2010 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:** May 2012
- **Percent Complete:** 45

Budget

- **Total Project Budget: $2.49M**
  - **DOE Share:** $1.99M
  - **Cost Share:** $0.51M
  - **FY08 Funding**
    - **DOE: $650K**
  - **FY09 Funding**
    - **DOE: $233K**
  - **FY10 Funding**
    - **DOE: $550K**

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)

Partners

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

Collaborations

- **3M Fuel Cell Components Program (Manufacturer)** – NSTF Catalyst & Membrane
- **Entegris** – Carbon Cell Separators

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
  - Demonstrate prototype electrolyzer system at NREL

FY09-2010 Objectives

- Fabricate Scaled-up Stack Components
  - DSM (290-cm^2)
  - Cell-Separators (290-cm^2)
- Assemble and operate short stacks at GES for 1000 hours
- Complete system CDR
- Begin fabrication of deliverable system

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	Performance DSM > Nafion® 1135 = Nafion®112	**100%** Mar-09
	Demonstrate electrolyzer lifetime with DSM membrane (80 C ≥ 1000 hrs)	Completed 1000 hrs @ 80°C. Testing indicates low membrane degradation rate, high life expectancy	**100%** Mar-09
	Scale-up DSM membrane to 290cm² Evaluate in short stack for 1000 hours	DSM substrates have been scaled-up to 290 cm². Cost of laser-drilled substrates reduced by 50%. Alternative chemically-etched DSM material identified for further cost reduction	**30%**
Cell Separator	Demonstrate performance comparable to dual-layer Ti separator	Life testing and H_2-embrittlement tests confirm longevity of Carbon/Titanium cell-separators	**100%** May-09
	Scale-up Carbon/Ti cell-separator Evaluate in short stack for 1000 hours	Carbon materials scaled-up. Cell-separator fabrication initiated	**20%**
System Development	Complete preliminary design review	Completed: P&ID, PFD, control diagrams, safety review, system layout and packaging drawings	**100%** Dec-09
	Complete critical design review Begin system assembly	Currently assembling major subsystems for bench-top evaluation (this includes H_2-dryer)	**20%**

Membrane Development Approach

DSM Membrane-GES

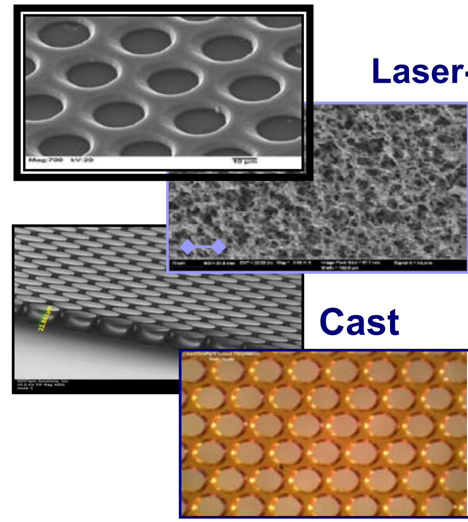
- PFSA ionomer incorporated in an engineering plastic support
  - High-strength
  - High-efficiency
  - No x-y dimensional changes upon wet/dry or freeze-thaw cycling
  - Superior to PTFE based supports

Bi-Phenyl Sulfone Membrane-VT

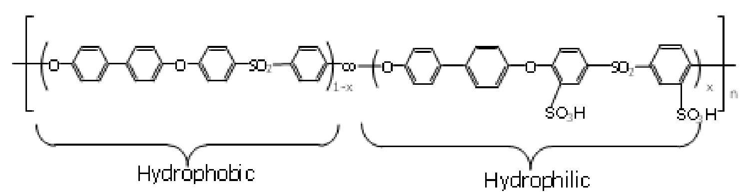
- Hydrocarbon Membranes
  - Inexpensive starting materials
  - Trade-off between conductivity and mechanical properties

Alternative Membranes-3M

- 3M's PFSA (850EW) Membrane



DSM Supports



Bi-Phenyl Sulfone, H form (BPSH)

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 have been used**
  - 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: *A real problem in electrolyzer separators!*

