

Fuel Cell Transportation Cost Analysis



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Project ID #FC018

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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

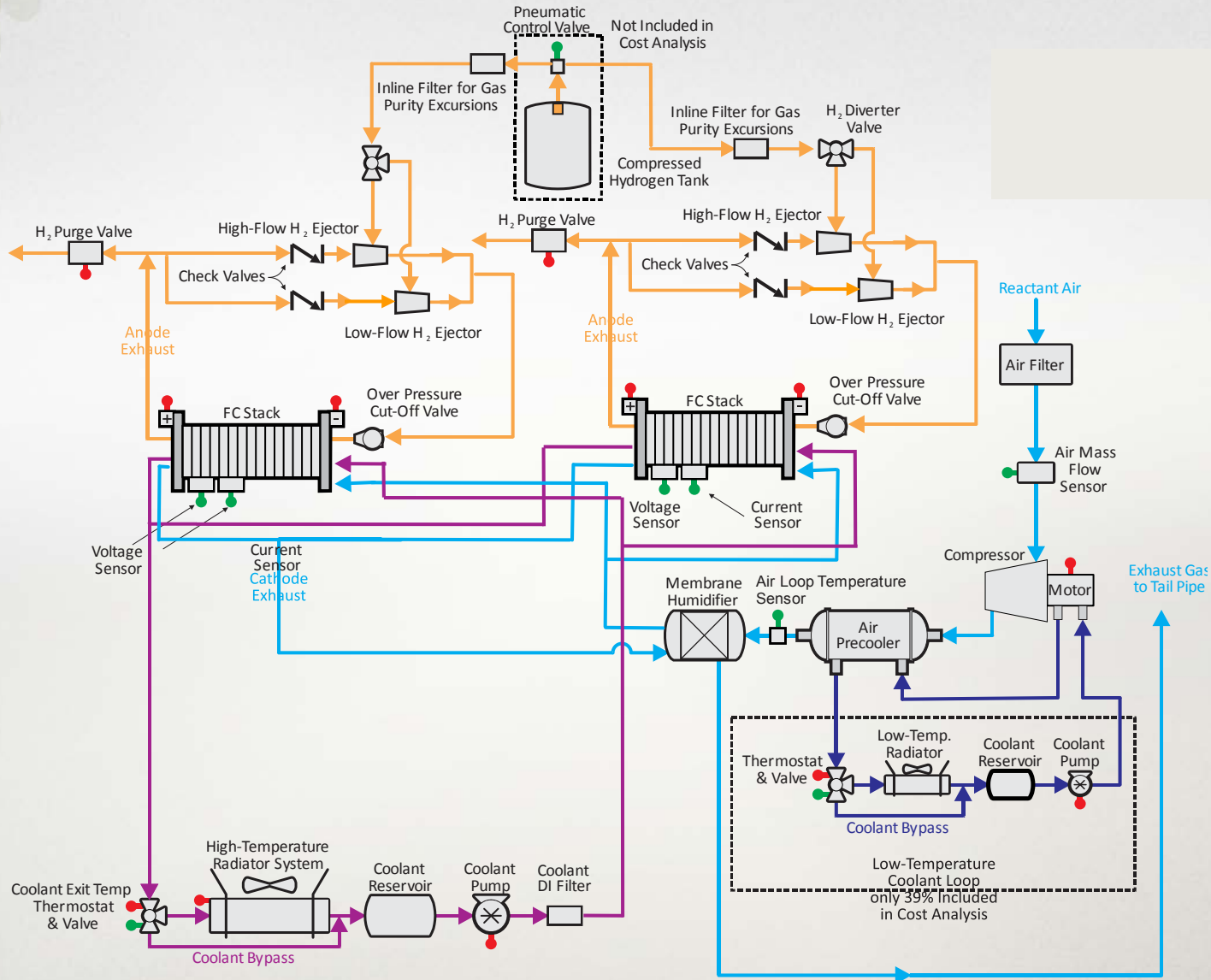
- **2012 Bus Cost Results**
 - Schematic
 - Bus applications overview and challenges
 - Specific parameter differences with automotive fuel cell systems (FCSs)
 - Cost curve
- **Gore low-cost MEA fabrication**
 - Diagram of general fabrication method
 - Key issues
 - Cost results
- **Gore Plate Frame 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



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 ($\text{kW}_{\text{e-gross}}$)
 - United Technologies Inc. (UTC) PureMotion®: 120 $\text{kW}_{\text{e-gross}}$
 - 160 kW net electric power ($\text{kW}_{\text{e-net}}$) 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-net} Bus



System design is similar to automotive configuration. Key differences include:
 5 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 TreadStone 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 crimped to Catalyst Coated Membrane (CCM)	Screen Printed Seal on MEA Subgaskets, GDL crimped 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 1 for Passenger Cabin (not in cost estimate) 1 for Fuel System (not in cost estimate)	2 for FC System 1 for Passenger Cabin (not in cost estimate) 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

