NaSi and NaSG Powder Hydrogen Fuel Cells

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SiGNa Chemistry

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Overview

Timeline

- Start date: 08/01/2008
- End date: 01/31/2010
- Percent complete: 28%

Barriers

- Hydrogen Storage Technology Capabilities
  - Specific Energy: 2kWhr/kg
  - Cost: $4/kWhr
- Enabling Technology for Near-Term High-Volume Fuel Cell Commercialization for Portable Applications

Budget

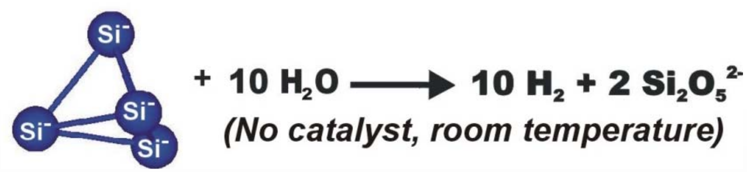
- Total funding in FY08: $1,845,000
  - DOE share: $1,476,000
  - Contractor share: $369,000
  - Bulk of funds to be spent in FY09
- Additional funding for FY09
  - $951,500
  - To be spent in FY09/FY10

Partners

- University of Texas Austin, Center for Electromechanics
  - Reactor Mechanism Research
  - Richard Thompson and Michael Lewis
- Trulite Inc.
  - 250W Fuel Cell Demonstration System
  - Ken Pearson

Technology Overview

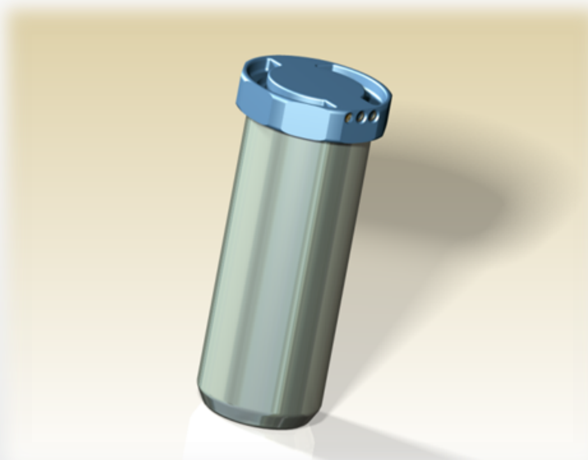
- Sodium Silicides rapidly liberate hydrogen from water (or water solutions) leaving a benign common industrial chemical (sodium silicate)
  - Sodium-Silica-Gel: 2Na-SG + H_2O → H_2 + $Na_2Si_2O_5$
  - Sodium Silicide: 2NaSi(s) + $5H_2O(\ell)$ → $5H_2(g)$ + $Na_2Si_2O_5(aq)$



- Significant System Benefits for Portable Power Applications (10 W to 3 kW)
  - **Safety:** Does not ignite or oxidize in air at standard conditions even when fully exposed to air (i.e. opened storage canister).
  - **Thermal Stability:** Material is stable over all practical temperature ranges (-55 to 300°C)
  - **Storage:** The material has been demonstrated to have a shelf-life of over two years but is capable for being stored for significantly longer
  - **Pressure:** The maximum developed pressure is determined by the system design not the material characteristics. The maximum pressure is expected to be under 50 psi (material capable of 1000's)
  - **Ease of Use:** No catalyst required to produce hydrogen gas
  - **By-products:** Generates a non-toxic aqueous waste, sodium silicate.

Objectives

- Demonstrate enabling hydrogen storage technology suitable for early fuel cell market applications with high volume potential
- Demonstrate the benefits of sodium silicide technology in a push-to-start hydrogen generator system
- Develop a demonstration system capable of ~250 W for applications such as battery re-chargers, remote telecommunications, emergency responders, backup power, and personal mobility (i.e. scooter, bicycle, Segway)
- Demonstrate technology to approach DOE Hydrogen storage targets even for small systems (<1kW)



Market Example: 11 Day Mission for Special Forces

Technology	Per Unit	Unit Cost	Mission Qty	Mission Wt.	Mission Cost
BA 5590	**140 W-hrs** (1.0 kgs)	$80	35 4,900 W-hrs	**35 kgs**	**$2,800**
SiGNa NaSi	**700 W-hrs** (1.42 kgs) • Packaging: 0.2 kgs • Powder: 0.4 kgs • Water: 0.8 kgs	$84 •Packaging: $20 • NaSi: $64 /kg	7 4,900 W-hrs	**11.4 kgs** • Cartridges: 9.9 kgs • Fuel Cell: 1.5 kgs	**$688** • Cartridges: $588 • Fuel Cell: $3000 / 30 missions = $100

Sodium Silicide provides significant value as compared to batteries with respect to weight, cost, and logistics.

