2011 Hydrogen Program

Annual Merit Review Meeting

PEM Electrolyzer Incorporating an Advanced Low Cost Membrane

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Project ID# PD030

Overview

Timeline

- **Project Start:** May 2008
- **Project End:** April 2011
- **Percent Complete:** 74

Budget

- **Total Project Budget: $2.49M**
  - **DOE Share:** $1.99M
  - **Cost Share:** $0.51M
  - **FY10 Funding**
    - **DOE: $550K**
  - **FY11 Funding**
    - **DOE:** $550K

Barriers

Hydrogen Generation by Water Electrolysis

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

DOE Targets: Distributed Water Electrolysis

Characteristics/units	2006	2012	2017-2020	GES Status (2011)
Hydrogen Cost ($/kg-$H_2$)	4.80	3.70	2.00 - 4.00	4.66
Electrolyzer Cap. Cost ($/kg-$H_2$)	1.20	0.70	0.30	0.60
Electrolyzer Efficiency %LHV (%HHV)	62 (73)	69 (82)	74 (87)	75.1 (88.8)

Partners

- **Parker Hannifin Corporation (Industry)**– System Development
- **Virginia Tech University (Academic)**– Membrane Development

Collaborations

- **3M Fuel Cell Components Program**– NSTF Catalyst & Membrane
- **Entegris** – Carbon Cell Separators
- **Tokuyama** – Low-Cost Membrane
- **Prof. R. Zalosh (WPI)** – Hydrogen Safety Codes

Relevance/Project Objectives

Overall Project Objectives

- Develop and demonstrate advanced low-cost, moderate-pressure PEM water electrolyzer system to meet DOE targets for distributed electrolysis.
  - Develop high efficiency, low cost membrane
  - Develop long-life cell-separator
  - Develop lower-cost prototype electrolyzer stack & system

Relevance

- Successfully developing a low-cost hydrogen generator will enable early adoption of fuel cell vehicles

FY 2010-11 Objectives

- Fabricate scaled-up stack components (DSM, cell-separators)
- Assembly electrolyzer stack/system
- Install electrolyzer stack into system & evaluate
- Deliver and Demonstrate prototype electrolyzer system at NREL

Low-Cost Electrolyzer Stack

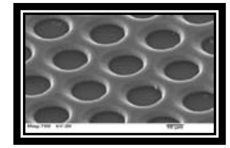
Milestones

	Go/No Go Decision Points	Progress Notes	%Complete
Membrane	■Demonstrate DSM membrane performance comparable to or better than that of Nafion®1135 at 80°C ■Demonstrate electrolyzer lifetime with DSM membrane (80°C ≥ 1000 hrs) ■Scale-up DSM membrane to 290cm² & Evaluate in short stack for 1000 hours	■Performance DSM > Nafion®1135 = Nafion®112, Completed 1000 hrs @ 80°C. ■Testing indicates low membrane degradation rate, high life expectancy ■Operated 5-cell for 1000-hours, Single-cell; > 2800+ hours. Use of chemically-etched DSM supports for further cost reduction.	**100%** (Mar-09) **100%** (Mar-09) **100%** (Dec-10)
Membrane	■Indentify new low-cost membranes for PEM-based electrolyzers , new low-cost catalysts	■Tokuyama hydrocarbon membranes under evaluation, 3M catalyst evaluated	**10%**
Cell Separator	■Demonstrate performance comparable to dual-layer Ti separator ■Scale-up Carbon/Ti cell-separator to 290-cm² ■Evaluate in short stack for 1000 hours.	■Operated 290-cm² cell-separators in 5-cell for 1000-hours. H_2-embrittlement testing confirms longevity of Carbon/Titanium cell-separators	**100%** (Dec-10)
Cell Separator	■Indentify & evaluate new low-cost Carbon materials for cell-separators	■Initiated ivestigation of low-cost carbon for future cost reductions	**20%**
Stack/System Development	■Complete preliminary design review	■Completed: P&ID, PFD, control diagrams, safety review, FMEA, system layout and packaging drawings	**100%** (Dec-09)
Stack/System Development	■Complete Stack & System assembly ■Evaluate efficiency of Stack & System ■Complete critical design review of system ■Evaluate thin frame design for further cost reduction of electrolyzer Stack.	■Electrolyzer stack fabricated. System near completion. ■Thin frames fabricated and tested in 160-cm² hardware.	**25%**

Membrane Development Approach

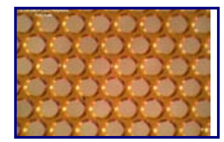
DSM Membrane-GES

- PFSA ionomer incorporated in an engineering plastic support
  - High-strength
  - High-efficiency
  - No x-y dimensional changes upon wet/dry or freeze-thaw cycling
  - Superior to PTFE based supports



Laser Drilled

x10 cost reduction

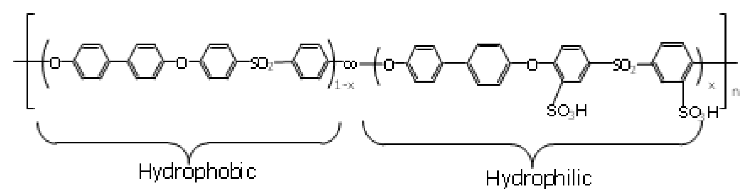


Chemically Etched

DSM Supports

Bi-Phenyl Sulfone Membrane-VT

- Hydrocarbon Membranes
  - Inexpensive starting materials
  - Trade-off between conductivity and mechanical properties



