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 2014
- Percent Complete: 70%

Budget

- Total Project Funding:
  - DOE Share: $2,140K
  - Contractor Share: $643K
- Funding for FY12: $400K
- Funding for FY13: $350K

Barriers

- All DOE System Targets*

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

Partners

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

Relevance: Technical

Three Technical Tasks Contribute to the Overall HSECoE Mission

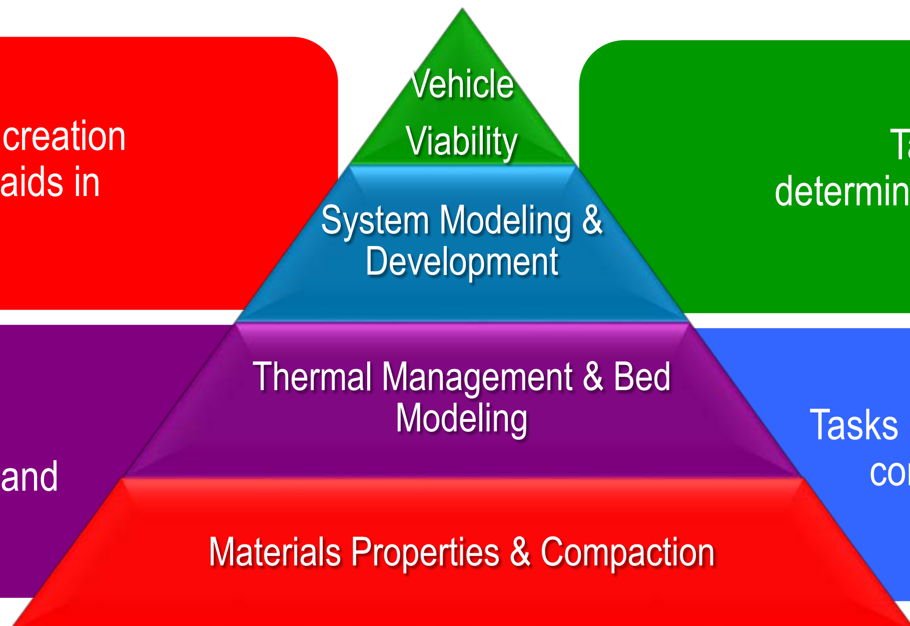
Task 1: Develop dynamic vehicle parameter model that interfaces with diverse storage system concepts
Task 2: Development of robust cost projections for storage system concepts
Task 3: Devise and develop system-focused strategies for processing and packing framework-based sorbent hydrogen storage media

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

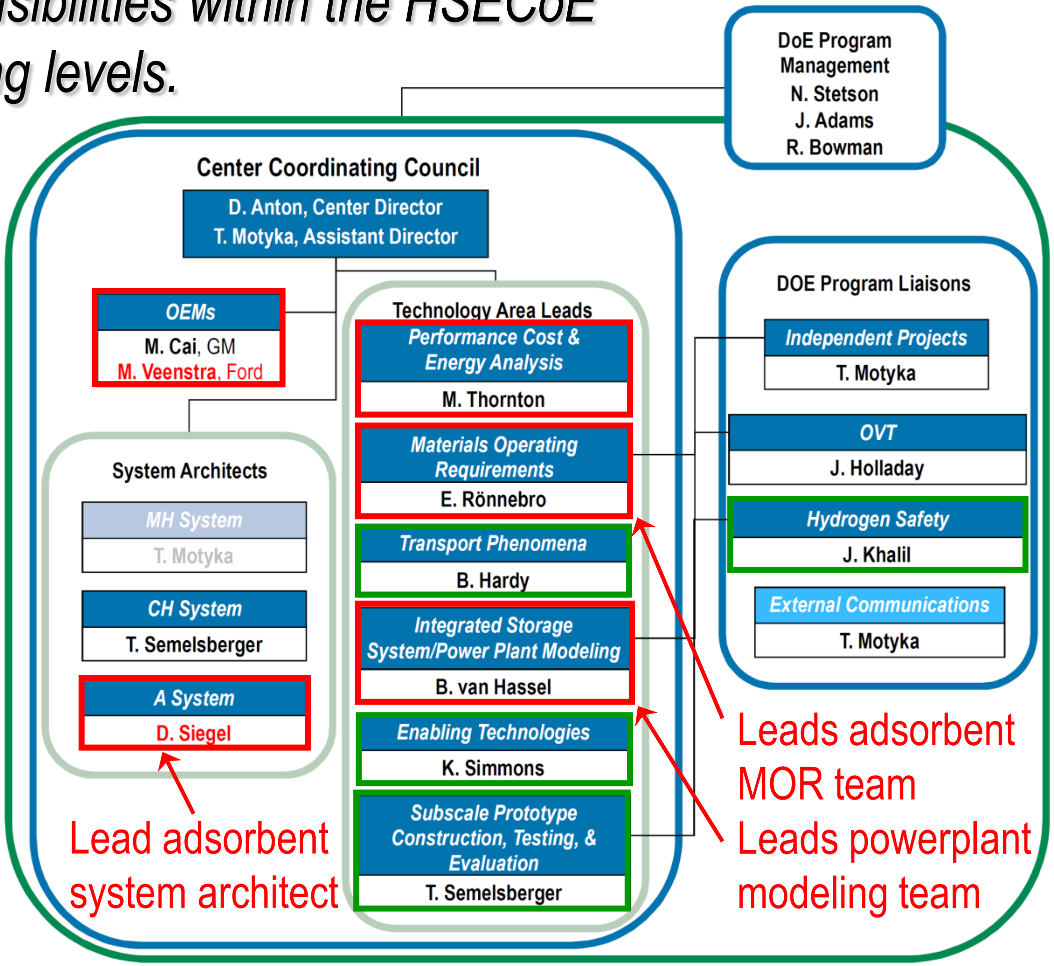
Tasks 1 & 2 models enable storage concepts to be exercised at the real-world vehicle level

Relevance: Organizational

Ford 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

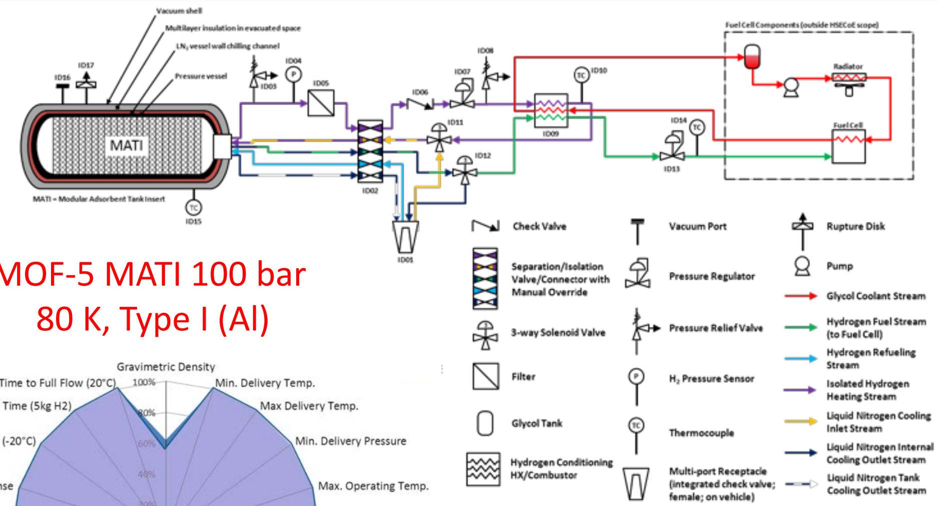


- Core contribution areas of project outcomes [red]
- Ancillary contribution areas of project outcomes [green]

Approach: System Architect and OEM perspective

System Architect Role (D. Siegel)

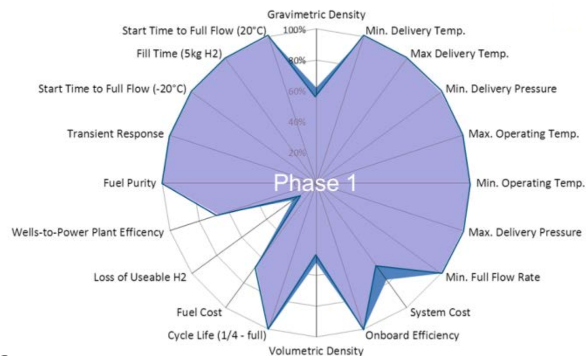
- Coordinated design/performance trade-offs
- Identified strategic decisions (i.e. pressure, temp, tank)
- Developed criteria for media selection and milestones
- Completed Phase 3 test plan and target matrix
- Organized analysis for Phase 3 Go/No-go Review

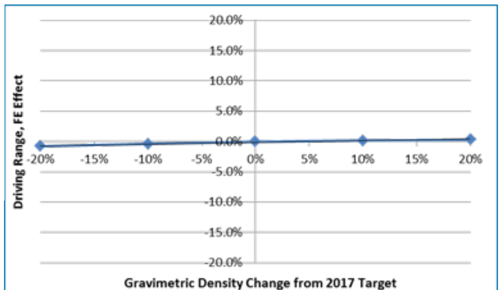


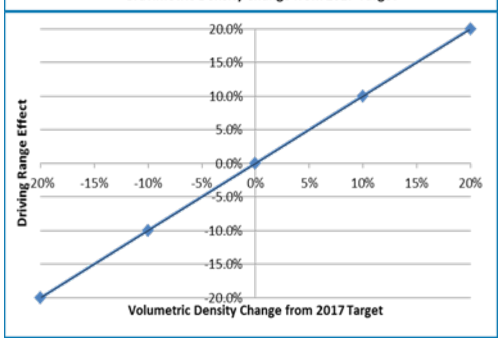
MOF-5 MATI 100 bar
80 K, Type I (Al)

OEM Perspective Role (M. Veenstra)

- Developed fuel cell model and vehicle use cases
- Supported cost studies with high volume analysis
- Provided FMEA guidance to avoid failure modes
- Quantified objective function for system rankings







System Score = Grav. Score + Cost Score + Vol. Score

Target Score = (% of Target Obtained)*∑(Importance * Correlation Constant)

Gravimetric Score = $S_{GD\%} (I_{FE} \times C_{GFE} + I_{DR} \times C_{GDR} + I_{VA} \times C_{GVA} + I_{VC} \times C_{GVC})$

