Ford/BASF-SE/UM Activities in Support of the Hydrogen Storage Engineering Center of Excellence

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Overview

Timeline

- Project Start: February 2009
- Project End: June 2015

Budget

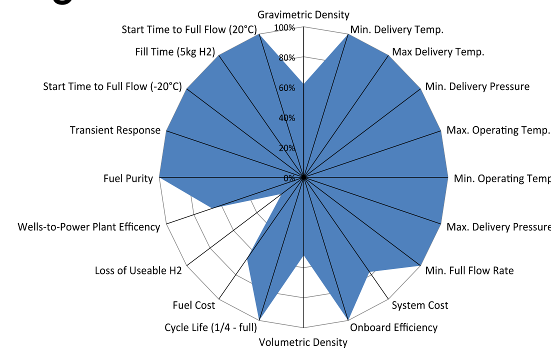
- Total Project Value: $2,783K
  - Cost Share: $643K
  - DOE Share: $2,140K
- DOE Funding Spent*: $1,715K

*as of 3/31/14

Barriers

- All DOE System Targets**
  - Volumetric Density
  - Gravimetric Density
  - System Cost

**http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf

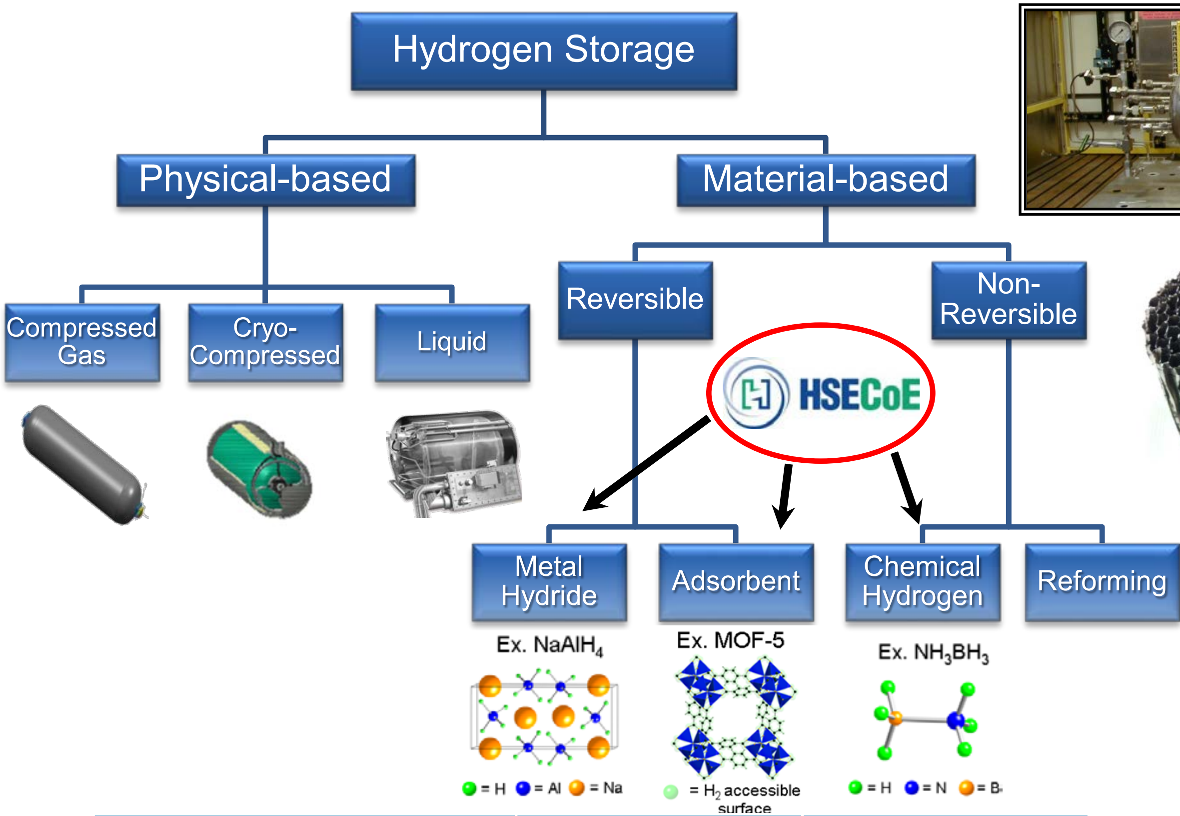


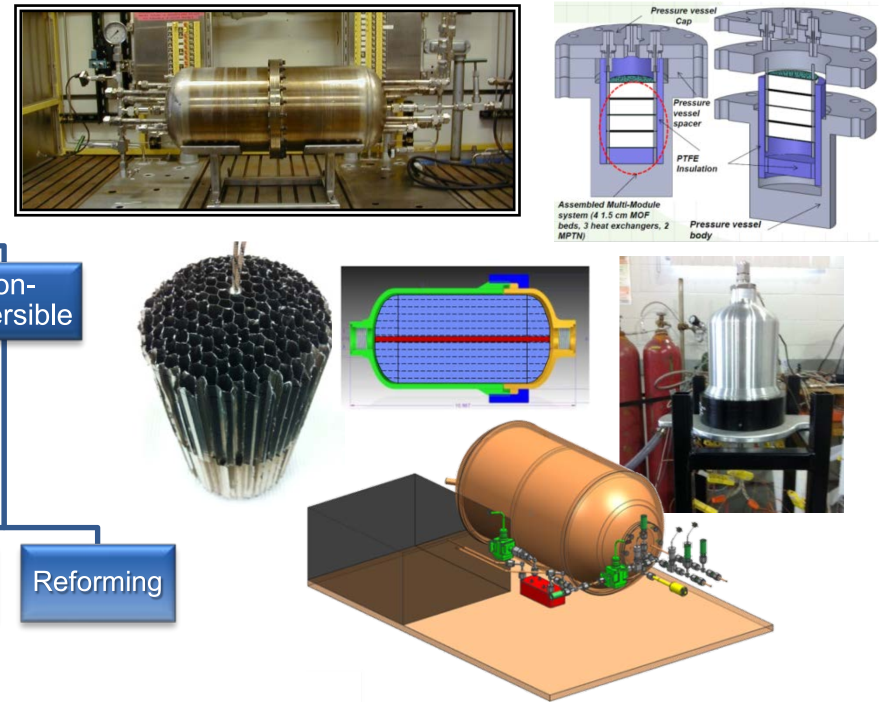
Adsorbent System Example

Partners

- Project Lead: Ford
- Subcontractors: BASF and U. Michigan
- Center Partners:

Relevance: Technical





DOE Target	2017	Ultimate
System Gravimetric Density	5.5% (1.8 kWh/kg)	7.5% (2.5 kWh/kg)
System Volumetric Density	40 g/l (1.3 kWh/l)	70 g/l (2.3 kWh/l)
Storage System Cost	\$400/kg (\$12/kWh)	\$266/kg (\$8/kWh)

Material-based hydrogen storage systems have higher potential to meet the DOE targets but have increased complexity over physical-based storage options

Relevance: Technical

Three Technical Tasks Contribute to the Overall HSECoE Mission

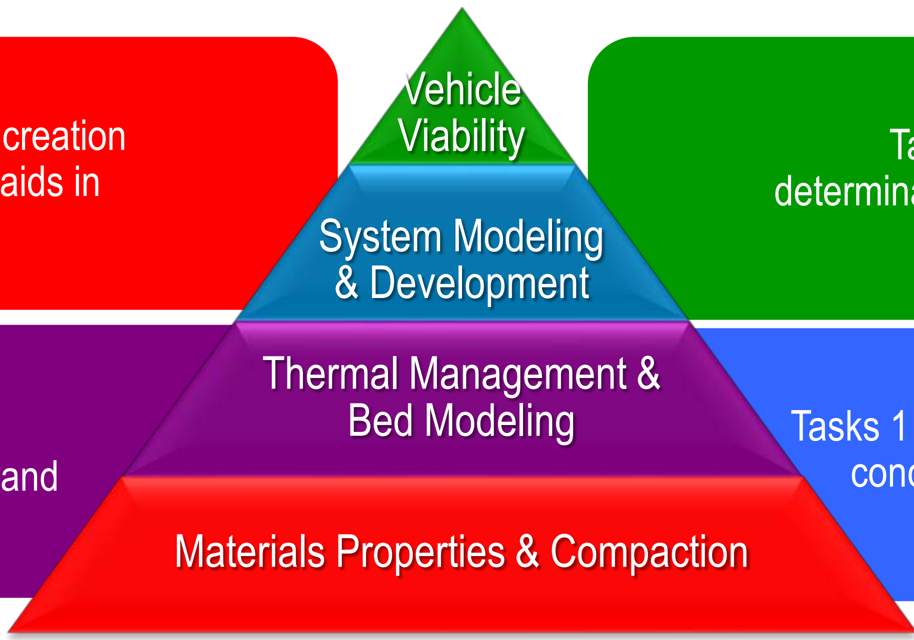
Task 1: Develop dynamic vehicle parameter model that interfaces with diverse storage system concepts