Bi-Phenyl Sulfone, H form (BPSH)

Alternative Membranes

- PFSA (850EW) Membrane-3M
- Hydrocarbon Membrane- Tokuyama

Approach is to optimize membrane ionomer EW and thickness, scale-up fabrication methods and techniques, and improve costs

High Durability Cell-Separator Approach

- **Requirements**
  - Gas-impermeable (separates H_2 and O_2 compartments)
  - High electrical conductivity and high surface conductivity
  - Resistant to hydrogen embrittlement
  - Stable in oxidizing environment
  - Low-Cost
- **Legacy Design**
  - Multi-Layer piece consisting of Zr on hydrogen side and Nb on oxygen side
- **Single or Dual-Layer Ti separators**
  - Ti subject to hydrogen embrittlement
  - Lifetime limited to <5000 hours, depending on pressure and operating conditions
- **Approach**
  - Develop a new low-cost dual-layer structure
    - Evaluate methods of bonding dissimilar metal films
    - Evaluate non-metal substrate with conductive coating

Hydrogen embrittlement in titanium cell-separators

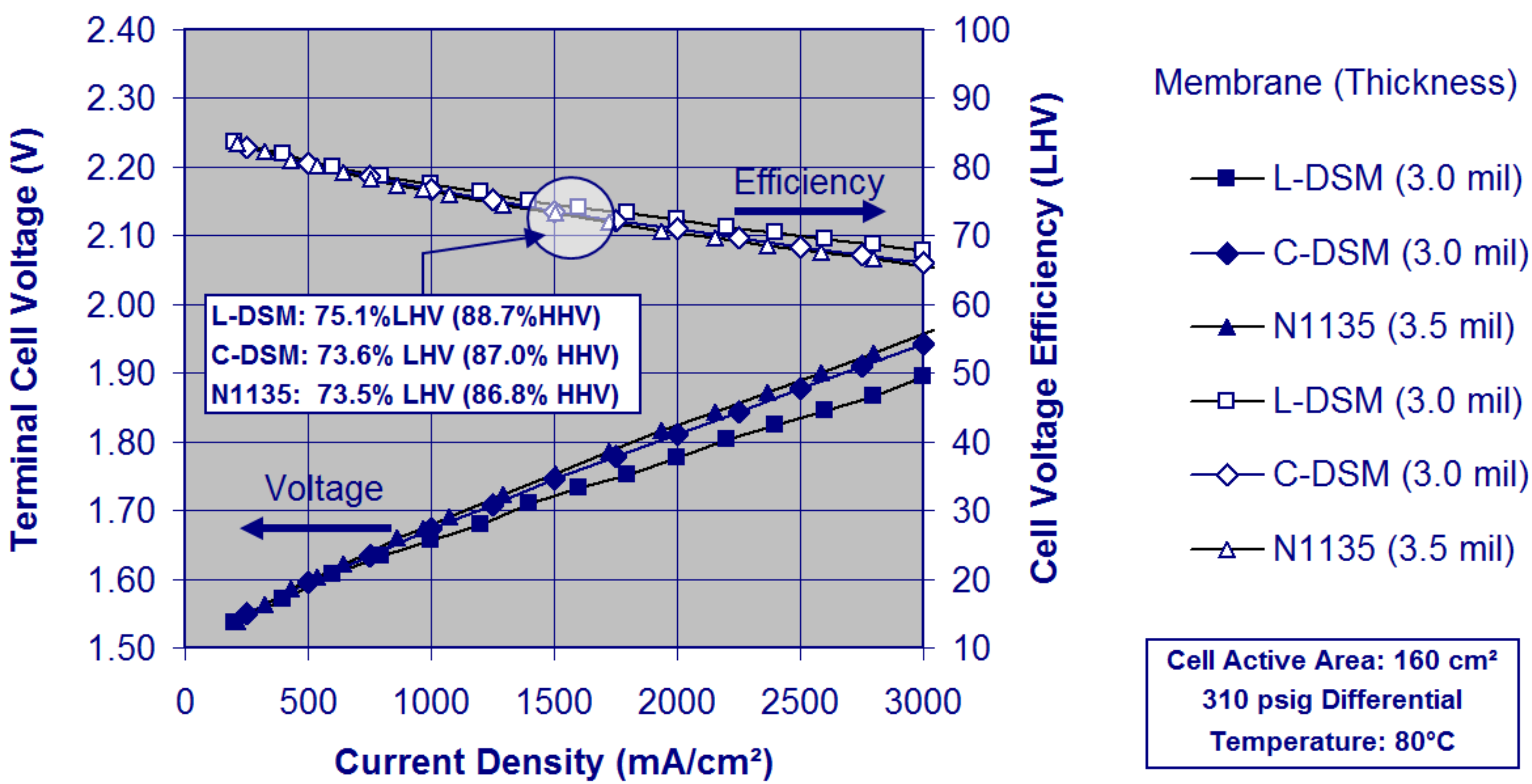
Titanium Cell-Separator with Carbon coating

