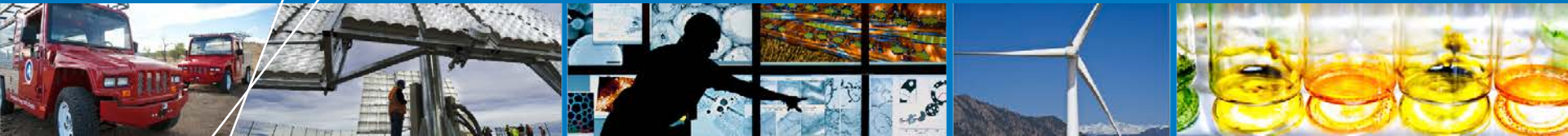


# System Design, Analysis, and Modeling for Hydrogen Storage Systems



**Matthew Thornton**  
**Jon Cosgrove and Jeff Gonder**  
**National Renewable Energy Laboratory (NREL)**  
**June 18, 2014**

Project ID # ST008

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

# Overview

## Timeline

**Project start date: FY09**

**Project end date: FY15**

**Percent complete: 85%**

## Budget

**FY13 DOE funding: \$100K**

**Planned FY14 DOE funding: \$125K**

**Total project value: \$1.8M**

**Cost share percentage: 0%**

## Barriers

**(A) System weight and volume**

**(B) System cost**

**(C) Efficiency**

**(E) Charge/discharge rate**

**(I) Dispensing technology**

**(K) System life-cycle assessments**

## Partners

Savannah River National Lab (SRNL) project lead, Pacific Northwest National Lab (PNNL), United Technologies Research Center (UTRC), Jet Propulsion Lab (JPL), Ford, General Motors (GM), Los Alamos National Lab (LANL), Oregon State University (OSU), University of Michigan (UM), and the DOE Vehicle Technologies Office.

# Relevance/Objectives

## Support the HSECoE with system design, analysis, modeling, and media engineering properties for materials-based hydrogen storage systems

- Manage Hydrogen Storage Engineering Center of Excellence (HSECoE) vehicle performance, cost, and energy analysis technology area.
- Vehicle Performance: Develop and apply model for evaluating hydrogen storage requirements, operation and performance trade-offs at the vehicle system level.
- Energy Analysis: Coordinate hydrogen storage system well-to-wheels (WTW) energy analysis to evaluate off-board energy impacts with a focus on storage system parameters, vehicle performance, and refueling interface sensitivities.
- Media Engineering Properties: Assist center in the identification and characterization of adsorbent materials that have the potential for meeting Department of Energy (DOE) technical targets for onboard systems.
- Lead effort to make select HSECoE wide models available for use by other researchers via Web-based portal.

# Objective: Vehicle Performance

- Develop and apply a model for evaluating hydrogen storage requirements, performance and cost trade-offs at the vehicle system level (e.g., range, fuel economy, cost, efficiency, mass, volume, on-board efficiency)
- Provide high level evaluation (on a common basis) of the performance of materials based systems:
  - Relative to DOE technical targets
  - Relative in class and across class for materials systems
  - Relative to physical storage systems
  - Relative to conventional vehicles

# Objective: HSECoE Model Web Access

Coordinate across the HSECoE to make select models developed under this effort available to other researchers and research organizations through Web-based access.

- Assist with model selection
- Coordinate model validation
- Coordinate model documentation
- Manage website and model posting
- Track and record Web activity
- Track and record model downloads

**Hydrogen Storage Engineering**  
CENTER OF EXCELLENCE

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Home

The Hydrogen Storage Engineering Center of Excellence (HSECoE) is working to help reduce our Nation's dependence on foreign energy sources by changing the way we power our cars, homes, and businesses. The HSECoE was selected through a competitive, merit reviewed solicitation process by DOE.

The Center addresses the significant engineering challenges associated with developing lower-pressure, materials-based, hydrogen storage systems for hydrogen fuel cell and internal combustion engine light-duty vehicles.

This project is incorporated into the DOE's Fuel Cell Technology Program, which consists of applied research and development activities, conducted through Center of Excellence materials and engineering teams, and independent projects focusing on materials and concepts, testing, and system analysis.

U.S. DEPARTMENT OF  
**ENERGY**

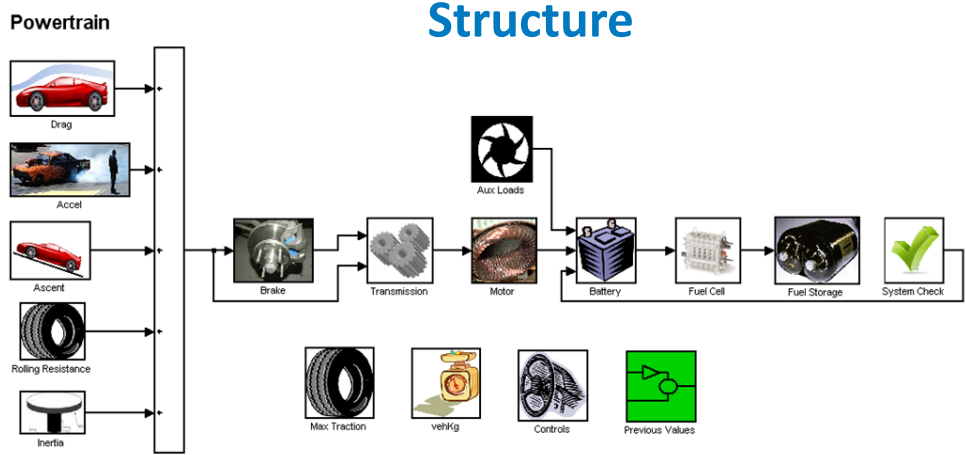
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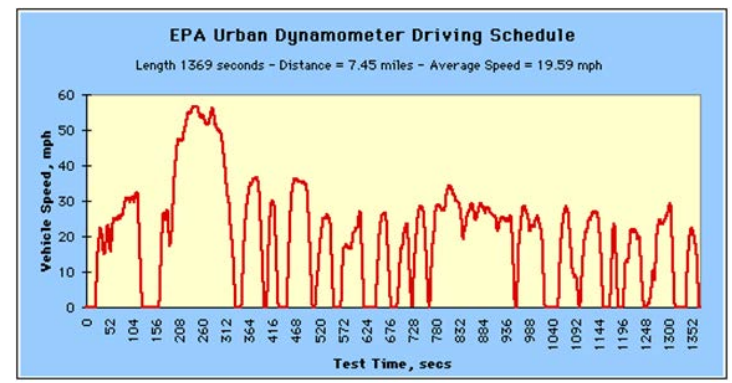
# Approach/Milestones

Date	Milestone	Status
10/13	Participate in the HSECoE face-to-face meeting and present on the status of the modeling efforts and development of GUI interface for the public release of the models.	100%
6/14	Update the chemical system model with Phase II performance data, integrate into the framework; document and release models to the public.	30%
6/14	Present modeling efforts of the HSECoE and the projected status of adsorbent systems to meet the DOE 2017 target of 5.5 wt.%.	50%
8/14	Report on vehicle system modeling of hydrogen storage impacts on vehicle range, acceleration, and fuel economy and associated trade-offs on volume and mass.	50%
8/14	NREL will work with center partners to set up and run vehicle simulations to evaluate the key volumetric, gravimetric, and onboard efficiency trade-offs over three test cases (drive cycles) and progress toward 2017 targets for two chemical hydrogen and two to three adsorbent system designs in support of final design selection for each material class for Phase III work.	25%
9/14	Report on progress of public release of HSECoE models.	0%
9/14	NREL will work with center partners to make enhanced and updated versions of the HSECoE "modeling framework", with four new storage system options, available for public access via the current Web portal.	0%