Task 2: Development of robust cost projections for storage system concepts

Task 3: Devise and develop system-focused strategies for processing and packing framework-based sorbent hydrogen storage media

Materials Properties
Task 3 data supports the creation of sorbent bed models & aids in tradeoffs analyses

Vehicle Viability
Tasks 1 & 2 models support determination of overall vehicle cost and performance



Bed Modeling
Task 3 data supports the validation of sorbent bed and system models

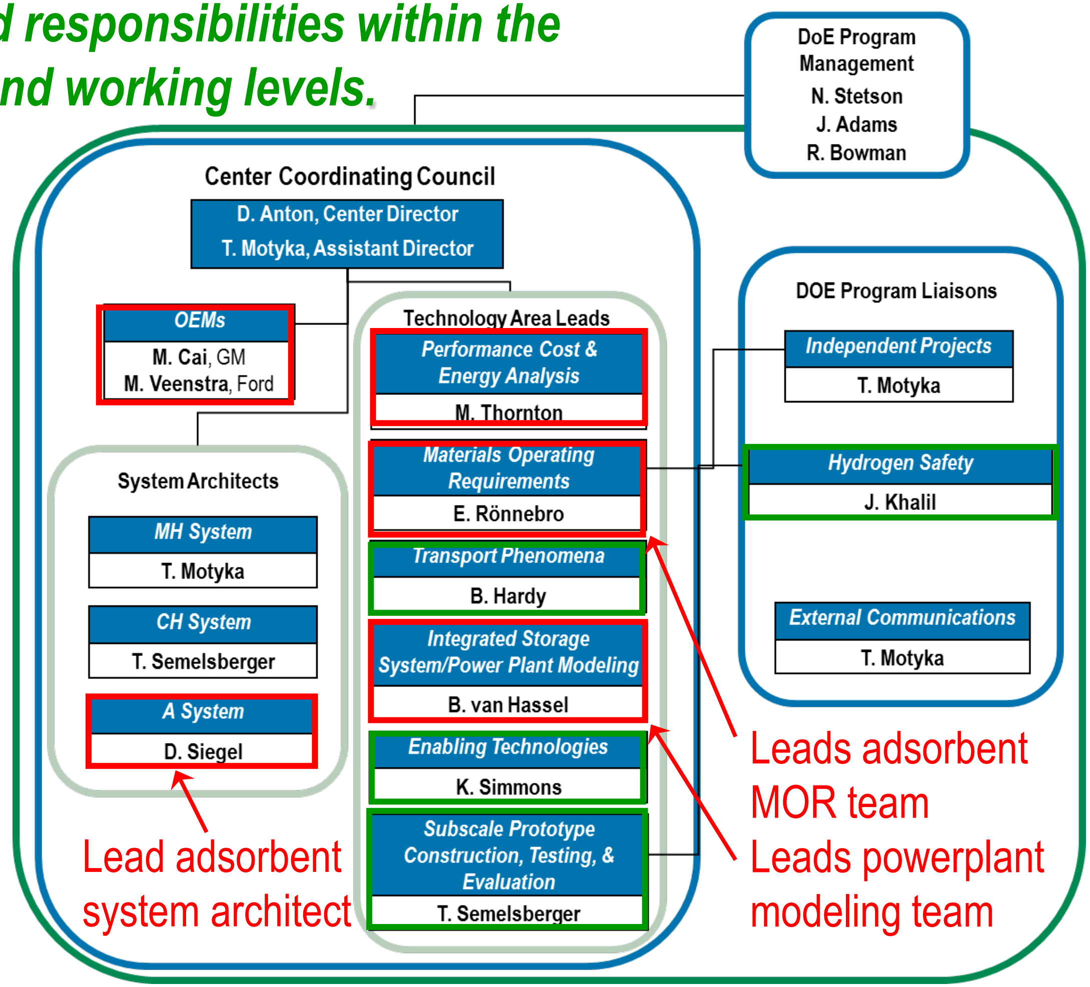
System Modeling
Tasks 1 & 2 models enable storage concepts to be exercised at the real-world vehicle level

Relevance: Organizational

Ford project has many roles and responsibilities within the HSECoE at both the executive and working levels.

Key organizational functions:

- As technical contributors, disseminate data & models across the HSECoE
- As team leads, foster inter-partner communication & streamline & align research
- Act as liaisons between the HSECoE and the C&S and Storage Tech. Teams
- Provide an automotive perspective & context



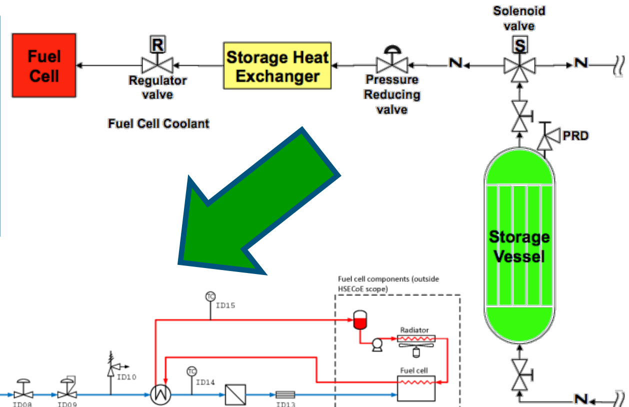
- Core contribution areas of project outcomes [red]
- Ancillary contribution areas of project outcomes [green]

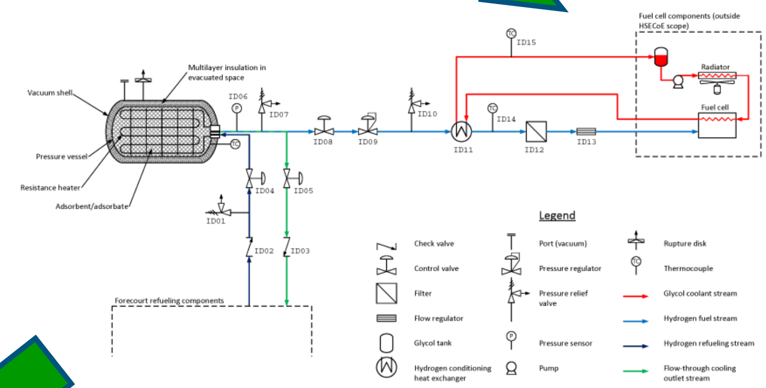
Approach: System Architect and OEM perspective

System Architect Role (D. Siegel)

- Performed analysis for Phase 3 Go/No-go
- Coordinated design status within Adsorbent Team
- Identified and prioritized the research gaps
- Developed SMART milestones and GANTT chart
- Completed operating conditions downselection process
- Organized regular meetings with Adsorbent Team

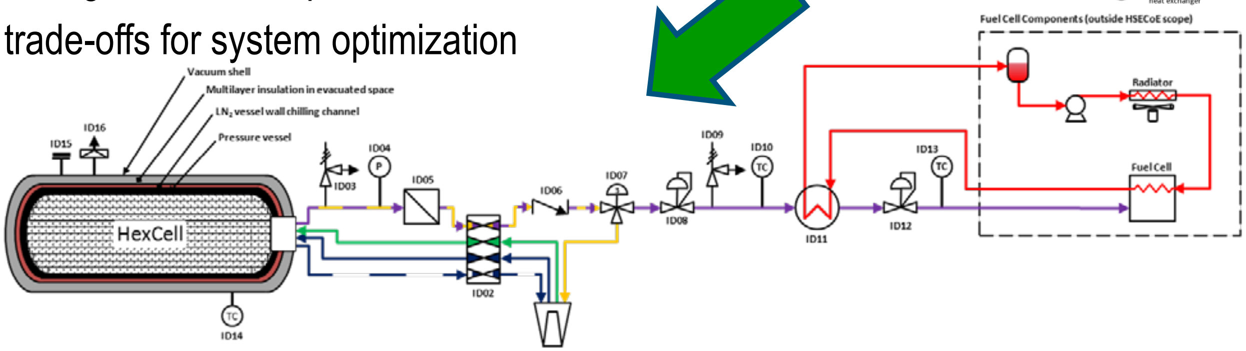
Phase 1 to 2
-developed detailed design and models
-focused concept on low pressure storage





OEM Perspective Role (M. Veenstra)

- Involved in the HSECoE framework model release
- Assisted in the system integration and cost analysis
- Coordinated design verification plan for FMEA
- Engaged in trade-offs for system optimization



Phase 2 to 3
-integrated components and optimized function
-reduction in system by 9.4 kg and 11.6 liters

Adsorbent system has progressed significantly from Phase 1

Approach: System Architect and OEM perspective

System Selection and Comparison for Phase 3 (useable 5.6 kg)

