Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications

Fuel Cell Tech Team Review

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The following report summarizes the results of a DOE funded assessment of the cost of a 80 kW (net) direct hydrogen Polymer Electrolyte Membrane (PEM) fuel cell system for transportation applications.

The results of the model should be considered only in conjunction with the assumptions used in selecting and sizing the system components. The PEM fuel cell stack and system cost analysis assumes Year 2008 technology status for individual components and projects their cost at production volumes of 500,000 vehicles/year.

In developing the system configuration and component manifest we have tried to capture all of the essential engineering components and important cost contributors. However, the system selected for costing does not claim to solve all of the technical challenges facing fuel cell transportation systems or satisfy DOE or FreedomCAR fuel cell vehicle performance targets.

Overview

This year's PEMFC cost analysis was based on minor updates to the bottom-up high-volume stack and BOP cost model developed in 2007.

Timeline

- Start date: Feb 2006
- Base period: May 2008
  - 100% complete
- Option Year 1: Feb 2009

Barriers

- Barriers addressed
  - B. Cost

	Cost Targets ($/kW)		
	2008	2010	2015
Fuel Cell System	70	45	30
Fuel Cell Stack		25	15

* *Manufactured at volume of 500,000 per year.*

Budget

- Total project funding
  - Base Period = $415K
  - No cost share, no contractors
- FY07 = $214K
- FY08 = $50K

Partners

- Project lead: TIAX
- Collaborate with ANL on system configuration and modeling
- Feedback from Fuel Cell Tech Team, Developers, Vendors

ANL = Argonne National Lab

Objectives

	Objectives
Overall	◆ Bottom-up manufacturing cost assessment of 80 kW direct-H_2 PEMFC system for automotive applications
2008	◆ High-volume (500,000 units/year) cost projection of ANL 2008 PEMFC system configuration assuming an NSTFC-based MEA and a 30 μm 3M-like membrane ➢ Bottom-up manufacturing cost analysis of stack and BOP components ➢ Sensitivity analyses on stack and system parameters ◆ EOS impacts on 2007/2008 BOP costs (EOS analysis of 2005 stack completed in FY2006)

BOP = Balance-of-Plant
NSTFC = Nano-Structured Thin Film Catalyst
MEA = Membrane Electrode Assembly
EOS = Economies of Scale

Background

This year, we updated the 2007 PEMFC cost assessment based on input from ANL on the 2008 stack performance parameters.

- In 2007, the PEMFC system configuration, materials, processes, performance assumptions and component specifications were evaluated
  - Based cost assessment on ANL 2007 PEMFC system configuration assuming an NSTFC-based MEA and a 30 μm 3M-like membrane
  - Performed bottom-up cost assessment of *both* stack and BOP components
- In 2008, we updated key stack performance specifications, with no change to the system layout, cell voltage, or stack operating conditions (no change to stack efficiency)
  - Revised power density and Pt loading based on ANL inputs
  - Gross stack power density = 716 mW/cm^2 (2007 = 753 mW/cm^2)
  - Total Pt loading = 0.25 mg/cm^2 (2007 = 0.3 mg/cm^2)
  - Gross stack power = 86.9 kW (2007 = 86.4 kW)

BOP = Balance-of-Plant

NSTFC = Nano-Structured Thin Film Catalyst

MEA = Membrane Electrode Assembly

EOS = Economies of Scale

Approach Overall Cost Assessment

Manufacturing cost estimation involves technology assessment, cost modeling, and industry input to vet assumptions and results.

Technology Assessment

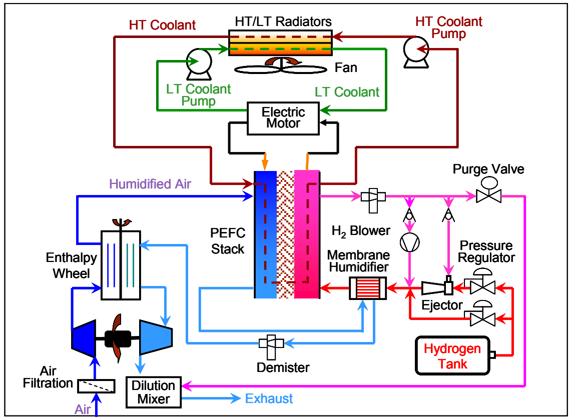
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Component Specifications
- Obtain Developer Input

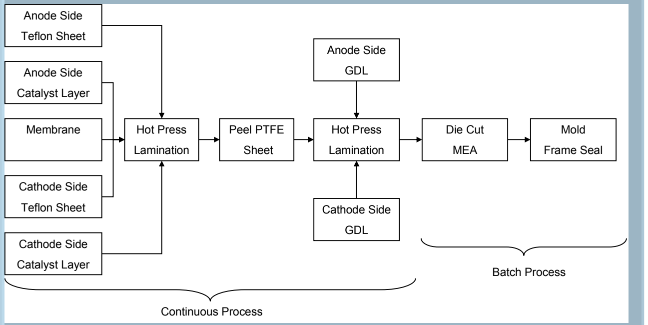
Cost Model and Estimates

- Develop Bulk Cost Assumptions
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Process Costs

Overall Model Refinement

- Obtain Developer and Industry Feedback
- Revise Assumptions and Model Inputs
- Perform Sensitivity Analyses





Anode Side Teflon Sheet

Anode Side Catalyst Layer

Membrane

Cathode Side Teflon Sheet

Cathode Side Catalyst Layer

Hot Press Lamination

Peel PTFE Sheet

Anode Side GDL

Hot Press Lamination

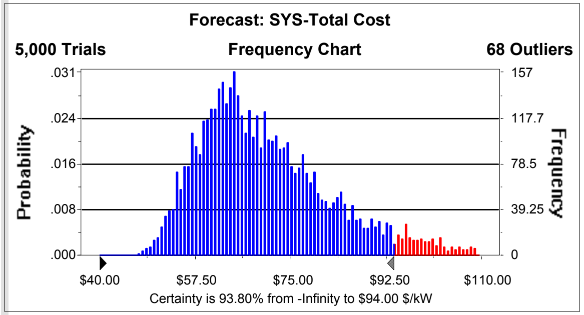
Cathode Side GDL

Die Cut MEA

Mold Frame Seal

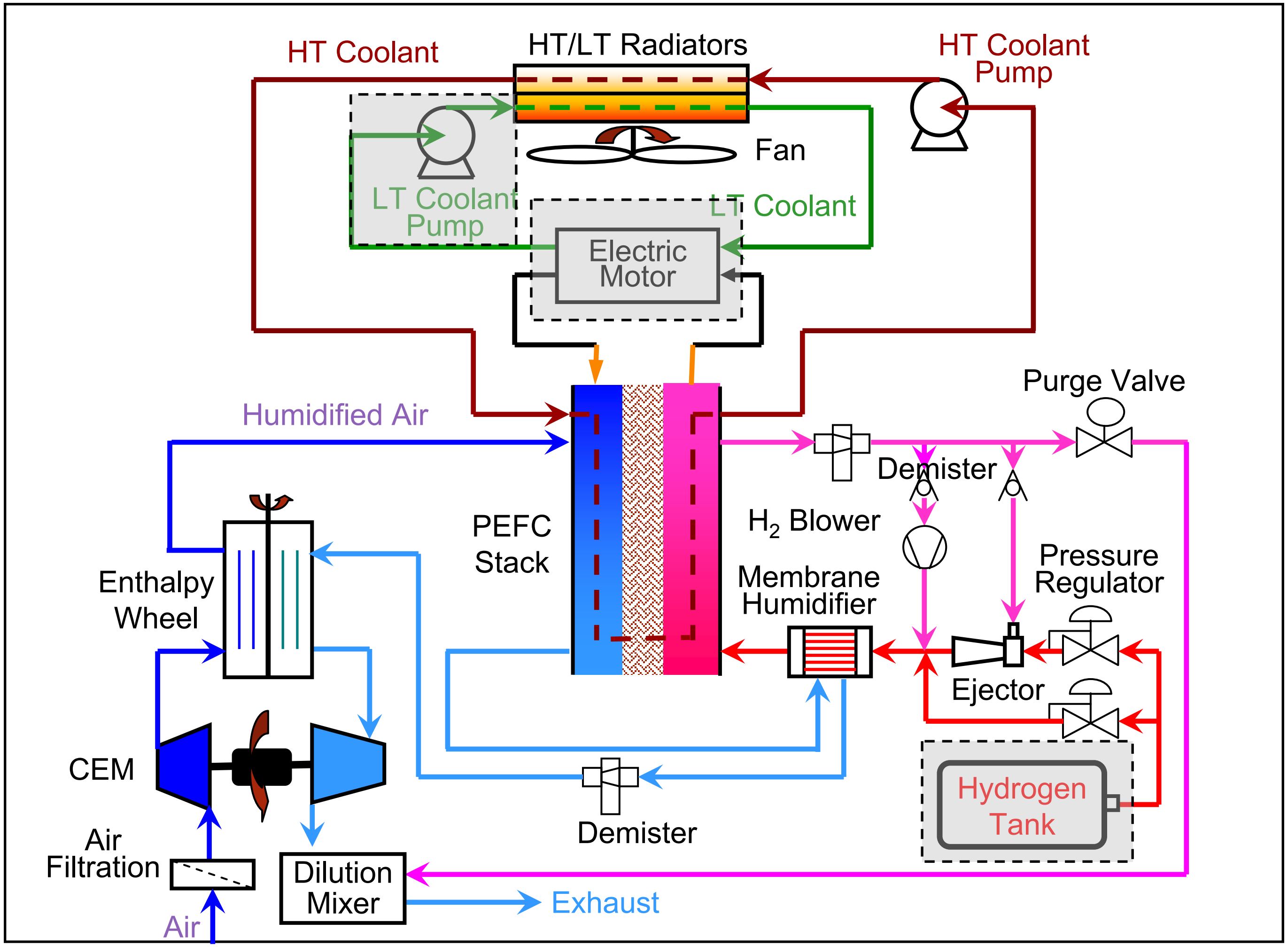
Continuous Process

Batch Process



BOM = Bill of Materials

We worked with Argonne National Laboratory (ANL) to define the 2008 system configuration, performance and component specifications[1].



