



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

This presentation does not contain any proprietary or confidential information

# 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

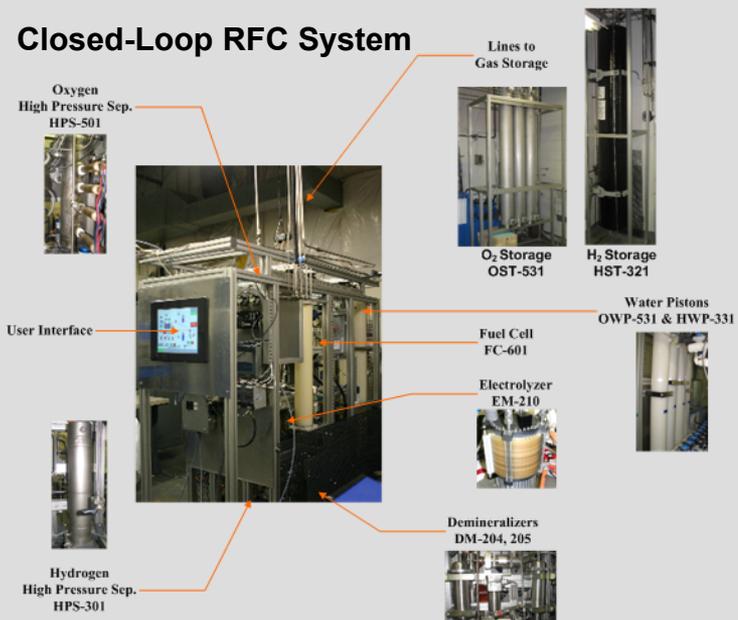
## Targets

DOE TARGETS: Distributed Water Electrolysis			
Characteristics/units	2006	2012	2017
Hydrogen Cost (\$/kg-H <sub>2</sub> )	4.80	3.70	<3.00
Electrolyzer Cap. Cost (\$/kg-H <sub>2</sub> )	1.20	0.70	0.30
Electrolyzer Efficiency %LHV	62	69	74
(%HHV)	(73)	(82)	(87)

## Collaborations

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

## Closed-Loop RFC System



## S-10 Electrolyzer System

6 kW Electrolyzer  
 ~ 40 SCFH-H<sub>2</sub> (~0.1 kg-H<sub>2</sub>/hr)  
 1500 ASF  
 1250 psi H<sub>2</sub> / Ambient O<sub>2</sub>  
 Volume ~ 6 ft<sup>3</sup>



# GES PEM Electrolyzer Systems

## EP-1 On-Site H<sub>2</sub> Generators

20 kW Electrolyzer  
 0.35 kg H<sub>2</sub> / hr  
 1500 ASF  
 1250 psi H<sub>2</sub> / Ambient O<sub>2</sub>  
 Volume ~ 16 ft<sup>3</sup>



## UUV Applications (V = 12.5 Ft<sup>3</sup>)

12 Cells - 0.17 ft<sup>2</sup> Cells/Stack  
 6-kW Electrolyzer  
 ~ 40 SCFH-H<sub>2</sub> (~0.1 kg-H<sub>2</sub>/hr)  
 High Current Density (1300-1500 A/ft<sup>2</sup>)  
 1000 psi H<sub>2</sub>/Ambient O<sub>2</sub>  
 No High-Pressure Water Feed Pump or Containment Vessel  
 UUV Applications

