2013 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

Timeline

- **Project Start:** Aug 2010
- **Project End:** June 2013
- **Percent Complete:** 95

Budget

- **Total Project Budget: $999K**
  - **Funding Received in FY11:** $499K
  - **Funding Received in FY12/13: 0K (Program Completely Funded)**

Barriers

Hydrogen Generation by Water Electrolysis

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

Technical Targets: Based on Distributed Forecourt Water Electrolysis[1]

Characteristics	Units	2015	2020	Giner Status (2013)
Hydrogen Levelized Cost[2]	\$/kg-H_2	3.90	<2.30	4.64
Electrolyzer Cap. Cost	\$/kg-H_2	0.50	0.50	1.05
Stack Efficiency	%LHV (kWh/kg)	76 (44)	77 (43)	72[3] (47)[3]

[1] 2012 MYRDD Plan. [2]Production Only. Utilizing H2A Ver.3 (Electric costs assumed to be \$0.069/kWh in 2015 case; \$0.037/kWh in 2020) . [3] Isothermal Compression at 5,000 psig adds ~5kWh/kg

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 user end site
- Eliminate need for mechanical hydrogen compression

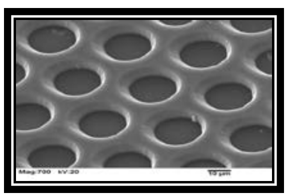
Impact

- 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

2012-13 Milestones

		Tasks	Progress Notes	% Complete
Membrane Evaluations	Task 1 & 3	■Membrane Evaluations □ Fabricate supported membranes for high-pressure operation □ DSM (Dimensionally Stable Membrane) □ Determine voltage and current (faradaic) efficiencies □ Establish models to determine optimal membrane and operating conditions	■Completed fabrication of innovative membranes for high pressure operation ■DSM membranes exhibit high mechanical stability and improved performance under pressurized conditions ■Completed modeling based on membrane performance data ■Determined cost of compressing hydrogen directly in stack	100%
Electrolyzer Cell & Stack-Design	Task 3 & 4	■Design, Build, and Test Electrolyzer Stack ■Utilize low-cost components in stack design ■Evaluate stack operation at 5,000 psig	■High pressure stack design complete ■Reinforcement rings utilized to maintain low-cost stack design ■Multi-cell Stack Assembled (20 cells) ■Successfully pressure tested stack to 6250 psi (1.2X operating pressure) ■**Successfully operated stack at 5,000 psig**	100%
Prototype System	Task 2, 5-9	■T2: Complete Detailed Analysis of Hydrogen Safety Codes and Standards	■Completed HAZOP/FMEA	100%
		■T5:Design/Build/Test 5,000 psig H2-Dryer ■T6-T7: Design/Build PEM Electrolyzer HRA system ■T8:Demonstrate Performance and Durability of “Unitized” Breadboard HRA System ■T9:Preliminary Design and Economic Analysis of Commercial HRA System	■System design completed and assembled ■System successfully operated at 5,000 psig ■Life test evaluations of system/stack at high pressure operation ongoing	80%

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

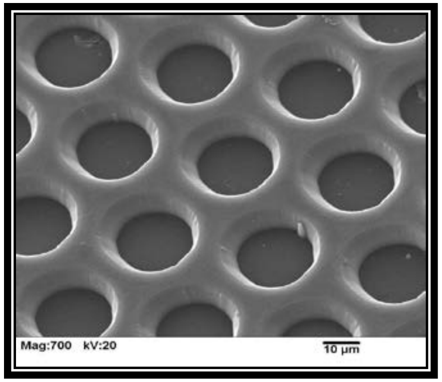


Figure 1. Scanning Electron Microscope (SEM) micrograph of the polymer membrane support structure with definable straight hole pattern

