# Fuel Cell Transportation Cost Analysis


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U.S. Department of Energy's (DOE's) 2013 Annual Merit Review and Peer Evaluation Meeting (AMR) for the Hydrogen and Fuel Cell Technologies (FCT) Program, Arlington, Virginia, May 14, 2013.


**Project ID #FC018**

# Overview

## Timeline

- Transportation FC Cost Analysis
  - Project start date: 11/30/12
  - Project end date: *9/13/16 (all 5 Budget Periods)*
  - Percent complete: 50% (of Year 2 budget)

## Budget

- Total project funding:
  - $1 Million over 5 years
  - FY13: $145K/$68k for SA/Labs

## Barriers

- System Cost:
  - Realistic, process-based system costs
  - Need for realistic values for current and future cost targets
- Demonstrates impact of technical targets & barriers on system cost:
  - Balance of plant components
  - Materials of construction
  - System size and capacity (weight and volume)

## Partners

- Argonne National Laboratory (ANL)
- National Renewable Energy Laboratory (NREL)

# Presentation Outline

- **2012 Bus Cost Results**
  - Schematic
  - Bus applications overview and challenges
  - Specific parameter differences with automotive fuel cell systems (FCSs)
  - Cost curve
- **Gore low-cost MEA fabrication**
  - Diagram of general fabrication method
  - Key issues
  - Cost results
- **Gore Plate Frame Humidifier Cost Analysis**
  - Review of 2012 configuration and cost projection
  - Diagram of plate frame construction and sizing
  - Steps in manufacture/assembly
  - Cost results
- **Quality Control Update**
  - Table of old vs. new quality control (QC) assumptions
  - Table of cost impact
- **Expanded polarization data and re-optimization**
  - Graph of new data
  - $/kilowatt (kW) optimization curve


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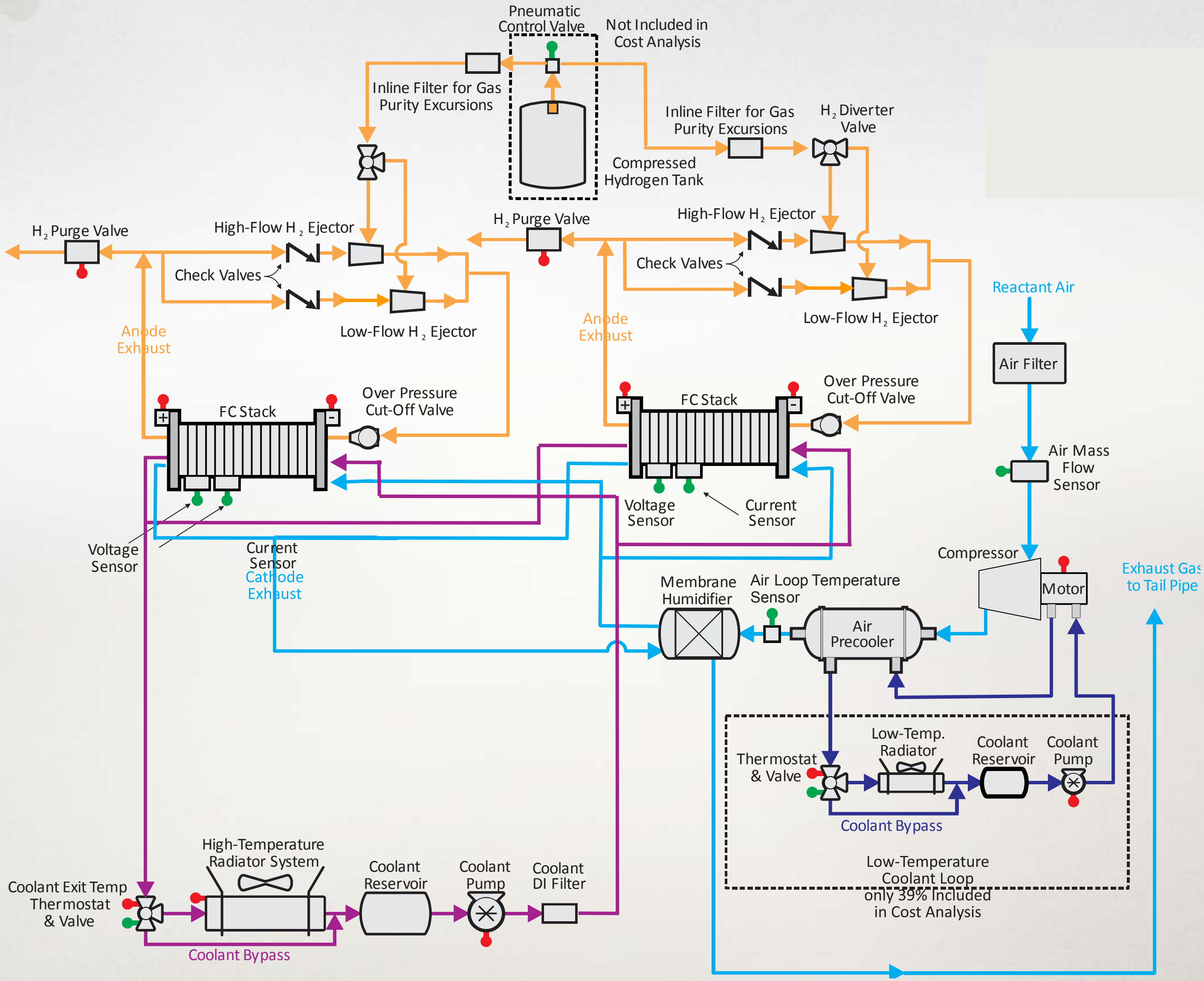
# Fuel Cell Bus Issues and Assumptions

- Analysis based on 40 foot transit buses
- Power Level
  - Varies: 70 kW (flat terrain, mild climate)
    180+ kW (hilly urban route, hot climate)
  - Ballard Inc.: 150 kW gross electric power ($kW_{e\text{-}gross}$)
  - United Technologies Inc. (UTC) PureMotion®: 120 $kW_{e\text{-}gross}$
  - 160 kW net electric power ($kW_{e\text{-}net}$) selected for cost modeling
- Accessory loads
  - Lights and heating ventilation and air conditioning (HVAC) loads can be very high (~30-60 kW)
- Routes
  - Drive cycles vary. No specific cycle selected for analysis.
- Production Rates
  - Annual demand in the United States (U.S.): ~4,000 buses/year
  - But most are small orders, 10-20 unit orders
  - Worldwide bus orders are much higher
  - 1,000 buses/year selected for cost modeling

# 2012 System Diagram for 160 $kW_{e\text{-}net}$ Bus




System design is similar to automotive configuration. Key differences include: two stacks (not one), lower pressure, no expander, and longer target lifetime.

# 2012 Transportation Fuel Cell System Details

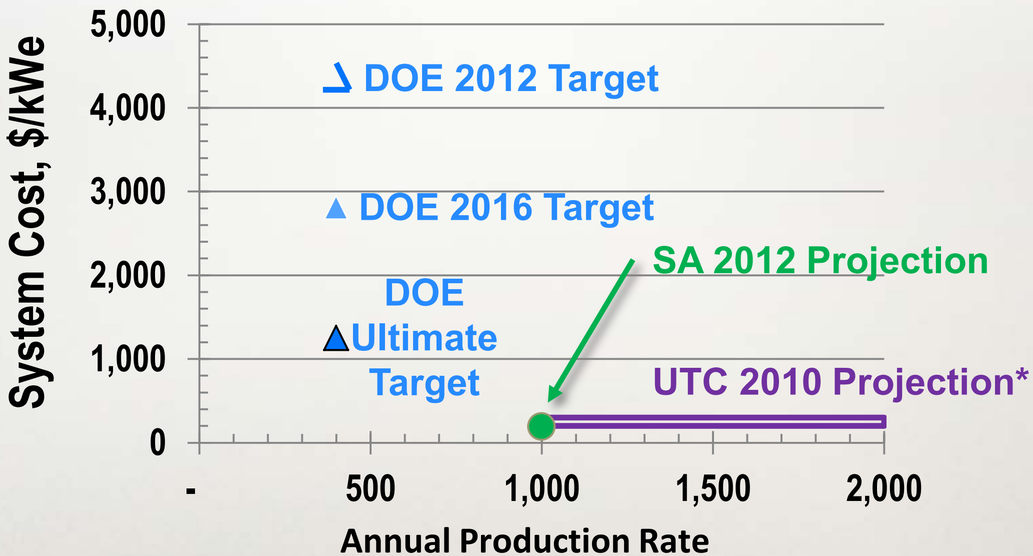
| | 2012 Auto Technology System | 2012 Bus Technology System |
|---|---|---|
| Power Density ($mW/cm^2$) | **984** | **716** |
| Total Pt loading ($mgPt/cm^2$) | **0.196** | **0.4** |
| Net Power ($kW_{net}$) | **80** | **160** |
| Gross Power ($kW_{gross}$) | 88.24 | 177.10 |
| Operating Pressure (atm) | **2.50** | **1.80** |
| Peak Stack Temp. (°C) | 87 | 74 |
| Active Cells | 369 | 739 |
| Membrane Material | Nafion on 25-micron ePTFE | Nafion on 25-micron ePTFE |
| Radiator/ Cooling System | Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler | Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler |
| Bipolar Plates | Stamped SS 316L with TreadSton Litecell™ Coating | Stamped SS 316L with TreadStone Litecell™ Coating |
| Air Compression | **Centrifugal Compressor, Radial-Inflow Expander** | **Centrifugal Compressor, Without Expander** |
| Gas Diffusion Layer (GDL) | Carbon Paper Macroporous Layer with Microporous Layer (Ballard Cost) | Carbon Paper Macroporous Layer with Microporous Layer (Ballard Cost) |
| Catalyst Application | 3M Nanostructured Thin Film (NSTF™) | 3M Nanostructured Thin Film (NSTF™) |
| Air Humidification | Tubular Membrane Humidifier | Tubular Membrane Humidifier |
| Hydrogen Humidification | None | None |
| Exhaust Water Recovery | None | None |
| Membrane Electrode Assembly (MEA) Containment and Gasketing | Screen Printed Seal on MEA Subgaskets, GDL crimpted to Catalyst Coated Membrane (CCM) | Screen Printed Seal on MEA Subgaskets, GDL crimpted to Catalyst Coated Membrane (CCM) |
| Coolant & End Gaskets | Laser Welded (Cooling gasket), Screen-Printed Adhesive Resin (End gasket) | Laser Welded (Cooling), Screen-Printed Adhesive Resin (End) |
| Freeze Protection | Drain Water at Shutdown | Drain Water at Shutdown |
| Hydrogen Sensors | 2 for FC System<br>1 for Passenger Cabin (not in cost estimate)<br>1 for Fuel System (not in cost estimate) | 2 for FC System<br>1 for Passenger Cabin (not in cost estimate)<br>1 for Fuel System (not in cost estimate) |
| End Plates/ Compression System | Composite Molded End Plates with Compression Bands | Composite Molded End Plates with Compression Bands |
| Stack Conditioning (hrs) | 5 | 5 |

