Low Cost, Metal Hydride Based Hydrogen Storage System for Forklift Applications (Phase II)

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Hawaii Hydrogen Carriers

US DOE Annual Merit Review Meeting

June 18, 2014

Project ID: ST 095

Overview

Timeline

- Start Date: August 2012
- End Date: November 2014
- Percent Complete: 75%

Barriers

A. System Weight and Volume
B. System Cost
D. Durability/Operability
E. Charging/Discharging Rates
I. Dispensing Technology
J. Thermal Management

Budget

- Total Funding Spent as of 3/31/14: $531,195
- Total Project Value: $1,099,526

Partners

- Sandia National Laboratory (SNL)
  - Simulations and Single-Tube Testing
- Hydrogenics
  - Fuel Cell Integration and Reservoir Testing

Relevance

Main Focus: Prove metal hydride solid state (MHSS) based systems provide a cost competitive, favorable H_2 storage option for zero-emission, low-speed material handling vehicles (e.g., forklifts) for industrial applications. Forklifts provide a means to incorporate fuel-cells and metal hydrides as onboard reversible fuel storage

Objectives (Sept. 2012 to Sept. 2014):

1. Optimize design of the MHSS fuel system for proton exchange membrane (PEM) fuel cell powered forklift applications (Sept. 2012 to May 2013)
2. Test, qualify, and certify the MHSS fuel system design (May 2013 to Nov 2013)
3. Conduct final fabrication and operational testing of the MHSS fuel system within an integrated systems environment (Sept. 2013 to Sept. 2014)

Current reporting year

Addresses barriers to move toward lower-cost technologies, reliable onboard reversible fuel storage performance, and technology readiness

Relevance

Current project

Current reporting year

Barriers	Battery Powered Forklift	High-Pressure H_2 Tank Fuel-Cell System Powered Forklift	Metal Hydride H_2 Tank Fuel-Cell System Powered Forklift
A. System Weight & Volume	Heavy, although it is needed in a forklift to help as a counterbalance	Fuel storage can be up to 35% less than metal hydride system, need to add ballast to reach the required weight of a battery pack	Heavy metal hydride material makes forklift applications attractive although additional ballast is still needed to reach the required weight of a battery pack
B. System Cost	Need chargers and battery exchangers (for 24/7 units)	Need high-pressure refueling infrastructure	Market entry into small forklift fleets, expensive refueling infrastructure not needed, use typical H_2 gas cylinders
D. Durability/Operability	Performance dropoff at the end of duty cycle and lifespan of batteries	Greater power stability and twice the lifespan of a battery powered fuel-cell	Hydride material can be brought to it's original state and storage capacity, can be easily integrated with PEM fuel cell
E. Charging/Discharging Rates	Long recharge times (up to 16 hrs), loss in productivity	Quick filling and discharging of high-pressure tanks, although compression energy is required (5 min)	The chosen hydride material will be able to meet the needs of the PEM fuel cell. <30 min charging but faster charging can be accomplished through "opportunity refills"
I. Dispensing Technology	Chargers and battery exchangers	Inlet ports and specialized nozzles for hydrogen dispensing have already been introduced into the market	High-cost infrastructure not required. Only standard compressed gas tanks and hydrogen pressure regulator
J. Thermal Management	No thermal management needed for battery	No thermal management needed for 350 bar high-pressure tank	Heat rejection with the radiator/fan from the PEM fuel cell will meet the heat rejection requirements during fueling. PEM fuel cell provides heat for H_2 desorption during use

Approach

Use the knowledge from Phase I* to design, build, test, qualify, and certify a metal hydride, fuel cell powered forklift.

1. Work with Hydrogenics to develop baseline reservoir dimensions and features to replace the current battery pack
2. Design single hydride tubes w/ SNL to measure hydrogen storage amounts, refill times, durability, discharge ability, and residual capacity at minimum discharge point for varying hydride tube characteristics (hydrogen distribution tube, amount of thermal enhancement material, type of thermal enhancement material)
3. Fabricate tubes, build experimental setup, and perform single hydride tube tests
4. Perform model verification with experimental results
5. After an optimum hydride tube configuration is chosen, design and build overall reservoir in given space inside the forklift power pack
6. Perform reservoir and fuel cell integration test with forklift followed by the on-site operational test

Current reporting year

*Phase I work included:
- metal hydride modeling studies indicating MHSS will operate per specifications for PEM fuel cell powered forklift applications
- determining Hy-Stor 208, AB5 hydride material has adequate hydrogen storage properties to be successfully utilized as the basis of the core of the system
- manufacturing, cost, and commercialization analysis showed that the solid-state storage system to be build

Approach

The Hydrogen Storage Engineering Center of Excellence (HSECoE) has studied hydrogen storage in the past. However, transferrable results are limited due to the different focus of work.