Cost Score = $S_{C\%} \times I_{VC} \times C_{CVC}$

Volumetric Score = $S_{VD\%} \times I_{DR} \times C_{VDR}$

Rating value based on how important to customer?
- Used HSTT OEM Analytic Hierarchy Process (AHP) with sales and survey data

Vehicle Attributes

		Fuel economy *(weight)*	Driving range	Vehicle acceleration	Vehicle Cost *Initial Price*
System Targets	***Importance:***	I_{FE}	I_{DR}	I_{VA}	I_{VC}
Gravimetric Density		C_{GFE}	C_{GDR}	C_{GVA}	C_{CVC}
System Cost					C_{GVC}
Volumetric Density			C_{VDR}		

HSECoE

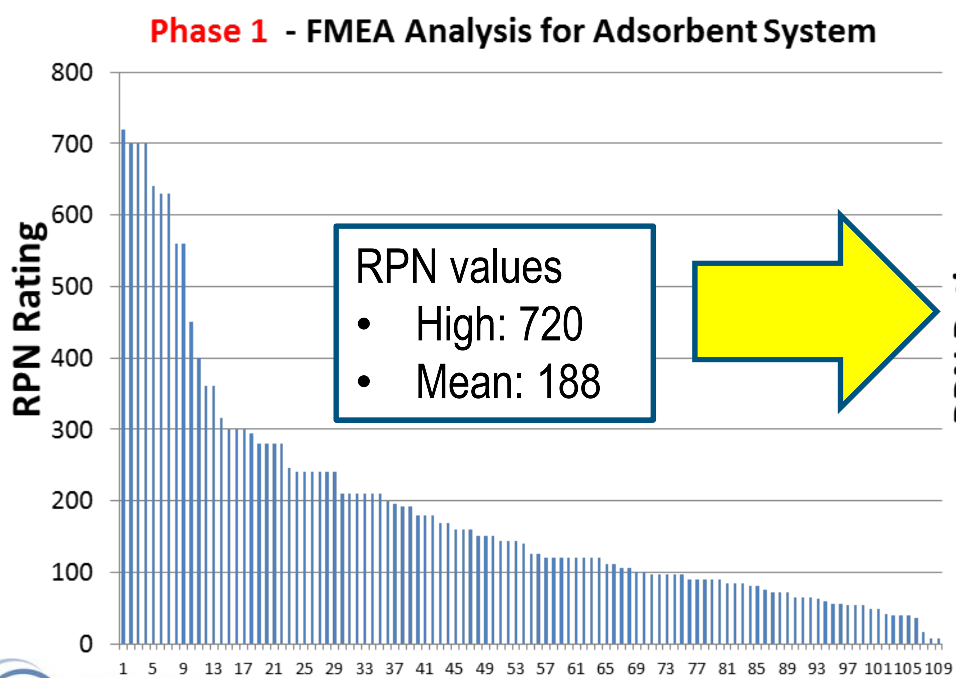
Progress: Reevaluated System Design FMEA

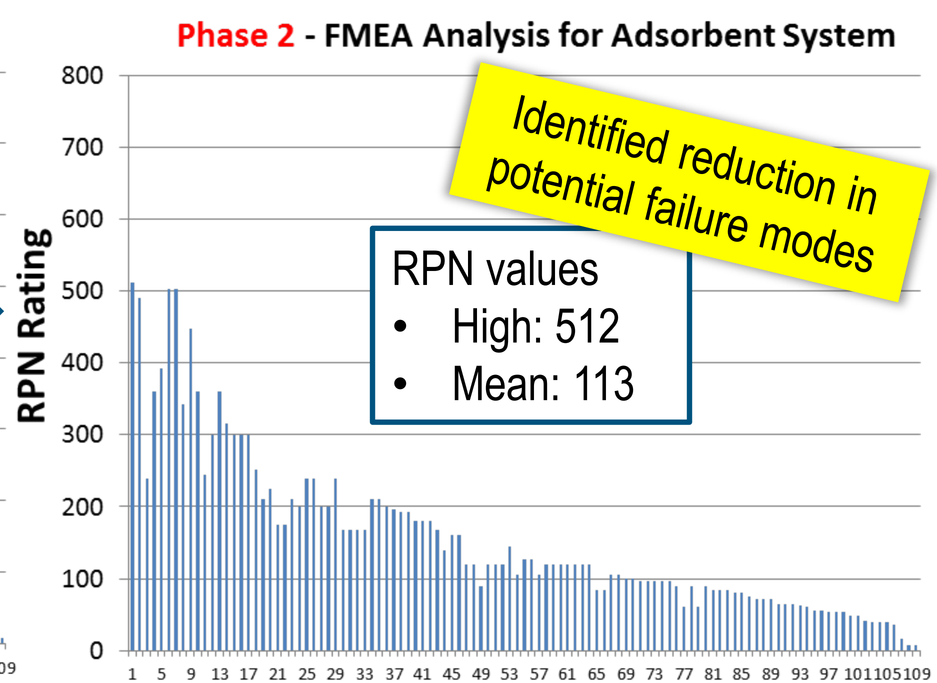
FMEA = Failure Mode and Effects Analysis (industry tool per SAE J1739)

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

Example actions during phase 2 for reducing the Risk Priority Number (RPN)

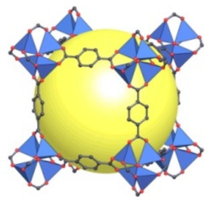
1. Completed initial homogenous material analysis and heat exchanger testing
2. Revised tank construction from composite to aluminum and completed cryogenic testing
3. Developed designs with deep-dive technical reviews, controls, and test plans for Phase 3



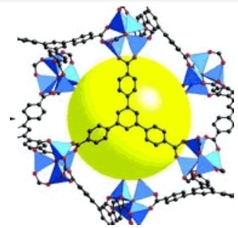


Progress: Adsorbent Material Down-Select

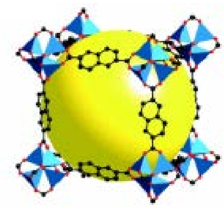
Materials For Project:



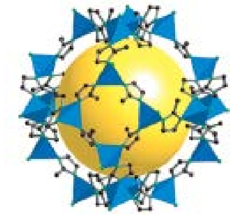
MOF-5
Basolite Z100-H



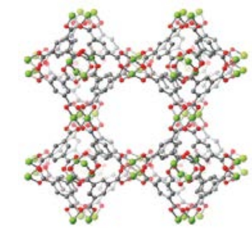
MOF-177
Basolite Z377



IRMOF-8
Basolite Z200



ZIF-8
Basolite Z1200



HKUST-1
Basolite C300

Material	Langmuir Surface Area (m^2/g)	Measured Max Excess Uptake (Wt·% H_2)	Literature Max Excess Uptake (Wt ·% H_2)	Measured Max Excess Uptake (g·H_2/L)	Measured Absolute Uptake @ 70 bar (Wt·%H_2) | (g·H_2/L)	DOE Targets (2017)
MOF-177	**5000**	**7.0**	**7.0-7.2**	**30 (SC) 13 (LP)**	**12.0 | 51 (SC) , 22 (LP)**	**Volumetric**
MOF-5	**3500**	**6.0**	**5.2-6.0**	**37 (SC) 6 (LP)**	**10.0 | 62 (SC), 10 (LP)**	**40 g·H_2/L**
IRMOF-8	**1700**	**3.3**	**3.5**	**15 (SC) 10 (LP)**	**4.3 | 19 (SC), 13 (LP)**	**Gravimetric**
ZIF-8	**1650**	**2.7**	**3.0-3.3**	**25 (SC) 6 (LP)**	**4.1 | 38 (SC), 9 (LP)**	**5.5 wt%·H_2**

'SC' and 'LP' indicate whether the volumetric capacities are based on single crystal (SC) or loose powder (LP) density, These values help by providing upper and lower bounds to volumetric uptake.

Adsorbent Material Down-selection was based on:

- Performance: MOF-5 outperforms MAXSORB in gravimetric density and in volumetric density (along with other MOFs).
- Availability: MOF-5 has been provided supplied in high quantities to the center by BASF
- Future Prospects: MOF-5 is a member of the larger class of Framework Materials, which has a large potential.
- Safety: MOF-5 in not believed to present any known safety hazards

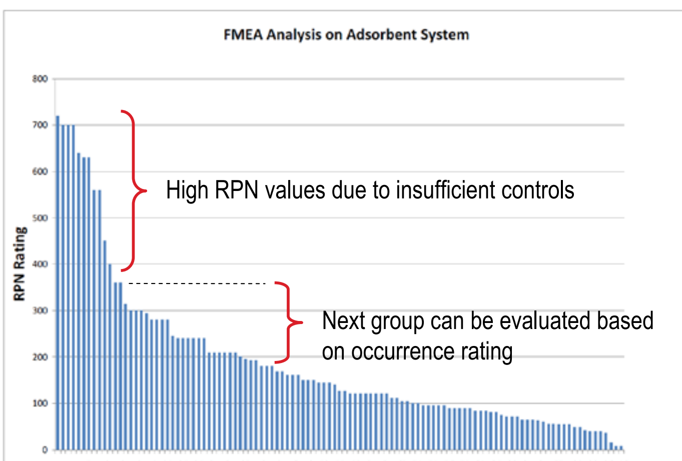
MOF-5 was selected as the primary adsorbent material for the HSECoE

Approach: Phase 2 SMART Milestones and Tasks

Adsorbent System		
Component	Partner	S*M*A*R*T Milestone
Materials Development	Ford/UM/ BASF	Report on ability to develop compacted MOF-5 adsorbent media having a total hydrogen material density of greater than or equal to 0.3 g/cc, H2 density of 11 wt. % and 33 g/liter and thermal conductivity of 0.5 W/m-K at P = 60-5 bar and T = 80-160K.
Materials Development	Ford/UM/ BASF	Report on ability to demonstrate a composite MOF-5 adsorbent monoliths having H2 effective kinetics equivalent to 5.6 kg usable H2 over 3 minutes and permeation in packed and powder particle beds with flow rate of 1 m/s superficial velocity and pressure drop of 5 bar.

