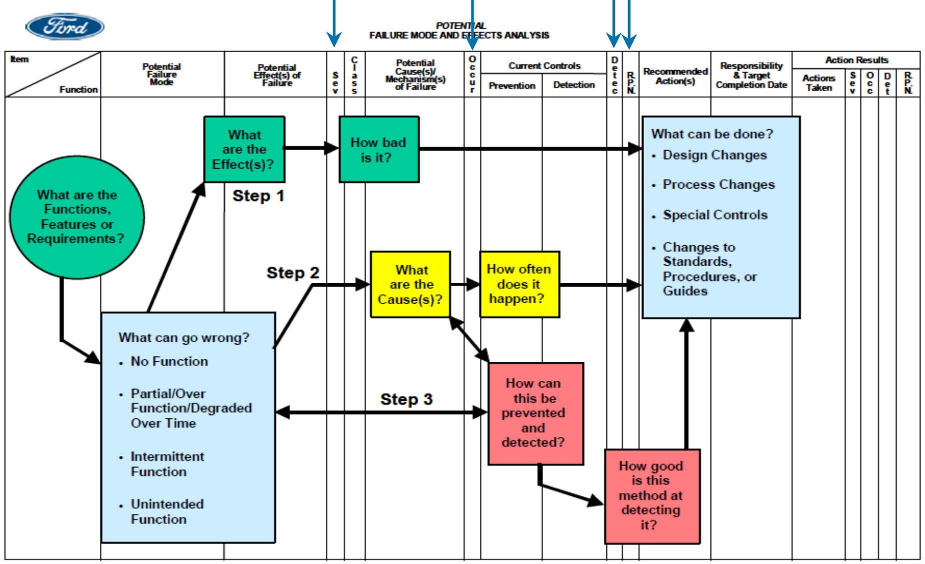
HSECoE

Argonne NATIONAL LABORATORY TIAX STRATEGIC ANALYSIS

FMEA *(Failure Modes and Effects Analysis)*

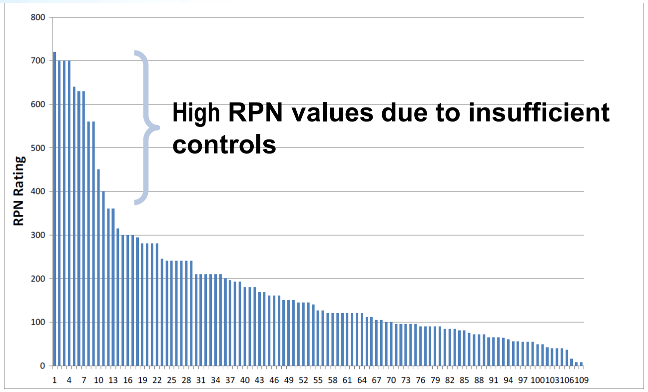
- **FMEA Completed for both Adsorbent and Chemical Hydride Systems**
- **Considered for deployed system**
  - Severity
  - Probability of Occurrence
  - Probability of Detection
    - **Risk Priority Number**



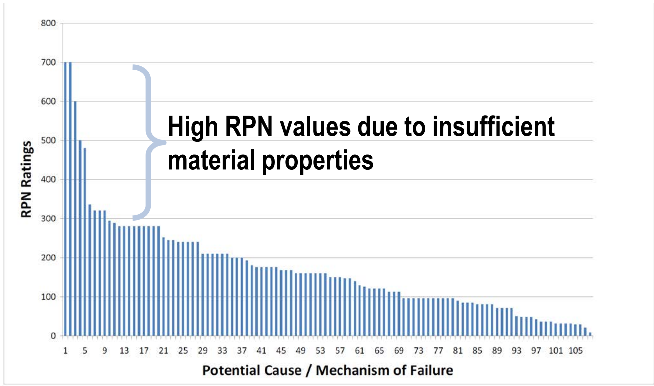


FMEA Results

Adsorbent System



Chemical Hydride System



Potential Cause	Failure Mode (RPN)	Actions
Material release rate insufficient due to inhomogeneous materials at end of life	Hydrogen supply unable to achieve full flow rate (720) Storage system only accepts partial fill (630) Storage system on-board efficiency < 90% (560) System only supplies partial capacity (560) Storage system fills in > 3.3 minutes (450)	Consider a vibration test Need to evaluate bed packing Use system models to evaluate sensitivity of contact resistance
Type IV tank liner incompatible with adsorbent or in-service activation	System unable to contain hydrogen due to component rupture (700) System exceeds allowable external leak rate limit (700)	Consider in-service process and evaluate the HDPE out-gassing
Material release rate insufficient due to impurities	Hydrogen supply unable to achieve full flow rate (640) Storage system only accepts partial fill (560) Storage system fills in > 3.3 minutes (400)	Add a cycle test with spec hydrogen at the limits of J2719
Fuel cell system requires higher delivery pressure	System only supplies partial capacity (560)	Need to confirm with the fuel cell tech team regarding the probability of the min. pressure increase

