2010 Hydrogen Program

Annual Merit Review Meeting

Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi

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Project ID# PD065

Overview

Phase I Program

Timeline

- **Project Start:** Oct 2009
- **Project End:** April 2010
- **Percent Complete:** 90%

Budget

- **Total Project Budget: $100k**

DOE Program Manager
Monterey Gardiner

Barriers

Hydrogen Generation by Water Electrolysis

- **G. Capital Cost**
- **H. System Efficiency**

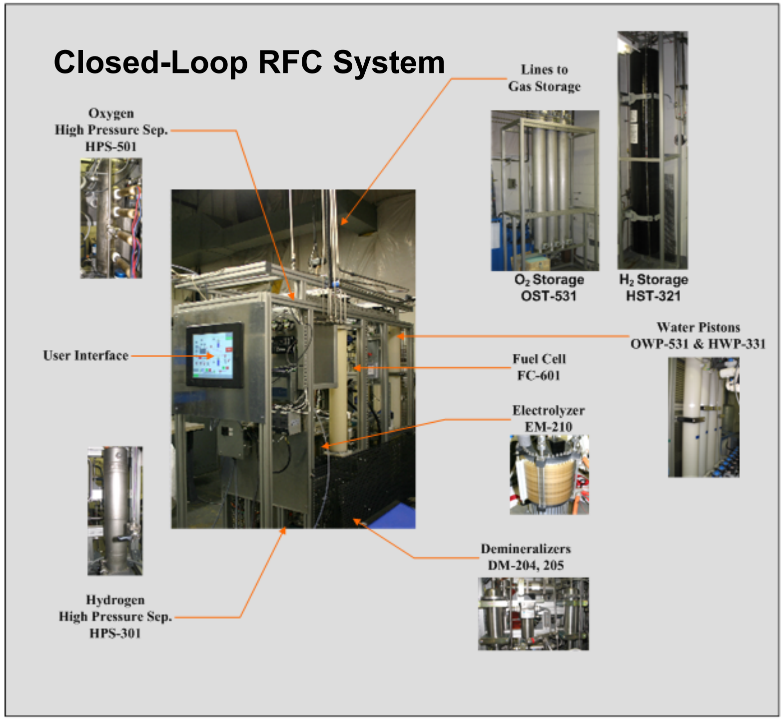
Targets

DOE TARGETS: Distributed Water Electrolysis			
Characteristics/units	**2006**	**2012**	**2017**
Hydrogen Cost ($/kg-$H_2$)	4.80	3.70	<3.00
Electrolyzer Cap. Cost ($/kg-$H_2$)	1.20	0.70	0.30
Electrolyzer Efficiency %LHV (%HHV)	62 (73)	69 (82)	74 (87)

Collaborations

- **Prof. R. Zalosh – Hydrogen Safety Codes**
- **IAS, Inc. – System Controls Design**
- **Other Giner Projects**

GES PEM Electrolyzer Systems

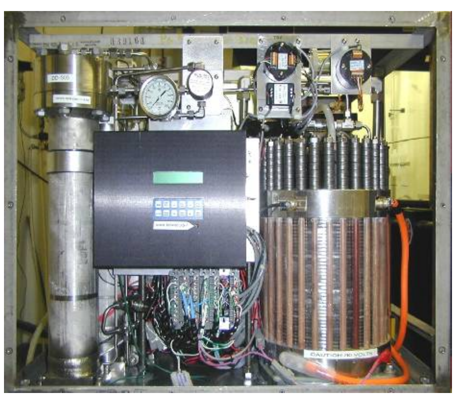


S-10 Electrolyzer System

6 kW Electrolyzer
~ 40 SCFH-H2 (~0.1 kg-H2/hr)
1500 ASF
1250 psi H2 / Ambient O2
Volume ~ 6 ft3

UUV Applications (V = 12.5 Ft^3)

12 Cells - 0.17 ft2 Cells/Stack
6-kW Electrolyzer
~ 40 SCFH-H2 (~0.1 kg-H2/hr)
High Current Density (1300-1500 A/ft2)
1000 psi H2/Ambient O2
No High-Pressure Water Feed Pump or Containment Vessel
UUV Applications



EP-1
On-Site H2 Generators

20 kW Electrolyzer
0.35 kg H2 / hr
1500 ASF
1250 psi H2 / Ambient O2
Volume ~ 16 ft3