Topic	HSCECoE	HHC (Current Study)	Comment (Current Reporting Year)
Target Application	Light-duty vehicles (10-11 wt%).	Industrial forklift (1.2 wt.%).	Different required material behavior. Need heavy material to provide counterbalance for forklift
Status	Eliminated work on metal hydride in FY2012, prior to addressing commercialization aspects.	On commercialization pathway.	Different focus of work. Site demonstration chosen on Oahu island using already-obtained Air Products H_2 gas cylinder packs
Cooling Method	Internal coolant tubes.	External cooled shell.	Different physical design. Single tube refill experiments proved that the reservoir could be filled in ~30 mins using the fuel cell's radiator and fan
Heating Method	Requires external H_2 burner.	Heated by fuel cell.	Different system design (some cold-start lessons are transferrable). Single tube discharge experiments proved that the reservoir can provide the hydrogen flowrate needed by the fuel cell powered forklift.
MH thermal conductivity	Compaction focus.	Various Expanded Natural Graphite (ENG) types.	Different approaches and materials – some qualitative transferability. Using ENG as flakes instead of worms.
Containment vessel	High temperature, high pressure (150 bar).	Near-ambient temperature, medium pressure (50 bar).	Different vessel requirements. Results in lower hydrogen pressure supply, no need for gas compression system.
Cost (project and system)	HSECoE funded at $40M; reaching system performance targets was primary goal.	$1.099M SBIR funds. Low-cost project, system, and refueling requirements is the focus.	Different ratio of innovative engineering to leveraging of off-the-shelf solutions.

Approach

Milestones and Go/No Go Decision

Project Year 1 (Sept 2012 – Sept 2013)

Month	Milestones and Go/No Go Decision	Comments	% Completed
4	System and sub-system specification (SSS) established	Specification list has been written and confirmed from the experimental metal hydride tube experiments.	100%
6	Hydride testing completed	Various refill and discharge scenarios were tested on different hydride tube configurations. One with the best overall performance was chosen for the final reservoir design.	100%
9	Reservoir design and testing completed	Hydride tubes and tubing have been welded and hydrostatically tested to 1.5x working pressure. Engineering drawings have been documented.	100%
12	Reservoir fabrication completed	Reservoir is completed, will perform leak and cycle testing once reservoir, fuel cell power pack arrives in Hawaii.	90%
	Go/No Go Decision: Modeling studies must show that final design will meet SSS and be fully amenable to integration with fuel cell	Single tube experiments confirmed the ability of the metal hydride reservoir to power the fuel cell without de-rating the forklift.	100%

Approach

Milestones and Go/No Go Decision

Project Year 2 (Sept 2013 – Nov 2014)

Month	Milestones and Go/No Go Decision	Comments	% Completed
4	Reservoir-fuel cell integration and testing completed	Bench integration of reservoir with PEM fuel cell and integration of PEM fuel cell/MHSS within sub-component frame almost completed	80%
7	Formal Qualification Test (FQT) and certification of reservoir completed	Reservoir testing to validate FEA and CFD modeling once unit arrives in Hawaii	0%
8	MHSS/PEMFC/forklift integration completed	Crown forklift has been procured and is located in Hawaii. Includes direct comparison between fabricated MHSS PEM fuel cell system and existing high pressure PEM fuel cell and battery power systems	10%
8	Performance data for integrated reservoir and fuel cell disseminated	Sub-component tests and comparison with numerical analysis	0%
11	Complete operational test of forklift	Currently coordinating the H_2 refueling setup with Hickam AFB	15%
12	Performance data for MHSS/PEMFC/forklift disseminated	Numerical analysis of the full scale systems integrations tests, standards/certification compliance	0%
13	License and teaming agreements finalized	Licenses, teaming agreements, and partnerships with forklift manufacturers	0%

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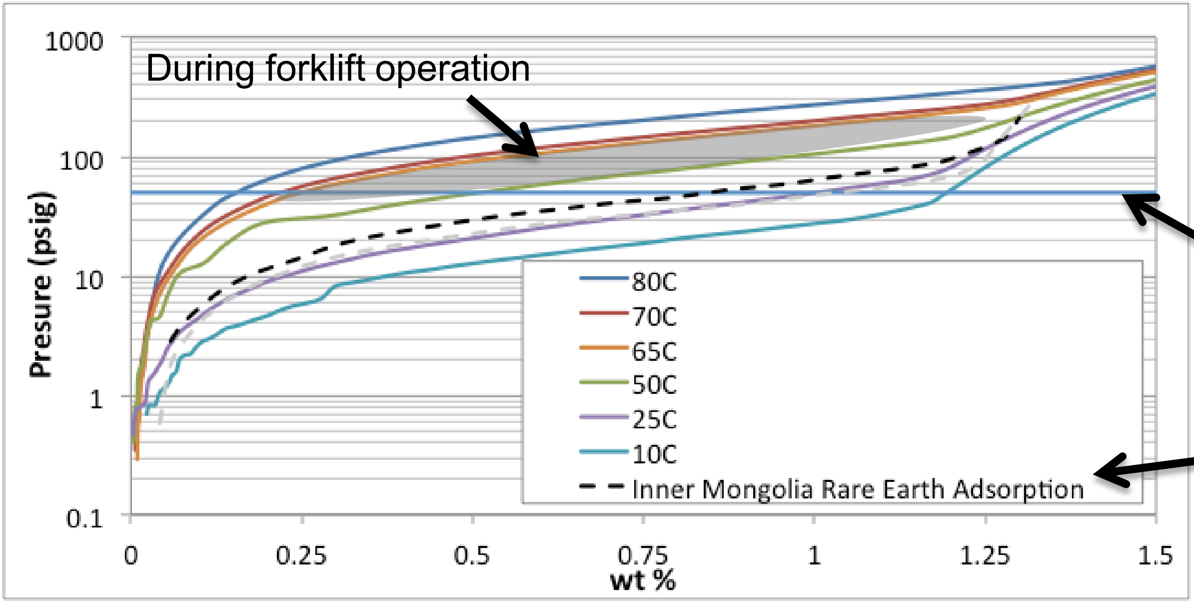
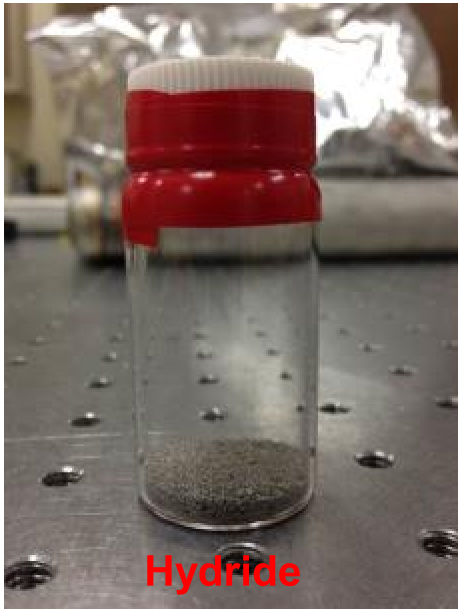
Accomplishments and Progress