Designing Low Cost Electrolyzer Stack and System

- **Objectives**
  - Reduce BOP capital cost
  - Reduce BOP power consumption
  - Increase stack active area
  - Improve safety and reliability
  - Design for high-volume manufacturing
- **Approach**
  - Team with large volume commercial manufacturer (domnick hunter group of **Parker-Hannifin**)
  - Redesign stack & system to eliminate or replace costly components
  - Laboratory evaluation of lower-cost components and subsystems
    - Design & test high efficiency H_2 dryer
  - Develop higher efficiency power electronics

System Design Specifications	
Production Rate	0.5 kg H_2/hr
Operating Pressure	300-400 psid ; H_2 300-400 psig; O_2 atm
Operating Temperature	50-90°C
Membrane	DSM with PFSA ionomer
Stack Size	290 cm^2/cell, 27 Cells
Stack Current Density	1500-2000+ mA/cm^2

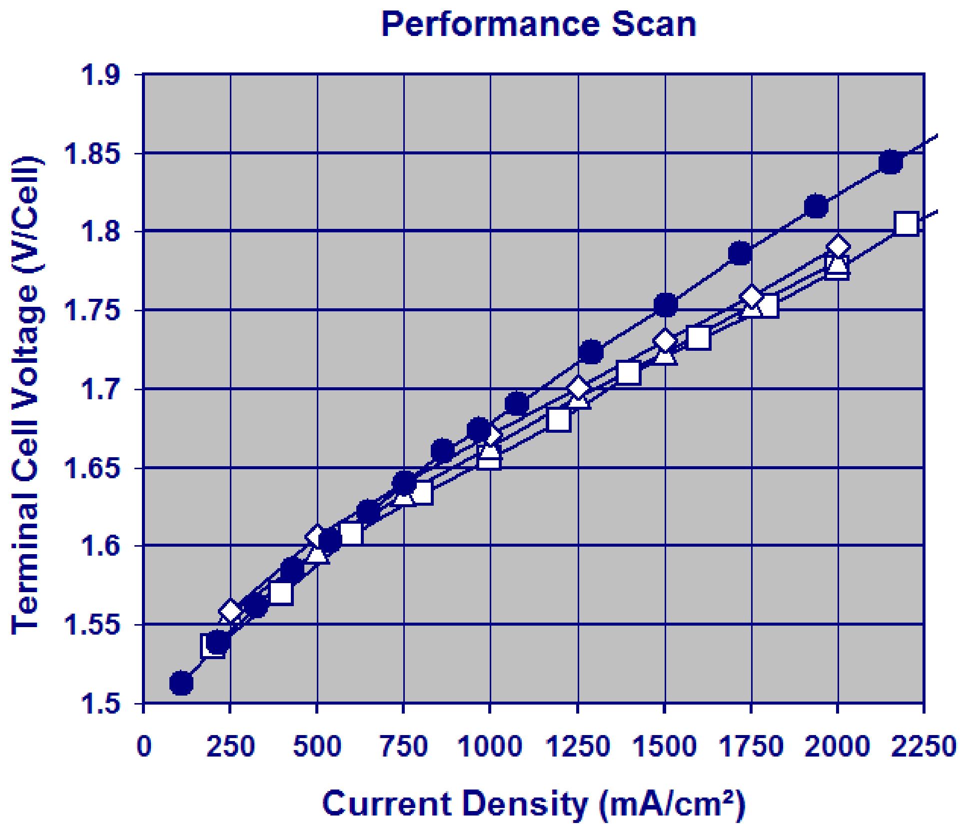
Membrane Progress: DSM



- **Performance Milestone** (Mar-2009/Mar-2010)
  - Performance of Laser-Drilled (L-) DSM > Chemically-Etched (C-) DSM > Nafion® 1135
- **C-DSM (1100EW) selected for electrolyzer build**
  - Lower cost, ease of fabrication