Internal HX and Media	Helical Coil + powder MOF-5	HexCell + powder MOF-5	MATI + 0.32 g/cc MOF-5 puck	700 bar* Compressed H_2
System Mass (kg)	178	159	164	128
System Volume (L)	328	320	270	224
Estimate System Cost at 500K units	$2,486	$2,376	$2,883	$3,134
System Rank (HSECoE utility function)	.593	.622	.616	.686
Gravimetric Capacity (g-H_2/g-system)	3.1 %	3.5 %	3.4 %	4.4 %
Volumetric Capacity (g-H_2/L-system)	17.0 g/l	17.5 g/l	20.7 g/l	25.0 g/l

- Full tank: P = 100 bar, T = 80 K
- Empty tank: P = ~5 bar, T = ~140 K
- Single, Aluminum (6061-T6) Type 1
- LN_2 vessel wall chilling channels

*2013 AMR references
ANL Project ID: ST001
SA Project ID: ST100

Approach: Enhance MOF Performance Potential

Key Objectives of the HSECoE:

- Design, model, and test innovative material-based systems for gap analysis
- Define required materials properties to meet the system technical targets
- Validate models with sub-scale prototype system for predictive capability
- Develop and provide system models for further material research

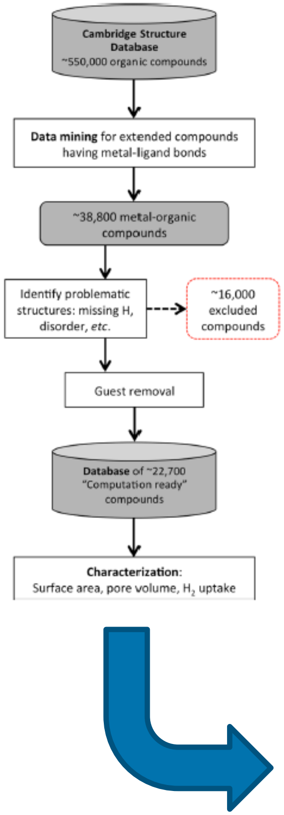
Reviewer Comments from 2013 AMR:

"It is highly unlikely that a system based on MOF-5 will meet the DOE targets. ***It would be helpful if a pathway to identifying an optimum adsorbent system could be provided***."

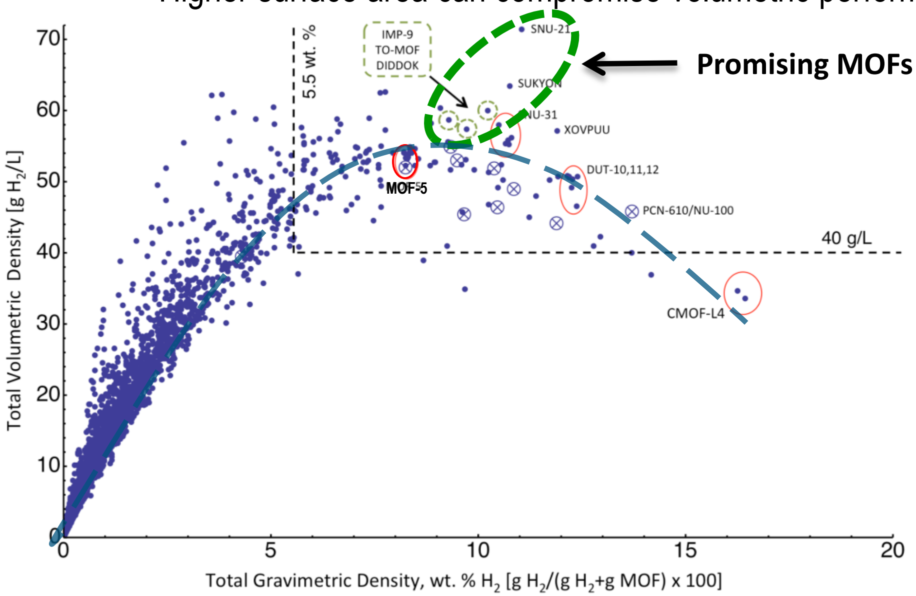
"Experimental and modeling ***analysis should be performed on a promising physisorption material*** that is different from MOF-5."

Progress: Enhance MOF Performance Potential

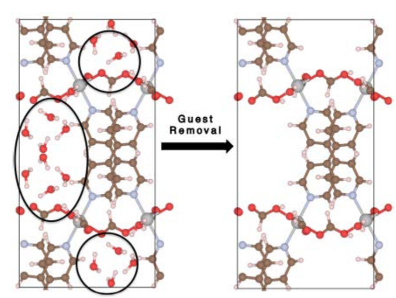
Additional gains in H_2 capacity may be realized using *known* MOFs



- Performed a comprehensive assessment of the theoretical capacities of several thousand known MOFs
  - Accomplished by mining the 600,000+ entry Cambridge Structured Database
  - Automated routines for structure cleanup and analysis
- Identified several MOF with the opportunity of having both high gravimetric and volumetric H_2 density
- Relationship between gravimetric and volumetric density is concave downward:
  - Optimal MOFs for H_2 have a surface area in the range of 3,100 – 4,800 m^2/g; density ~ 0.55 g/cm^3
  - Higher surface area can compromise volumetric performance



Recommendation: de-emphasize maximizing surface area, and focus on synthesis of robust, solvent-free MOFs



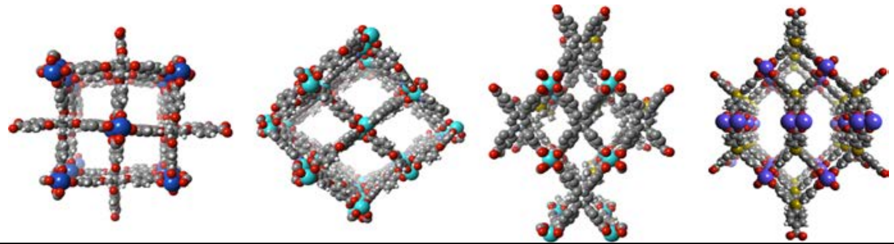
Goldsmith, Wong-Foy, Cafarella, and Siegel, *Chem. Mater.*, 25, 3373 (2013)

Approach: Enhance MOF Performance Potential

- Four MOF Targets of Opportunity were identified
- Exhibit high gravimetric and volumetric densities simultaneously
- Overlooked compounds: no/limited experimental evaluation

Can these be synthesized in a robust form?

(No retained solvent, no pore collapse)



35 bar & 77 K Modeled Values (measured)	EPOTAF (SNU-21)	DIDDOK	LURGEL (TO-MOF)	ENITAX (IMP-9)	MOF-5
Total Grav. (wt. %)	11	10.2	9.7	9.3	8.2 (8.4)
Total Volumetric (g/L)	71	60	57	59	52 (54)
Crystal Density (g/cm^3)	0.58	0.53	0.53	0.57	0.59
BET Surface Area (m^2/g)	5208 (700-900)	4651	4386 (680)	4162	3660 (3800)
Notes	Best performer. H_2 uptake measured previously: 5 wt. %	No measurements	CO_2 uptake measured	No measurements	For reference purposes

Goldsmith, Wong-Foy, Cafarella, and Siegel, *Chem. Mater.*, 25, 3373 (2013)

Potential system improvements are 34% gravimetric & 37% volumetric

Approach: Phase 3 SMART Milestones and Tasks

Component	Partner	Proposed SMART Milestones for Phase 3	Due Date
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**.	12/31/2013
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	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	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
Additional task:		Explore approaches to **maximize the MOF-5 "real-world" material properties**: advance thermal conductivity, mass transport, and safety	

Project approach based on collaborative HSECoE SMART milestones

Progress: MOF-5 Manufacturing Scale-up

Milestone Task: 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.

´7 L scale´ synthesis:

Becher
Laboratory stirrer
$\text{Yield}_{\text{Terephtalic acid}}$: 81 mol%
Surface area: 2680 m^2/g
Batch Amount: >0.1 kg

´60 L scale´ synthesis:

Steal reactor
Plant stirrer
$\text{Yield}_{\text{Terephtalic acid}}$: 81 mol%
Surface area: 2905 m^2/g
Batch Amount: > 1 kg

´200 L scale´ synthesis:

Steal reactor
Plant stirrer
$\text{Yield}_{\text{Terephtalic acid}}$: 81 mol%
Surface area: 2937 m^2/g
Batch Amount: > 3 kg
STY: >150 $kg/m^3/d$

Crystallizing	Filtering Washing	Drying	Milling	MOF-5 Powder
Reactor	Filter	Oven	Mill	Drum

Successful Phase 3 MOF-5 scale-up and delivery of a 9.3 kg drum

Progress: MOF-5 Manufacturing Scale-up

Milestone Task: 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.