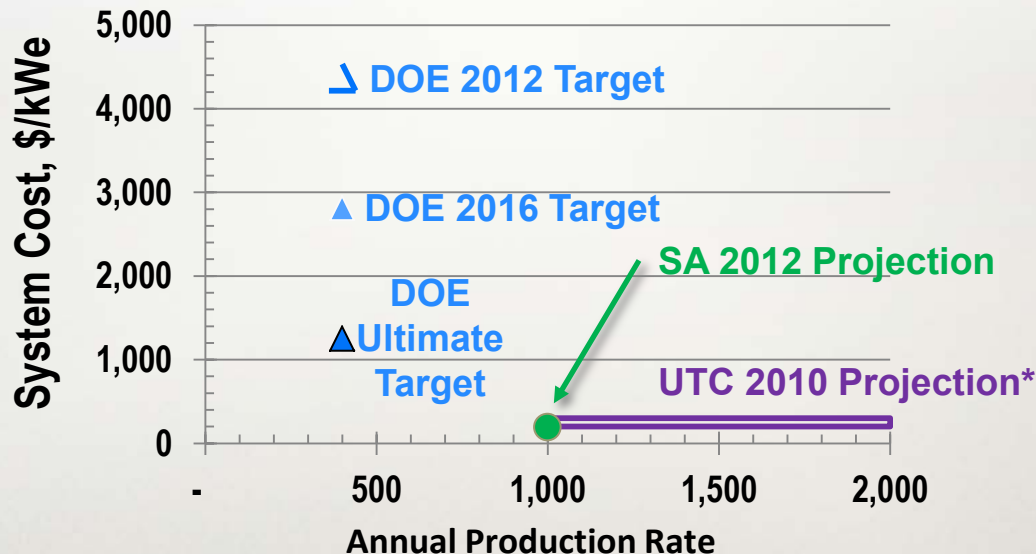
← No expander



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

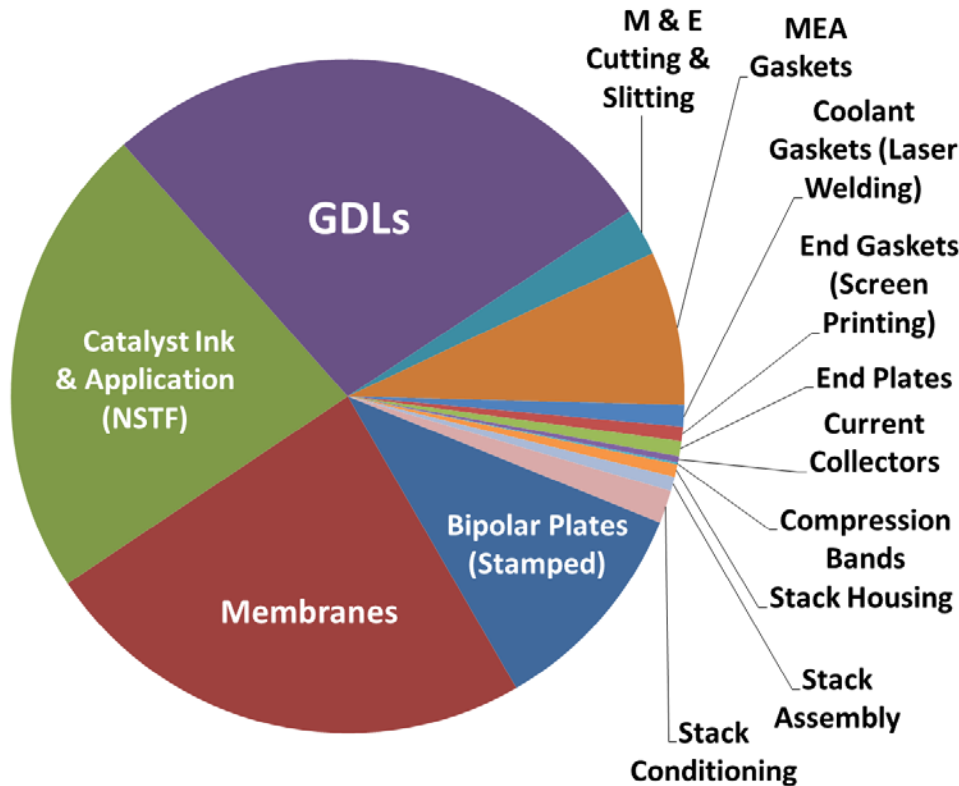
	2012 Bus System
Annual Production Rate	1,000
System Net Electric Power (Output)	160
System Gross Electric Power (Output)	177.10
Fuel Cell Stacks	\$21,651.24
Balance of Plant	\$8,707.03
System Assembly & Testing	\$152.34
Total System Cost (\$)	\$30,510.60
Total System Cost (\$/kW_{net})	\$190.69
Total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