MOF-5 Material Development Tasks

- Density of ≥ 0.3 g/cc with **total capacity**: ≥ 11% and ≥ 33 g/l
- **Thermal conductivity** of ≥ 0.5 W/m-K at 5-60 bar and 80-160 K
- Demonstrate **effective kinetics** for 3 minute fill of 5.6 kg
- Demonstrate **permeation** with flow rate of 1 m/s and pressure drop of 5 bar

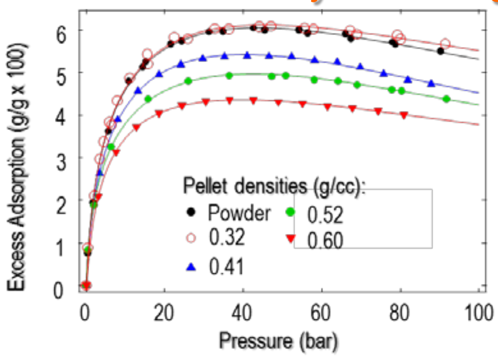


MOF-5 Material FMEA Tasks

- **Non-homogenous bed:** Evaluate material variation (i.e. surface area, density, thermal conductivity, scale-up, etc.)
- **Air exposure & in-service activation**: Need to quantify the level of allowable air exposure and in-service activation.
- **Cycling over lifetime:** Pressure cycling test of pellets
- **Impurity effects:** Evaluate effects with hydrogen purity at or beyond the limits of SAE J2719
- **Safety Assessment:** Determine the ignition energy levels for handling of the dust and internal pressure effects

Progress: MOF-5 Gravimetric Density Results

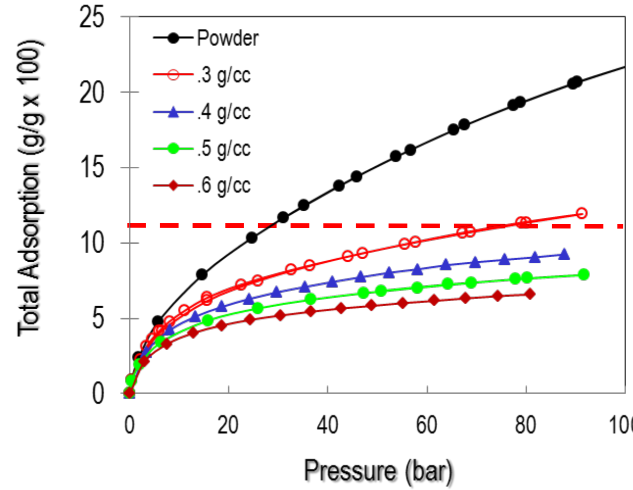
Milestone Task: Density of ≥ 0.3 g/cc with total capacity ≥ 11% at 5-60 bar and 80-160 K



Impact of Densification

- No impact on excess adsorption at 0.3 g/cc but ~40% reduction in total adsorption due to void volume

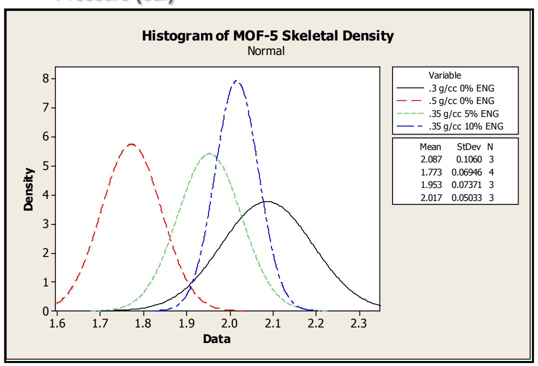
$$Adsorption_{total} = m_{sorbent}\left(n_{ex} + v_{void}\rho_g\right)/(m_{sorbent} + N_t)$$



Skeletal Density

- Conducted a study of skeletal density variations for multi-densities and ENG

$$v_{void} = 1/\rho_{bulk} - 1/\rho_{sk}$$



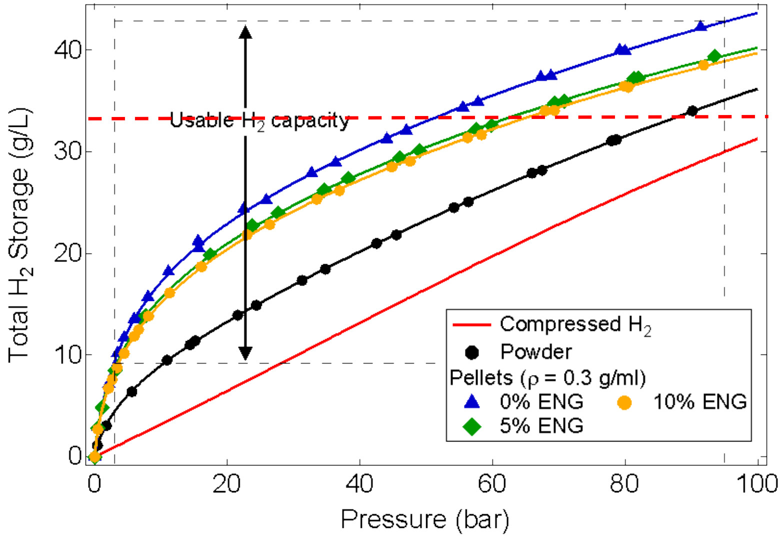
Powder 60 bar & 80 K	Powder 5-60 bar & 80 K	0.3 g/cc 60 bar & 80 K	0.3 g/cc 5-60 bar & 80 K	0.3 g/cc 5-60 bar & 80-160 K
17 %	**12 %**	**10 %**	**7 %**	**9 %**
60% packing efficiency:	*18 %*	*14 %*	*10 %*	*12 %*

Total capacity of ≥ 11% is possible with a 0.3g/cc pellet and 60% packing

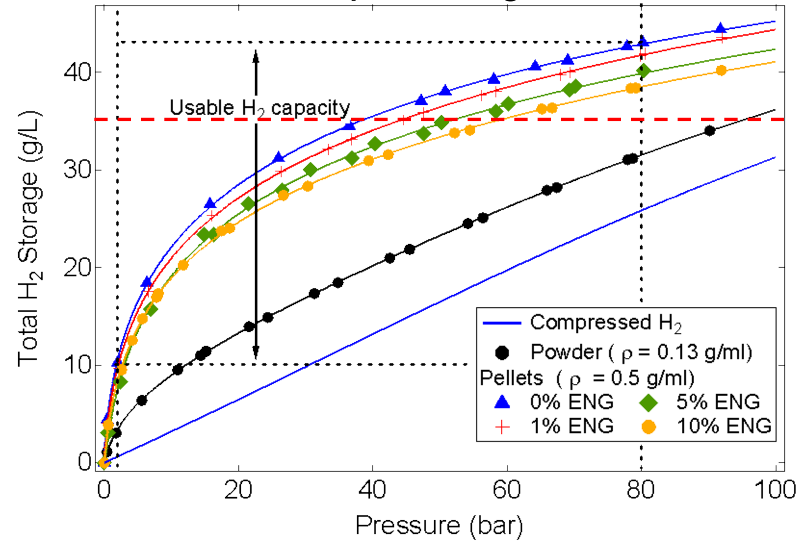
Progress: MOF-5 Volumetric Density Results

Milestone Task: Density of ≥ 0.3 g/cc with total capacity ≥ 33 g/l at 5-60 bar and 80-160 K

ρ = 0.3 g/cc



ρ = 0.5 g/cc



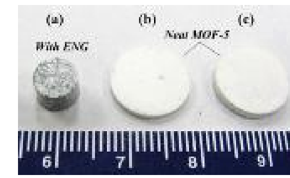
- Note: All curves currently assume skeletal densities of 2 g/cc and 100% packing efficiency.

Powder 5-60 bar & 80 K	0.3 g/cc + 5% ENG 5-60 bar & 80 K	0.3 g/cc + 5% ENG 5-60 bar & 80-160 K	0.5 g/cc + 5% ENG 5-60 bar & 80 K	0.5 g/cc + 5% ENG 5-60 bar & 80-160 K
20 g/l	**22 g/l**	**31 g/l**	**22 g/l**	**34 g/l**
60% packing efficiency:	*20 g/l*	*26 g/l*	*21 g/l*	*27 g/l*

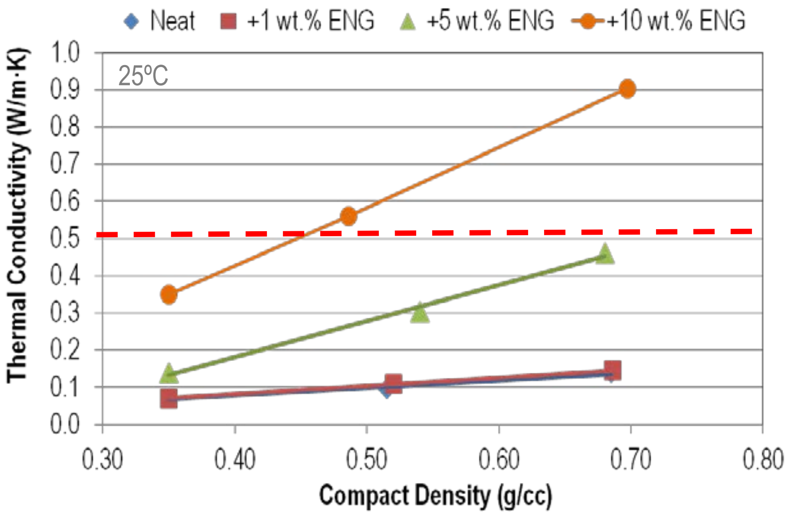
Total capacity of ≥ 33 g/l at 5-60 bar is theoretically achievable with 80-160 K