Metal Hydride Characteristics

Metal Hydride: **Hy-Stor® 208** ($MmNi_{4.5}Al_{0.5}$)

- AB5 Alloy
  - A: hydride forming metal (usually a rare earth metal, Mischmetal)
  - B: non-hydride forming element (can be doped with other metals to improve stability)
- Measured Pressure-Composition-Temperature (PCT) graph





50 psi H_2 supply lower limit of the fuel cell

Data provided by Chinese supplier

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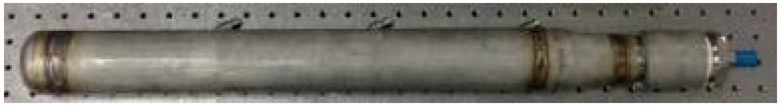
Accomplishments and Progress

Results of metal hydride single tube experiments

- Experimental Hydride Tube Configurations
  1. Base experiment: 1% ENG, no distribution tube
  2. Weight ENG experiment: 5% ENG, no distribution tube
  3. Distribution tube experiment: 1% ENG, distribution tube
  4. Form of ENG experiment: 1% ENG, no distribution tube



- Three Fill/Discharge Tests
  1. Fill #1: Aggressively fill to determine ENG and hydrogen distribution design
  2. Discharge #1: Aggressively discharge to determine ENG and hydrogen distribution design
  3. Fill #2: Prove operation with orifice controlled fill at low final pressure (400 psig)
  4. Discharge #2: Prove operation to meet realistic run data of forklift
  5. Fill #3: Prove operation with orifice controlled fill at high final pressure (750 psig)
  6. Discharge #3: Prove operation to meet cold start up needs over hydrogen content rage

Primary Objective: Determine distribution tube configuration and optimal amount and type of heat transfer enhancement material to achieve satisfactory internal temperature profiles and best overall performance

Hypotheses:
- Tube 2 should have a smaller temperature difference radially than Tube 1 (due to ENG %s)
- Tube 3 should have a smaller temperature difference axially than Tube 1 (due to H_2 distribution tube)
- A difference in temperatures should be apparent between Tubes 4 and 1 (same % ENG but different form)

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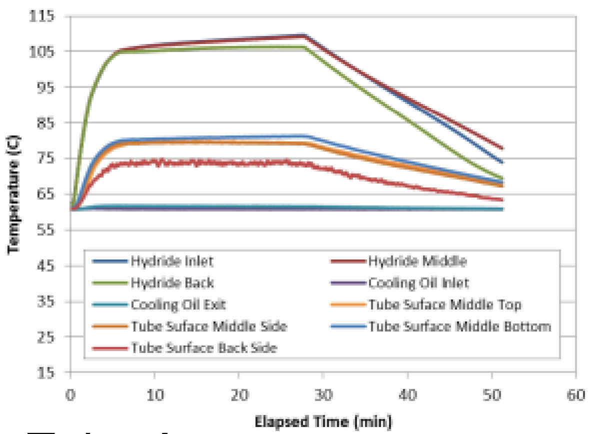
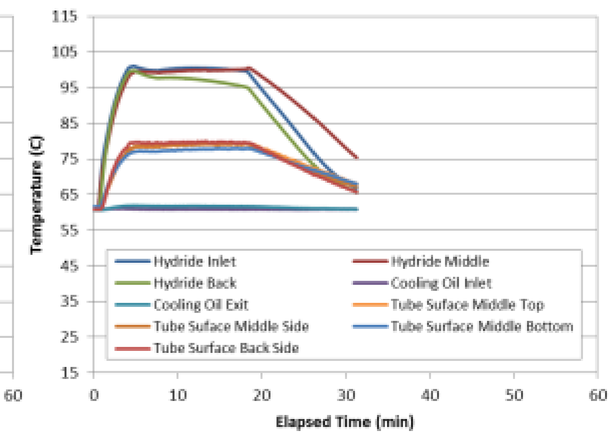
Accomplishments and Progress

Results of metal hydride single tube experiments (cont.)