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

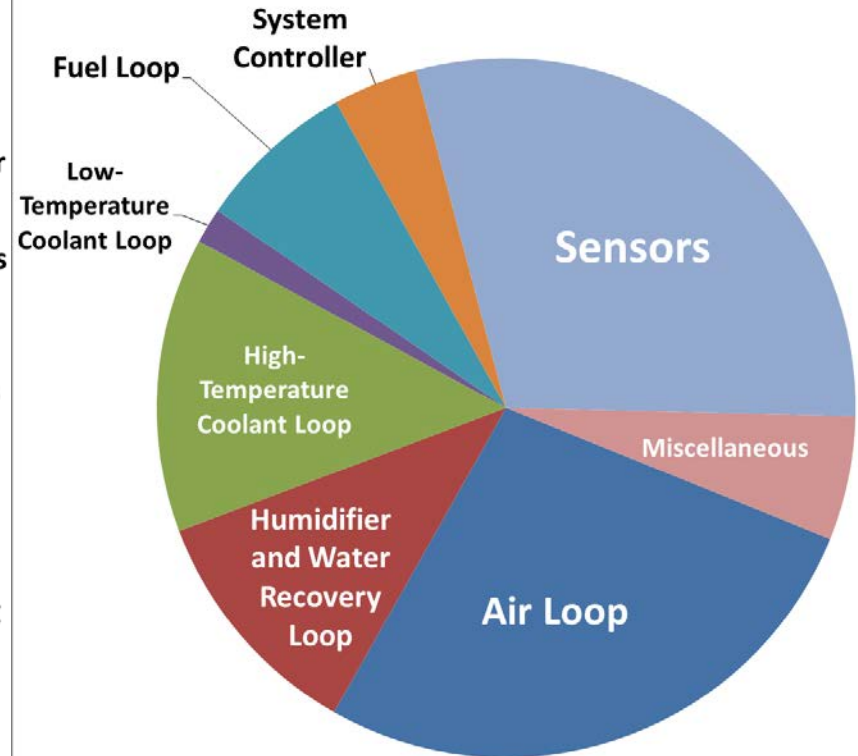
2012 Bus Stack and BOP Costs

Bus Stack Costs



Total Stack Cost: \$21,651

Bus BOP Costs

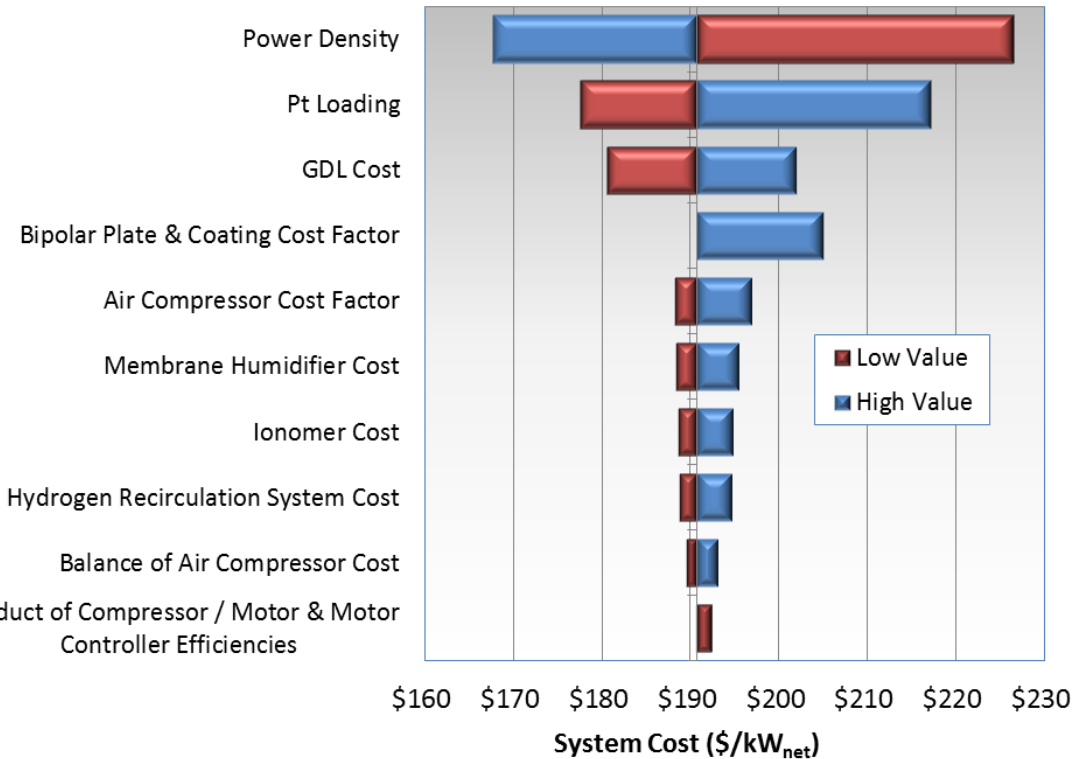


Total BOP Cost: \$8,707

- 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

2012 Bus Results Tornado Chart

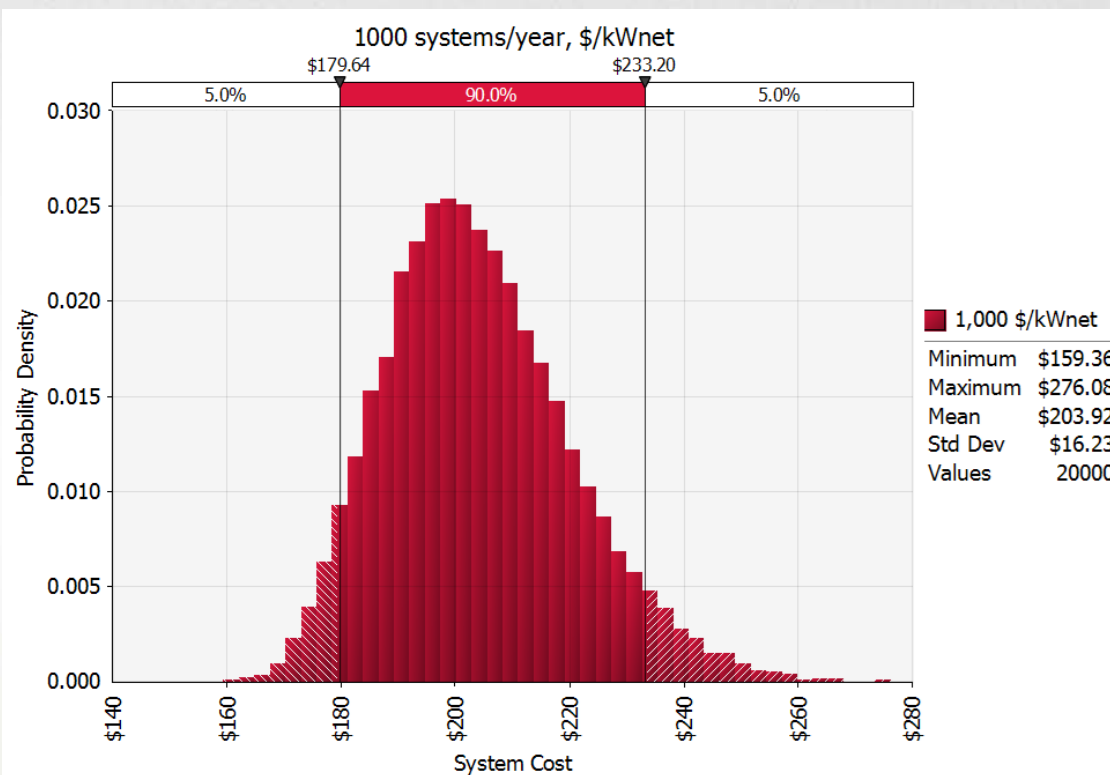


System Cost (\$/kW _{net}), 1,000 sys/year				
Parameter	Units	Low Value	Base Value	High Value
Power Density	mW/cm ²	500	716	984
Pt Loading	mgPt/cm ²	0.2	0.4	0.8
GDL Cost	\$/m ²	\$74.10	\$115.87	\$151.02
Bipolar Plate & Coating Cost Factor		1	1	2
Air Compressor Cost Factor		0.8	1	1
Membrane Humidifier 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-net}



Bus confidence range is wider than for auto:

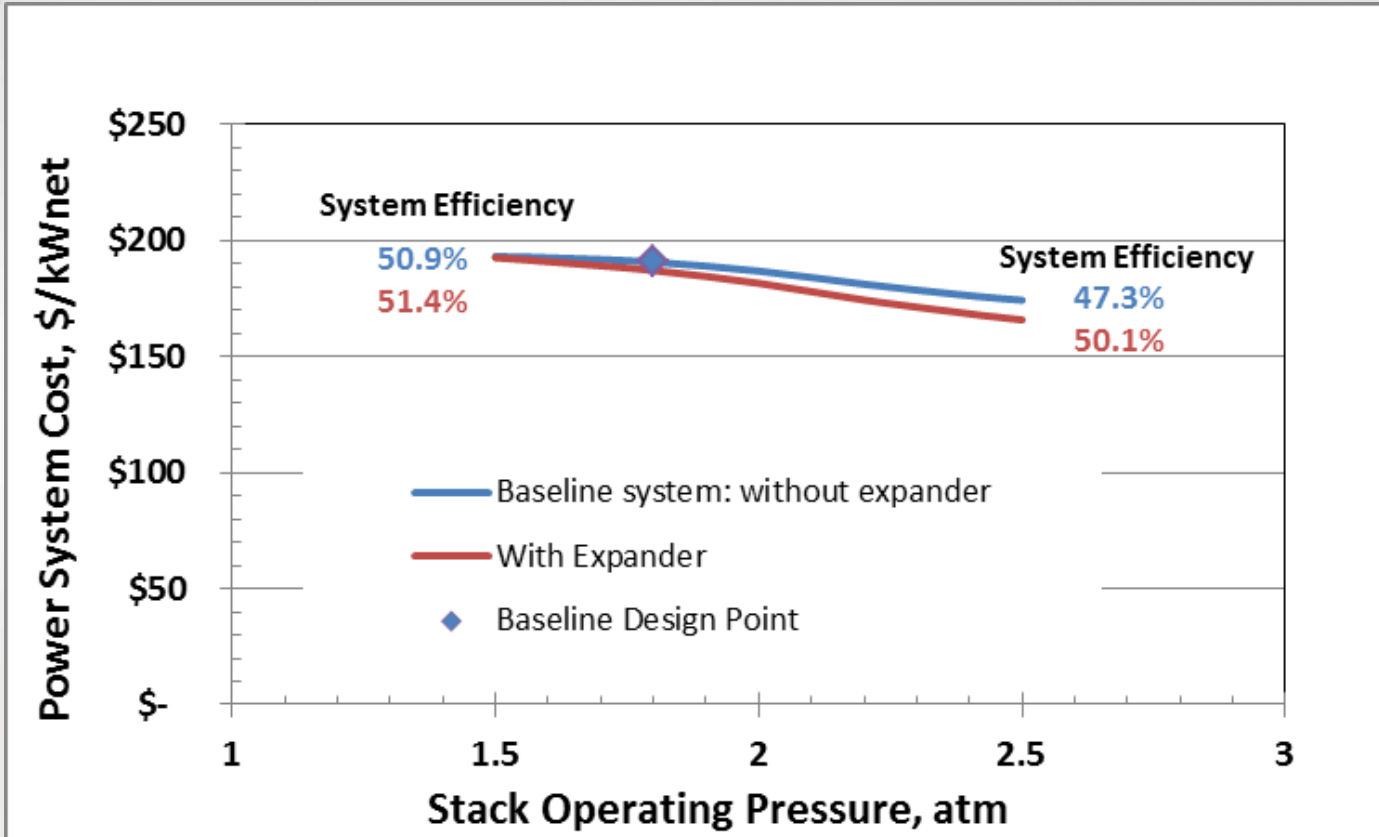
Bus: -6% and +22%

Auto: -2% and +11%

2012 Bus Technology Monte Carlo Analysis, 1k sys/year				
Parameter	Unit	Minimum Value	Likeliest Value	Maximum Value
Power Density	mW/cm ²	500	716	984
Pt Loading	mgPt/cm ²	0.2	0.4	0.8
Ionomer Cost	\$/kg	\$45.65	\$204.00	\$500.00
GDL Cost	\$/m ²	\$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