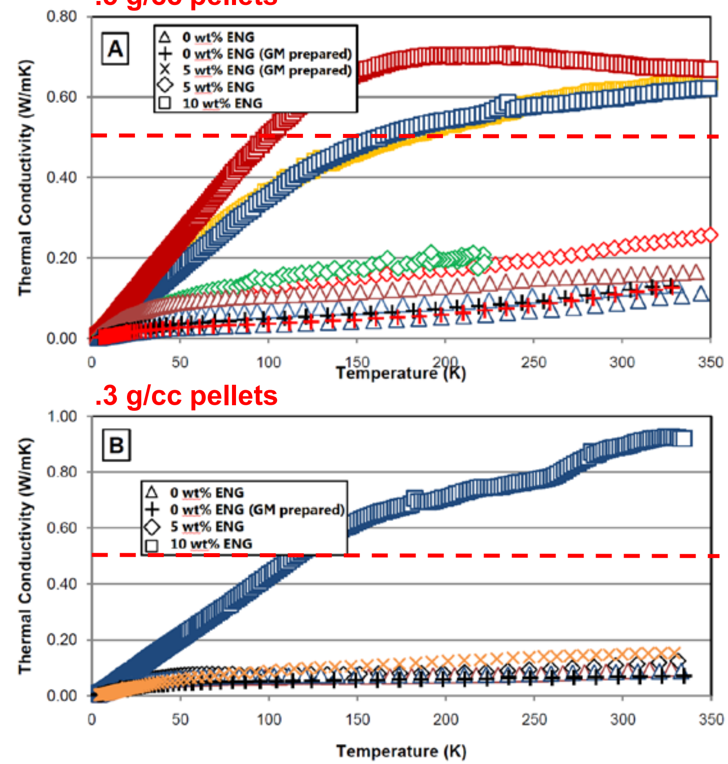
Progress: Thermal Conductivity of MOF-5

Milestone Task: Thermal Conductivity of ≥ 0.5 W/m-K at 5-60 bar and 80-160 K



Thermal Conductivity Data of MOF-5 and MOF-5/ENG Composites





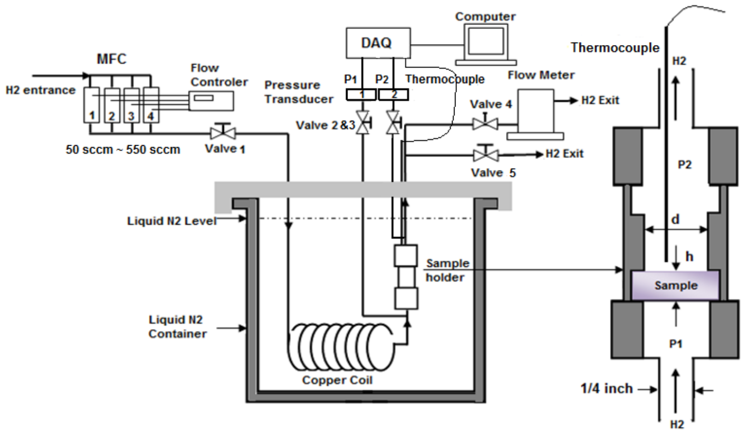
GM R&D Data – 2012 AMR

- MOF-5 has an extremely low thermal conductivity and needs further advancement to optimize the heat exchanger concepts and system design.
- Enhanced Natural Graphite (ENG) at 10 wt% has been shown to significantly improve (~4× to 6x depending on temperature) the thermal conductivity.

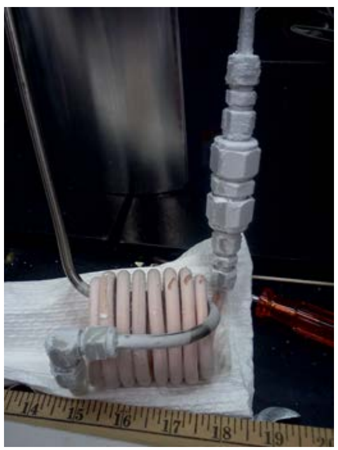
Thermal conductivity of ≥ 0.5 W/m-K requires 10 wt% ENG at ~100 to 150 K

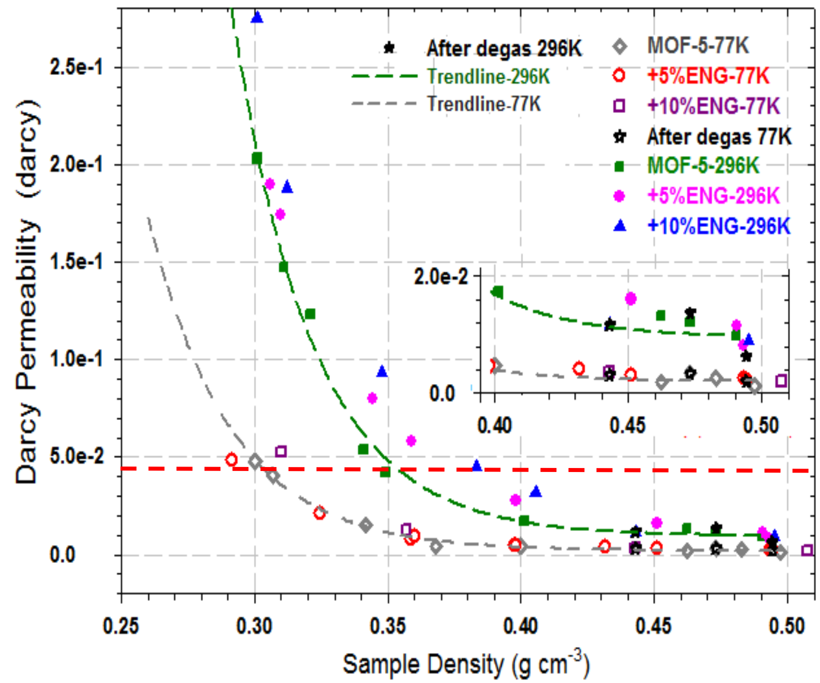
Progress: Permeation Testing of Densified MOF-5

Milestone Task: Demonstrate permeation with flow rate of 1 m/s and pressure drop of 5 bar



a. Setup diagram b. Sample Holder





Darcy permeability of hydrogen versus sample density from the data

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

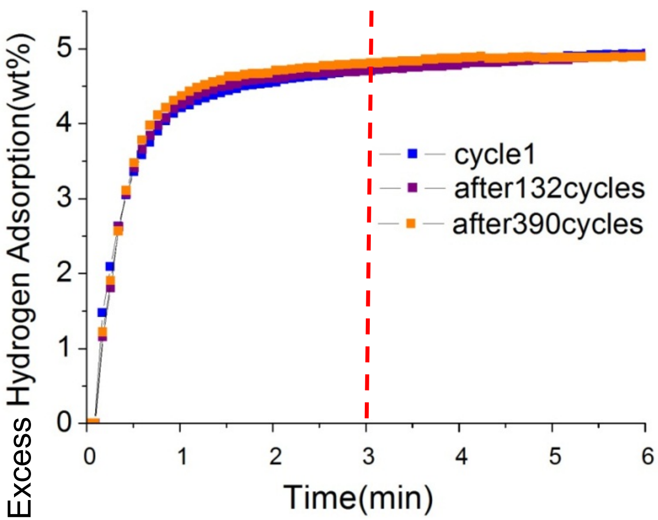
Pellets of .3 g/cc (77 K) have a projected pressure drop of 3.6 bar at 1 m/s

Projection based on an extrapolation based on test data at .12 m/s with a Darcy of .0486 *(or .0465 compressible gas equation)*

Progress: Effective Kinetics and Cycle Testing

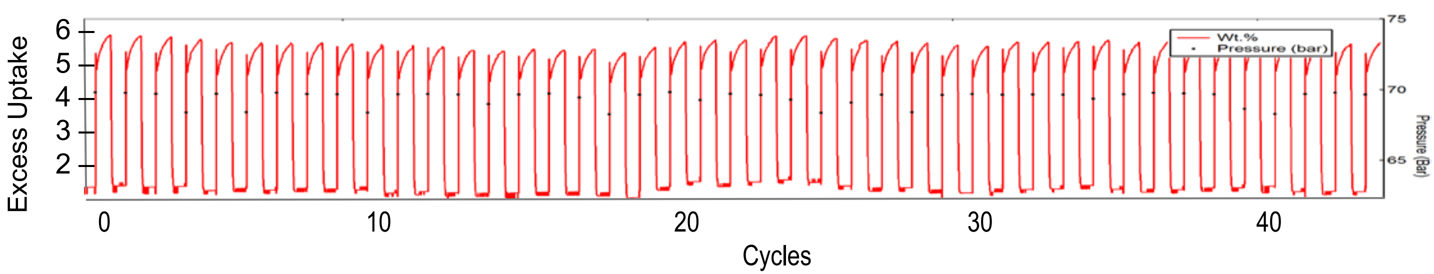
Milestone Task: Demonstrate effective kinetics for 3 minute fill of 5.6 kg

MOF-5 Pellet, Density=0.39g/cc



MOF-5 pellets have high rate of kinetics and is maintained over multiple cycles.

Initial cycle testing of powder (below) over 240 cycles and pellets over 390 cycles provide stable results for both kinetics and uptake adsorption %.

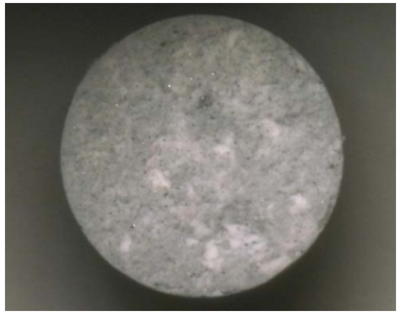
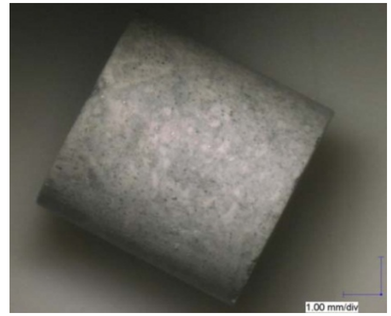


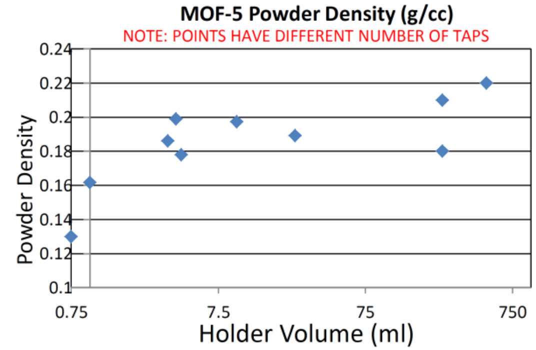
MOF-5 pellet testing demonstrates consistent kinetics and uptake

Progress: Homogenous Evaluation of MOF-5

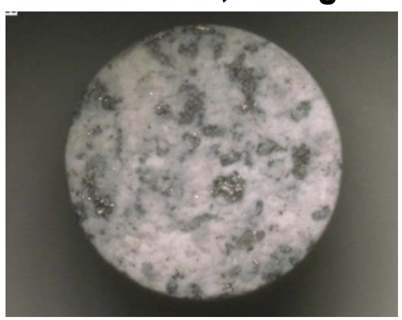
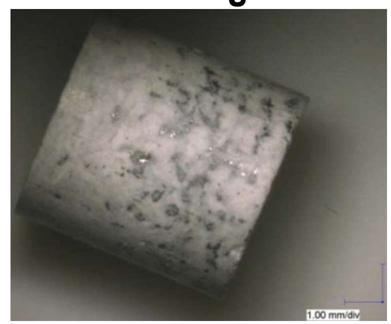
FMEA Task: Non-homogenous Bed Failure Mode - Evaluate pellet variation

