2012 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 II SBIR Program

### Timeline

- **Project Start: Aug** 2010
- **Project End:** Aug 2012
- **Percent Complete: 55**

### Budget

- **Total Project Budget: $999k**
  - **Funding Received in FY11:** $499K
  - **Planned Funding for FY12:** $0K*

*Project has been fully funded

### Barriers

Hydrogen Generation by Water Electrolysis

- G. Capital Cost
- H. System Efficiency

### Targets

| **DOE TARGETS: Distributed Water Electrolysis** | | | |
|---|---|---|---|
| **Characteristics/units** | **2006** Status | **2012** Target | **2017** Target |
| 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) |

http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf

### Partners

- **Prof. R. Zalosh –** Hydrogen Safety Codes
- **IAS, Inc. –** System Controls Design
- **3M Fuel Cell Components Program (Manufacturer) –** NSTF Catalyst & Membrane
- **Entegris –** Carbon Cell Separators
- **DE-FC36-08GO18065 -** PEM Electrolyzer Incorporating an Advanced Low-Cost Membrane

# Relevance/Project Objectives

### *Overall Project Objectives*

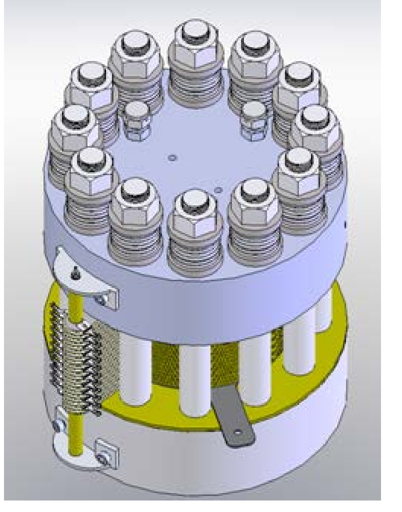
- Detail design & demonstrate subsystems for a unitized electrolyzer system for residential refueling at 5,000 psi to meet DOE targets for a home refueling appliance (HRA)
- Design and fabricate 5,000 psi electrolyzer stack
- Fabricate & demonstrate 5,000 psi system

### *Relevance*

- Successfully developing a low-cost residential refueling appliance will enable early adoption of fuel cell vehicles
- Permit hydrogen generation at end user site
- Eliminate need for mechanical hydrogen compression

### *Impact*

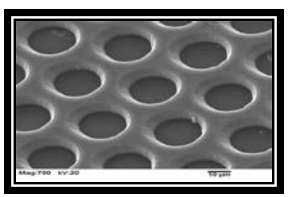
- Successfully developing a low-cost residential refueling appliance will overcome barriers in capital cost via elimination of storage and compression



# Approach: Overview

## Membrane Evaluation

- Develop/evaluate high pressure, high strength membranes compatible with 5,000 psi operation
- Determine membrane voltage and faradaic efficiencies
- Engineer membrane properties
  - Ionomer's conductivity
  - Membrane thickness & gas permeability
- Evaluate cathode-feed thermosiphon-based operation



Enabling Technology: DSM™

- DSM-PFSA ionomer incorporated into thermoplastic support

## Electrolyzer Cell & Stack-Design

- Develop enabling Stack technologies for 5,000 psi operation
- Innovative designs to reduce Stack material costs
  - Evaluate use of stack dome enclosure
  - Anode membrane supports materials
  - Cell Frames
    - Thermoplastics (low-cost) vs. metal (higher strength)
    - Cell frame stress analysis
  - Reduce parts count/cell
  - Carbon cathode support structures
    - Multi functional part
    - Eliminates 20+ component parts
    - Enables high pressure operation
  - Single piece separator
    - Eliminates hydrogen embrittlement
- Fabricate electrolyzer Stack utilizing low-cost cell components
- Evaluate overboard and crossover sealing to 1.25X operating pressure (6250 psi)

## Prototype System

- Design/Develop/Test 5,000 psi prototype electrolyzer system
- Innovation required to overcome significant cost issues related to
  - High-pressure components
  - Phase separators
  - Valves and pumps
- Take advantage of advances & developments on related Giner/DOE projects and system designs
- Improve safety and reliability
  - Conduct safety analysis for high pressure hydrogen generators
- Demonstrate 5,000 psi operation