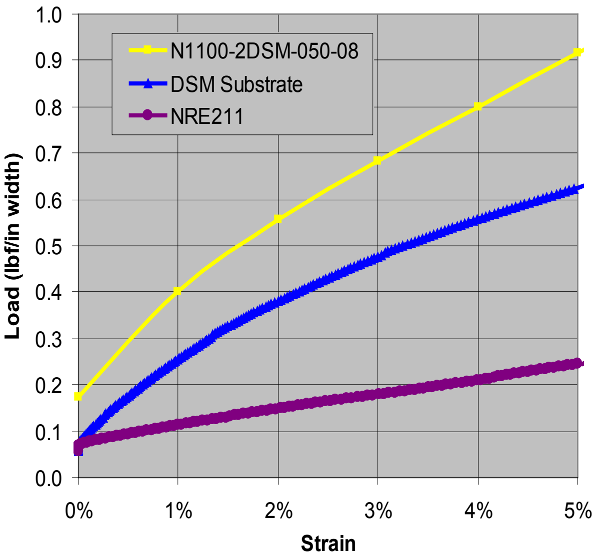
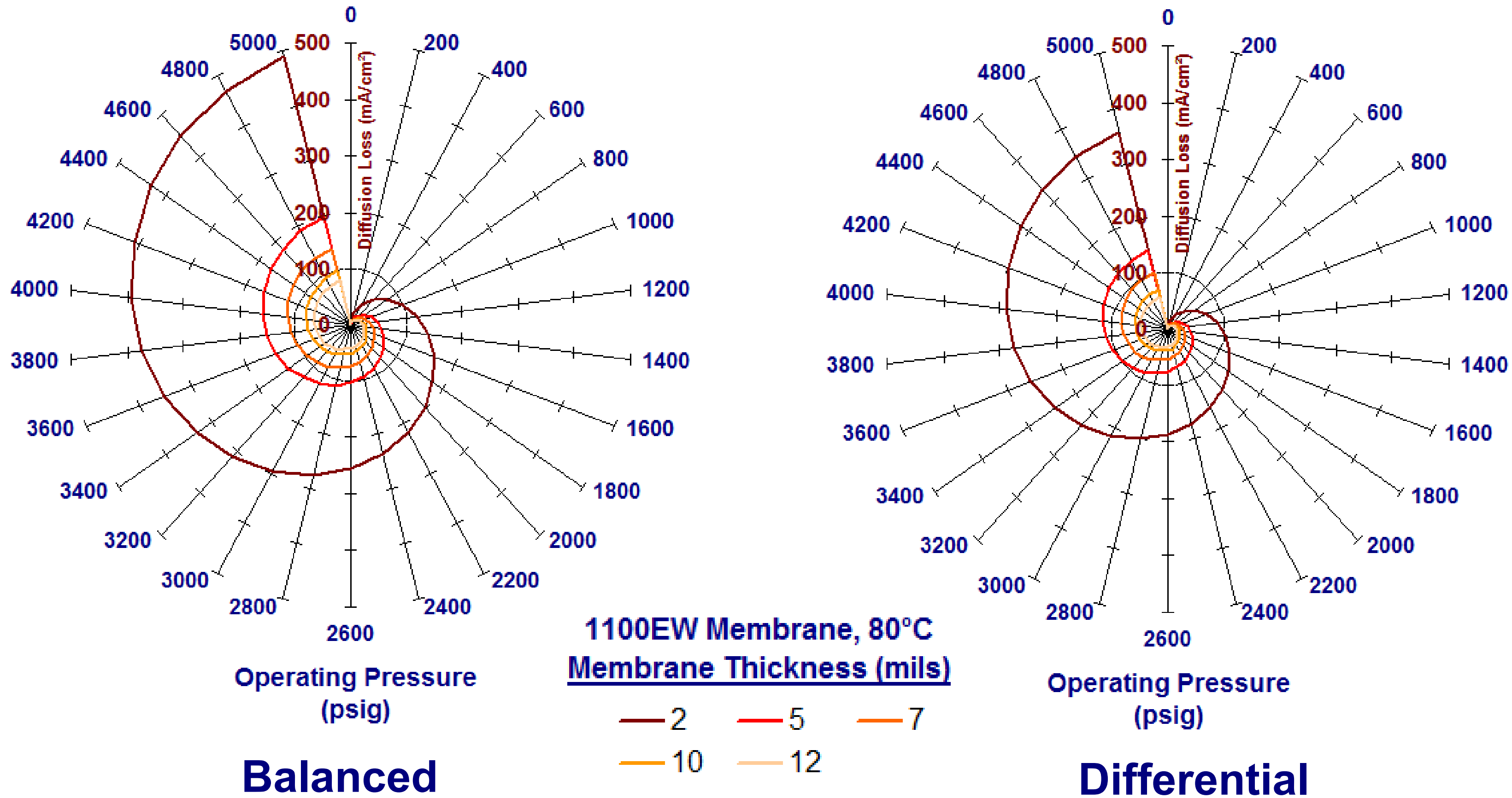


Figure 2. Dynamic Mechanical Analysis (DMA) shows the increased tensile strength of the DSM™ versus its components (wet at 80°C)