# Approach: Develop HSSIM (Vehicle Model)



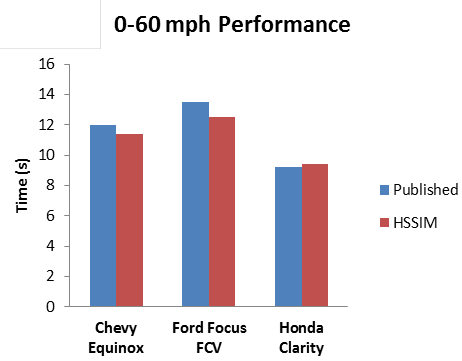
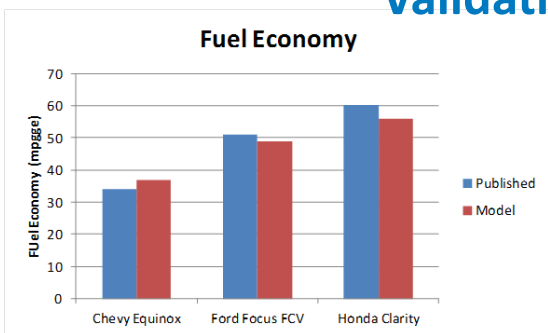
## Drive Cycles



## Output

- Fuel economy (mpgge) based on EPA-adjusted five cycle estimate
- Range (miles) from adjusted mpgge
- Onboard efficiency (%)
- Hydrogen flow (moles/s)
- Vehicle performance

## Validation



SAE International

**Development of a Vehicle-Level Simulation Model for Evaluating the Trade-Off between Various Advanced On-Board Hydrogen Storage Technologies for Fuel Cell Vehicles**

2012-01-1227  
Published 04/16/2012

Matthew Thornton, Aaron Brooker and Jonathon Cosgrove  
National Renewable Energy Laboratory

Michael Veenstra  
Ford Motor Company

Jose Miguel Pasini  
United Technologies Research Center

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doi:10.4271/2012-01-1227

**ABSTRACT**

One of the most critical elements in engineering a hydrogen fuel cell vehicle is the design of the on-board hydrogen storage system. Because the current compressed-gas hydrogen storage technology has several key challenges, including cost, volume and capacity, material-based storage technologies are being evaluated as an alternative approach. These material-based hydrogen storage technologies include metal hydrides, chemical hydrides, and adsorbent materials, all of which have drawbacks of their own. To optimize the engineering of storage systems based on these materials, it is critical to understand the impacts these systems will have on the overall vehicle system performance and what trade-offs between the hydrogen storage systems and the vehicle systems might exist that allow these alternative storage approaches to be viable.

To gain a better understanding of the interactions that exist between various material-based hydrogen storage systems and the vehicle system as well as the engineering challenges that exist when integrating one of these systems with a vehicle, the National Renewable Energy Laboratory (NREL) developed a vehicle-level model designed to be sensitive to these issues. The Hydrogen Storage Simulation Model (HSSIM) was developed under the Hydrogen Storage

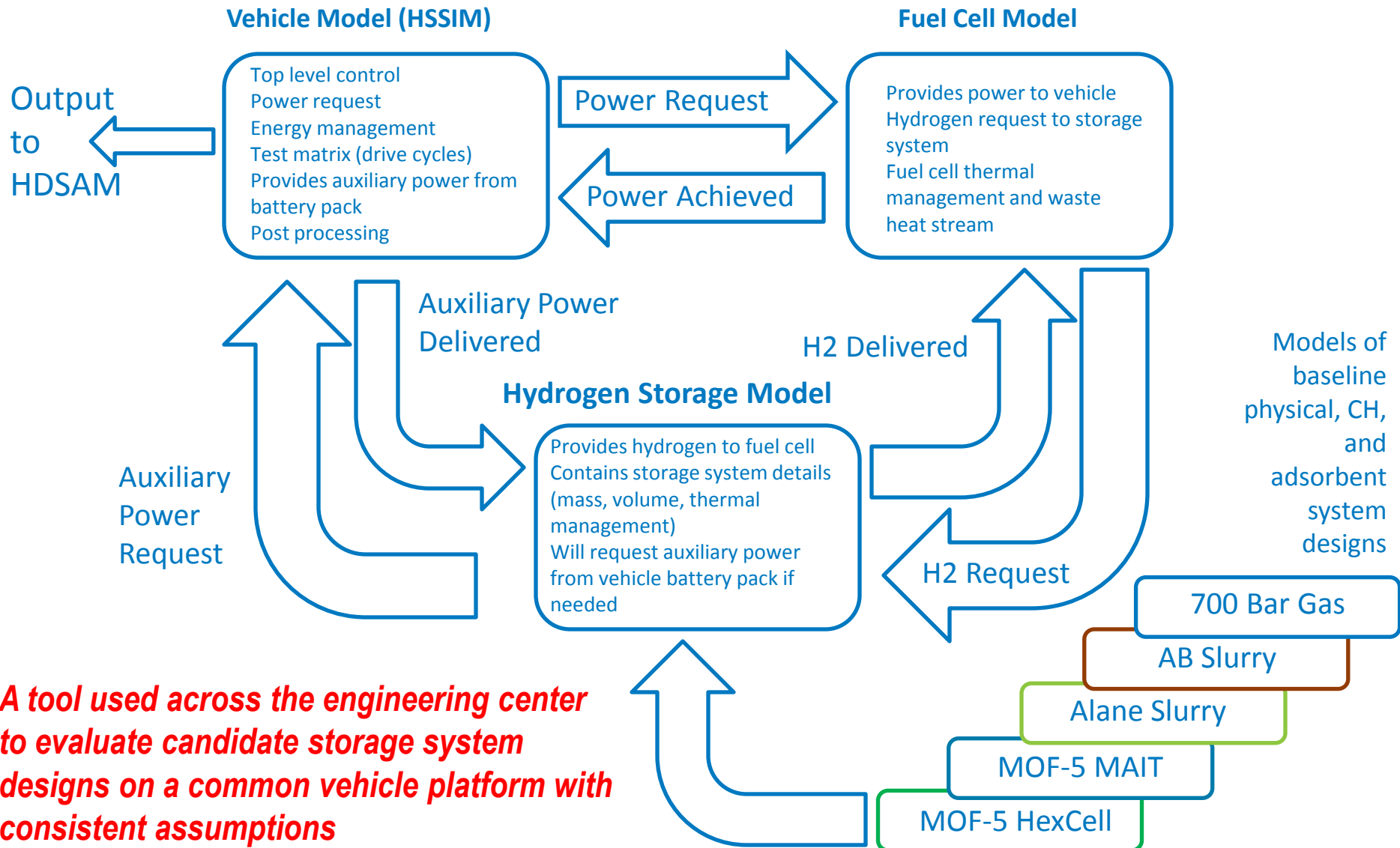
Engineering Center of Excellence (HSECoE) as a specialized tool that could be used to assist in the design and engineering of material-based hydrogen storage systems being considered by the HSECoE. This tool is designed to not only allow for understanding key trade-offs, but also to have a seamless integration with the HSECoE fuel cell and detailed hydrogen storage system models and to evaluate progress towards the U.S. Department of Energy's hydrogen storage technical targets. This model has been integrated with a fuel cell model developed by Ford Motor Company in a HSECoE common modeling framework developed by United Technologies Research Center and other HSECoE partners.