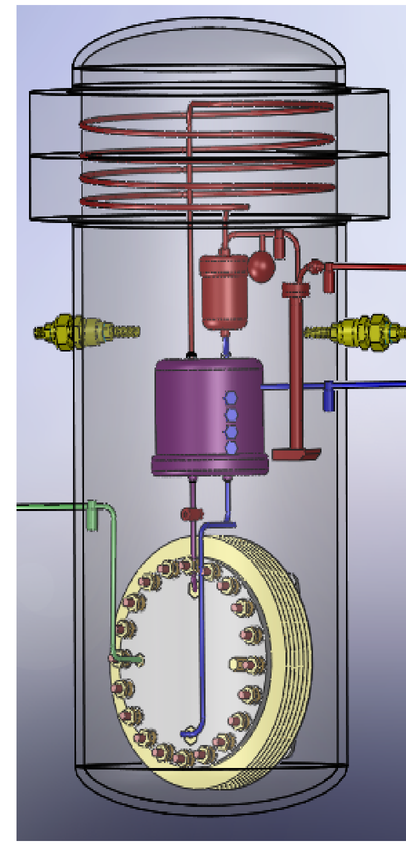
Relevance/Project Objectives

Overall Project Objectives

- Develop conceptual design for a unitized electrolyzer system for residential refueling at 5,000 psi to meet DOE targets for a home refueling apparatus.
  - Complete Preliminary System and Stack Design for Unitized PEM Electrolyzer for Home Refueling Applications
  - Evaluation PEM Membrane at High Pressure Operation
  - Economic Feasibility Studies

Relevance

- Successfully Developing a Low-Cost Residential Refueling Appliance Will Enable Early Adoption of Fuel Cell Vehicles



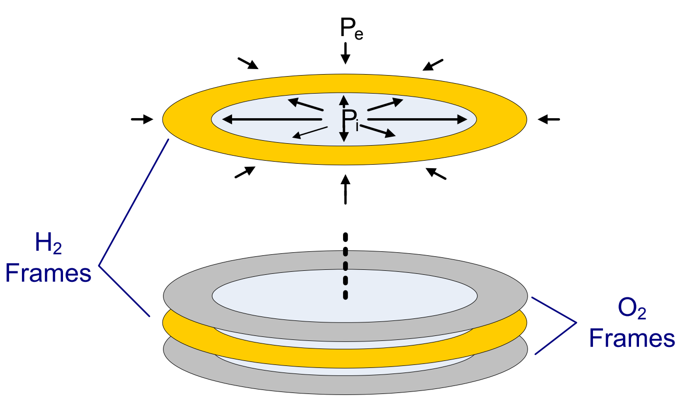
Milestones

Go/No Go Decision Points	Progress Notes	% Complete
System Development: Complete Preliminary Design	**Completed:** ■ Survey of Applicable Domestic and International Hydrogen Generation/Refueling Safety Codes and Standards ■ Preliminary System Design for Unitized PEM Electrolyzer for Home Refueling Applications ■ Preliminary Design of a 5000 psi “Unitized” Stack and Hydrogen/Water Phase-Separator ■ Economic Feasibility Studies	**100%**
Membrane: Evaluate PEM Membrane at High Pressure Operation	**Completed:** ■ 6-Cell Short Stack Built with Advanced DSM™ ■ Completed Testing at Balanced 100 and 600 psig Pressures ■ Completed Polarization Scans @ 80°C ■ Planning 2500 psig Tests	**90%**

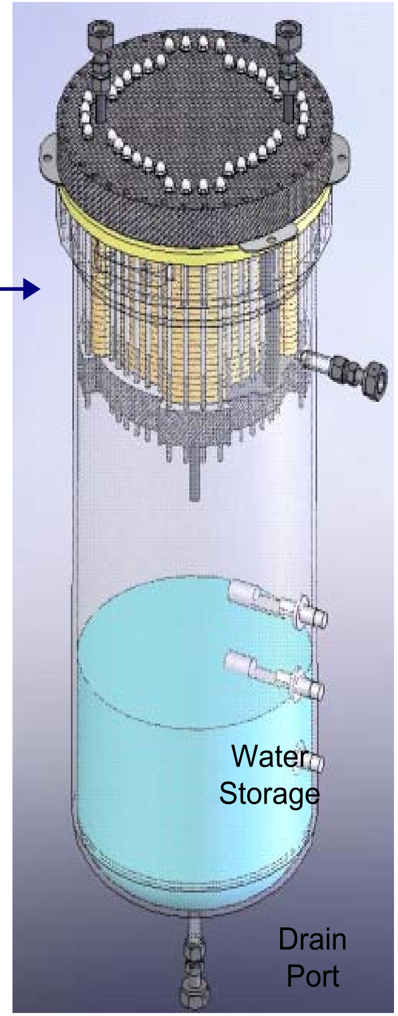
Innovative Approach to High Pressure Electrolyzer Operation

- Innovation Required to Overcome Significant Issues
  - Improve Efficiency
    - Good voltage performance
    - Reduce high gas cross-over rates
  - Supported MEA (long life)
  - Reduce Expense of High-Pressure Components
    - Stack
    - Phase separators
    - Valves, pumps, and piping
  - Safety
    - High pressure compressible gases
    - High pressure flammable hydrogen
    - High pressure high purity oxygen
- PEM Electrolysis Proven Under Balanced Pressure Conditions
  - To 3,000 psi with Gen 1 Navy stacks
  - Aerospace stacks at 400, 1,200, and 2,000 psi