Nafion is a registered trademark of E.I. du Pont Nemours and Company

Performance: Scaled-up DSM & Stack Hardware



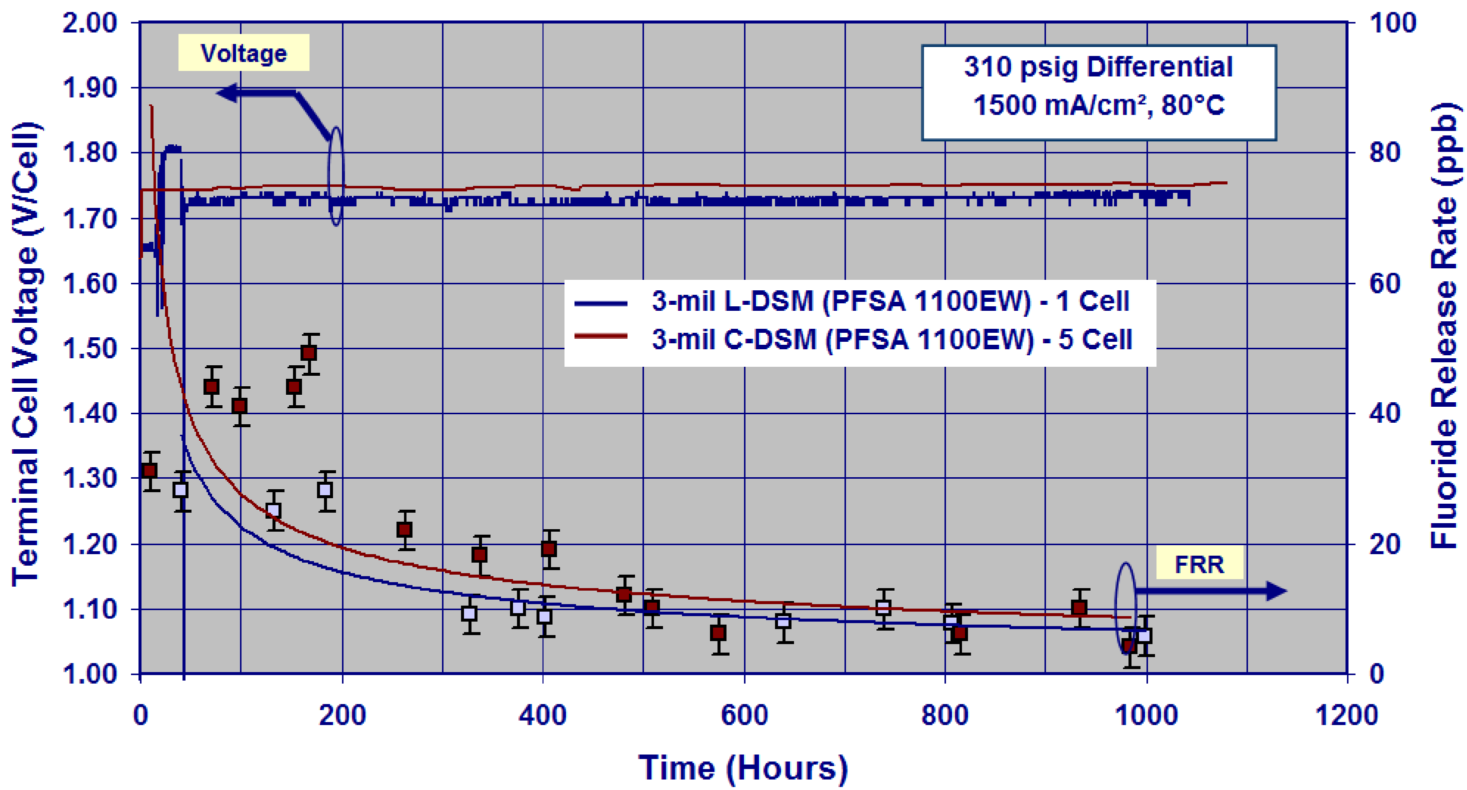
Test Conditions:
80°C
320-330 psig Cathode (H_2)
20 psig Anode (H_2O/O_2)

MEA/Hardware:
DSM thickness (3 mil)
C(poco)/Ti seperator used in scaled-up 290-cm² HW

HW	#Cells	MEA
160-cm² (□)	1	C-DSM
290-cm² (△)	1	C-DSM
290-cm² (◇)	5	C-DSM
160-cm² (●)	1	Nafion 1135

- **Milestone (Dec-2010): 5-cell Scaled-up Short-Stack**
  - Performance comparable to 160-cm² HW w/DSM > Nafion 1135®
  - Electrolyzer Stack utilizes scaled-up 290-cm² cell components (DSM, carbon/titanium, cell-separators)