This paper focuses on the development, structure, and validation of the vehicle model HSSIM and the framework are then used to obtain trade-offs for various specific material-based storage system designs. This includes hydrogen storage sizing analyses, mass compounding analyses, range versus volume studies, and vehicle and component performance analyses, such as acceleration rates and fuel cell and energy storage interactions.

**INTRODUCTION**

The Hydrogen Storage Engineering Center of Excellence (HSECoE), sponsored by the U.S. Department of Energy

# Approach: Modeling Framework





# Approach: Model Access Website

<http://hsecoe.org>



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This project is incorporated into the DOE's Fuel Cell Technology Program, which consists of applied research and development

activities, conducted through Center of Excellence materials and engineering teams, and independent projects focusing on materials and concepts, testing, and system analysis.



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## Model Access/Description Sub-Page



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Models

### News

- Acceptability Envelope Tool released for metal hydride storage.
- 3D Metal Hydride Finite Element model released.
- Other models will be released in the near future.

[What is the Metal Hydride Acceptability Envelope \(AE\)?](#)

[AE Model](#)

[What is the Metal Hydride Finite Elements \(MHFE\) Model?](#)

[MHFE Model](#)

[A Base Case Study: Sodium Aluminum Hydride \(MHFE-SAH\)](#)

[Downloads:](#)



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# Approach: Model Access Website

## Model Documentation and Downloads



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### Models

**What is the Metal Hydride Acceptability Envelope (AE)?**

The design and evaluation of metal hydride storage systems require the use of detailed numerical models to support more studies, with significant amount of time and monetary investment. Therefore, it is important to have a tool that can help design and storage level systems capable of achieving selected performance targets.

Savannah River National Laboratory, as leader of the DRI HSECoE, has developed such a tool, called the Acceptability Envelope.

The Acceptability Envelope tool can be used by researchers and scientists to determine which properties the system needs to have to achieve determined targets and compare different materials to each other. The code has been developed for metal hydrides and it provides a preliminary but precise idea on which materials can attain desired objectives (such as DOE targets). The results obtained can be used as inputs to more sophisticated models to develop a prototype design and predict the full-scale storage system behavior.

**ACCEPTABILITY ENVELOPE - THE HSECoE MODELS**

**AE Model**

**What is the Metal Hydride Finite Elements (MHFE) Model?**

**MHFE Model**

**A Base Case Study: Sodium Aluminum Hydride (MHFE-SAH)**

**Downloads**



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### Models

**News**

- What is the Metal Hydride Acceptability Envelope (AE)?**
- AE Model**
- What is the Metal Hydride Finite Elements (MHFE) Model?**
- MHFE Model**
- A Base Case Study: Sodium Aluminum Hydride (MHFE-SAH)**

**Downloads**

**Metal Hydride Acceptability Envelope (MHAE)** The MHAE allows the user to evaluate the distance (in rectangular or cylindrical coordinates) between two surfaces or walls inside the bed, containing the metal hydride material, needed to attain determined targets, with selected material properties. The file MHAE-RC refers to the rectangular coordinate model, while MHAE-CC refers to the cylindrical coordinate model.

**Metal Hydride Finite Element - Sodium Aluminum Hydride (MHFE-SAH)** MHFE-SAH is a 3D model, developed under COMSOL 4.2a, which allows the user to see the thermo-chemical behavior of a storage system composed of sodium aluminum hydride material. The storage bed is based on a shell-and-tube, finned heat transfer system, with the structure and geometry of the UTRC prototype.

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E-mail \*



# Accomplishment: Model Posting

- **MH Acceptability Envelope**      **SRNL**      **complete**
- **MH Finite Element Model**      **SRNL**      **complete**
- **Physical H2 Framework Modes** **UTRC/NREL**      **complete**
- **MH Framework Model**      **UTRC/SRNL/NREL**      **complete**
- **Tank Volume/Cost Model**      **PNNL**      **complete**
- **CH Framework Model**      **UTRC/PNNL/NREL**      **6/2014**
- **AD Framework Model**      **UTRC/SRNL/NREL**      **9/2014**
- **AD Finite Element Model**      **SRNL**      **3/2015**

# Tanks/Volume Cost Model

Type 3 Tank sizing code units na

## Notes on Calculation Strategy

### Input parameters

Operating Temperature C na  
 Operating Pressure Bar 250  
 Tank Material - Carbon Fiber  
 Liner Material Aluminum

Fiber Translation Efficiency % 80%

### Primary Geometry Specification: Internal

Tank Length (Internal) [L<sub>0</sub>] cm 0  
 Tank Radius (Internal) [R<sub>0</sub>] cm 22.5  
 Tank Volume Goal (Internal) [V<sub>0</sub>] ccm 105,000

### Tank Geometry Calculation

Tank Internal Length (cm) [L] cm 81.0  
 Tank Internal Radius (cm) [R] cm 22.5  
 Tank Internal Volume Actual (ccm) [V] ccm 105,000  
 Volume goal attainment % 100.0%

### Tank Liner estimate

total burst pressure load bar 562.5  
 liner burst load factor % 21.0%  
 liner burst load bar 118.1  
 Liner ultimate strength (Room Temp.) Bar 3103.0  
 Liner Thickness [t] cm 0.86

### Upper Bound Wall Thickness Calculation

Carbon Fiber Composite Material strength Bar 15306  
 Safety Factor - 2.25  
 Wall Radius = R+t cm 23.4  
 Tank Wall thickness (ideal) cm 1.072949179  
 Layer thickness increment cm 0.09144  
 # layers 12  
 Rounded up thickness cm 1.09728  
 Minimum layer thickness cm 0.27432  
 Final wall thickness cm 1.09728

Final safety factor 2.30  
 Estimated burst pressure Bar 575.3

### Lower Bound Wall Thickness Calculation

Liner ultimate strength (RT) Bar 3103  
 Liner can support Bar 118.125  
 Adjusted Burst Pressure on Composite Bar 444.375  
 Tank Wall thickness (ideal) cm 0.847629852  
 Layer thickness increment cm 0.09144  
 # layers 10  
 Rounded up thickness cm 0.9144  
 Minimum layer thickness cm 0.27432  
 Final wall thickness cm 0.9144  
 Load share estimate %CF 79%

### Mass Calculations

	Low Bound	High Bound
Internal Radius (cm)	22.5	22.5
Internal Length (cm)	81.0	81.0
liner thickness (cm)	0.9	0.856529971
wall thickness (cm)	0.9144	1.09728
liner density (kg/ccm)	0.002663	0.002663
wall density (kg/ccm)	0.001611	0.001611