Proposed Approach: Unitized Design Concept



Electrolyzer Cell Frames



GES Electrolyzer Stack-Dome Assemblies

Approach: Utilize a Low-Cost Cell Design

- Take Advantage of Advances & Developments on Related Giner Projects
- Carbon Cathode
  - Multi functional part
  - One piece replaces two subassemblies
    - Eliminates 20+ component parts
  - Enables high pressure operation
  - Demonstrated to 2,000psi (balanced and differential)
- Low Precious Metal Loadings
  - 10x reduction
  - Demonstrated performance
- Single Piece Separator
  - Eliminates hydrogen embrittlement
  - One subassembly reduces cell part count by 30%

Approach: High Pressure Electrolyzer Membrane

- **PEM Electrolyzer Efficiency**
  - Increase Ionomer's Conductivity (Low EW)
  - Thin MEA – reduces membrane resistance
  - Operate at High Temperature – reduces MEA resistance
  - Reduce Ionomer's Permeability
  - Enabling Technology: DSM™

Membrane for High Pressure Operation

System requires a high-efficiency membrane - DSM™

- **Superior Mechanical Properties**
  - No x-y dimensional changes upon wet/dry or freeze-thaw cycling
  - Much Stronger Resistance to tear propagation
  - Superior to PTFE-based supports
  10x stronger base properties
- **Improve MEA Mfg**
  - Ease of handling
  - Direct catalyst inking onto membranes
- **Improve Stack Seals**
  - Potential to bond support structures into bipolar frame to eliminate sealing issues
- **Customized MEAs**
  - Vary ionomer and thickness
  - Provide more support at edge regions and/or at ports

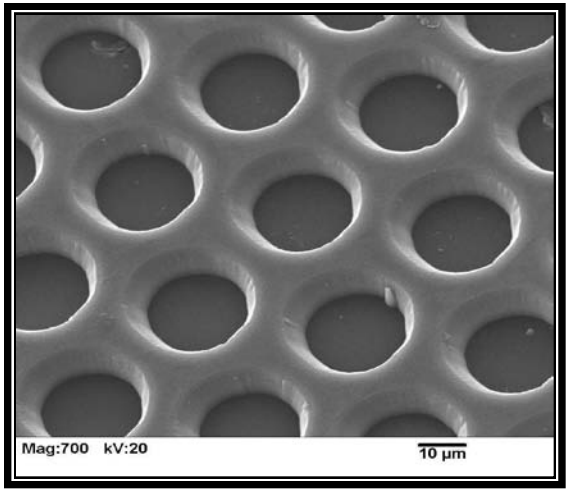


Figure 1. Scanning Electron Microscope (SEM) micrograph of the polymer membrane support structure with definable straight hole pattern

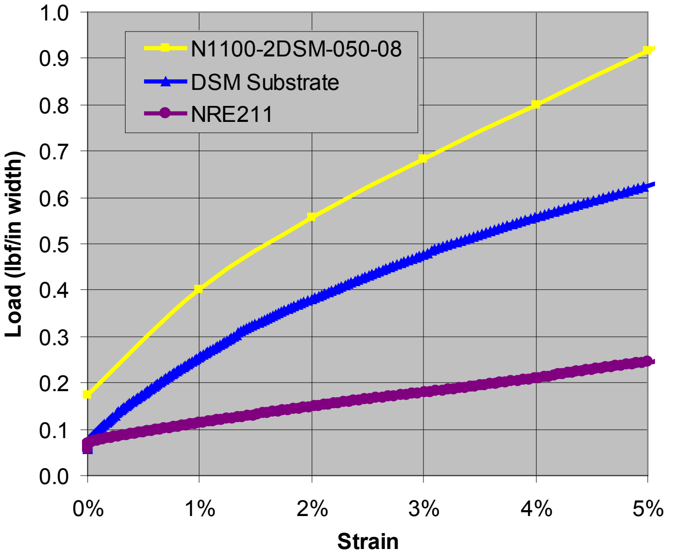


Figure 2. Dynamic Mechanical Analysis (DMA) shows the increased tensile strength of the DSM™ versus its components (wet at 80°C)