Potential Cause	Failure Mode (RPN)	Actions
Not able to charge supply fuel due to the plugged plumbing (8)	System unable to supply hydrogen (320) Hydrogen supply unable to achieve full flow rate (320) Storage system only accepts partial fill (280) Storage system does not accept fuel (280)	Need to evaluate low temperature properties of the media Add settling/flocculation test for evaluating clogging
Incomplete phase separation (8)	Hydrogen supply pressure below 5 bar (320) System only supplies partial capacity (280) Storage system on-board efficiency < 90% (280) System only supplies partial capacity (245)	Assess the separator effectiveness and quantify the hydrogen in spent fuel
Volume displacement from solids build-up in bladder tank (7)	Storage system only accepts partial fill (294)	Lab scale test of pressurizing the slurry
Filling receptacle allows air exposure to fuel (7)	System exceeds allowable external leak rate limit (280)	Need to evaluate the system effects to air exposure
Incomplete reaction of the media (7)	Hydrogen supply pressure below 5 bar (320) Storage system on-board efficiency < 90% (245)	Evaluate if material build-up within the reactor can still provide heat transfer
BOP components fail to close (7)	System exceeds allowable internal leak rate limit (280)	Include BOP components in bench tests and evaluate cycles

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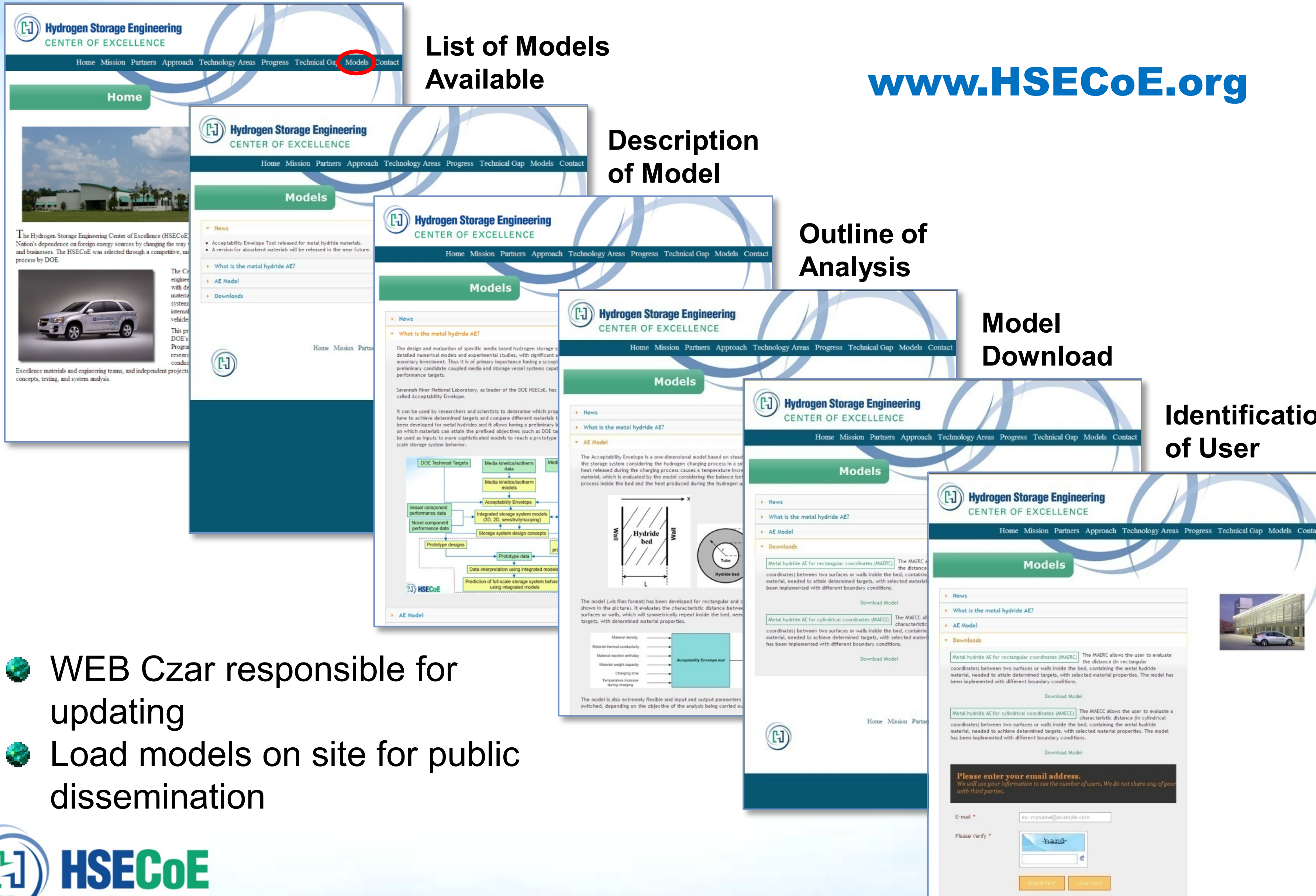
New Updated WEB Site Launched

www.HSECoE.org



List of Models Available

Description of Model

Outline of Analysis

Model Download

Identification of User

- WEB Czar responsible for updating
- Load models on site for public dissemination