Membrane Progress: Life Testing



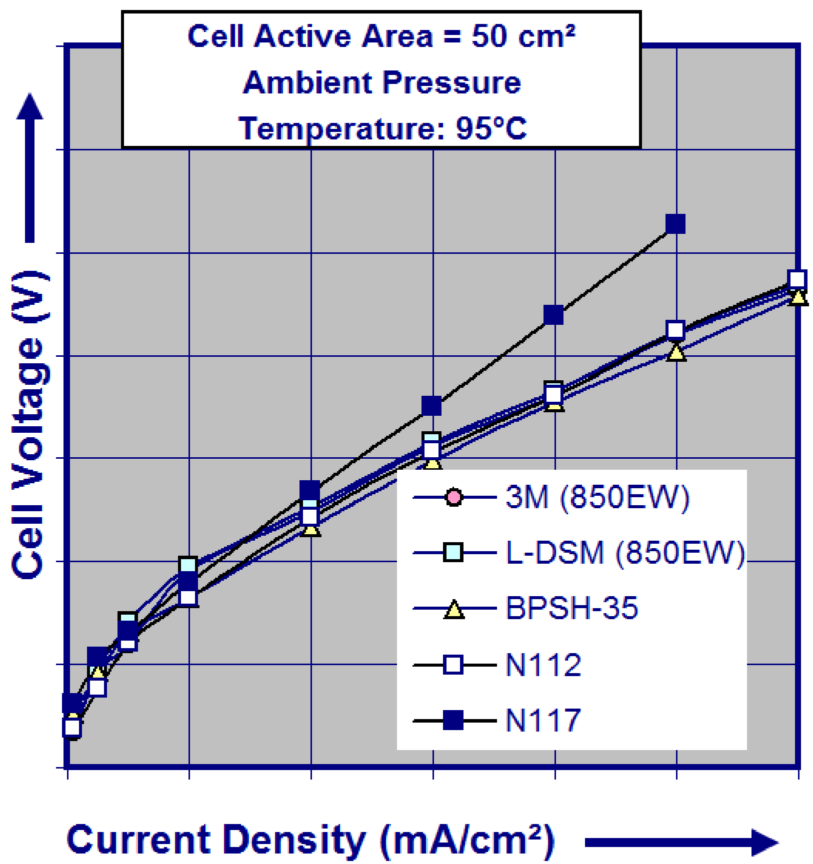
Performance

- Completed 1000 Hour Life Test Milestones
  - 1-cell (160-cm²) & 5-cell (290-cm²)
  - 5-cell includes scaled-up components
  - 1.73-1.75V (~88% HHV)
- DSM MEA from 5-cell short stack re-assembled into a single-cell stack, total operating time = 2800+ hours

Membrane Degradation (Estimated Lifetime)

- F ion Release Rate: 3.7 μg/hr (<10 ppb)
- DSM -1100EW (Stabilized Ionomer): ~55,000 hours

Membrane/Catalyst Evaluations



3M Catalyst Performance

- 3M NSTF cathode catalyst performance equivalent to GES (Jan 2010)
- **Successful testing of 3M NSTF PtIr anode catalyst, performance equivalent to GES (Feb 2011)**
- Pt loadings of 3M anode & cathode catalyst are one-order magnitude lower than currently in use (~0.10 to 0.15mg Pt/cm²)!
- 3M catalyst: Life testing required

Membrane Performance

- BPSH-35 ≅ 3M ≅ DSM ≅ Nafion® 112 > Nafion® 1135
- 3M 850EW is stabilized ionomer
- Initiated Tokuyama membrane evaluation
  - Low-Cost hydrocarbon membrane
  - Life testing > 5000 hours in DMFC (Tokuyama)