Batch Code	Reactor Size [L]	Amount [kg]	BET [m²/g]	LSA [m²/g]	Zn [wt%]	C [wt%]	Crystal size [µm]	Particle size [mm]
GP0372	200	3.1	2937	3838	32	37	0.2-2.0	
GP0374	200	3.5	2870	3794	34	37	0.2-2.0	
GP0375	200	3.2	2955	3896	34	37	0.2-2.0	
GP0378	Mix	9.3	2937	3877	30	37	0.2-2.6	0.1-1.3
GP0326	60	1	2905	3891	34	37	0.2-3.0	0.1-1.4
Scale-Up Difference:			**1%**	**.4%**				**7%**
Reference GW0116	7	.14	2680	3547			0.2-2.0	

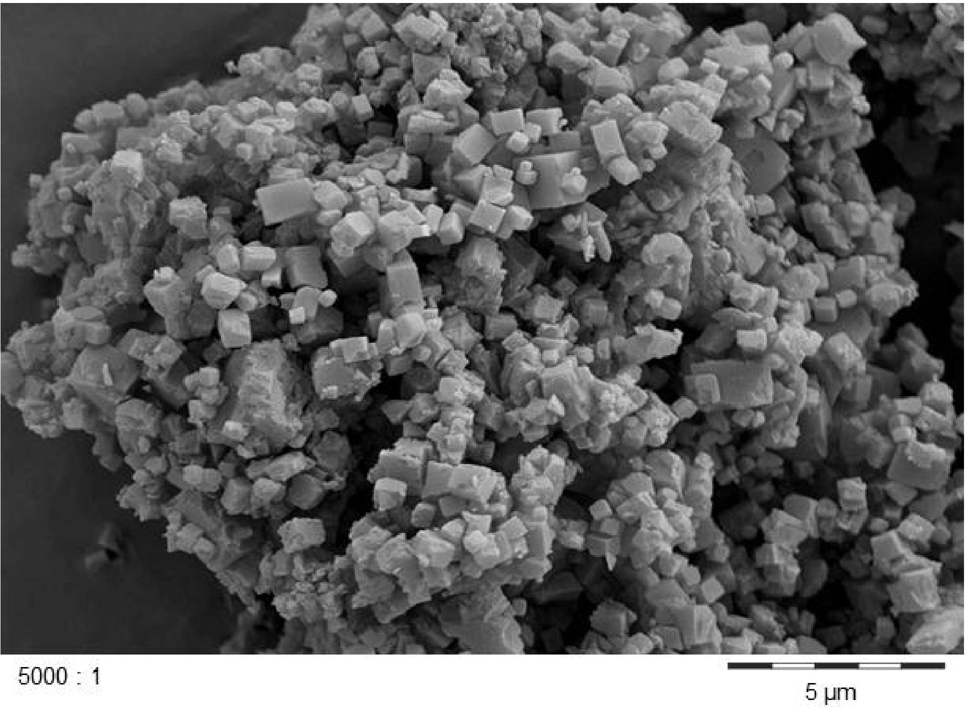
MOF-5 scale-up material achieved target of 10% of lab-scale synthesis

Progress: MOF-5 Manufacturing Scale-up

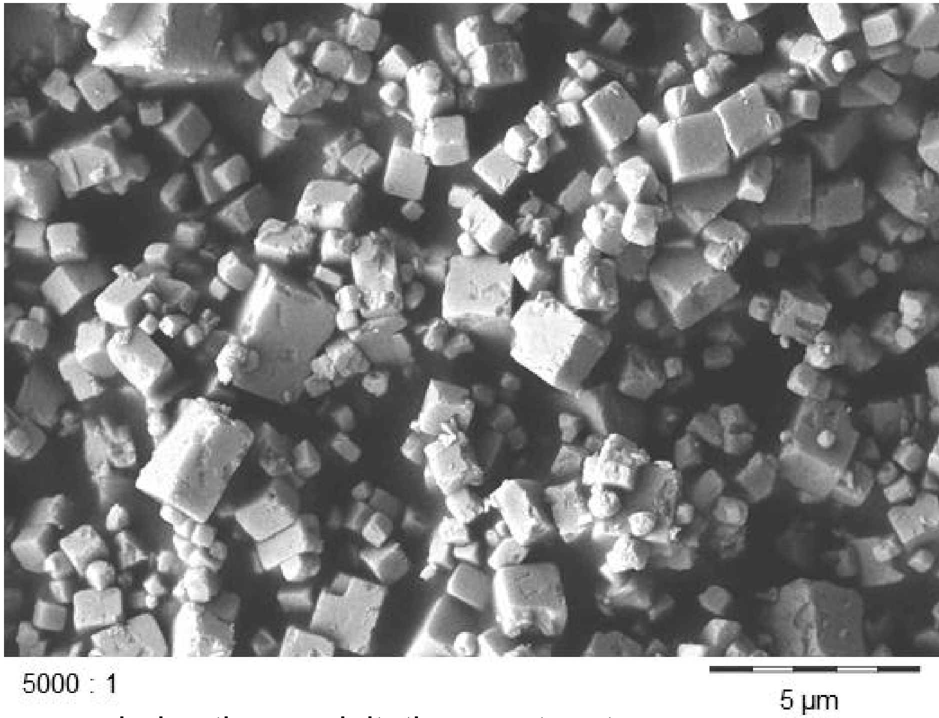
Milestone Task: Conduct a scale-up of the MOF-5 manufacturing process to deliver > 9 kg

Crystal size SEM microscopy comparison analysis - magnification 5000:1

200 L Batch



60 L Batch



Crystal size variation can occur as a result of different stirring energy during the precipitation reactor step.

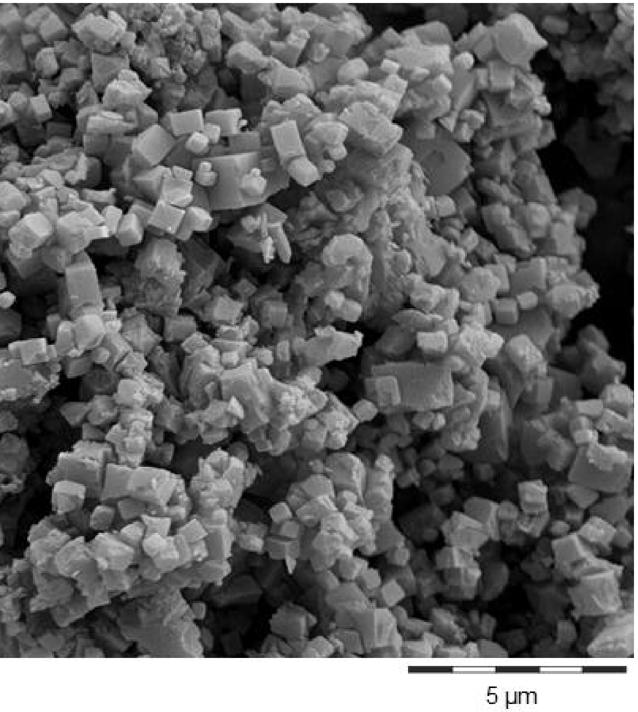
MOF-5 scale-up material has comparable crystal size with lab-scale

Progress: MOF-5 Manufacturing Scale-up

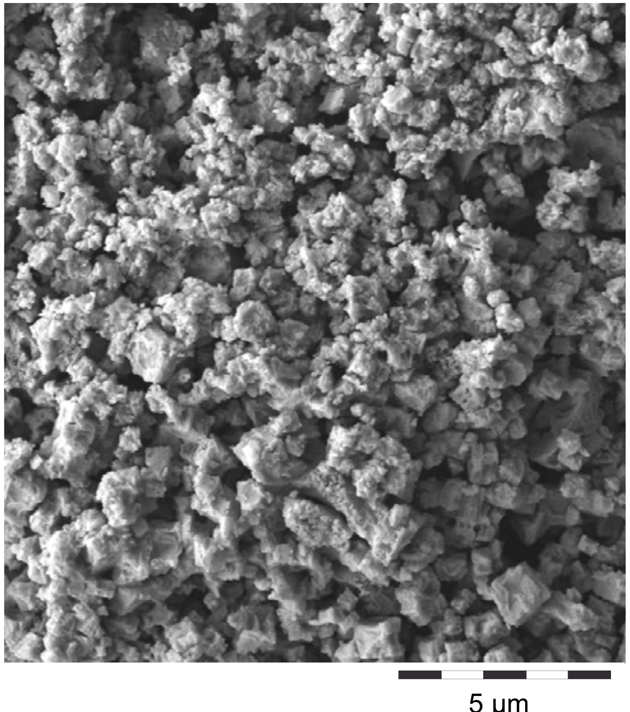
Milestone Task: Conduct a scale-up of the MOF-5 manufacturing process to deliver > 9 kg