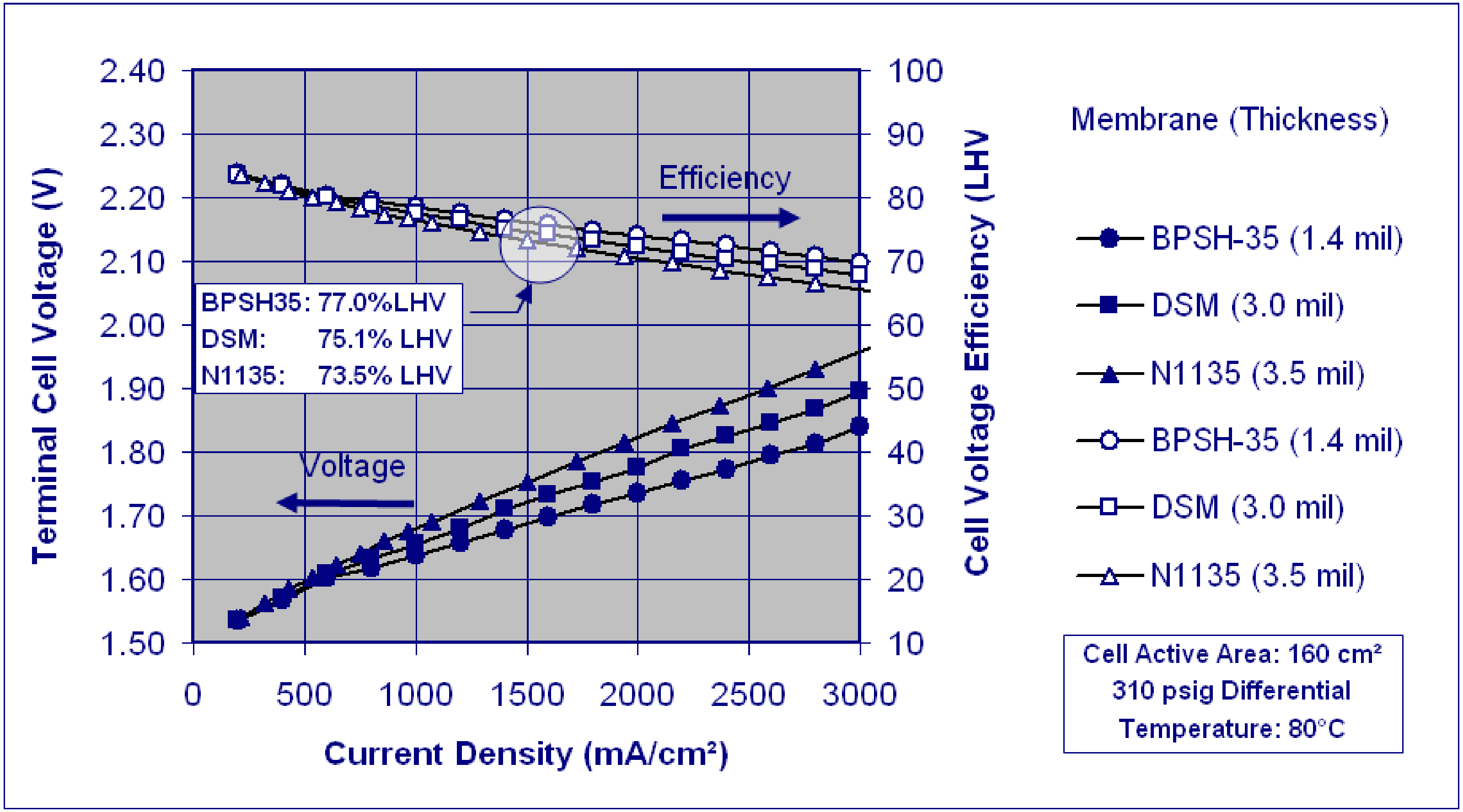
Designing Low Cost Electrolyzer Stack and System

- **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 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-PFSA
Stack Size	290 cm^2/cell, 28 Cells
Stack Current Density	1500-2000+ mA/cm^2