# Approach: 2011-12 Milestones

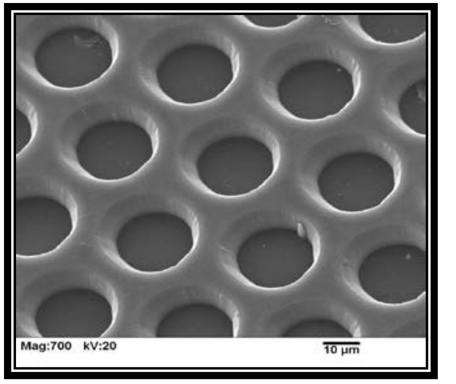
| | | Tasks | Progress Notes | % Complete |
|---|---|---|---|---|
| Membrane Evaluations | Task 1 & 3 | ■Evaluate membrane performance<br>☐ Determine voltage and current (faradaic) efficiencies<br>☐ Determine performance of cathode-feed and Thermosiphon-based designs<br>☐ Complete comparison to balanced and differential pressure operation | ■Test Stand modifications complete<br>■Innovative components designed for high pressure membrane evaluations<br>■Thermosiphon and cathode feed studies completed<br>■Performed 50 $cm^2$ 2000 psig (pumped cathode feed) electrolysis tests in a pressure dome | 80% |
| Electrolyzer Cell & Stack-Design | Task 3 & 4 | ■Design/Build/Test Electrolyzer Stack<br>■Evaluate/Optimize Pressure Containment Dome for low-cost system development | ■Stack design complete<br>■Low-cost reinforcement rings utilized to maintain low-cost stack design<br>■Initial pressure testing at 6250 psi (1.2X operating pressure completed<br>■Stack pass overboard and cross-cell leakage testing<br>■Dome evaluations complete | 75% |
| Prototype System | Task 2, 5-9 | ■T2: Complete Detailed Analysis of Hydrogen Safety Codes and Standards | ■Phase I codes and standards work updated<br>■Preparing to conduct HAZOP/FMEA | 60% |
| | | ■T5:Design/Build/Test 5,000 psig H2-Dryer<br>■T6-T7: Design/Build PEM Electrolyzer HRA system<br>■T8:Demonstrate Performance and Durability of “Unitized” Breadboard HRA System<br>■T9:Preliminary Design and Economic Analysis of Commercial HRA System | ■System P&ID finalized<br>■Hydrogen dryer design complete<br>■Procurement of system components initiated | 20% |

# Progress: Membrane Development

**Enabling technology: DSM™ Membranes**

- **High-strength high-efficiency membranes**
  - Improved strength without adversely impacting conductivity
  - No x-y dimensional changes upon wet/dry or freeze-thaw cycling
  - Much Stronger Resistance to tear propagation
  - Superior to PTFE-based supports
- **Improve MEA Mfg**
  - Ease of handling
  - Direct catalyst inking onto membranes
  - Low-cost, chemically-etched support
- **Improve Stack Seals**
  - Potential to bond support structures into bipolar frame to eliminate sealing issues
  - Provide more support at edge regions and at ports
- **Customized MEAs for High Pressure**
  - Engineered membrane thicknesses to achieve highest voltage and faradaic efficiencies

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



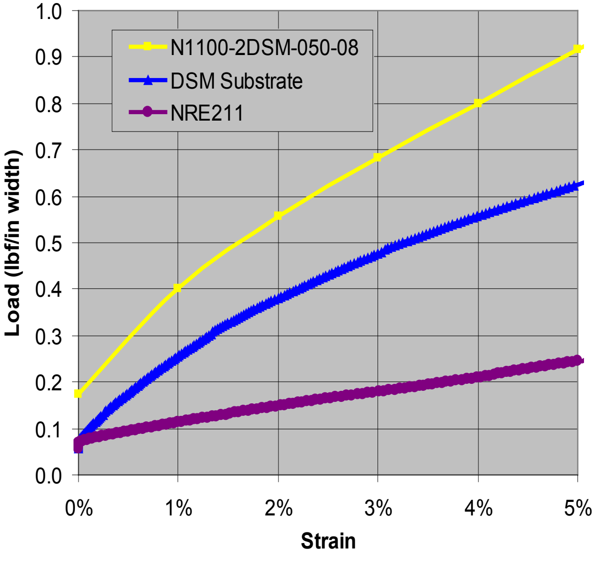
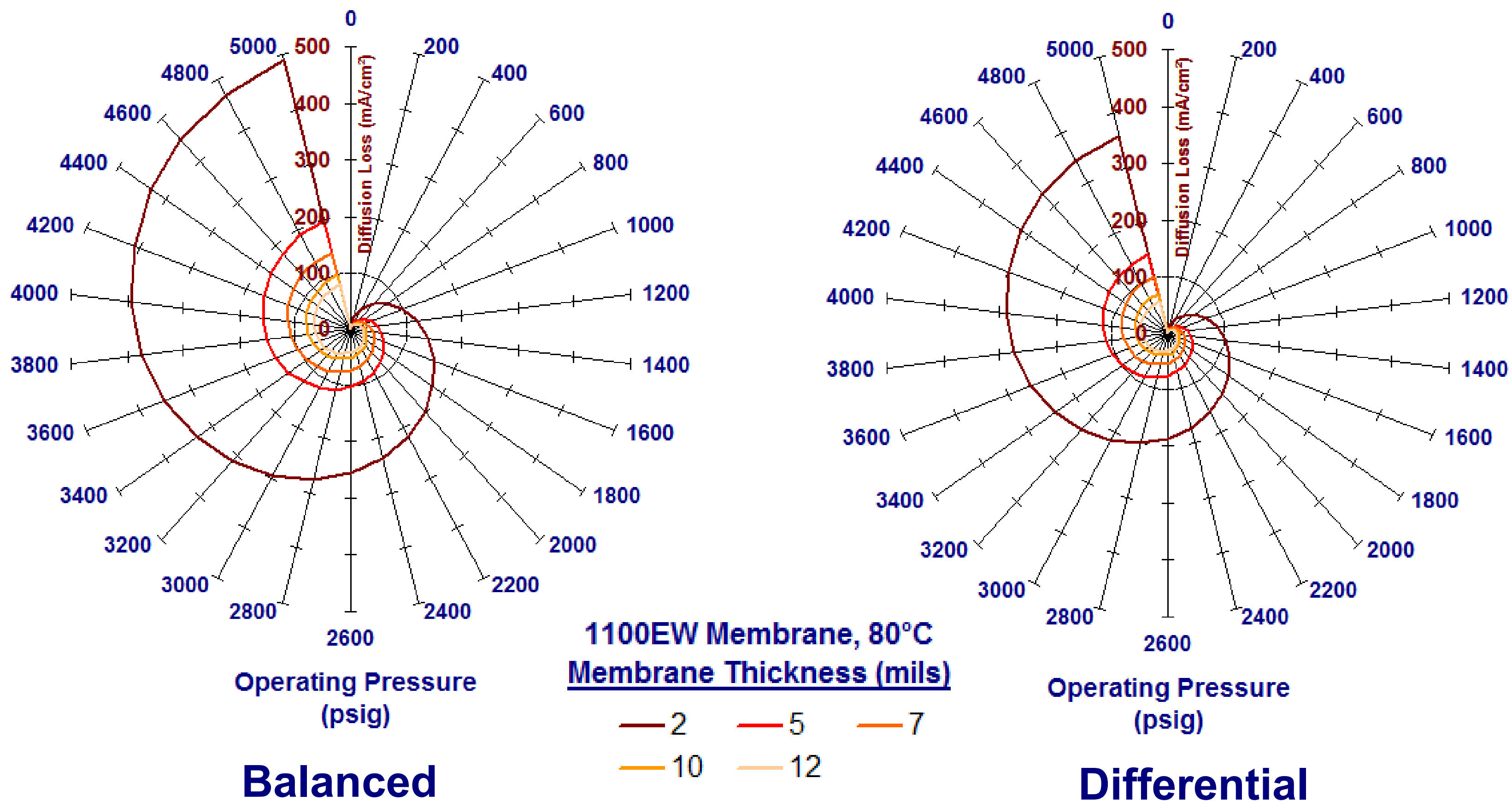