← Lower power density
← Higher cat. loading
← Higher net power
← Lower pressure
← No expander

Nafion is a registered trademark of E. I. duPont de Nemours and Company

# 2012 Bus Total System Cost Results: ~$200/kW at 1,000 systems per year

| | 2012 Bus System |
|---|---|
| **Annual Production Rate** | **1,000** |
| System Net Electric Power (Output) | 160 |
| System Gross Electric Power (Output) | 177.10 |
| Fuel Cell Stacks | $21,651.24 |
| Balance of Plant | $8,707.03 |
| System Assembly & Testing | $152.34 |
| Total System Cost ($) | $30,510.60 |
| Total System Cost ($/$kW_{net}$) | $190.69 |
| Total System Cost ($/$kW_{gross}$) | $172.28 |

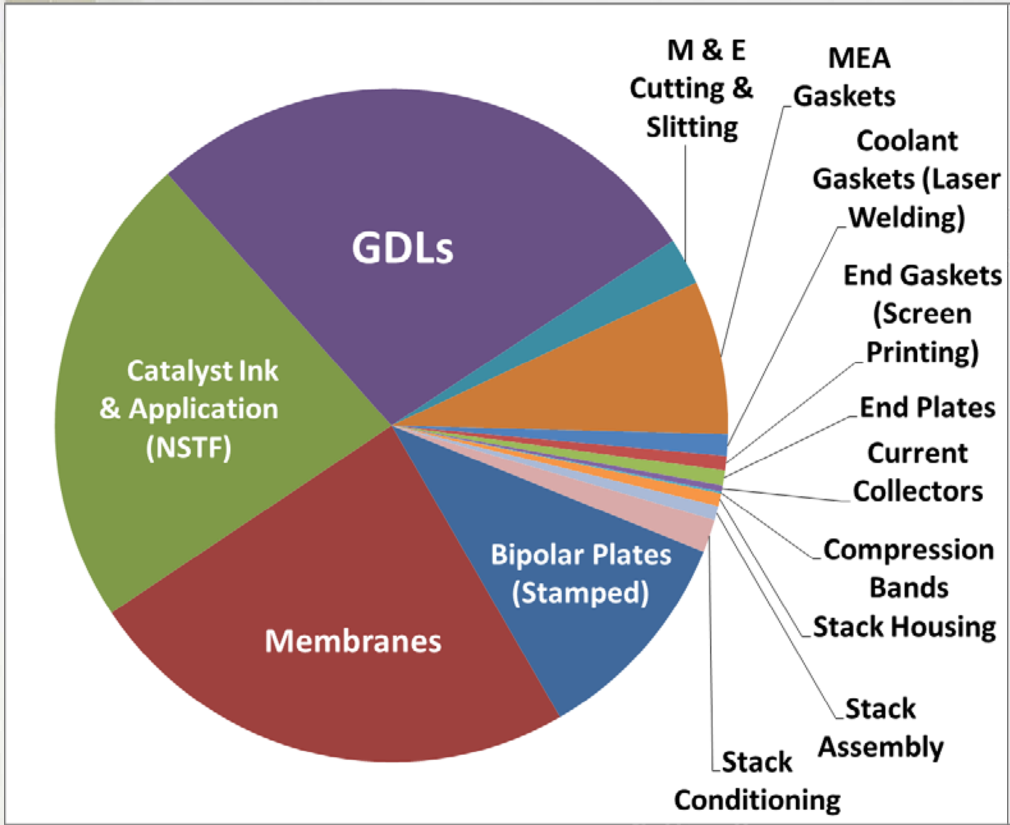



DOE Targets include Fuel Cell plus Batteries whereas SA Target are Fuel Cell only.

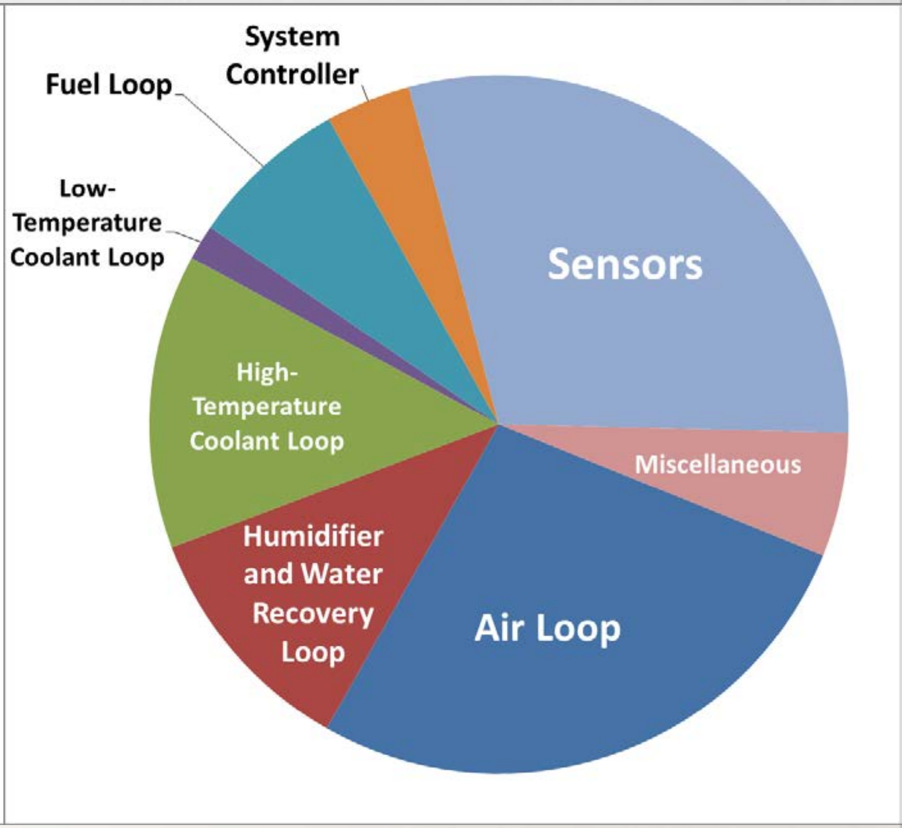
* 2010 DOE AMR Joint DOE/DOT Bus Workshop, "Progress and Challenges for PEM Transit Fleet Applications", Tom Madden, UTC, 7 June 2010: 2010 UTC Preliminary Bus Fleet Cost Target: $200-300/kW in 1,000's per year.

# 2012 Bus Stack and BOP Costs

**Bus Stack Costs**




**Bus BOP Costs**

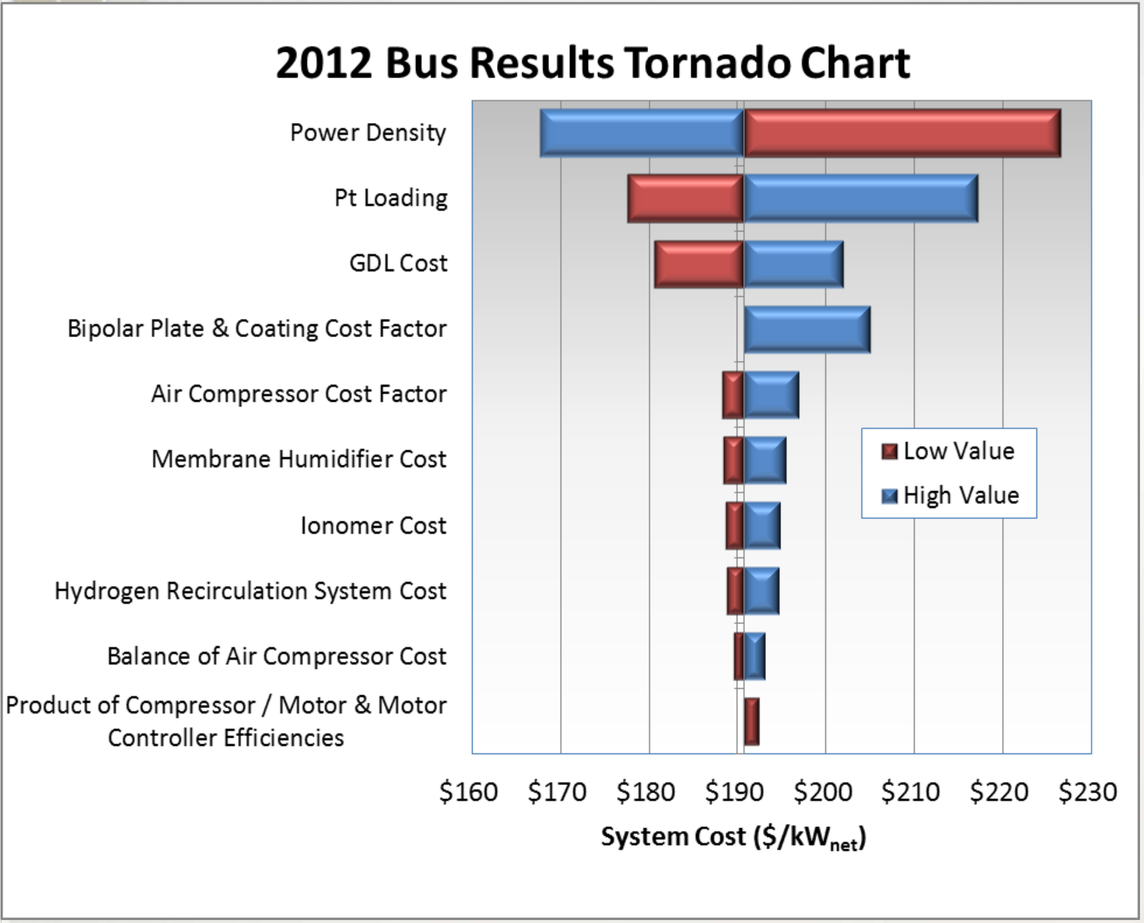



**Total Stack Cost: $21,651**

**Total BOP Cost: $8,707**

- **Stack cost dominated by the MEA components**
- **BOP costs dominated by sensors and air loop**