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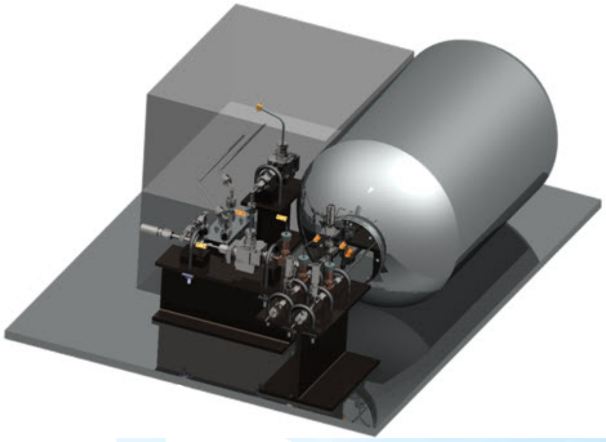
Future Work

- **Chemical Hydride System**
  - Improved Slurry/Solvent Compositions/Properties
  - Improved Chemical Trap Properties
  - Flow Through Reactor Design and Evaluation
  - Gas/Liquid Separator Evaluation
- **Adsorbent System**
  - Media Compaction/Characterization
  - Advanced HX System Evaluation
  - Advanced Insulation Evaluation
  - Cryogenic Materials Evaluation
- **Phase 3 Preparations**
  - Construct Phase 3 Test Facilities
  - Design Phase 3 Test Protocols

Cryogenic Adsorbent System



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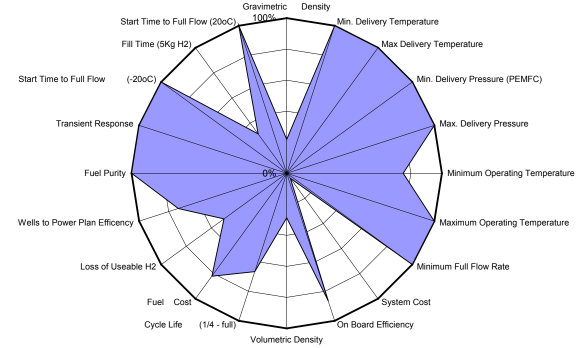
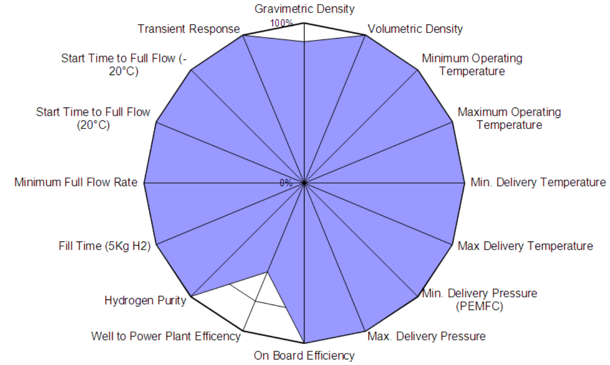
Conclusion

- **None of the media considered to date will allow systems to meet all of the DoE technical targets simultaneously but most can be met.**
- **Chemical Hydrides and Adsorbent Systems hold the highest near term promise of approaching the DoE 2017 Technical Targets.**
- **Chemical Hydride transport is facilitated by incorporation into a liquid via slurry or dissolution.**

