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

May 15, 2013

Project ID: ST 095

Overview

Timeline
- Start Date: August 2012
- End Date: July 2014
- Percent Complete: 30%

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

Budget
- Total project funding: $1,099,526
- Funding for FY2013: $568,331

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):

Current reporting year

1. Optimize design of the MHSS fuel system from 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)

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

Relevance

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	Lost productivity as batteries lose charge/age	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	The chosen hydride material will be able to meet the needs of the PEM fuel cell
I. Dispensing Technology	Battery chargers	Inlet ports and specialized nozzles for hydrogen dispensing have already been introduced into the market	Standard industrial gas cylinders, no specialized infrastructure required
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

Current project

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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

Current reporting year (items 1–3)

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 (to be purchased) followed by the on-site operational test

*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	HSECoE	HHC (Current Study)	Comment
Target Application	Light-duty vehicles (10-11 wt%).	Industrial forklift (1.2 wt.%).	Different required material behavior.
Status	Eliminated work on metal hydride (MH) in FY2012, prior to addressing commercialization aspects.	On commercialization pathway.	Different focus of work.
Cooling Method	Internal coolant tubes.	External cooled shell.	Different physical design.
Heating Method	Requires external H_2 burner.	Heated by fuel cell.	Different system design (some cold-start lessons are transferrable).
MH thermal conductivity	Compaction focus.	Various Expanded Natural Graphite (ENG) types.	Different approaches and materials – some qualitative transferability.
Containment vessel	High temperature, high pressure (150 bar).	Near-ambient temperature, medium pressure (50 bar).	Different vessel requirements.
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 will be confirmed once hydride testing is complete	90%
6	Hydride testing completed	Currently testing which includes materials tests (pressure vs. temperature performance, thermal and kinetic performance, formalized absorption/desorption performance of the hydride, and cycling performance)	40%
9	Reservoir design and testing completed	Produce engineering drawings and component/material specifications, fabrication and testing of components such as internal tubes	25%
12	Reservoir fabrication completed	Perform leak and cycle testing of reservoir	0%
	Go/No Go Decision: Modeling studies must show that final design will meet SSS and be fully amenable to integration with fuel cell	In progress	40%

Approach

Milestones and Go/No Go Decision

Project Year 2 (Sept 2013-Sept 2014)

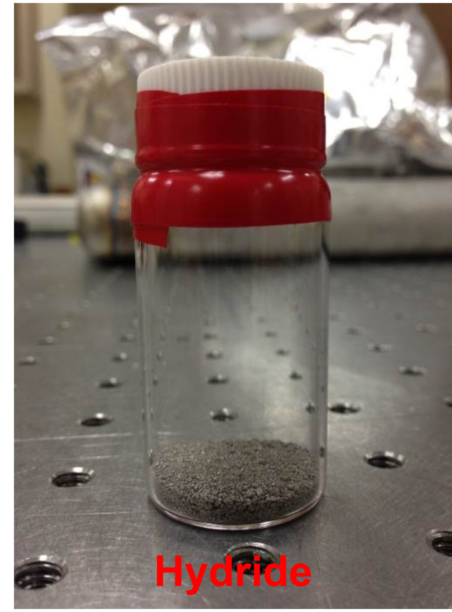
Month	Milestones and Go/No Go Decision	Comments	% Completed
3	Reservoir-fuel cell integration and testing completed	Bench integration of reservoir with PEM fuel cell and integration of PEM fuel cell/MHSS within sub-component frame	0%
6	Formal Qualification Test (FQT) and certification of reservoir completed	Reservoir testing to validate FEA and CFD modeling	0%
7	MHSS/PEMFC/forklift integration completed	Includes direct comparisons performance capabilities of the fabricated MHSS PEM fuel cell system and existing high pressure PEM fuel cell and battery power systems	0%
7	Performance data for integrated reservoir and fuel cell disseminated	Sub-component tests and comparison with numerical analysis	0%
10	Complete operational test of forklift	Final and updated test procedures	0%
11	Performance data for MHSS/PEMFC/forklift disseminated	Numerical analysis of the full scale systems integrations tests, standards/certification compliance	0%
12	License and teaming agreements finalized	Licenses, teaming agreements, and partnerships with forklift manufacturers	0%

Accomplishments and Progress

Materials

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)
- 75-100 micron size particles
- Sufficient storage capacity: 1.2 wt%
- Provides up to ~225 psi H_2 pressure at PEM fuel cell temperature of 60C
- Density (measured, unhydrided): 4472 kg/m^3
- Thermal conductivity (hydrided): 1.25 W/m-K



Expanded Natural Graphite (ENG)

- Mix with Hy-Stor 208 to increase the overall thermal conductivity of the metal
- Two forms of ENG
  - Flakes from Anthracite Industries, Inc
  - Worms from SGL Group
    - Previous literature suggests the worms are better at transferring heat radially compared to the flakes