Battery Disposal/Storage

Technical Approach

Task 1.0 System Engineering

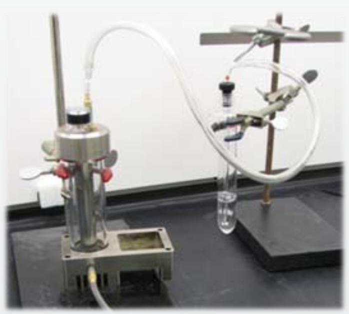
Key Specifications

- **Powder**
  - •Current: >3100 W-Hr/kg (LHV)
  - •Advanced: >4100 W-Hr/kg (LHV)
- **Packaged Canister**
  - •Current: 1336 W-Hr/kg (LHV)
  - •Advanced:1676 W-Hr/kg (LHV)
- **Cartridge Capacity**
  - •>500 W-Hr (net Fuel Cell)
  - •< 1 kg

Task 2.0 Breadboard Testing and Reaction Control Mechanism

Initial Results

- **Reactor Volume**
  - •Demonstrated 100mL reactor
  - • Fabricated 1 Liter reactor
- **Material Characteristics**
  - High Density
  - Fast Reaction Times
- **Lessons Learned**
  - Hydrogen Filtration
  - Water Distribution



Task 3.0 Hardware Development

Key Specifications

•Push-to-Start Hydrogen

•System: <2kg

•Suitable for lab H_2 generation or fuel cell company evaluation

Task 4.0 Fuel Cell System Integration

Specs/Acquisition

•250W with water recirculation

•Initiated sub-contract

Task 5.0 Advanced Materials Research and Manufacturing Methods

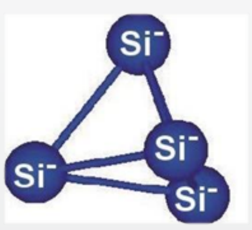
Status

•H_2 purity analysis (on-going)

•Initiated manufacturing process dev.

•Initiate work for additive for low temperature operation (FY2009)

•Initiate Advanced Material Research (FY2009)



SiGNa CHEMISTRY

System Engineering

Progress

- Approaching DOE Targets Even for Small, Portable Hydrogen Storage Applications
  - Specific Energy
    - Current Tech.: 1336 W-Hr/kg, LHV
    - Next Gen. Tech.: 1664 W-Hr/kg, LHV
  - Cost
    - Sodium and Silicon are only production material cost
    - $4.47 / kW-Hr
- Biggest Unknown: Over-Stoich Water
  - Assumptions based on purchased sodium silicate / water solution
  - NaSi reactivity and sodium silicate solubility will compete for water
  - Temperature control and water feed system under development to perform detailed study

Systems Analysis

System Engineering for H250	NaSi	NaSi (no over-stoch water)	Adv. Silicide	Adv. Silicide (no over-stoch water)
Hydrogen				
Powder Weight (kg)	0.50	0.50	0.50	0.50
Theoritical Powder Performance	9.8%	9.8%	13.0%	13.0%
Estimated Powder Performance	9.5%	9.5%	12.5%	12.5%
H2 Weight (gm)	48	48	63	63
Water				
Water Stoich (kg)	0.42	0.42	0.56	0.56
% Recapture	50%	50%	50%	50%
Water Weight, Recaptured (kg)	0.21	0.21	0.28	0.28
Net Stoich Water (kg)	0.21	0.21	0.28	0.28
Over. Stoich Water (kg)	***0.27***	***0.00***	***0.27***	***0.00***
Total Water Required (kg)	*0.48*	*0.21*	*0.55*	*0.28*
Weight				
Canister Weight (kg)	0.20	0.20	0.20	0.20
Canister + Water + Powder (kg)	***1.18***	***0.91***	***1.25***	***0.98***
Energy/Density				
Chemical Energy (W-Hr), LHV	***1,582***	***1,582***	***2,081***	***2,081***
Specific Energy, Powder (W-Hr/kg), LHV	3,164	3,164	4,163	4,163
Specific Energy, Powder + Stoich. Water w/ 50% Recapture + Over-Stoich. Water + Canister (W-Hr/kg), LHV	***1,336***	***1,734***	***1,664***	***2,125***