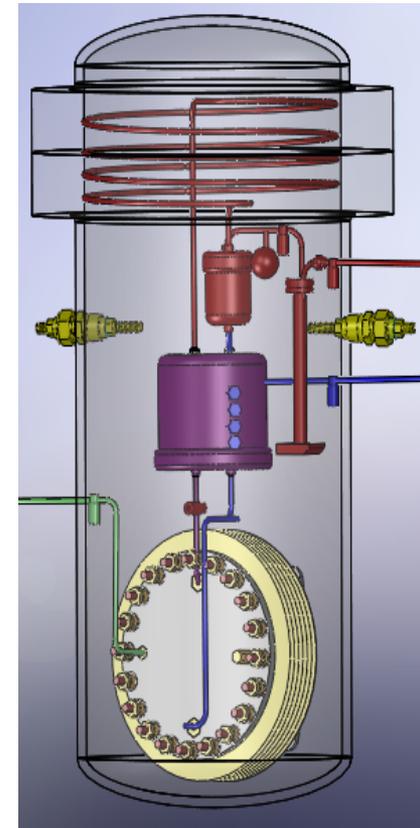
# Relevance/Project Objectives

## *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



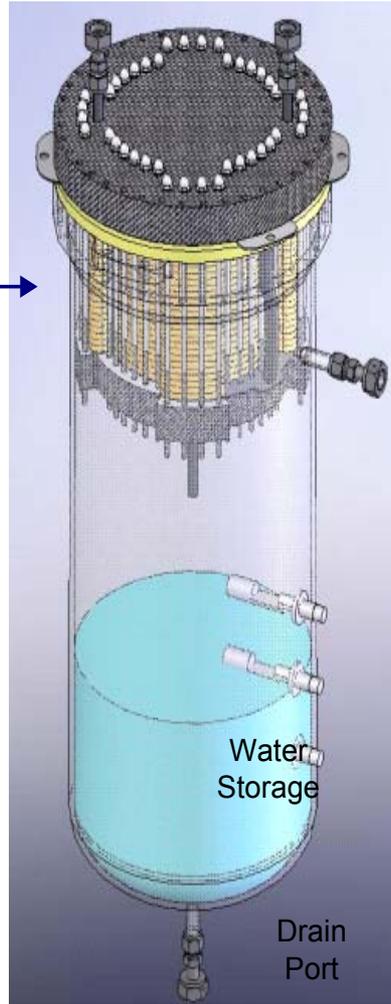
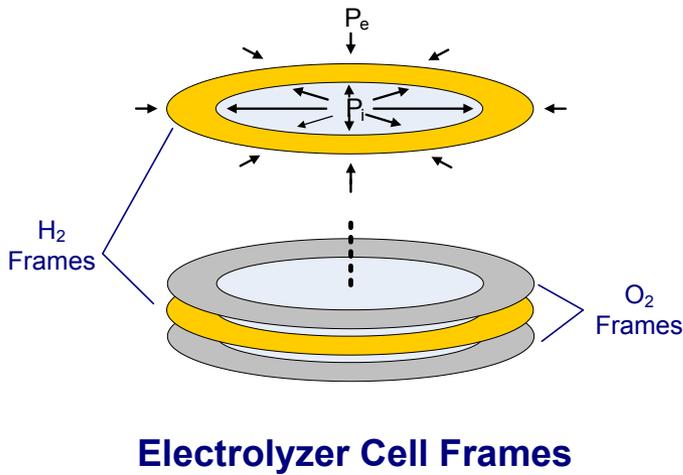
# Milestones

Go/No Go Decision Points	Progress Notes	% Complete
<p><b>System Development:</b> Complete Preliminary Design</p>	<p><b>Completed:</b></p> <ul style="list-style-type: none"> <li>■ Survey of Applicable Domestic and International Hydrogen Generation/Refueling Safety Codes and Standards</li> <li>■ Preliminary System Design for Unitized PEM Electrolyzer for Home Refueling Applications</li> <li>■ Preliminary Design of a 5000 psi “Unitized” Stack and Hydrogen/Water Phase-Separator</li> <li>■ Economic Feasibility Studies</li> </ul>	<p><b>100%</b></p>
<p><b>Membrane:</b> Evaluate PEM Membrane at High Pressure Operation</p>	<p><b>Completed:</b></p> <ul style="list-style-type: none"> <li>■ 6-Cell Short Stack Built with Advanced DSM™</li> <li>■ Completed Testing at Balanced 100 and 600 psig Pressures</li> <li>■ Completed Polarization Scans @ 80°C</li> <li>■ Planning 2500 psig Tests</li> </ul>	<p><b>90%</b></p>