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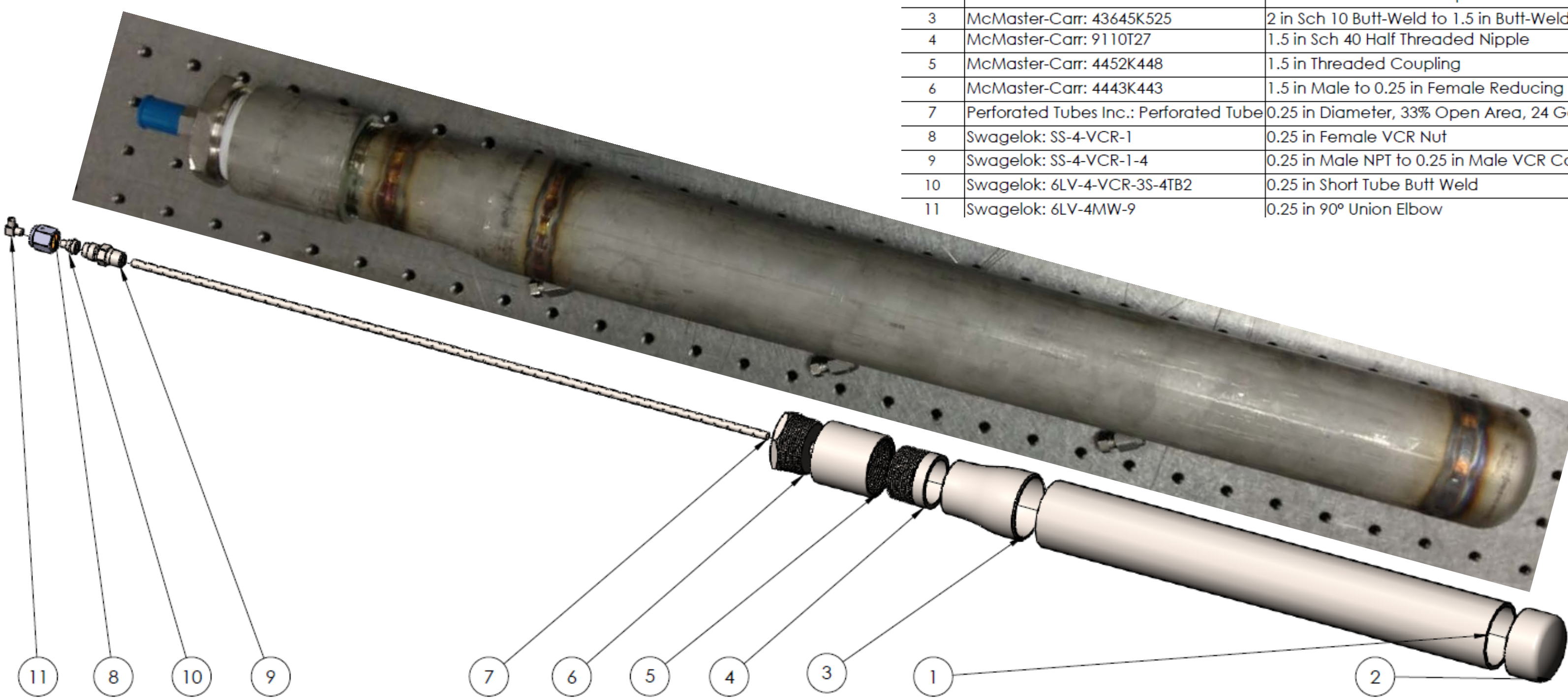
Accomplishments and Progress

Hydride tube

- No custom parts were made to keep overall cost low (fabricated to ASME code)
- All stainless steel 316L parts, weldments accordance with ASME codes
- 2” nominal pipe diameter, Sch 10 thickness, 640 mm long
- Each tube can hold around 4.4 kg of Hy-Stor 208 and 50 g of H_2
- 1000 psi pressure rating