GES

Cell-Separator Progress

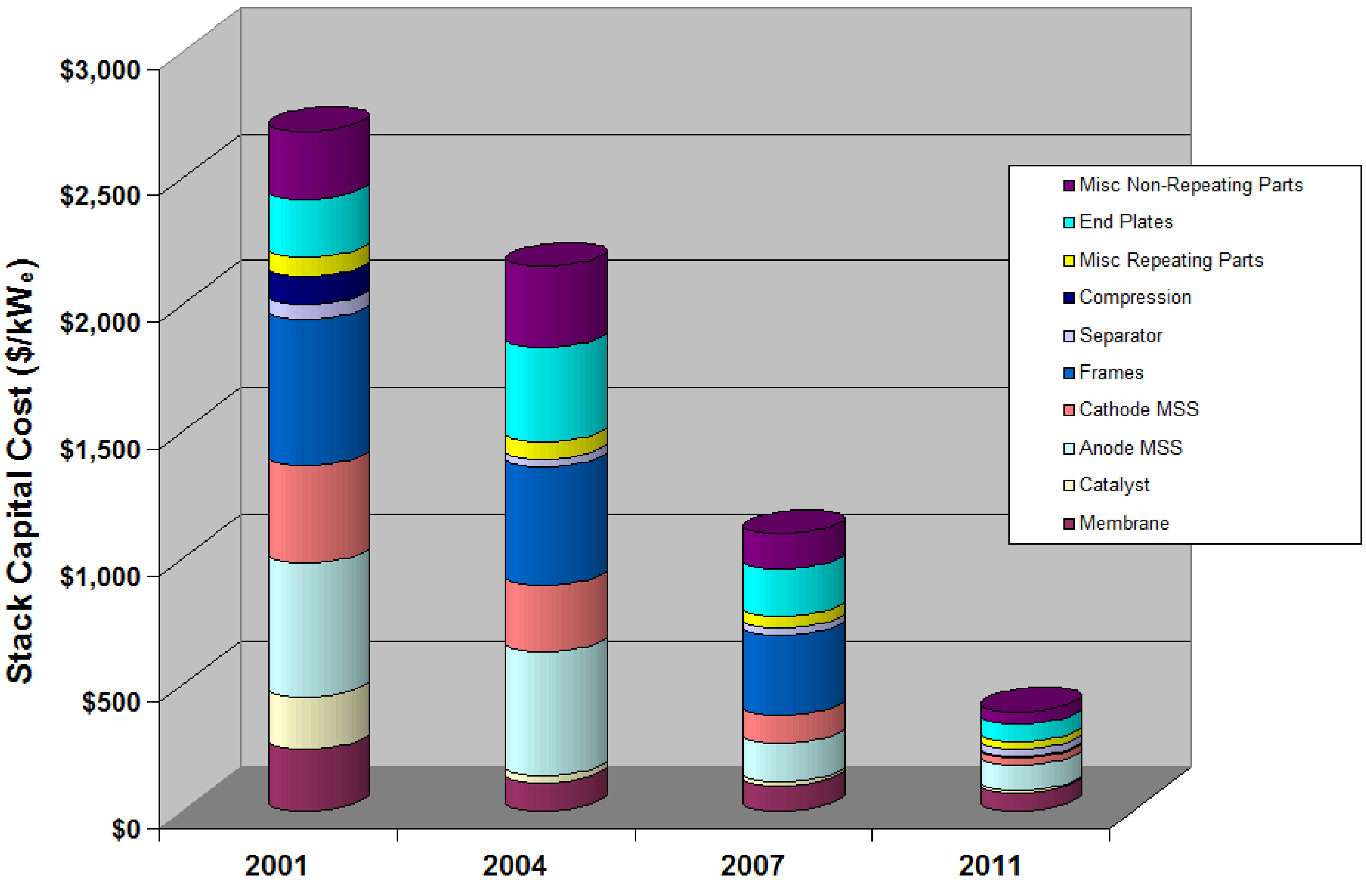
Carbon/Titanium

- Carbon/Titanium Cell-Separators Scaled-up to 290-cm² (Milestone Oct-2010)
  - Evaluated in 5-cell short stack for 1000-hours
  - Single cell-separator testing ongoing (2700+ hours)
  - Cell-Separators fabricated with low porosity carbon
    - POCO Pyrolitic Graphite (Surface Sealed)
    - Low hydrogen uptake (embrittlement)
    - **Life-time estimate > 60,000 hours**
- Analysis
  - C/Ti: No carbon delaminating or loss in thickness
  - Zr/Ti & ZrN/Ti (PVD coatings)
    - Delamination, contaminated DI water
- New low-cost carbon materials identified

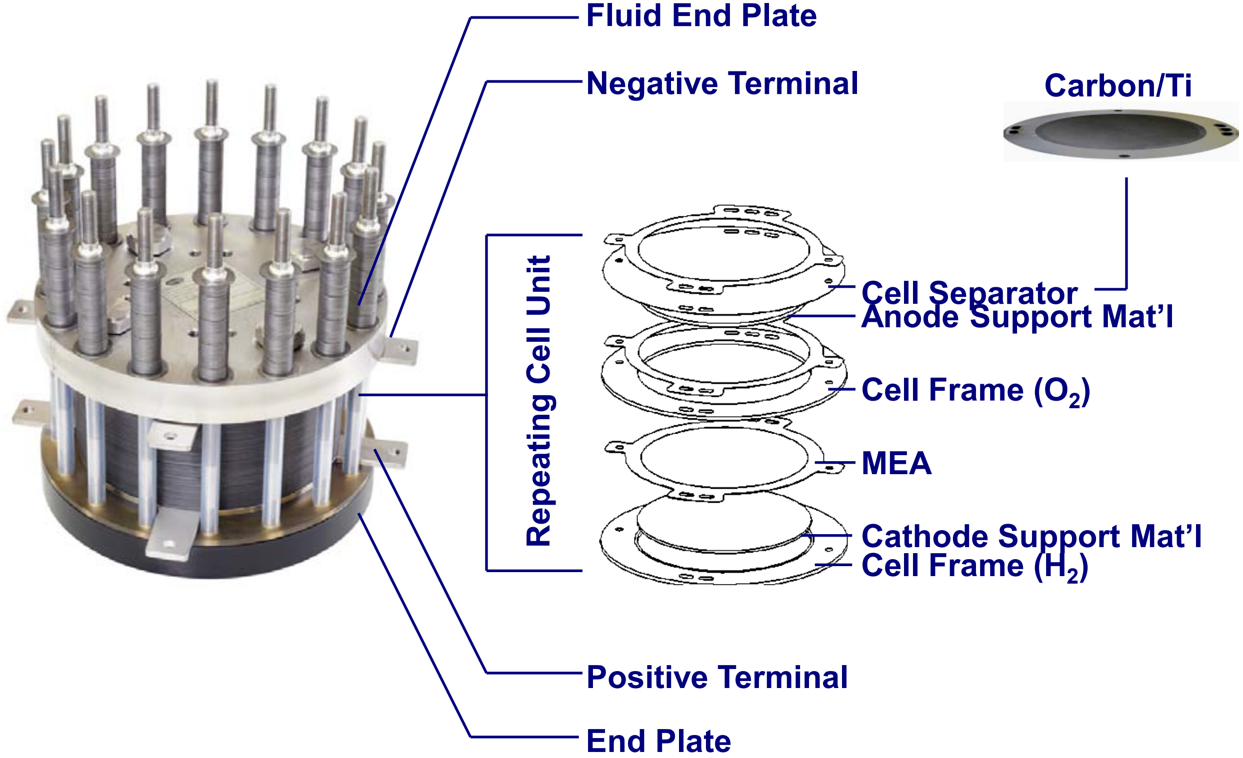
Cell -Separator	Time (Hours)	H_2 uptake (ppm)
C/Ti (290-cm²)	**1000**	**105**
C/Ti (160-cm²)	500	64
Zr/Ti(160-cm²)	500	140
ZrN/Ti (160-cm²)	500	31
Dual Layer Ti (160-cm²)	500	1105
Ti (baseline)	0	~60
Ti Failure/Embrittlement: ~8000 ppm		