Not included in the fuel cell system cost assessment

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[1] R. K. Ahluwalia, X. Wang and R. Kumar, Fuel Cell Systems Analysis, 2008 USDOE Hydrogen Program Review, Arlington, VA, June 9-13, 2008.

Approach Costing Methods

We used a bottom-up approach to determine high-volume (500,000 units/year) manufacturing cost for the major stack and BOP components.

Stack Components

- Catalyst Coated Membrane
- Electrodes
- Gas Diffusion Layer (GDL)
- Membrane Electrode Assembly (MEA)
- Bipolar Plates
- Seals

» Develop production process flow chart for key subsystems and components

» Obtain raw material prices from potential suppliers

» Estimate manufacturing costs using TIAX cost models (capital equipment, raw material costs, labor rates)

BOP Components

- Radiator
- Membrane Humidifier (MH)
- Enthalpy Wheel Humidifier (EWH)
- Compressor-Expander-Module (CEM)
- H_2 Blower

» Develop Bill of Materials (BOM)

» Obtain raw material prices from potential suppliers

» Develop production process flow chart for key subsystems and components

» Estimate manufacturing costs using TIAX cost models and Boothroyd Dewhurst Design for Manufacturing & Assembly (DFMA®) software

- We used experience-based estimates for stack components such as sensors, controls, control board and wire harness. We also used experience-based estimates for BOP components such as the enthalpy wheel motor, H_2 ejectors, radiator fan, coolant pump, valves and regulators.
- We used the TIAX technology-based cost model for the radiator, MH and EWH, while we used DFMA® software for the CEM and H_2 blower.

Approach Bottom-up BOP Costing Tools

We used two different bottom-up costing tools to perform the cost analysis on the BOP components.

Costing Tools

- TIAX Technology-Based Cost Model
  - Radiator
  - Enthalpy Wheel Humidifier
  - Membrane Humidifier
- DFMA® Concurrent Costing Software
  - Compressor Expander Module
  - H_2 Blower

TIAX Technology-Based Cost Model

- Defines process scenarios according to the production volume
- Easily defines both continuous as well as batch processes
- Breaks down cost into various categories, such as material, labor, utility, capital, etc.
- Assumes dedicated process line – yields higher cost at low production volumes

DFMA® Concurrent Costing

- Has a wide range of built-in manufacturing databases for traditional batch processes, such as casting, machining, injection molding, etc.
- Initially developed for the automotive industry; not well suited for processes used in manufacture of PEMFC stacks
- Does not assume dedicated process line – yields lower cost at low production volumes

[1] We used experience-based estimates (as opposed to bottom-up costing) for components such as the enthalpy wheel motor, H_2 ejectors, radiator fan, coolant pump, valves and regulators.

Approach BOP Economies of Scale

For the EOS analysis, we developed three production scenarios - pilot plant, semi-scaled, and full-scaled - to represent a phased advance from proof-of-concept to mature manufacturing process.

- Pilot Plant
  - Low volume production
  - Proof-of-concept of the manufacturing process
  - Goal is to adapt the manufacturing process to high volume production
- Semi-Scaled
  - Low-to-medium volume production
  - Adapted manufacturing process
  - Goal is to validate the manufacturing process for high volume production
- Full-Scaled
  - High volume production
  - Mature manufacturing process
  - Goal is to sustain a low-cost, high-throughput, high-reliability manufacturing process

Material price, process type, process parameters, choice of equipment and level of automation (i.e. equipment capital cost) were varied across *each* of the three scenarios.

Results Stack Material Assumptions

To be consistent with the 3M-like stack design, we made the following material assumptions for the cost projection.

Component	Parameter	Selection
Membrane	Material	3M PFSA (EW=825)
	Supported	No
Electrodes (Cathode and Anode)	Catalyst	Ternary $PtCo_xMn_y$ alloy
	Type	Nano-Structured Thin Film
	Supported	Organic whiskers
Gas Diffusion Layer (GDL)	Material	Woven carbon fiber
	Porosity	70%
Bipolar Plate	Type	Expanded graphite foil
Seal	Material	Viton®

There are no differences between the material assumptions for the 2007 and 2008 PEMFC stack.

Stack performance assumptions were updated by ANL based on their modeling of an NSTFC-based MEA and a 30 μm 3M-like membrane.

Key Stack Performance Assumptions		2005[1]	2007[2,3]	2008[4]
Net power	kW_e	80	80	80
Gross power	kW_e	**89.5**	**86.4**	**86.9**
Gross power density	mW/cm^2	**600**	**753**	**716**
Cell voltage (rated power)	V	0.65	0.68	0.685
Pt loading (total)	mg/cm^2	**0.75**	**0.30**	**0.25**
Membrane thickness	μm	50	30	30
Stack temperature	ºC	80	90	90
Pressure (rated power)	atm	2.5	2.5	2.5
Stack eff. (rated power)	% LHV	52	54	54

[1] E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104

[2] R.K. Ahluwalia and X. Wang, Reference Fuel Cell System Configurations for 2007: Interim Results, ANL, Feb. 6, 2007

[3] R.K. Ahluwalia, X. Wang and R. Kumar, Fuel Cell Systems Analysis, DOE Hydrogen Program Review, May 15-18, 2007

[4] R. K. Ahluwalia, X. Wang and R. Kumar, Fuel Cell Systems Analysis, 2008 USDOE Hydrogen Program Review, Arlington, VA, June 9-13, 2008

We developed stack specifications consistent with the performance assumptions.

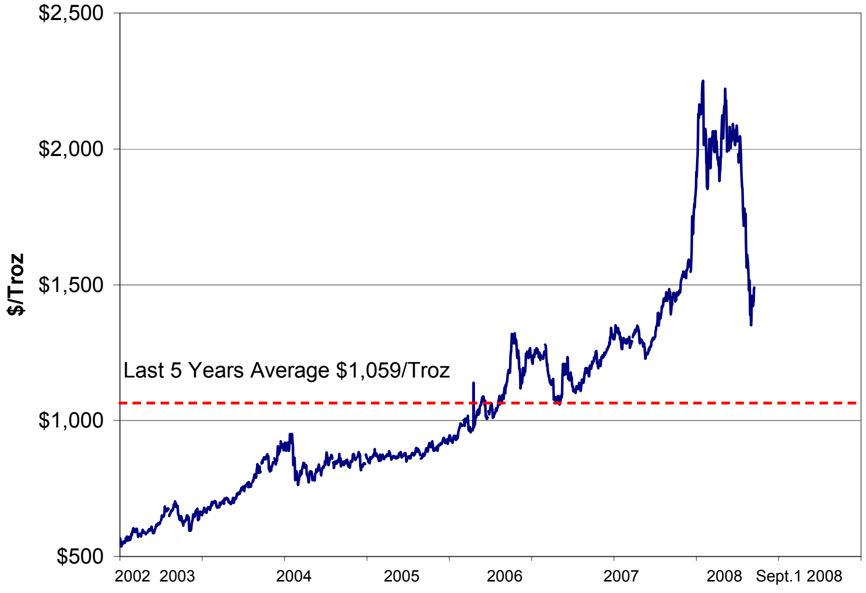
TIAX Assumptions	Units	2005[1]	2007	2008
Production volume	units/yr	500,000	500,000	500,000
Pt price	\$/g (\$/tr.oz.)	29.0 (900)	35.4 (1100)	35.4 (1100)
Number of stacks	#	2	2	2
Number of cells per stack	#	231	221	219
Active cell area	% Total cell area	85%	85%	85%
Active area per cell	cm^2	323	260	277
Cell pitch	cells/inch (cells/cm)	9.55 (3.76)	9.75 (3.84)	9.75 (3.84)
Stack voltage (rated power)	V	150	150	150

[1] E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104

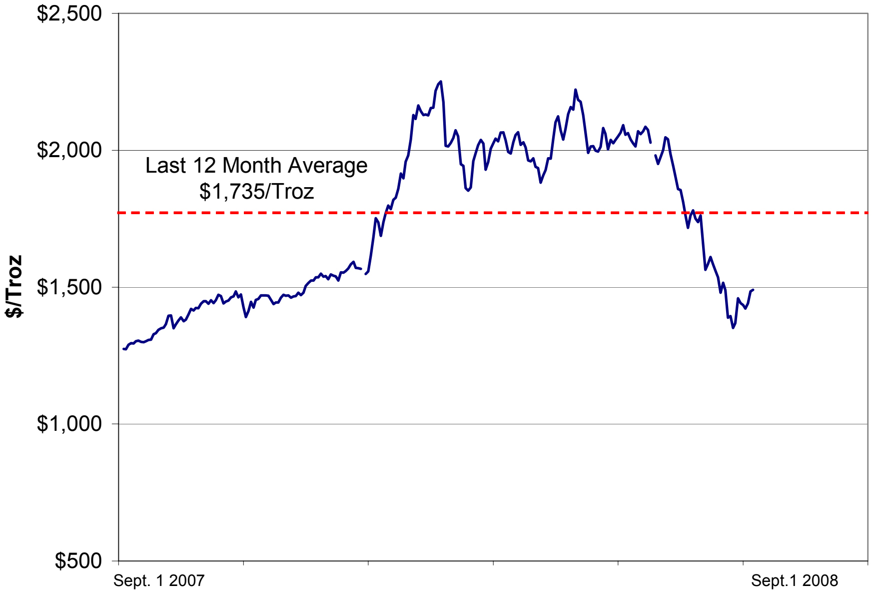
We assumed a Pt price of \$1,100/tr.oz. for the baseline analysis and captured the impact of variation in Pt price through single- and multi-variable sensitivity analyses.