# 2012 Bus System Single-Variable Analysis:
## Power Density & Pt Loading are primary uncertainties



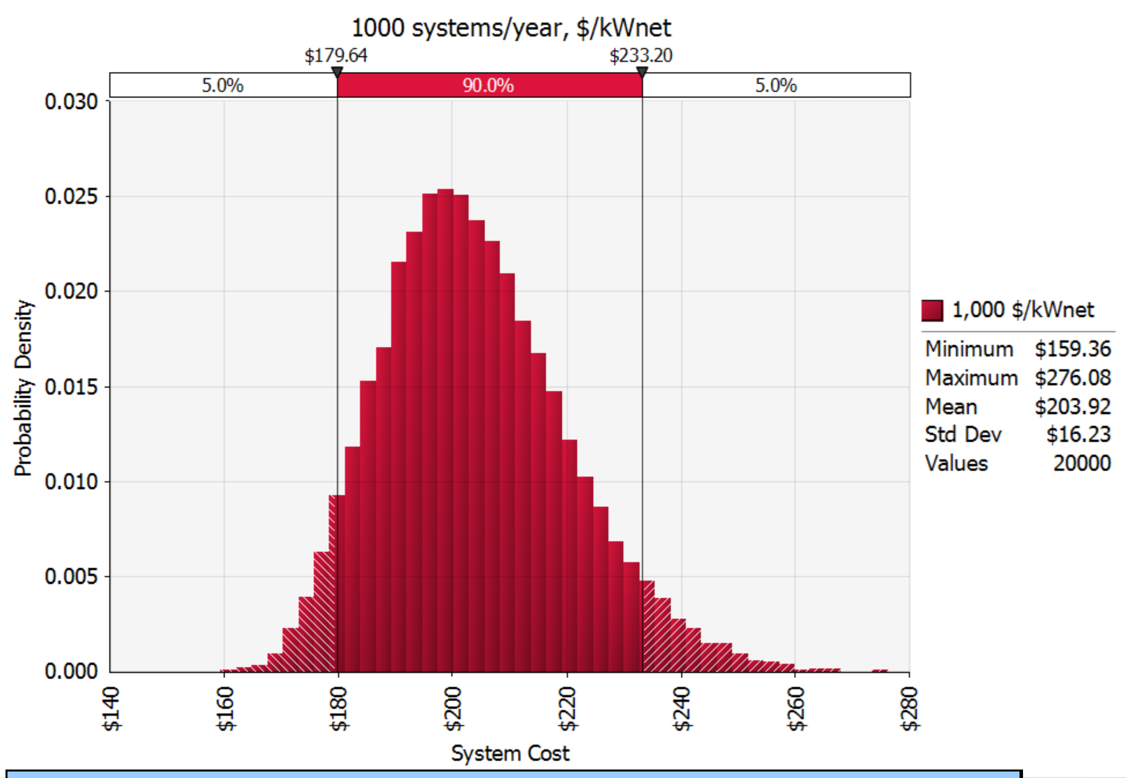

| System Cost ($/kWnet), 1,000 sys/year | | | | |
|---|---|---|---|---|
| **Parameter** | **Units** | **Low Value** | **Base Value** | **High Value** |
| Power Density | $mW/cm^2$ | 500 | **716** | 984 |
| Pt Loading | $mgPt/cm^2$ | 0.2 | **0.4** | 0.8 |
| GDL Cost | $\$/m^2$ | $74.10 | **$115.87** | $151.02 |
| Bipolar Plate & Coating Cost Factor | | 1 | **1** | 2 |
| Air Compressor Cost Factor | | 0.8 | **1** | 1 |
| Membrane Humidifier Cost | $/system | $382.83 | **$765.66** | $1,531.32 |
| Ionomer Cost | $/kg | $45.65 | **$204.00** | $500.00 |
| Hydrogen Recirculation System Cost | $/system | $321.00 | **$641.99** | $1,283.98 |
| Balance of Air Compressor Cost | $/system | $185.25 | **$370.50** | $741.00 |
| Product of Compressor / Motor & Motor Controller Efficiencies | % | 51% | **59%** | 64% |
| **2012 Bus System Cost** | | | | **$190.69** |

**Upper & lower limits are based on auto analysis limits (which were vetted with Fuel Cell Tech Team for auto application).**

# 90% Confidence System Cost is between $180 & $233/kW$_{e\text{-}net}$

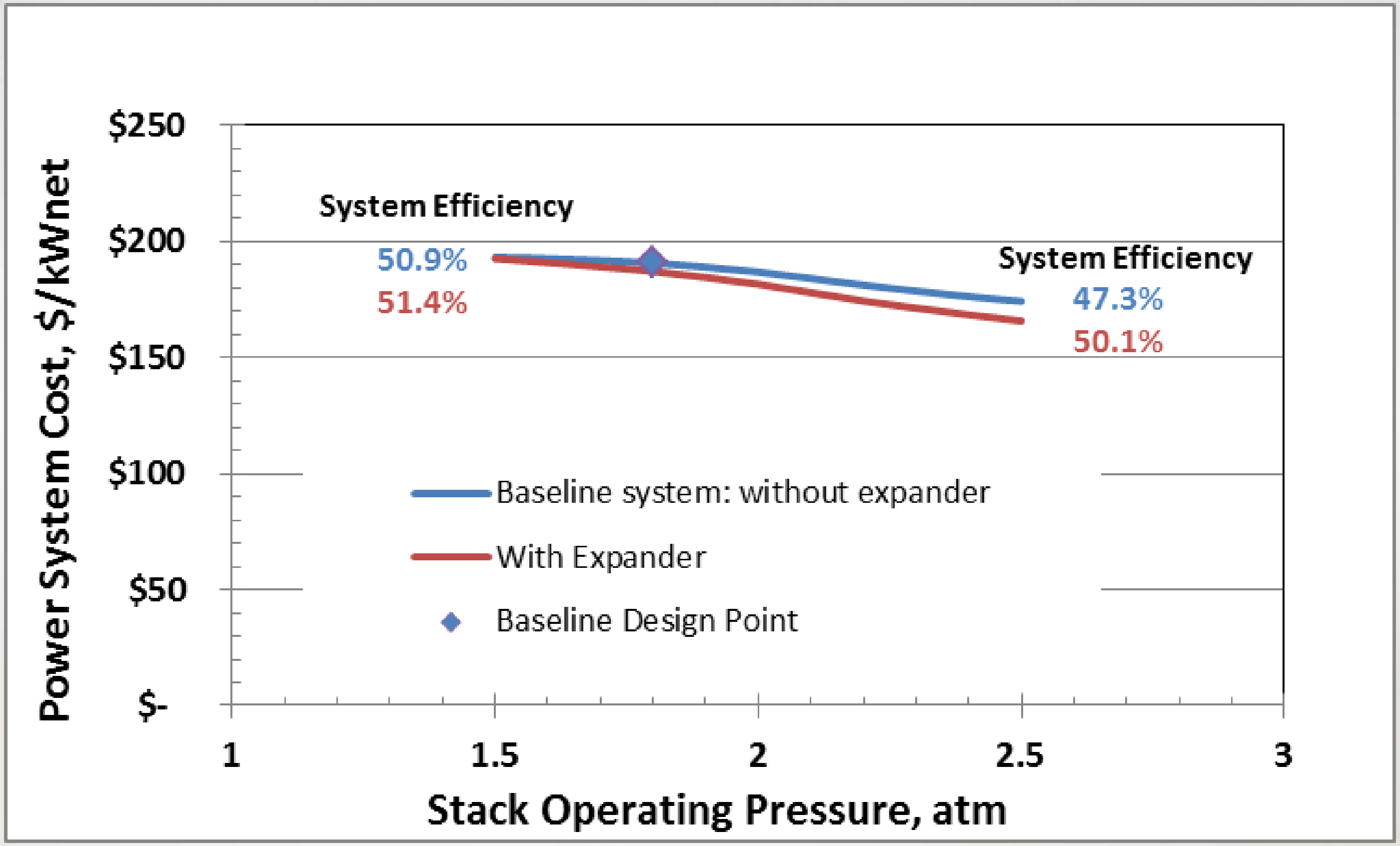
Bus confidence range is wider than for auto:

Bus: -6% and +22%
Auto: -2% and +11%




| 2012 Bus Technology Monte Carlo Analysis, 1k sys/year | | | | |
|---|---|---|---|---|
| **Parameter** | **Unit** | **Minimum Value** | **Likeliest Value** | **Maximum Value** |
| Power Density | **mW/cm2** | 500 | **716** | 984 |
| Pt Loading | **mgPt/cm2** | 0.2 | **0.4** | 0.8 |
| Ionomer Cost | **$/kg** | $45.65 | **$204.00** | $500.00 |
| GDL Cost | **$/m2** | $84.10 | **$115.87** | $151.02 |
| Bipolar Plate & Coating Cost Factor | | 1 | **1** | 2 |
| Membrane Humidifier Cost | **$/system** | $382.83 | **$765.66** | $1,531.32 |
| Product of Compressor / Expander / Motor & Motor Controller Efficiencies | | 0.510 | **0.588** | 0.64 |
| Air Compressor Cost Factor | | 0.8 | **1** | 1.5 |
| Balance of Air Compressor Cost | **$/system** | $185.25 | **$370.50** | $741.00 |
| Hydrogen Recirculation System Cost | **$/system** | $321.00 | **$641.99** | $1,283.98 |

# 2012 Bus System Sensitivity to Exhaust Gas Expander Use




- Sensitivity analysis suggests that 2.5 atm system with exhaust gas expander results in lowest system cost
- Difference between system design with & without expander is observed to be very small (<4%)

# Bus Cost Analysis Future Actions

- Conduct 2013 Update
- Examine additional system manufacturing rates
  - 200, 400, and 1,000 systems per year
- Reconsider extent of vertical integration
- Incorporate additional feedback on bus design/costing assumptions
- Reconsider air compression system
- Update membrane humidifier cost analysis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# 2013 Light Duty Automotive Cost Update

- Alternative MEA fabrication method (Gore)
- Plate Frame Humidifier (Gore/dPoint)
- Stack Quality Control equipment re-evaluation
- Updated polarization performance and cost optimization


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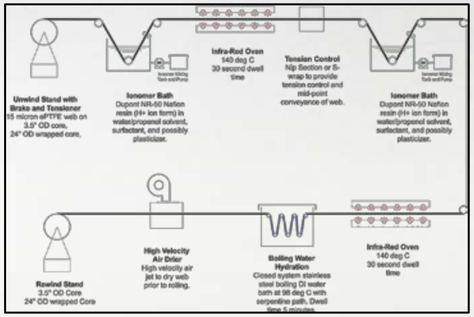
# Evaluation of Alternative MEA Fabrication

## Previous (2012) Membrane Electrode Assembly (MEA) Process

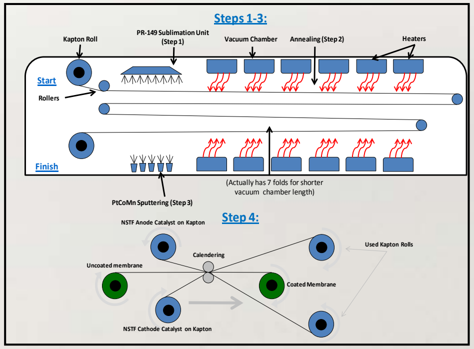
- Membrane Fabrication
  - Roll-to-Roll process
  - Occluding pores of ePTFE substrate

- MEA Formation via Vacuum Process
  - 3M Nanostructured Thin Film (NSTF) process
    - Sublimation of PR-149
    - Anneal (to grow high surface area whiskers)
    - Vacuum deposition to coat whiskers with ternary catalyst
  - Hot calendaring to bond NSTF electrodes to membrane