Property	Units	DOE Target FC Bipolar Plates 2015	GES C/Ti Cell-Separator 2011
Cost	$/kW	3	> 10
Weight	kg/kW	<0.4	0.08
Electrical Conductivity	S/cm	> 100	>300 (680 Poco)
Flexural Strength	MPa	>25	86.1 (Poco)
Contact Resistance to GDL (MEA interface)	mΩ. cm²	< 20 @ 150 N/cm²	17 @ 350 N/cm²

Stack Progress: Cost Reduction



Stack Progress:
Advancements & Cost Reductions



The repeating cell unit comprises 90% of electrolyzer stack cost

(2007-2010)

- Increased active area (290cm²)
- Reduced catalyst loadings
- Reduced Part Count 41 to 16
- Pressure Pad: Sub-assembly eliminated
- Molded Thermoplastic Cell Frame
- Cell-Separators: Replaced Nb/Ti with Carbon/Ti

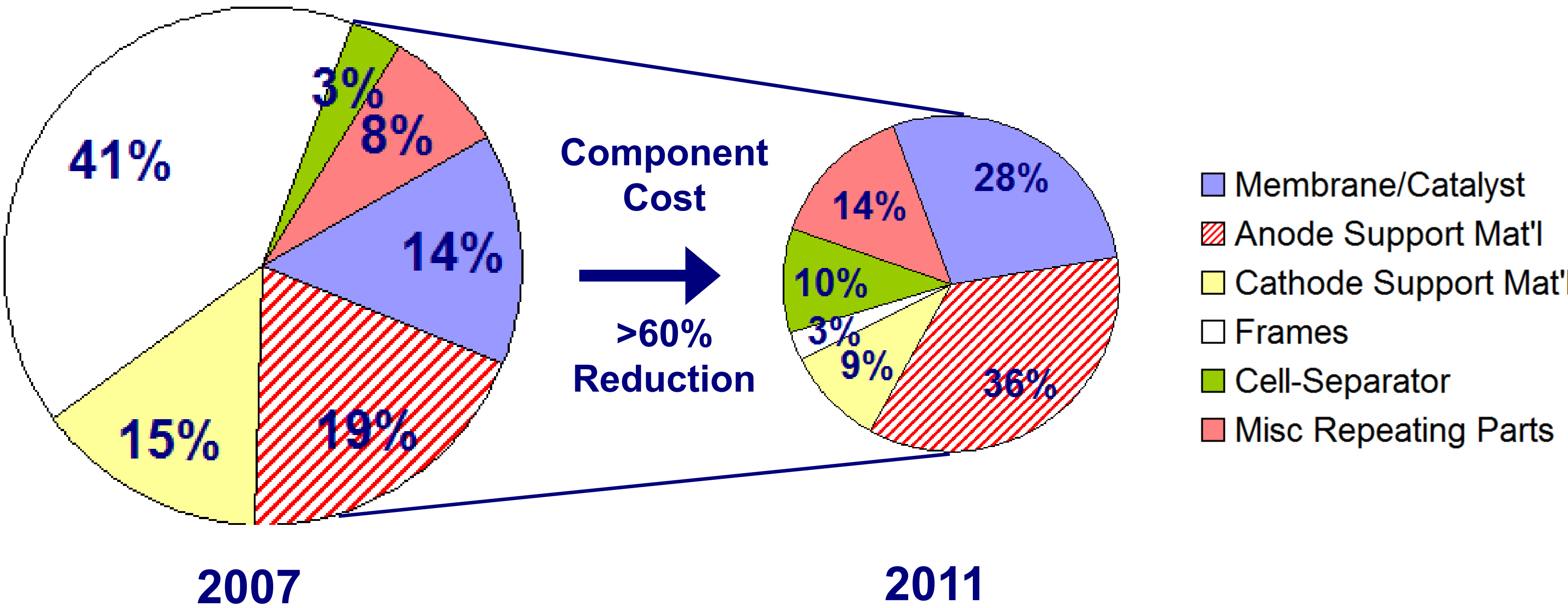
(2010-2011)

- Frame Thickness reduced (by 30%)
  - Reduces Cathode & Anode Support Mat'l
- Reduced Part Count from 16 to 10 Parts/Cell-50% labor reduction
- Nb and Zr mat'l in Anode & Cathode supports eliminated- up to 98% material cost reduction
- DSM MEAs fabricated w/chem-etch supports- 90% cost reduction
- Carbon Steel End Plate (previously S.S.) - 66% material cost reduction

(Future)

- Frame thickness reduced by 90%
- Carbon Steel Fluid End Plate
- Poco in carbon/Ti cell-separators replaced w/low-cost carbon (Entegris).
- Further catalyst reductions (3M)
- Increase Cell-Size
- Low-Cost Ionomers (Tokuyama)