Platinum at $1,100/tr.oz. is close to the average price ($1,059/tr.oz.) over the last five years.

Last Five Years' Platinum Price



Last Twelve Months' Platinum Price

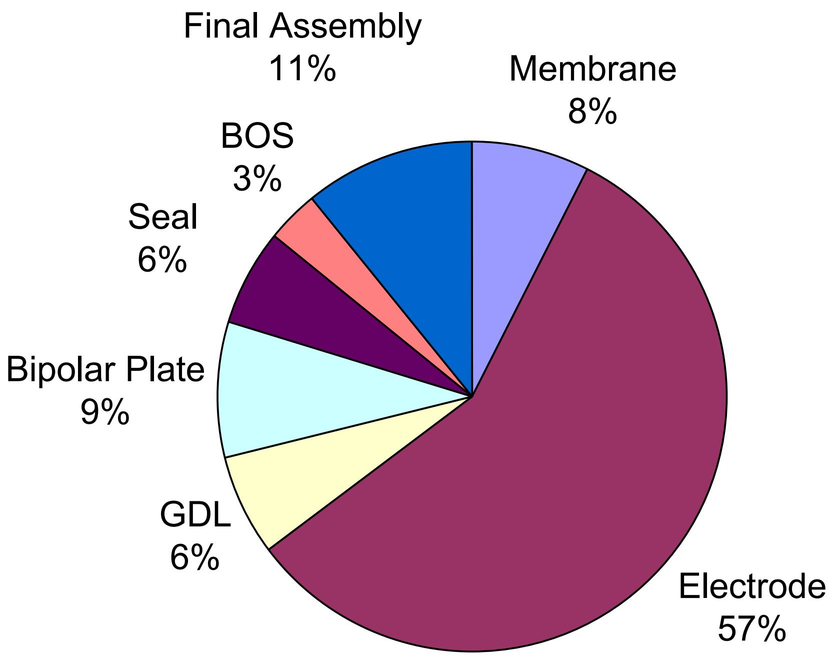


The Pt price averaged over the last 12 months is ~ $1,735/tr.oz.

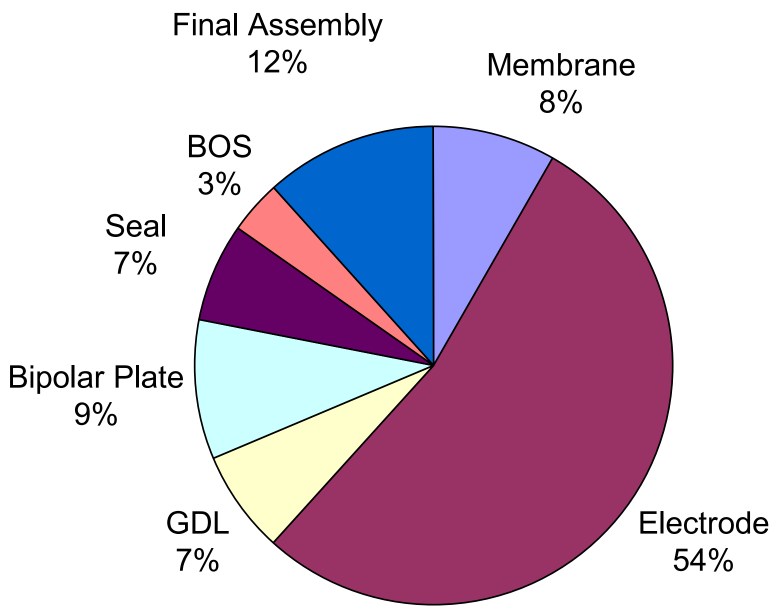
The electrodes represent approximately 54% of the $29/kW fuel cell stack cost in 2008.

Stack Manufactured Cost[1] – 80 kW Direct-H_2 PEMFC

2007: $31/kW, $2,480



2008: $29/kW, $2,320



[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

BOS = Balance-of-Stack

Results System Cost Breakout

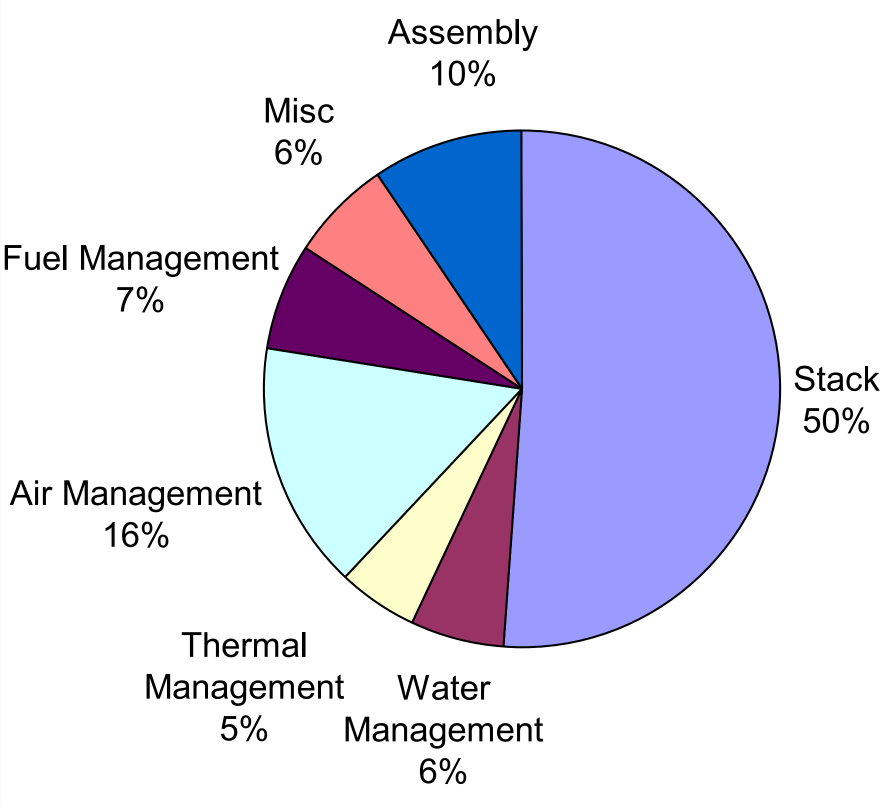
Both stack and BOP component costs are significantly reduced from the 2005 cost assessment.

PEMFC System Cost[1] ($/kW)	2005 OEM Cost	2007 OEM Cost[1,2]	2008 OEM Cost[1,2]
Stack	**67**	**31**	**29**
Water Management	8	3.3	3.3
Thermal Management	4	2.8	2.8
Air Management	14	8.9	8.9
Fuel Management	4	3.8	3.8
Miscellaneous	7	3.1	3.1
Assembly	4	5.5	5.5
Total	**108**	**59**	**57**

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

[2] Assumes 15% markup to the automotive OEM for BOP components

2008 PEMFC System OEM Cost[1,2] ($57/kW$_{\text{net power}}$, $4,560)



BOP and assembly costs together represent ~ 50% of the PEMFC system cost in 2008, as compared to ~ 38% in 2005.

The high-volume factory cost for the 2007/2008 BOP components is projected to be $1,350.

BOP Sub-system	Component	Technology Basis	Factory Cost[1], $ (without supplier markup)	OEM Cost[1], $ (with 15% supplier markup)
Water Management	Enthalpy wheel air-humidifier	Emprise	160	184
	Membrane H_2-humidifier	PermaPure	58	66
	Other	-	10	10
Thermal Management	Automotive tube-fin radiator	Modine	57	65
	Radiator fan[2]	-	35	35
	Coolant pump[3]	-	120	120
	Other	-	5	5
Air Management	Compressor-Expander-Motor (CEM)	Honeywell	535	615
	Other	-	97	97
Fuel Management	H_2 blower	Parker Hannifin	193	222
	H_2 ejectors[4]	-	40	40
	Other		41	41
TOTAL			1351	1500

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system.