Ext Radius (cm) 24.27092997 24.45380997  
 Ext Length (cm) 84.56168819 84.92744819

Liner Ext Radius (cm) 23.35652997 23.35652997  
 Liner Ext Length (cm) 82.73288819 82.73288819

exterior volume (L) 126.5489622 128.9213116  
 Liner ext volume (L) 115.1036997 115.1036997  
 internal volume (L) 105 105

wall volume (ccm) 11445.26251 13817.61194  
 liner volume (ccm) 10103.69967 10103.69967

Carbon Fiber Composite mass (kg)	18.44	22.26
Aluminum liner mass (kg)	26.91	26.91
total mass (kg)	45.34	49.17

exterior L:D 1.742036426 1.73648704  
 Layers of composite (minimum is 3) 10 12

### Tank Efficiency

Gravimetric (L/kg) 2.32 2.14

### Tank Material Cost

aluminum material cost (\$/kg)	4.45	4.45
Carbon fiber composite cost (\$/kg)	30.65	30.65
aluminum line cost (\$)	119.73	119.73
Carbon fiber composite cost (\$)	565.13	682.27
Tank Wall total material cost (\$)	684.87	802.01



Pacific Northwest  
NATIONAL LABORATORY

# Framework Model GUI

## Initial screen

The screenshot shows the 'Hydrogen Vehicle Simulation Framework' GUI. It is divided into several sections:

- System selection:** A dropdown menu showing 'MH-GH3s v3'.
- System description:** A text area containing 'Generic metal hydride model 30 kJ/mol enthalpy of dehydrogenation.'
- Running scenario:** Includes 'Type of run' (Single run selected), 'Test case' (1 Fuel economy test ...), and a 'Run simulation' button.
- Storage system variables - Single run:** A table of parameters with input fields and value ranges.
- Results (at end of simulation):** A list of scalar results with input fields.
- Plot area for time traces:** A graph showing 'Temperature [C]' vs 'time [s]'.

Annotations and callouts include:

- 'Single-run only' pointing to the 'Type of run' section.
- 'System-specific parameters' pointing to the 'Storage system variables' table.
- 'Default values filled in' pointing to the 'Refueling fraction' field.
- 'Value ranges' pointing to the 'Hydride mass' field.
- 'Hover over for tooltips' pointing to the 'Gravimetric capacity' field.
- 'Scalar results' pointing to the 'Results' list.
- 'Plot area for time traces' pointing to the graph.
- 'Stop' pointing to the 'Stop simulation' button.
- 'Save scalar results' pointing to the 'Save results' button.
- 'Generate MATLAB plots of time traces (used for further editing)' pointing to the 'Generate all plots' button.

Variable	Unit	Range	Value
Auxiliary loads	kW	(0.2 - 2)	0.7
Combustor efficiency	-	(0.5 - 1)	0.9
Extra volume	L	(0 - 200)	0
Hydr. crystal density	kg/m <sup>3</sup>	(500 - 7000)	851.41
Hydr. weight fraction	-	(0.01 - 0.2)	0.11
Hydride mass	kg	(1 - 400)	66
Hydride void fraction	-	(0.2 - 0.6)	0.3
Inert weight fraction	-	(0 - 0.4)	0.1
Refueling fraction	-	(0.5 - 1)	0.85
Refueling pressure	bar	(60 - 110)	100
Refueling temperature	C	(-20 - 50)	39.7

Variable	Unit	Value
H2 delivered	kg	
H2 used	kg	
Gravimetric capacity	%	
Volumetric capacity	g/L	
Temperature		
Pressure		
Fuel economy	mpgge	
Range	miles	
Distance traveled	miles	

# Framework Model GUI

## Initial screen

**Figure 1: Vehicle simulation framework**

### Hydrogen Vehicle Simulation Framework

Select storage system: Test system (dropdown menu open showing: Test system, Compressed 350 bar, **Compressed 700 bar**, MH-GH/3s v3)

Running scenario: Test case (dropdown menu open showing: 1 Fuel economy test (UDDS+HWY, 24C), 2 Aggressive cycle (US06, 24C), **3 Cold cycle (HT=3, 20C)**, 4 Hot cycle (SC03, 35C))

Storage system variables - Single run

Auxiliary loads	kW	(0.2 - 2)	0.7
Tank aux power	W	(0 - 1000)	100

Results (at end of simulation)

H2 delivered	kg	Distance traveled	miles
H2 used	kg	EPA Fuel economy	mpgge
Usable H2	kg	EPA Range	miles
Storage system mass	kg		
Storage system volume	L		
Gravimetric capacity	%		
Volumetric capacity	g/L		
On-board efficiency	%		
Temperature	C		
Pressure	bar		

Buttons: Run simulation, Stop simulation, Save results

---

**Figure 1: Vehicle simulation framework**

### Hydrogen Vehicle Simulation Framework

Select storage system: MH-GH/3s v3

Running scenario: Test case (dropdown menu open showing: 1 Fuel economy test (UDDS+HWY, 24C), 2 Aggressive cycle (US06, 24C), **3 Cold cycle (HT=3, 20C)**, 4 Hot cycle (SC03, 35C))

Storage system variables - Single run

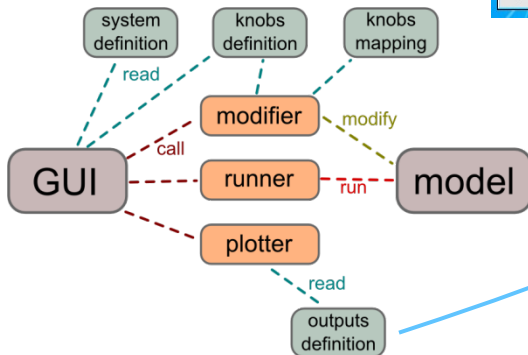
Auxiliary loads	kW	(0.2 - 2)	0.7	Inert weight fraction	(0 - 0.4)	0.1
Compressor efficiency	-	(0.5 - 1)	0.9	Refueling pressure	(60 - 110)	100
Extra volume	L	(0 - 200)	0	Refueling temperature	(-20 - 50)	39.7
Hydr. crystal density	kg/m3	(500 - 7000)	851.41			
Hydr. weight fraction	-	(0.01 - 0.2)	0.11			
Hydride mass	kg	(1 - 400)	5			
Hydride void fraction	-	(0.2 - 0.6)	0.3			

Results (at end of simulation)

H2 delivered	kg	Distance traveled	miles
H2 used	kg	EPA Fuel economy	mpgge
Usable H2	kg	EPA Range	miles
Storage system mass	kg		
Storage system volume	L		
Gravimetric capacity	%		
Volumetric capacity	g/L		
On-board efficiency	%		
Temperature	C		
Pressure	bar		

Buttons: Stop simulation, Save results, Generate all plots

Temperature [C] plot: 0 to 1.0 over time [s] 0 to 1.0



# Framework Model GUI—Inputs

scenario

Storage system variables - Single run

Auxiliary loads	kW	(0.2 - 2)	0.7	Inert weight fraction	-	(0 - 0.4)	0.1
Combustor efficiency	-	(0.5 - 1)	0.9	Refueling fraction	-	(0.5 - 1)	0.85
Extra volume	L	(0 - 200)	0	Refueling pressure	bar	(60 - 110)	100
Hydr. crystal density	kg/m3	(500 - 7000)	851.41	Refueling temperature	C	(-20 - 50)	39.7
Hydr. weight fraction	-	(0.01 - 0.2)	0.11				
Hydride mass	kg	(1 - 400)	5				
Hydride void fraction	-	(0.2 - 0.6)	0.3				