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

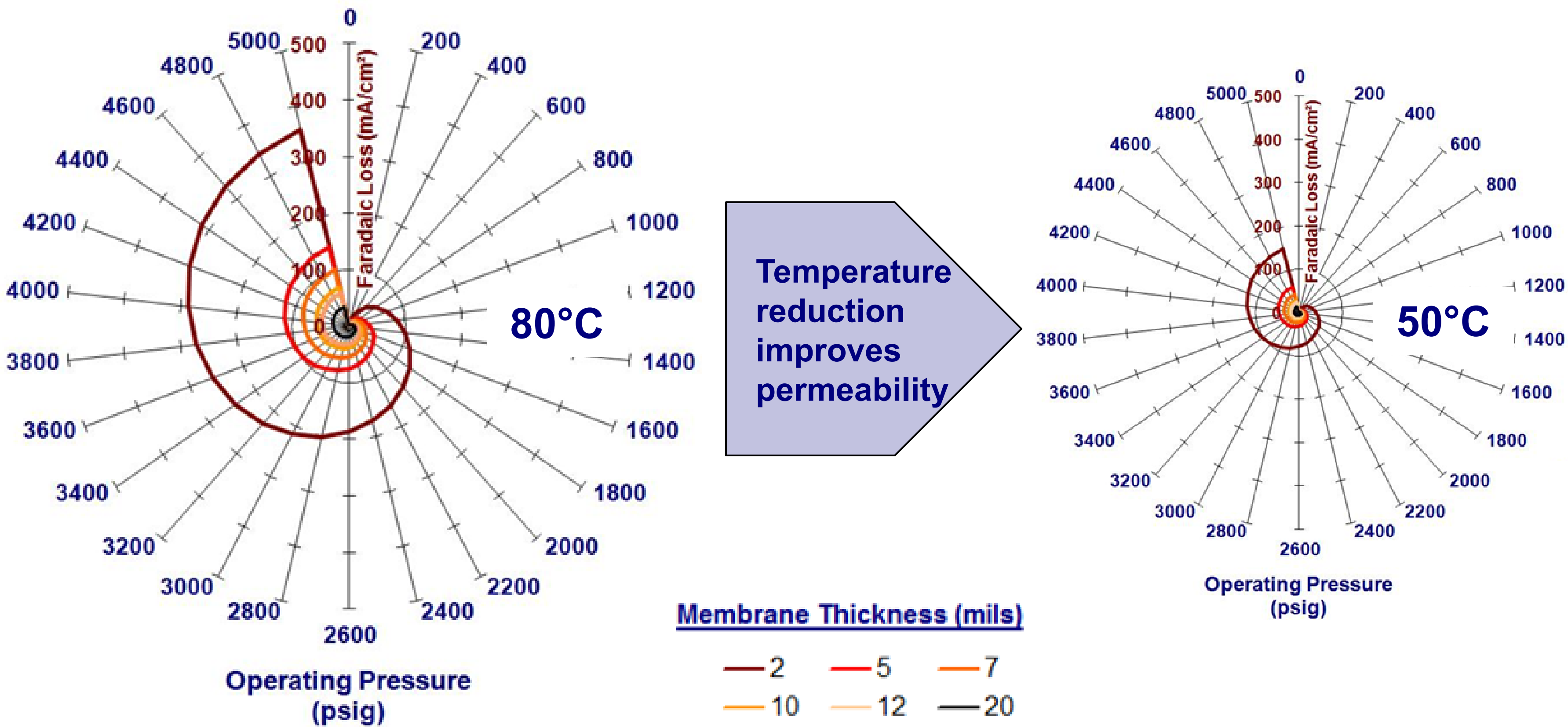
Pressure vs. Diffusion (H_2/O_2 Cross-Over)



- Faradaic efficiency models created based on collected data
  - Significant gain in faradaic efficiencies in differential-pressure operating mode as a result of reduced gas cross-over

Progress: Membrane: Faradaic Efficiency:

Differential Pressure Operation & Temperature

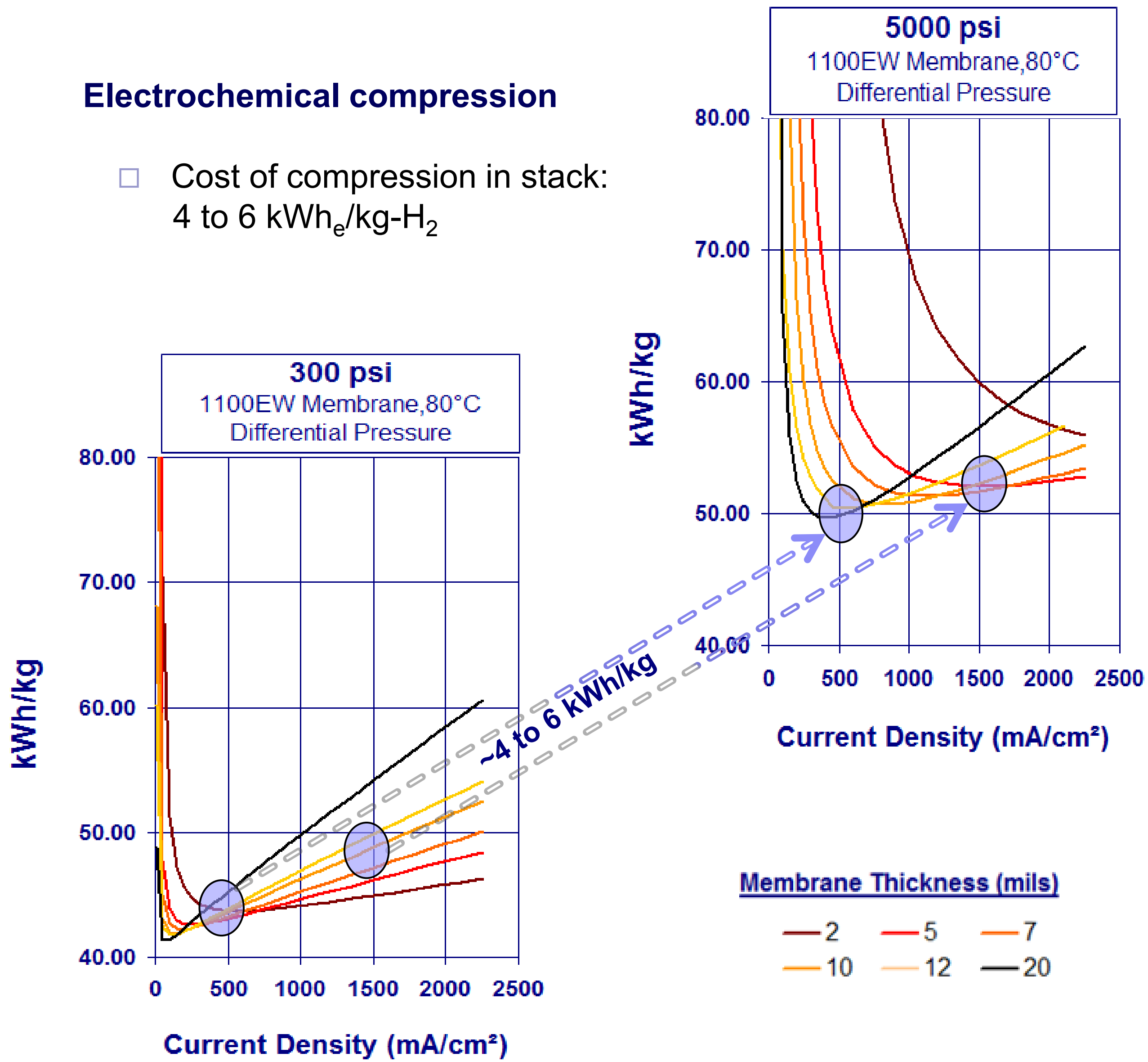


- Faradaic Efficiency highly dependent on membrane thickness, operating pressure and temperature
- Gas diffusion losses are lower in differential-pressure operating
- Similar faradaic losses in PEM fuel cells and electrochemical H_2 compressors under same operating conditions & membrane selection

Stack Efficiency: High Pressure Operation

Electrochemical compression

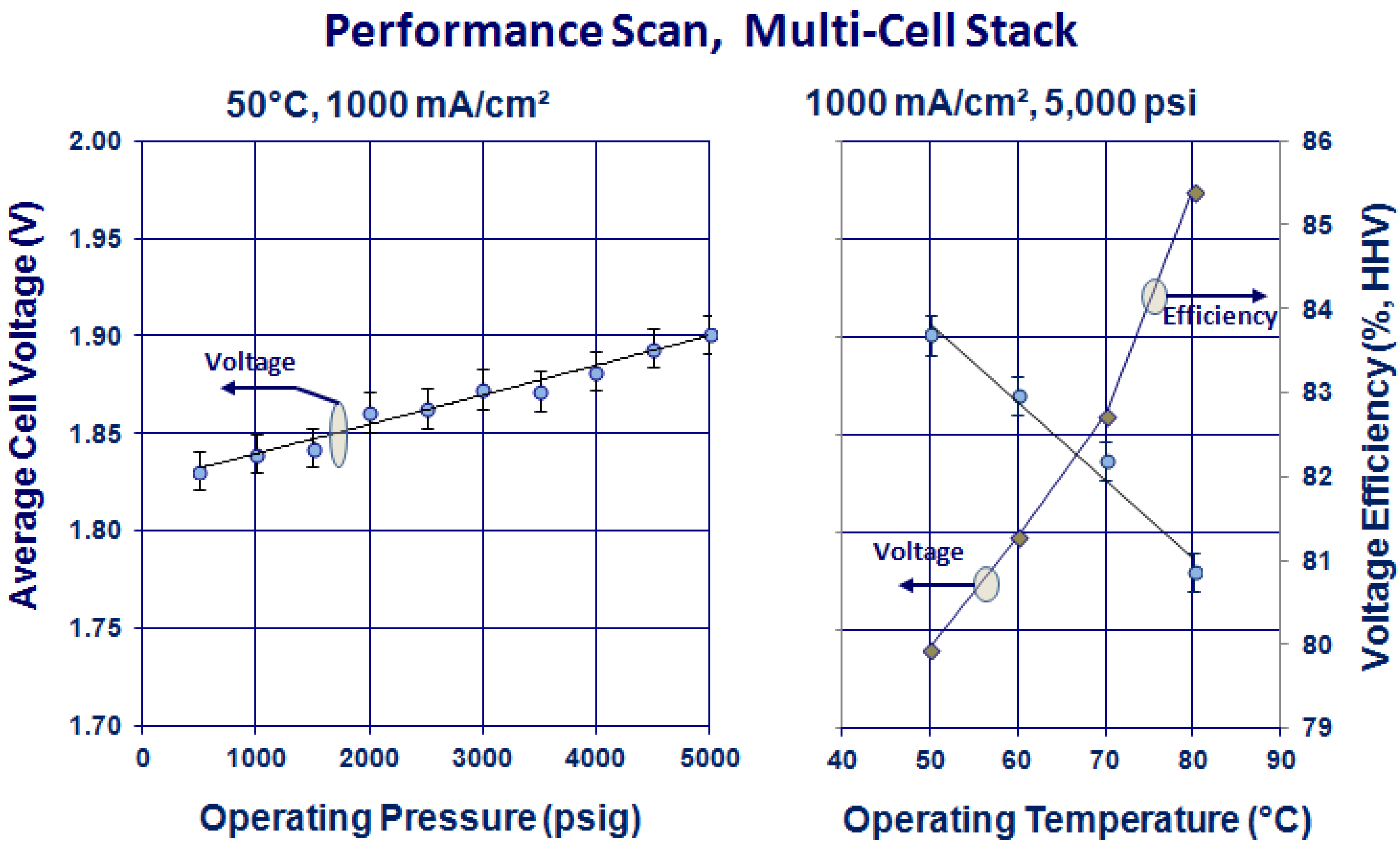
- Cost of compression in stack: 4 to 6 $kWh_e/kg\text{-}H_2$