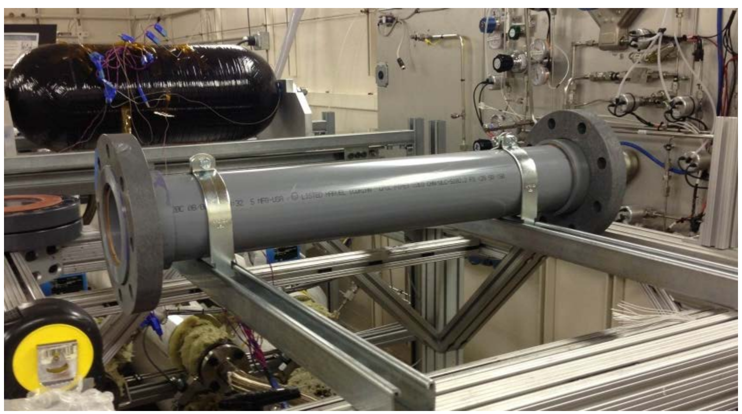
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	McMaster-Carr: 4378K79	2 in Diameter Nominal SS316L Sch 10 Pipe	1
2	McMaster-Carr: 43645K376	2 in Sch 10 Butt-Weld Cap	1
3	McMaster-Carr: 43645K525	2 in Sch 10 Butt-Weld to 1.5 in Butt-Weld Reducer	1
4	McMaster-Carr: 9110T27	1.5 in Sch 40 Half Threaded Nipple	1
5	McMaster-Carr: 4452K448	1.5 in Threaded Coupling	1
6	McMaster-Carr: 4443K443	1.5 in Male to 0.25 in Female Reducing Bushing	1
7	Perforated Tubes Inc.: Perforated Tube	0.25 in Diameter, 33% Open Area, 24 Gauge Thickness	1
8	Swagelok: SS-4-VCR-1	0.25 in Female VCR Nut	1
9	Swagelok: SS-4-VCR-1-4	0.25 in Male NPT to 0.25 in Male VCR Connector	1
10	Swagelok: 6LV-4-VCR-3S-4TB2	0.25 in Short Tube Butt Weld	1
11	Swagelok: 6LV-4MW-9	0.25 in 90° Union Elbow	1

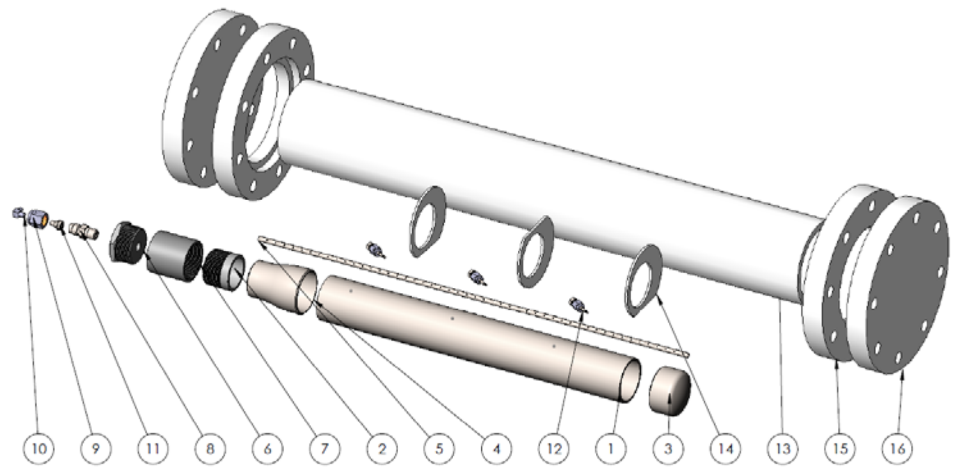


Accomplishments and Progress

Experimental Setup

- Experimental hydride tubes have angled holes where thermocouples will be inserted to measure internal tube temperature
- CPVC shell to house heat transfer fluid, baffles included to enhance heat transfer rate (4 pass-through)





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8	Swagelok: SS-4-VCR-1-4	0.25 in Male NPT to 0.25 in Male VCR Connector	1
9	Swagelok: SS-4-VCR-1	0.25 in Female VCR Nut	1
10	Swagelok: 6LV-4MW-9	0.25 in 90° Union Elbow	1
11	Swagelok: 6LV-4-VCR-3S-4TB2	0.25 in Short Tube Butt Weld	1
12	Thermocouple		3
	Swagelok: 6LV-2-VCR-3S-2TB7	0.125 in Short Tube Butt Weld Gland	1
	Swagelok: SS-2-VCR-1	0.125 in Female VCR Nut	1
	Swagelok: SS-2-VCR-4	0.125 in Male VCR Connector	1
	Swagelok: SS2-VCR-3-2MTW	0.125 in Male Weld Gland	1
13	McMaster-Carr: 6803K59	4 in Diameter Nominal CPVC Sch 80 Pipe	1
14	McMaster-Carr: 8748K117	0.125 in thick CPVC	3
15	McMAster-Carr: 6826K179	4 in CPVC Flange Sch 80	2
16	McMaster-Carr: 4881K971	4 in CPVC Blind Flange CPVC	2