# 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



**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

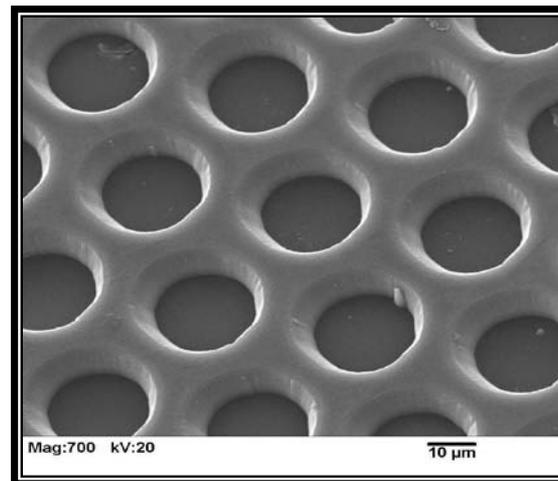
- Ease of handling
- Direct catalyst inking onto membranes

## ■ Improve Stack Seals

- Potential to bond support structures into bipolar frame to eliminate sealing issues

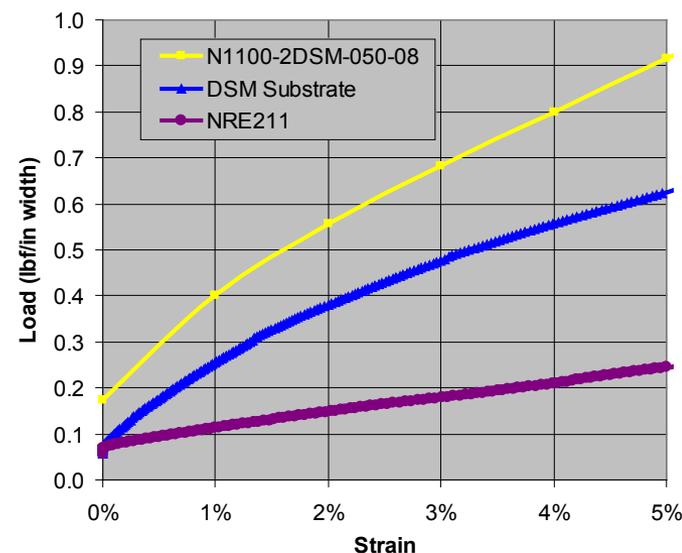
## ■ Customized MEAs

- 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