DSM Membrane Fabrication

- At high pressure operation (5000 psi), thicker membranes provide higher faradaic efficiency but lower voltage efficiency
- 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
- Multi-cell electrolysis evaluation at 5,000 psi

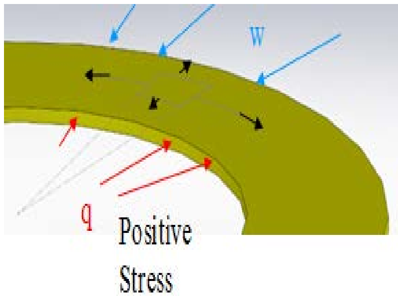
Progress: Membrane: Voltage Efficiency:
Evaluation and Optimization

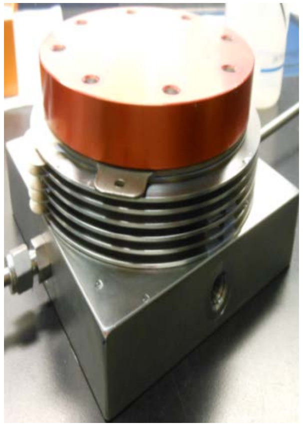


- Membrane testing conducted in finalized high-pressure stack hardware

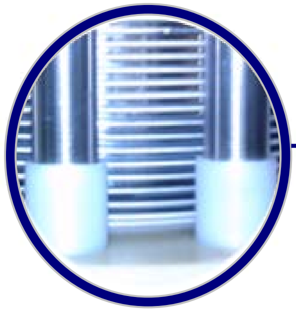
Progress: Electrolyzer Cell/Stack Design

- Cell Frame analysis
  - Outer cell-frame hoop-stress and clamping force analysis complete
  - Cell frame designs include use of outer reinforcement ring
    - Eliminates Dome enclosure with improved cell frame design
    - Enables use of low-cost stack components
- 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
- Stack proof pressure tested to 6250 psig operating pressure
- Final stack assembly includes use of round fluid endplates





Evaluation Hardware

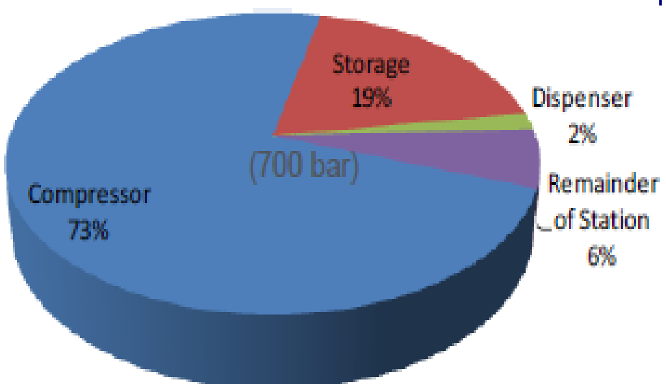


Cell-Frame Reinforcement Ring

Final Hardware (20-Cell Stack)

Challenges: Stack Operating Pressures

Generating Hydrogen at high pressure eliminates need for mechanical compressor



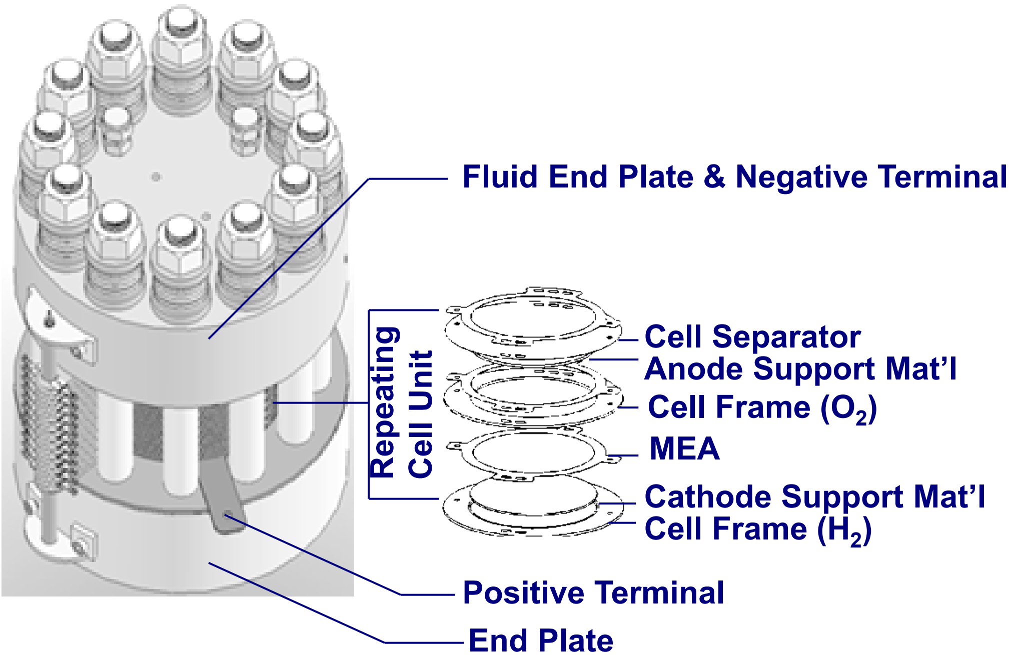
CSD Costs
2010 Refueling Station (2010 Technology)[1]