[2] Assumes $35/unit based on automotive radiator vendor catalog price, scaled for high volume production

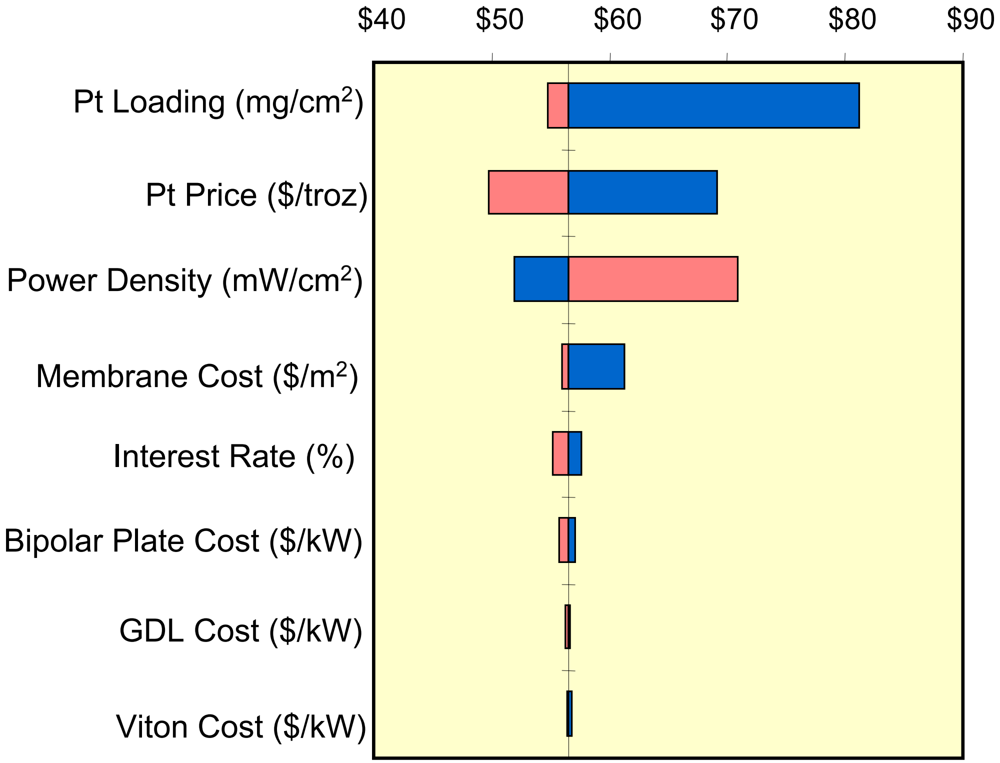
[3] Assumes $120/unit, based on 2005 PEMFC Costing Report: E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104

[4] Assumes $20/unit, and 2 ejectors, based on 2005 PEMFC Costing Report: E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104

Results 2008 Stack Single Variable Sensitivity

Pt loading, power density, and Pt cost are the top three drivers of the PEMFC system cost[1].

2008 PEMFC System OEM Cost[1] ($/kW)



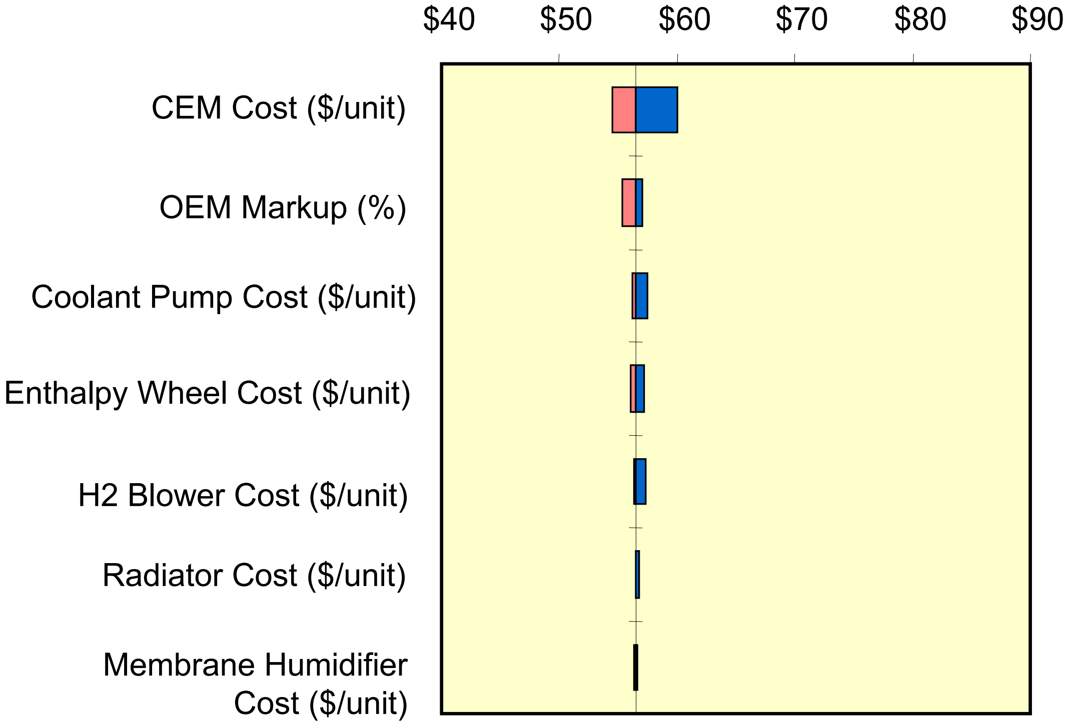
#	Variables	Min.	Max.	Base	Comments
1	Pt Loading (mg/cm^2)	0.2	0.75	0.25	Minimum: DOE 2015 target[2]; Maximum: TIAX 2005 report[3]
2	Pt Cost ($/tr.oz.)	450	2250	1100	Minimum: ~ 108-year min. in 2007 $[4]; Maximum: 12-month maximum LME price[5]
3	Power Density (mW/cm^2)	350	1000	716	Minimum: industry feedback; Maximum: DOE 2015 target[2].
4	Membrane Cost ($\$/m^2$)	10	50	16	Minimum:GM[6] study; Maximum: DuPont[7] projection from 2002
5	Interest Rate	8%	20%	15%	Based on industry feedback
6	Bipolar Plate Cost ($/kW)	1.8	3.4	2.7	Based on component single variable sensitivity analysis
7	GDL Cost ($/kW)	1.7	2.2	2.0	Based on component single variable sensitivity analysis
8	Viton Cost ($/kg)	39	58	48	Based on industry feedback

1. High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.
2. http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf
3. Carlson, E.J. et al., “Cost Analysis of PEM Fuel Cell Systems for Transportation”, Sep 30, 2005, NREL/SR-560-39104
4. www.platinum.matthey.com
5. www.metalprices.com
6. Mathias, M., ”Can available membranes and catalysts meet automotive polymer electrolyte fuel cell requirements?”, Am. Chem. Soc. Preprints, Div. Fuel Chem., 49(2), 471, 2004
7. Curtin, D.E., “High volume, low cost manufacturing process for Nafion membranes”, 2002 Fuel Cell Seminar, Palm Springs, Nov 2002

Results 2007/2008 BOP Single Variable Sensitivity

Among the BOP components, the CEM has the greatest impact on the PEMFC system cost[1].