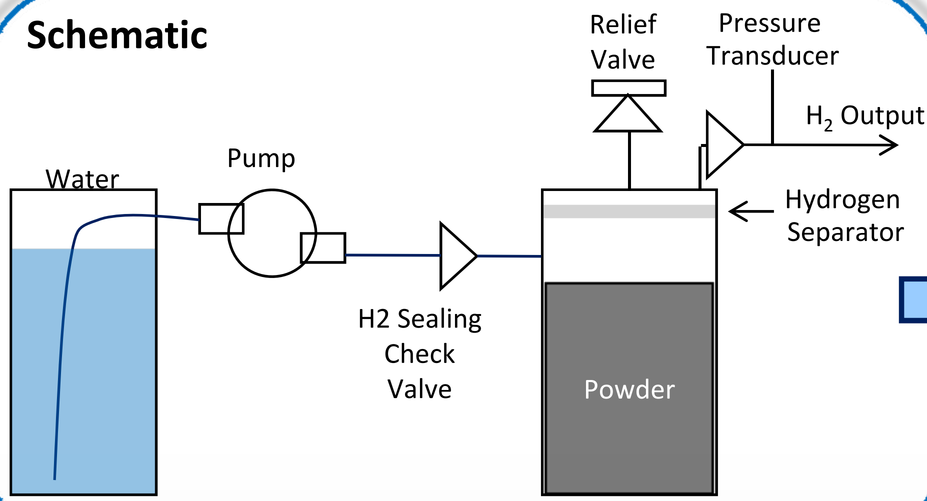
Cost Analysis*

	2010	2011	2013	2015
Sodium ($/kg)	$ 3.08	$ 3.08	$ 3.08	$ 3.08
Silicon ($/kg)	$ 6.42	$ 6.42	$ 6.42	$ 6.42
Sodium Silicide Production ($/kg)	$ 90.00	$ 50.00	$ 20.00	$ 7.00
Sodium Silicate Use ($/kg)	$ (2.38)	$ (2.38)	$ (2.38)	$ (2.38)
Total ($/kg)	**$ 97.13**	**$ 57.13**	**$ 27.13**	**$ 14.13**
$/kWh |powder	$ 30.70	$ 18.06	$ 8.58	$ 4.47