**2012 Membrane Fab.**




**2012 MEA Fab.**




Nafion and Kapton are registered trademarks of E. I. duPont de Nemours & Company

# NEW for 2013:

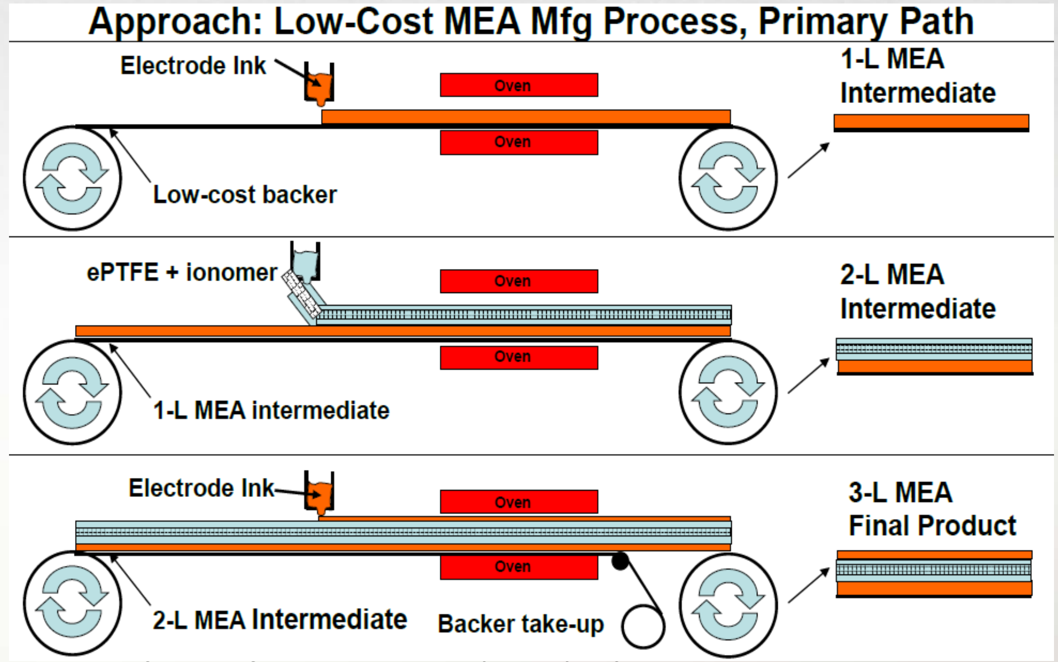
## Gore Low Cost MEA Manufacturing Process

# Gore MEA Manufacturing Process Description

**Station 1: Anode Application**

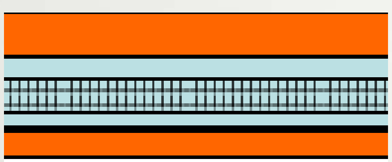
**Station 2: Electrolyte Applied to Anode**

**Station 3: Cathode Application**




Source: 2012 Gore AMR Presentation "Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies Engineered for Rapid Conditioning", F.C. Busby, W.L. Gore & Assoc., 16 May 2012.

- 3-Layer MEA Finished Product



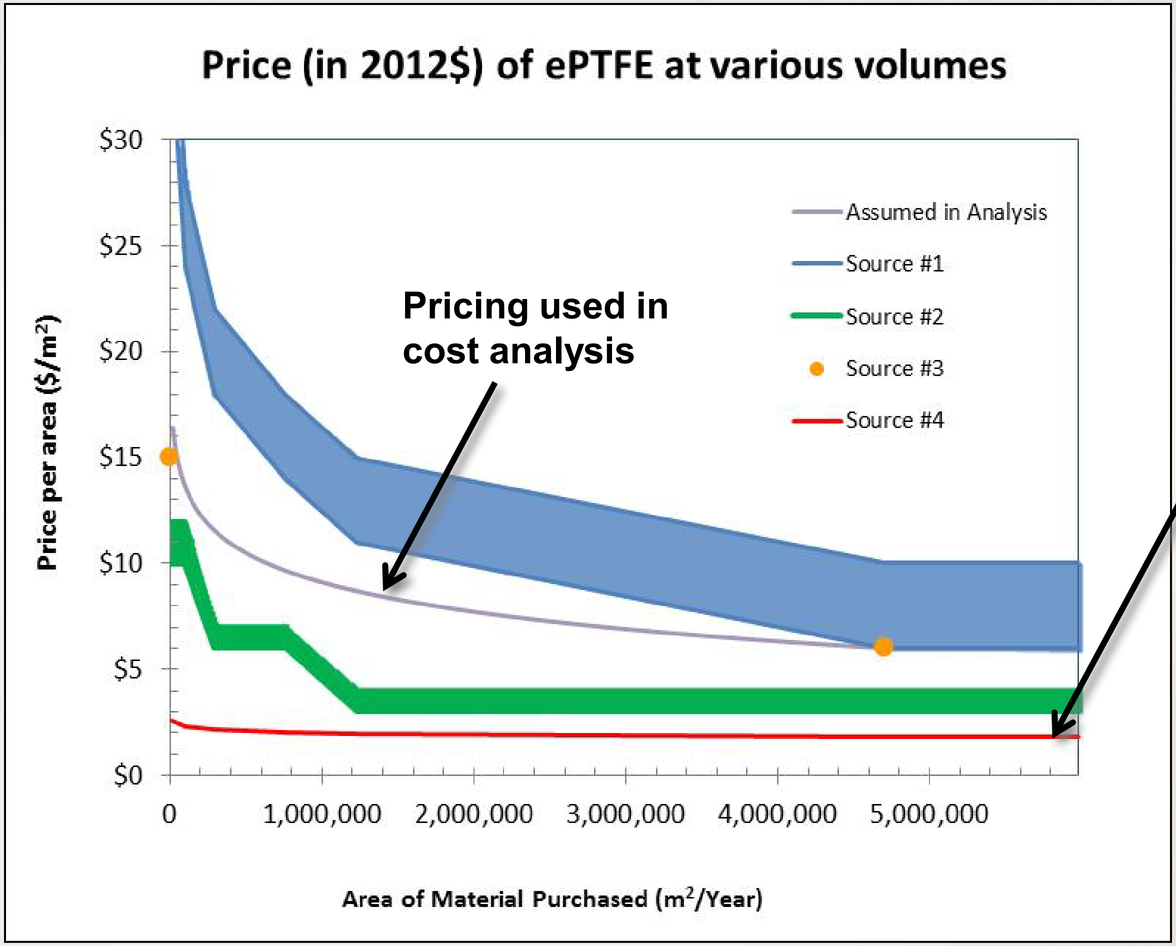
150 μm cathode (Pt on Carbon) (ink comp. from Umicore US Pat. #7,141,270)

25 μm Nafion® on ePTFE (comp./applic. parameters from DuPont US Pat. #7,648,660 B2)

50 μm anode (Pt on Carbon) (ink comp. from Umicore US Pat. #7,141,270)

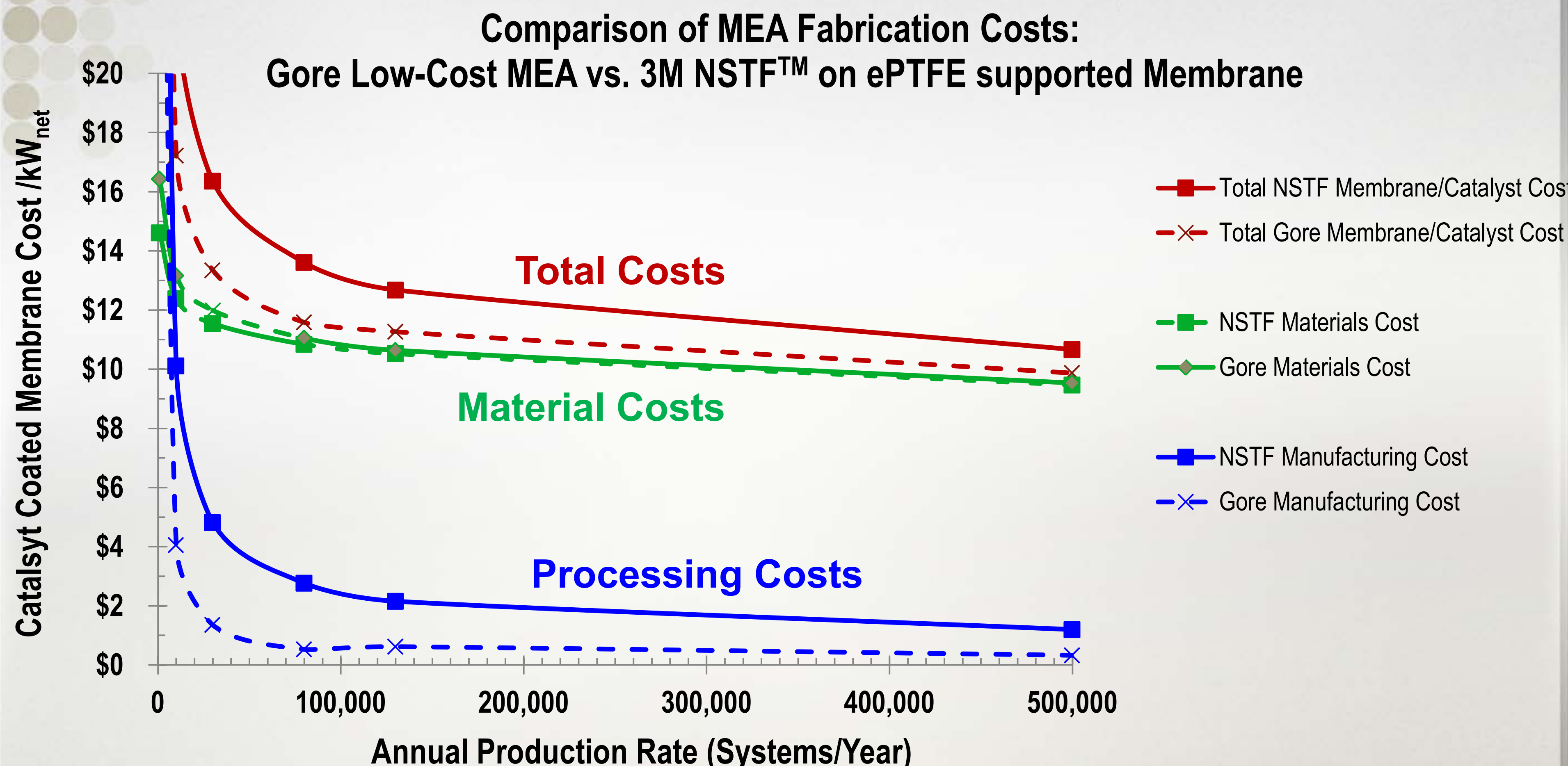
- Key Features
  - Rapid, Roll-to-Roll based deposition (10+ meters/min web speed)
  - No vacuum processes