Membrane Progress

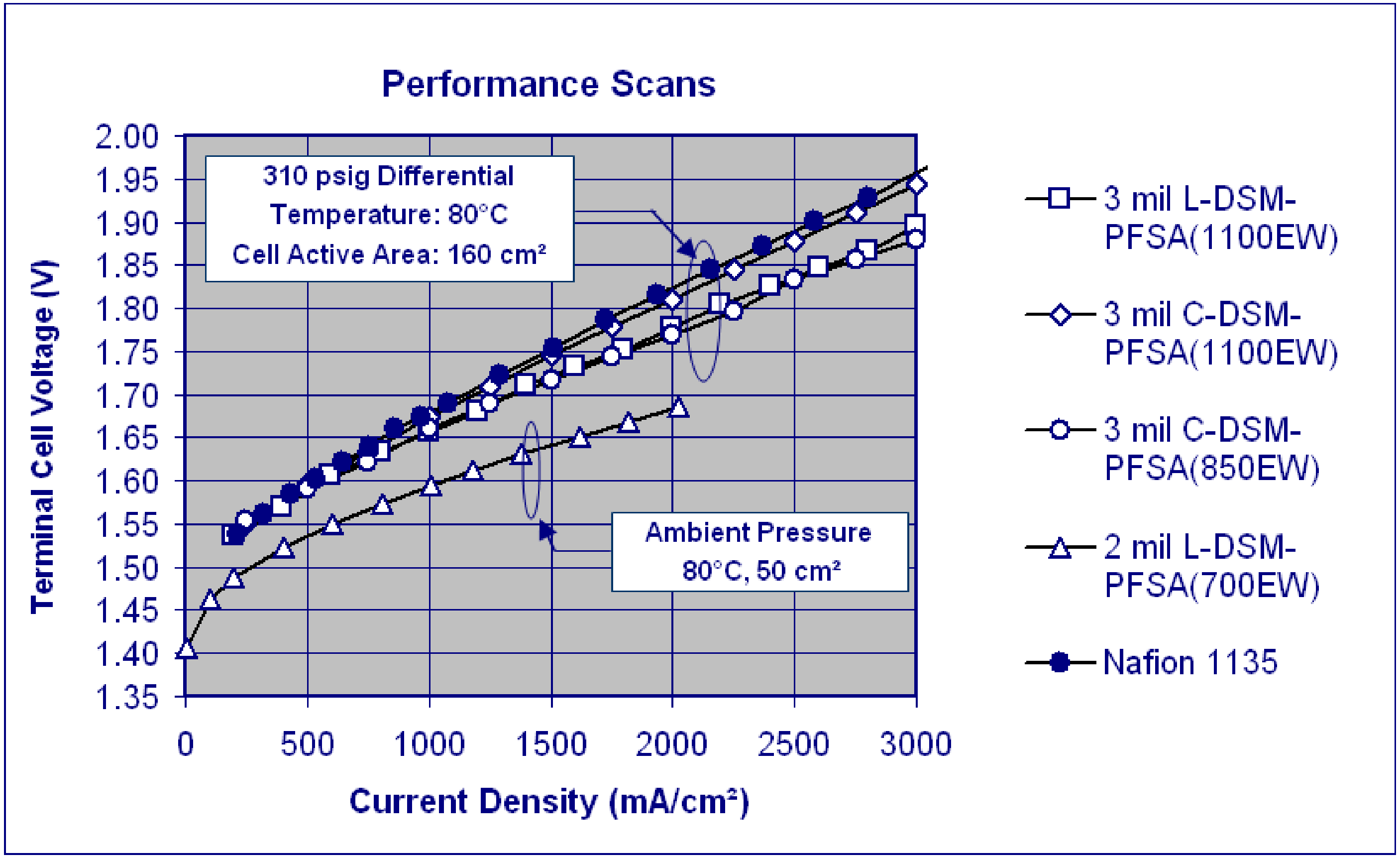


- **Membrane Performance: BPSH-35 > DSM(1100EW) > Nafion® 1135**
- **Performance Milestone** (Mar-09)
  - **Performance of 3-mil Laser-Drilled DSM (PFSA-1100EW) > Nafion® 1135**