**Figure 2. Dynamic Mechanical Analysis** (DMA) shows the increased tensile strength of the DSM™ versus its components (wet at 80°C)

## **Progress: Membrane: Faradaic Efficiency:** Balanced vs. Differential Pressure Operation

### Pressure vs. Diffusion ($H_2/O_2$ Cross-Over)

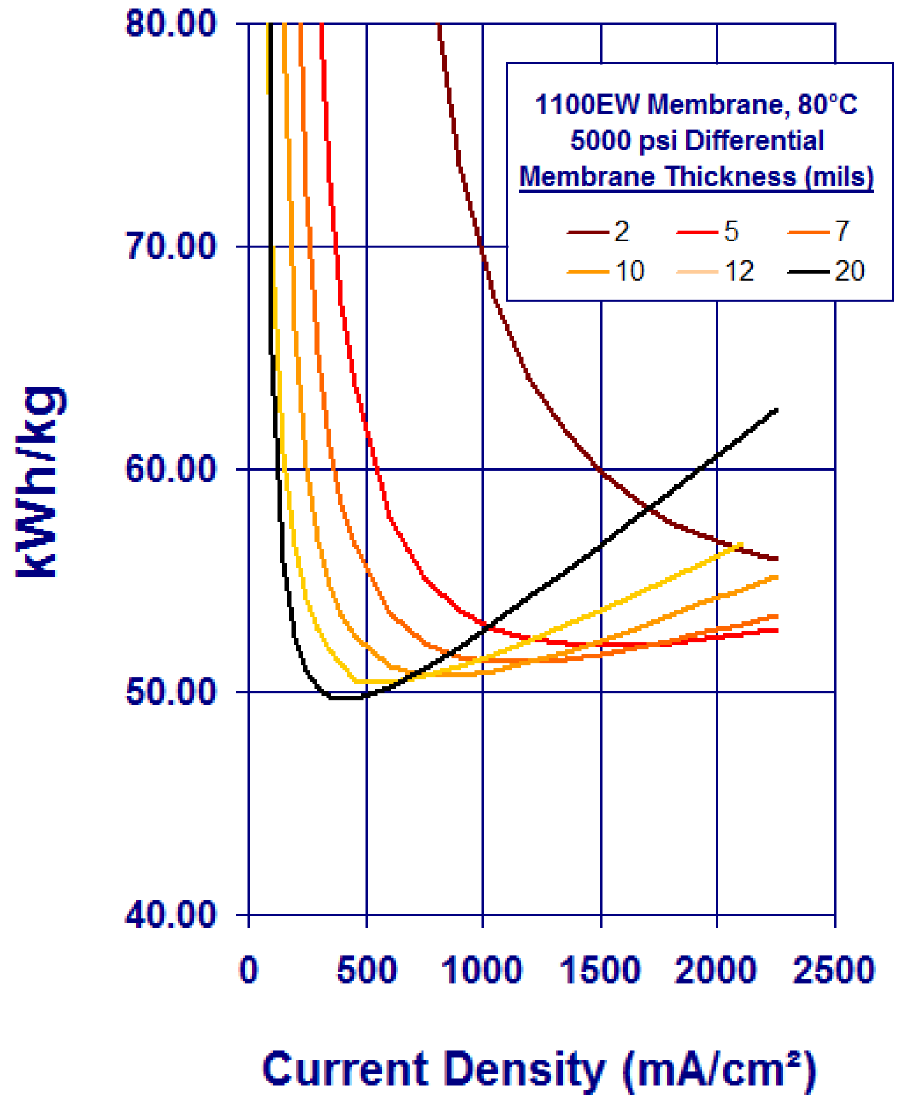



- Significant gain in faradaic efficiencies in differential-pressure operating mode as a result of reduced gas cross-over

# Progress: Membrane

**DSM Membrane Fabrication**

- Modeling indicates thicker membranes provide higher overall efficiencies at high pressure operation (5000 psi)
- DSM membrane thickness of 7,10, 12, 20 mils (1100EW) fabricated
  - Low-cost, chemically-etched supports utilized in DSM fabrication
  - DSM exhibit higher compressive strength than Nafion membrane of similar thickness
- Single-cell electrolysis evaluation at 5,000 psi to begin after completion of test stand modifications

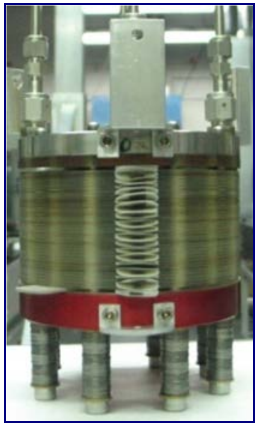