Hyrdride Tub

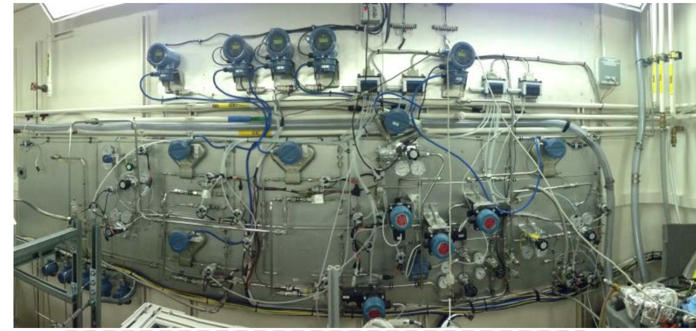
Accomplishments and Progress

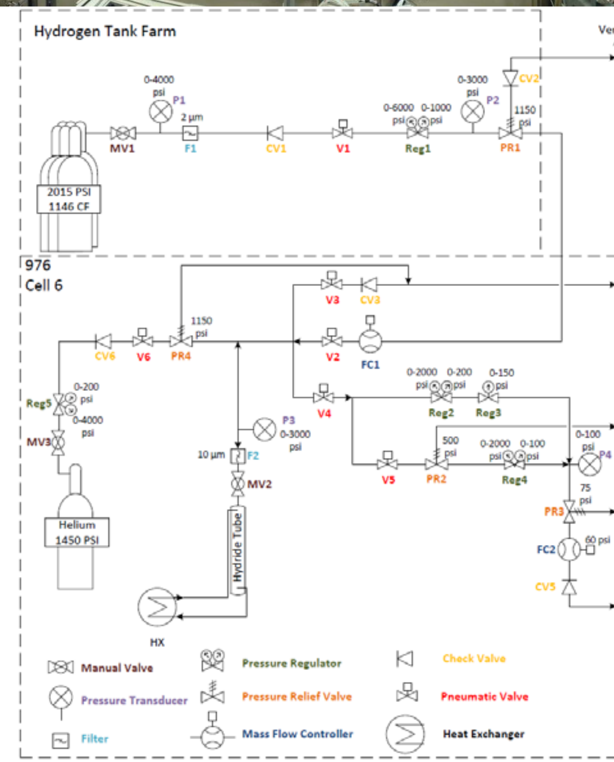
Experimental Process Flow Diagram

- Planned experiments
  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

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

- **Objectives** of single-tube experimental tests
  1. **Refill time**: How long it takes a tube to be filled
  2. **Maximum H_2 capacity**: How much H_2 can a tube hold
  3. **Durability**: Refill time is not increased nor is maximum H_2 capacity reduced over cycling
  4. **Discharge ability**: Heat transfer fluid mimicking that of the fuel cell discharge, ability of the tube to provide the required flow rate and pressure
  5. **Residual capacity at minimum discharge point**: The amount of H_2 left in the system when the tube can no longer provide the required flow rate of pressure

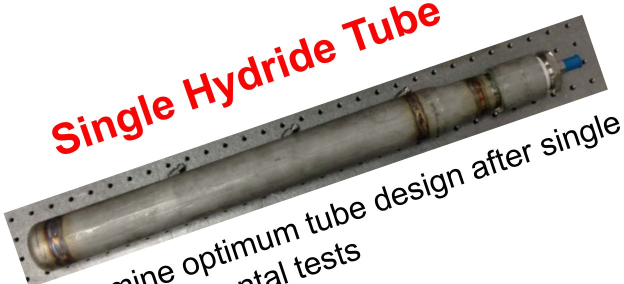




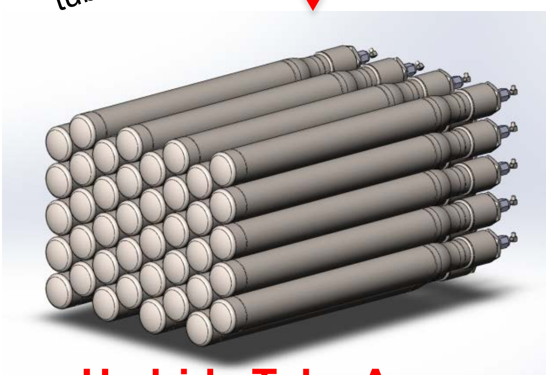
Accomplishments and Progress

Integration

Single Hydride Tube



Determine optimum tube design after single tube experimental tests

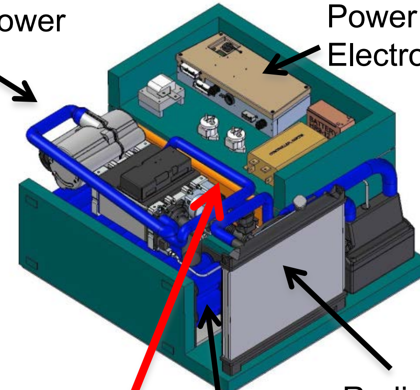


Hydride Tube Array

- **Staggered array of 40 tubes**
- **Maximize number of rows/column to improve heat transfer**
- **Baffles will be used to alternate fluid flow**

Fuel Cell Power Module

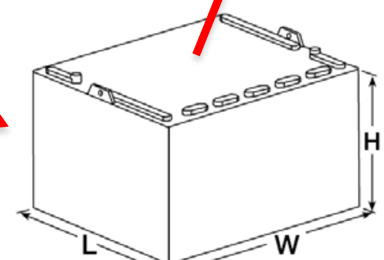
Power Electronics



Radiator

Ultra Capacitors

Fuel Cell Power Pack



Hydride Reservoir

- **Reservoir Dimensions: L x W x H 470mm x 700mm x 370mm**

Forklift

- **Manufacturer: Crown**
- **5,000 lb lifting capacity**
- **48 Volt**
- **36” battery compartment**