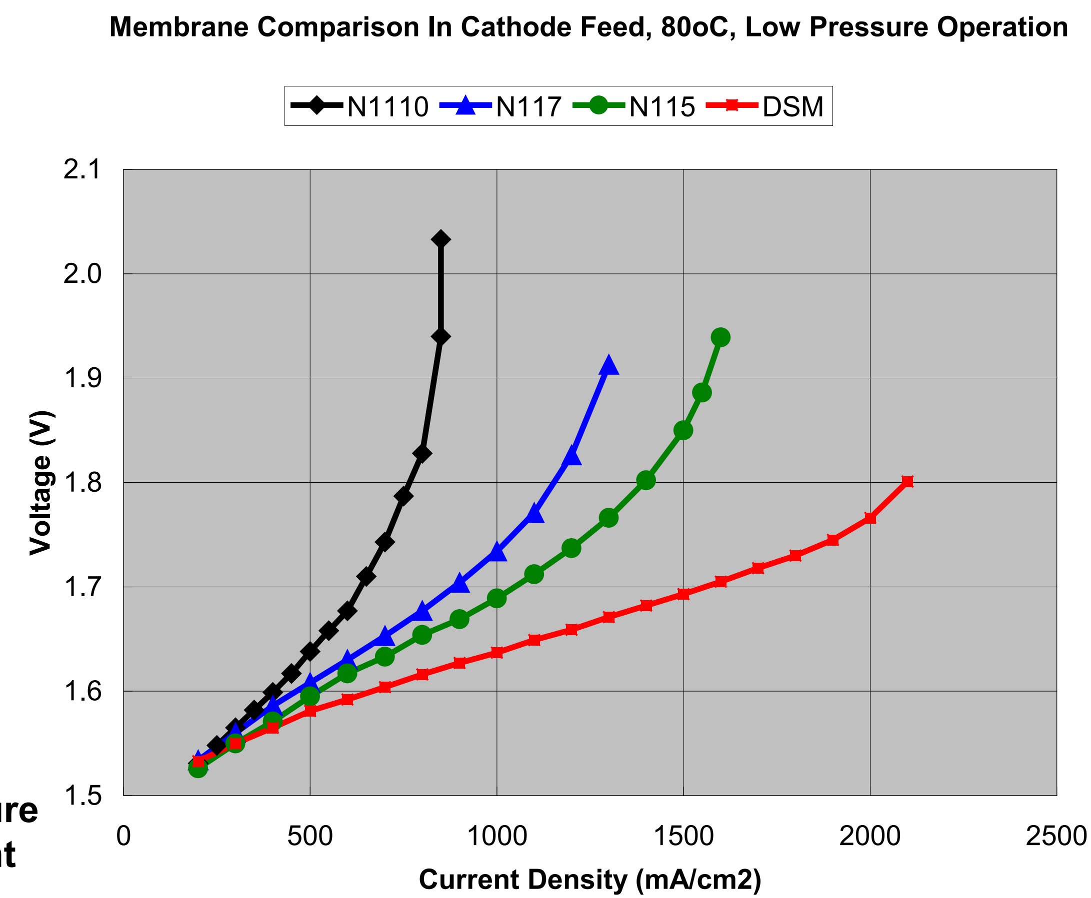
Demonstration of DSM™ in Cathode Feed

- **Cathode Feed**
  - System configuration advantages
  - Limits Max. current density

- **Performance of the Advanced DSM™ is superior to that of Nafion® 117 and 115**

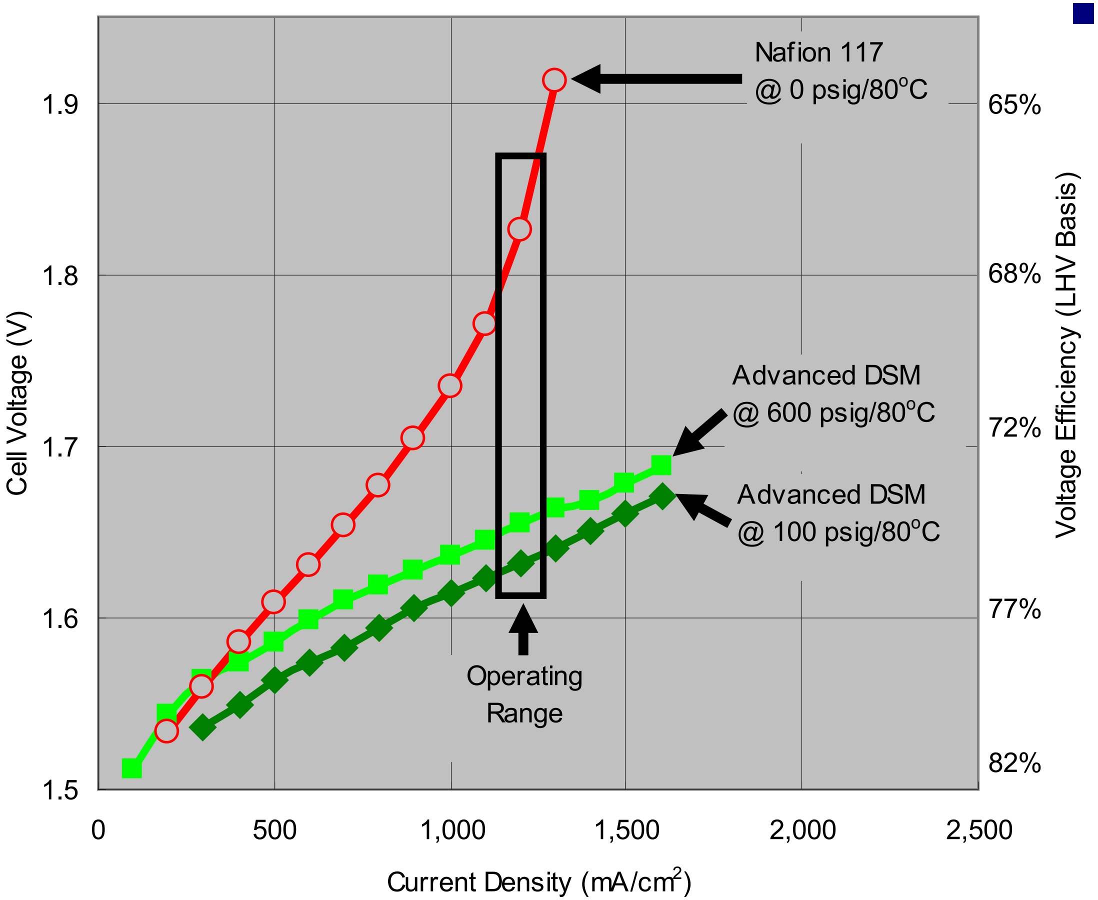
- **Current Density Limits**
  - N1110 = 600 mA/cm²
  - N117 = 900 mA/cm²
  - N115 = 1200 mA/cm²
  - DSM = 1800+ mA/cm²