FTP-75, -20C

simulation

Running scenario

Test case

3 Cold cycle (FTP-75, -20C)

1 Fuel economy test (UDDS+HWY, 24C)

2 Aggressive cycle (US06, 24C)

3 Cold cycle (FTP-75, -20C)

4 Hot cycle (SC03, 35C)

Storage system variables

Auxiliary loads

## Key Parameters

- Storage system
- Test case / drive cycle
- Auxiliary loads
- System specific
  - Hydride mass (MH sys)
  - Tank aux power (test sys)

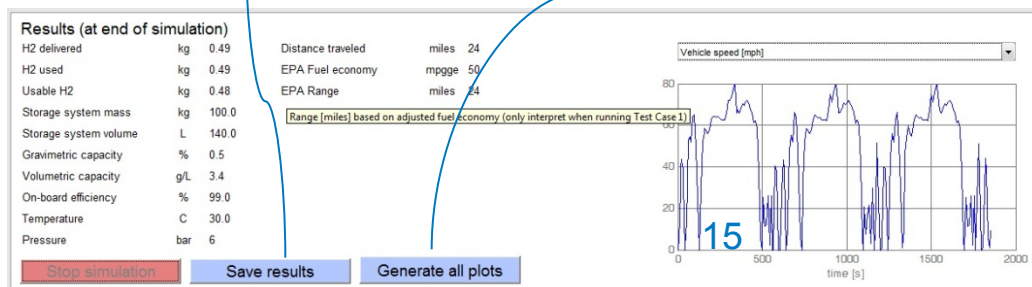
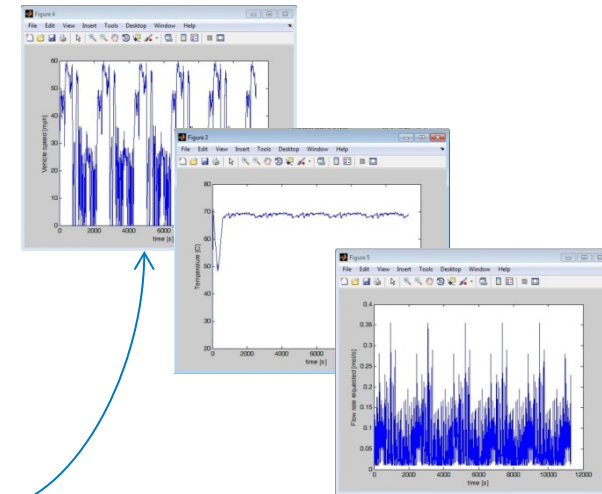
## Key Results

- Volumetric and gravimetric capacity
- Fuel economy and range (case 1)
- Onboard efficiency
- H2 flow rate

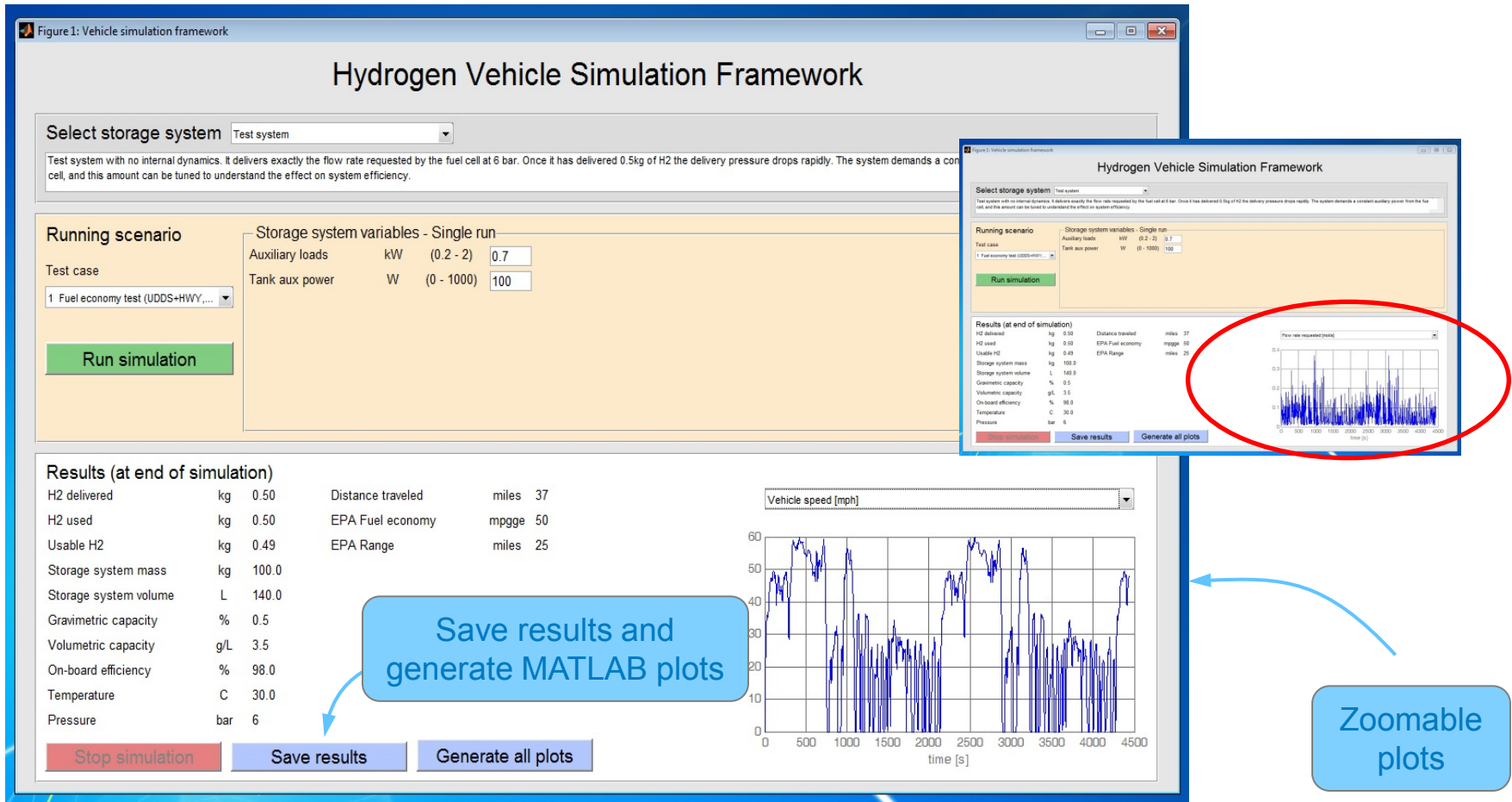
Save results to generate summary text files and MATLAB® figures

```

example2.m - Notepad
File Edit Format View Help
System: MH-GV35 v3
Description:
Generic metal hydride model 30 kg/mol
Running scenario:
Test case: 1 Fuel economy test (UDDS+HWY, 24C)
Storage system & vehicle variables:
Auxiliary loads [kW]: 0.7
Combustor efficiency [-]: 0.9
Extra volume [L]: 0
Hydr. crystal density [kg/m3]: 851.415
Hydr. weight fraction [-]: 0.11
Hydride mass [kg]: 5
Hydride void fraction [-]: 0.3
Inert weight fraction [-]: 0.1
Refueling fraction achieved [-]: 0.85
Refueling pressure [bar]: 100
Refueling temperature [C]: 39.7
Scalar results:
Distance traveled [miles]: 97
EPA Fuel economy [mpgge]: 49
EPA Range [miles]: 60
Gravimetric capacity [kg]: 3.7
H2 delivered [kg]: 1.30
H2 used [kg]: 1.31
On-board efficiency [%]: 97.5
Pressure [bar]: 5
Storage system mass [kg]: 34.8
Storage system volume [L]: 44.3
Temperature [C]: 69.3
Usable H2 [kg]: 1.27
Volumetric capacity [g/L]: 28.8
    
```