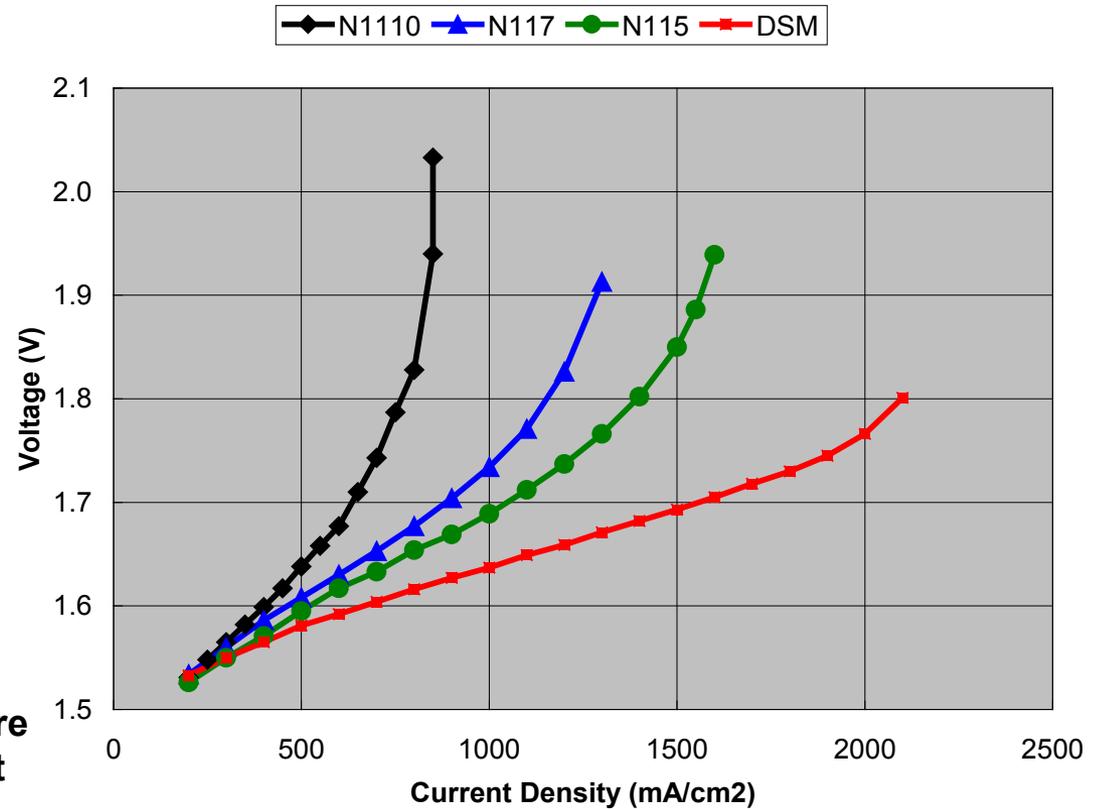
## ■ Current Density Limits

- N1110 = 600 mA/cm<sup>2</sup>
- N117 = 900 mA/cm<sup>2</sup>
- N115 = 1200 mA/cm<sup>2</sup>
- DSM = 1800+ mA/cm<sup>2</sup>

## ■ High Pressure Operation

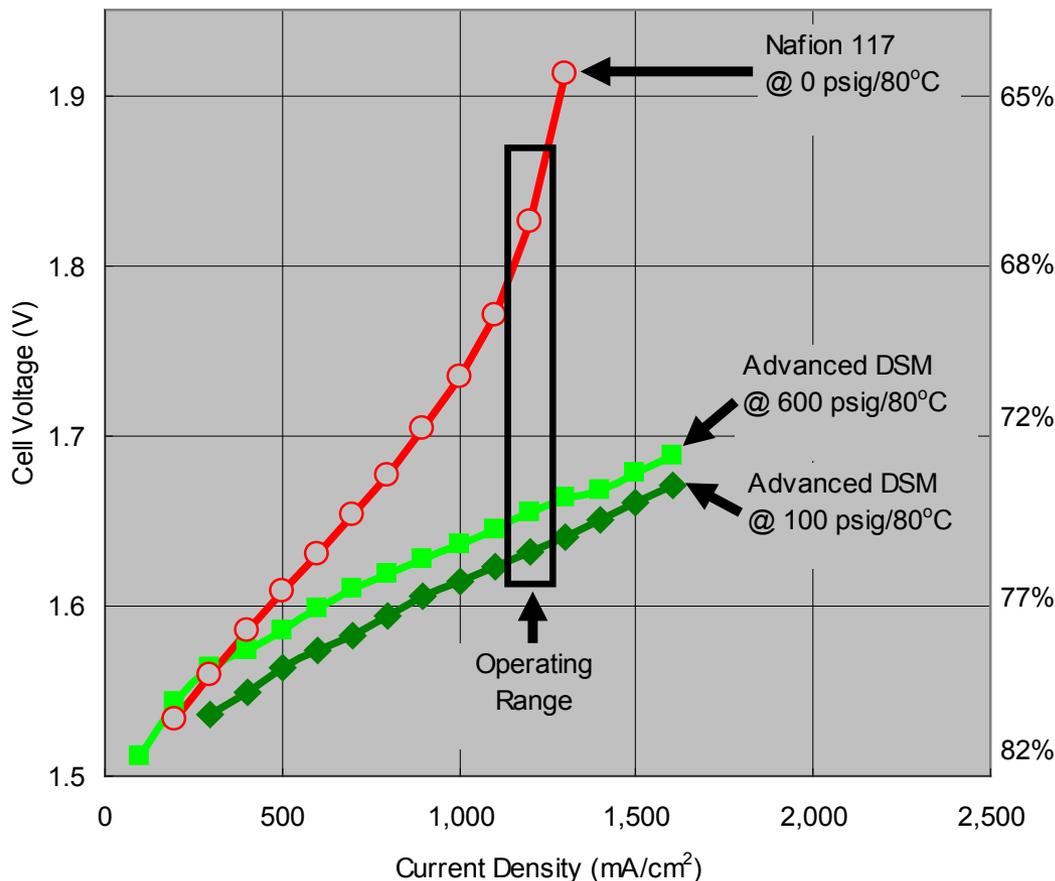
- Similar performance benefits measured at balanced pressure
- Anticipate higher Max. current with differential pressure operation