## Progress: Membrane: Demonstration of DSM™ in Pressure Dome

**Performance Evaluations: Cathode Feed, Dome Utilization, & Water-fed Thermosiphon tests**

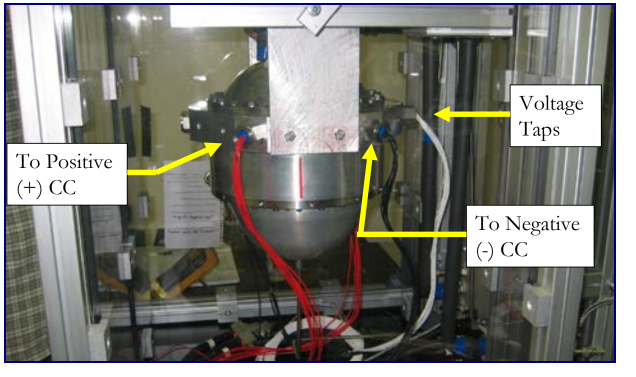
- DSM evaluated in cathode feed mode at 2000 psig balanced pressure
  - Pressurized Dome enables utilization of low-cost, low-pressure stacks
    - Requires gas source for pressurization
  - DSM (1100EW) Performance:1.79V @ 1500 mA/cm², 2000 psig (voltage efficiency: 87% HHV)
  - DSM (790 EW) Performance: Higher voltage efficiency, however higher gas permeation

- Thermosiphon Testing
  - Reduces the need for water pump
  - Performance: 1.8V @ 800 mA/cm²
    - Low current density limit
    - More cells required (>stack costs)
  - Tradeoff: Anode-feed, utilizing water pump will allow higher current density operation & lower cell requirement



**17-Cell Stack**
**Evaluation Hardware**

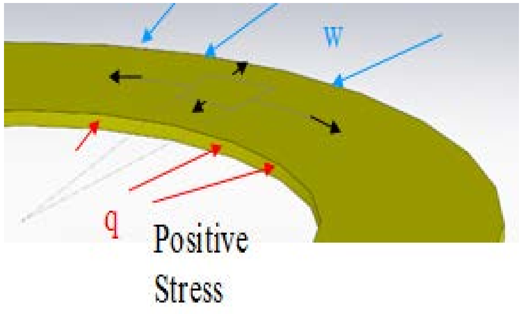
**Dome**



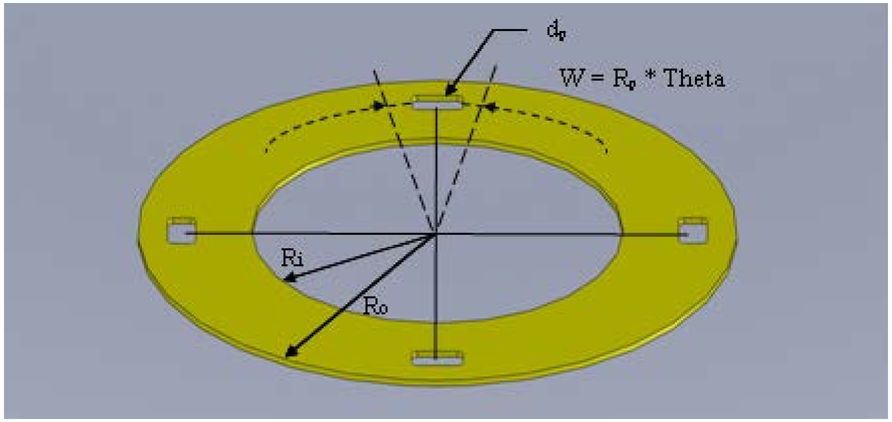
# Progress: Electrolyzer Cell/Stack Design