Membrane Progress

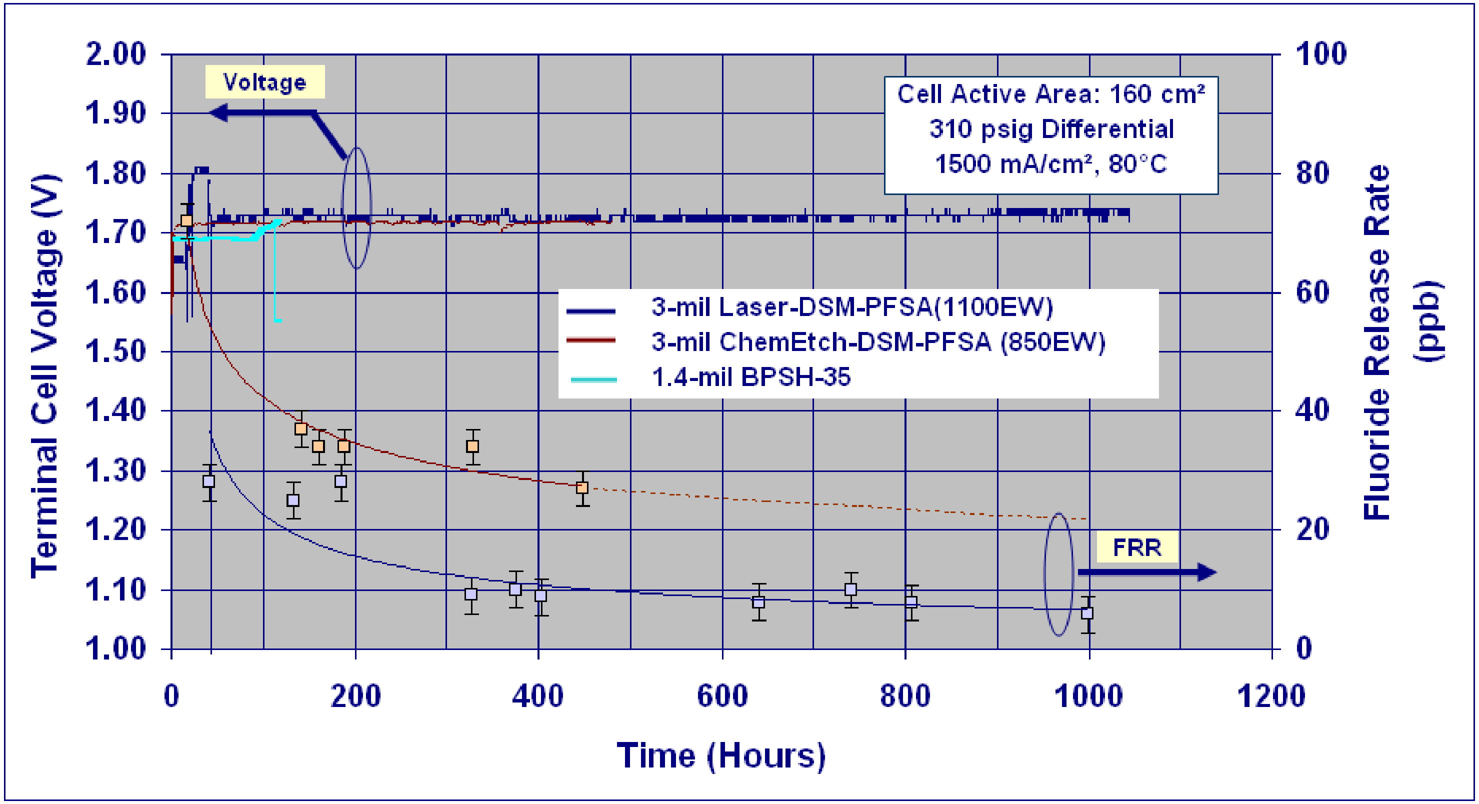
Supported Membrane

DSM™: Laser-Drilled vs. Chemically-Etched



Membrane Progress

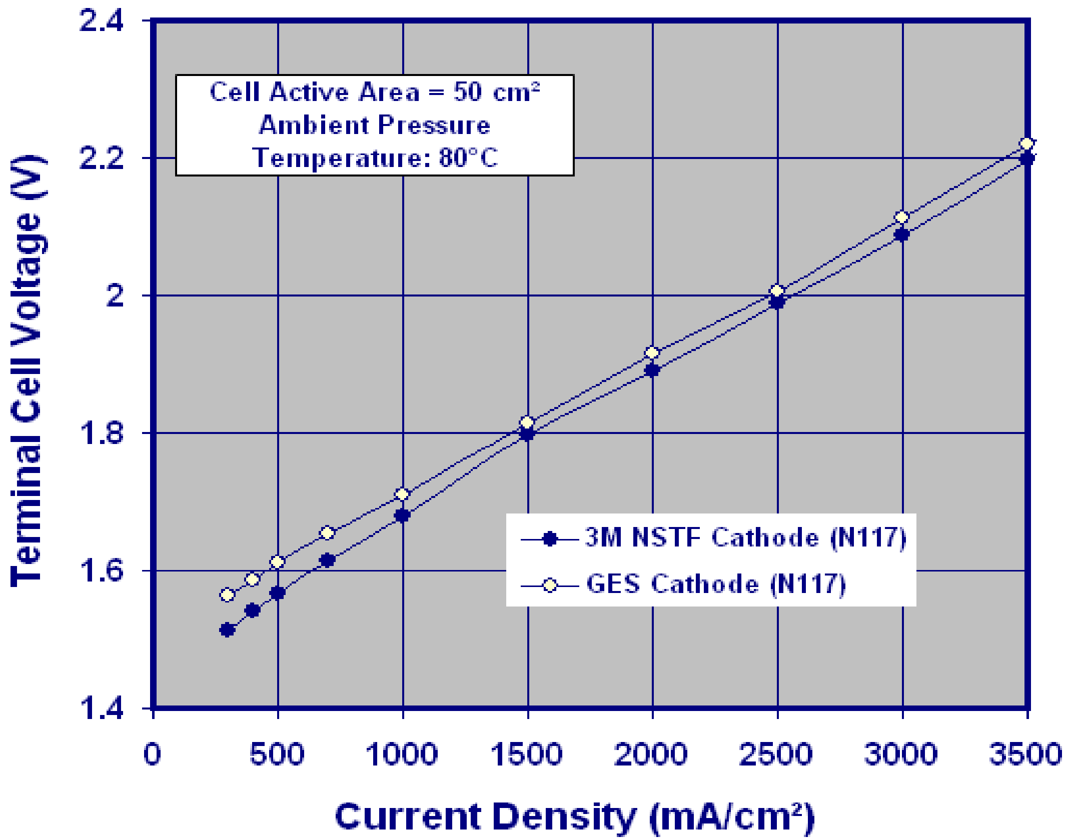
Life Testing



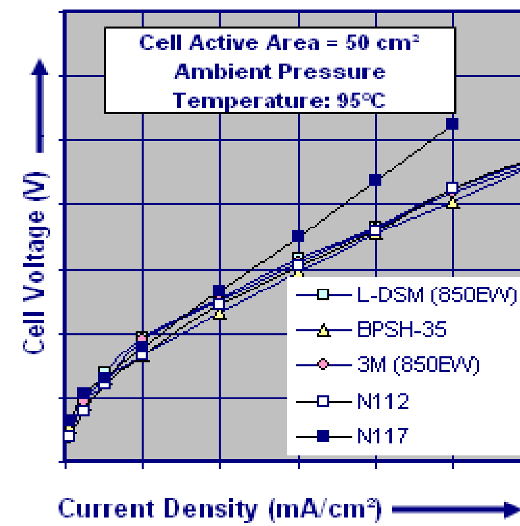
- **Membrane Performance**
  (3-mil Laser Drilled DSM PFSA(1100EW)
  - Voltage:1.71-1.73V
  - Efficiency: 75.1% LHV (88.8% HHV)
  - Completed 1000 Hour Life Milestone
- **Membrane Degradation (Estimated Lifetime)**
  - F ion Release Rate: 3.7 μg/hr (<10 ppb)
  - DSM -1100EW Stabilized Ionomer: ~55,000 hours
  - DSM – 850EW Non-Stabilized Ionomer: <20,000 hours
  - BPSH-35: Life test fail due to H_2 X-over (pinhole detected)

Membrane/Catalyst Evaluations

Catalyst Evaluation