2013 Light Duty Automotive Cost Update

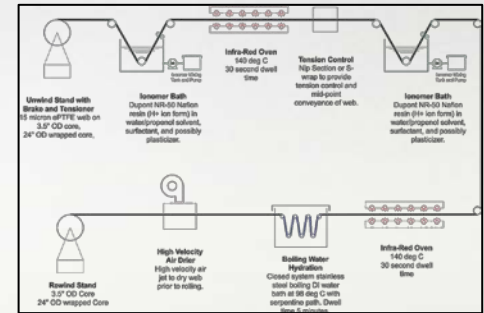
- Alternative MEA fabrication method (Gore)
- Plate Frame Humidifier (Gore/dPoint)
- Stack Quality Control equipment re-evaluation
- Updated polarization performance and cost optimization

Evaluation of Alternative MEA Fabrication

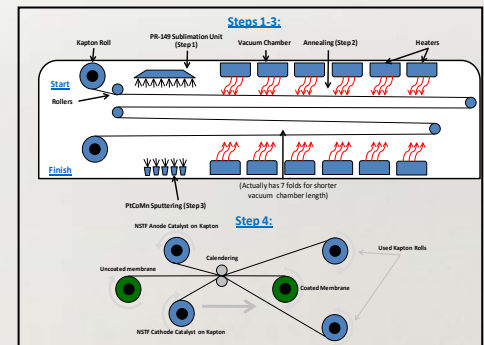
Previous (2012) Membrane Electrode Assembly (MEA) Process

- 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.



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NEW for 2013:

Gore Low Cost MEA Manufacturing Process

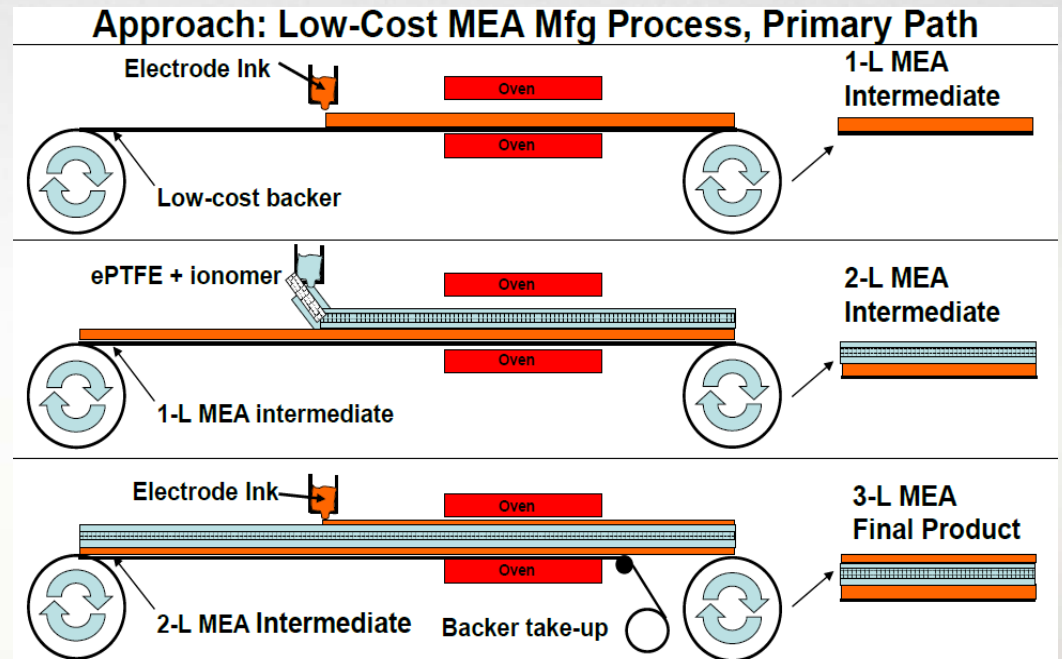


Gore MEA Manufacturing Process Description

Station 1: Anode Application

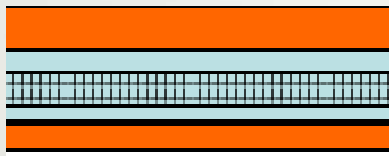
Station 2: Electrolyte Applied to Anode

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)

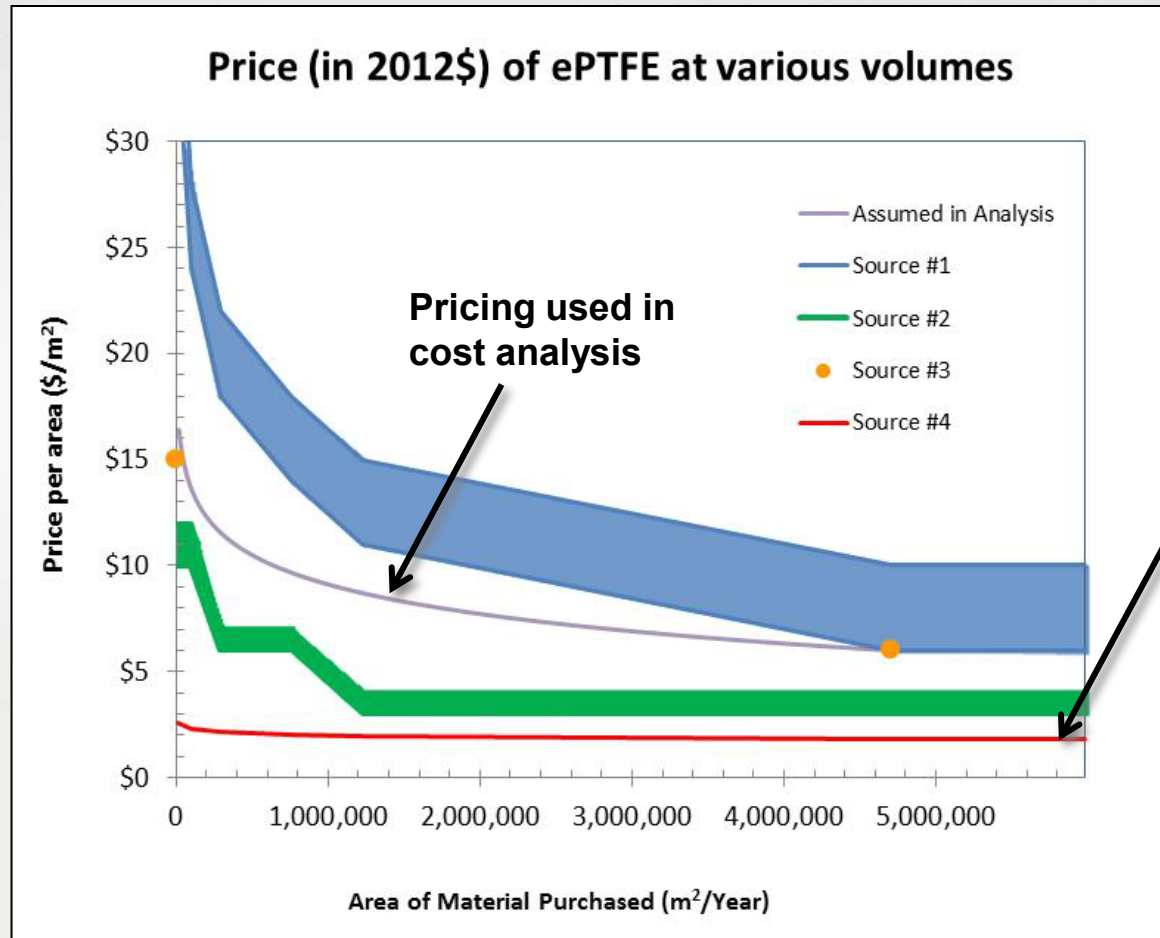
50 μm anode (Pt on Carbon) (ink comp. from Umicore US Pat. #7,141,270)