*Prices for Sodium & Silicon Based on Quotes From US Vendors

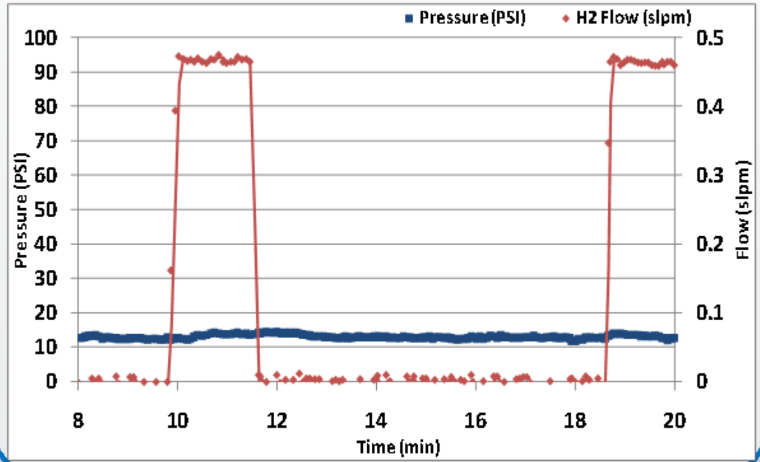
H_2 Generator Development

Schematic



Laboratory Unit

Controlled H_2 Generation



Beta Systems
October 2009

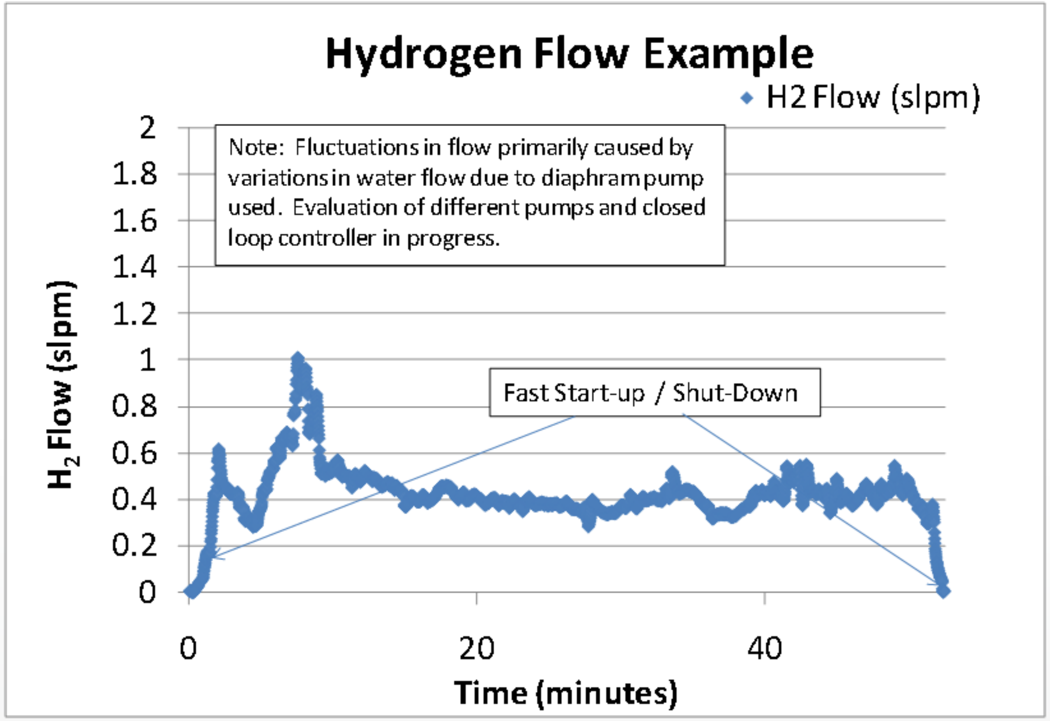
General Purpose H_2 Generator For Fuel Cell Partner Evaluation and Industrial Use

Breadboard Result Summary

Progress

Breadboard Testing Overview

- Repeated demonstration of high flows / fast reaction times in a small system
- Powder Energy Density: ~3200 W-Hr/kg (LHV of H2)
- Maximum of 48 gm Tested in a Single Fixture
- Demonstrated 3 Re-starts

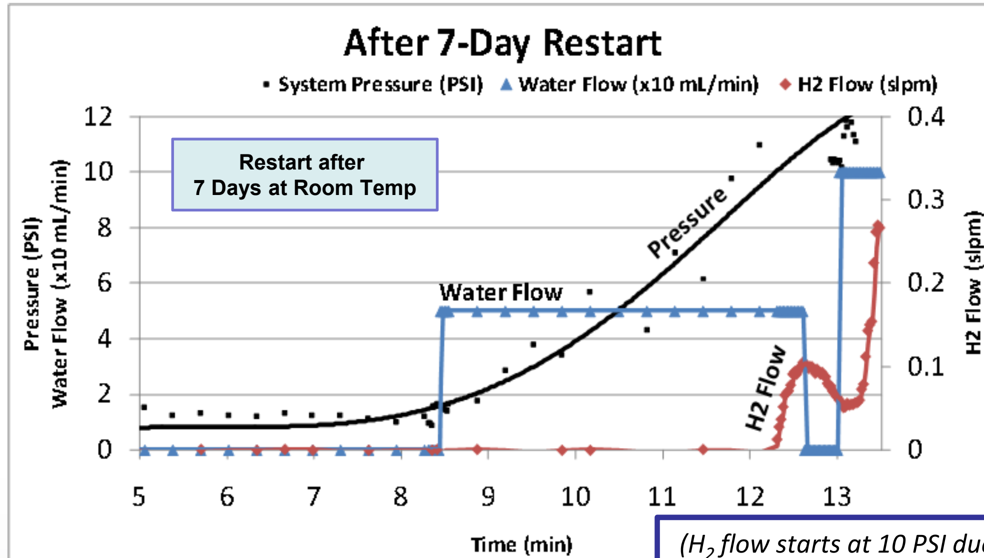


Date	Serial	Test #	Powder Type	Mass (g)	H2 (std L)	Grams H2	Correct mL H20	Watt-Hrs/Kg Powder
1/29/2009	BB4NI	23	NaSi	26	28.6	2.4	82.9	1586.0
1/30/2009	BB4Ni	24	NaSi	21.4	23.8	2.0	77.2	1603.2
2/2/2009	BB4Ni	27	NaSi	17.9	19.5	1.6	59.6	1568.8