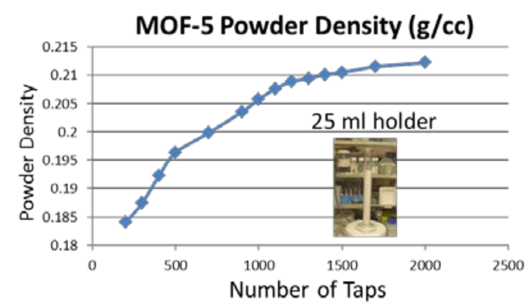
- **GW0118 – pellets 6x6 mm,1 +/- 0.01% graphite, .377 g/cc with σ = .012 g/cc**



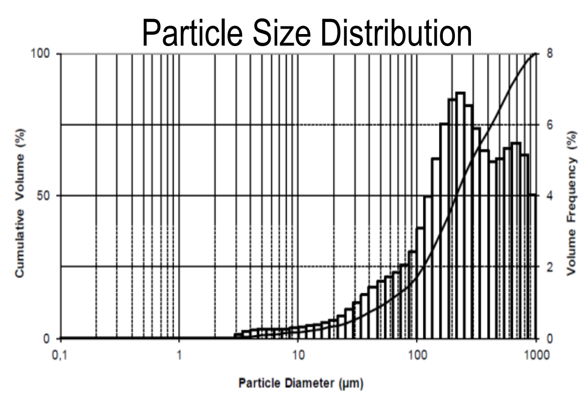
- **GW0117 – pellets 6x6 mm, 5 +/- 0.1% ENG, .391 g/cc with σ = .013 g/cc**



- **Property Characteristics and Variations**

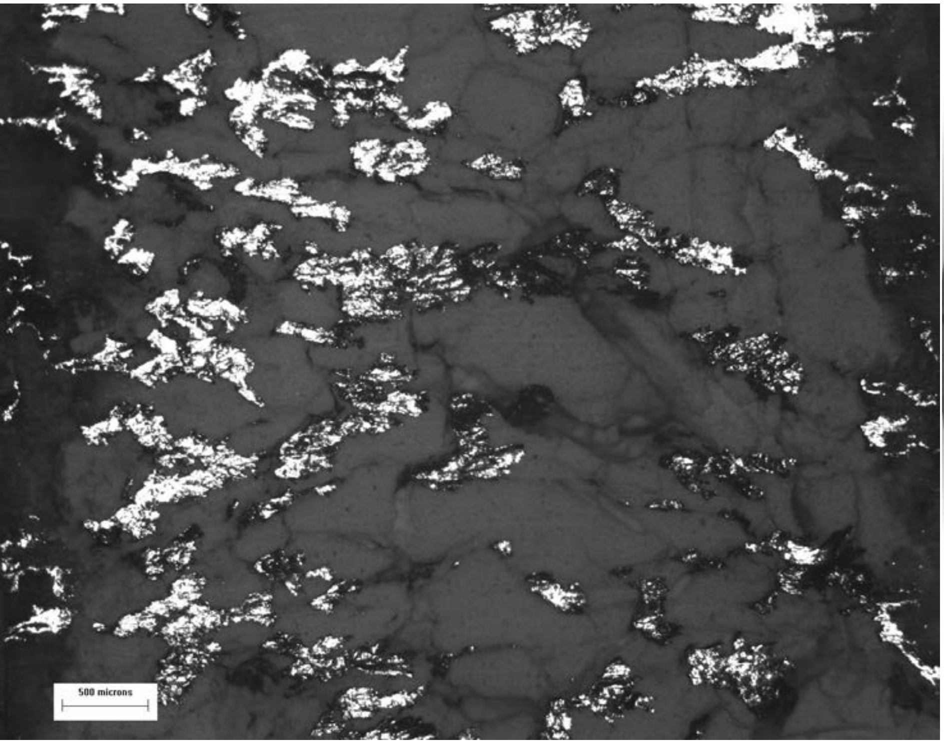
Type	Particle Size (mm) or Pellet Dia. (mm)	Density [BASF] (g/cc)	BET SA [B-F] (m^2/g)	Pore Volume [B-F] (cm^3/g)
Powder	*99% conf:* < .86	.19 (tap density)	2680-2763	1.27
Pellets neat	*99% conf:* 5.9 - 6.0	*99% conf:* .34 - .41	2477-2489	1.18 - 1.21
Pellets+5%ENG	*99% conf:* 5.9 - 6.0	*99% conf:* .35 - .43	2387-2702	1.14 - 1.18



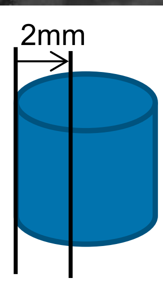
HSECoE

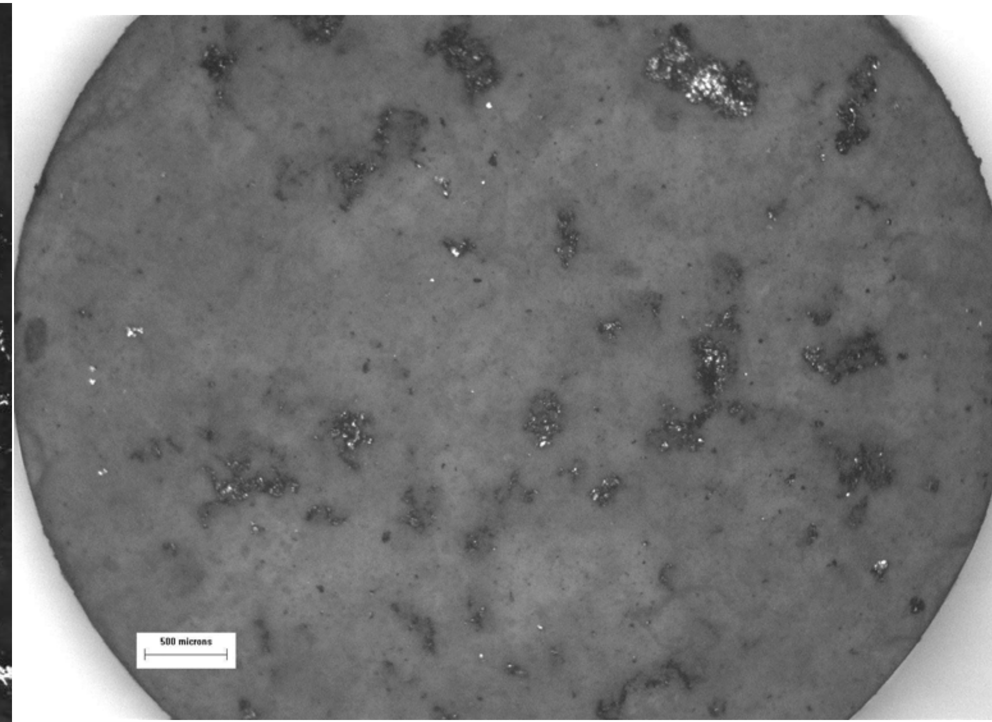
Progress: Microscopy Analysis of MOF-5 & ENG

FMEA Task: Non-homogenous Bed Failure Mode - Evaluate pellet variation

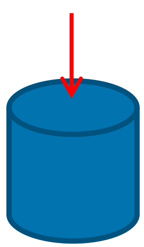


MOF-5 + 5wt% ENG, D=0.39 g/cc
Magnification 25x



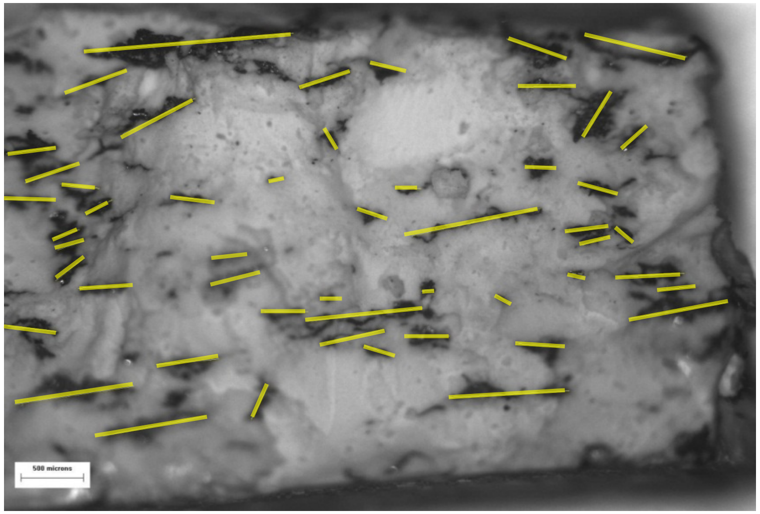


MOF-5 + 5wt% ENG, D=0.39 g/cc
6mm x 6mm pellet
Magnification 25x

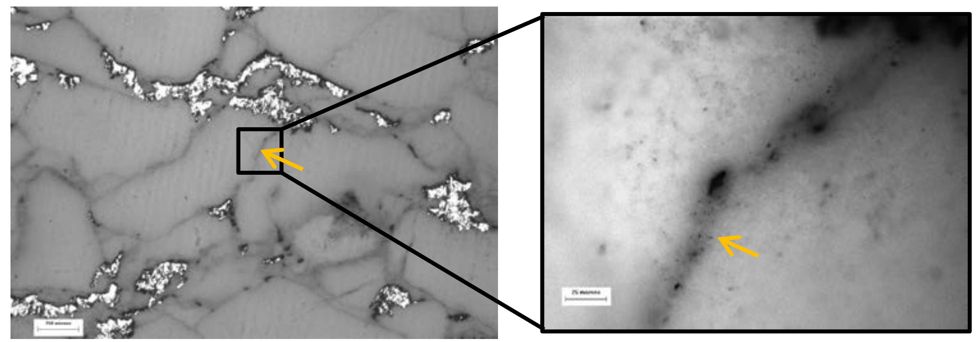


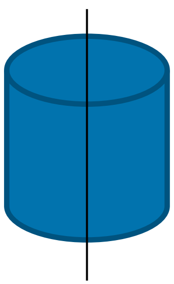
Progress: Microscopy Analysis of MOF-5 & ENG