Membrane Evaluation



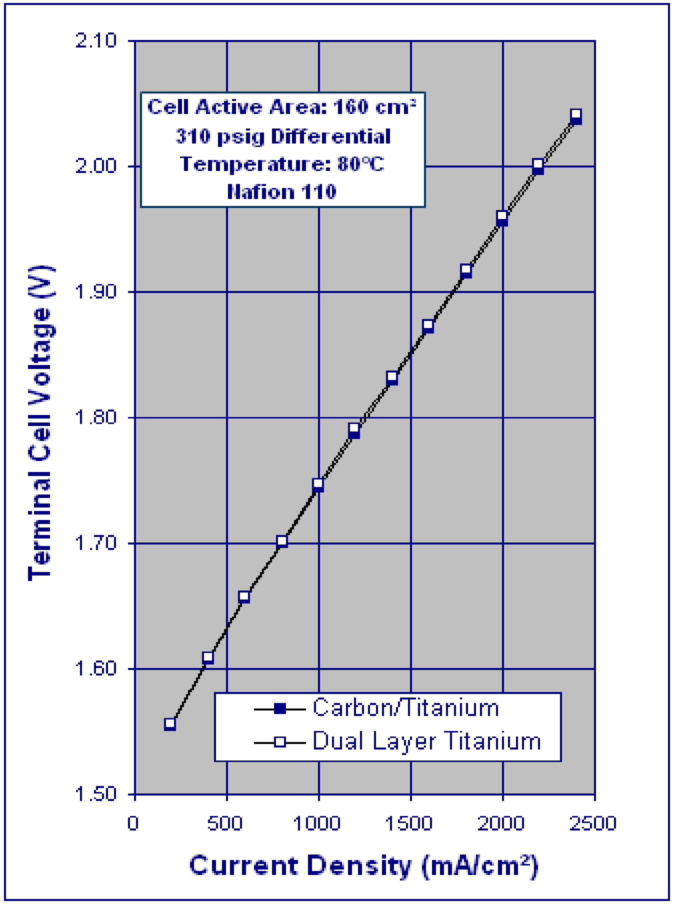
- **Catalyst Performance**
  3M catalyst performance is equivalent to GES cathode catalyst but is one order of magnitude lower in Pt loading
- **Membrane Performance**
  BPSH-35 ≅ 3M ≅ DSM ≅ N112 > N1135
- 3M 850EW (Stabilized ionomer)

Cell-Separator

Separator Fabrication & Evaluation

Carbon/Ti

- Properties
  - Conductivity (S/cm) > 300
  - Low Porosity
    - POCO Pyrolitic Graphite (Surface Sealed)
- Evaluation (500 hrs)
    - Water Quality: 14.7 MΩ
    - No loss in carbon thickness
  - Hydrogen embrittlement analysis
    - Carbon/Ti: 64ppm H_2
      - Life Time Estimate: >60,000 hours
    - Dual Layer Ti: 1105 ppm H_2
      - Life Time Estimate: <5,000 hours