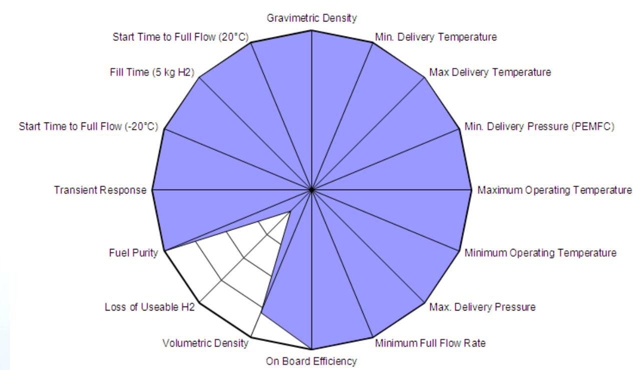
Metal Hydride System



Chemical Hydride System



Adsorbent System



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Technical Back-Up Slides

Materials Properties

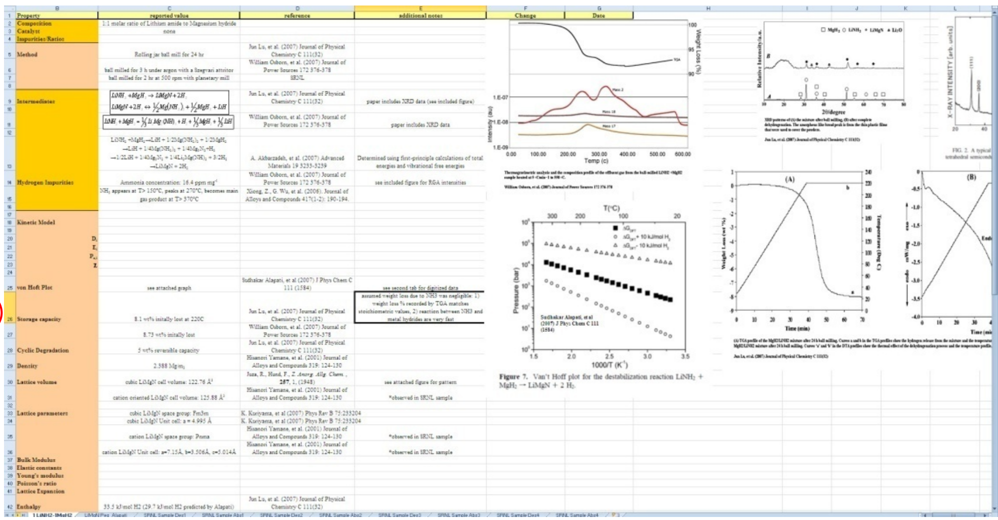
Materials Performance Models

Chemical Hydrides: $\left(\frac{dC}{dt}\right) = A\exp\left(-\frac{E}{RT}\right)(C)^{\chi}$

Metal Hydrides: $\left(\frac{dC}{dt}\right) = A\exp\left(-\frac{E}{RT}\right)\left(\frac{P_e - P}{P_e}\right)(C)^{\chi}$

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

Materials Catalogue Developed And Deployed on SharePoint®



- **Materials Data:**
  - **Kinetics in the entire P & T space anticipated**
  - **Thermodynamic Properties**
    - **ΔH, c_p ...**
  - **Physical Properties**
    - **ρ_c, ρ_p, κ_p, ...**