[1]http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fy13_budget_request_rollout.pdf

5,000 psi
Multi-Cell Stack
PEM-based
Electrolyzer Stack

Hydrogen at 5,000 psig
(Ambient O_2)
Generated directly in
PEM Electrolyzer

Stack Progress: Advancements & Cost Reductions



The repeating cell unit comprises >90% of electrolyzer stack cost

Stack Improvements

Stack Cost Reductions

- **Utilizing containment ring enables use of low-cost stack (*see PD030 low-cost stack*)**
  - Reduced Part Count from 41 to 10 Parts/Cell-50% labor reduction
  - Pressure Pad: Sub-assembly eliminated
  - Molded Thermoplastic Cell Frames
  - Carbon/Ti Cell-Separators
  - DSM MEAs fabricated w/chem-etch supports- 90% cost reduction
  - **Stack designed to accommodate high multi-cell count (50 cells/stack)**

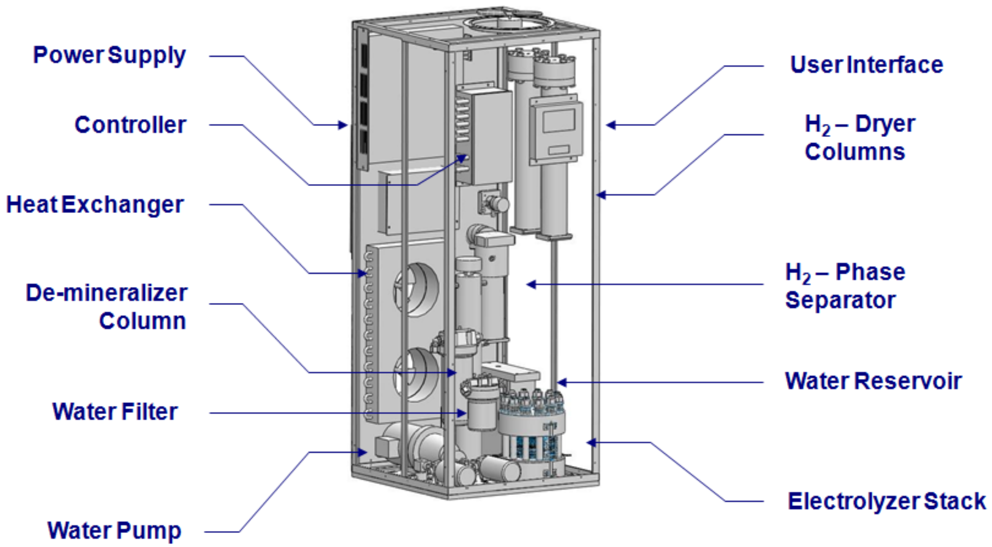
Progress: System

System Assembly Completed

- P&ID, PFD, Control Diagrams
- Safety review complete
- Hydrogen-dryer analysis complete
- High efficiency BOP components selected

System Design Specifications	
Dimensions	Dimensions: 5.5′ tall x 2.5′ long x 2.5′′ wide
Production Rate	Minimum: 41g H_2/hr (0.49 kg per 12 hour period) Maximum: 56g H_2/hr (0.67 kg per 12 hour period)
Operating Pressure	H_2O to 5000 psig; O_2 atm
Operating Temperature	50-80°C
Membrane	DSM-PFSA 7mil
Stack spec	20 Cells Utilizes low cost stack components (See PD030)
Stack Current Density	1200-1600 mA/cm²

Progress: System



- Adjustable operating pressure (up to 6,000 psig)
- Replaceable desiccant dryer
- No gas storage requirement
- Eliminated stack enclosure (Dome)
- Safety features include:
  - Cabinet ventilation. Electrical lockouts. Hydrogen detector. Over-pressure release. High temperature, and low/high cell voltage shut down. Flash arrestor.
- Blue tooth accessible
  - System can be controlled/monitored from 30ft distance

System Progress: Efficiency

Stack Current Density

Hydrogen Production & Losses	Units	1200 mA/cm²	1600 mA/cm²
Stack H_2-Production	kg-H_2/hr	0.0448	0.0597
Membrane permeation losses (@60°C)	kg-H_2/hr	-0.0023 (-5.1%)	-0.0023 (-3.8%)
Phase-Separator (-0.14%)	kg-H_2/hr	-0.0009	-0.0013
H_2-Dryer (desiccant dryer)	kg-H_2/hr	0.0000	0.0000
Total H_2-Production	kg-H_2/hr	**0.0416**	**0.0561**