FMEA Task: Non-homogenous Bed Failure Mode - Evaluate pellet variation

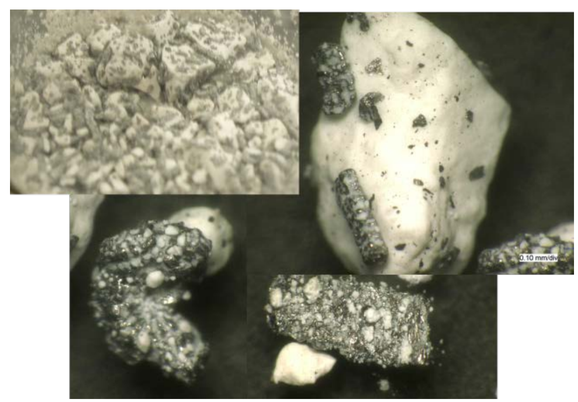


MOF-5 + 5wt% ENG, D=0.39 g/cc
Boundary lines between ENG and MOF-5, magnifications of 50x and 400x





ENG orientation angle within pellets		
	Avg. Angle(degrees)	Avg. Length(mm)
1	24.30	0.364
2	24.95	0.310
3	20.70	0.315
4	23.44	0.254
5	19.12	0.322
Avg:	**22.50**	**0.31**
Std Dev:	**2.49**	**0.04**



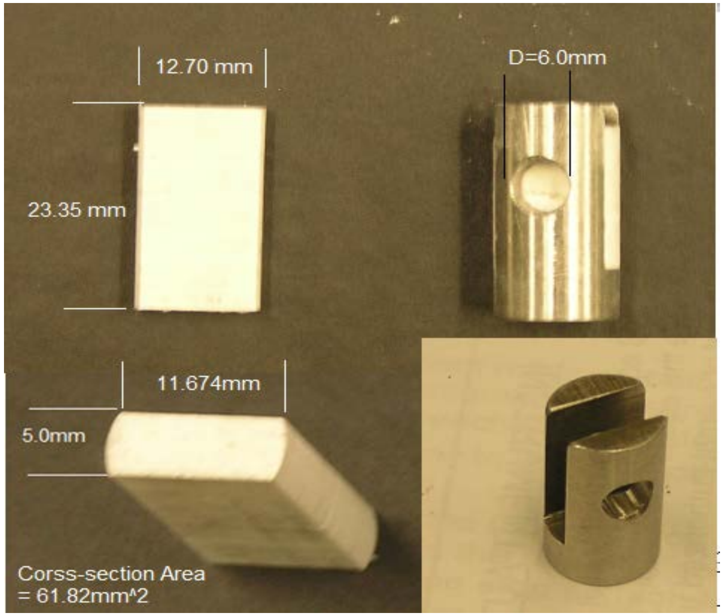
ENG particles form around MOF-5 conglomerates during processing

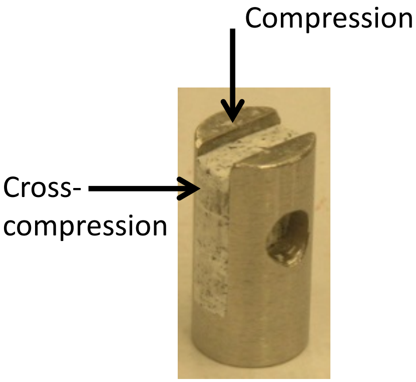
ENG deposits in the MOF-5 have a horizontal orientation preference

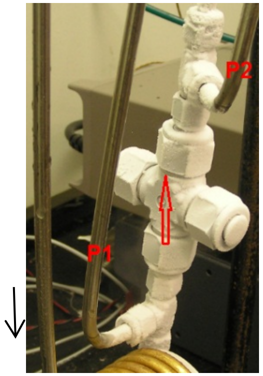
Progress: Anisotropic Effects of MOF-5 & ENG

FMEA Task: Non-homogenous Bed Failure Mode - Evaluate pellet variation

Anisotropic permeation evaluation was studied with specialized pellets







MOF-5+5% ENG, D=0.4 g/cc permeability in the cross-compression direction are listed in red to compare with the compression direction in black.

Table 2. MOF-5+5wt % ENG sample density vs Darcy permeability& diffusivity

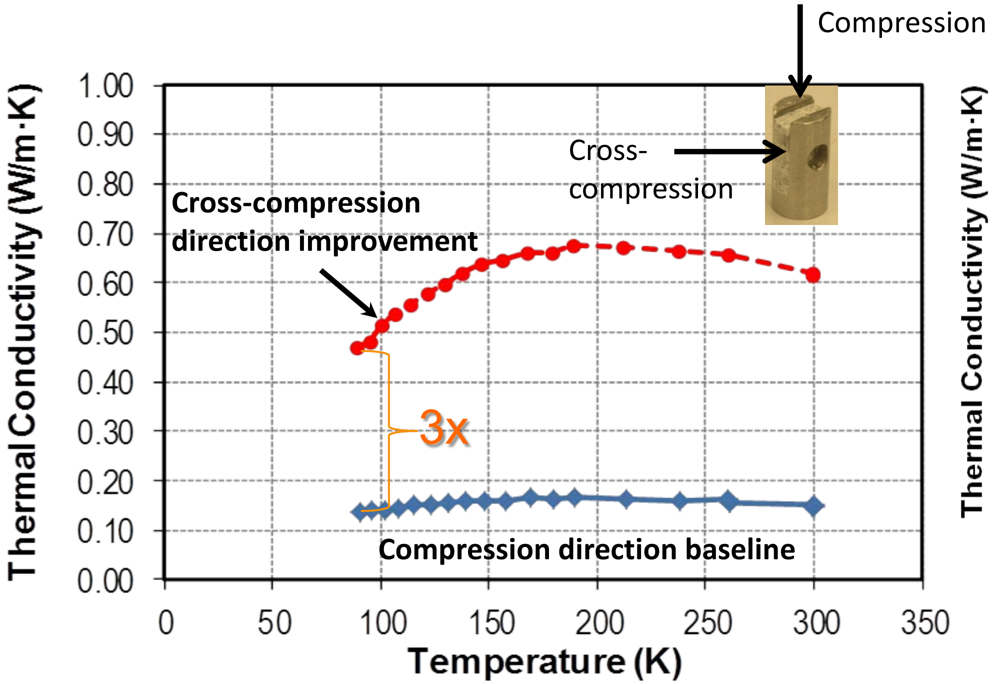
MOF-5 +5% ENG at 296 K				MOF-5 +5% ENG at 77 K			
D (gcm^{-3})	κ,	$κ_c$ (Darcy)	D_f (m^2s^{-1})	D(gcm^{-3})	κ,	$κ_c$ (Darcy)	D_f (m^2s^{-1})
0.3057	0.1896,	0.1743	2.086×10^{-3}	0.2914	0.0486,	0.0465	1.373×10^{-3}
0.3096	0.1741,	0.1717	1.942×10^{-3}	0.3244	0.0209,	0.0193	5.877×10^{-4}
0.3244	0.0796,	0.0689	9.028×10^{-4}	0.3587	0.0081,	0.00679	2.292×10^{-4}
0.3587	0.0581,	0.0461	6.314×10^{-4}	0.3600	0.0094,	0.00809	2.671×10^{-4}
0.3981	0.0278,	0.0185	3.059×10^{-4}	0.3974	0.0044,	0.0032	1.258×10^{-4}
0.4040	**0.0409**	**0.0214**	**$4.524x10^{-4}$**	0.3981	0.0046,	0.0036	1.321×10^{-4}
0.4510	0.0160,	0.0087	1.764×10^{-4}	**0.404**	**0.0111**	**0.00825**	**$3.610x10^{-4}$**
0.4908	0.0114,	0.0020	1.275×10^{-4}	0.4317	0.0041,	0.0031	1.169×10^{-4}
0.4933	0.0081,	0.0036	8.929×10^{-5}	0.4510	0.0029,	0.0020	8.314×10^{-5}
0.4942	0.0064,	0.0029	7.053×10^{-5}	0.4933	0.0026,	0.0018	7.411×10^{-5}
				0.4942	0.0022,	0.0015	5.971×10^{-5}

Specialized anisotropic pellet has a ~2x improvement in the permeability

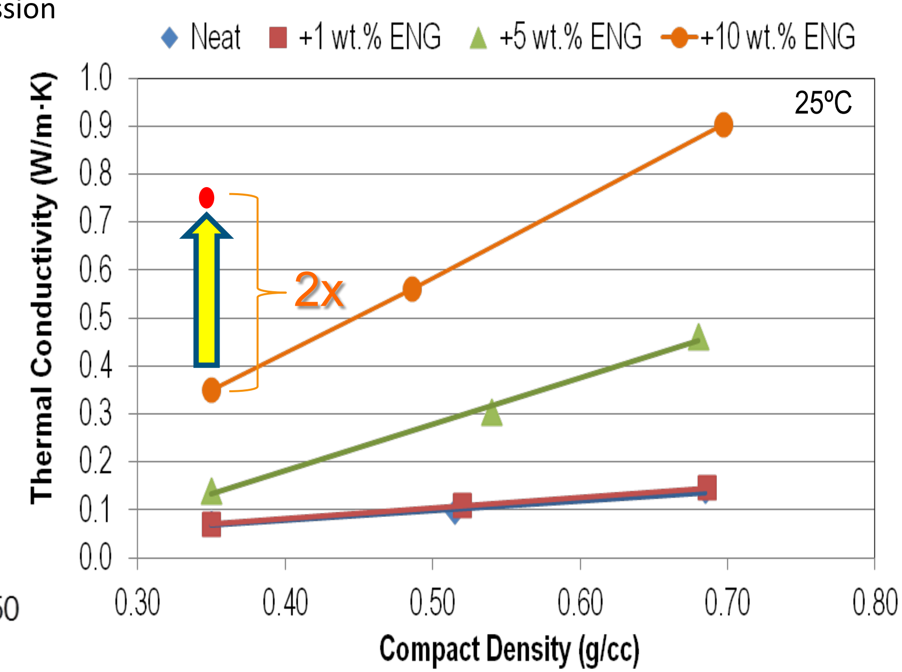
Progress: Anisotropic Effects of MOF-5 & ENG