120C/60bar/15hrs Abs 70C/1bar Desorption			100C/1bar Desorption			110C/1bar Desorption			120C/1bar Desorption			80C/1bar Desorption		
t/ h	t/ h	wt%	t/ h	t/ h	wt%	t/ h	t/ h	wt%	t/ h	t/ h	wt%	t/ h	t/ h	wt%
17.28076	0.0000	-1.1485%	17.78116	0.0000	-2.6114%	15.92968	0.0000	-2.4216%	15.84628	0.0000	-2.3089%	16.64692	0.0000	-1.0579%
17.29744	0.0167	-1.1022%	17.79784	0.0167	-2.5425%	15.94636	0.0167	-2.3095%	15.86296	0.0167	-2.1174%	16.6636	0.0167	-1.0012%
17.31412	0.0334	-1.0592%	17.81452	0.0334	-2.4875%	15.96304	0.0334	-2.2010%	15.87964	0.0334	-1.9457%	16.68028	0.0334	-1.0004%
17.3308	0.0500	-1.0580%	17.8312	0.0500	-2.4404%	15.97972	0.0500	-2.1145%	15.89632	0.0500	-1.8102%	16.69696	0.0500	-0.9551%
17.34748	0.0667	-1.0409%	17.84788	0.0667	-2.3994%	15.9964	0.0667	-2.0181%	15.913	0.0667	-1.6388%	16.71364	0.0667	-0.9500%
17.36416	0.0834	-1.0438%	17.86456	0.0834	-2.3523%	16.01308	0.0834	-1.9218%	15.92968	0.0834	-1.4835%	16.73032	0.0834	-0.9389%
17.38084	0.1001	-1.0306%	17.88124	0.1001	-2.3093%	16.02976	0.1001	-1.8296%	15.94636	0.1001	-1.3325%	16.747	0.1001	-0.9098%
17.39752	0.1168	-1.0117%	17.89792	0.1168	-2.2926%	16.04644	0.1168	-1.7475%	15.96304	0.1168	-1.1777%	16.76368	0.1168	-0.9048%
17.4142	0.1334	-1.0286%	17.9146	0.1334	-2.2319%	16.06312	0.1334	-1.6595%	15.97972	0.1334	-1.0350%	16.78036	0.1334	-0.9000%
17.43088	0.1501	-1.0139%	17.93128	0.1501	-2.1993%	16.0798	0.1501	-1.5796%	15.9964	0.1501	-0.8886%	16.79704	0.1501	-0.9072%
17.44756	0.1668	-1.0050%	17.94796	0.1668	-2.1489%	16.09648	0.1668	-1.4939%	16.01308	0.1668	-0.7562%	16.81372	0.1668	-0.8844%
17.46424	0.1835	-1.0123%	17.96464	0.1835	-2.1144%	16.11316	0.1835	-1.3983%	16.02976	0.1835	-0.6140%	16.8304	0.1835	-0.8758%
17.48092	0.2002	-1.0076%	17.98132	0.2002	-2.0521%	16.12984	0.2002	-1.3028%	16.04644	0.2002	-0.4979%	16.84708	0.2002	-0.8632%
17.4976	0.2168	-1.0031%	17.998	0.2168	-2.0059%	16.14652	0.2168	-1.2332%	16.06312	0.2168	-0.3939%	16.86376	0.2168	-0.8586%
17.51428	0.2335	-1.0065%	18.01468	0.2335	-1.9735%	16.1632	0.2335	-1.1418%	16.0798	0.2335	-0.3059%	16.88044	0.2335	-0.8382%
17.53096	0.2502	-1.0100%	18.03136	0.2502	-1.9354%	16.17988	0.2502	-1.0544%	16.09648	0.2502	-0.2360%	16.89712	0.2502	-0.8497%
17.54764	0.2669	-0.9975%	18.04804	0.2669	-1.8973%	16.19656	0.2669	-0.9632%	16.11316	0.2669	-0.1860%	16.9138	0.2669	-0.8412%
17.56432	0.2836	-0.9769%	18.06472	0.2836	-1.8353%	16.21324	0.2836	-0.8898%	16.12984	0.2836	-0.1681%	16.93048	0.2836	-0.8108%
17.581	0.3002	-0.9965%	18.0814	0.3002	-1.7892%	16.22992	0.3002	-0.8283%	16.14652	0.3002	-0.1322%	16.94716	0.3002	-0.8225%
17.59768	0.3169	-0.9662%	18.09808	0.3169	-1.7472%	16.2466	0.3169	-0.7530%	16.1632	0.3169	-0.1363%	16.96384	0.3169	-0.8062%
17.61436	0.3336	-0.9797%	18.11476	0.3336	-1.7272%	16.26328	0.3336	-0.6837%	16.17988	0.3336	-0.1363%	16.98052	0.3336	-0.7899%
17.63104	0.3503	-0.9715%	18.13144	0.3503	-1.6773%	16.27996	0.3503	-0.6084%	16.19656	0.3503	-0.1324%	16.9972	0.3503	-0.7856%
17.64772	0.3670	-0.9751%	18.14812	0.3670	-1.6433%	16.29664	0.3670	-0.5609%	16.21324	0.3670	-0.1145%	17.01388	0.3670	-0.7752%
17.6644	0.3836	-0.9569%	18.1648	0.3836	-1.5775%	16.31332	0.3836	-0.5055%	16.22992	0.3836	-0.1065%	17.03056	0.3836	-0.7710%
17.68108	0.4003	-0.9705%	18.18148	0.4003	-1.5317%	16.33	0.4003	-0.4699%	16.2466	0.4003	-0.0986%	17.04724	0.4003	-0.7749%
17.69776	0.4170	-0.9523%	18.19816	0.4170	-1.4978%	16.34668	0.4170	-0.4244%	16.26328	0.4170	-0.1106%	17.06392	0.4170	-0.7626%
17.71444	0.4337	-0.9600%	18.21484	0.4337	-1.4659%	16.36336	0.4337	-0.3750%	16.27996	0.4337	-0.1026%	17.0806	0.4337	-0.7384%
17.73112	0.4504	-0.9438%	18.23152	0.4504	-1.4161%	16.38004	0.4504	-0.3453%	16.29664	0.4504	-0.0947%	17.09728	0.4504	-0.7422%
17.7478	0.4670	-0.9476%	18.2482	0.4670	-1.3703%	16.39672	0.4670	-0.3216%	16.31332	0.4670	-0.1067%	17.11396	0.4670	-0.7300%
17.76448	0.4837	-0.9553%	18.26488	0.4837	-1.3166%	16.4134	0.4837	-0.2920%	16.33	0.4837	-0.1207%	17.14009	0.4932	-0.7160%
17.78116	0.5004	-0.9689%	18.28156	0.5004	-1.2906%	16.43008	0.5004	-0.2802%	16.34668	0.5004	-0.0988%	17.14732	0.5004	-0.7198%
17.79784	0.5171	-0.9429%	18.29824	0.5171	-1.2410%	16.44676	0.5171	-0.2604%	16.36336	0.5171	-0.1028%	17.164	0.5171	-0.7037%
17.81452	0.5338	-0.9348%	18.31492	0.5338	-1.2012%	16.46344	0.5338	-0.2467%	16.38004	0.5338	-0.1029%	17.18068	0.5338	-0.7035%
17.8312	0.5504	-0.9305%	18.3316	0.5504	-1.1674%	16.48012	0.5504	-0.2467%	16.39672	0.5504	-0.0989%	17.19736	0.5504	-0.6914%
17.84788	0.5671	-0.9542%	18.34828	0.5671	-1.1216%	16.4968	0.5671	-0.2349%	16.4134	0.5671	-0.0909%	17.21404	0.5671	-0.6794%
17.86456	0.5838	-0.9460%	18.36496	0.5838	-1.0839%	16.51348	0.5838	-0.2270%	16.43008	0.5838	-0.1209%	17.23072	0.5838	-0.6653%
17.88124	0.6005	-0.9260%	18.38164	0.6005	-1.0560%	16.53016	0.6005	-0.2152%	16.44676	0.6005	-0.1029%	17.2474	0.6005	-0.6731%
17.89792	0.6172	-0.9259%	18.39832	0.6172	-1.0143%	16.54684	0.6172	-0.2192%	16.46344	0.6172	-0.1069%	17.26408	0.6172	-0.6690%
17.9146	0.6338	-0.9256%	18.415	0.6338	-0.9726%	16.56352	0.6338	-0.2192%	16.48012	0.6338	-0.0910%	17.28076	0.6338	-0.6529%
17.93128	0.6505	-0.9374%	18.43168	0.6505	-0.9567%	16.5802	0.6505	-0.2192%	16.4968	0.6505	-0.1070%	17.29744	0.6505	-0.6569%
17.94796	0.6672	-0.9372%	18.44836	0.6672	-0.9150%	16.59688	0.6672	-0.2153%	16.51348	0.6672	-0.1030%	17.31412	0.6672	-0.6369%