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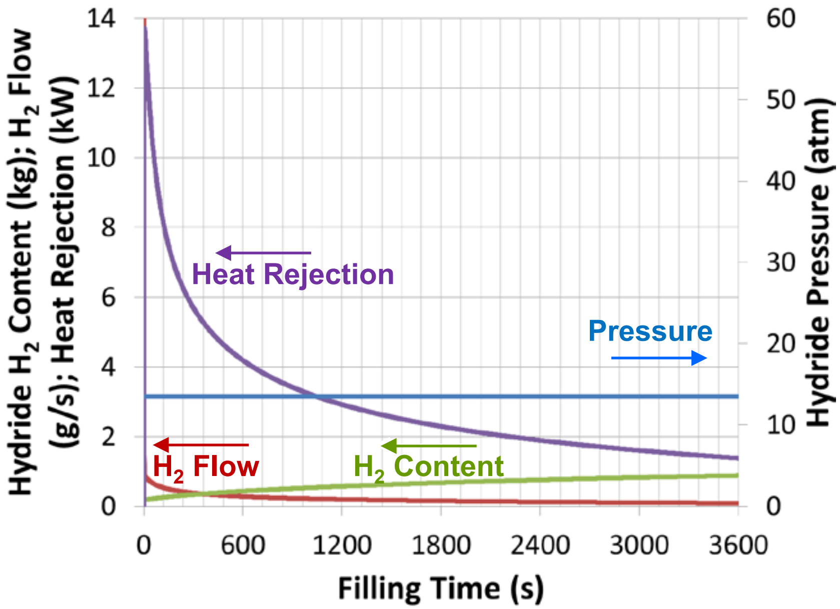
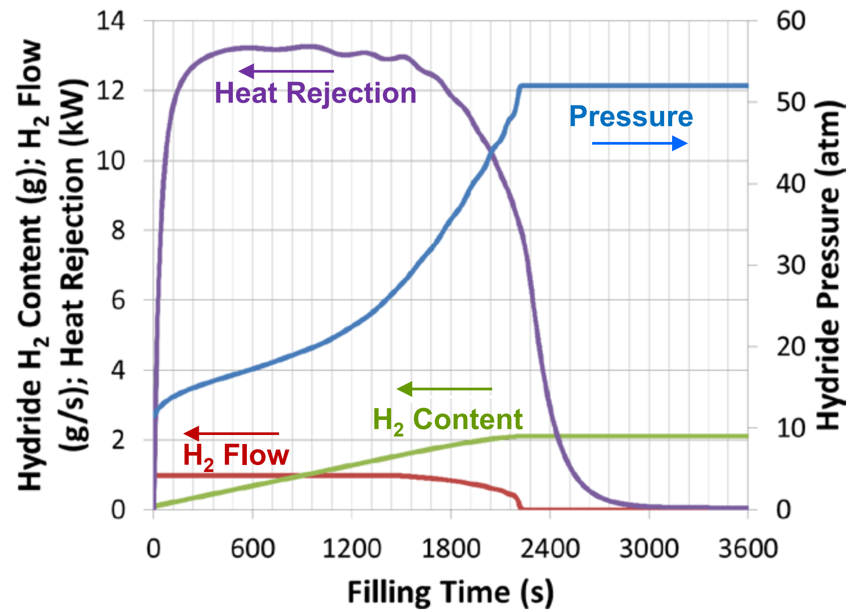
Accomplishments and Progress

When constrained to 14 kW heat rejection, a constant supply pressure must be limited and the system only reaches 42% capacity by 60 min.



For the same 14 kW maximum heat rejection, flow-controlled refueling via orifice reaches 99.9% capacity in 37 min.



System modeling shows that sustained maximum utilization of the system's limited heat rejection capacity is the key to efficient refueling. Constant flow methods perform better than constant pressure methods.

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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)	1.63 - 2.13	Hydrogenics high-pressure hydrogen tank can hold up to 1.65 kg
Energy Density (kg/liter of H_2)	0.0378 minimum	Dependent on resultant hydride packing density (presently 3.5 g/cm^2) and required ENG volume which will be determined after the experimental tests (around 1-5 wt%)
Specific Energy (kg H_2/kg)	1% maximum	Currently, the specific energy (kg H_2/kg reservoir) is approximately 0.50%. This will be finalized once the design is finalized. Reservoir mass includes: hydride, hydrogen, cooling fluid (water), expanded natural graphite (ENG), tubes, and shell/baffles.
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)
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.
Hydrogen Delivery Rate (L/min)	130	The maximum delivery rate that is required to supply the Hydrogenics system is 130 liters/min.