# Framework Model GUI—Model Results





# Framework—Model Results

```

example2.txt - Notepad
File Edit Format View Help
System: Test system

Description:
Test system with no internal dynamics. It delivers exactly the flow rate requested by the

Running scenario:
Test case: 2 Aggressive cycle (us06, 24C)

Storage system & vehicle variables:
Auxiliary loads [kw]: 0.7
Tank aux power [W]: 100
    
```

```

example2.txt - Notepad
File Edit Format View Help
System: MH-GH/3s v3

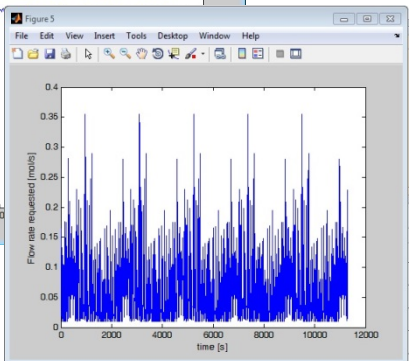
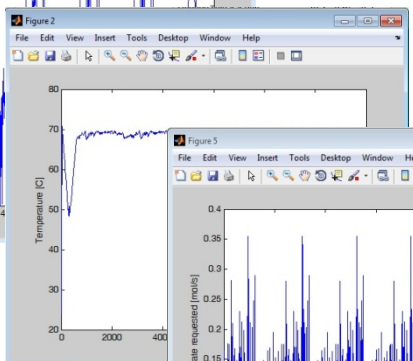
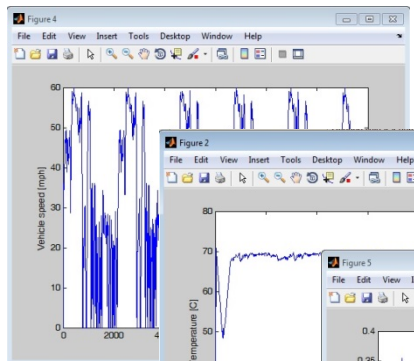
Description:
Generic metal hydride model 30 kJ/mol enthalpy of dehydrogenation.

Running scenario:
Test case: 1 Fuel economy test (UDDS+Hwv, 24C)

Storage system & vehicle variables:
Auxiliary loads [kw]: 0.7
Combustor efficiency [-]: 0.9
Extra volume [L]: 0
Hydr. crystal density [kg/m3]: 851.415
Hydr. weight fraction [-]: 0.11
Hydride mass [kg]: 15
Hydride void fraction [-]: 0.3
Inert weight fraction [-]: 0.1
Refueling fraction achieved [-]: 0.85
Refueling pressure [bar]: 100
Refueling temperature [C]: 39.7

Scalar results:
Distance traveled [miles]: 97
EPA Fuel economy [mpgge]: 49
EPA Range [miles]: 64
Gravimetric capacity [%]: 3.7
H2 delivered [kg]: 1.30
H2 used [kg]: 1.31
On-board efficiency [%]: 97.5
Pressure [bar]: 5
Storage system mass [kg]: 34.8
Storage system volume [L]: 44.3
Temperature [C]: 69.3
Usable H2 [kg]: 1.27
volumetric capacity [g/L]: 28.8
    
```

Save results and generate summary text files and MATLAB figures



**Results (at end of simulation)**

H2 delivered	kg	0.49	Distance traveled	miles	24
H2 used	kg	0.49	EPA Fuel economy	mpgge	50
Usable H2	kg	0.48	EPA Range	miles	24
Storage system mass	kg	100.0			
Storage system volume	L	140.0			
Gravimetric capacity	%	0.5			
Volumetric capacity	g/L	3.4			
On-board efficiency	%	99.0			
Temperature	C	30.0			
Pressure	bar	6			

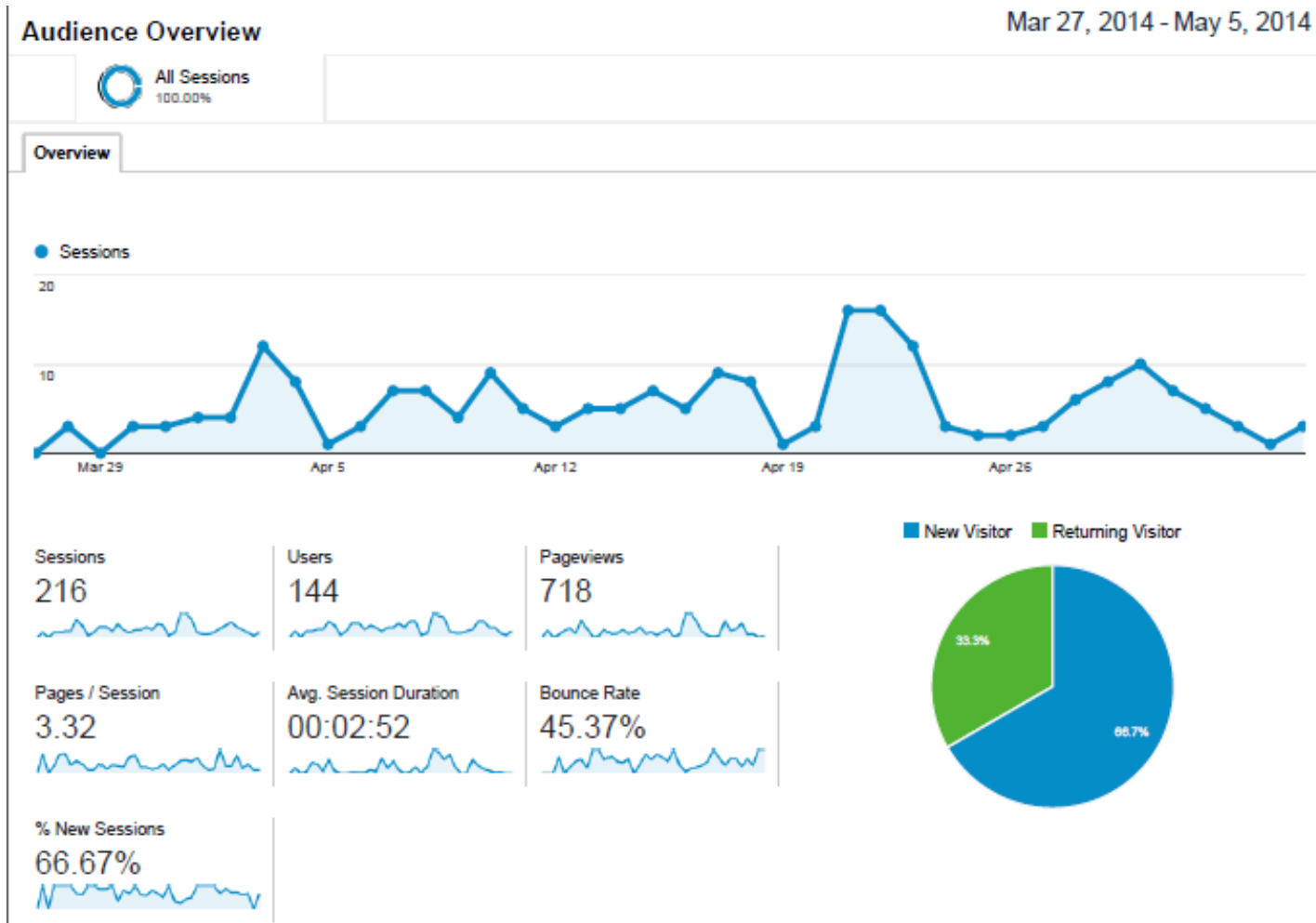
Range [miles] based on adjusted fuel economy (only interpret when running Test Case 1)