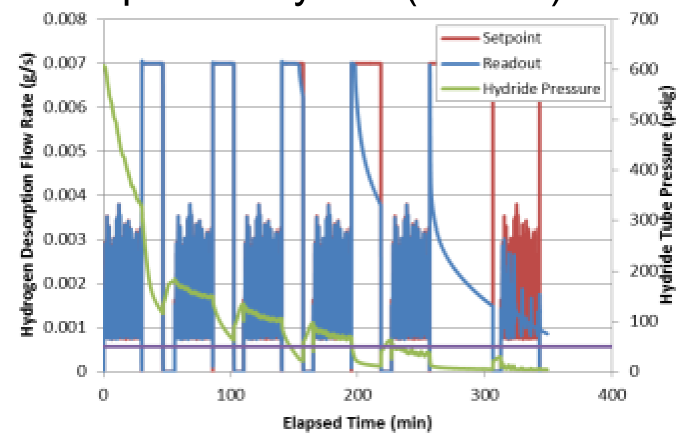
Tube 1



Tube 2



Typical forklift discharge run profiles cycled (Tube 1)



Take-Aways:

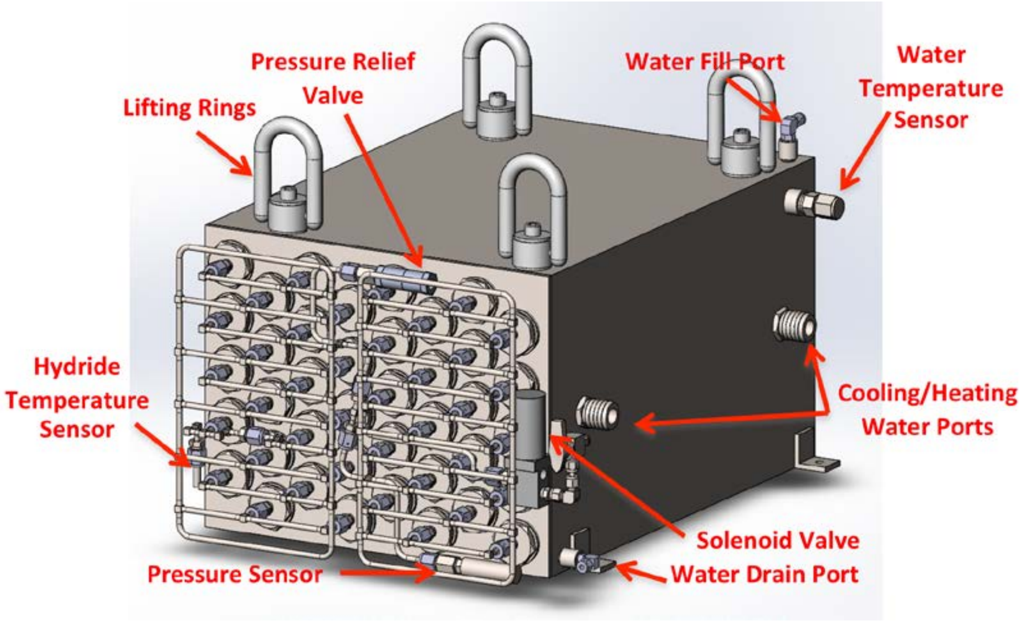
- Temperature profiles for baseline tube (Tube 1) and tube with more ENG (Tube 2) (pictures above), showed very similar temperature differences radially- Tube 2 ruled out due to benefits in minimizing temperature gradient were not as high as expected
- Similar results in temperature difference (not pictured) were also seen between Tube 1 (ENG flakes) and Tube 4 (ENG worms)- Tube 4 also ruled out, will use ENG as flakes
- The temperatures between Tubes 1 and 3 (not pictured) also show very small differences axially- Tube 3 ruled out, no H_2 distribution tube needed
- Each hydride tube has about 7.9 g of usable H_2 at start-up at 17C temperature (tube needs to be 84% full)

1% ENG as flakes w/o the distribution tube was chosen as the hydride tube configuration

Accomplishments and Progress

CAD modeling of overall reservoir design

- Forty 2” nominal pipe diameter tubes, 5 by 8 staggered tube array
- Hydrostatically pressure tested to 1,500 psi (2x operating pressure)
- Modified tube components to minimize part count and increase tube internal volume- 79.22 in^3 vs. 80.89 in^3
- Water enters/leaves through a distribution plate to equally spread water flow across tubes. Contains 3 baffles to alternate water flow to help with heat transfer



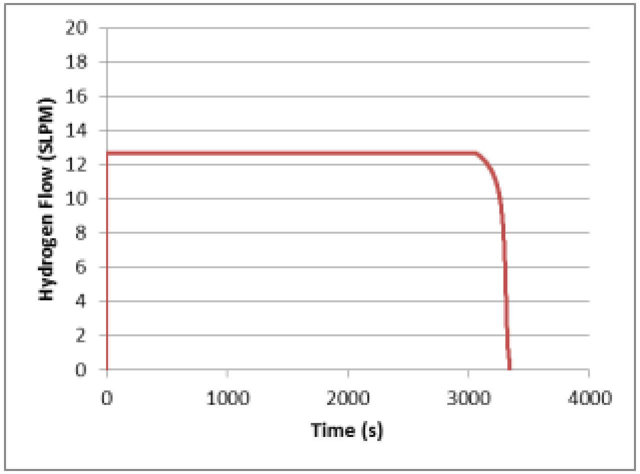
Accomplishments and Progress

Additional metal hydride single tube tests

- Additional refinement tests were done to the hydride tube chosen from the original tests to mimic typical test runs in the forklift/fuel cell system.