Accomplishments and Progress

System/Subsystem Specification Table (cont.)

Parameter	Specification	Supporting Information
Refill Time (minutes)	<60	The charging of the hydride is exothermic (DH = -23 kJ/mol). Refill time is highly dependent on the maximum heat rejection rate of the PEM fuel cell system's coolant loop properties and radiator. Optimal refueling strategies are being designed including flow-controlled refueling and allowance for so-called "opportunity fills."
Cycle Life (cycles)	10,000	Still to be determined.
Transient Response Time	Minimal	Due to closed loop nature of the system, the transient response time will be minimal
Cost of Complete System ($US)	15,000 maximum	Preliminary investigations show that lower cost components are readily available and a system could be built that would meet our cost target.

Collaborations

- **<u>Sandia National Labs</u> (25%)**
  J. Pratt, T. Johnson, A. Harris, and D. Dedrick
  Federal Laboratory, within DOE Hydrogen and Fuel Cells Program
- **<u>Hydrogenics</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% Hawaii Hydrogen Carriers
Systems Engineering	60% Sandia National Lab 20% Hydrogenics 20% Hawaii Hydrogen Carriers
Task 1: Solid state metal hydride fuel cell system design and optimization	50% Sandia National Lab 50% Hawaii Hydrogen Carriers
Task 2: Reservoir fabrication and testing	100% Hawaii Hydrogen Carriers
Task 3: Integration of reservoir and PEM fuel cell	60% Hawaii Hydrogen Carriers 40% Hydrogenics
Task 4: Formal Qualification Test (FQT) and certification of integrated prototype	15% Sandia National Lab 85% Hawaii Hydrogen Carriers
Task 5: Final solid state metal hydride PEM fuel cell forklift site operational test	100% Hawaii Hydrogen Carriers

Future Work

- **Complete tasks as scheduled.**
  - **Task 1**: Solid State Metal Hydride Fuel System Design and Optimization (50/50%, SNL/HHC)– Months 1-9
    - Hydride performance testing (materials) and testing of experimental hydride tubes
  - **Task 2**: Reservoir Fabrication and testing (100% HHC)– Months 9-11
    - Fabricate reservoir sub-assembly, perform leak tests and cycle reservoir
  - **Task 3**: Fabrication of Integrated Prototype of Reservoir-PEM Fuel Cell System (70/30%, HHC/Hydrogenics)– Months 12-13
    - Integrating MHSS reservoir system with PEM fuel cell, then integrating reservoir/PEM fuel cell system with forklift
  - **Task 4**: Formal Qualification Test and Certification (85/15% HHC/SNL)– Months 11-17
    - Reservoir testing to validate system modeling and single-tube experiments
  - **Task 5**: Final Solid State Metal Hydride PEM Fuel Cell Forklift Site Operational Test (100% HHC)– Months 14-17
    - Collect operational data and obtain licensing, teaming agreements, and partnerships with forklift manufacturers