Crystal size SEM microscopy comparison analysis - magnification 5000:1

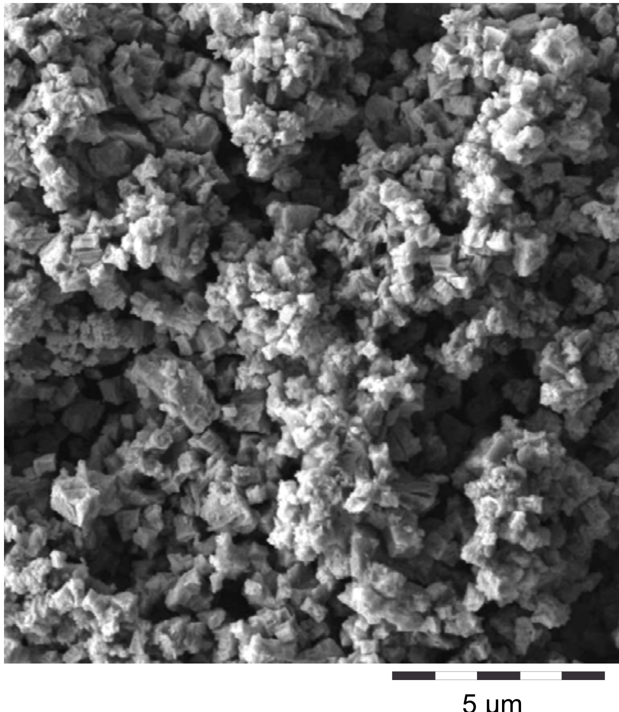
GP0372



GP0374



GP0375



Crystal surface roughness variation can occur as a result of different washing times during the solvent filtering step.

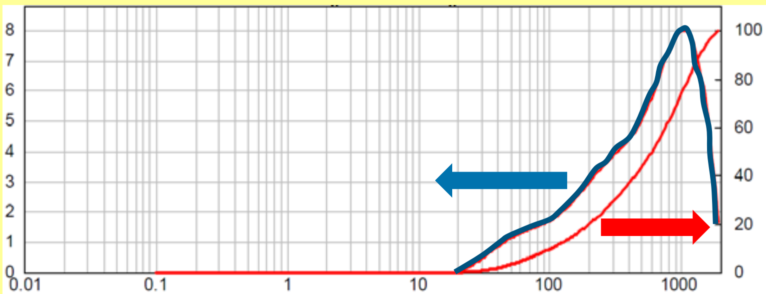
MOF-5 scale-up material has repeatable crystal size between batches

Progress: MOF-5 Manufacturing Scale-up

Milestone Task: Conduct a scale-up of the MOF-5 manufacturing process to deliver > 9 kg

60 L Batch

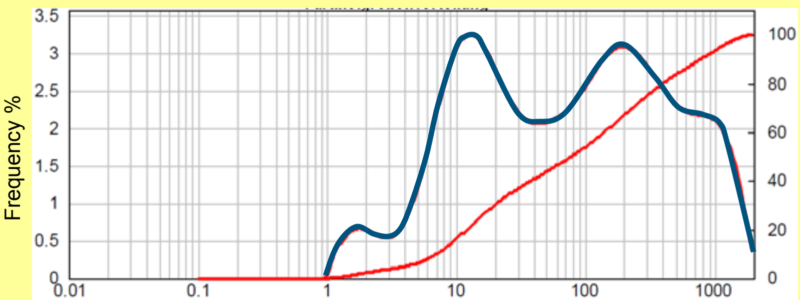
Low Dispersion Rate Pressure (.2 bar)



Particle Size (µm)

Cumulative Distribution	10%	50%	90%
	103.6 µm	604.8 µm	1403.1 µm

High Dispersion Rate Pressure (3.5 bar)

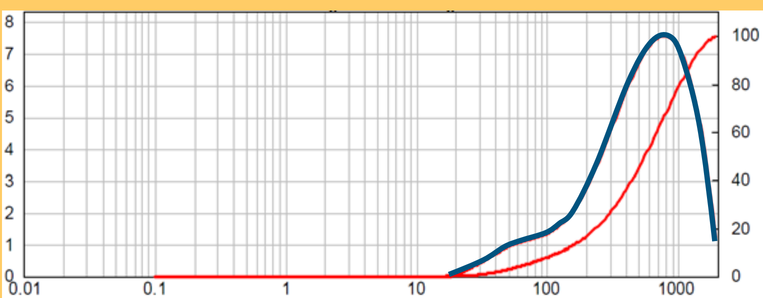


Particle Size (µm)

Cumulative Distribution	10%	50%	90%
	7.0 µm	77.8 µm	781.1 µm

200 L Batch

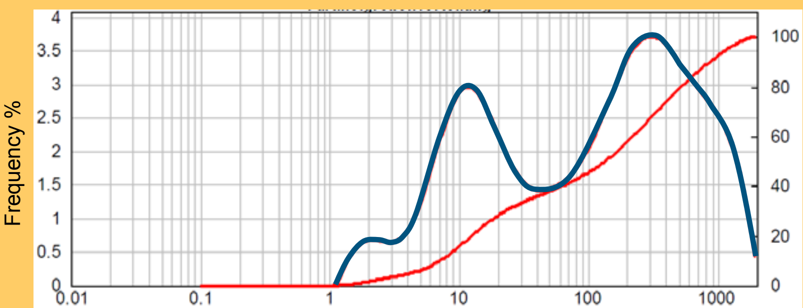
Low Dispersion Rate Pressure (.2 bar)



Particle Size (µm)

Cumulative Distribution	10%	50%	90%
	123.1 µm	557.9 µm	1310.8 µm

High Dispersion Rate Pressure (3.5 bar)



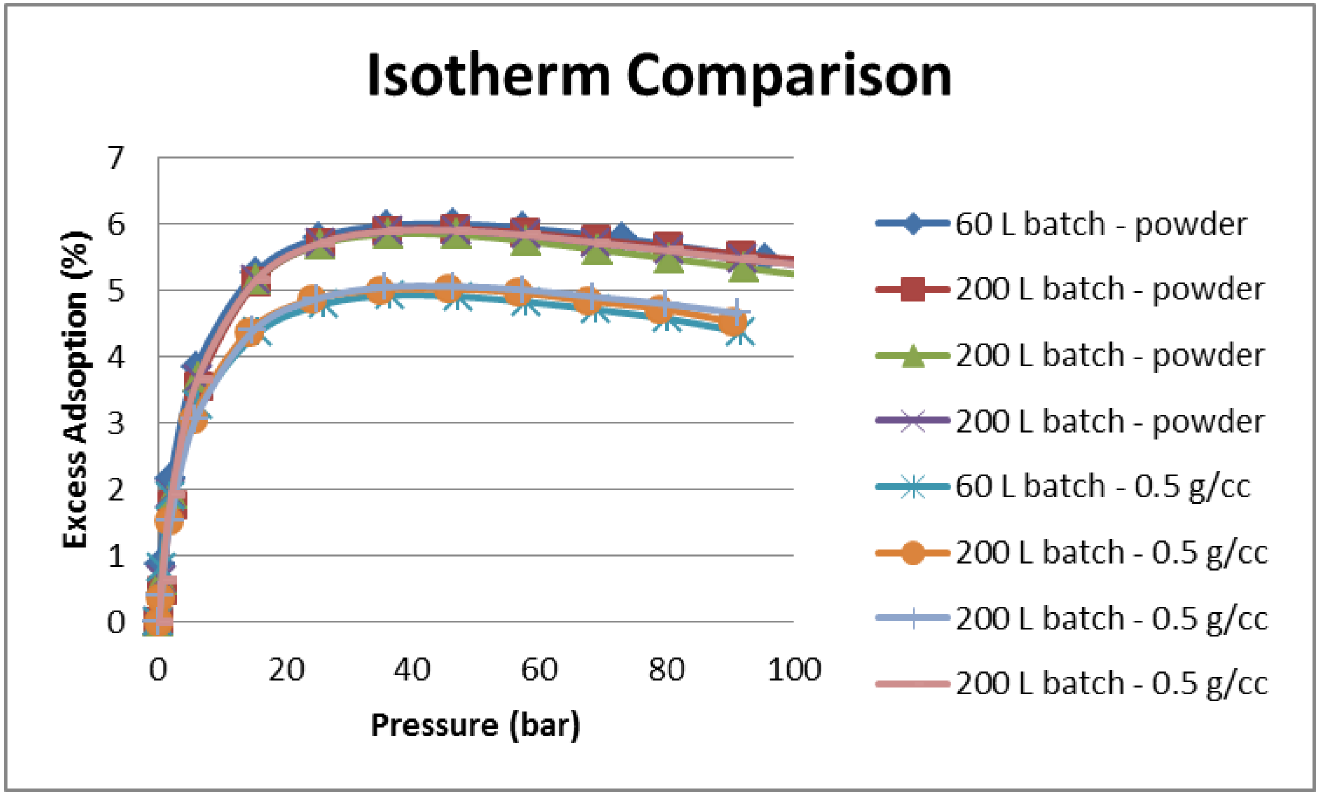
Particle Size (µm)

Cumulative Distribution	10%	50%	90%
	7.1 µm	135.6 µm	872.4 µm

MOF-5 scale-up material has consistent particle size as lab-scale

Progress: MOF-5 Manufacturing Scale-up

Milestone Task: 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.