- **High Pressure Operation**
  - Similar performance benefits measured at balanced pressure
  - Anticipate higher Max. current with differential pressure operation



Membrane Progress

Supported Membrane Demonstration of DSM™ in Cathode-Feed 50-cm² Cell



- **Performance of the Advanced DSM™ is superior to that of Nafion® 117**
  - DSM™ has demonstrated stable short-term operation
  - Membrane is expected to be highly durable; this requires verification
  - Low volume production (Other Government-funded projects)
    - Demonstrated fabrication processes
    - Reduced labor content by over 60% from prototypes
    - Quality assurance processes in place
    - Development required to further reduce labor content

Progress: System Design

- Set Goal: Simplify System Design Through Unitization & Component Elimination (Especially Rotating Equipment)
- Evaluated Various Electrolyzer Design Operating Modes To Realize Goal
  - Active anode water feed
  - Active cathode water feed
  - Static cathode water feed
  - Thermosiphon water feed
- Evaluated ALL System Components for Unitization Within Pressure Dome
- Batch Processing (to simplify design/reduce costs)
  - Store feed water for nightly H_2 generation
  - Off-line dryer regeneration during daytime
- Reviewed Existing Codes & Standards
  - Do any “showstoppers” exist?

Progress: System Design (cont)

	Anode Feed	Cathode Feed	Static Cathode Feed
Current Density	Highest	High (with DSM™)	High (with DSM™)
Efficiency	Highest	High (with DSM™)	High (with DSM™)
Water Feed Pump	Low Pressure Pump Required	High Pressure Pump Required	None
Cooling	Provided by water flow	Provided by water flow	Alternate cooling system required
# of vessels	5	3	3
Continuous Operation Capability?	YES	YES	Batch processing required
Number of Pumps	1	1	0

Progress: System Design (cont)

- Evaluated ALL System Components for Unitization Within Pressure Dome

Component	Result	Comment
Electrolyzer stack	UNITIZE	
Separators	UNITIZE	
Heat exchangers	UNITIZE/Eliminate	Substitute Passive Cooling
Gas dryer	UNITIZE	
Solenoid Valves	UNITIZE	
Pressure regulator	UNITIZE	
Sensors	Eliminate or UNITIZE	Where Possible
Polishing Deionizer	UNITIZE	
Main Deionizer	NOT unitized	10 Year Resin Supply
Controller	NOT unitized	
Power supply	NOT unitized	
Dispensing hose & nozzle	NOT unitized	

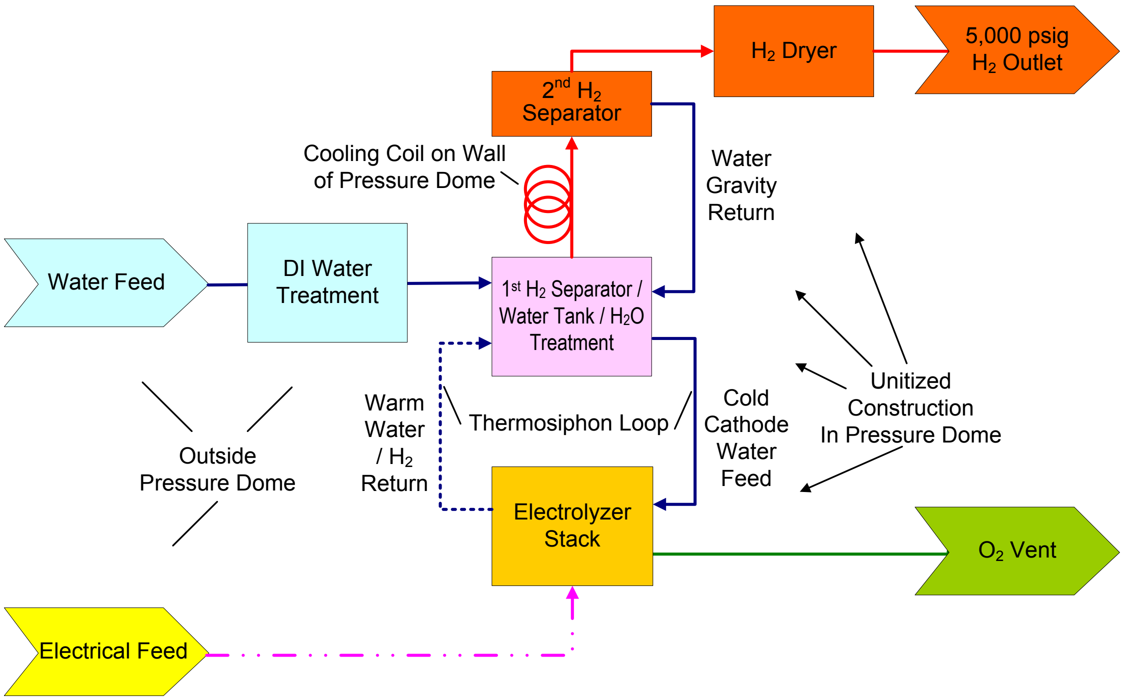
- Advantages
  - Single pressure vessel
  - Zero ΔP across component part walls enables use of plastic components and piping