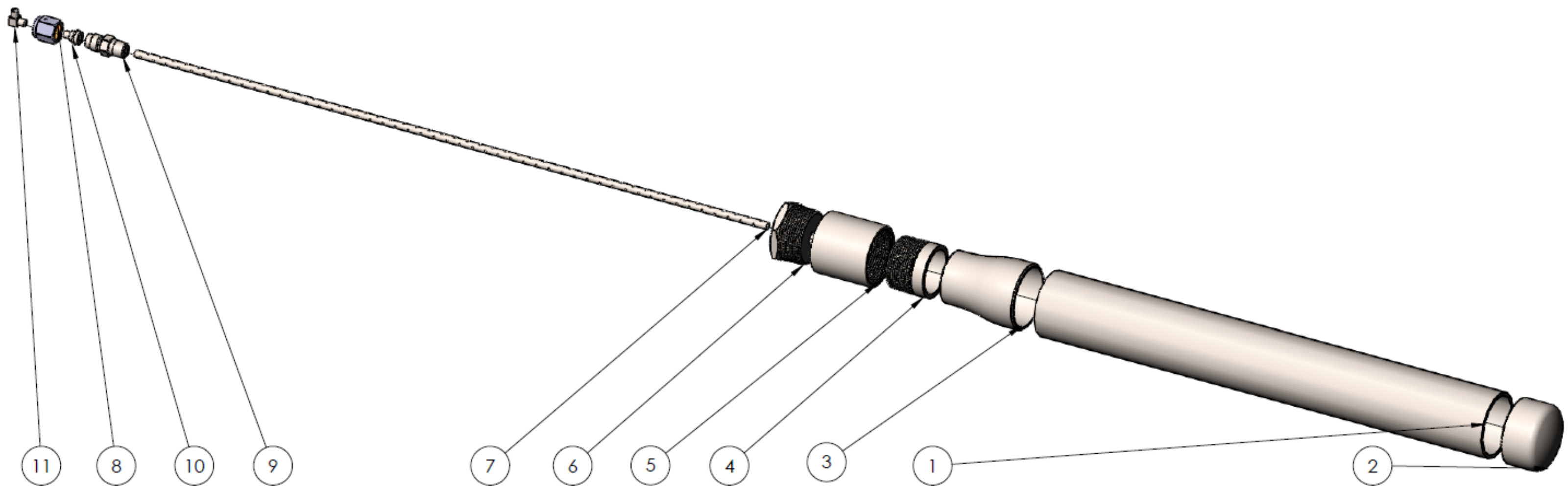
Summary

- **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**: Use the information from Phase I which outlined a plan to build, certify, and test a market-ready, metal hydride, fuel cell forklift system and continue on its goal as a viable replacement option to a battery or high pressure tank
- **Technical Accomplishments and Progress**: Experimental tubes designed and built. Working on experimental setup and hydride material characteristic testing. Continue designing and modifying pre-existing fuel cell power pack to integrate metal hydride reservoir.
- **Technology Transfer/Collaborations**: Developing ongoing partnerships with Sandia National Laboratory and Hydrogenics. We have begun to establish direct contact with potential end-users including a consortium of wholesale seafood companies in Iceland
- **Proposed Future Research**: Continue with project schedule

Technical Back-Up Slides

Technical Back-Up Slides

- **Pressure rating of off-the-shelf components**



Items	Description	Part No.	Pressure Rating (psig)
1	2" Unthreaded pipe	McMaster 4378K56	1,113
2	2" Butt weld cap	McMaster 43645K376	1,113
3	2" x 1.5" Butt weld reducing coupling	McMaster 43645K525	1,113
4	1.5" Threaded-on-one-end nipple	McMaster 9110T27	1,399
5	1.5" Threaded coupling	McMaster 4452K448	1,000
6	1.5" x ¼" Hex reducing bushing	McMaster 4443K443	3,000
7	¼" VCR x ¼" Male NPT Adapter	Swagelok SS-4-VCR-1-4	10,000

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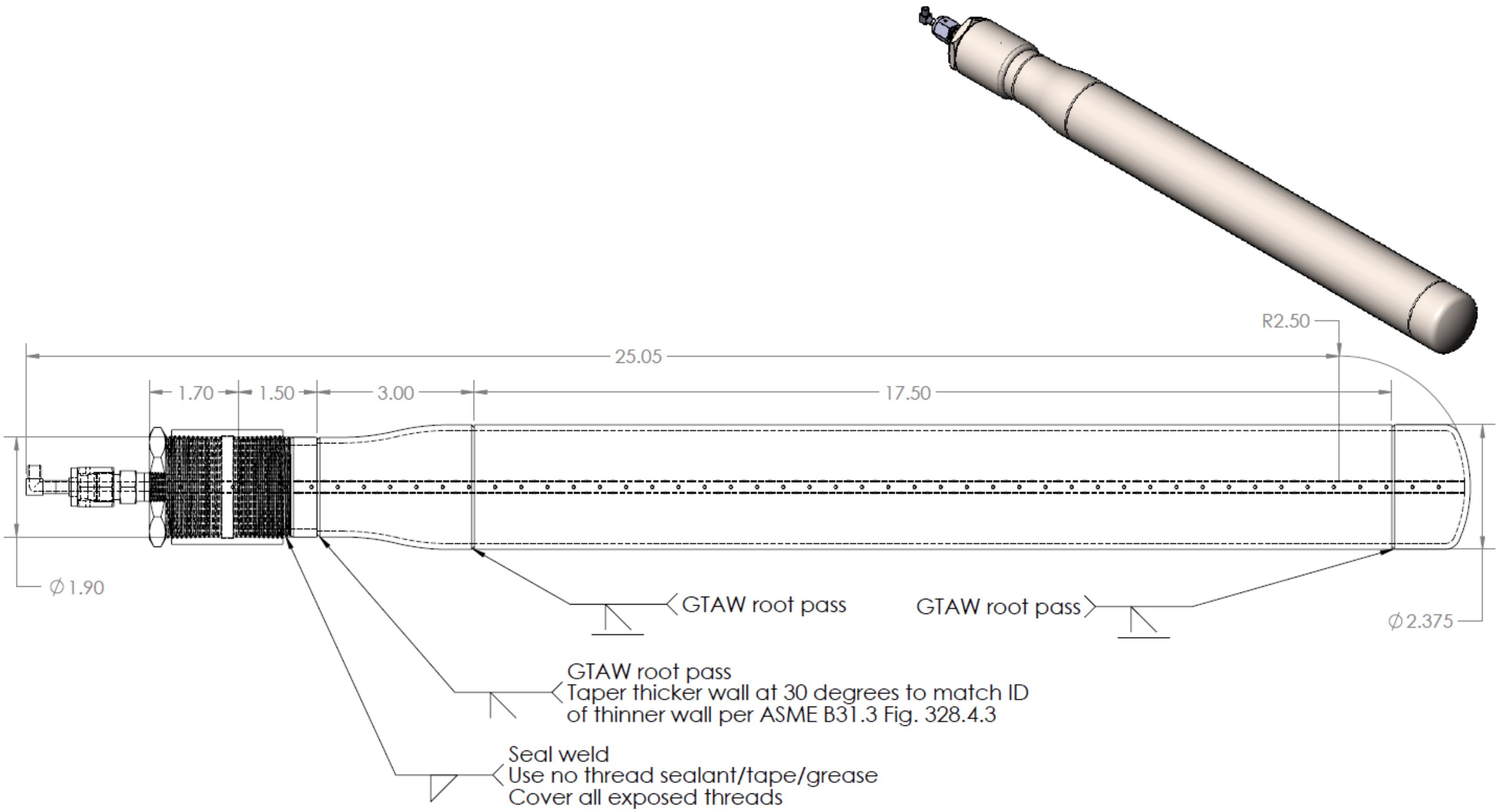
Technical Back-Up Slides