Stack Progress: Repeating Cell Cost

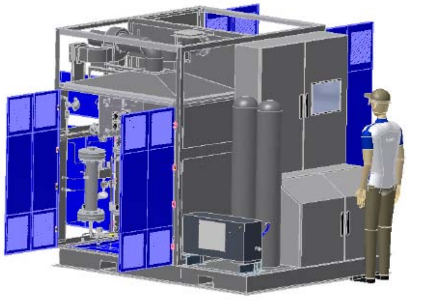


Anode Support Material & MEAs (membrane & catalyst) dominate cost of the electrolyzer stack

System Progress

- Assembly: >80% Complete
- System design complete: P&ID, PFD
- Safety:
  - Manuals covering Hydrogen Safety& Response Plan
  - Reviewed National & International Codes & Standards (Prof. Zalosh – H_2 safety expert)
  - GES contributed comments to ISO/DIS 22734-2 draft

- Failure Modes and Effects Analysis (FMEA) -Analysis indicates highest degree of safety with use of Dome over stack
  - Eliminates highest severity cases related to hydrogen ignition & electrocution
  - Satisfies Codes Pertinent to Hydrogen Refueling Systems
  - Dome design modified for lower cost
  - Pressurized dome: reinforces stack during high pressure operation (future study)



System Specs

Dimensions: 7.20′ tall x 6.6′ long x 7.84′ wide.

Water Consumption: 5.75 liters/hr

Stack Power Requirement: 24 kW

Cooling Requirement: 3.3 kW

Production Rate

0.5 kg H_2/hr (-3% dryer)

2.0 kg-H_2/hr (w/larger Stack & Power Supply)

Operating Pressure

H_2 350 psig; O_2 atm

Operating Temperature

80°C

Membrane

DSM-PFSA,

Stack Size

290 cm²/cell, 27 Cells

Stack Current Density

~1750 mA/cm²

System Progress: Assembly

Controller & Power Supply

- Power Supply Efficiency: 94%
- 30kW, 600A, 50V
- Stack Requirement: 23.8kW

H_2 –Dryer (H_2** Compartment)**

- Dryer Efficiency: 96-97%
- Dual desiccant bed
- H_2 cooling prior to dryer

Electrolyzer Stack & Dome (O_2** Compartment)**

- Stack Efficiency: 88%
- Output: 0.5 kg-H_2/hr
- Stack Voltage: 47 V (27 Cells @1.75 V/cell,1741mA/cm²)
- Dome can accommodate >90-cell stack
- Use of Dome satisfies Codes Pertinent to Hydrogen Refueling Systems

GES

Projected H_2 Cost

Specific Item Cost Calculation **Hydrogen Production Cost Contribution**		
H2A Model Version (Yr)	Rev. 2.1.1 (FY2010)	Rev. 2.1.1 (FY2011)
Capital Costs	<$0.79	$0.60
Fixed O&M	<$0.49	<$0.39
Feedstock Costs $1.54 min. @ 39.4 $kWh_e/kg\text{-}H_2$	$1.86 **(DSM)**	$1.86 **(DSM)**
Byproduct Credits	$0.00	$0.00
Other Variable Costs (including utilities)	$0.01	$0.01
Total Hydrogen Production Cost ($/kg) (Delivery not included)	**3.15**	**2.86**
Delivery (H2A default)	1.80	1.80
Total Hydrogen Production Cost ($/kg)	**4.95**	**4.66**

H2A Model Analysis Forecourt Model

- Design capacity: 1500 kg H_2/day
- Assume large scale production- costs for 500th unit
- Assume multiple stacks/unit
  - Low-cost materials and component manufacturing
- 333 psig operation. H_2 compressed to 6250 psig
- Operating Capacity Factor: 70%
- Industrial electricity at $0.039/kWhr

Future Plans for FY2010-11

- **Parker**
  - Fabricate deliverable system
  - Operate/Evaluate system
  - Complete critical design review
- **GES**
  - Deliver Stack to Parker
  - Assist in system start-up at Parker facilities
  - Receive and install operating system at GES
  - Verify stack/system performance
  - Prepare for shipment to NREL
  - Continue investigation on low-cost components
    - Frame Thickness/Material cost reduction
    - Low-cost carbon for cell-separators
    - Membrane/catalysts
    - Further reduction in components/cell

Summary

- **Demonstrated membrane reproducibility and durability**
  - Demonstrated DSM membrane performance better than that of Nafion 1135 at 80°C
  - Demonstrate DSM membrane lifetime at 80°C for 1000 hours
    - Single-cell (160cm²), 5-Cell (290cm²)
    - Single-cell (290cm²) life test ongoing – 2800+ hours
- **Cell Separator Development:**
  - Demonstrated performance comparable to dual-layer Ti separator in 160-cm² & 290-cm² electrolyzer
  - Demonstrated significantly reduced hydrogen embrittlement with carbon/Ti separators
    - Expected cell-separator lifetime in the range > 60,000 hours
- **Scaled-Up Stack Design**
  - Completed preliminary stack design review
    - Stack Assembly Complete
    - Significant progress made in stack cost-reduction (cell-components, membrane, & catalyst)
- **System Development:**
  - Completed preliminary system design review
    - P&ID, PFD, Layout, FMEA, Safety Reviews
    - System near completion