Membrane Comparison In Cathode Feed, 80oC, Low Pressure Operation



# Membrane Progress

*Supported Membrane Demonstration of DSM™ in Cathode-Feed 50-cm<sup>2</sup> 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<sub>2</sub> 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  $\Delta P$  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<sub>2</sub> 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

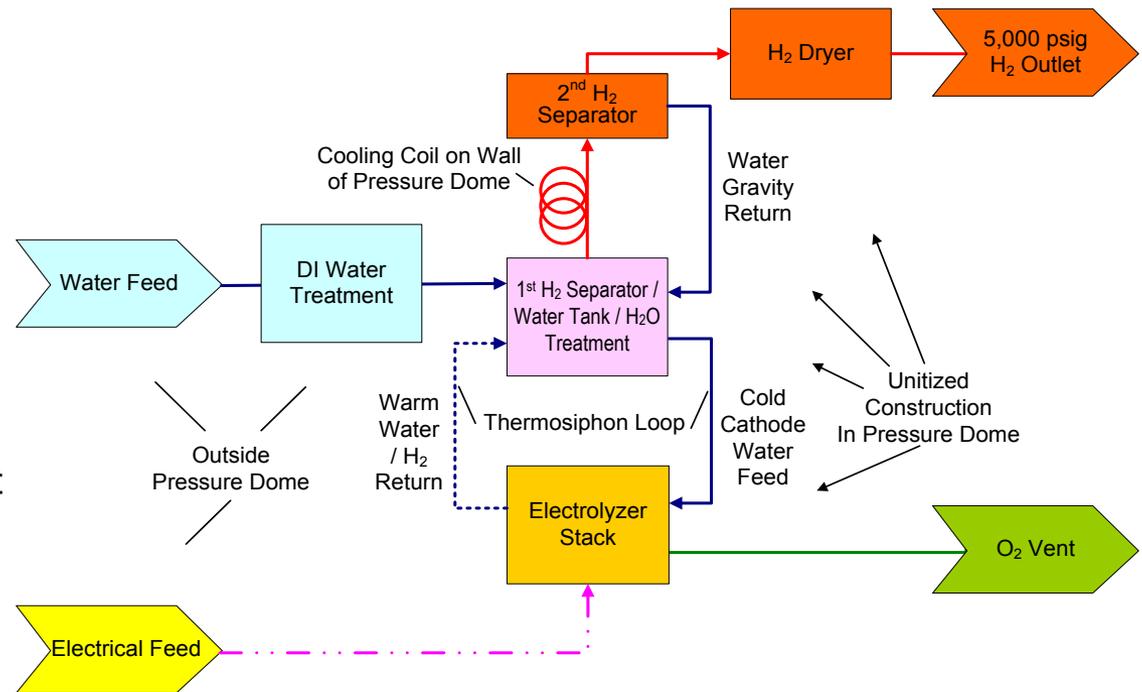
## □ P&ID, PFD Completed

- Equipment and Flow Paths Determined
- Instrumentation Selected
- Flow Rates and Conditions Calculated