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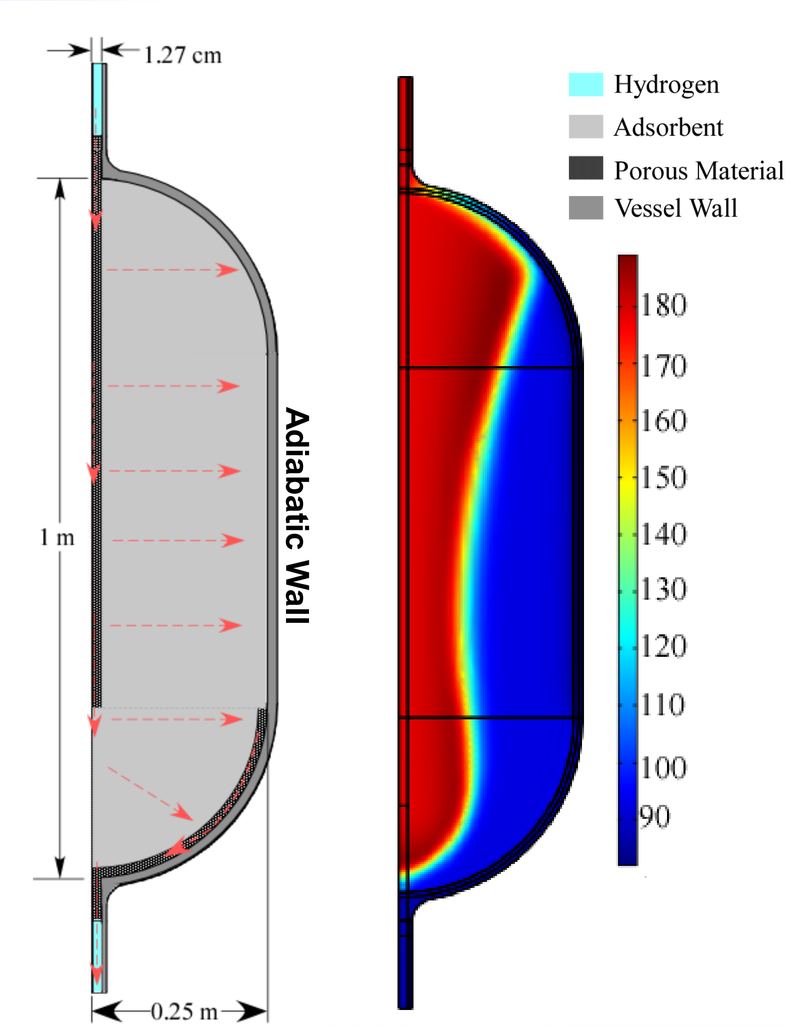
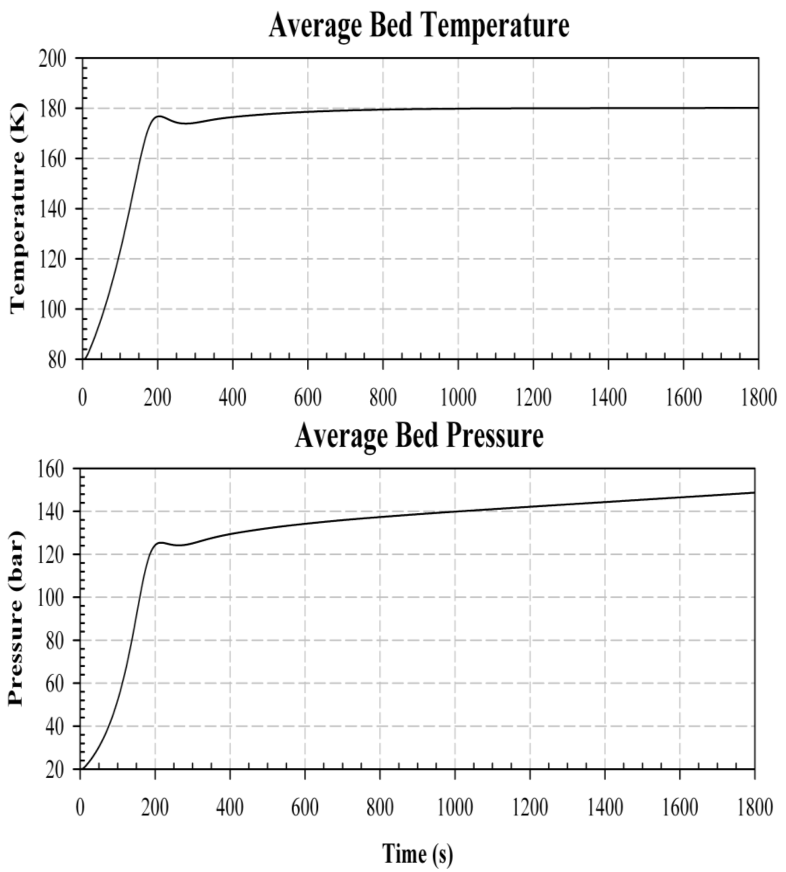
Storage System Modeling