Power Consumption	Units	1200 mA/cm²	1600 mA/cm²
Electrolyzer Stack	kW_e	**2.28**	**3.21**
DC power supply & control (87% eff.)	kW_e	+0.286	+0.390
PLC Rack & sensors	kW_e	0.05	0.05
Electrolyzer Water Pump	kW_e	0.20	0.20
Heat exchanger fans	kW_e	0.03	0.03
H_2-Dryer	kW_e	0.0	0.0
Total Power Consumption (w/Dryer)	kW_e	**2.76**	**3.67**

Overall Efficiencies	Units	1200 mA/cm²	1600 mA/cm²
Electrolyzer Stack (includes permeation)	kWh_e/kg	**51.8**	**52.2**
System	kWh_e/kg	**66.3**	**65.4**

Operating Range: 1200-1600 mA/cm², 60°C

Permeation Losses

Permeation Losses as percentage of product

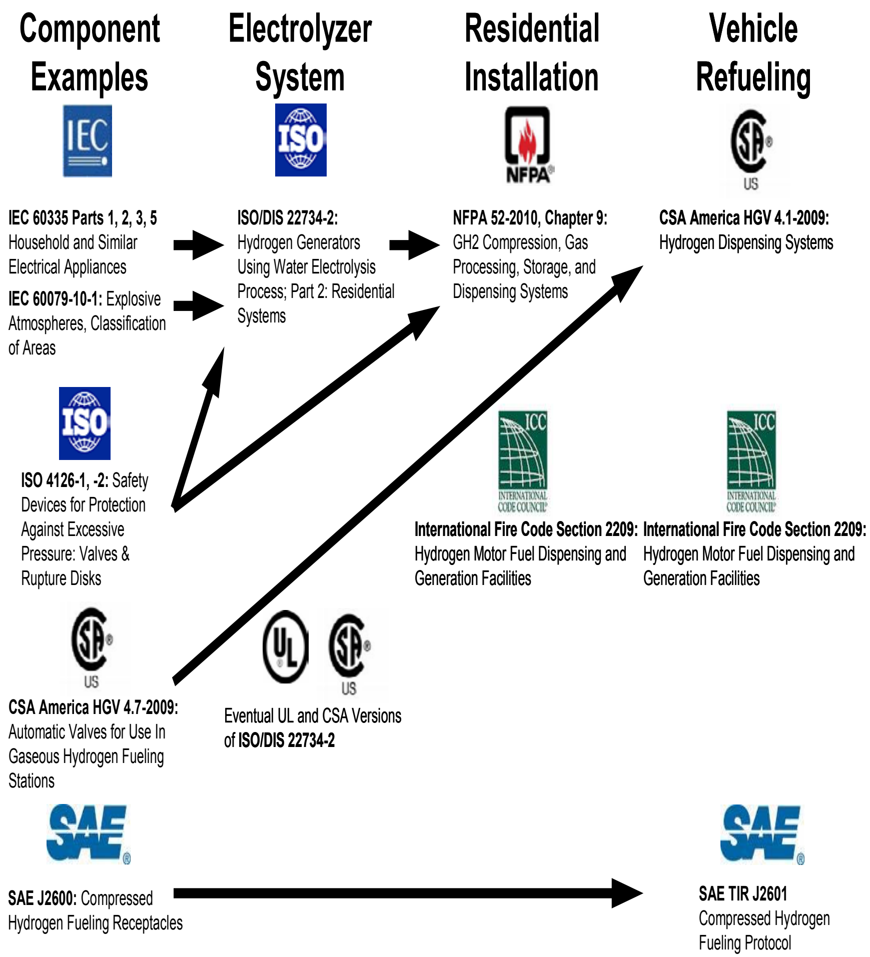
Regenerative H2-Dryer not required for low flows. Two (2) replaceable desiccant columns used for drying

Off-the-shelf Power Supply adds 6.9 kWh_e/kg-H_2

Permeation losses @ 5,000 psig & 60°C add:
5.1 kWh_e/kg-H_2 at 1200 mA/cm², (46.7 kWh_e/kg @ 0 psi)
3.8 kWh_e/kg-H_2 at 1600 mA/cm², (48.6 kWh_e/kg @ 0 psi)

Power Supply inefficiency adds ~7.0 kW_e/kg-H_2 (State of the art @ 96% efficiencies can reduce this to ~2.0 kW_e/kg-H_2)