# ePTFE Price Comparison: Wide Range of Vendor Estimates



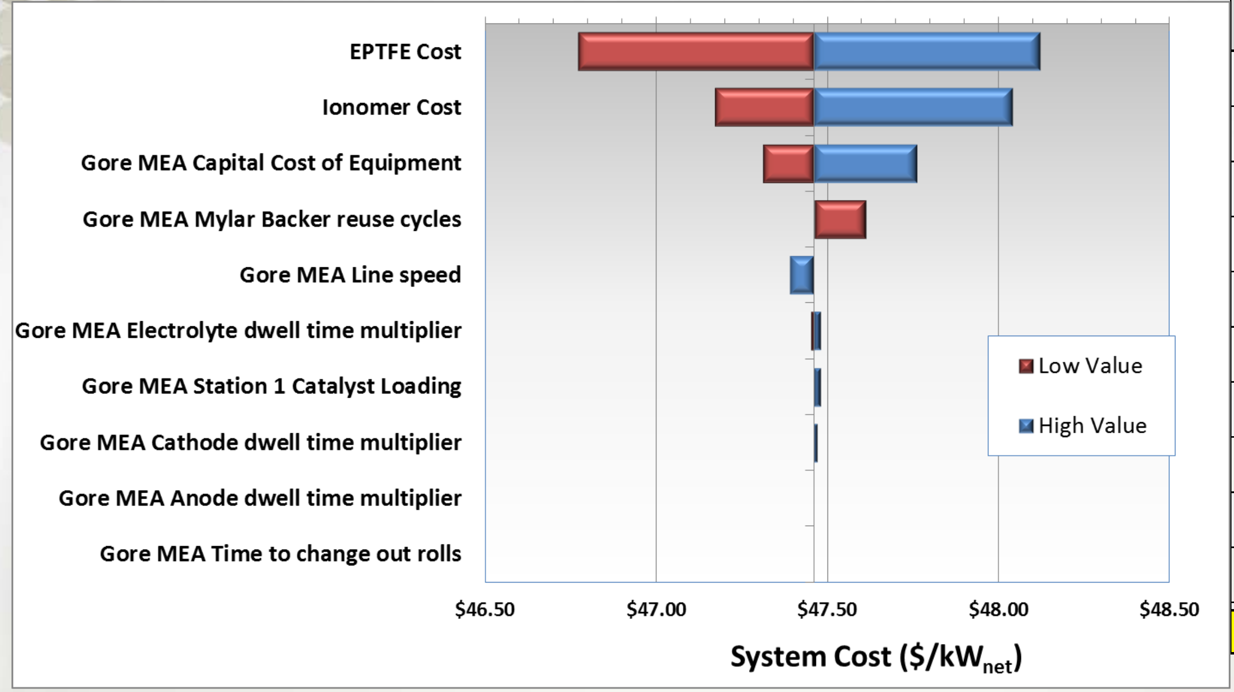

- Cost of starting materials (PTFE) dependent on grade and quality
- "Fuel cell grade" more expensive than "textile grade"
- Material produced within US more expensive than material produced in countries with lower wages

# Gore MEAs and 3M NSTF™/Membrane Catalyst Coated Membrane are expected to have similar costs




- Material costs are about the same (since dominated by Pt cost)
- Gore processing costs are expected to be lower due to non-vacuum processing and faster line speeds
- Total costs are quite similar
- Polarization performance is critical factor in selection

# MEA Sensitivity




| System Cost ($/kWnet), 500,000 sys/year | | | | |
|---|---|---|---|---|
| Parameter | Units | Low Value | Base Value | High Value |
| EPTFE Cost | $/m$^2$ | 1.82 | 6 | 10 |
| Ionomer Cost | Multiplier | 0.5 | 1 | 2 |
| Gore MEA Capital Cost of Equipment | Multiplier | 0.5 | 1 | 2 |
| Gore MEA Mylar Backer reuse cycles | cycles | 1 | 5 | 10 |
| Gore MEA Line speed | m/min | 3 | 10 | 300 |
| Gore MEA Electrolyte dwell time multiplier | multiplier | 0.5 | 1 | 2 |
| Gore MEA Station 1 Catalyst Loading | mg/cm2 | - | 0.05 | 0.146 |
| Gore MEA Cathode dwell time multiplier | multiplier | 0.5 | 1 | 2 |
| Gore MEA Anode dwell time multiplier | multiplier | 0.5 | 1 | 2 |
| Gore MEA Time to change out rolls | min | 1 | 10 | - |
| **2013 Auto System Cost** | | | **$47.46** | |

Mylar is a registered trademark of DuPont Teijin Films.

- Top three cost uncertainties:
  - ePTFE cost
  - Maximum coating speed
  - Ionomer cost
- None the less, MEA uncertainty is still only~ +/-2% for each variable.

- Caveat: MEA performance assumed to equal that of modeled 3M NSTF MEA

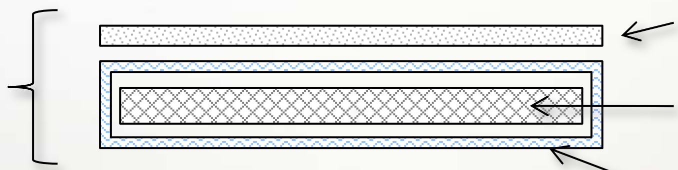
# Evaluation of Alternative Humidifier Design

## Previous (2012) Humidifier Concept

- Tubular membrane system (~1500 2-mm diameter tubes)
- Based on Perma-Pure LLC design
- Based on (only) 2m$^2$ of membrane area => under-designed

## NEW for 2013:
## Gore Plate-Frame Humidifier Concept

Repeat Unit



Stainless steel flow field

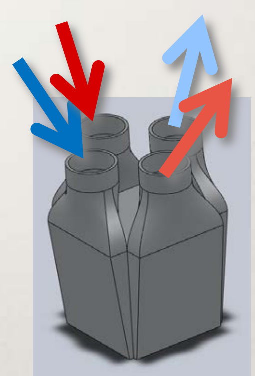
Stainless steel flow field

Composite membrane pouch (i.e. a loop of membrane with open ends)

Primary air (dry air) flows in cross flow direction over outside of pouch.
Secondary flow (wet air) flows through inside of pouch.

**Primary Air Flow**

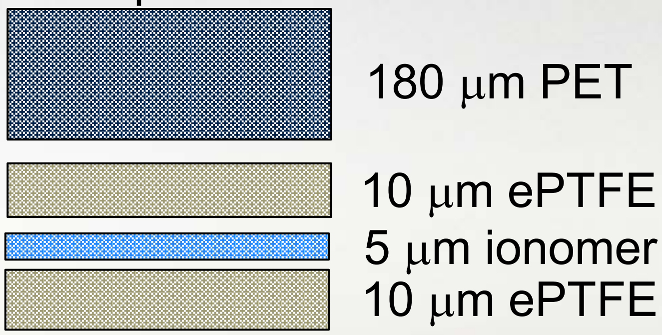
**Secondary Air Flow**



# Formation of Composite Membrane

- Steps:
  - Unroll ePTFE layer on Mylar® backer
  - Die-slot coat layer of ionomer onto ePTFE
  - Unroll second ePTFE layer onto ionomer
  - Pass through continuous curing oven
  - Laminate with PET layer
  - Wind onto roll

Assumed Construction of Composite Membrane




**Cost is based on an SA interpretation of open-literature sources of how the composite membrane might be constructed/fabricated.**


# Overview of Manufacturing Steps

| Station No. | Purpose | Method |
|---|---|---|
| 1 | Formation of Composite Membrane | Web converting machinery |
| 2 | Secondary Flow Field Fabrication | Electro-chemical etching |
| 3 | Formation of membrane pouch | Custom machinery |
| 4 | Primary Flow Field Fabrication | Sheet metal stamping |
| 5 | Assembly of “pouch stack” | Robotic assembly |
| 6 | Housing formation | Aluminum die-casting |
| 7 | Final assembly | Manual/Robotic assembly |
| 8 | System Test | Air flow pressure drop, leakage measurement |

# Humidifier System Cost: ~$80 at 500k sys/year

(based on 1.5m$^2$ of humidifier membrane per system)

All at 500k systems per year

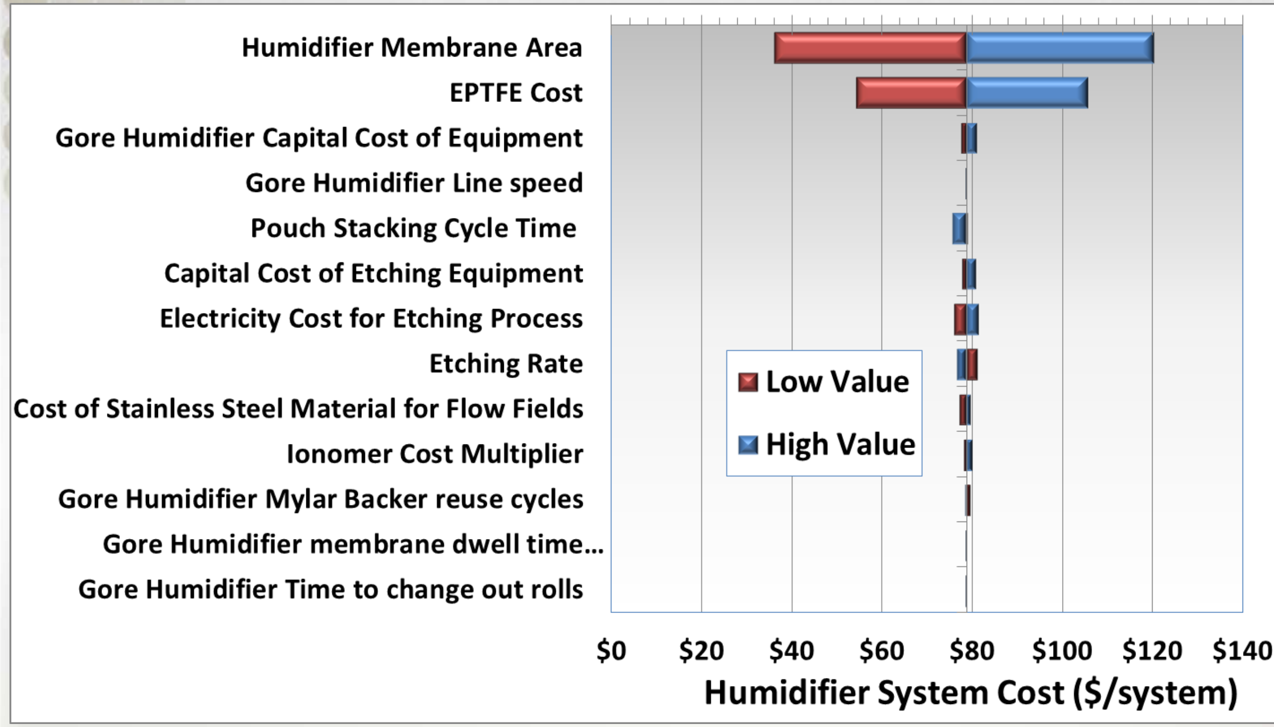
| Component Costs per Humidifier System | | Materials | Manuf. | Tools | Secondary Operations | Markup | Total |
|---|---|---|---|---|---|---|---|
| Station 1: Membrane Fabrication | $/stack | $27.58 | $2.16 | $0.15 | $0.00 | $7.47 | $37.35 |
| Station 2: Humidifier Etching (Flow Field Plates) | $/stack | $7.06 | $10.38 | $0.00 | $0.00 | $0.00 | $17.44 |
| Station 3: Pouch Forming | $/stack | $0.41 | $1.28 | $0.05 | $0.00 | $0.00 | $1.74 |
| Station 4: Stamp SS ribs | $/stack | $0.60 | $1.41 | $3.38 | $0.00 | $0.00 | $5.39 |
| Station 5: Stack Forming | $/stack | $1.35 | $6.76 | $0.00 | $0.00 | $0.00 | $8.12 |
| Station 6: Stack Housing | $/stack | $5.05 | $0.50 | $1.21 | $0.00 | $0.00 | $6.76 |
| Station 7: Assembly of Stack into Housing | $/stack | $0.00 | $1.60 | $0.00 | $0.00 | $0.00 | $1.60 |
| Station 8: System Test | $/stack | $0.00 | $0.32 | $0.00 | $0.00 | $0.00 | $0.32 |
| **Totals =** | | **$42.05** | **$24.42** | **$4.78** | **$0.00** | **$7.47** | **$78.72** |