Net: assumes 50% fuel cell conversion efficiency

Water Feed Network

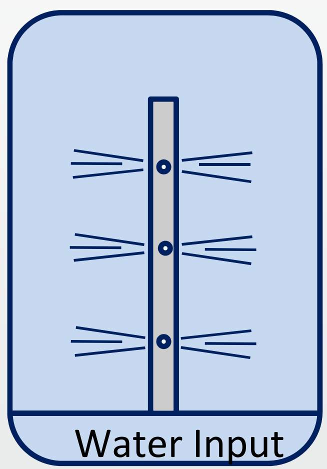
- **Issue:** Sodium Silicate Waste Product Can Slow Restarting
- **Solution:** Multiple Water Injection Ports Distributed Through Powder
- **Initial Results**
  - Significant decrease in system restart time
  - 3 Re-starts Demonstrated on 48 gm of powder
    - Start #2: > 24 hrs off time
    - Start #3: > 168 hours off time
    - Approximately 1/3 consumed per use = 25 W-Hrs (net fuel cell)



(H_2 flow starts at 10 PSI due to back-pressure regulator)

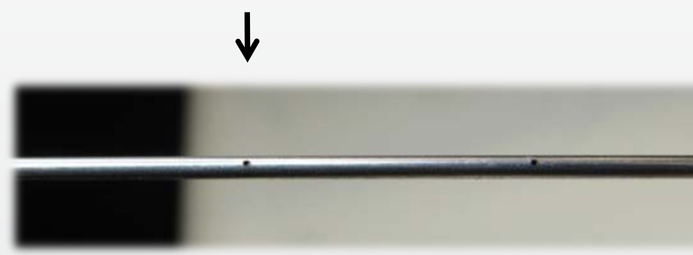
Spiraled water feed network tube

Water feed tube spraying inside Canister



Close-up of laser drilled holes in water feed tube

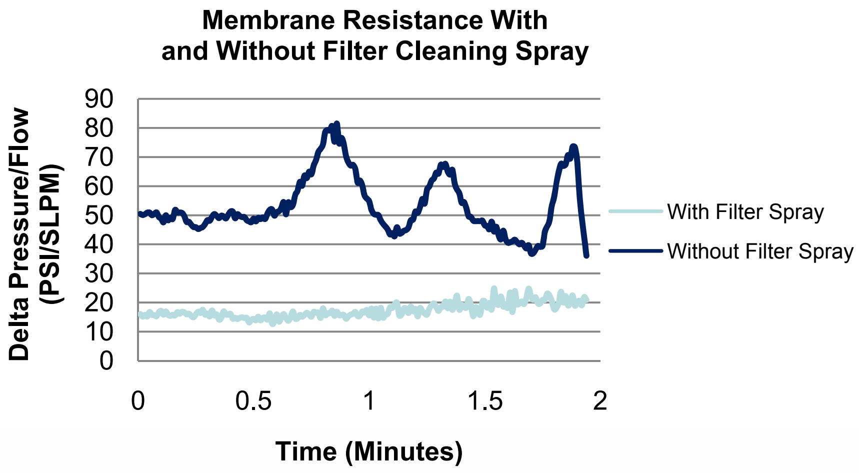
0.0051” Hole

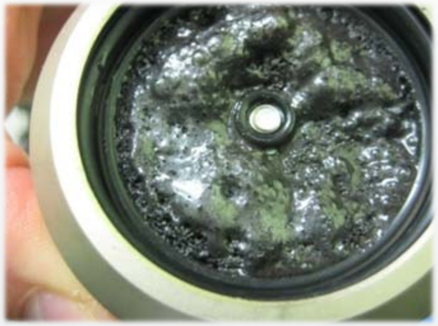


Filtration Cleaning

Progress

- Significant foaming observed in test reactor with cross-sectional area of ~1.5 in^2
- Almost zero foaming observed in test reactor with cross sectional area of ~6 in^2
- Using small / low volume reactor: a cleaning nozzle is required
- All spray water runs-off to reaction sites and utilized
- Initial testing was done with crude holes spraying on the filter in isolated areas
- Current laser drilled precision holes with controlled spray patterns are under evaluation