Performance Milestone (May-09)

Preliminary System Design

- P&ID, PFD completed
- Series of workshops completed with manuals covering:
  - Hydrogen Safety& Response Plan
  - System Training & Operation
  - System Manufacturing
  - Failure Modes and Effects Analysis (FMEA)
- System Layout Complete
- Component evaluations
  - Water Pump: (80% eff.)
    - Multistage centrifugal
  - H_2-Dryer: (>97% eff.)
    - Full scale prototype designed and built
  - Rectifier: (93-95% eff)

FMEA

PROB-ABILITY	SEVERITY			
	Catastrophic I	Critical II	Marginal III	Negligible IV
Frequent				
Probable				
Occasional				
Remote			1	
Improbable	7	12	1	
Incredible	12	2		

Colour indicates class:-	Class A	Class B	Class C	Class D

Risk Class	Initial Status
A	5
B	3
C	24
D	3

Risk Class	Current Status
A	0
B	0
C	32
D	3

- System design improvements and the use of a Dome eliminate the highest severity cases
- Highest severity cases related to hydrogen ignition (Class A), & electrocution (Class B)

Codes Pertinent to Hydrogen Refueling System

Component Examples

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 Systems

ISO/DIS 22734-2:
Hydrogen Generators Using Water Electrolysis Process

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

Vehicle Refueling

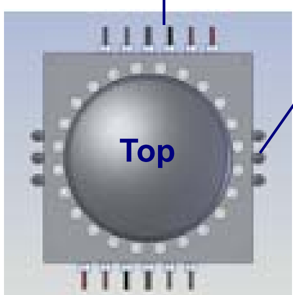
CSA America HGV 4.1-2009:
Hydrogen Dispensing Systems

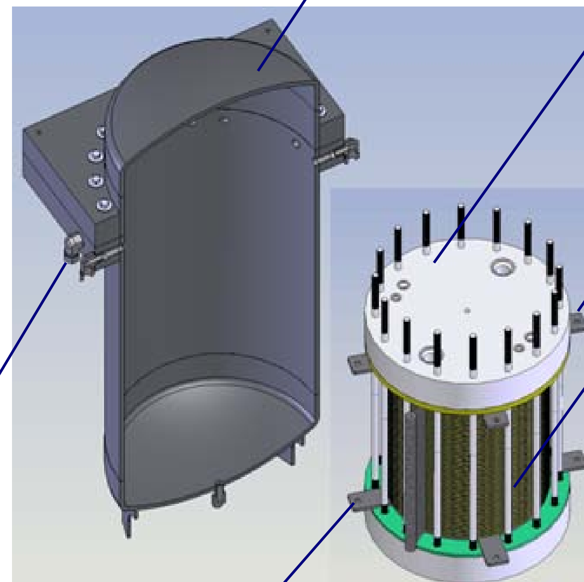
NFPA 52-2010, Chapter 9:
GH2 Compression, Gas Processing, Storage, and Dispensing Systems

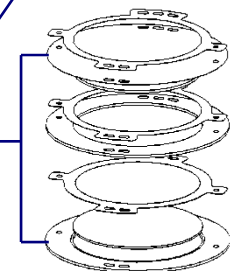
International Fire Code Section 2209:
Hydrogen Motor Fuel Dispensing and Generation Facilities

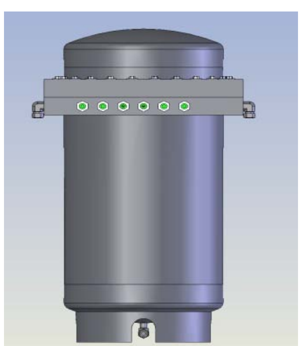
SAE TIR J2601:
Compressed Hydrogen Fueling Protocol