- Membrane & Flow fields make up 2/3rds of cost.
- Materials are about half of total cost.
- Potential for cost reduction:
  - Further membrane area reduction
  - Alternative flow field formation/materials

# Humidifier membrane cost dominated by material cost

| Component | Per unit costs (at 500k sys/yr) | Total per unit costs (at 500k sys/yr) |
|---|---|---|
| Materials | | |
| 2 layers of ePTFE | 2 x $1.5m^2_{memb.}$ x $8.2/$m^2_{ePTFE}$ => $26 | Materials Total = ~$27.5 |
| Ionomer material | $75/kg => $1.2 | |
| PET layer | $0.3 | |
| Processing | $2.1 | ~$2.1 |
| Markup (to membrane supplier) | 25% markup at 500k systems/yr | ~$7.4 |
| Total composite humidification membrane | | ~$37 |

# Humidifier Sensitivity: Primary uncertainty due to membrane area required




| Parameter | Units | Low Value | Base Value | High Value |
|---|---|---|---|---|
| Humidifier Membrane Area | $m^2$ (cells) | 0.5 (25 cells) | 1.5 (75 cells) | 2.6 (130 cells) |
| EPTFE Cost | $/$m^2$ | 1.76 | 7.05 | 12.85 |
| Gore Humidifier Capital Cost of Equipment | Multiplier | 0.5 | 1 | 2 |
| Gore Humidifier Line speed | m/min | 3 | 10 | 300 |
| Pouch Stacking Cycle Time | sec | 5 | 9 | 11 |
| Capital Cost of Etching Equipment | Multiplier | 0.5 | 1 | 2 |
| Electricity Cost for Etching Process | $/kWh | 0.04 | 0.08 | 0.12 |
| Etching Rate | microns/min | 10 | 13.33 | 20 |
| Cost of Stainless Steel Material for Flow Fields | $/kg | 1.5 | 1.96 | 2.25 |
| Ionomer Cost Multiplier | Multiplier | 0.5 | 1 | 2 |
| Gore Humidifier Mylar Backer reuse cycles | cycles | 1 | 5 | 10 |
| Gore Humidifier membrane dwell time multiplier | multipler | 0.5 | 1 | 2 |
| Gore Humidifier Time to change out rolls | min | 1 | 10 | 15 |
| **2013 Gore Humidifier System Cost** | | | **$78.73** | |



- Top two cost uncertainties:
  - Required membrane area
  - ePTFE cost
- While this uncertainty is high (-54%/+52%), the overall humidifier cost is low compared to total power system cost.

# Quality Control (QC) Update

- 2012 QC diagnostics reviewed by QC expert at NREL (Mike Ulsh) and improvements identified.
- More rigorous definition of QC equipment
- General Approach:
  - Postulate required resolution required for defect identification
  - Specify equipment needed for required line speed
  - Don’t let QC equipment be the pacing component
- Summary of Changes
  - High resolution cameras for roll-to-roll manufacturing lines
  - More rigorous analysis leads to higher cost systems
  - QC impact is still relatively low.
    - But cost of not developing high rate QC systems can be very high
    - NREL presentation (Mike Ulsh) presents some cost impacts.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# Quality Control Update Details

| Part Tested | 2011/2012 Diagnostic System | 2013 Diagnostic System | Comment on Change | Detection Resoluion | Total QC Cost (at 500k sys/yr) | Fault/Parameters Tested |
|---|---|---|---|---|---|---|
| **Membrane Station 1 (electrode)** | XRF (point measurement only) OR IR/DC | **IR/DC** | Applied to Gore MEA manufacturing process. | 2mm x 2mm | $190k | Uneveness of electrode conductivity as indicator of electrode thickness variation. |
| **Membrane Station 2 (ePTFE/Ionomer)** | Optical Detection System | **Optical Detection System** | Applied to Gore MEA manufacturing process. Compute # of cameras needed based on pixels per line, FOV, target resolution. | 20 micron | $392k | Visual inspection to locate pinholes in ionomer, discolorations that would indicate thickness variation or other problems. |
| **Membrane Station 3 (electrode)** | XRF (point measurement only) OR IR/DC | **IR/DC** | Applied to Gore MEA manufacturing process. | 2mm x 2mm | $190k | Uneveness of electrode conductivity as indicator of electrode thickness variation. |
| **NSTF Catalyst** | Previously IR Camera (cooled) which was supposed to IR/DC but is still developmental. | Not used. | Not needed for Gore MEA. | | | Catalyst Loading, particle size, defects, general Pt uniformity |
| **NSTF Catalyst** | Previously IR Camera (cooled) which was supposed to IR/DC but is still developmental. | Not used. | Not needed for Gore MEA. | | | Catalyst Loading, particle size, defects, general Pt uniformity |
| **MEA (after cutting/slitting)** | XRF (point measurement only) | Not used. | Not needed (since now 3M subgasketing approach). Also XRF does not work for this failure mode. | | | Thickness, cracks, delamination |
| **Gasketed MEA (Subgasket)** | Optical Thickness and Surface Topology System | Optical Detection System (commercial system from Keyence) | Nanovea system is overkill. Switching to ODS. | 0.6mm | $80k | Misalignmnet of subgasket and membrane. Folds, bends, tears, scratches in subgasket or membrane. |
| **Bipolar Plate** | NIST Non-Contact Laser Triangulation Probe | **NIST Non-Contact Laser Triangulation Probe, Optical Detection System (commercial system from Keyence)** | Triang. Probes (3) used in a single pass (or possible two passes) to detect minute anolmolies in flow field channel formation and out of flatness. Single pass only provides small fraction of areal inspection. Optical system used to scan entire plate to detect gross anomolies. | ~30 micron over 3 scan lines (one side of plate, 3 probes, single pass), 0.6 mm for Optical Camera (entire plate, one side) | $100.6k | Triangulation: flow field depth, plate flatness. Optical System: general dimensions, completeness of manifold apertures. |
| **GDL (Microporous Layer)** | Mass Flow Meter | Mass Flow Meter | Same. | | | Proper layer coverage |
| **GDL (Microporous Layer)** | Viscometer | Viscometer | Same. | | | Proper layer coverage |
| **GDL (Final Product)** | Inline Vision System | Ballard Optical Detection System | Since Ballard has custom system, keep with their estimates. | <=0.5mm | $100k | Cracks, improper layer coverage, defects |
| **End Plate** | Conveyor Mass Scale | Commercial vision system (from Keyence) | Change to ODS. Inspect both sides (with flip in between). | 0.6mm | $100k | Completeness of injection molding |
| **End Plate** | Human Visual Inspection | Human Visual Inspection | Eliminate | | | Completeness of injection molding, surface texture/color |
| **Laser Welding for Bipolar Plates** | Optical Seam Inspection System | Optical Seam Inspection System | Same. | | | Completeness of laser weld |

# Improved Polarization Model from ANL

- Based on additional 3M NSTF™ cell measurements
- Includes bipolar plate voltage loss (i.e. models stack performance, not just cell performance)
- Extended to 3 atm (from previous 2.5 atm upper limit)

$$E = (\text{Cell Voltage}) = V_0 + V_1(I - I_r) + V_2(I - I_r)^2 + \frac{RT}{F}\ln(0.1417 + 11.26L_{Pt} - 24.167L_{Pt}^2) + (-0.07118 + 1.2853L_{Pt} - 6.7816L_{Pt}^2 + 9.825L_{Pt}^3)I^2$$

$V_0 = a_0 + b_0 SR + c_0 SR^2, \quad V$

$V_1 = a_1 + b_1 SR + c_1 SR^2, \quad V(A \cdot cm^{-2})^{-1}$

$V_2 = a_2 + b_2 SR + c_2 SR^2, \quad V(A \cdot cm^{-2})^{-2}$

$I_r = a_3 + b_3 SR + c_3 SR^2, \quad A \cdot cm^{-2}$

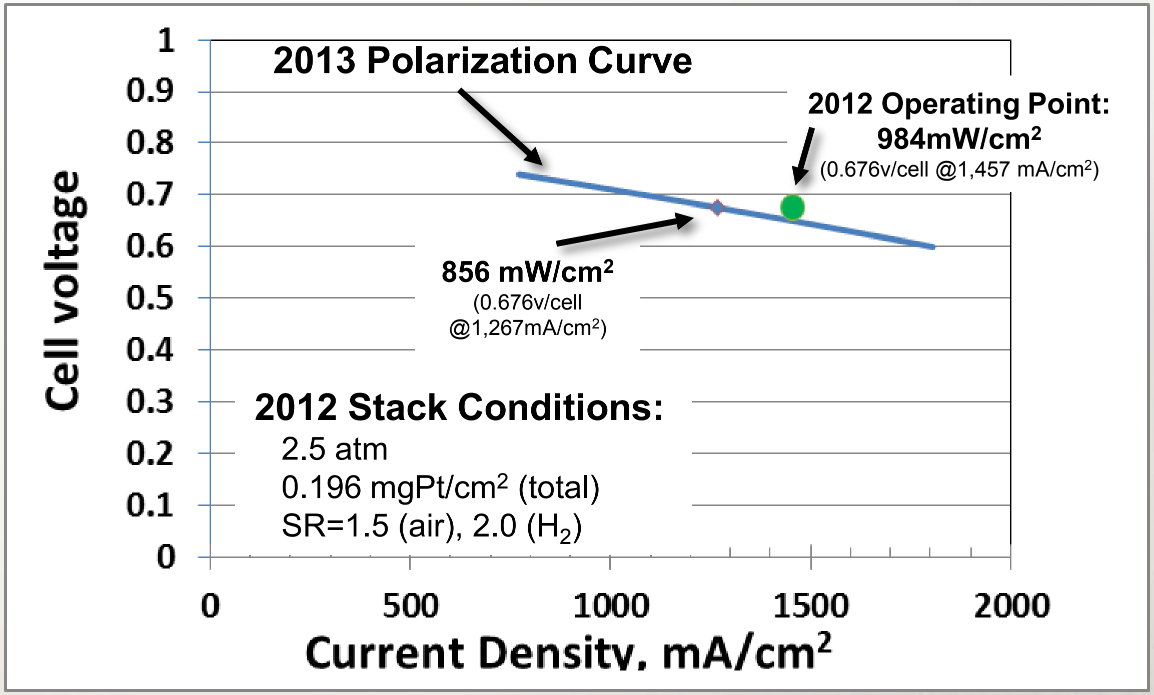
$I$ = Cell Current Density, $A \cdot cm^{-2}$