FMEA Task: Non-homogenous Bed Failure Mode - Evaluate pellet variation

MOF-5 specialized pellet .37 g/cc + 5% ENG
Cross-compression thermal conductivity



MOF-5 specialized pellet .36 g/cc + 10% ENG
Cross-compression thermal conductivity

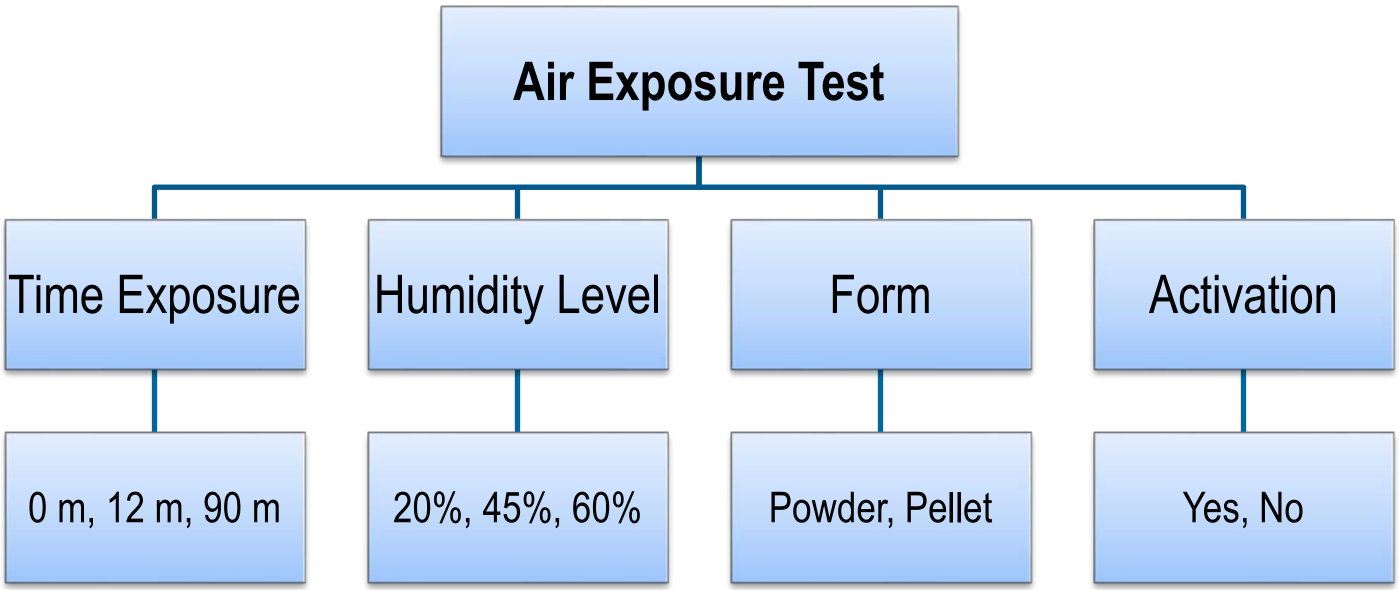


Specialized anisotropic pellet has a ~2x to 3x improvement in the conductivity

Progress: Humidity and Air Exposure Testing

FMEA Task: Air exposure & In-service Activation Failure Mode

Design of experiments testing initiated to evaluate the hydrogen uptake effect

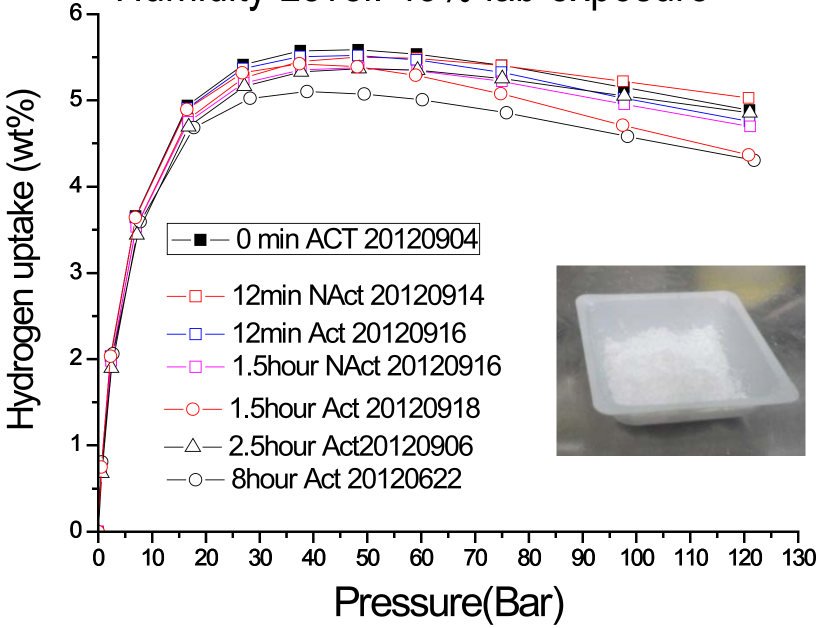


Ford Lab - typical climate control over 24 hr period
Humidity Level: 46.1% σ = .06%
Temperature: 22.2 C σ = .3 C

Progress: Humidity and Air Exposure Testing

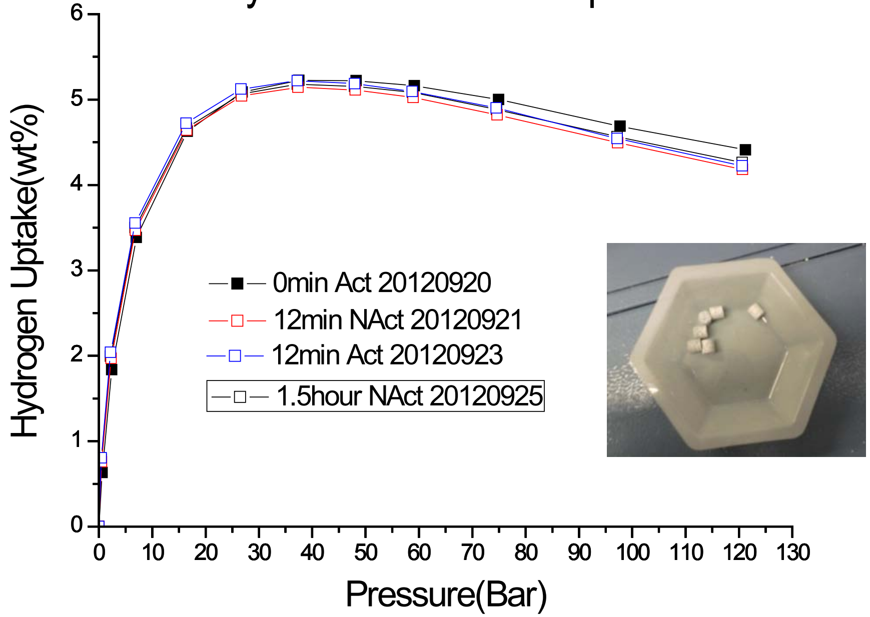
FMEA Task: Air exposure & In-service Activation Failure Mode

MOF-5 powder test
Humidity Level: 45% lab exposure



- 12 minute exposure (Act): 1.2% peak decrease
- 12 minute exposure (NAct): 1.5% peak decrease
- 1.5 hr exposure (Act): 3.5% peak decrease
- 1.5 hr exposure (NAct): 3.7% peak decrease
- 2.5 hr exposure (Act): 3.9% peak decrease
- 8 hr exposure (Act): 9.2% peak decrease

MOF-5 pellet test, D=0.357 g/cc
Humidity Level: 45% lab exposure



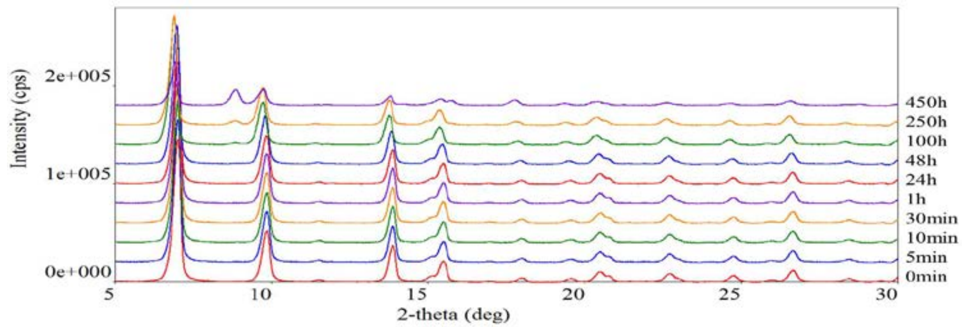
- 12 minute exposure (Act): 0.1% peak decrease
- 12 minute exposure (NAct): 1.5% peak decrease
- 1.5 hr exposure (NAct): 0.9% peak decrease

MOF-5 had limited degradation with 1.5 hr lab humidity (45%) exposure

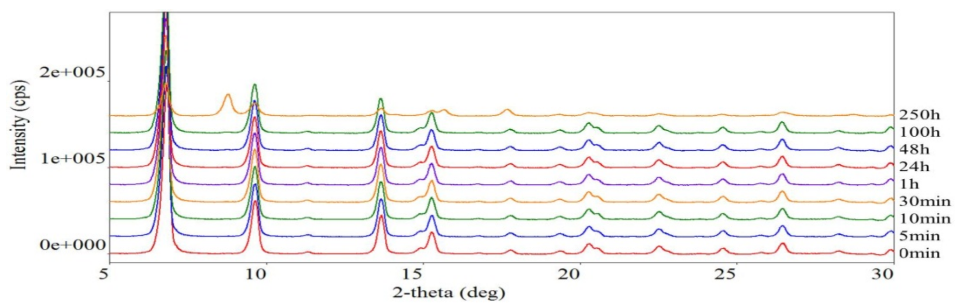
Progress: Humidity and Air Exposure Testing

FMEA Task: Air exposure & In-service Activation Failure Mode

MOF-5 powder XRD (not activated)
Humidity Level: 45% lab exposure



MOF-5 powder XRD (activated)
Humidity Level: 45% lab exposure



XRD lab humidity results support the hydrogen uptake measurements

Progress: MOF-5 Dust Ignition Safety Testing

FMEA Task: Containment Failure Mode – Material handling or rupture with ignitable dust mixture

Assumption: Worst case scenarios
Evaluation: Safe handling of MOF-5, tank operation and rupture
Experiments and results:

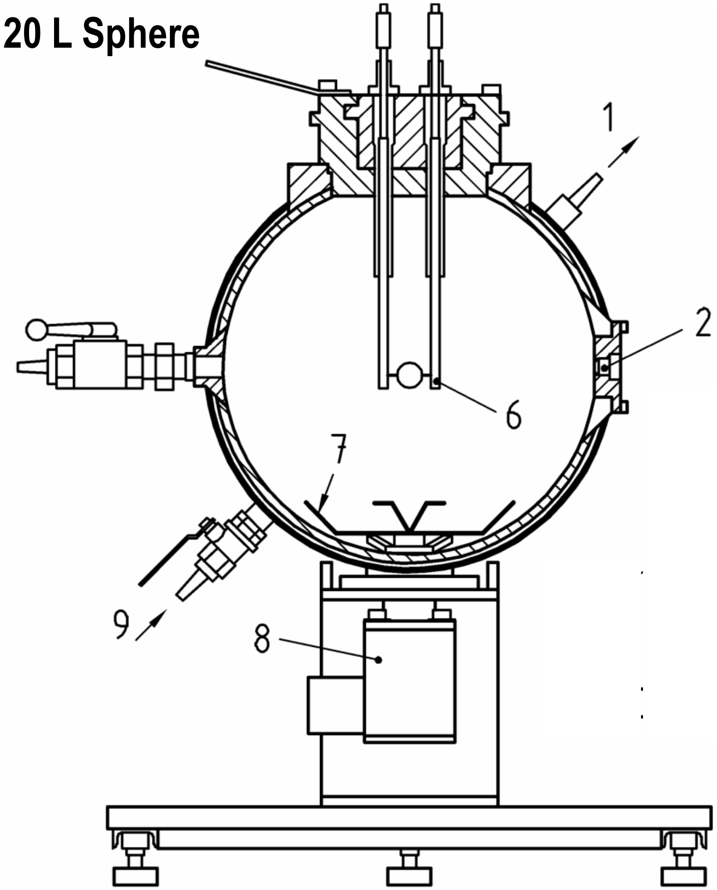
1) Differential Scanning Calorimetry:
No chemical reaction between MOF-5 and hydrogen (energy release or onset temp)

2) Dust Explosibility Tests
The Hartman tube test did not ignite the MOF-5 with about 4 J of energy. The 20 L sphere dust test did result in ignition with a high energy level of 2 kJ. MIE is between these values with the exact value to be determined with further test data.

Reference Information:
- Static electric spark is typically 22 mJ

Material	Minimum Ignition Energy
Aluminum Dust	15 mJ
Magnesium Dust	40 mJ
Coal Dust	30 to 60 mJ
Grain-based Flour	240 mJ

20 L Sphere



Analyses done by BASF's safety engineering group in Ludgwigshafen, Germany in an accredited laboratory according to DIN EN ISO/ IEC 17025. All standard test methods are performed according to official guidance documents.

Summary: Phase 2 SMART Milestones and Tasks

MOF-5 Material Development Tasks	Status
Density of ≥ 0.3 g/cc with total capacity: ≥ 11% and ≥ 33 g/l	✓ Demonstrated a theoretical total capability of ≥ 33 g/l for densities of ≥ 0.3 g/cc and potential for 11 wt %
Thermal Conductivity of ≥ 0.5 W/m-K at 5-60 bar and 80-160 K	✓ Demonstrated thermal conductivity of ≥ 0.5 W/m-K can be approached with 10% ENG at ~100 to 150 K
Demonstrate effective kinetics for 3 minute fill of 5.6 kg	✓ Conducted sub-scale cycle test that provided effective kinetics with the potential of a 3 minute fill
Demonstrate permeation with flow rate of 1 m/s and pressure drop of 5 bar	✓ Provided permeation data that indicates a *projected* pressure drop of 3.6 bar at 77 K for .3 g/cc

MOF-5 Material FMEA Tasks	Status
Non-homogenous bed evaluation	✓ Completed microscopy analysis and evaluated potential to optimize with anisotropic properties
Air exposure & in-service activation	✓ Initiated a design of experiments for humidity exposure
Cycling over lifetime	✓ Confirmed over 390 cycles without degradation
Impurity effects	✓ Planned a design of experiments for impurity exposure
Safety Assessment	✓ Completed ignition and internal pressure evaluation

Future Work: Complete Neutron Imaging Analysis

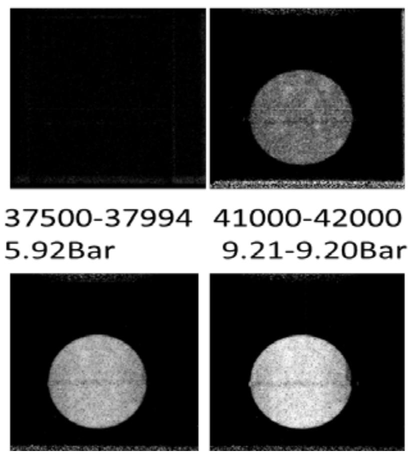
Completed *in situ* neutron imaging of MOF-5 pellets for model validation and mass transport analysis (1st Quarter 2013).

Results and Next Steps:

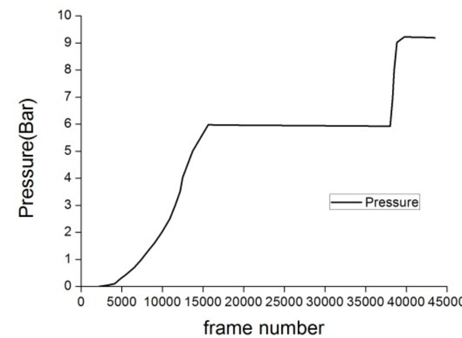
1. Characterized transient behavior associated with recharge and discharge as a function of rate and degree of fill.
2. Evaluated multiple orientations and ENG levels for anisotropic effects.
3. Calculate intensity and validate the mass transport models.

2200-3284 0-0.043Bar | 7405-8198 1.0-1.3Bar

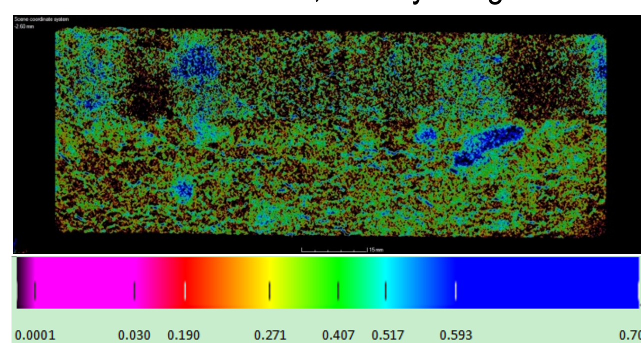
37500-37994 5.92Bar | 41000-42000 9.21-9.20Bar



Pressure vs. Frame number



Tomography for MOF-5 pellet with 10% ENG, density=0.4g/cc



The ENG particle (density=2.2g/cc) should have attenuation coefficient μ=0.608, which corresponds to dark blue

Horizontal

Vertical w/ ring

Vertical w/o ring

Future Work: Technical gaps & near-term plans

1. Demonstrate engineering concepts

- Scale-up and characterization of MOF-5 materials based on production manufacturing process
- Synthesis of 10 kg MOF-5 for system testing at UQTR and pucks for MATI system at OSU

2. Required material properties

- Alternative approaches to enhanced thermal conductivity
- Robustness and failure mode testing:
  - Powders vs pellets handling and alternative loading configurations
  - Clean vs. “dirty” H_2 (impurities other than humidity based on SAE J2719)
  - Failure mode and degradation mechanisms (i.e. thermal and cycle effects)
- Evaluate theoretical potential of MOFs and predict expected material properties

3. Develop and validate engineering models

- Validate and refine integrated framework model based on system testing
- Translate sub-scale system test results to full scale vehicle simulations
- Identify cost/function benefits for system associated with the integration of components

Phase 3 SMART Milestones

- Report on the ability to enhance thermal conductivity beyond 10% ENG at operating temperatures
- Report on the degradation and failure modes associated with real-world operating conditions
- Determine the parameters and viability of a production on-board sorbent system

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 nine 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 2 Technical Targets: Onboard Hydrogen Storage Systems

Storage Parameter	Units	2010	2017	Ultimate
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass) [a]	kWh/kg (kg H_2/kg system)	1.5 (0.045)	1.8 (0.055)	2.5 (0.075)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume)	kWh/L (kg H_2/L system)	0.9 (0.028)	1.3 (0.040)	2.3 (0.070)
Storage System Cost [b]:	$/kWh net ($/kg H_2)	TBD (TBD)	TBD (TBD)	TBD (TBD)
• Fuel cost [c]	$/gge at pump	3-7	2-4	2-4
Durability/Operability:				
• Operating ambient temperature [d]	ºC	-30/50 (sun)	-40/60 (sun)	-40/60 (sun)
• Min/max delivery temperature	ºC	-40/85	-40/85	-40/85
• Operational cycle life (1/4 tank to full) [e]	Cycles	1000	1500	1500
• Min delivery pressure from storage system; FC= fuel cell, ICE= internal combustion engine	bar (abs)	5 FC/35 ICE	5 FC/35 ICE	3 FC/35 ICE
• Max delivery pressure from storage system [f]	bar (abs)	12 FC/100 ICE	12 FC/100 ICE	12 FC/100 ICE
• Onboard Efficiency	%	90	90	90
• "Well" to Powerplant Efficiency	%	60	60	60
Charging / Discharging Rates:				
• System fill time (5 kg)	min (kg H_2/min)	4.2 (1.2)	3.3 (1.5)	2.5 (2.0)
• Minimum full flow rate	(g/s)/kW	0.02	0.02	0.02
• Start time to full flow (20°C) [g]	s	5	5	5
• Start time to full flow (-20°C) [g]	s	15	15	15
• Transient response 10%-90% and 90% - 0% [h]	s	0.75	0.75	0.75
Fuel Purity (H_2 from storage) [i]:	% H_2	SAE J2719 and ISO/PDTS 14687-2 (99.97% dry basis)		
Environmental Health & Safety:				
• Permeation & leakage [j]	Scc/h	Meets or exceeds applicable standards		
• Toxicity	-			
• Safety	-			
• Loss of useable H_2 [k]	(g/h)kg H_2 stored	0.1	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