• Key Features

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



ePTFE Price Comparison: Wide Range of Vendor Estimates

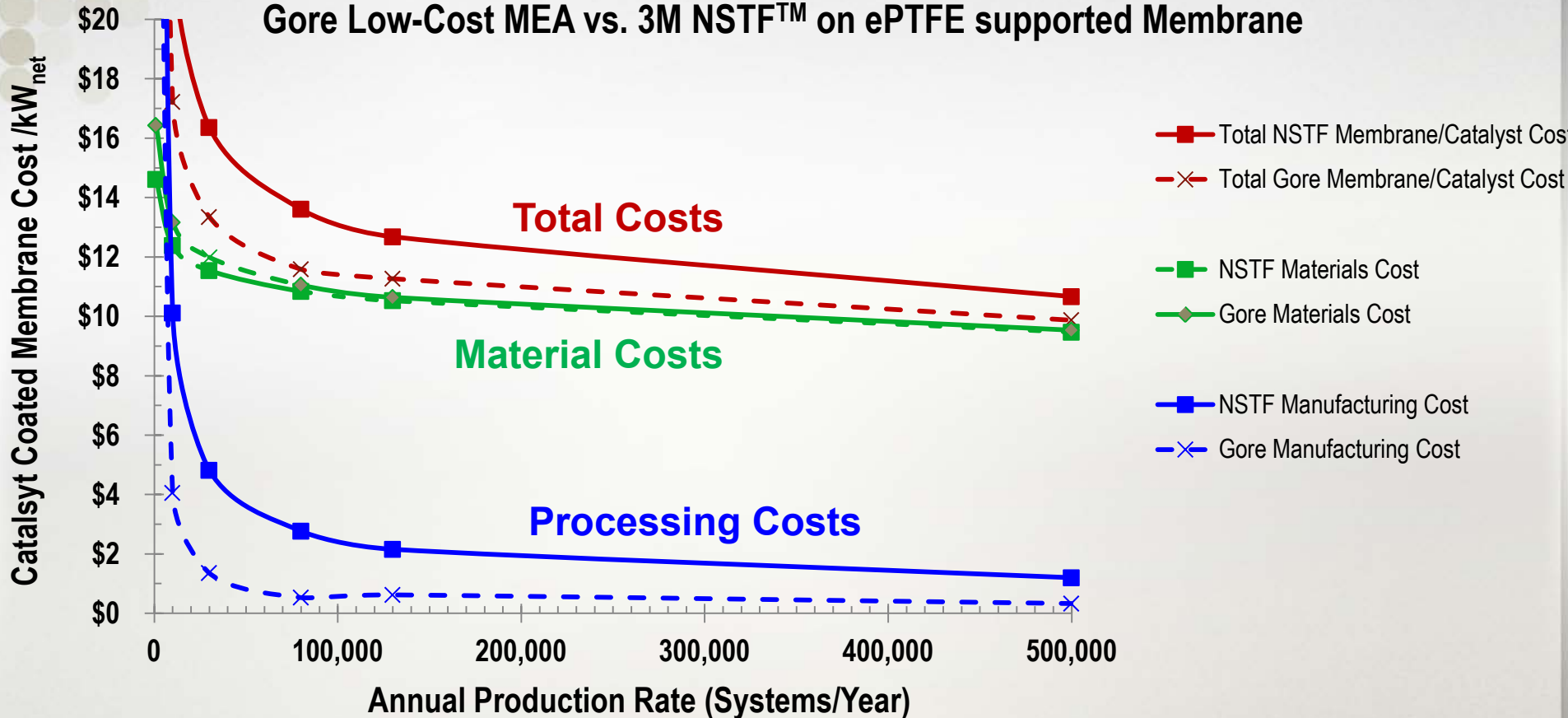


Chinese textile ePTFE probably not suitable for fuel cell applications

- 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

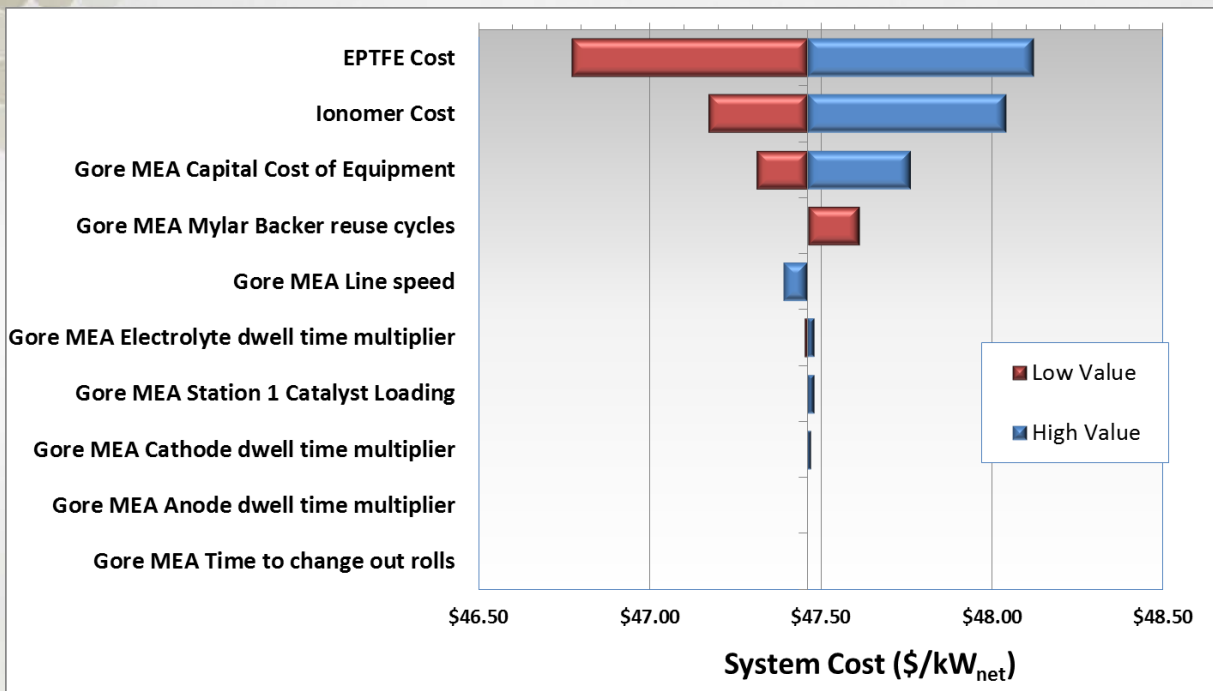
Comparison of MEA Fabrication Costs:
Gore Low-Cost MEA vs. 3M NSTF™ on ePTFE supported Membrane