2008 PEMFC System OEM Cost[1] ($/kW)

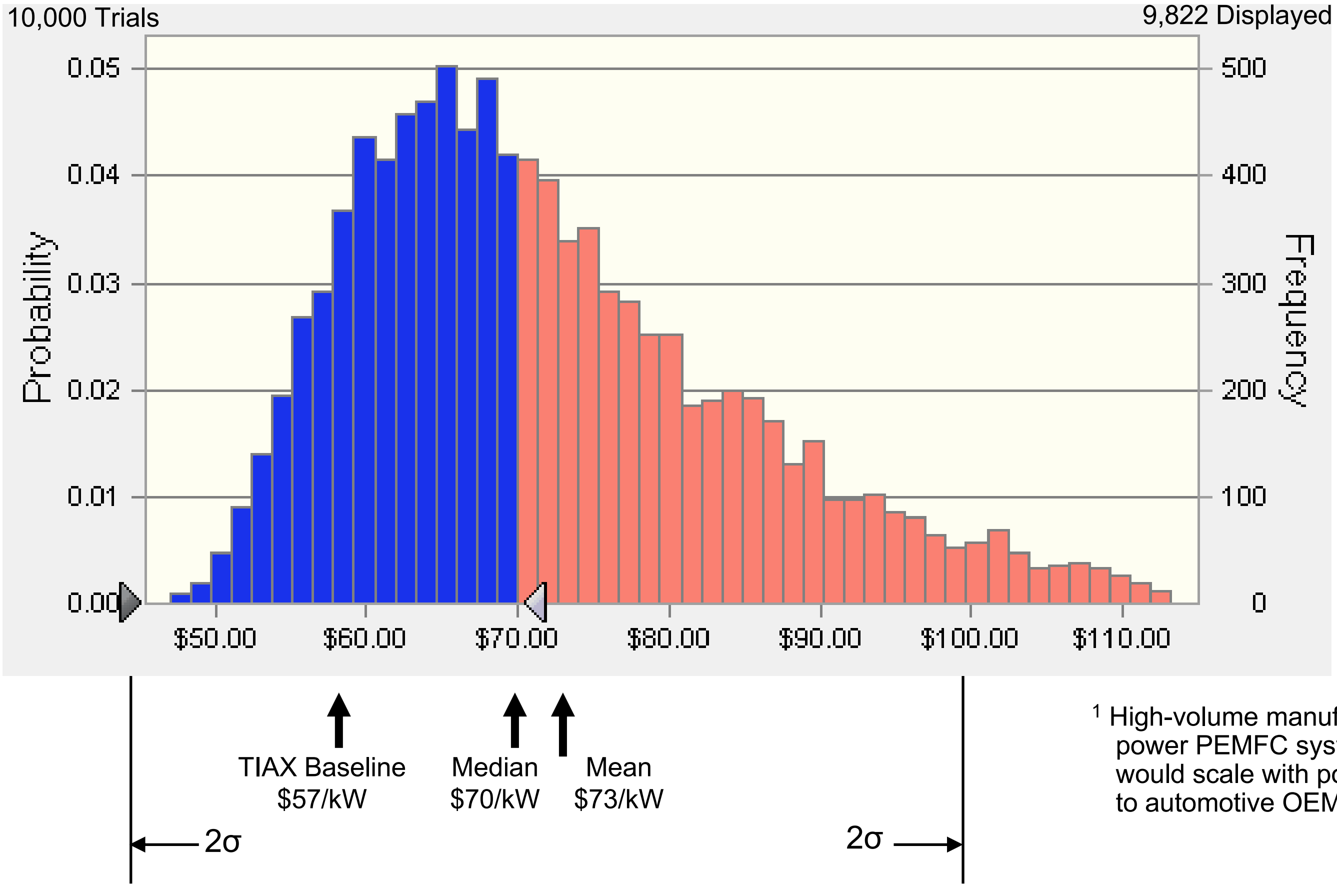


#	Variables	Min.	Max.	Base	Comments
1	CEM Cost ($/unit)	368	808	535	Based on component single variable sensitivity analysis
2	OEM Markup	5%	20%	15%	Based on industry feedback
3	Coolant Pump Cost ($/unit)	80	200	120	Based on industry feedback
4	Enthalpy Wheel Cost ($/unit)	123	217	160	Based on component single variable sensitivity analysis
5	H2 Blower Cost ($/unit)	178	259	193	Based on component single variable sensitivity analysis
6	Radiator Cost ($/unit)	46	71	56	Based on component single variable sensitivity analysis
7	Membrane Humidifier Cost ($/unit)	46	62	58	Based on component single variable sensitivity analysis

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.

Monte Carlo analysis shows that the high-volume PEMFC system OEM cost ranges between $45/kW and $101/kW (± 2σ).

2008 PEMFC System OEM Cost[1] ($/kW)



Cost[1]	$/kW
Mean	73
Median	70
Std. Dev.	14
TIAX Baseline	57

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.

Summary 2008 System - Comparison to Targets

The 2008 PEMFC stack and system costs are ~ 15-30% higher than the DOE 2010 cost targets.

PEMFC Sub-System	Factory Cost[1], \$/kW (without supplier markup)	OEM Cost[1,2], \$/kW (with 15% supplier markup)	DOE 2010 Cost Target[3], \$/kW
Stack	**29**		**25**
Balance of Plant	**26**	**28**	**20**
Water management (enthalpy wheel, membrane humidifier)	2.8	3.3	
Thermal management (radiator, fan, pump)	2.7	2.8	
Air management (CEM, motor controller)	7.9	8.9	5
Fuel management (H_2 blower, H_2 ejectors)	3.4	3.8	
Miscellaneous and assembly	8.6		
Total System	**55**	**57**	**45**

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

[2] Assumes 15% markup to the automotive OEM for BOP components

[3] FreedomCAR targets are \$20/kW for the stack and \$35/kW for the total system.

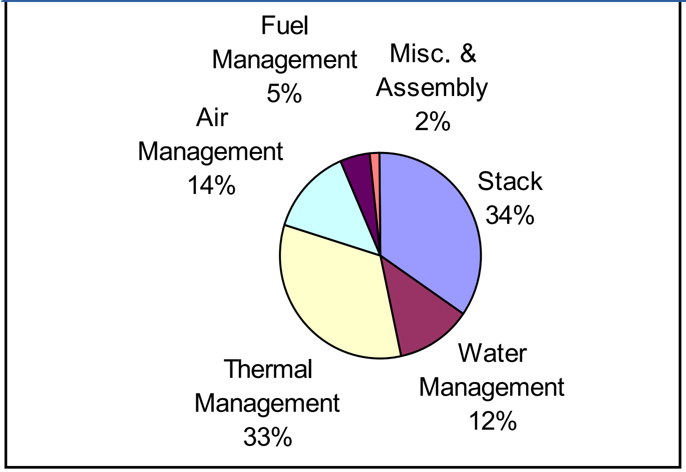
Summary 2008 System - Volume and Weight

While our focus is on cost, we also independently evaluated power density and specific power for the stack and system.

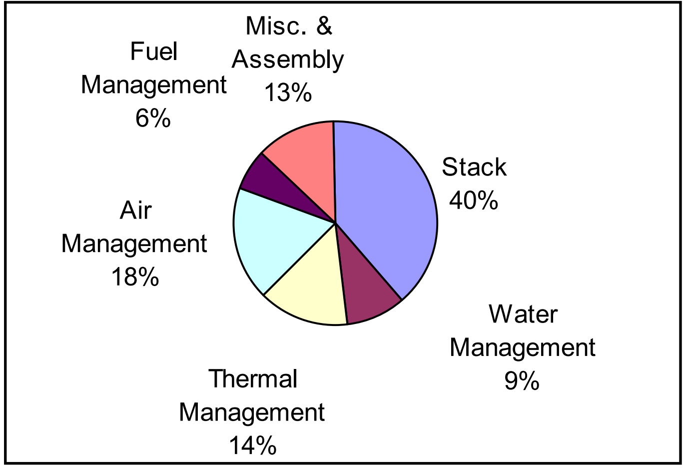
PEMFC Sub-System	Volume[1] (L)	Weight (kg)	DOE 2010 Target
Stack	**41**	**44**	
Power density[1,2] (W_e/L)	1,940		2,000
Specific power[2] (W_e/kg)	1,803		2,000
Balance of Plant	**79**	**71**	
Water management (enthalpy wheel, membrane humidifier)	15	11	
Thermal management (radiator, fan, pump)[3]	40	16	
Air management (CEM, motor controller)	17	21	
Fuel management (H_2 blower, H_2 ejectors)	5	7	
Miscellaneous and assembly	2	15	
Total System	**120**	**115**	
Power density[1,2] (W_e/L)	668		650
Specific power[2] (W_e/kg)	694		650

[1] Does not include packing factor, which would lower volumetric power density.
[2] Based on stack net power output of 80 kW, and **not** on the gross power output of 86.9 kW
[3] The radiator fan and coolant pump were in the Misc. category in 2005 and 2007

2008 PEMFC System Volume (120 L)



2008 PEMFC System Weight (115 kg)



Future Work

We will obtain industry feedback on our 2008 input assumptions and cost results and write a comprehensive, peer-reviewable report covering our 2007 PEMFC cost analysis.

- Prepare a comprehensive report on the 2007 PEMFC cost analysis (high-volume, bottom-up stack and BOP cost)
- Interview developers and stakeholders for feedback on 2008 PEMFC performance and cost assumptions and overall results
- Incorporate feedback into stack and BOP bottom-up cost models

Acknowledgement

Thank You

Questions?

Backup Slides Stack - $/kW Cost

2008 stack costs on a per kW basis are slightly lower than the 2007 stack costs primarily due to the decreased Pt loading.

Manufactured Cost[1], $/kW	2005	2007	2008	2010 DOE Target	Cost drivers / Comments
Membrane	4	2	2	10	Power density changed from 600 mW/cm^2 (2005), to 753 mW/cm^2 (2007), to 716 mW/cm^2 (2008) Pt loading decreased from 0.75 mg/cm^2 (2005), to 0.3 mg/cm^2 (2007), to 0.25 mg/cm^2 (2008) Woven carbon fiber cost decreased from $30/kg (2005) to $20/kg (2007 & 2008) Changed window frame from nitrile rubber ($5/lb, 2005) to Viton® ($20/lb, 2007 & 2008)
Electrodes	52	18	16		
GDL	3	2	2		
Seal	1	2	2		
Bipolar plates	3	3	3	5	
BOS	1	1	1		Includes stack manifold, bolts, end plates, current collector
Final Assembly	2	3	3		2007 & 2008 cost includes QC but not stack conditioning, while 2005 cost includes neither
Total[2]	**67**	**31**	**29**	**25**	

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Estimates are not accurate to the number of significant figures shown.

[2] Results may not appear to calculate due to rounding of the 2005, 2007, and 2008 cost results.

BOS = Balance-of-Stack

2008 stack costs on an active area basis are slightly lower than the 2007 stack costs primarily due to the decreased Pt loading.

Component	2005 Cost[1] ($/m²)	2007 Cost[1] ($/m²)	2008 Cost[1] ($/m²)	Cost drivers / Comments
Membrane	23	16	16	30 µm unsupported membrane; DOE 2010 target = $20/m²
Electrode	279	120	102	Pt cost increased from $900/tr.oz. (2005) to $1100/tr.oz. (2007, 2008); Pt loading decreased from 0.75 mg/cm² (2005) to 0.3 mg/cm² (2007) to 0.25 mg/cm² (2008); power density changed from 600 mW/cm² (2005), to 753 mW/cm² (2007), to 716 mW/cm² (2008)
GDL	18	13	13	Woven carbon fiber cost decreased from $30/kg (2005) to $20/kg (2007 & 2008)
Bi-polar plate	N/A	N/A	N/A	All plates have cooling channels
Bipolar plate with cooling	17	18	18	
Seal	6	13	13	Changed window frame from nitrile rubber ($5/lb, 2007) to Viton® ($20/lb, 2007 & 2008)
BOS	6	6	6	
Final Assembly	10	23	23	2007 & 2008 cost includes QC but not conditioning, while 2005 cost includes neither
Total	**361**	**210**	**191**	

In 2005, material costs were higher for the membrane (2 mil), electrodes (Pt loading = 0.75 mg/cm²) and GDL (woven carbon fiber = $30/kg).