MOF-5 scale-up material has equivalent performance as lab-scale

Progress: MOF-5 Robustness to H_2 Impurity

Milestone Task: 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%.

Impurity degradation projections

Constituent	Chemical Formula	Limits	Laboratory Test Methods to Consider and Under Development[e]	Impurity per cycle [g]	Impurity in 300 cycles	*Estimated effect on MOF-5*
Hydrogen fuel index	H_2	**> 99.97%**				
Total allowable non-hydrogen, non-helium, non-particulate constituents listed below		100				
Acceptable limit of each individual constituent						
Water[a]	H_20	**5**	ASTM D7653-10, ASTM D7649-10	0.031	**9.3 g**	**≤2% destruction of surface area**
Total hydrocarbons[b] (C_1 basis)		**2**	ASTM D7675-11	0.0124	**3.7 g**	*<0.1% surface area blocking*
Oxygen	O_2	**5**	ASTM D7649-10	0.031		*no effect*
Helium		**300**	ASTM D1945-03	1.86		*no effect*
Nitrogen, Argon	N_2, Ar	**100**	ASTM D7649-10	0.62		*no effect*
Carbon dioxide	CO_2	**2**	ASTM D7649-10, ASTM D7653-10	0.0124	**3.7 g**	*<0.1% surface area blocking*
Carbon monoxide	CO	**0.2**	ASTM D7653-10	0.00124	**0.4 g**	*<0.1% surface area blocking*
Total sulfur[c]		**0.004**	ASTM D7652-11	0.0000248	**0.01 g**	*potential damage -not detectable at impurity level*
Formaldehyde	HCHO	**0.01**	ASTM D7653-10	0.000062		*no effect*
Formic acid	HCOOH	**0.2**	ASTM D7550-09, ASTM D7653-10	0.00124	**0.4 g**	*potential damage -not detectable at impurity level*
Ammonia	NH_3	**0.1**	ASTM D7653-10	0.00062	**0.2 g**	*potential damage -not detectable at impurity level*
Total halogenates[d]		**0.05**	(Work Item 23815)	0.00031	**0.1 g**	*potential damage -not detectable at impurity level*
Particulate Concentration		**1 mg/kg**	ASTM D7650-10 , ASTM D7651-10			

See SAE J2719 for original reference

Hypothesis: MOF-5 will only have minor effects during impurity testing

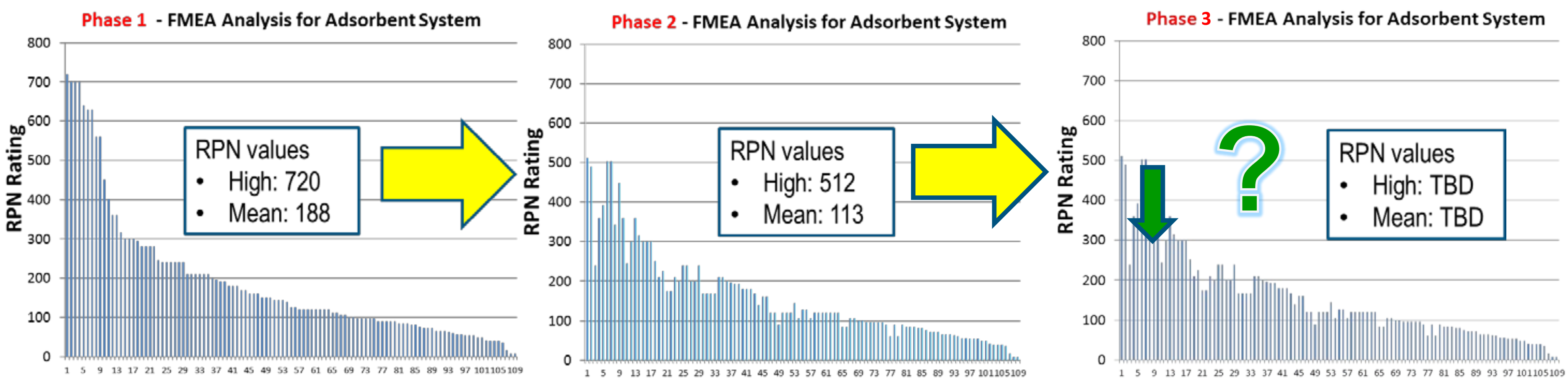
Progress: FMEA - Failure Mode Reduction

FMEA = Failure Mode and Effects Analysis (industry tool per SAE J1739)

- Identifies and evaluates the potential failure of a product and its effects
- Documents the risk and helps prioritize the key actions to reduce failures

Top Failure Modes for Adsorbent System at phase 2 with Risk Priority Number (RPN) >300

1. Material release rate insufficient due to non-homogenous materials or bed
2. Material release rate insufficient due to impurities (from station at single time or lifetime)
3. Tank incompatible with adsorbent or in-service activation
4. Material release rate insufficient due degradation in heat transfer in bed and to the thermal management system

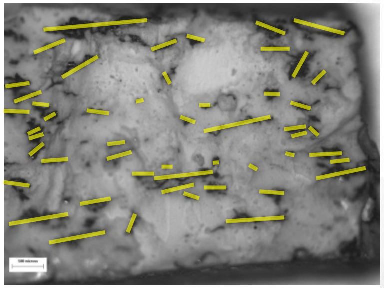


Additional failure mode reductions are expected at the end of Phase 3

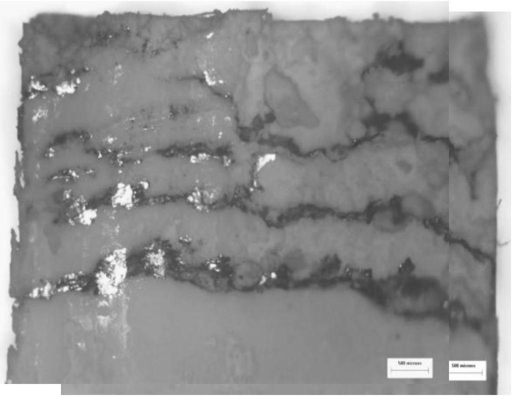
Progress: Maximize MOF-5 Material Properties

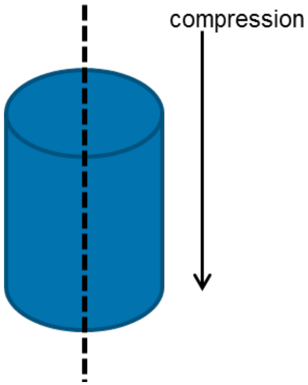
Explore approaches to advance thermal conductivity, mass transport, and safety

MOF-5 with random ENG



MOF-5 with ENG layers

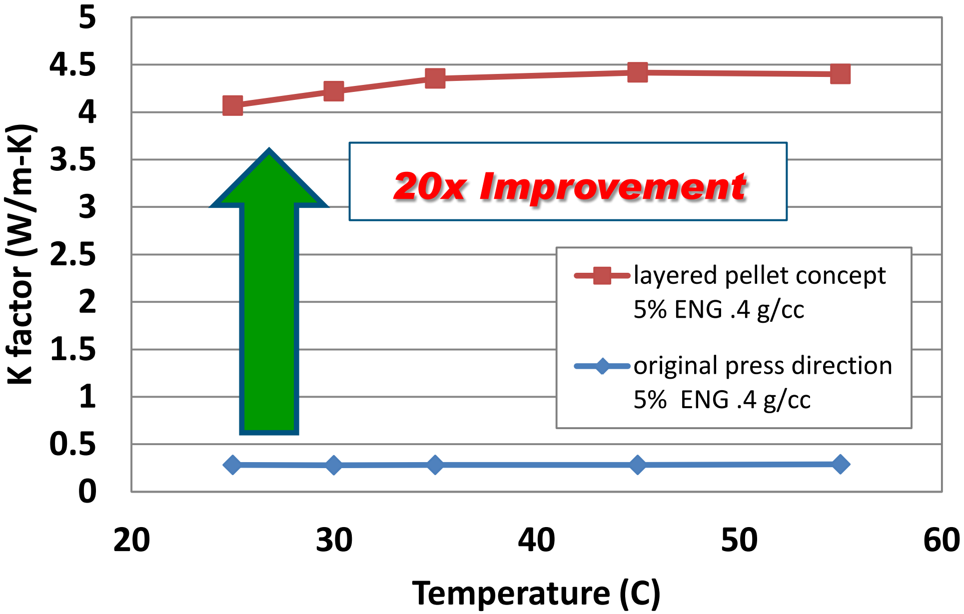




The pellet was formed by filling the die with alternating layers of MOF-5 and ENG. When all the layers were filled the pellet was pressed. The ENG appears to form one connected layer across the pellet.