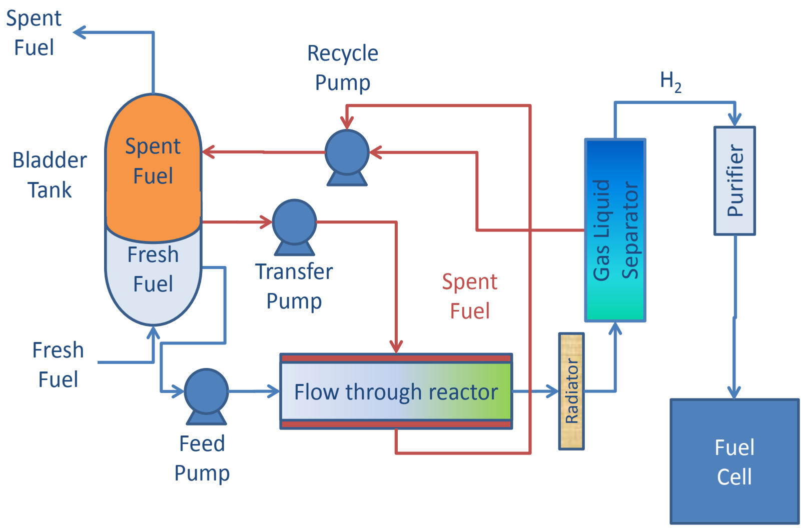
Detailed FEM Thermal/Mass Analysis ⇨ Lumped Parameter Models