- Demonstrations which include potential heating/cooling fluid temperature tests:
  - Recharge experiments at 0%, 25%, 50%, and 75% tank capacity
    - Measure fill time and fluid temperatures
    - Mimic temperatures at room temperature or when fuel cell is warm after use

New fill profile using measured PCT results from Task 1-B

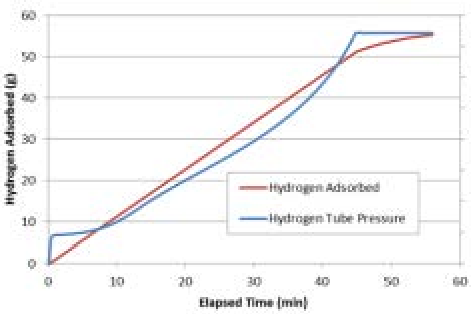


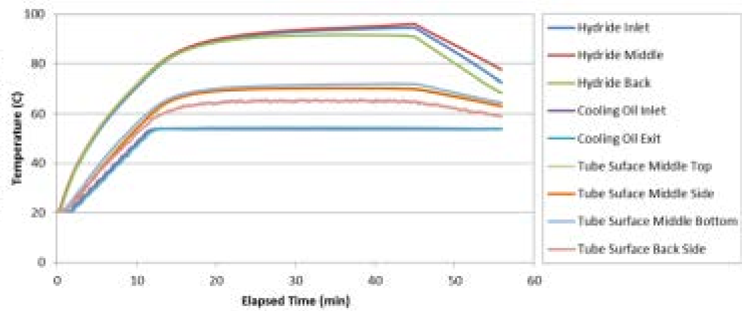
  - Continuous discharge profile using the projected realistic forklift use profiles
    - Starts with the cold start profile in the original experiments
    - Measure run time and fluid temperatures
    - Mimic temperatures at room temperature or when fuel cell is warm after use

Accomplishments and Progress

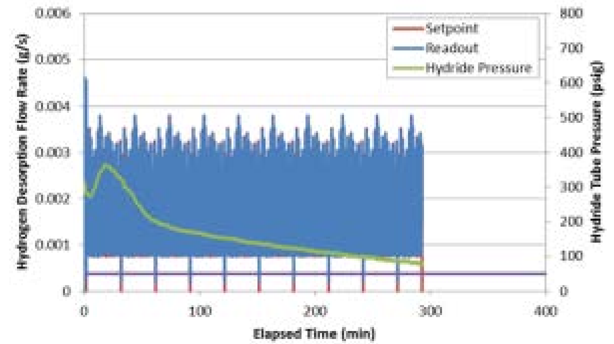
Additional metal hydride single tube tests (cont.)

Sample hydrogen content, tube pressure, and temperature profiles for refills





Sample hydrogen desorption flow rate and hydride tube pressure profile



Take-Aways:

- Total amount of hydrogen stored in each tube is 55 grams (2.2 kg in the reservoir)
- At a tube pressure of 50 psig (lower limit needed by the fuel cell), the tubes still have 15 g of H_2 at 60C. Tank is “empty” at 27% of full capacity
- If a normal duty cycle was running continuously (operator takes no break), it will take approximately 6 hours for the reservoir to be “empty”.
- There is no significant difference in performance when filling at the beginning of the day (cold) than in the afternoon (warm). However, it is still recommended to fill when forklift use is completed for the day as it will be easier to start up the next time of use
- During a fill, once the tube reaches 750 psig, the reservoir tank will be 88% full. This fuel level is sufficient for start-up due to the original tube tests. If operator is okay with this, refill times will be shorter since the fill profile will be incomplete leading to refill times between 8-30 mins vs. 23-46 mins)

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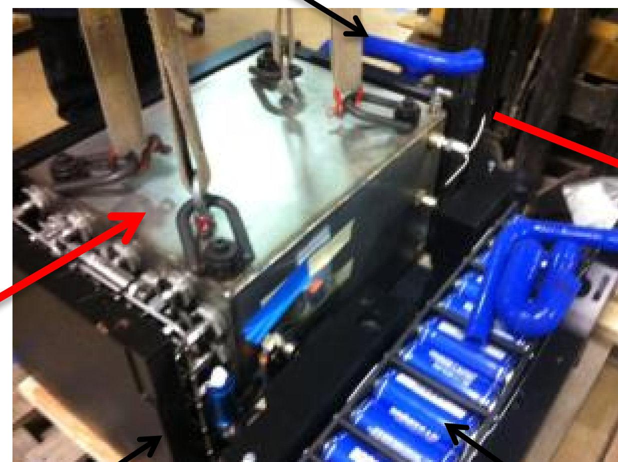
Accomplishments and Progress

Integration

Single Hydride Tube

Hydride Reservoir

Radiator



Metal Casting

Fuel Cell Power Pack

Ultra Capacitors

Forklift

- Hazards and Operability Study (HAZOP) and Failure Mode and Effects Analysis (FMEA) were completed among HHC, SNL, and HYGS
- Forklift has been procured and located on Oahu
  - Manufacturer: Crown
  - Model: FC 4040-60
  - 48 Volt
  - 36" battery compartment
  - 5,000 lb lifting capacity