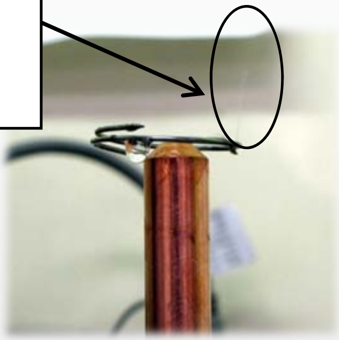


No Filter Cleaning

Filter Cleaning Nozzles Used

Only Two Nozzles Used

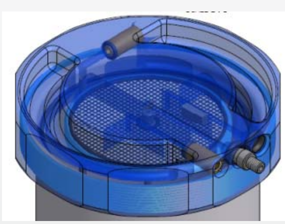
Fine Water Spray From Micro-Nozzle

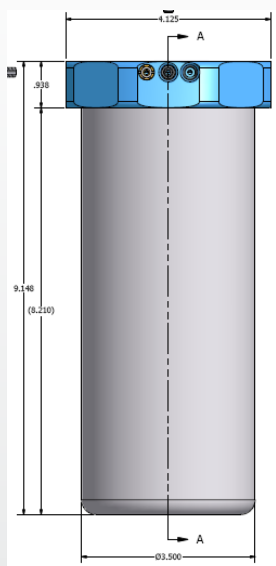


Cartridge Design

Design Characteristics

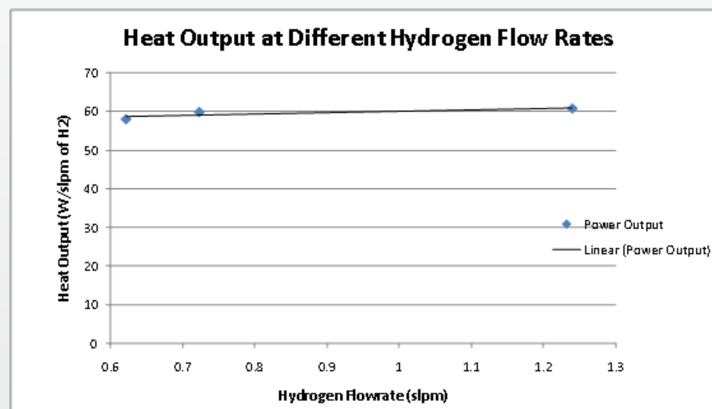
- Up to 500 gm Per Cartridge (Limit Set by DOT Shipping Regulations)
- Stores all waste product
- Net Fuel Cell Energy
  - >800 W-Hr / Catridge
- Low Pressure
  - Nominal: 30 psi
  - Max. Continuous Design: 100 psi
  - Expected Burst: >300 psi
- Dimensions: 3.5” Dia X 9” Length
- Weight
  - 0.28 kg in 2009
  - 0.20 kg in 2010
- Thin Walled Canister Designed for Heat Removal
  - 60 W / slpm|H_2