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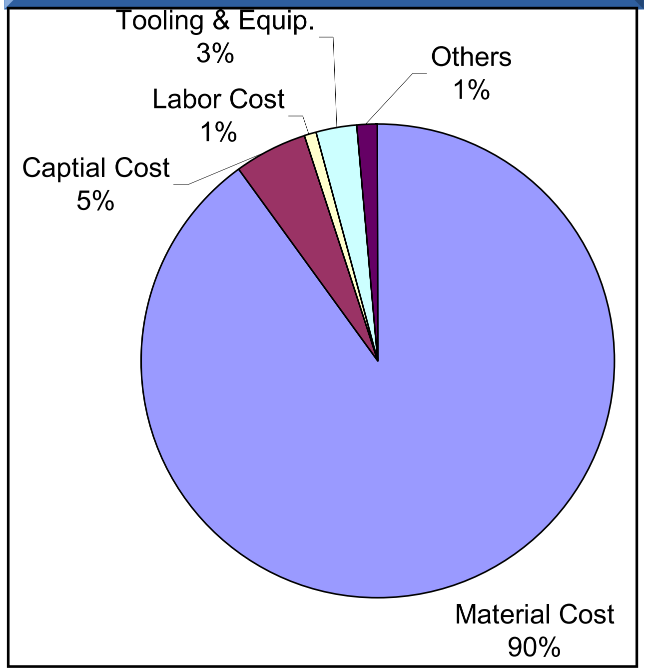
[1] Manufactured cost on an active area basis

Backup Slides 2008 Stack - Material Costs

Material costs dominate the manufactured cost of the stack components. For example, materials make up 90% of the total MEA cost.

Manufactured Cost	**2007 MEA[1] ($/m²)**	**2008 MEA[1] ($/m²)**
Material *- Membrane* *- Electrode* *- GDL*	135.48 - 13.89 - 109.61 - 11.98	117.71 - 13.83 - 91.90 - 11.98
Capital Cost	7.08	6.57
Labor	0.99	1.02
Tooling & Equipment	3.80	3.73
Other[2]	1.73	1.71
Total	**149**	**131**

2008 MEA Cost ($131/m²)



In 2007, the MEA cost was higher due to higher Pt loading (0.3 mg/cm² in 2007 vs. 0.25 mg/cm² in 2008).

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[1] m² of active area and kW of net power

[2] Other costs include utilities, maintenance, and building

Backup Slides 2008 Stack - Electrode Cost

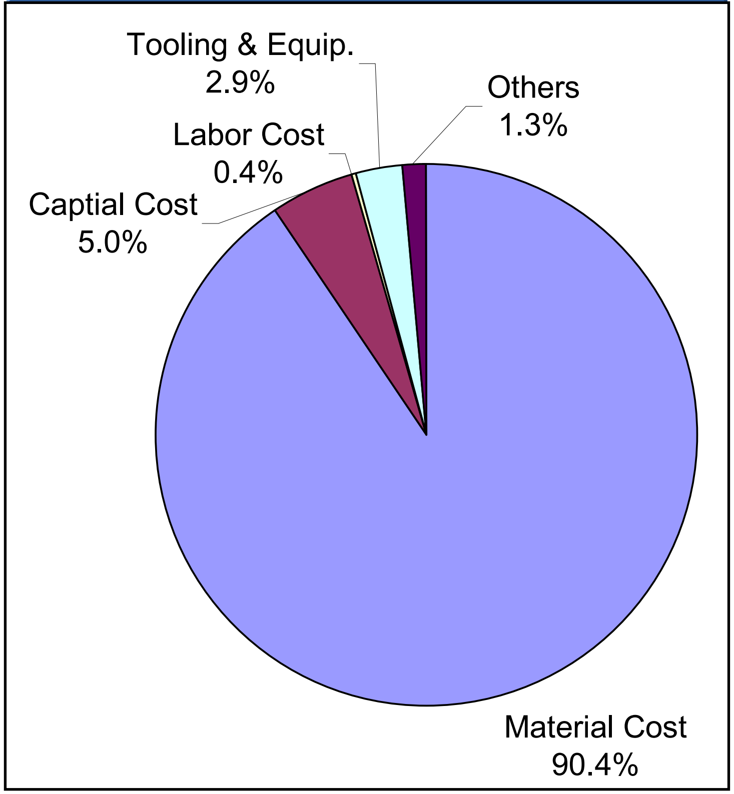
Platinum price dominates the electrode costs. We have assumed Pt price to be $1,100/tr.oz. or $35.4/g.

Manufactured Cost	Anode[1] ($/m²)	Cathode[1] ($/m²)	Total[1] ($/m²)
Material	31.19	60.71	91.90
Capital Cost	1.86	3.26	5.12
Labor	0.17	0.20	0.37
Tooling	1.13	1.82	2.95
Other[2]	0.510	0.79	1.329
Total	**35**	**67**	**102**

[1] m² of active area

[2] Other costs include utilities, maintenance, and building

Electrodes' Cost ($102/m²)



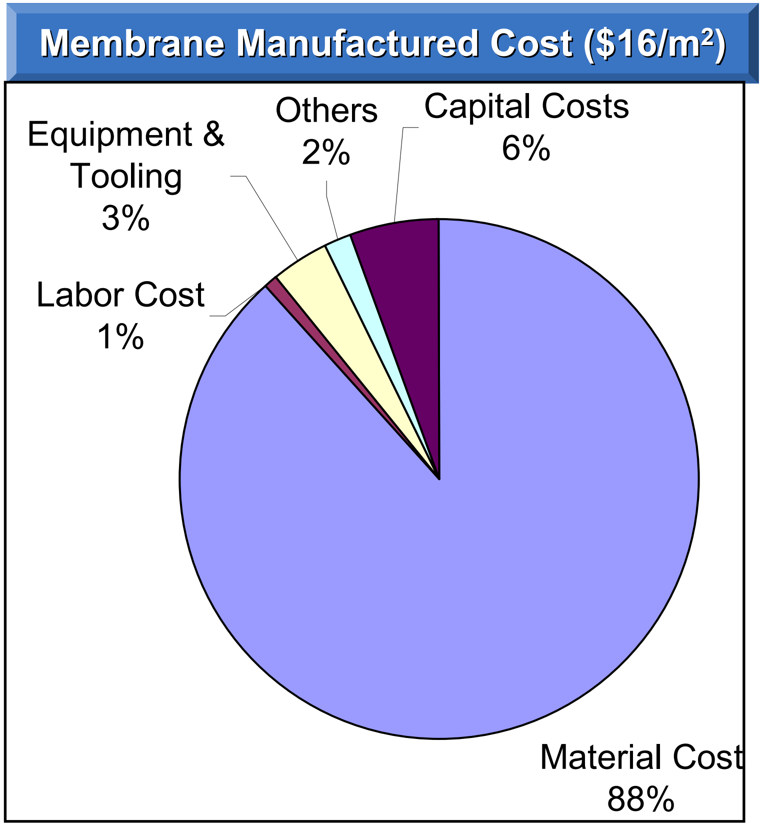
Backup Slides 2008 Membrane Cost Breakdown

The estimated membrane cost on an active area basis is $16/m^2, with material cost representing about 88% of the total cost.

Membrane Manufactured Cost[1]				
Component	**Material**		**Process**	
	($/m^2)	**($/kg)**	**($/m^2)**	**($/kg)**
Film Handling	0.31	6.71	0.23	5.01
Coating	11.70	254.38	0.39	8.54
Drying & Cooling	0.00	0.00	1.02	22.25
Quality Control	0.00	0.00	0.07	1.47
Laminating	0.00	0.00	0.06	1.28
Packaging	1.82	39.61	0.07	1.61
Subtotal	**13.83**	**301.85**	**1.85**	**40.15**
Total	**15.68 ($/m^2)**			
	340.85 ($/kg)			

[1] Manufactured cost on an active area basis or per kg of finished membrane basis (accounts for scrap and yield)

Membrane Manufactured Cost ($16/m^2)



In 2005, the membrane cost was $23/m^2 due to higher material costs (2 mil) and higher process costs (double pass required for coating).

The total capital investment on membrane equipment is about $20 million to meet the requirement of 500,000 vehicles annual production.

- 500,000 vehicles would require 6 million square meter of membrane annually
  - Stack gross power = 86.9 kW
  - Stack power density = 716 mW/cm^2
  - Downtime ~ 20%
  - Yield assumption ~ 95%
- Operating 3 shifts (20 hours)/day, 240 days/year
  - Required production rate is ~ 4,167 stacks/day
- A single coating line (1.2 mil membrane) is estimated to cost about $6 million and a total of 3 lines would be required to meet this annual production.

The 1.2 mil membrane needs only a single pass to complete the coating process; this may lead to a lower failure rate and higher yield assumption.