SR = $O_2$ Stoic. Ratio

$R = 8.314$ = Universal Gas Constant, $J \cdot mol^{-1} K^{-1}$

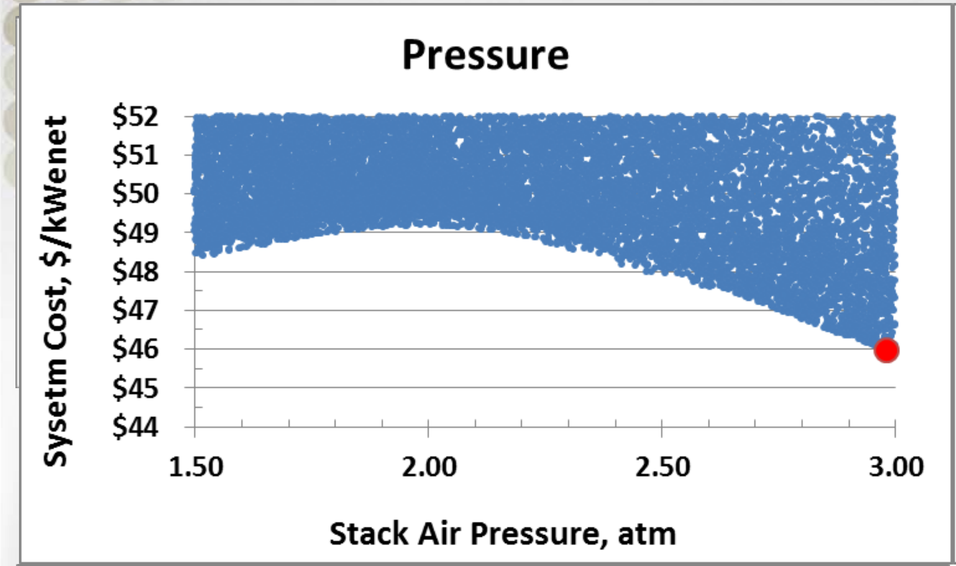
$F = 96{,}485$ = Faraday's Constant, $c \cdot mol^{-1}$

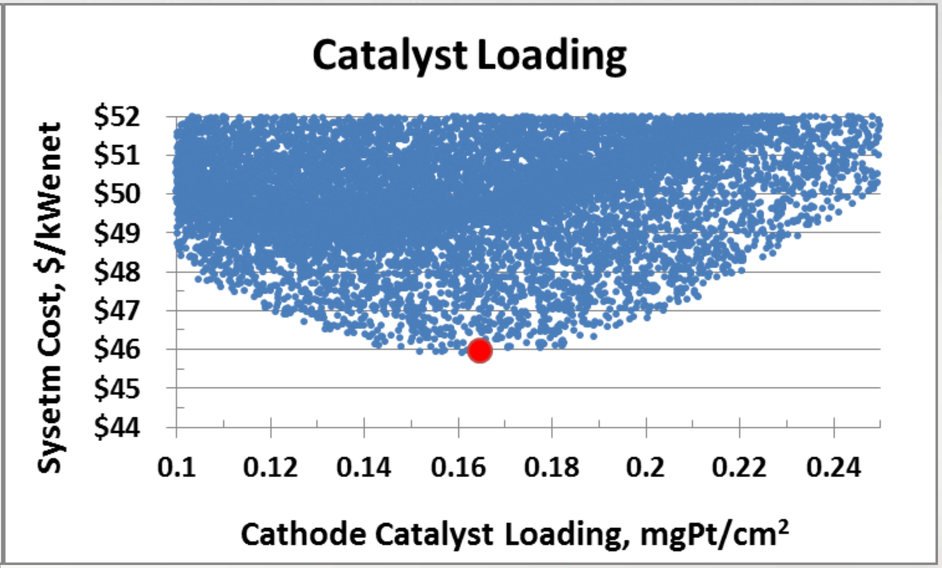
$L_{Pt}$ = Cathode Catalyst Loading, $mg_{Pt} \cdot cm^{-2}$

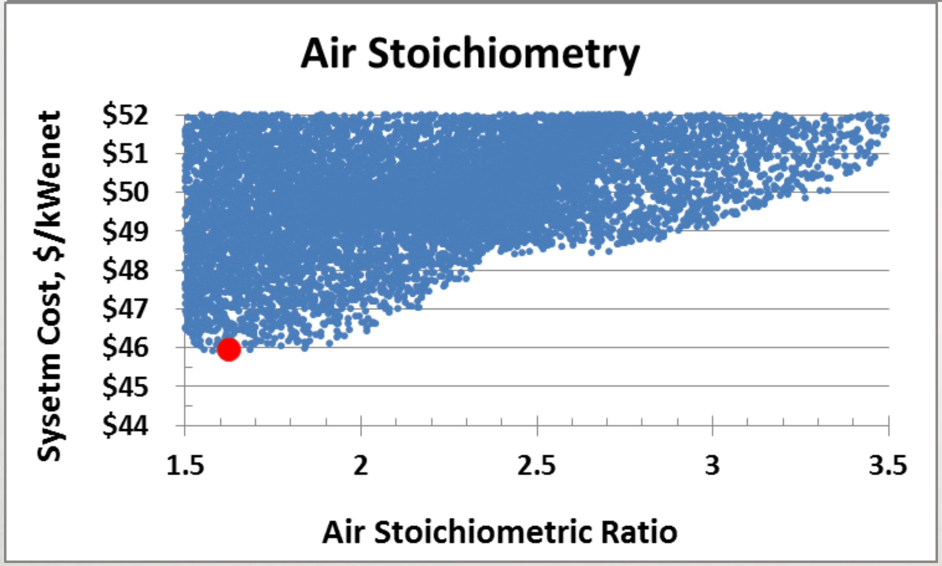


# Monte Carlo Re-optimization of Operating Conditions

(at 500k systems/year)




- Monte Carlo analysis conducted varying stack operating conditions (pressure, catalyst loading, air stoic. ratio)
- Minimum system cost achieved at:
  - Pressure: 3 atm
  - Catalyst loading: 0.215 $mgPt/cm^2$ total (0.5 anode/0.165 cathode)
  - Air Stoichiometry: 1.6
  - Other conditions: $H_2$ Stoic.=2.0 $T_{coolant\_exit}$=88°C

# Operating Conditions Re-optimization
(at 500k systems/year)

| | | 2012 AMR | With 2013 BOP Changes | 2013 AMR Status (with BOP & Pol. Changes |
|---|---|---|---|---|
| Annual Production Rate | system/year | 500,000 | 500,000 | 500,000 |
| Stack Efficiency @ Rated Power | % | 55% | 55% | 55% |
| Cell Voltage @ Rated Power | V/cell | 0.676 | 0.676 | 0.676 |
| Oxygen Stoichiometric Ratio | | 1.5 | 1.5 | 1.6 |
| Stack Operating Pressure @ Rated Power | atm | 2.5 | 2.5 | 3 |
| Stack Coolant Temperature (stack exit) | °C | 82 | 82 | 77 |
| Total Platinum-Group Catalyst Loading | $mgPt/cm^2$ | 0.2 | 0.2 | 0.21 |
| MEA Areal Power Density @ Rated Power | $mW/cm^2$ | 984 | 984 | 1,080 |
| Polarization Performance Basis | | 2012 ANL | 2012 ANL | 2013 ANL |
| **System Cost** | **$\$/kW_{enet}$** | **$46.95** | **$46.32** | **$47.46** |

2013 AMR estimate remains ~ $47/kW.

This is a mid-year estimate and will be further refined.

# Collaborations

- **Argonne National Labs**
  - Stack polarization modeling
  - System design and modeling support
  - Specify key system parameters and range of sensitivity studies
- **National Renewable Energy Laboratory**
  - Expertise on manufacturing and quality control systems
  - Consultation on fuel cell bus systems
- **Industry Collaborators**
  - Technology Developers:
    - Ford, Gore, dPoint Technologies, Ballard, Faraday Technologies
  - Suppliers:
    - Numerous ePTFE suppliers, Robot vendors, steel, Mylar®, adhesives, die-slot coating systems, etc.
  - Vet results and provide manufacturing process insight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# Proposed Future Work

- Bus Systems
  - Extend manufacturing rates: 200, 400, and 1000 per year
  - Reconsider extent of vertical integration
  - Explore air compressor alternatives
  - Incorporate plate frame membrane humidifier analysis
  - Document results
- Auto Systems
  - Continue 2013 update
  - More fully explore pressure/polarization optimization
  - Continue vetting of assumptions
  - Document results

# Conclusions

- Bus cost estimates consistent with Industry (UTC) projection ($191/kW$_{e\text{-}net}$ at 500ksystems/year)
- Auto cost optimization occurs at ~3atm (up from 2.5 atm in 2012 analysis)
- Gore MEA processing cost lower than 3M NSTF™ projections but similar total cost
- Plate Frame Humidifier estimated at ~$80/system (at 500ksystems/year) consistent with industry projections
- Quality control systems projected to add ~1% to system cost, but saves much more in avoided scrap.


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# Summary

- Overview
  - Annually updated cost analysis of automobile & bus fuel cell systems
  - Exploring subsystem alternative configurations
  - In year 2 of 5 year transportation project
- Relevance
  - Cost analysis used to assess practicality of proposed power system, determine key cost drivers, and provide insight for direction of R&D priorities
- Approach
  - Process based cost analysis methodologies (e.g. DFMA)
- Accomplishments
  - 2012 Automobile & Bus analysis complete (report available)
  - 2013 Automotive & Bus analysis underway
  - New subsystems analyzed:
    - Plate frame humidifier
    - Low cost roll-to-roll MEA manufacture (Gore system)
    - Improved quality control techniques
- Collaborations
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
- Future Work
  - Conclude 2013 Auto & Bus analysis
  - Explore alternative air compressor systems


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# Backup slides



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# 2012 Bus Total System Cost Results

| | 2012 Bus System |
|---|---|
| **Annual Production Rate** | **1,000** |
| System Net Electric Power (Output) | 160 |
| System Gross Electric Power (Output) | 177.10 |
| Fuel Cell Stacks | $21,651.24 |
| Balance of Plant | $8,707.03 |
| System Assembly & Testing | $152.34 |
| Total System Cost ($) | $30,510.60 |
| Total System Cost ($/$kW_{net}$) | $190.69 |
| Total System Cost ($/$kW_{gross}$) | $172.28 |

2010 UTC Preliminary Bus Fleet Cost Target: $200-300/kW in 1,000's per year

(from 2010 DOE AMR Joint DOE/DOT Bus Workshop, "Progress and Challenges for PEM Transit Fleet Applications", Tom Madden, UTC, 7 June 2010.)

**2012 DOE Fuel Cell Technologies Program Record**

| | 2012 Status | 2016 Target | Ultimate Target |
|---|---|---|---|
| Production Rate | 400 sys/year | 400 sys/year | 400 sys/year |
| Power Plant Cost[1] | $700k | $450k | $200k |
| System Cost per kW (if 160kW) | $4,375/kW | $2,812/kW | $1,250/kW |

[1] The power plant is defined as the fuel cell system and the battery system. The fuel cell system includes supporting subsystems such as the air, fuel, coolant, and control subsystems. Power electronics, electric drive, and hydrogen storage tanks are excluded.