## Electrolyzer cell & stack modeling

- Cell Frame analysis
  - Outer cell-frame hoop-stress and clamping force analysis complete
  - Cell frame designs include use of outer reinforcement ring
    - Possibility of eliminating Dome enclosure with improved cell frame design



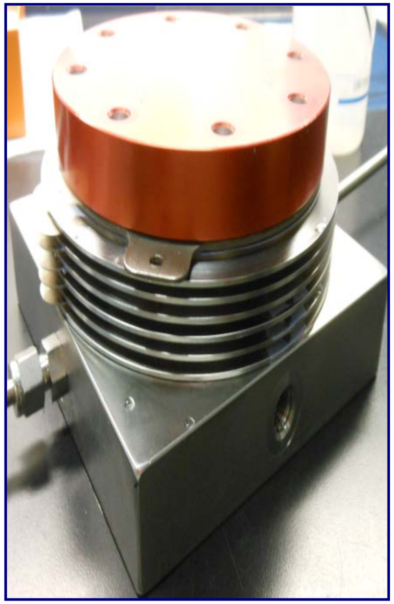

- Anode Support Structure
  - Fabricated advanced anode supports that enable
    - Lower Pressure Drop
    - Provide improved membrane support at pressures exceeding 6000 psi differential

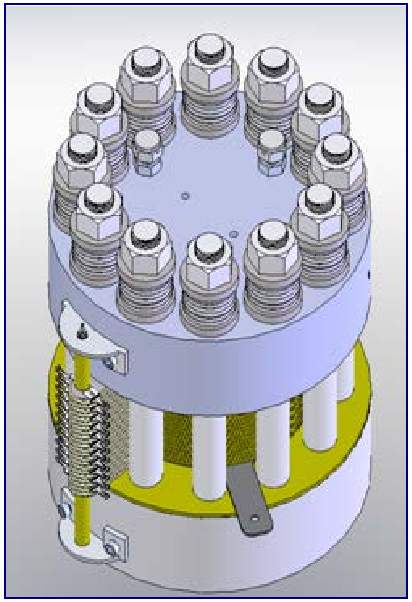



- Cathode Support Structures
  - Multi functional part
  - Eliminates 20+ component parts
  - Enables high pressure operation

# Progress: Electrolyzer Stack

- 5,000 psi Stack Design: Complete
- 6-Cell Stack assembled
  - Differential Pressure Operation
  - Utilizes metal containment rings over cathode cell-frames
    - Eliminates stack enclosure (Dome) while enabling method for high-pressure operation
    - Permits use of low-cost thermoplastic injection molded cell frames
- Stack proof pressure tested to 6250 psig operating pressure
- Final stack assembly includes use of round fluid endplate