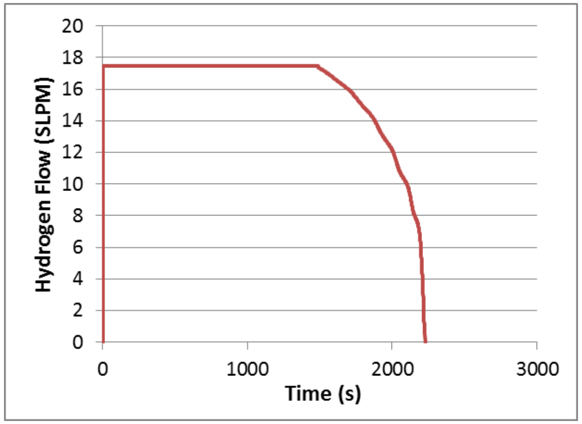
- **Hydride tube with weldments**



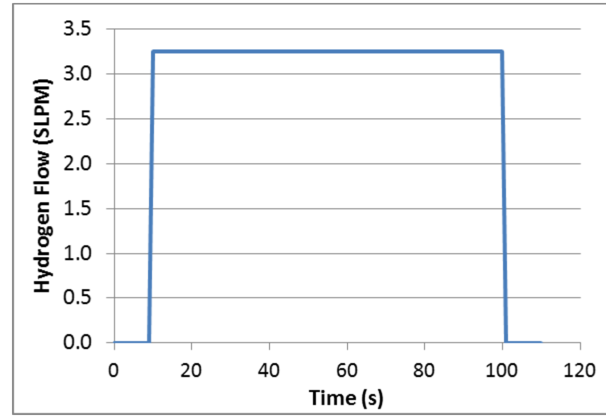
Technical Back-Up Slides

- **Experimental tube – simulated operation flow profiles**

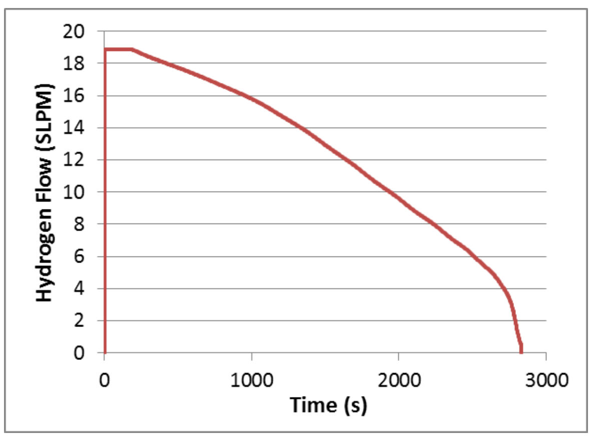
Fill:
Orifice at high supply P (750 psig)



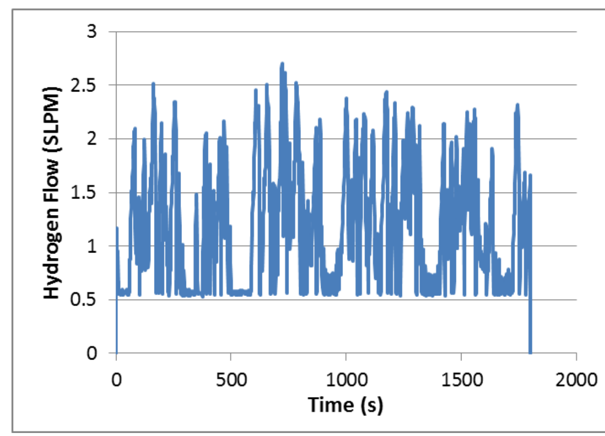
Discharge:
Cold startup at maximum flow



Fill:
Orifice at medium supply P (400 psig)



Discharge:
Projected realistic use profile



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Technical Back-Up Slides

- **Simulink® system model overview**