(Ford Patent Pending)

MOF-5 layered pellet .33 g/cc + 5% ENG
Cross-compression thermal conductivity



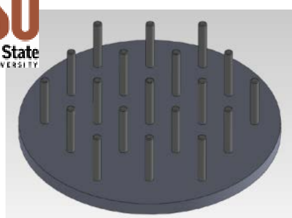
MOF thermal conductivity break-through using aligned ENG

Progress: Maximize MOF-5 Material Properties

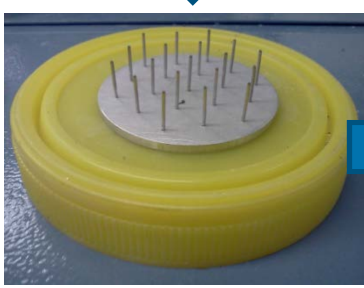
Explore approaches to advance thermal conductivity, mass transport, and safety

MOF-5 formation with pins

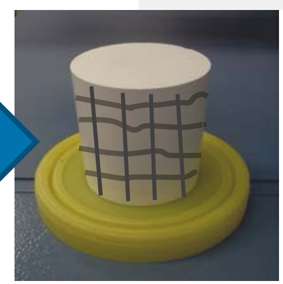
Formed the MOF-5 bed around the pins to increase conduction enhancement.



Two (solid & hollow) aluminum pin configurations were formed that had .1 cm diameter with roughly a 1 cm height (depth into the MOF5 bed) with spacing of about 1 cm

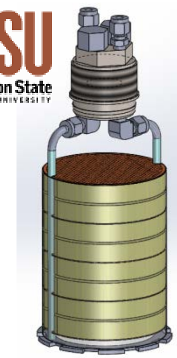


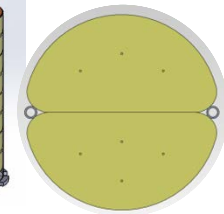
Pucks: ø5 cm x 1.5 cm

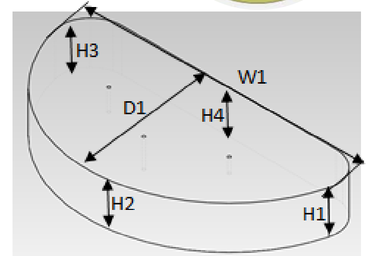


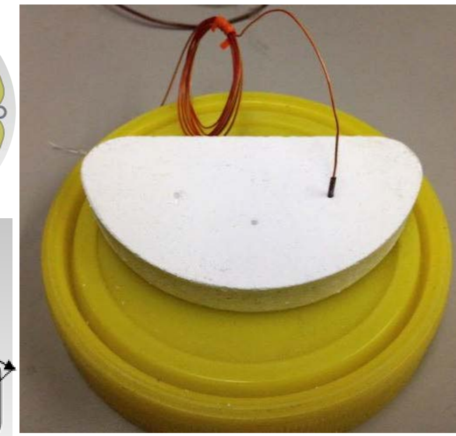
ENG layering +pins

MATI Puck formation









High repeatability with forming

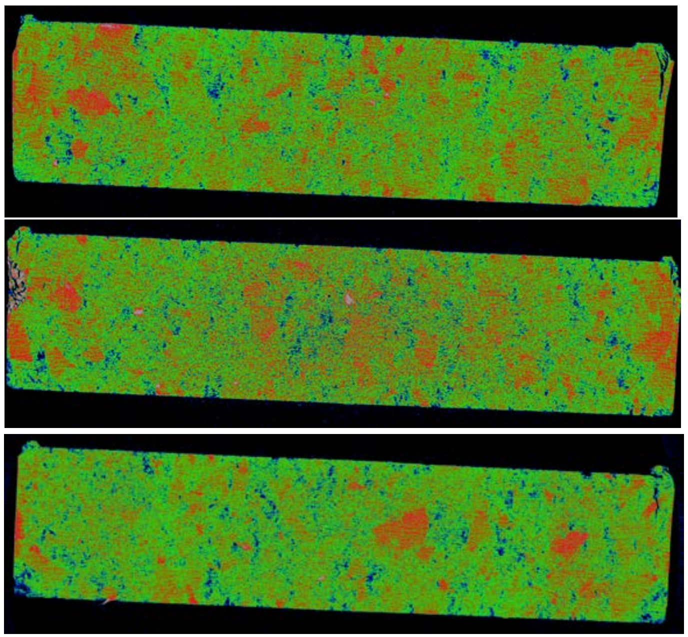
	Weight (g)	Density (g/cc)	Avg Height (mm)	D1 (mm)	W1 (mm)
A	23.39	0.40	15.14	50.23	96.33
B	23.42	0.40	15.28	50.23	96.35
C	23.35	0.40	15.08	50.25	96.35
D	23.41	0.41	14.93	50.22	96.38
E	23.46	0.40	15.27	50.26	96.39
F	23.52	0.40	15.25	50.24	96.37
Average:	**23.43**	**0.40**	**15.16**	**50.24**	**96.36**
Std Dev:	**0.059**	**0.003**	**0.139**	**0.015**	**0.022**

Puck formation offers additional enhancements to thermal conductivity

Progress: Maximize MOF-5 Material Properties

Explore approaches to advance thermal conductivity, mass transport, and safety

MicroCT analysis: the density difference within a puck at .40 g/cc and 10 wt.% ENG density. The scan confirmed an average density of 0.41g/cc (density: red > green > blue)

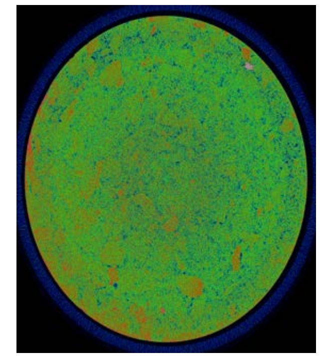


Sample Section Distributions

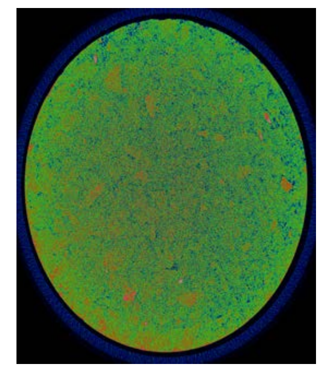
Mean density: 0.443g/cc
Standard deviation: 0.123g/cc

Mean density: 0.439g/cc
Standard deviation: 0.145g/cc

Mean density: 0.420g/cc
Standard deviation: 0.134g/cc



Mean density=0.411g/cc

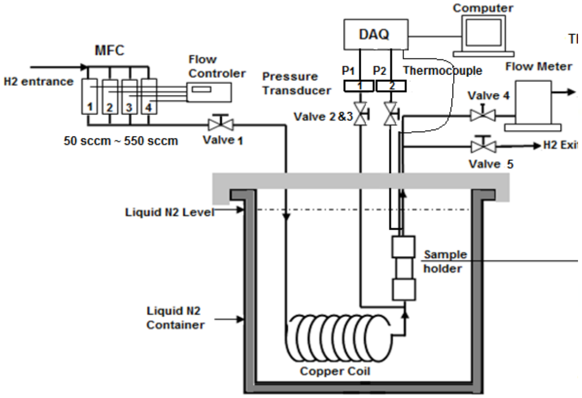


Mean density=0.406g/cc

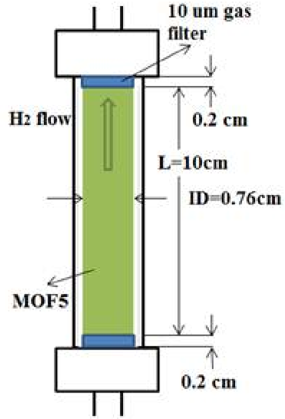
Scanning tools provide opportunity to optimize pellet & puck formation

Progress: Maximize MOF-5 Material Properties

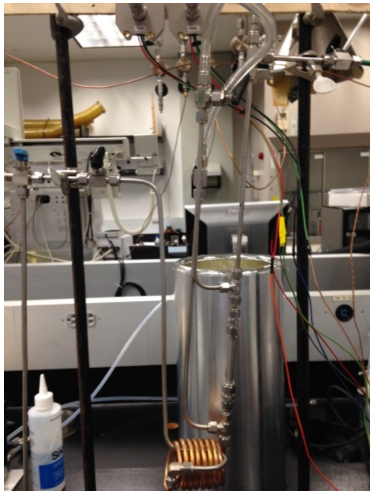
Explore approaches to advance thermal conductivity, mass transport, and safety