- 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 (\$/kW _{net}), 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/cm ²	-	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



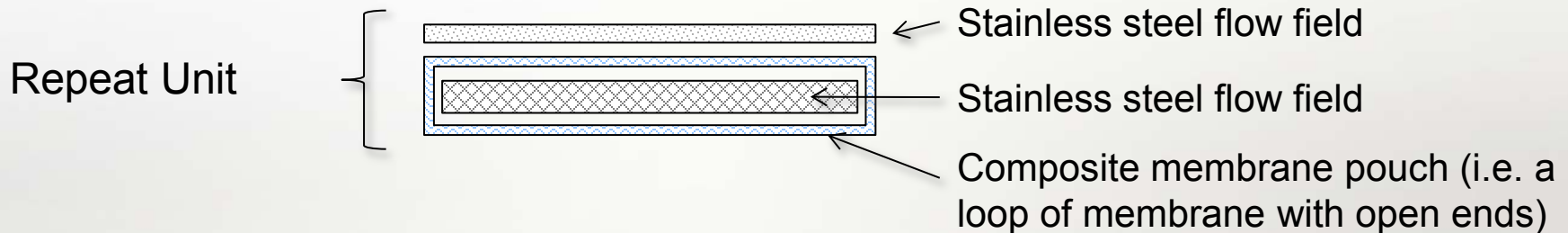
Evaluation of Alternative Humidifier Design

Previous (2012) Humidifier Concept

- Tubular membrane system (~1500 2-mm diameter tubes)
- Based on Perma-Pure LLC design
- Based on (only) 2m² of membrane area => under-designed

NEW for 2013:

Gore Plate-Frame Humidifier Concept

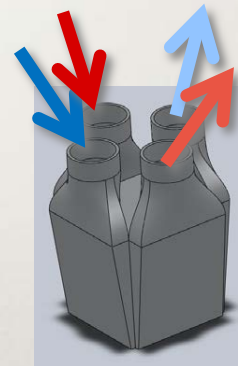


Primary air (dry air) flows in cross flow direction over outside of pouch.
Secondary flow (wet air) flows through inside of pouch.

**Primary
Air Flow**



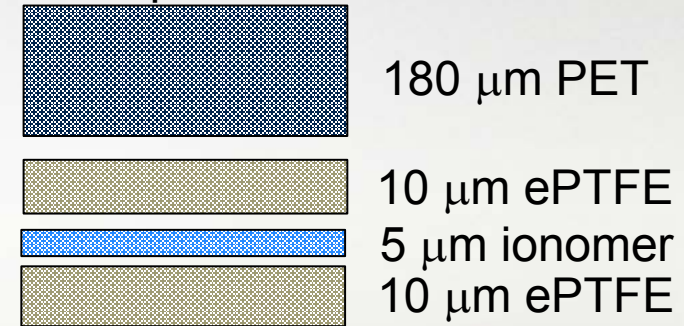
Secondary Air Flow



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 1.5m² 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

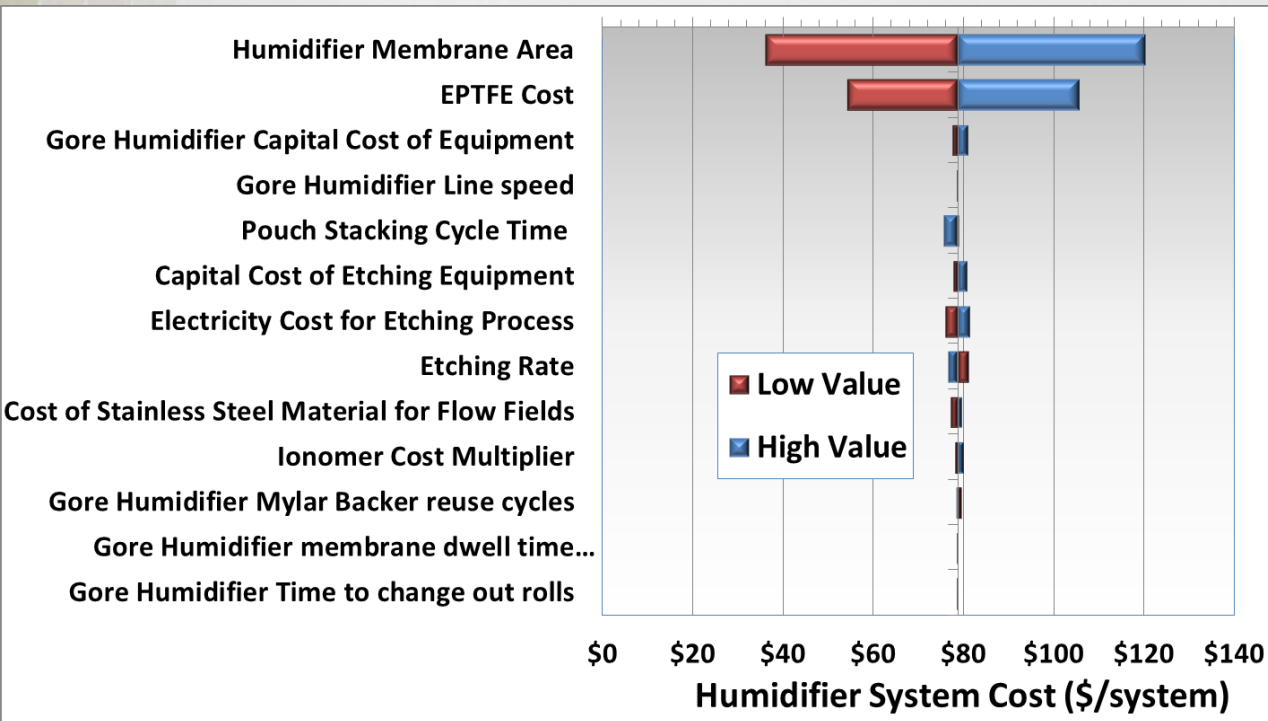


Humidifier membrane cost dominated by material cost

Component	Per unit costs (at 500k sys/yr)	Total per unit costs (at 500k sys/yr)
Materials		
2 layers of ePTFE	$2 \times 1.5\text{m}^2_{\text{memb.}} \times \$8.2/\text{m}^2_{\text{ePTFE}}$ => \$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	multiplier	0.5	1	2
Gore Humidifier Time to change out rolls	min	1	10	15

2013 Gore Humidifier System Cost \$78.73

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- 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.