Weight Balance

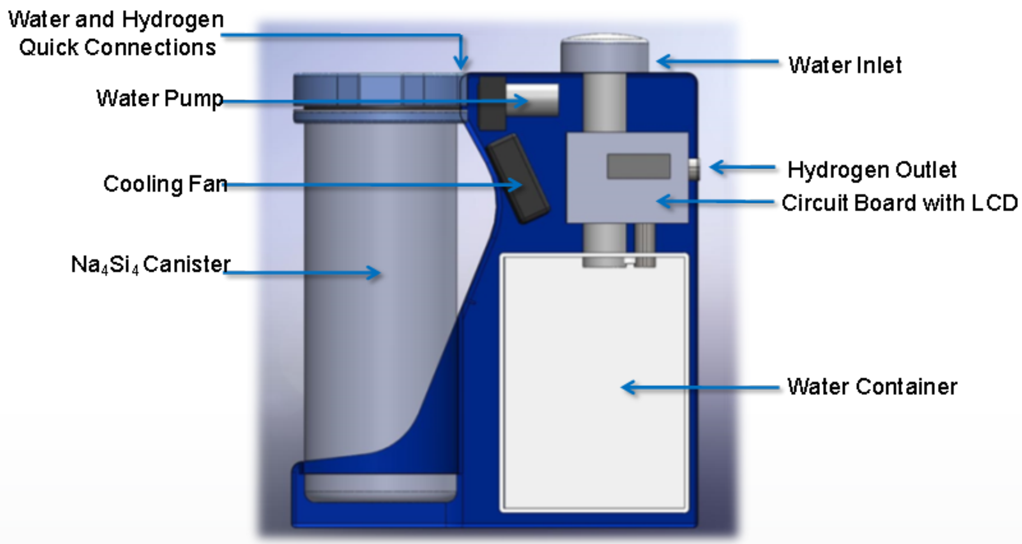
Canister Part Description	Pre-Production Weight (kg)	Estimated Production Wt (kg)
Can	0.11657	**0.09909**
Cap/Can Capture Ring	0.02082	**0.01770**
Cap	0.10718	**0.06431**
O-Ring (cap to can ID seal)	0.00091	**0.00091**
Dip Tube (reaction cahmber pressure relief)	0.00272	**0.00204**
O-Ring (pressure relief valve seal)	0.00091	**0.00091**
Pressure Relief Valve	0.00925	**0.00925**
Retaining Ring, Internal Self Locking (relief valve)	0.00091	**0.00091**
Filter Capture Ring	0.00590	**0.00000**
O-Ring (H_2 output filter ID)	0.00091	**0.00000**
O-Ring (H_2 output filter OD)	0.00091	**0.00000**
Filter (H_2 output)	0.00136	**0.00136**
Screen (H2 output)	0.00741	**0.00000**
RFID Transponder	0.00045	**0.00045**
Fitting (center fluid feed)	0.00045	**0.00045**
Tube (center fluid feed)	0.00272	**0.00272**
Tube (H_2 filter sprayer)	0.00091	**0.00091**
O-Ring (H_2/H_2O I/O ports)	0.00091	**0.00091**
Check Valve (H_2/H_2O I/O ports)	0.00454	**0.00454**
Total Weight (kg) (Less NaSi and Water)	0.28	**0.20**



H_2 Generator Development

Specifications

- Dimensions: 9” X 9” X 10” (height)
- Approx. System Weight: <2 kg
- H2 Flow Rate (Continuous): 3 slpm
- H2 Flow Rate (Peak): 8 slpm (0.25 Seconds every 2 minutes)
- Watt-Hrs/Cartridge: >1500 W-Hr (LHV)
- Regulated Output Pressure: 25 psi
- Initial Target Operating Temp: -5 to 40°C
- Start-up Time: 1 min
- Restarts: >5 / catridge (expect >10 to 20)



Seeking Development Partners for Beta System Evaluation: October 2009

Collaborations

- Subcontract to Trulite Inc.
  - Development of a 250W Fuel Cell System with Water Recirculation
  - Status: Subcontract has been awarded. Early stages of development.
  - Principal Investigator: Ken Pearson

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Clean, reliable power – anywhere.

- Subcontract to the University of Texas Austin, Center for Electromechanics
  - Alternative reaction mechanism development and control
  - Status: Subcontract has been awarded. Early stages of development.
  - Principal Investigators: Richard Thompson and Michael Lewis

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Proposed Future Work

- FY2009
  - Complete hydrogen purity verification
  - Complete development of prototype system
  - Demonstrate technology in an end customer application (late FY2009 – Early FY2010)
  - Research and develop high volume manufacturing methods for sodium silicide
  - Conduct additional experiments with additives to improve low temperature operability (below freezing)
  - Initiate research on ultra-high density sodium silicides
- FY2010
  - Deliver ~10 systems for Hydrogen Generator beta testing (early FY2010)
  - Improve hydrogen generation system performance and robustness
  - Work with development partners for end system integration
  - Demonstrate high volume manufacturing process for sodium silicide
  - Continued research on ultra-high density silicides

Summary

- Sodium silicides enable real-time hydrogen generation for portable applications that require low weight and cost
- Sodium silicides have unique technical attributes that enable simple systems with significant benefits over competitive hydrogen storage technologies
  - Fast starting
  - Low temperature
  - Low pressure
  - Long term storage
  - High temperature stability
- Continued research on ultra-high density sodium silicides will enable packaged fuel to approach doe targets of 2 kW-Hr/kg and $4/kW-Hr for mobile power solutions