Vehicle speed [mph]

Stop simulation Save results Generate all plots

# Accomplishments: Model Website Analytics

## Site Visits

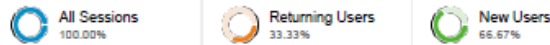


# Accomplishments: Model Website Analytics

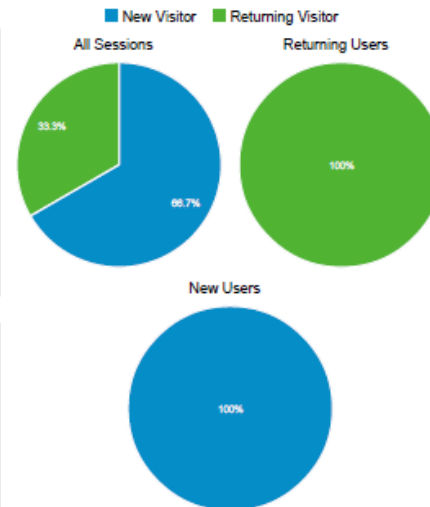
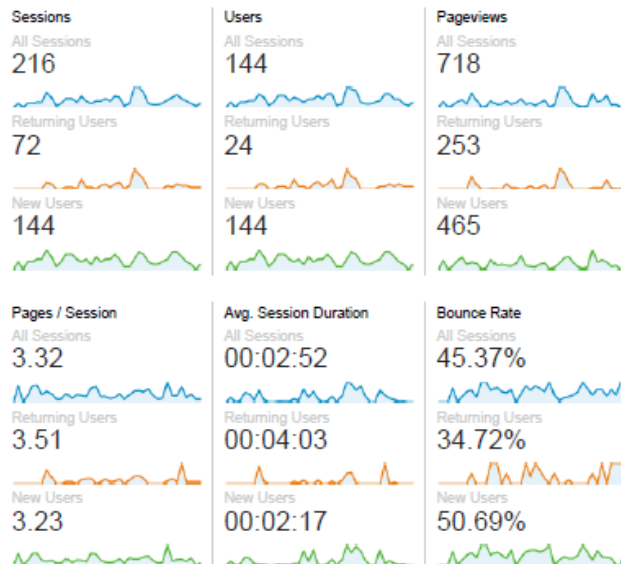
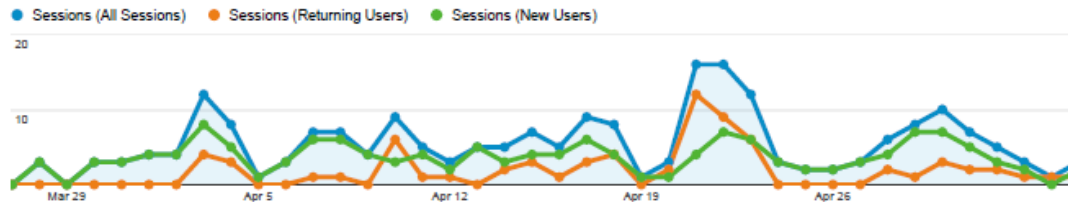
## New versus Return Visits