Accomplishments and Progress

System/Subsystem Specification Table

- Based on the hydride material and fuel cell forklift requirements

Parameter	Specification	Supporting Information
Energy Storage Capacity (kg)	2.2	Hydrogenics high-pressure hydrogen tank can hold up to 1.65 kg. There is 1.6 kg of usable H_2 from the experiments. **(Was assumed to be between 1.63 to 2.13 kg during the last AMR)**
Energy Density (kg/liter of H_2)	0.0132	Available space given in the forklift is 700 mm x 470 mm x 370 mm (121.173 L volume). There is approximately 1.6 kg of usable H_2. This value is well below the 0.03 kg/L 2015 target for material handling equipment.
Specific Energy (kg H_2/kg)	0.0053	Reservoir mass includes: hydride, hydrogen, cooling fluid (water), expanded natural graphite (ENG), tubes, and shell/baffles. Reservoir weight is currently 414.75 kg. **(was 0.5% last AMR)**
Operating Temperatures (˚C)	15 - 60	The upper limit of the cooling fluid in the Hydrogenics PEM fuel cell system (modified HyPM® 8) is 60C. Cold startup is designed for 15C, the lowest expected at deployment site (Honolulu). **(Unchanged since last AMR)**
Operating Pressures (psi abs)	55-1015	Low operating pressure are the hydrogen supply pressure specification required for the Hydrogenics fuel cell. The low limit may be stretched down to 40-45 psi. The upper limit is the maximum refueling pressure. **(Unchanged since last AMR)**
Hydrogen Delivery Rate (L/min)	130	The maximum delivery rate that is required to supply the Hydrogenics system is 130 liters/min. **(Unchanged since last AMR)**
Refill Time (minutes)	46 max	From recharge experiments, it will take 46 mins to fill the reservoir to completely full. Opportunity refills yield refill times on the order of 8 to 30 minutes which is the preferred method in refilling the forklift.

Accomplishments and Progress

System/Subsystem Specification Table (cont.)

Parameter	Specification	Supporting Information
Cycle Life (cycles)	10,000	Still to be determined. **(Unchanged since last AMR)**
Transient Response Time	Minimal	Due to closed loop nature of the system, the transient response time will be minimal. **(Unchanged since last AMR)**
Cost of Complete System ($US)	11,000	Have yet to determine multi-unit and mass production manufacturing costs which should result in reductions in the price of components, materials, and welding. **(was assumed to be $15,000 max during the last AMR)**

Additional items

- Provisional patent filed November 27, 2013– Application Number 61909767
- Forklift demonstration at Hickam AFB using Air Products H_2 8-packs, provide TK16 H_2 nozzle to utilize in current system and provide for local fleet
- Project was not reviewed last year (2013)

Collaborations

- **<u>Sandia National Labs (SNL)</u> (25%)**

  J. Pratt, T. Johnson, and D. Dedrick

  Federal Laboratory, within DOE Hydrogen and Fuel Cells Program

- **<u>Hydrogenics (HYGS)</u> (15%)**

  M. Xu, A. Hill, and R. Sookhoo

  Industry, outside DOE Hydrogen and Fuel Cells Program

Work Plan Activity	Performer(s)
Project Management	100% HHC
Systems Engineering	60% SNL, 20% HYGS, 20% HHC
Task 1: Solid state metal hydride fuel cell system design and optimization	50% SNL, 50% HHC
Task 2: Reservoir fabrication and testing	100% HHC
Task 3: Integration of reservoir and PEM fuel cell	60% HHC, 40% HYGS
Task 4: Formal Qualification Test (FQT) and certification of integrated prototype	15% SNL, 85% HHC
Task 5: Final solid state metal hydride PEM fuel cell forklift site operational test	100% HHC

***Interactions**: Adrian Narvaez has been onsite at SNL for 18 mo. with daily interactions with Dr. Pratt using SNL's experimental facilities. HHC conducts bi-weekly teleconference calls with HYGS assessing progress and addressing upcoming duties. Recently, Adrian spent a week at HYGS during the integration of the fuel cell with the metal hydride reservoir.*

Remaining Challenges and Barriers

- **Transportation of Fuel Cell Power Pack and Metal Hydride Reservoir System to HHC (Hawaii)**
  - Follow necessary shipping procedures
- **Hydrogen Fueling on Hickam AFB**
  - Hydrogen refueling installment onsite using nozzle receptacle
- **Market Development**
  - Establish partnership with fuel-cell manufacturer

Proposed Future Work

- **Complete tasks as scheduled.**
  - **Task 2**: Reservoir Fabrication and testing (100% HHC)
    - Perform leak tests and cycle reservoir once unit reaches Hawaii due to less stringent shipping restrictions
    - Coordinate with HYGS the shipping to Hawaii
  - **Task 3**: Fabrication of Integrated Prototype of Reservoir-PEM Fuel Cell System (70/30%, HHC/Hydrogenics)
    - Integrating MHSS reservoir system with PEM fuel cell at Hydrogenics
    - Integrating reservoir/PEM fuel cell system with forklift at Hawaii Hydrogen Carriers
  - **Task 4**: Formal Qualification Test and Certification (85/15% HHC/SNL)
    - Reservoir testing to validate system modeling and single-tube experiments
    - Planned testing at Hickam Air Force Base
  - **Task 5**: Final Solid State Metal Hydride PEM Fuel Cell Forklift Site Operational Test (100% HHC)
    - Construct hydrogen refueling piping using hydrogen 8-pack cylinders
    - Collect operational data and obtain licensing, teaming agreements, and partnerships with forklift manufacturers
    - Hire marketing research and development personnel
  - **Deliverable**: Final Reporting (100% HHC)