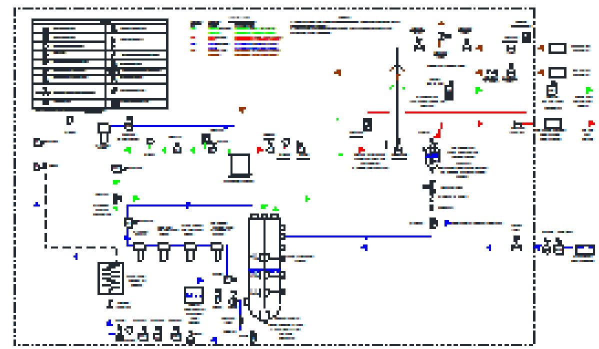


**Stack design incorporates use of containment rings for high pressure operation**

# Progress: System Design

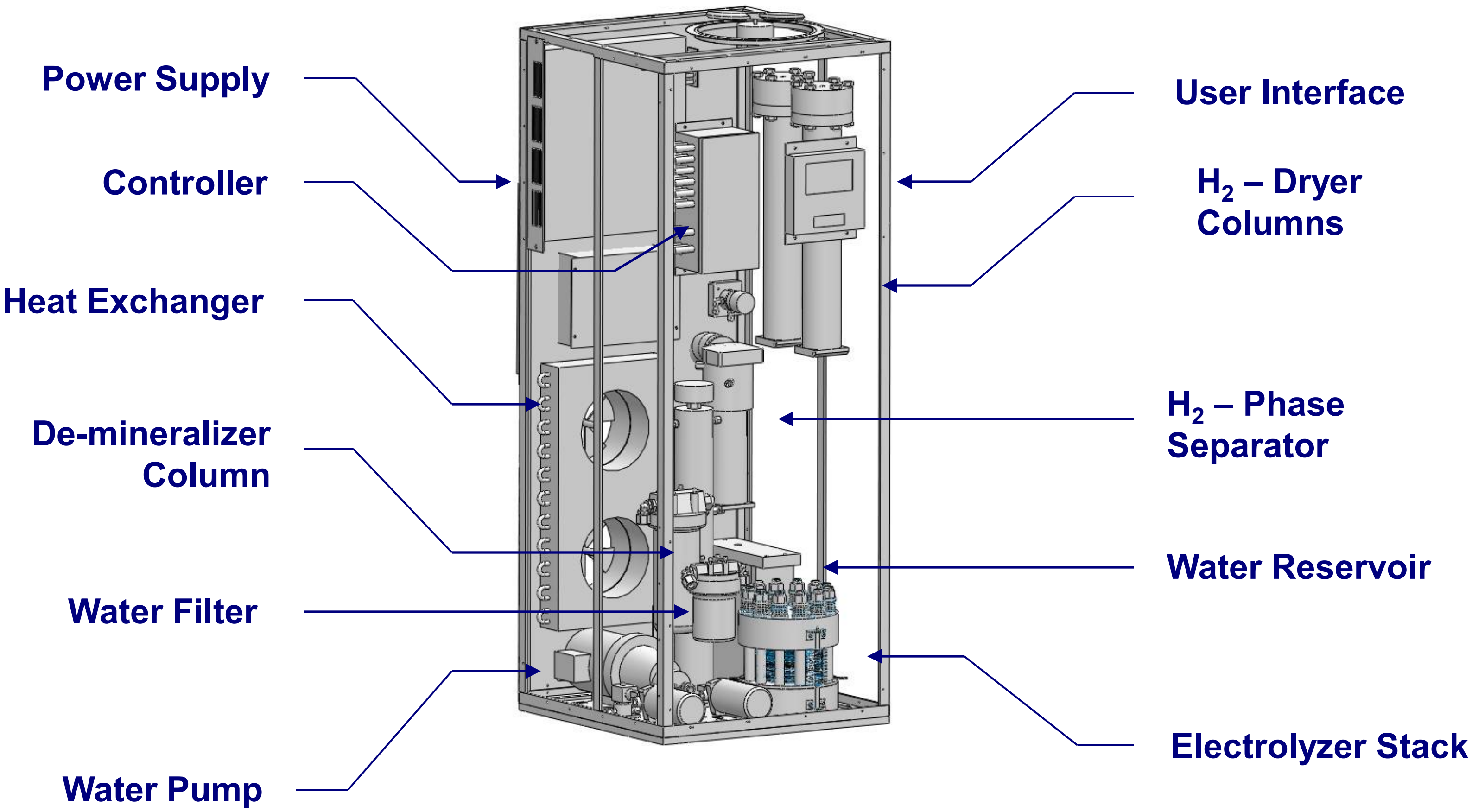
- P&ID, PFD, Control Diagrams
  - Equipment and Flow Paths Determined
  - Instrumentation Selected
  - Flow Rates and Conditions Calculated
- Safety review complete
- System BOP components identified
- System layout initiated
- Hydrogen-dryer analysis complete

## System Design Specifications



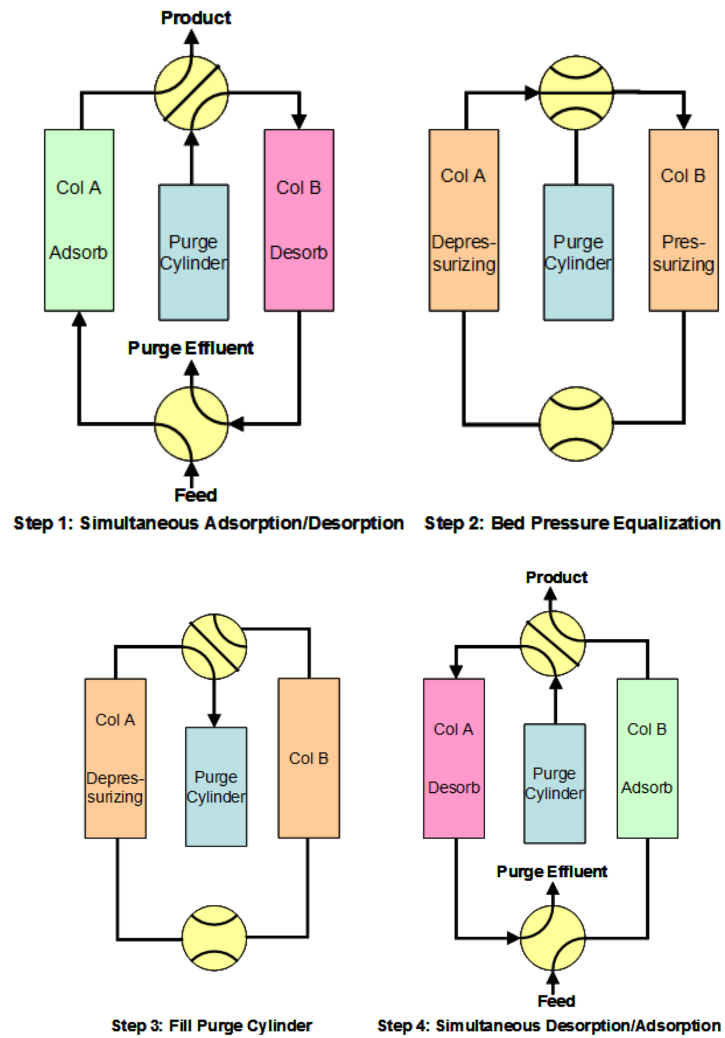
| | |
|---|---|
| **Production Rate** | 41.6g $H_2$/hr<br>(0.5 kg over 12 hours) |
| **Operating Pressure** | 5000 psid ;<br>$H_2$ 5000 psig; $O_2$ atm |
| **Operating Temperature** | 80°C |
| **Membrane** | DSM-PFSA<br>7-20 mil |
| **Stack Size** | 50 cm²/cell<br>10 Cells |
| **Stack Current Density** | 1200-1900 mA/cm² |