### Audience Overview

Mar 27, 2014 - May 5, 2014



#### Overview



# Accomplishments: Model Website Analytics

## User Flows

Users Flow

Mar 1, 2014 - May 5, 2014

All Sessions  
100.00%

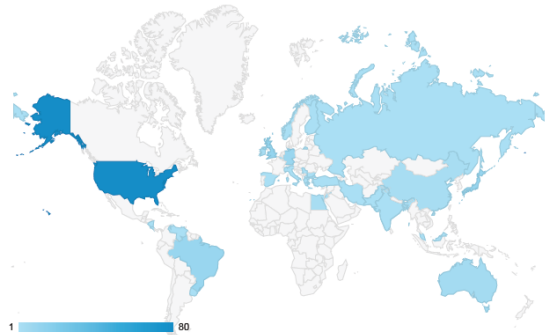


# Accomplishments: Model Website Analytics

## Visitor Locations

Location Mar 23, 2014 - Apr 22, 2014

All Sessions 100.00%
   
 Map Overlay
   
 Summary

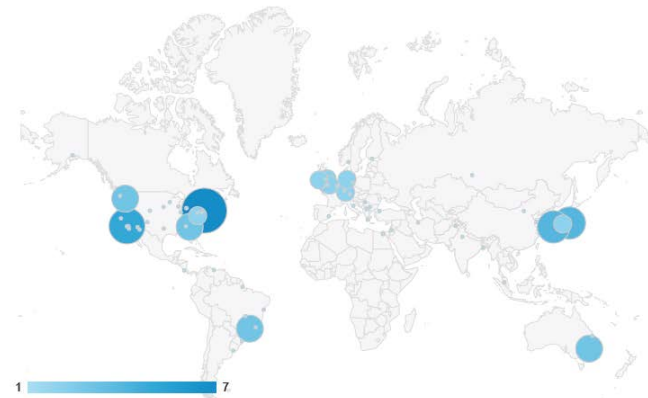


Country / Territory	Acquisition			Behavior			Conversions		
	Sessions	% New Sessions	New Users	Bounce Rate	Pages / Session	Avg. Session Duration	Goal Conversion Rate	Goal Completions	Goal Value
	151 % of Total: 100.00% (151)	64.90% Site Avg: 64.90% (0.00%)	98 % of Total: 100.00% (98)	43.71% Site Avg: 43.71% (0.00%)	3.27 Site Avg: 3.27 (0.00%)	00:03:04 Site Avg: 00:03:04 (0.00%)	0.00% Site Avg: 0.00% (0.00%)	0 % of Total: 0.00% (0)	\$0.00 % of Total: 0.00% (\$0.00)
1. United States	80 (52.98%)	51.25%	41 (41.84%)	30.00%	3.71	00:03:51	0.00%	0 (0.00%)	\$0.00 (0.00%)
2. United Kingdom	11 (7.28%)	72.73%	8 (8.16%)	36.36%	3.55	00:03:20	0.00%	0 (0.00%)	\$0.00 (0.00%)
3. Japan	10 (6.62%)	30.00%	3 (3.06%)	50.00%	4.20	00:05:03	0.00%	0 (0.00%)	\$0.00 (0.00%)
4. Brazil	9 (5.96%)	100.00%	9 (9.18%)	100.00%	1.00	00:00:00	0.00%	0 (0.00%)	\$0.00 (0.00%)
5. Germany	8 (5.30%)	87.50%	7 (7.14%)	12.50%	4.88	00:03:20	0.00%	0 (0.00%)	\$0.00 (0.00%)
6. Australia	4 (2.65%)	50.00%	2 (2.04%)	25.00%	4.00	00:01:50	0.00%	0 (0.00%)	\$0.00 (0.00%)
7. Bangladesh	2 (1.32%)	100.00%	2 (2.04%)	100.00%	1.00	00:00:00	0.00%	0 (0.00%)	\$0.00 (0.00%)
8. Belgium	2 (1.32%)	100.00%	2 (2.04%)	0.00%	6.00	00:13:57	0.00%	0 (0.00%)	\$0.00 (0.00%)
9. China	2 (1.32%)	100.00%	2 (2.04%)	100.00%	1.00	00:00:00	0.00%	0 (0.00%)	\$0.00 (0.00%)
10. Egypt	2 (1.32%)	100.00%	2 (2.04%)	50.00%	1.50	00:00:18	0.00%	0 (0.00%)	\$0.00 (0.00%)

New Custom Report

Mar 23, 2014 - Apr 22, 2014

All Sessions 75.50%
   
 Report Tab



City	Sessions
	114 % of Total: 75.50% (151)
1. Stratford	7 (6.14%)
2. Los Angeles	5 (4.39%)
3. (not set)	4 (3.51%)
4. Yokohama	4 (3.51%)
5. Fukuoka	4 (3.51%)
6. Sydney	3 (2.63%)
7. Sao Paulo	3 (2.63%)
8. Aiken	3 (2.63%)
9. Richland	3 (2.63%)
10. Stuttgart	2 (1.75%)

# Accomplishments: Response to Reviewers' Comments

- **Comment: There is a lack of variation in powertrain configurations. The project team should add range extender powertrain sensitivity analysis.**
  - Response: The powertrain and vehicle platforms included in the vehicle performance modeling task were limited by design due to project budget and time constraints.
- **Comment: It would be instructive to redo the analyses on a fixed volume basis. FCEVs will have a fixed packaging volume for fitting the storage system on board the vehicle. Greater discrimination between the various storage concepts could result from a fixed-volume analysis.**
  - Response: The focus of the vehicle level analysis for this project was to perform simulations on a fixed usable H<sub>2</sub> mass basis. As such, most of the analyses used a 5.6 kg usable H<sub>2</sub> assumption and the storage models were designed and coded to be consistent with this assumption. That said, a fixed volume analysis was performed in FY12. A summary table of the results from this study is presented on the following slide.

# Results: Fixed Volumetric Effects on Range Analysis

Example simulated volume effects on vehicle range and onboard usable H<sub>2</sub> (from framework) for various adsorbent system designs

For three fixed volume scenarios: 140/205/253 liters

Hydrogen Storage System	Adjusted Fuel Economy (mpgge)	Usable H <sub>2</sub> (kg)	Range (mi) Usable H <sub>2</sub>	Gravimetric Capacity (weight percent)	Volumetric Capacity (g/L)	Volume (L)
Powder MOF-5 60 bar 80k Al	51.11	2.00	102.20	2.80	12.86	140 <sup>1</sup>
Powder MOF-5 60 bar 40k CF	51.30	4.20	215.50	6.61	29.84	140
0.52 g/cc MOF-5 200 bar 80k Al	50.47	3.35	169.10	2.68	23.94	140
0.52 g/cc MOF-5 200 bar 40k CF	50.62	4.60	232.90	4.18	32.59	140
Powder MOF-5 60 bar 80k Al	50.95	2.80	142.70	3.15	13.67	205
Powder MOF-5 60 bar 40k CF	50.97	6.70	341.50	7.97	32.64	205
0.52 g/cc MOF-5 200 bar 80k Al	49.93	5.35	267.10	2.92	26.11	205
0.52 g/cc MOF-5 200 bar 40k CF	50.18	7.30	366.30	4.61	35.51	205
Powder MOF-5 60 bar 80k Al	50.73	3.60	182.60	3.39	14.18	253
Powder MOF-5 60 bar 40k CF	50.89	8.60	437.60	8.68	33.96	253
0.52 g/cc MOF-5 200 bar 80k Al	49.32	6.85	337.90	3.02	27.05	253
0.52 g/cc MOF-5 200 bar 40k CF	49.71	9.30	462.30	4.77	39.56	253

<sup>1</sup> Actual volume used = 155.56 L, which represents the lowest value in the data set available.

# Response to Reviewers Comments, Cont.

- **Comment: The progress in MOF-5 isotherm measurement appears to be slow, perhaps due to limited funding.**
  - Response: The "material characterization" component of this effort was only involved with sorbents, and leveraged the vast amount of information generated by the Hydrogen Sorption Center of Excellence. This part of the effort provided guidance for identifying potential sorbents for the Engineering Center and providing the specific engineering properties needed to make down-selections and to improve model confidence. Most of this activity in the past focused on non-metal organic framework materials (MOFs), and ultimately, since MOFs were selected for Phase II and Phase III activities, the vast majority of the work and information provided was down selected. At this time, the main focus of the NREL "material characterization" effort is involved with model validation, especially for temperatures below 75 K.



# Collaboration and Coordination: Web Model Team Roles and Responsibilities

- Storage system model development, coding and documentation—convert models to appropriate format for use in framework (Simulink®). PNNL and SRNL
- Framework management—GUI development and storage system model integration. UTRC
- Vehicle model development and validation—framework output management and validation. Storage system model integration and framework update posting. NREL
- Fuel cell model development and validation. Ford
- Framework model and standalone model posting and Web portal management, NREL
- Model documentation. NREL, PNNL, Ford, SRNL, UTRC



Management of collaboration efforts across organizations is done through monthly and on-demand modeling team telecons, bi-annual face-to face-meetings, and through SharePoint



# Proposed Future Work

- Focus on model validation and model Web access
  - Add CH models to Framework (June)
  - Add Adsorbent models to Framework (September)
  - Post Adsorbent finite element model similar to MH FE Model
- Continue to run vehicle simulations to:
  - Evaluate the impact of changes to Phase III storage system designs and refinements
- Energy analysis
  - Work complete
- Media engineering properties
  - Work complete

# Summary

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- Manage HSECoE vehicle performance, cost, and energy analysis technology area.
- Lead effort to make models developed by HSECoE available to other researchers via Web-based portal.
- Vehicle Performance: Develop and apply model for evaluating hydrogen storage requirements, operation and performance trade-offs at the vehicle system level.

# Technical Back-Up Slides

# Results: Fixed Volumetric Effects on Range Analysis

Example simulated volume effects on vehicle range and onboard usable H<sub>2</sub> (from framework) for various adsorbent system designs

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