Summary

- **Relevance**: Prove that metal hydride solid state (MHSS) based systems provide a cost competitive favorable H_2 storage option for zero-emission, low-speed materials handling vehicles (e.g., forklifts) for industrial applications.
- **Approach**: Continue on the work from Year 1. Perform single metal hydride experiments and choose a final design that will be incorporated into an overall reservoir design. Construct metal hydride reservoir and integrate into HYGS fuel cell power pack, which will in turn be integrated into a forklift that will be procured.
- **Technical Accomplishments and Progress**: Experimental tubes tested and tube configuration was chosen. Model and build metal hydride reservoir. HYGS integrate the reservoir with their fuel cell system. A forklift was purchased and demonstration site was chosen.
- **Proposed Future Research**: Continue with project schedule with demoing metal hydride/fuel cell powered forklift in Hawaii

Technical Back-Up Slides

Technical Back-Up Slides

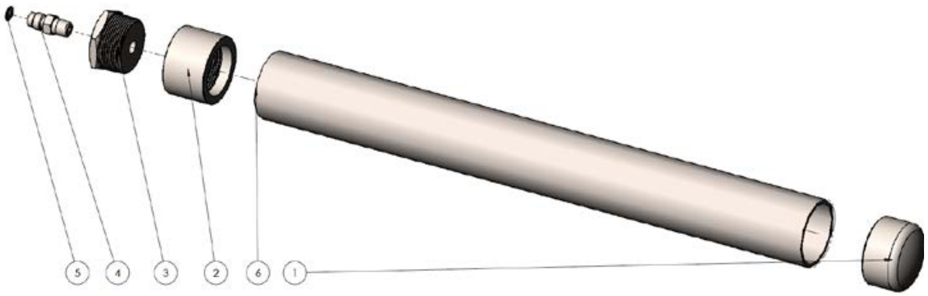
- **Metal hydride single tube test results**

Hydride Tube Fill Results

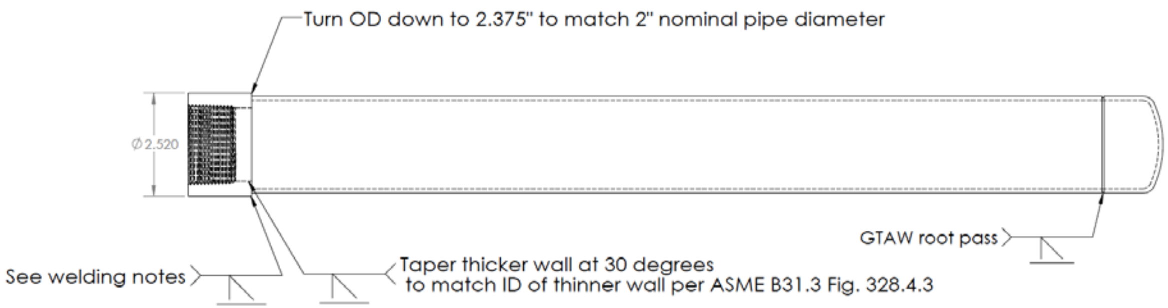
Tube	Run	Pressure	Meas. H_2 adsorbed	Actual H_2 adsorbed	Refill Time	Total H_2 in reservoir	Weight %
		psia	g	g	min	kg	
1	1F	739.97	51.72	50.29	52.07	2.0116	1.16
1	2F	397.66	39.46	38.69	47.24	1.5476	0.89
1	3F	751.82	49.6	48.14	37.48	1.9256	1.11
2	1F	753.21	43.89	42.43	31.3	1.6972	1.15
2	2F	404.95	39.31	38.52	47.43	1.5408	1.05
2	3F	753.47	40.63	39.17	37.6	1.5668	1.07
3	1F	752.1	55	53.54	54.74	2.1416	1.25
3	2F	397.04	45.8	45.03	47.35	1.8012	1.05
3	3F	718.97	50.24	48.85	37.18	1.954	1.14
4	1F	754.98	57.16	55.7	67.03	2.228	1.29
4	2F	393.51	43.06	42.3	47.25	1.692	0.98
4	3F	749.56	47.75	46.3	37.16	1.852	1.07
1 (rep.)	1F	754.53	56.14	54.68	51.27	2.1872	1.26
1 (rep.)	2F	389.2	47.53	46.78	47.19	1.8712	1.08
1 (rep.)	3F	654.4	50.22	48.95	37.16	1.958	1.13