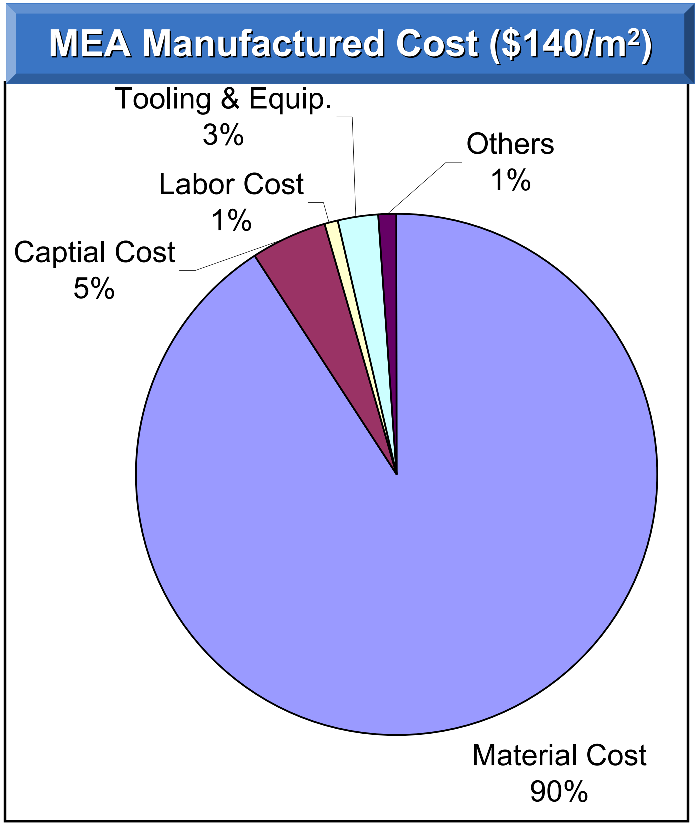
Backup Slides 2008 Membrane Electrode Assembly Cost

On an active area basis, the MEA and seal together cost $140/m².

Manufactured Cost[1]	MEA ($/m²)	Frame Seal ($/m²)
Material *- Membrane* *- Electrode* *- GDL*	117.71 - 13.89 - 91.90 - 11.98	5.03
Capital Cost	6.57	1.27
Labor	1.02	0.93
Tooling & Equipment	3.73	1.10
Other[2]	1.71	0.50
Subtotal	**130.74**	**8.83**
Total	**139.57**	

[1] Manufactured cost on an active area basis

[2] Other costs include utilities, maintenance, and building



In 2005, the MEA and seal cost was $325/m² due to higher material costs for the membrane (2 mil), electrodes (Pt loading = 0.75 mg/cm²) and GDL (woven carbon fiber = $30/kg).

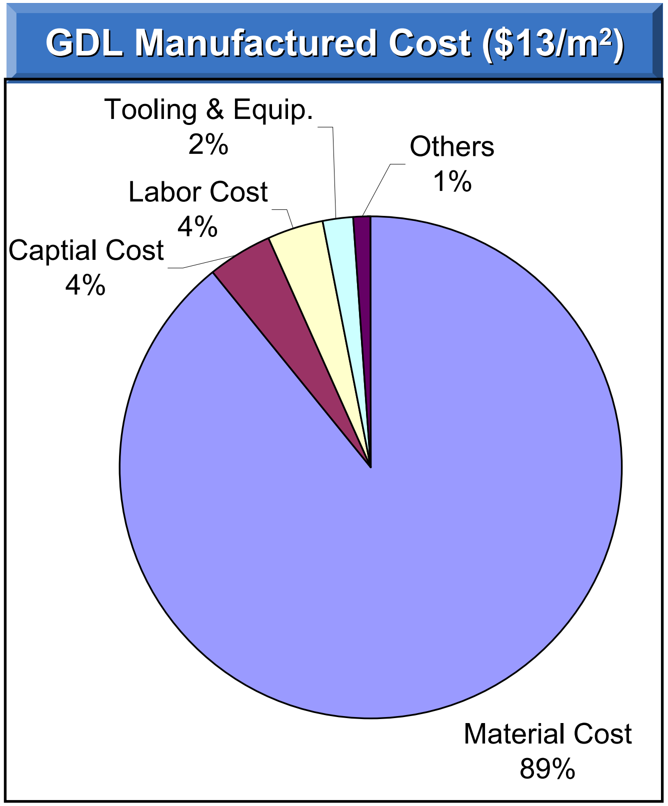
Backup Slides 2008 Gas Diffusion Layer Cost

The anode GDL has the same cost as the cathode GDL, of ~ $13/m²$.

Prepare Hydrophobic → Mix Hydrophobic → Spray Hydrophobic → Dry Hydrophobic → Coat Carbon → Heat Treat → Sinter

Manufactured Cost[1]	GDL ($/m^2)
Material	11.98
Capital Cost	0.57
Labor	0.52
Tooling	0.24
Other[2]	0.16
Total	**13.47**

[1] Manufactured cost on an active area basis
[2] Other costs include utilities, maintenance, and building

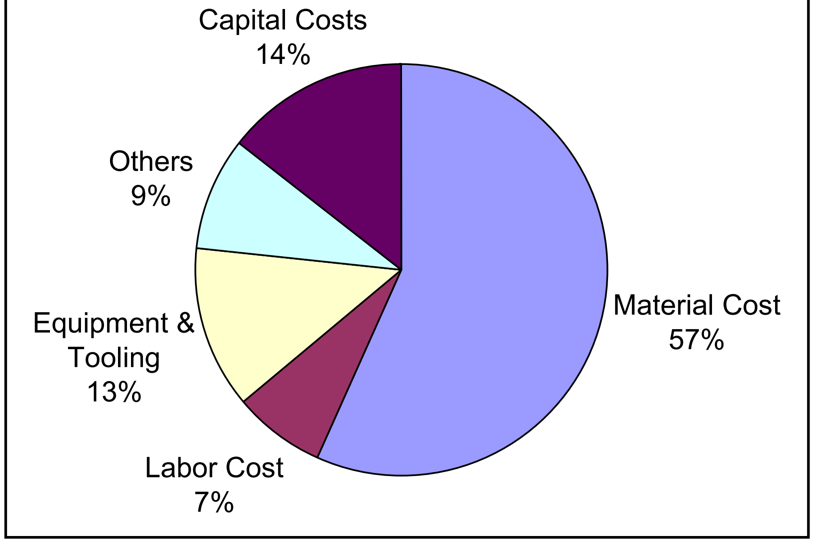

GDL Manufactured Cost ($13/m^2)

We estimate the expanded graphite foil bipolar plate cost is $18/m² at high volume.

Bipolar Plate Manufactured Cost[1] ($/m²)		
Component	**Material**	**Process**
Roll Form	10.24	0.97
Impregnation		1.09
Calendar		0.70
Compression Molding		2.25
Die Cut		0.60
Curing		2.11
Subtotal	**10.24**	**7.70**
Total	**17.94**	

[1] Manufactured cost on an active area basis

Bipolar Plate Manufactured Cost ($18/m²)



We assumed a raw graphite flake cost of $1.2/lb and expanded graphite flake cost of $2/lb.

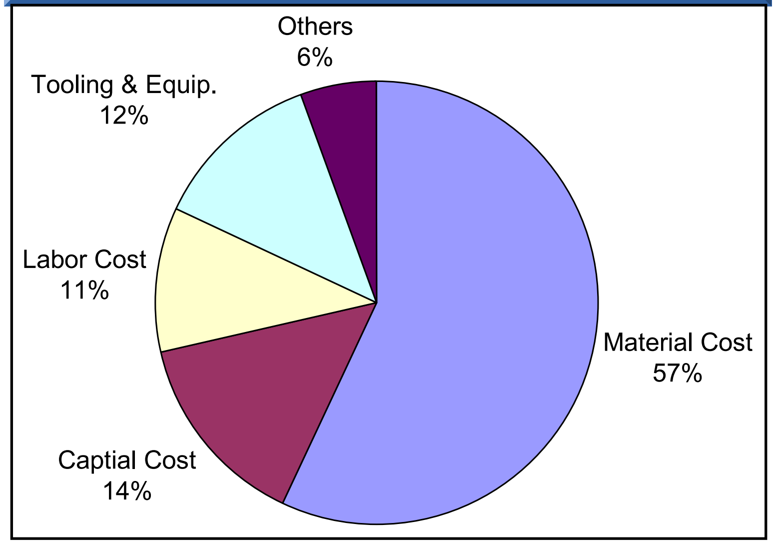
Transfer molding is used to fabricate the seals between the MEA and bipolar plate (cooling plate).

Transfer Molding
Bipolar Plate Gasket

Manufactured Cost[1]	Seals ($\$/m^2$)
Material	5.03
Capital Cost	1.27
Labor	0.93
Tooling	1.10
Other[2]	0.50
Total	**8.83**

[1] Manufactured cost on an active area basis
[2] Other costs include utilities, maintenance, and building

Seals' Manufactured Cost ($\$9/m^2$)



The seal material is Viton® which costs about $20/lb.

Backup Slides 2008 Stack Cost Breakdown

Detailed results of 2008 fuel cell stack cost breakdown.