Preliminary Stack Design





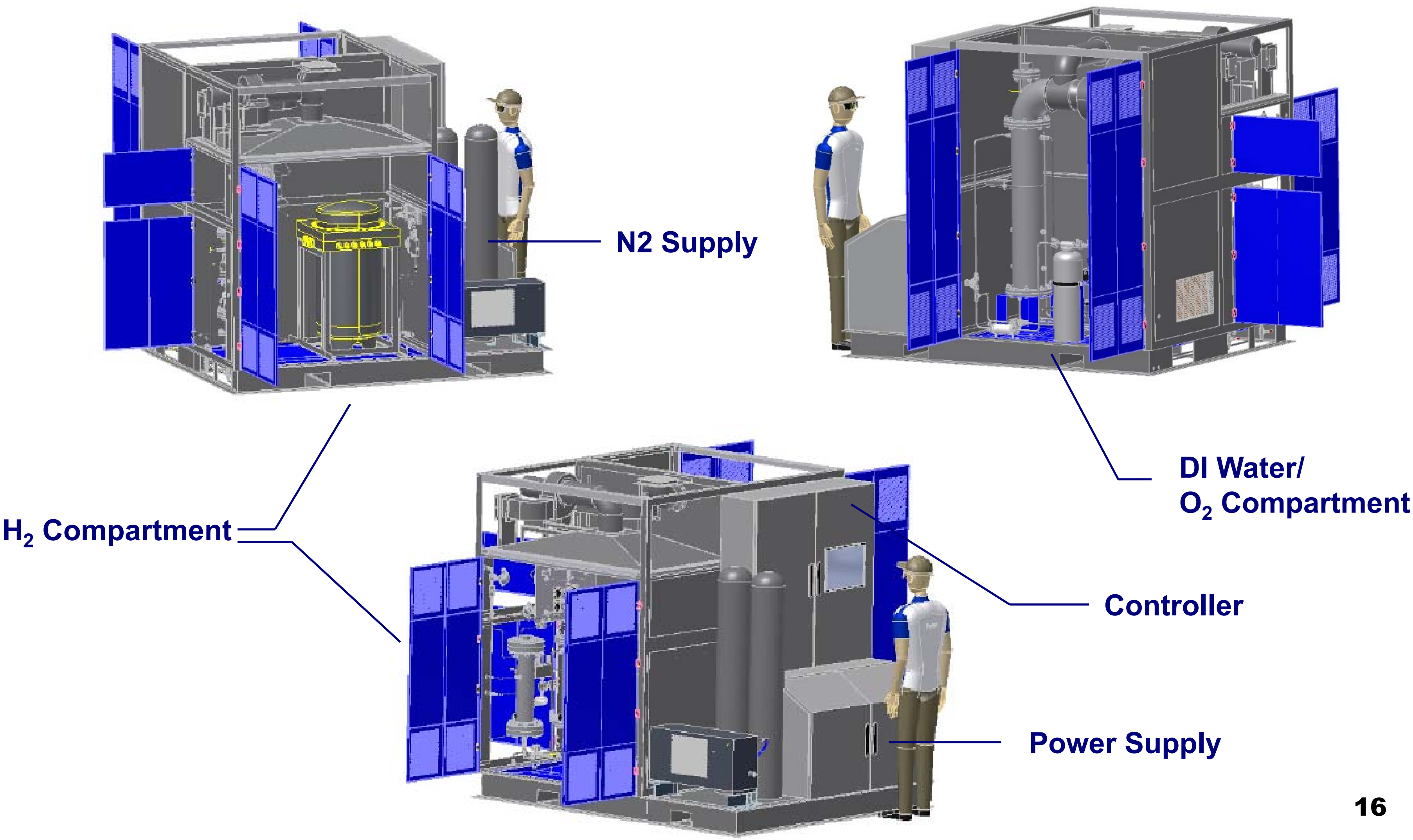




- **Pressurized Dome**
- **N_2 pressure 500 psig monitored electronically**
- **Dome material: carbon steel**
- **Design Failure Modes and Effects Analysis indicates highest degree of safety**
- **Dome can house largest stack envisioned (61-cells); smaller stacks can always fit in this Dome**