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	Unevenness 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	Unevenness 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 anolmilies 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 anomalies.	~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)

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

$$V_0 = a_0 + b_0SR + c_0SR^2, \quad V$$

$$V_1 = a_1 + b_1SR + c_1SR^2, \quad V(\text{A} \cdot \text{cm}^{-2})^{-1}$$

$$V_2 = a_2 + b_2SR + c_2SR^2, \quad V(\text{A} \cdot \text{cm}^{-2})^{-2}$$

$$I_r = a_3 + b_3SR + c_3SR^2, \quad \text{A} \cdot \text{cm}^{-2}$$

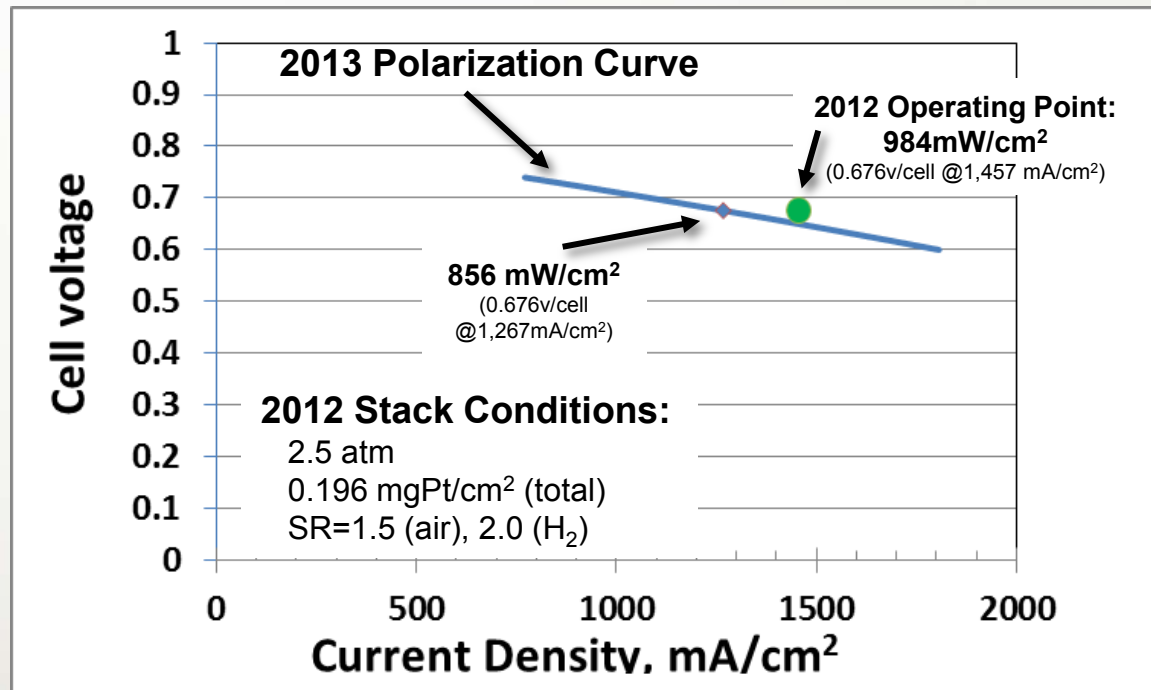
$$I = \text{Cell Current Density}, \quad \text{A} \cdot \text{cm}^{-2}$$

SR = O₂ Stoic. Ratio

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

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

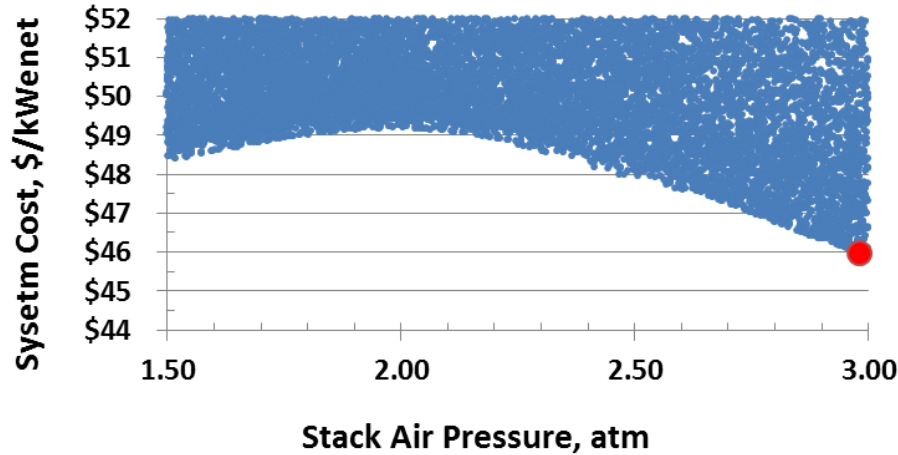
$$L_{Pt} = \text{Cathode Catalyst Loading}, \quad \text{mg}_{Pt} \cdot \text{cm}^{-2}$$



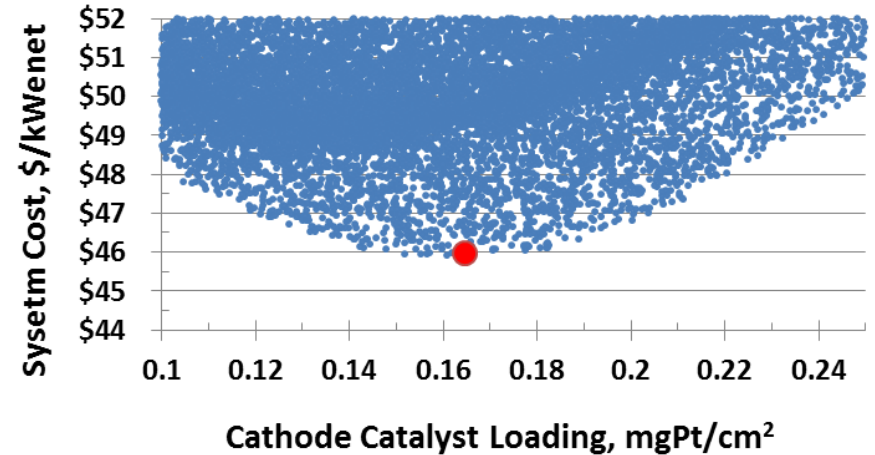
Monte Carlo Re-optimization of Operating Conditions

(at 500k systems/year)