## □ System Layout Complete

## □ Component Studies

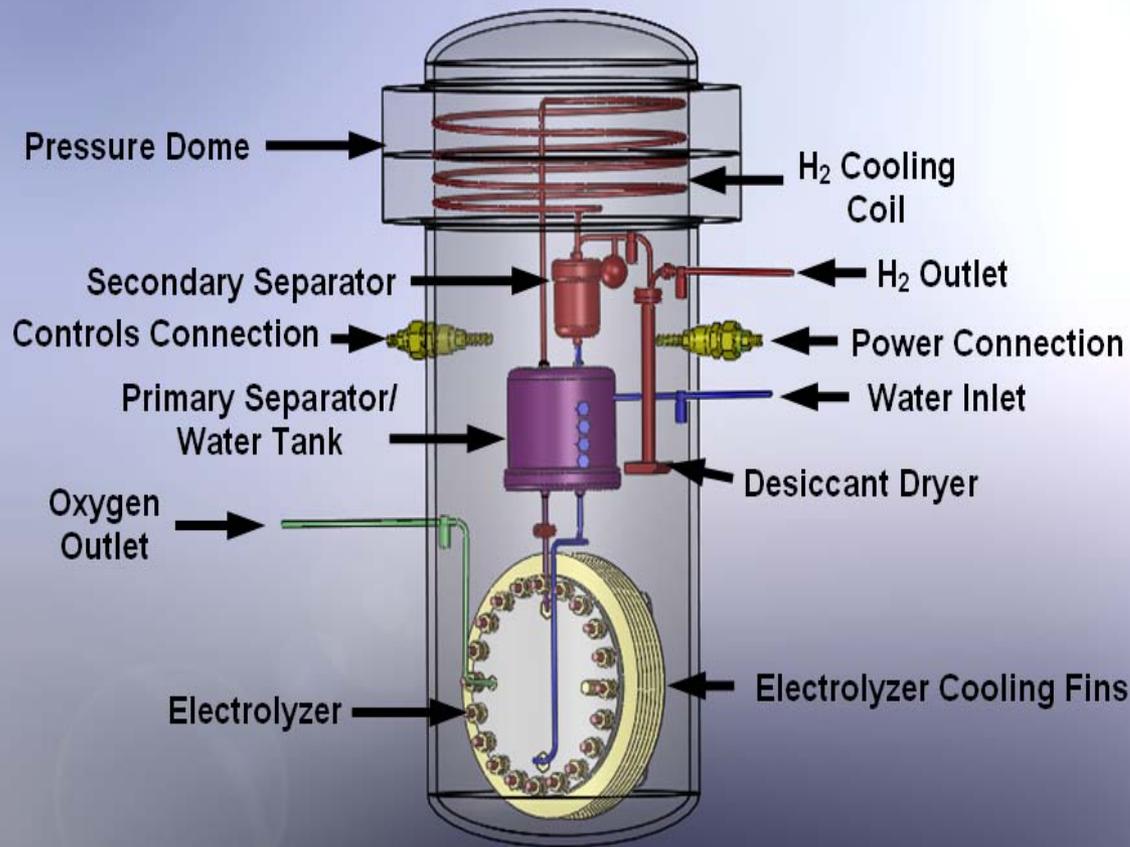
- Preliminary Electrolyzer Stack Designed
- Passive Stack Cooling Sized
- Prelim. Pressure Containment Dome Designed
- Passive Hydrogen Cooling Sized
- Prelim. Regenerative Dryer Designed
- Cathode Circulation Thermosiphon (Natural Circulation) Designed