Progress: System Design (cont)

- Identified & Developed Solutions for Key Design Issues, Elements and Components
  - High pressure electrical feed through
    - Solution demonstrated/used by Giner on NASA program
  - Method of H_2 dryer regeneration
    - No heater required
  - Heat rejection
    - Passive systems
  - System control
    - Day/night cycle
- Hydrogen Embrittlement
  - Plastic component parts are not susceptible
  - Barrier coating of metal dome interior

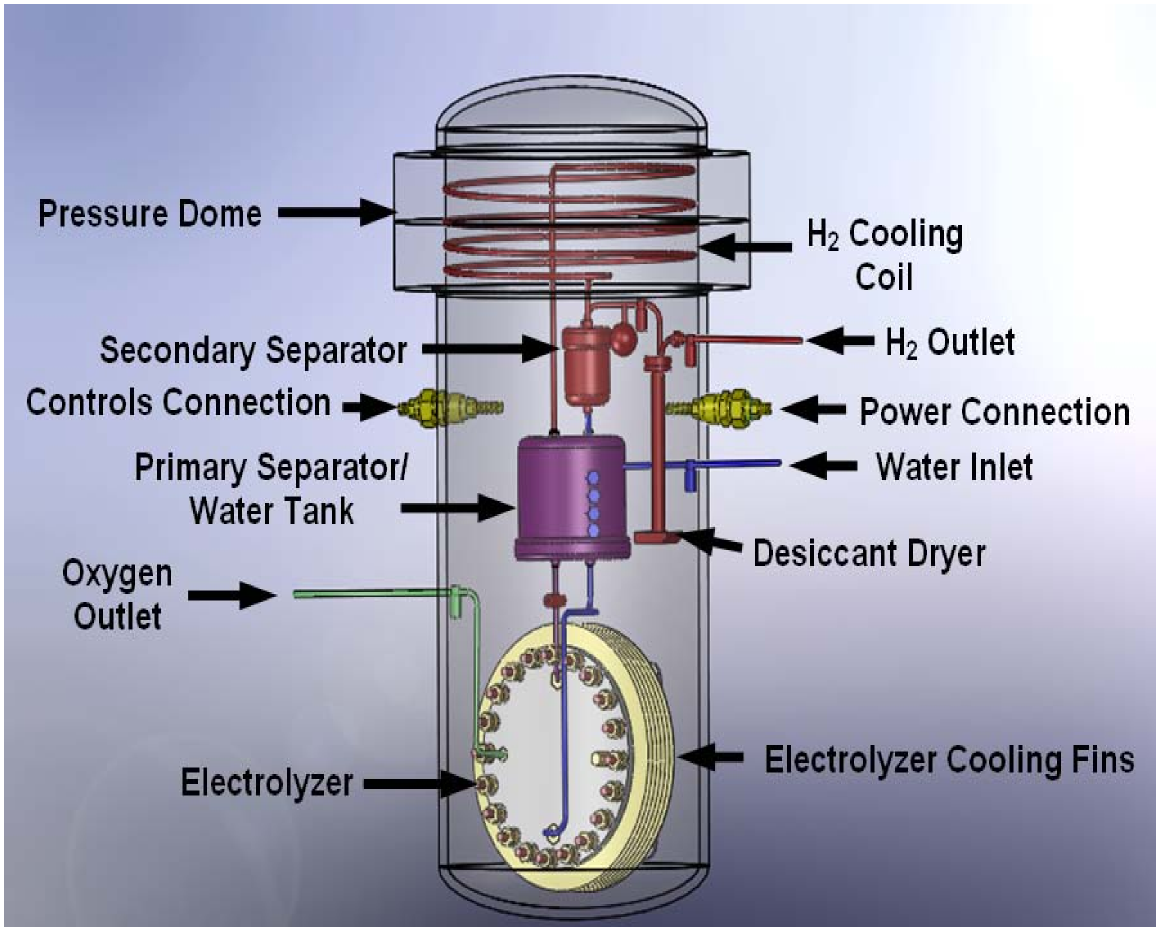
Progress: Preliminary System Design

- P&ID, PFD Completed
  - Equipment and Flow Paths Determined
  - Instrumentation Selected
  - Flow Rates and Conditions Calculated
- System Layout Complete
- Component Studies
  - Preliminary Electrolyzer Stack Designed
  - Passive Stack Cooling Sized
  - Prelim. Pressure Containment Dome Designed
  - Passive Hydrogen Cooling Sized
  - Prelim. Regenerative Dryer Designed
  - Cathode Circulation Thermosiphon (Natural Circulation) Designed



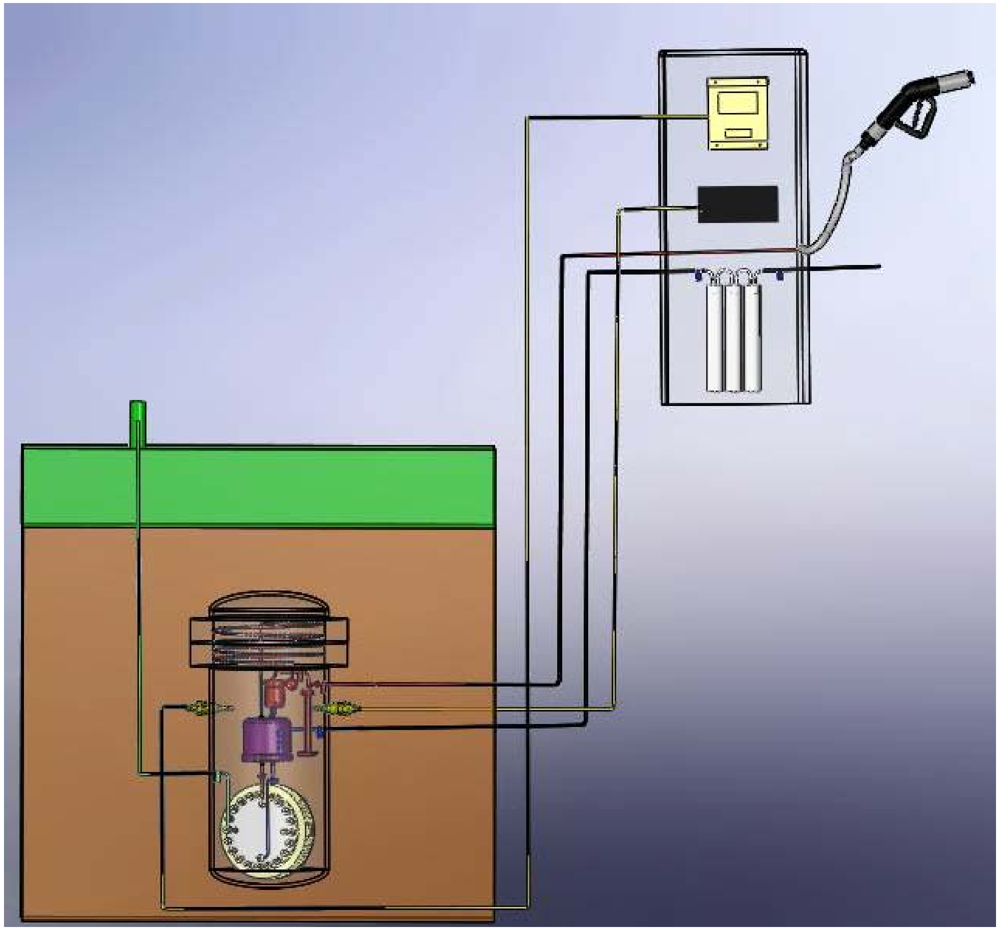
Cathode Feed Process Flow Diagram

Progress: Preliminary System Design
(Unitized Packaging Layout)



- Operates in Thermosiphon Cathode Feed Mode
- Low-Pressure Stack Hardware
  - Thin end plates
  - Machine bolts not specialty metal parts
  - Thermoplastic frames
- Utilize Pressure Inside Pressure Containment Dome
  - Minimizes stack compression needs
  - Benefits contact resistance
  - Allows use of unreinforced plastic frames
  - Enhances safety
  - Use unreinforced, low-cost components and piping

Progress: Preliminary System Design
(System Installation)



- Electrolyzer Assembly Buried Outdoors Below Frost Line
- Auxiliary Assembly Installed in Homeowner's Garage
  - Main deionizer (10 year resin supply)
  - Power supply
  - System controller
  - Refueling assembly & nozzle
- Interconnections Between Two Assemblies
  - Deionized water
  - H_2 delivery
  - Power wiring
  - Control wiring
- Homeowner Utilities
  - Potable water
  - 120 VAC 20 A circuit
- Vents to Atmosphere
  - Hydrogen
  - Oxygen