Technical Back-Up Slides

- **Modified hydride tube with weldments**



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	McMaster-Carr: 43645K376	2" Sch 10 Butt-Weld Cap	1
2	McMaster-Carr: 4443K678	1.5" Threaded Half Coupling	1
3	McMaster-Carr: 4443K443	1.5" Male to 0.25" Female Reducing Bushing	1
4	Swagelok: SS-4-VCR-1-4	0.25" Male NPT to 0.25" Male VCR Connector	1
5	Swagelok: SS-4-VCR-2-.5M	0.5 Micron Filter	1
6	McMaster-Carr: 4378K79	2" Diameter Nominal SS316L Sch 10 Pipe	1

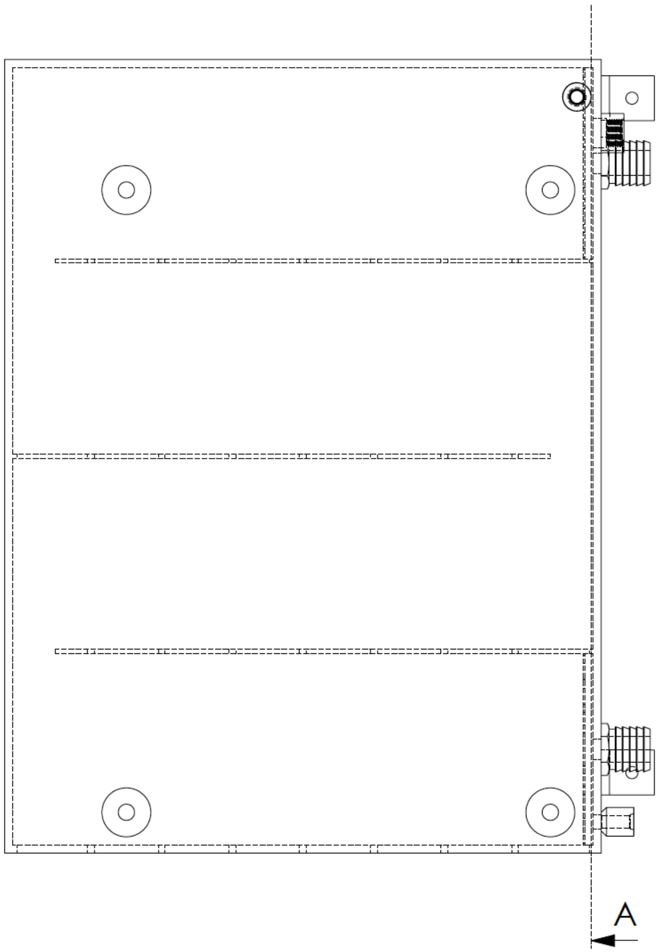


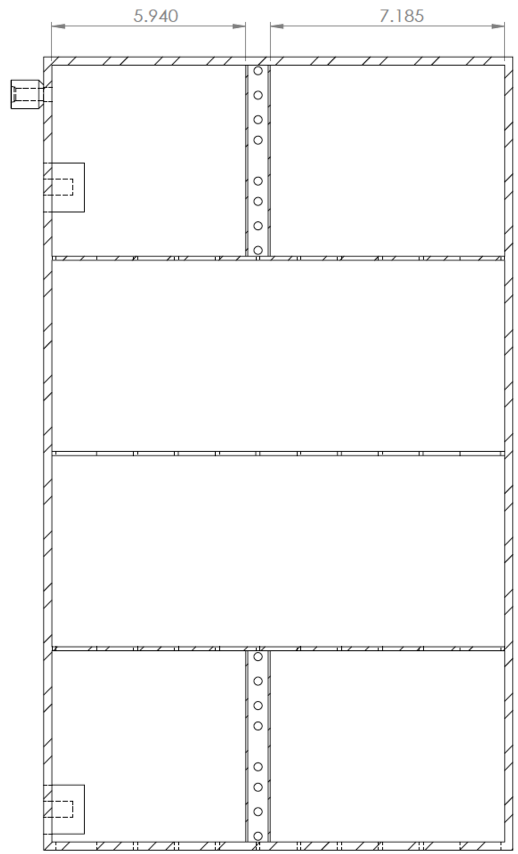
Welding Notes:

1. Slightly chamfer OD of coupling (ref. B16.25 para 3.2(a))
2. GTAW root pass
3. Welders qualified per ASME B31.3
4. All welds use SS316L filler metal (ER316L electrode)

Technical Back-Up Slides

- **Internal reservoir with baffles and water distribution plate**





SECTION A-A

Technical Back-Up Slides

- **Additional metal hydride single tube test results**

Summary of Refill Results

Percent Full	Reservoir Initial Temperature	Initial Hydride Tube Hydrogen Content	Initial Hydride Tube Pressure	Fill Profile Duration	Time needed to reach 750 psig	Hydrogen Adsorbed When Tube Reaches 750 psig	Percent Full when Tube Reaches 750 psig
%	C	g	psig	min	min	g	%
0	25	15	50	43	30	38.0	89
0	60	15	50	46	29	37.1	88
25	60	25	80	40	22.6	25.5	92
50	60	35	133	30	13.5	17.6	93.6
75	60	45	171	23	8	10.9	98

Summary of Discharge Results

Percent Full	Reservoir Initial Temperature	Final Hydride Tube Hydrogen Content	Final Hydride Tube Pressure	Discharge Profile Duration	Hydrogen Desorbed
%	C	g	psig	hr:min	g
0	25	15	50	6:08	37.8
25	25	25	80	4:47	30
50	25	35	133	3:11	20
75	25	45	171	1:36	10