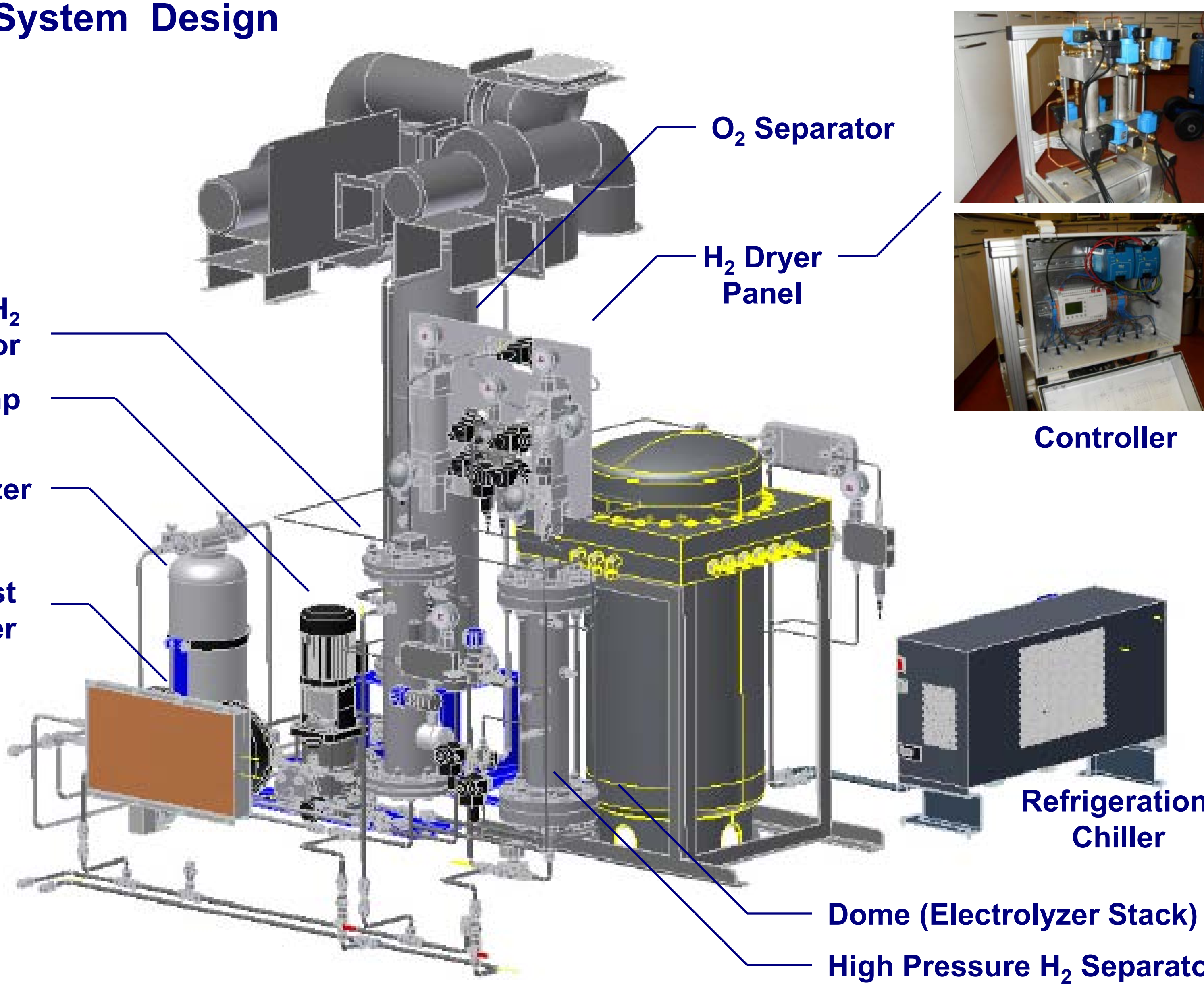
<u>Stack Design Includes</u>
- Increased active area (290cm²)
- Reduced catalyst loadings (Future reductions w/ 3M catalyst)
- Reduced Part Count
- Pressure Pad: Sub-assembly eliminated
- Molded Thermoplastic Cell Frame

Preliminary System Design (System Layout)



Preliminary System Design Cont..

Internal Layout
(Walls Removed)



Projected H_2 Cost

Specific Item Cost Calculation **Hydrogen Production Cost Contribution**		
H2A Model Version (Yr)	Rev. 2.0 (FY2009)	Rev. 2.1.1 (FY2010)
Capital Costs	$0.86	<$0.79
Fixed O&M	$0.53	<$0.49
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)	$0.02	$0.01
***Total Hydrogen Production Cost* ($/kg)** (Delivery not included)	**3.28**	**3.15**
Delivery (H2A default)	1.92	1.80
Total Hydrogen Production Cost ($/kg)	**5.20**	**4.95**

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**
  - Continue fabrication & evaluation of key components (bench top)
  - Critical design review
  - Fabricate deliverable system
  - Operate system
- **GES**
  - Fabricate scaled-up 'short stack' prototype (0.1kg-H_2/hr)
    - DSM (290-cm^2)
    - Cell-Separators (290-cm^2)
  - Operate short stacks at GES for 1000 hours
  - Assist in system start-up at Parker facilities
  - Receive and install operating system at GES
  - Add cells to stack to increase capacity
  - Verify stack/system performance
  - Prepare for shipment to NREL
- **VT**
  - One last round of membrane fabrication
  - Evaluate 100 hour durability

Summary

Significant progress has been made in Membrane, Stack, and System development

- **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
    - Expected DSM membrane lifetime in the range of 50,000 hours
    - BPSH membrane failed life-testing
- **Cell Separator Development:**
  - Demonstrated performance comparable to dual-layer Ti separator in 160-cm^2 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
    - Utilizing low cost components
- **System Development:**
  - Completed preliminary system design review
    - Piping & Instrumentation Diagrams (P&ID) and Process Flow Diagram (PFD)
    - FMEA & Safety Reviews
    - System Layout and Packaging