**Cathode Feed Process Flow Diagram**

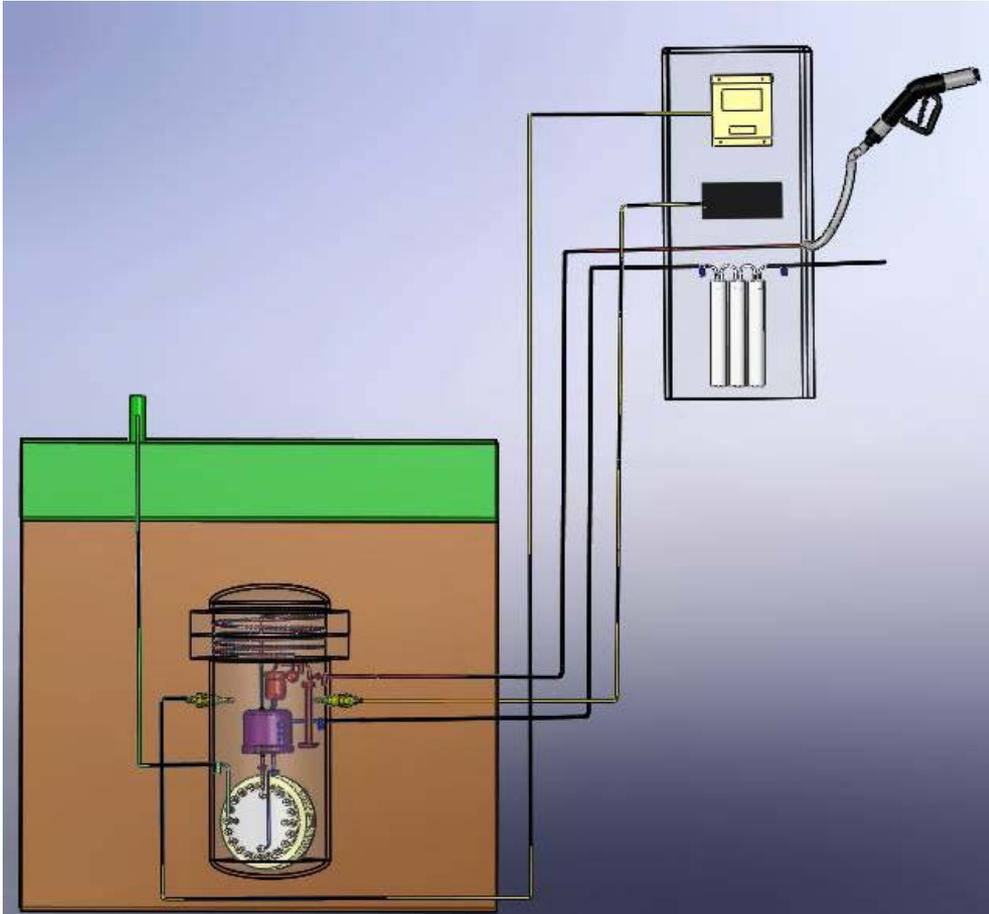
# Progress: Preliminary System Design

## (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<sub>2</sub> delivery
  - Power wiring
  - Control wiring
- Homeowner Utilities
  - Potable water
  - 120 VAC 20 A circuit
- Vents to Atmosphere
  - Hydrogen
  - Oxygen

# Progress: Residential H<sub>2</sub> Refueling Appliance Applicable Codes & Standards

- Retained Prof. Zalosh – H<sub>2</sub> 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:** GH<sub>2</sub> 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<sub>2</sub> Cost

Cumulative Number of Units	System Capital Costs (\$)						
	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
<b>Total Cost of System(\$)</b>	<b>40,690</b>	<b>18,376</b>	<b>10,589</b>	<b>6,994</b>	<b>3,592</b>	<b>2,093</b>	<b>1,220</b>

## 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
<b>Total Cost of Delivered Hydrogen (\$/kg-H<sub>2</sub>)</b>	<b>25.56</b>	<b>12.80</b>	<b>8.34</b>	<b>6.29</b>	<b>4.34</b>	<b>3.48</b>	<b>2.99</b>

## H2A Model Analysis

Forecourt Model rev 2.1.1

- Design capacity:  
1 kg H<sub>2</sub>/day
- Operating Capacity  
Factor 64%
- Single stack/unit
  - Low-cost materials  
and component  
manufacturing
- H<sub>2</sub> generated at  
5000 psig – no H<sub>2</sub>  
compressor needed
- Renewable electricity at  
\$0.039/kWhr (nights &  
weekends)
- \$2.99/kg-H<sub>2</sub> 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<sub>2</sub> 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™
  - High efficiency
- Codes & Regulations Review Completed
- Hydrogen Costs Meet DOE Target of \$3/kg
  - Will require significant sales volumes