# 2012 Bus Stack and BOP Costs

## Bus Stack Costs

| | 2012 Bus System |
|---|---|
| **Annual Production Rate** | **1,000** |
| System Net Electric Power (Output) | 160 |
| System Gross Electric Power (Output) | 177.10 |
| Bipolar Plates (Stamped) | $1,141.17 |
| MEAs | |
| Membranes | $2,595.88 |
| Catalyst Ink & Application (NSTF) | $2,466.74 |
| GDLs | $2,959.34 |
| M & E Cutting & Slitting | $245.32 |
| MEA Frame/Gaskets | $799.98 |
| Coolant Gaskets (Laser Welding) | $111.62 |
| End Gaskets (Screen Printing) | $74.80 |
| End Plates | $77.51 |
| Current Collectors | $32.20 |
| Compression Bands | $10.00 |
| Stack Housing | $66.55 |
| Stack Assembly | $73.63 |
| Stack Conditioning | $170.88 |
| Total Stack Cost (single stack) | $10,825.62 |
| Total Stack Cost ($/$kW_{net}$) | $135.32 |
| Total Stack Cost ($/$kW_{gross}$) | $122.25 |

## Bus BOP Costs

| | 2012 Bus System |
|---|---|
| **Annual Production Rate** | **1,000** |
| System Net Electric Power (Output) | 160 |
| System Gross Electric Power (Output) | 177.10 |
| Air Loop | $2,355.14 |
| Humidifier and Water Recovery Loop | $964.62 |
| High-Temperature Coolant Loop | $1,187.73 |
| Low-Temperature Coolant Loop | $142.73 |
| Fuel Loop | $641.99 |
| System Controller | $342.14 |
| Sensors | $2,573.98 |
| Miscellaneous | $498.71 |
| Total BOP Cost | $8,707.03 |
| Total BOP Cost ($/$kW_{net}$) | $54.42 |
| Total BOP Cost ($/$kW_{gross}$) | $49.16 |

# DOE Bus Targets (from 2012 DOE Fuel Cell Record)

| Parameter | Units | 2012 Status | Ultimate Target |
|---|---|---|---|
| **Bus Lifetime** | years/miles | 5/100,000 [a] | 12/500,000 |
| **Power Plant Lifetime**[b,c] | hours | 12,000 | 25,000 |
| **Bus Availability** | % | 60 | 90 |
| **Fuel Fills** [d] | per day | 1 | 1 (<10 min) |
| **Bus Cost** [e] | $ | 2,000,000 | 600,000 |
| **Power Plant Cost**[b, e] | $ | 700,000 | 200,000 |
| **Road Call Frequency (Bus/Fuel-Cell System)** | miles between road calls (MBRC) | 2,500/10,000 | 4,000/20,000 |
| **Operating Time** | hours per day/days per week | 19/7 | 20/7 |
| **Scheduled and Unscheduled Maintenance Cost** [f] | $/mile | 1.20 | 0.40 |
| **Range** | miles | 270 | 300 |
| **Fuel Economy** | mgde[g] | 7 | 8 |

a Status represents data from NREL fuel cell bus evaluations. New buses are currently projected to have 8 year / 300,000 mile lifetime.

b The power plant is defined as the fuel cell system and the battery system. The fuel cell system includes supporting subsystems such as the air, fuel, coolant, and control subsystems. Power electronics, electric drive, and hydrogen storage tanks are excluded.

c According to an appropriate duty cycle.

d Multiple sequential fuel fills should be possible without increase in fill time.

e Cost projected to a production volume of 400 systems per year. This production volume is assumed for analysis purposes only, and does not represent an anticipated level of sales.

f Excludes mid-life overhaul of power plant.



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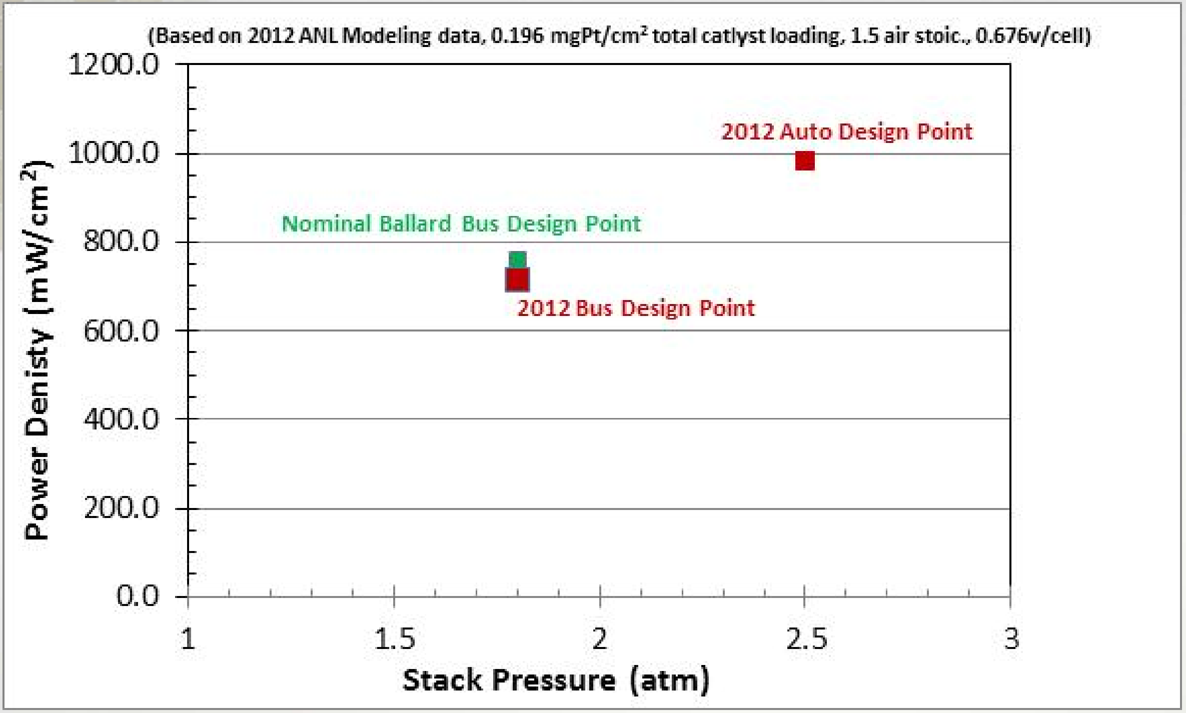
# 2012 Bus System BOL Performance Parameters




| Performance Parameter | 2012 Bus BOL Value |
|---|---|
| Cell Voltage | 0.676 V/cell |
| Current Density | 1,060 mA/cm$^2$ |
| Power Density | 716 mW/cm$^2$ |
| Peak Pressure | 1.8 atm |
| Coolant Outlet Temperature | 74 °C |
| Air Stoichiometry | 1.5 |
| Total Catalyst Loading | 0.4 mgPt/cm$^2$ |

- Catalyst loading is performance modeled at the 2012 auto loading (0.196 Pt/cm$^2$) but cost modeled at 0.4 mgPt/cm$^2$.
- 1.8 atm operation is consistent with Ballard and other bus systems. At this pressure, an exhaust gas expander is not used.
- Lower operating temperature is consistent with bus operation, where maximum power is demanded for a low fraction of operating time. Low temperature also improves system lifetime.

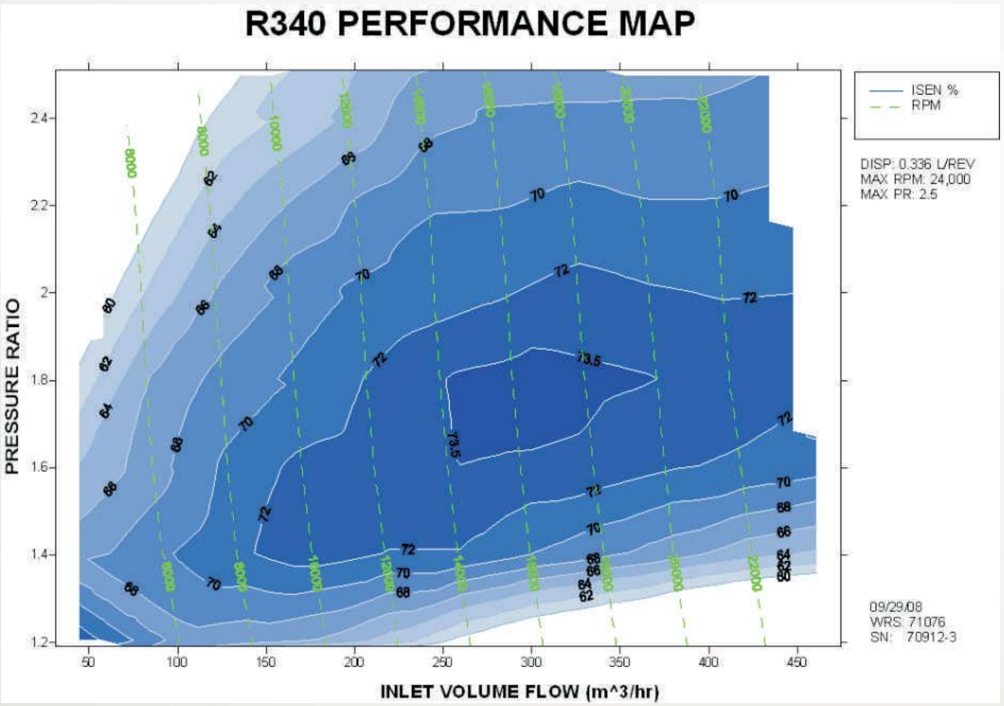
# Bus Air Compression Assumptions & Options

- Auto System:
  - 2.5 atm Compressor/Expander/Motor (CEM)
  - 180krpm centrifugal compressor, radial in-flow expander, integrated with permanent magnet motor
  - ~ 250 $kg_{air}$/hour & ~6 $kW_{input}$ electric motor
- Bus System
  - 1.8 atm compressor, no expander
  - ~ 463 $kg_{air}$/hour & ~ 16 $kW_{input}$ electric motor
- Two choices for Bus Air Compressor
  - Analogy to Auto Fuel Cell System
    - 180 krpm centrifugal compressor with integrated PM motor
    - Adaptation of existing DFMA analysis (based on Honeywell design)
    - 75% isentropic compression efficiency
    - ~$2,000 per unit (based on DFMA at 1,000 systems/year)
    - Price used in cost modeling
  - Analogy to Existing Truck/Fuel Cell Air Compressors
    - ~24 krpm Twin Vortex compressor
    - Modeled as Eaton super-charger
    - 73.5% isentropic compression efficiency
    - Price analogy to aftermarket superchargers ($5-8k per system)
    - To be analyzed next year in consultation with Eaton

# Eaton Compressor

(to be examined as part of 2013 analysis)

**Isentropic efficiency map of the Eaton R340 supercharger**




**Interior view of the Eaton R340 supercharger**

**Interior view of the R340 supercharger vortices**