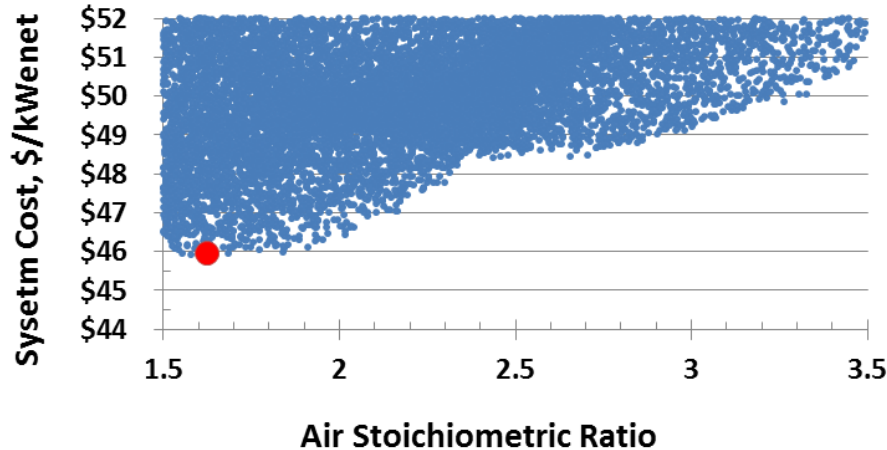
Pressure



Catalyst Loading



Air Stoichiometry



- 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/cm² total (0.5 anode/0.165 cathode)
 - Air Stoichiometry: 1.6
 - Other conditions: H₂ 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

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 ($\$191/\text{kW}_{\text{e-net}}$ at 500k systems/year)
- Auto cost optimization occurs at $\sim 3\text{atm}$ (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 $\sim \$80/\text{system}$ (at 500k systems/year) consistent with industry projections
- Quality control systems projected to add $\sim 1\%$ to system cost, but saves much more in avoided scrap.

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





Backup slides

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.

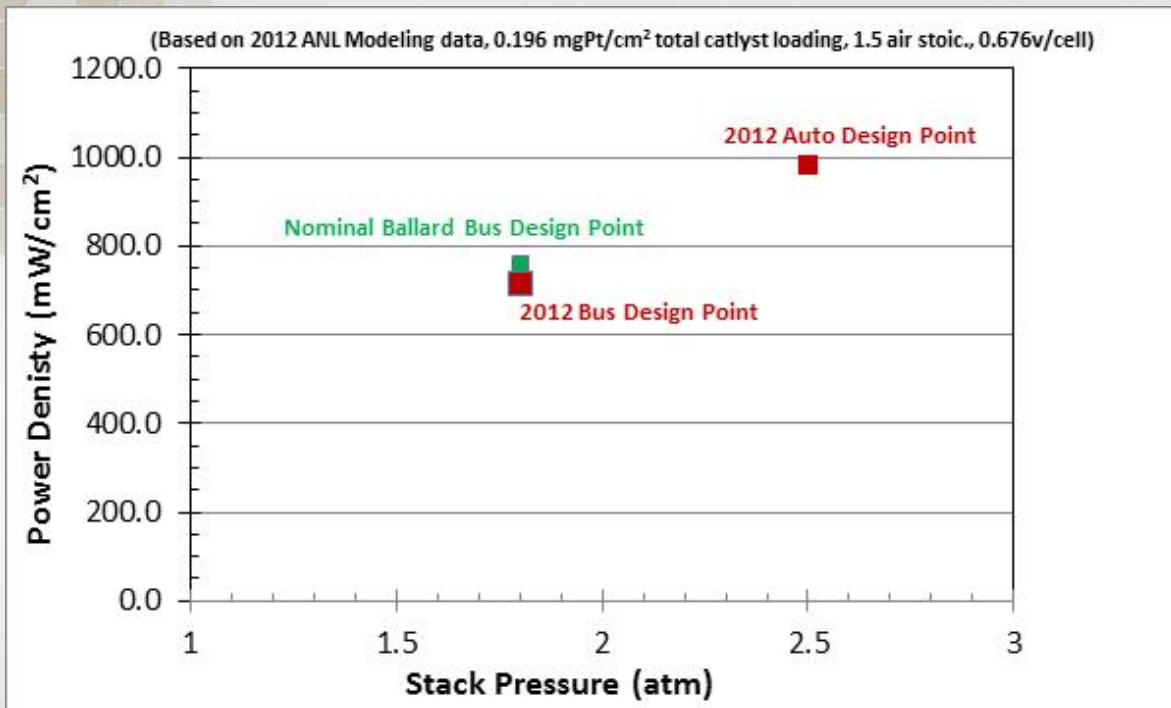
d Multiple sequential fuel fills should be possible without increase in fill time.

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.



2012 Bus System BOL Performance Parameters



- Catalyst loading is performance modeled at the 2012 auto loading (0.196 Pt/cm²) but cost modeled at 0.4 mgPt/cm².
- 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.

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

Bus Air Compression Assumptions & Options

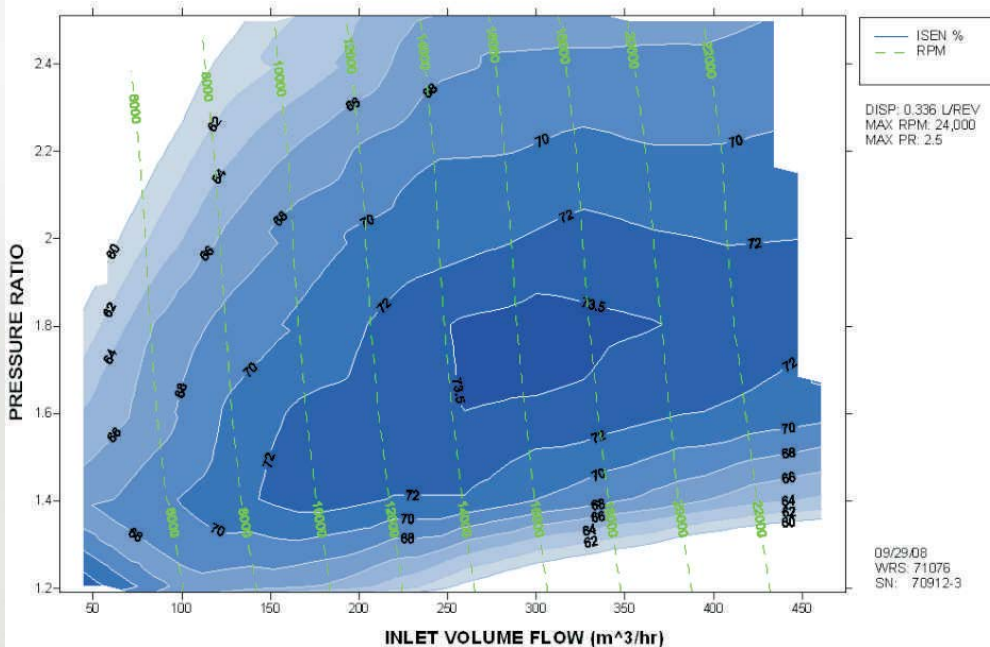
- Auto System:
 - 2.5 atm Compressor/Expander/Motor (CEM)
 - 180krpm centrifugal compressor, radial in-flow expander, integrated with permanent magnet motor
 - $\sim 250 \text{ kg}_{\text{air}}/\text{hour}$ & $\sim 6 \text{ kW}_{\text{input}}$ electric motor
- Bus System
 - 1.8 atm compressor, no expander
 - $\sim 463 \text{ kg}_{\text{air}}/\text{hour}$ & $\sim 16 \text{ kW}_{\text{input}}$ 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
 - $\sim \$2,000$ 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 ($\$5\text{-}8\text{k}$ 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

R340 PERFORMANCE MAP



Interior view of the Eaton R340 supercharger



Interior view of the R340 supercharger vortices