# Progress: System Layout



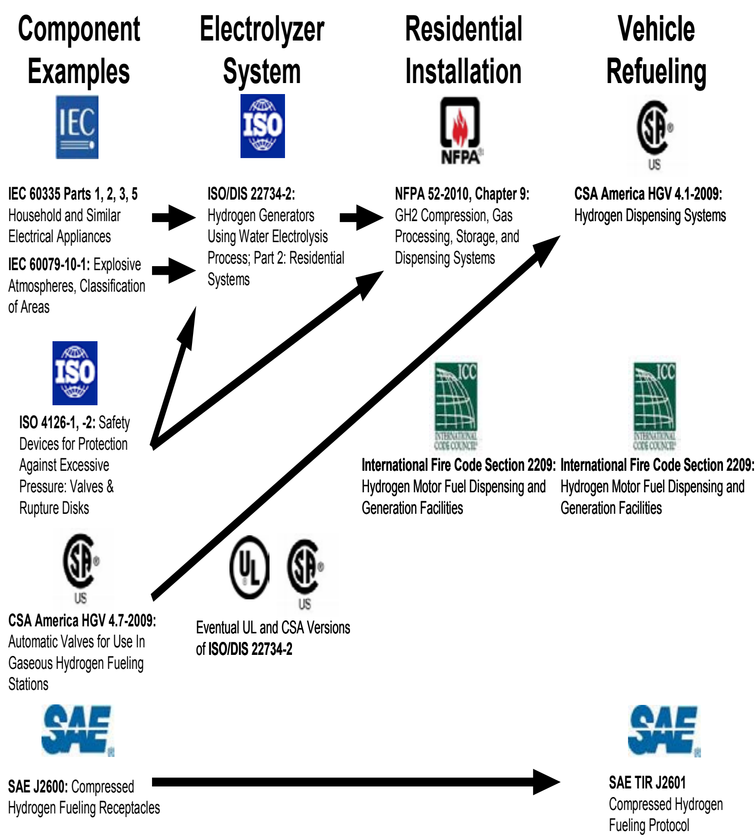
# Progress: Hydrogen Dryer Optimization

- Reduced hydrogen drying requirements at 5000 psi
  - A single desiccant dryer column is sufficient for Home Refueling Unit
- Investigating use of regenerative $H_2$-dryers to reduce maintenance and user intervention (safety) in larger units
- Dual column regenerative $H_2$-dryers typical loss is 3 to 4% H2 (see Work conducted under DOE program PD030)
- Improved regeneration drying cycle similar to that used in adsorption of carbon dioxide in manned spacecraft[1]
  - Reduces hydrogen losses by 50% as compared to conventional $H_2$ regenerative dryers