Progress: Safety Codes Pertinent to Residential Hydrogen Refueling Systems

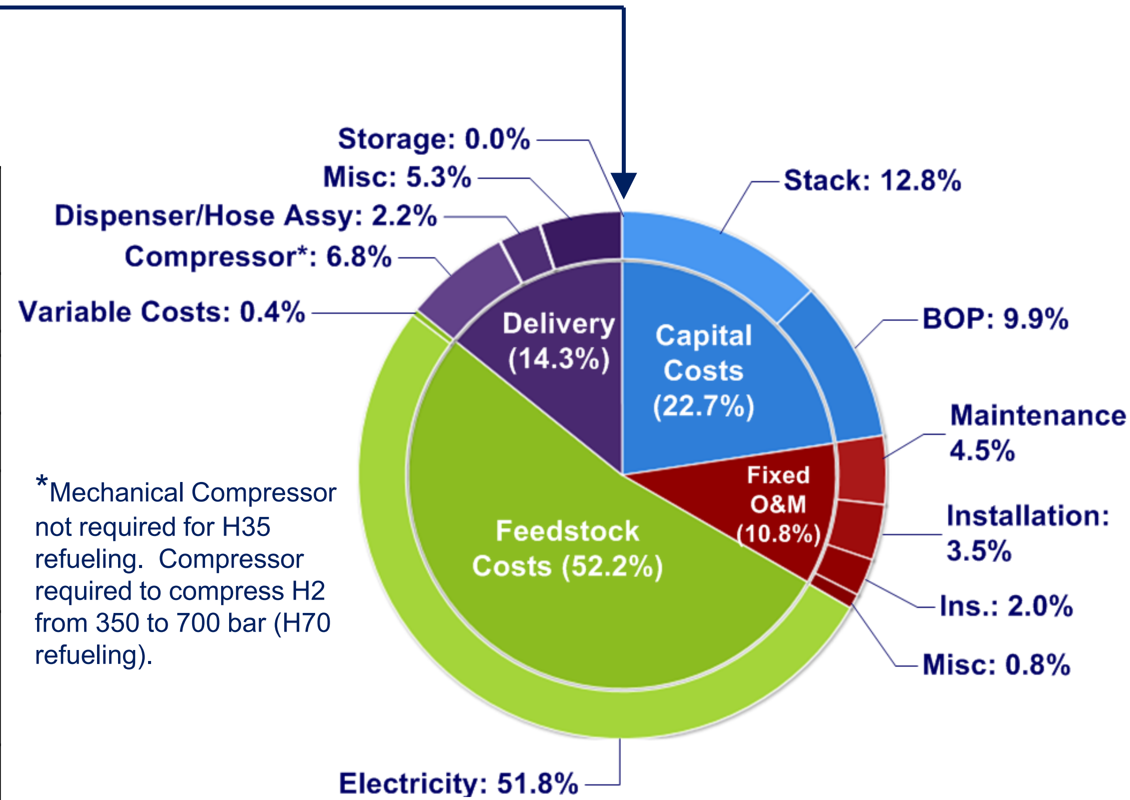


- Prof. Zalosh – H_2 safety expert
- Reviewed National & International Codes & Standards
- Giner Contributes Comments to ISO/DIS 22734-2:2011
  - Defines the construction, safety and performance requirements of packaged hydrogen gas generation appliances
  - ISO 22734-2:2011 is applicable to hydrogen generators intended for indoor and outdoor residential use in sheltered areas, such as car-ports, garages, utility rooms and similar areas of a residence
  - Not Applicable to generators that supply Oxygen as a product

Projected H_2 Cost

Based on Forecourt H2A Model (Ver. 3.0)

H_2 Production Cost Contribution	**DOE Target (2020)**	**Home Refueler (2013)**
Capital Costs	$0.50	$1.05
Fixed O&M	$0.20	$0.50
Feedstock Costs System Efficiency: 65 kWh_e/kg -H_2	$1.60 **($0.037/kW)**	$2.40 ($0.037/kW)
Other Variable Costs (including utilities)	<$0.10	$0.02
***Total Hydrogen Production Cost* ($/kg)**	**2.30**	**3.98**
Delivery (CSD)	$1.70	$0.66 (5,000 psig output, no Storage or Forecourt Station Requirements)
***Total Hydrogen Production Cost* ($/kg)**	**<4.00**	**4.64**



*Mechanical Compressor not required for H35 refueling. Compressor required to compress H2 from 350 to 700 bar (H70 refueling).

- H2A Ver. 3 includes higher installation costs and higher pressure requirement for H70 hydrogen refueling
  - Hydrogen pressure requirement 12,688 psig (previously 6,250 psig)
- **Progress inline with achieving *new* 2020 Target of <$4.00/kg-$H_2$**
  - Delivery: No Storage (or *forecourt* station costs)
  - Can achieve <$4.00 kg/$H_2$ for 5,000 psig vehicle refueling
  - Improving stack output pressure to 12,000 psig is required to meet 2020 target for H70 refueling

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

- Program Near Completion
  - Continue Stack/System life testing in current system
    - Optimization studies
- Future considerations
  - Assemble and test 50-cell, 5,000 psig electrolyzer stack
  - Develop membranes with reduced permeability

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^{TM}
  - Customized for 5,000 psi operation
    - Improved reliability & stability, safety, efficiency
- Testing Progress
  - 5,000 psig stack hardware assembly and evaluation complete
- "Unitized" Breadboard HRA System Design & Fabrication Complete
  - 5,000 psig Operation with 20-cell stack
- Hydrogen Costs Meet DOE Target of $4/kg for H35 refueling. H70 refueling will required higher pressure stacks and system components