Progress: Residential H_2 Refueling Appliance Applicable Codes & Standards

- Retained Prof. Zalosh – H_2 safety expert
- Reviewed National & International Codes & Standards
- Giner Invited to Contribute Comments to ISO/DIS 22734-2 Draft
- One Significant Concern
  - NFPA 52-2100, Chapter 9 (no indoor refueling)
  - International fire code – no impediment to indoor refueling
  - NFPA should be approached to resolve discrepancy

Design Progress: Codes Pertinent to Residential Hydrogen Refueling Systems

Component Examples

IEC 60335 Parts 1, 2, 3, 5
Household and Similar Electrical Appliances

IEC 60079-10-1: Explosive Atmospheres, Classification of Areas

ISO 4126-1, -2: Safety Devices for Protection Against Excessive Pressure: Valves & Rupture Disks

CSA America HGV 4.7-2009: Automatic Valves for Use In Gaseous Hydrogen Fueling Stations

SAE J2600: Compressed Hydrogen Fueling Receptacles

Electrolyzer System

ISO/DIS 22734-2:
Hydrogen Generators Using Water Electrolysis Process; Part 2: Residential Systems

Eventual UL and CSA Versions of **ISO/DIS 22734-2**

Residential Installation

NFPA 52-2010, Chapter 9:
GH2 Compression, Gas Processing, Storage, and Dispensing Systems

International Fire Code Section 2209:
Hydrogen Motor Fuel Dispensing and Generation Facilities

Vehicle Refueling

CSA America HGV 4.1-2009:
Hydrogen Dispensing Systems

International Fire Code Section 2209:
Hydrogen Motor Fuel Dispensing and Generation Facilities

SAE TIR J2601
Compressed Hydrogen Fueling Protocol

Design Progress: Projected H_2 Cost

	System Capital Costs ($)						
Cumulative Number of Units	**1**	**10**	**100**	**1,000**	**10,000**	**100,000**	**1,000,000**
Electrolyzer Stack	19,140	8,644	4,982	2,901	1,690	985	574
BOP	17,850	8,061	4,644	3,533	1,576	918	535
System Assembly Labor	3,700	1,671	963	560	326	190	111
Total Cost of System($)	40,690	18,376	10,589	6,994	3,592	2,093	1,220

Specific Item Cost Calculation

Hydrogen Production Cost Contribution

Number of Units	**1**	**10**	**100**	**1,000**	**10,000**	**100,000**	**1,000,000**
Capital Costs*	23.57	10.81	6.35	4.30	2.35	1.49	0.99
Fixed O&M	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock Costs ($0.04/kWh)	1.98	1.98	1.98	1.98	1.98	1.98	1.98
Byproduct Credits	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Variable Costs (including utilities)	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total Cost of Delivered Hydrogen ($/kg-$H_2$)	**25.56**	**12.80**	**8.34**	**6.29**	**4.34**	**3.48**	**2.99**

H2A Model Analysis

Forecourt Model rev 2.1.1

- Design capacity: 1 kg H_2/day
- Operating Capacity Factor 64%
- Single stack/unit
  - Low-cost materials and component manufacturing
- H_2 generated at 5000 psig – no H_2 compressor needed
- Renewable electricity at $0.039/kWhr (nights & weekends)
- $2.99/kg-$H_2$ at volume of 1 Million/yr

Collaborations

- Professor Robert Zalosh
  - Vendor
  - University
  - Initial review of applicable codes and standards
  - Will lead to ongoing safety analysis in Phase II
- IAS, Inc.
  - Vendor
  - For-profit company
  - Projection of control system development and production costs
  - Will lead to controller prototypes in Phase II
- GES, LLC (DOE Cost-Shared Grant DE-FC36-08GO18065)
  - Same Company
  - For-profit company
  - Within DOE H_2 program
  - Multiple overlapping component and subsystems (also Parker, 3-M and Entegris)
- GES, LLC (Government and Private Electrolyzer Development Programs)
  - Several NASA programs, one DARPA Prime Contractor, several private electrolyzer companies

Proposed Future Work (Phase II Plans)

- Detail Design & Demonstration of Subsystems
  - Static cathode feed stack
  - Pressure dome
  - Hydrogen dryer regeneration
  - Passive heat exchange
  - Control system
  - DI water system
  - Dispensing hose and nozzle
  - Investigate low-cost, high-efficiency power supply
- Fabricate & Demonstrate Unitized System
- Identify & Team With Commercialization Partner(s)

Summary

- Innovative System Design
  - No compressors, pumps, or fans required
  - Only one pressure vessel
  - Reduces costs (capital, operating & maintenance)
  - Improves reliability, safety, efficiency
- Innovative High Strength Low Permeability Supported Membrane Required
  - Advanced DSM^{TM}
  - High efficiency
- Codes & Regulations Review Completed
- Hydrogen Costs Meet DOE Target of $3/kg
  - Will require significant sales volumes