[1]http://hdl.handle.net/2060/19680012458

# Progress: Safety Codes Pertinent to Residential Hydrogen Refueling Systems



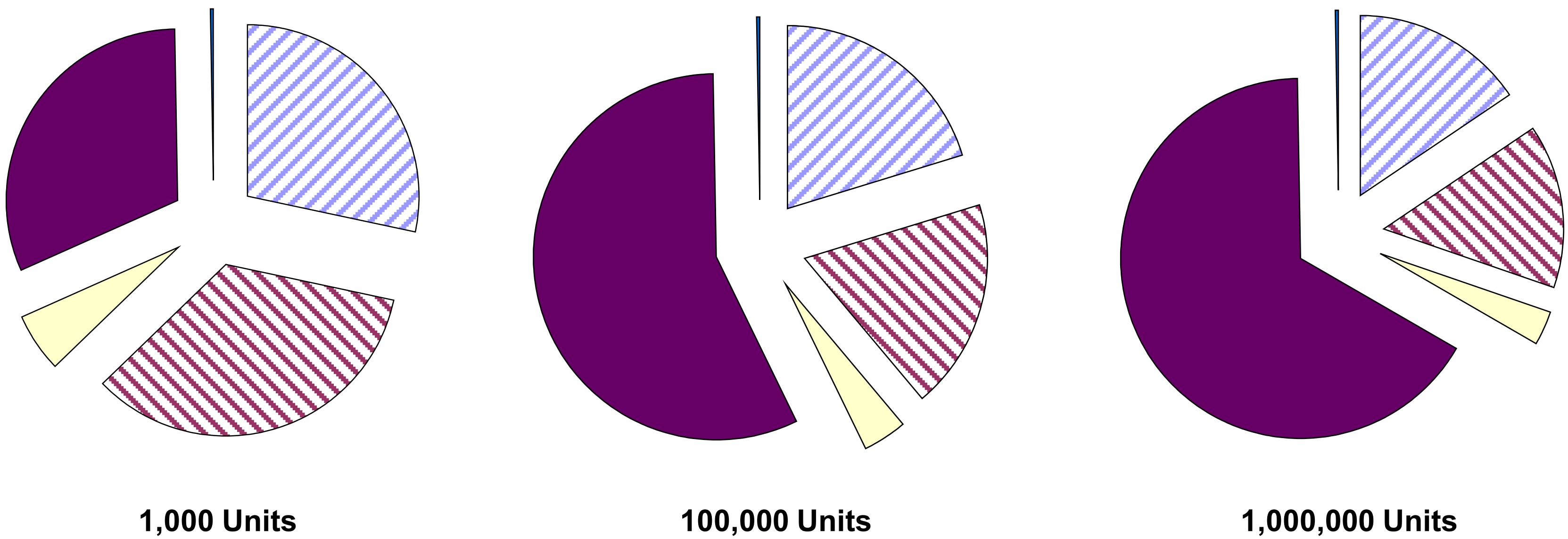

- Prof. Zalosh – $H_2$ safety expert
- Reviewed National & International Codes & Standards
- Giner Invited to Contribute Comments to ISO/DIS 22734-2 Draft
- Issues
  - NFPA 52-2100, Chapter 9 (no indoor refueling)
  - International fire code – no impediment to indoor refueling
  - NFPA will be approached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

# Additional Codes/Standards

- Residential Installation and Vehicle Refueling
  - NFPA 55, Standard for Storage, Use and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders and Tanks
  - International Fire Code Section 3005, Use and Handling of Compressed Gases
  - International Fire Code Section 3503, General Requirements, Flammable Gases
  - CGA G-5.4, Standard for Hydrogen Piping Systems at Consumer Locations (Compressed Gas Association)
  - CGA G-5.5, Hydrogen Vent Systems (Compressed Gas Association)
  - SAE J2600, Compressed Hydrogen Surface Vehicle Refueling Connection Devices
  - ISO 17268:2006, Gaseous Hydrogen Land Vehicle Refueling Connection Devices
- Additional Codes Need Consideration
  - Proposed ASTM Analysis Methods for Hydrogen Purity, etc.

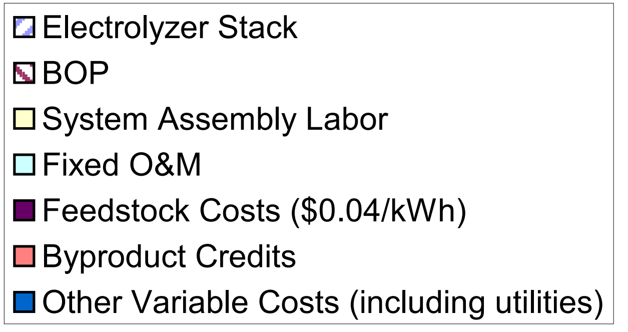
# Design Progress: Projected $H_2$ Cost

## H2A Model Analysis (Forecourt Model rev 2.1.1)




- Design capacity: 1 kg $H_2$/day
- Operating Capacity Factor: 64%
- Single stack/unit

- $H_2$ 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
  - Review of applicable codes and standards
  - Assist with HAZOP/FMEA safety analysis
- IAS, Inc.
  - Vendor
  - For-profit company
  - Will develop low-cost controller prototypes
  - Will assist with control system development and projecting production costs
- GES, LLC (DOE Cost-Shared Grant DE-FC36-08GO18065)
  - Same Company
  - For-profit company
  - Within DOE $H_2$ program
  - Multiple overlapping components and subsystems [also Parker, 3-M (NSTF Catalyst & Membrane) and Entegris (Carbon Cell Separators)]
- GES, LLC (Government and Private Electrolyzer Development Programs)
  - Same Company
  - For-profit company
  - Outside DOE $H_2$ program
  - Several NASA programs, one DARPA Prime Contractor, electrolyzers for several private companies

# Proposed Future Work (This Year and Next)

- Complete detailed HAZOP/FMEA Analysis of Hydrogen Refueling Appliance
- Assemble and Test Full-Scale Electrolyzer Stack
- Complete Design, Fabrication & Demonstration of Unitized HRA System Components
- Build/Test 5,000 psig Home Refueling Appliance (HRA)
- Preliminary Design and Economic Analysis of Commercial HRA System

# Summary

- Innovative Stack & System Design
  - No compressors or gas storage required
  - Reduces costs (capital, operating & maintenance)
- Innovative High-Strength Low-Permeability Supported Membrane Required
  - Advanced DSM™
  - Customized for 5,000 psi operation
    - Improved reliability, safety, efficiency
- Testing Progress
  - 2,000 psi electrolysis testing complete
  - 5,000 psi stack hardware evaluation complete
- "Unitized" Breadboard HRA System Design Complete
  - Procurement and fabrication of BOP initiated
- Hydrogen Costs Meet DOE Target of $2 - $4/kg
  - Will require significant sales volumes