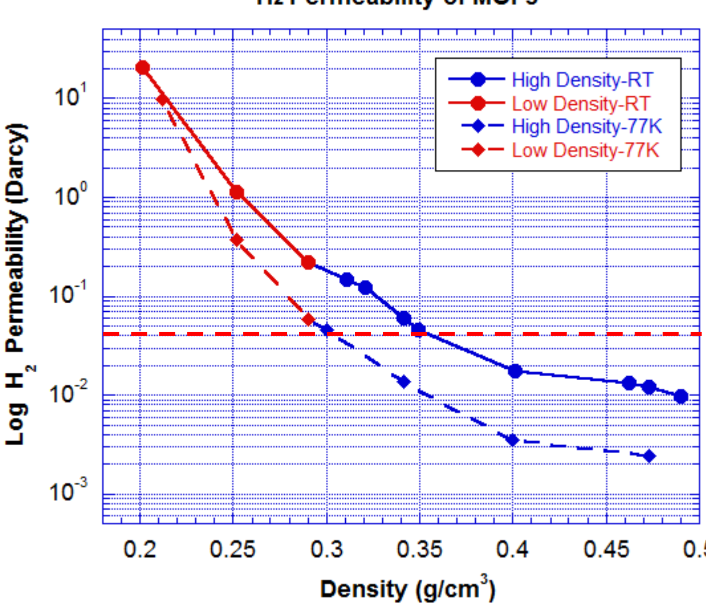
a. Setup diagram



b. Sample Holder



Darcy permeability of hydrogen through sample at various densities from the RT test data



$$\Delta P = \frac{v \mu h}{\kappa} \qquad v = velocity \quad \mu = visocity \quad h = height \quad k = Darcy$$

Target line based on permeation with flow rate of 1 m/s and pressure drop of 5 bar for flow through cooling

Major increase in mass transport permeability with low density powder

Progress: Maximize MOF-5 Material Properties

Explore approaches to advance thermal conductivity, mass transport, and safety

Explosion Severity of Dust Cloud, K_{st} (ASTM E 1226)

- Test provides an indication of the severity of a dust cloud explosion
- Data produced:
  - Maximum developed pressure, P_{max}
  - Maximum rate of pressure rise, $(dP/dt)_{max}$
- Deflagration index (explosion severity) K_{st}

$K_{st} = (dP/dt_{max})\ V^{1/3}$ [bar.m/s] where V is the volume of the test vessel

- Used for the design of deflagration protection

Based on test data using 1m³ and 20L Vessels and 10KJ Ignition Source

Dust Explosion Class	K_{st} (bar * m/s)	Characterization
St 0	0	Non-explosible
St 1	$0 < K_{st} < 200$	Weak to moderately explosible
St 2	$200 < K_{st} < 300$	Strongly explosible
St 3	$K_{st} > 300$	Very strongly explosible

TEST RESULTS FOR MOF-5

Maximum explosion pressure: 6.3 bar abs

Deflagration index (K_{st}) value: 48 bar * m / s

Dust explosion class: St 1

MOF-5 testing resulted in a low explosion class and deflagration index

Summary: Phase 3 SMART Milestones and Tasks

SMART Milestone Tasks	Status
Conduct a scale-up of the MOF-5 manufacturing process > 9 kg	✓ Delivered 9.3 kg of MOF-5 for Phase 3 to HSECoE partners within 10% of lab-scale synthesis material
Evaluate MOF-5 degradation cycles using impurity levels as stated in SAE J2719	✓ Degradation projections completed and initial cycling has started with ammonia impurity without degradation
Complete the failure mode and effects analysis (FMEA) based on the Phase 3	✓ Initiated design verification plan (DVP) to align the FMEA action items with the Phase 3 test results
Support system model release and validation with Phase 3 performance results	✓ Provided fuel cell model to Simulink framework based on validated data and participated in modeling group

Additional Tasks	Status
Enhance thermal conductivity	✓ Demonstrated significant improvements (20x) in thermal conductivity with anisotropic ENG layering
Conduct compaction puck formation	✓ Formulated the MATI half pucks with embedded thermocouples with high consistency
Extend permeation flow evaluation	✓ Tested flow hydrogen flow parameter through powders
Complete safety assessment	✓ Provided deflagration index based on explosive severity cloud safety testing

Future Work: Complete Phase 3 Tasks

- Complete MOF-5 degradation cycle testing based on impurity levels as stated in SAE J2719 and report on the ability to mitigate to less than 10%.

- 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. Reduce the risk priority numbers (RPN) from the phase 2 peak/mean and identify key failure modes.

- Complete the optimization approaches to enhance thermal conductivity, mass transport, and density variations in formed pucks.

- Support the modeling validation using Phase 3 test data, further integration of the system BOP components for the cost analysis, and prepare for HSECoE project summary documentation to guide material researchers.

Collaborations: HSECoE Partners

- SRNL (federal lab collaborator): team lead for sorbent (bed) transport phenomena, adsorbent system modeling, and center management
- Universite du Quebec a Trois-Rivieres (university collaborator): adsorption system test bench and MOF-5 isotherm validation
- GM (industrial collaborator): sorbent materials operating parameters, sorbent system modeling, and helical coil heat exchanger development
- Oregon State University (university collaborator): development of micro-channel internal bed heat exchanger and combustors
- Hexagon Lincoln (industrial collaborator): pressure vessel development for hydrogen storage system concepts
- PNNL (federal lab collaborator): team lead for cost modeling, bill of materials, and materials operating requirements
- UTRC (industrial collaborator): material particulate testing, MOF-5 thermal conductivity measurements, and on-board system modeling
- NREL (federal lab collaborator): vehicle level modeling, wells-to-wheels analysis, MOF-5 isotherm validation, and low temperature isotherms
- JPL (federal lab collaborator): insulation development and cryogenic parameter evaluation

Interactions include monthly team meetings (sorbent system, material operating req., system modeling), regular data and information exchanges, and ten HSECoE face-to-face meetings

Technical Back-up Slides

General FMEA Overview and Approach

The FMEA is based on the required system functions from the technical targets.

Table 1. Technical System Targets: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles[a]			
Storage Parameter	**Units**	**2017**	**Ultimate**
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass) [b]	kWh/kg ($kg\ H_2/kg$ system)	1.8 (0.055)	2.5 (0.075)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume) [b]	kWh/L ($kg\ H_2/L$ system)	1.3 (0.040)	2.3 (0.070)
Storage System Cost:	\$/kWh net ($\$/kg\ H_2$)	12 400	8 266
• Fuel cost [c]	\$/gge at pump	2-4	2-4
Durability/Operability:			
• Operating ambient temperature [d]	°C	-40/60 (sun)	-40/60 (sun)
• Min/max delivery temperature	°C	-40/85	-40/85
• Operational cycle life (1/4 tank to full)	Cycles	1,500	1,500
• Min delivery pressure from storage system	bar (abs)	5	3
• Max delivery pressure from storage system	bar (abs)	12	12
• Onboard efficiency [e]	%	90	90
• "Well" to powerplant efficiency [e]	%	60	60
Charging/Discharging Rates:			
• System fill time (5 kg)	min ($kg\ H_2/min$)	3.3 (1.5)	2.5 (2.0)
• Minimum full flow rate	(g/s)/kW	0.02	0.02
• Start time to full flow (20°C)	s	5	5
• Start time to full flow (-20°C)	s	15	15
• Transient response at operating temperature 10-90% and 90-0%	s	0.75	0.75
Fuel Quality (H_2 from storage): [f]	% H_2	SAE J2719 and ISO/PDTS 14687-2 (99.97% dry basis)	
Environmental Health & Safety:			
• Permeation & leakage [g]	-	Meets or exceeds applicable standards	
• Toxicity	-		
• Safety	-		
Loss of Useable H_2: [h]	$(g/h)/kg\ H_2$ stored	0.05	0.05

Cost of Ownership
(Provide a competitive system)

Accept Fuel
(Fill storage system)

Deliver Fuel
(Supply H_2 from storage system)

Store Fuel
(Manage H_2 in the system)

General FMEA Overview and Approach

Severity x Occurrence x Detection = RPN

Effect	Ranking
Hazardous without warning	10
Hazardous with warning	9
Very High	8
High	7
Moderate	6
Low	5
Very Low	4
Minor	3
Very Minor	2
None	1

Probability of Failure	Ranking
Very High: Persistent Failures	10
	9
High: Frequent Failures	8
	7
Moderate: Occasional Failures	6
	5
	4
Low: Relatively Few Failures	3
	2
Remote: Failure is Unlikely	1

Likelihood of Detection	Ranking
Absolute Uncertainty	10
Very Remote	9
Remote	8
Very Low	7
Low	6
Moderate	5
Moderately High	4
High	3
Very High	2
Almost Certain	1

Risk

Priority

Number