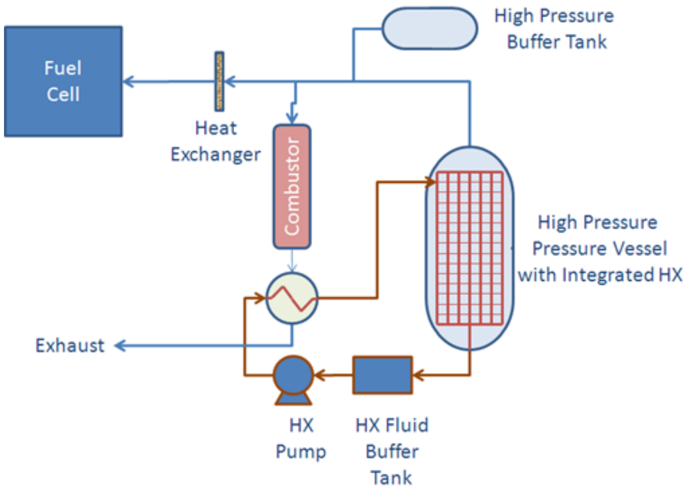


SRNL 200 bar
AX-21
Flow-Through

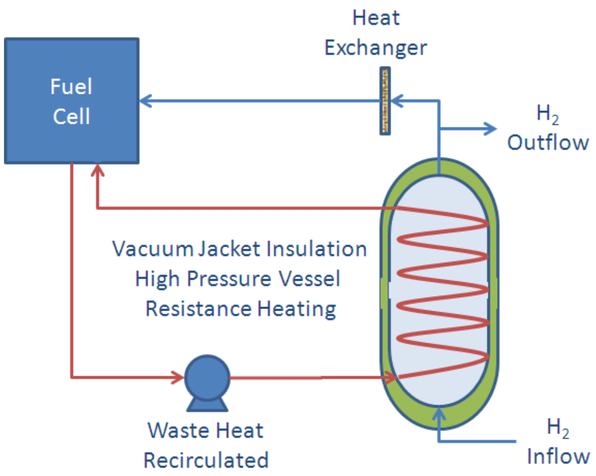
System Concepts



Fluid Chemical Hydride System



Metal Hydride System



Cryo-Adsorbent System

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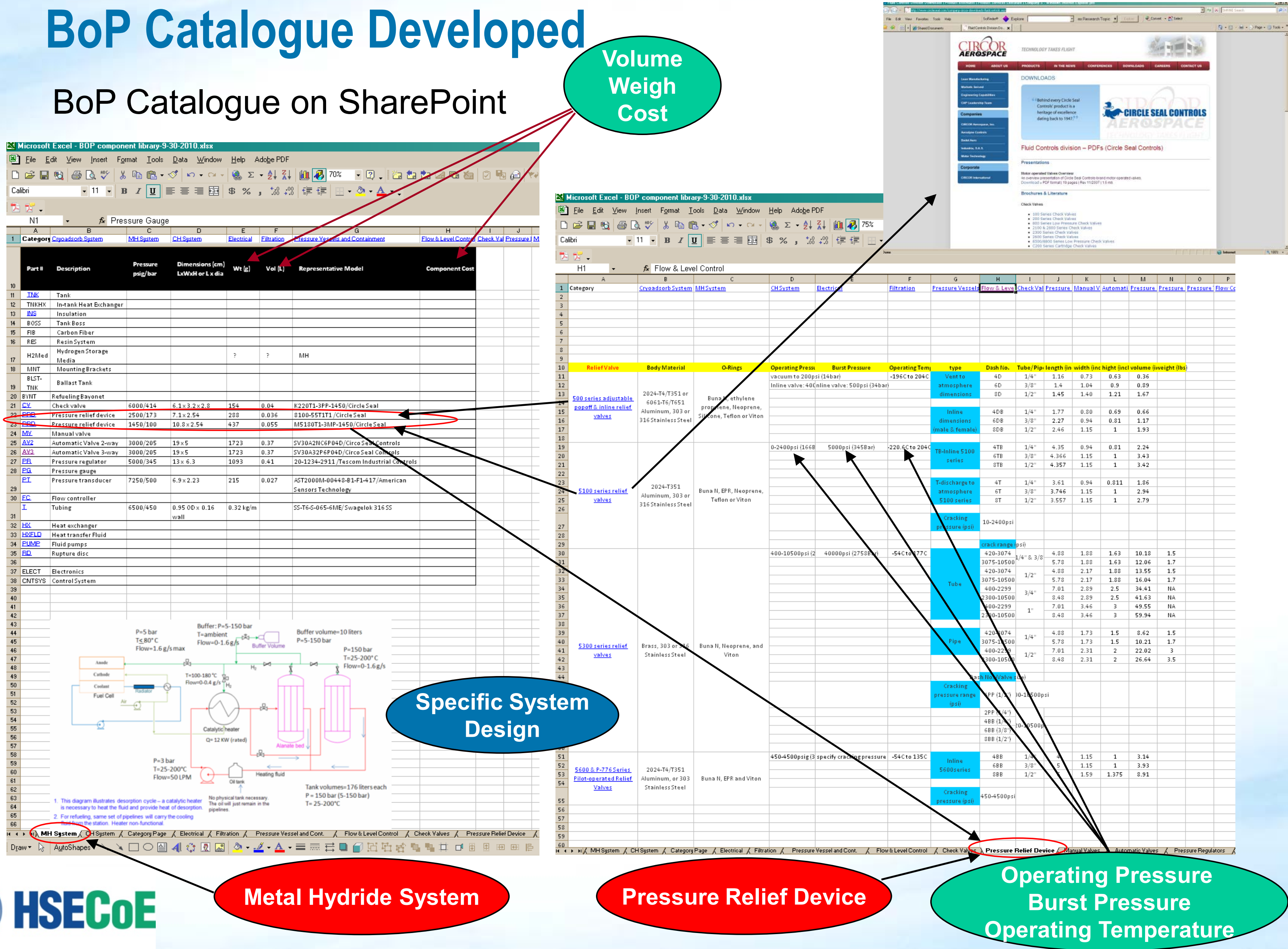
BoP Catalogue Developed

BoP Catalogue on SharePoint



Integrated Model Framework

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