Stack Costs[2]		Active Area Basis[1]				Total Fuel Cell Module Weight	Total Fuel Cell Module Mtl Cost ($)	Total Fuel Cell Module Process Cost ($)	Total Fuel Cell Module Cost ($)	Total Fuel Cell Module Cost[2] ($/kW)
		Mtl Cost ($\$/m^2$)	Process Cost ($\$/m^2$)	Total Cost ($\$/m^2$)	Unit Cell Weight/Area (g/cm^2)					
MEA	**Anode GDL**	$6.0	$0.7	$6.7	0.02	3	$73	$9	$82	$1
	Anode Active Layer	$31.2	$3.7	$34.8	0.00	0	$379	$44	$423	$5
	Electrolyte	$13.8	$1.8	$15.7	0.00	1	$168	$22	$190	$2
	Cathode Active Layer	$60.7	$6.1	$66.8	0.00	0	$737	$74	$811	$10
	Cathode GDL	$6.0	$0.7	$6.7	0.02	3	$73	$9	$82	$1
MEA Total		**$117.7**	**$13.1**	**$130.8**	**0.05**	**7**	**$1,429**	**$159**	**$1,588**	**$20**
Bipolar Coolant Plate		$10.2	$7.7	$17.9	0.10	24	$124	$93	$218	$3
Bipolar Interconnect[2]		$0.0	$0.0	$0.0	0.24	0	$0	$0	$0	$0
Gaskets						1	$78	$80	$158	$2
End Plates						2	$4	$6	$10	$0.1
Current Collector						1	$1	$2	$4	$0
Insulator						1	$8	$9	$18	$0
Outer Wrap						3	$8.9	$13.7	$22.6	$0.28
Tie Bolts						3	$22	$2	$24	$0
Final Assy								$273	$273	$3
Total Unit Cell		**$127.9**	**$20.8**	**$148.7**	**0.22**	**40**	**$1,676**	**$638**	**$2,314**	**$29**

[1] Manufactured cost on an active area basis

[2] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

We analyzed the manufactured cost of the PEM fuel cell Balance of Plant (BOP) at different production volumes based on the 2007 BOP configuration and sizing/specifications.

- At low production volumes, material and processing costs will not benefit from Economies of Scale (EOS), making the overall system more expensive than at high volumes.
- Stack components, because of their large number and compatibility with continuous processes, will realize EOS sooner than BOP components. (We completed the EOS analysis on the 2005/2006 stack in FY2006).
- BOP represents ~46% of the 2007 PEMFC system cost, thus bringing the relative importance of EOS analysis of BOP cost on par with that of the stack cost.
- Understanding the major cost contributors at low volume can highlight nearer term approaches and processes that might be necessary during the early stages of FCV commercialization.

The DOE has requested costs for production volumes of 100 units/year for 4 consecutive years, 30K/yr, 80K/yr, 130K/yr, and then 500K/yr.

We estimated the raw material price at different production volumes for key materials used in the BOP components.

Variation of Price with Production Volume

- Raw Material & Purchased Component Price
  - 100 - 30,000 1.4X
  - 30,000 - 80,000 1.2X
  - 80,000 - 500,000 1.0X

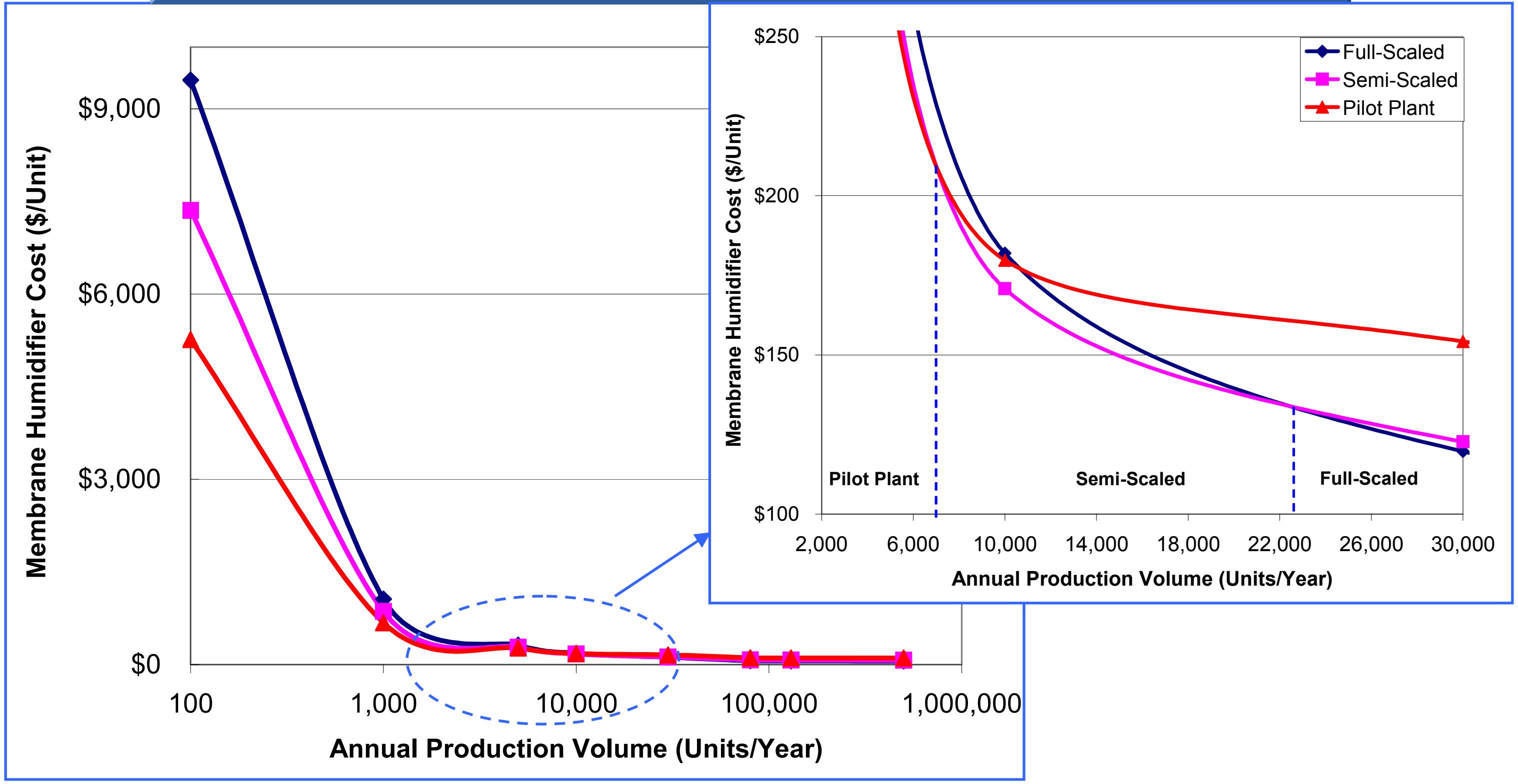
Major Materials Cost ($/kg)	**Annual Production Volume (Units/Year)**							
	100	**1,000**	**5,000**	**10,000**	**30,000**	**80,000**	**130,000**	**500,000**
Stainless Steel 316	$9.80	$9.80	$9.80	$8.40	$8.40	$7.00	$7.00	$7.00
Cordierite	$6.16	$6.16	$6.16	$5.28	$5.28	$4.40	$4.40	$4.40
Nafion	$246.40	$246.40	$246.40	$211.20	$211.20	$176.00	$176.00	$176.00
Cast Aluminum	$4.90	$4.90	$4.90	$4.20	$4.20	$3.50	$3.50	$3.50
Clad Aluminum 3003	$5.49	$5.49	$5.49	$4.70	$4.70	$3.92	$3.92	$3.92
Polyphenyl sulphone (PPS)	$6.16	$6.16	$6.16	$5.28	$5.28	$4.40	$4.40	$4.40
NdFeB Magnet	$123.20	$123.20	$123.20	$105.60	$105.60	$88.00	$88.00	$88.00

The cycle time, automation level (i.e. equipment capital cost) and material price are the major scaling parameters between the production scenarios.

Parameters		Pilot Plant	Semi-Scaled	Full-Scaled
Automation Level		Semi-Automated	Fully Automated	Fully Automated
Process Cycle Time (min/unit)	Extrude Nafion Tube	4.8	2.4	1.6
	Hydrogen Peroxide Bath	12.0	6.0	4.0
	Sulfuric Acid Bath	12.0	6.0	4.0
	Tap Water Bath	12.0	6.0	4.0
	De-ionized Water Bath	12.0	6.0	4.0
	Injection Molding End Housing	1.5	0.8	0.5
	Wind Tube	2.6	1.3	0.9
	Cast in Place	3.0	1.5	1.0
	Assembly	3.0	1.5	1.0
Process Equipment Cost ($/station)	Extrude Nafion Tube	$50,000	$75,000	$100,000
	Hydrogen Peroxide Bath	$100,000	$150,000	$200,000
	Sulfuric Acid Bath	$100,000	$150,000	$200,000
	Tap Water Bath	$100,000	$150,000	$200,000
	De-ionized Water Bath	$100,000	$150,000	$200,000
	Injection Molding End Housing	$100,000	$150,000	$200,000
	Wind Tube	$50,000	$75,000	$100,000
	Cast in Place	$50,000	$75,000	$100,000
	Assembly	$5,000	$7,500	$10,000

The transition between production scenarios occur at volumes of approximately 7,000 and 23,000 units per year.

Membrane Humidifier Factory Cost ($/unit)



MH Cost ($/Unit)	Annual Production Volume (Units/Year)							
	100	1,000	5,000	10,000	30,000	80,000	130,000	500,000
Full-Scaled	$9,530.12	$1,066.52	$314.31	$182.08	$119.78	$64.17	$60.75	$57.71
Semi-Scaled	$7,428.83	$874.49	$291.99	$180.98	$143.77	$86.20	$85.21	$83.34
Pilot Plant	$5,327.55	$682.47	$269.67	$179.88	$154.35	$108.02	$104.57	$104.21

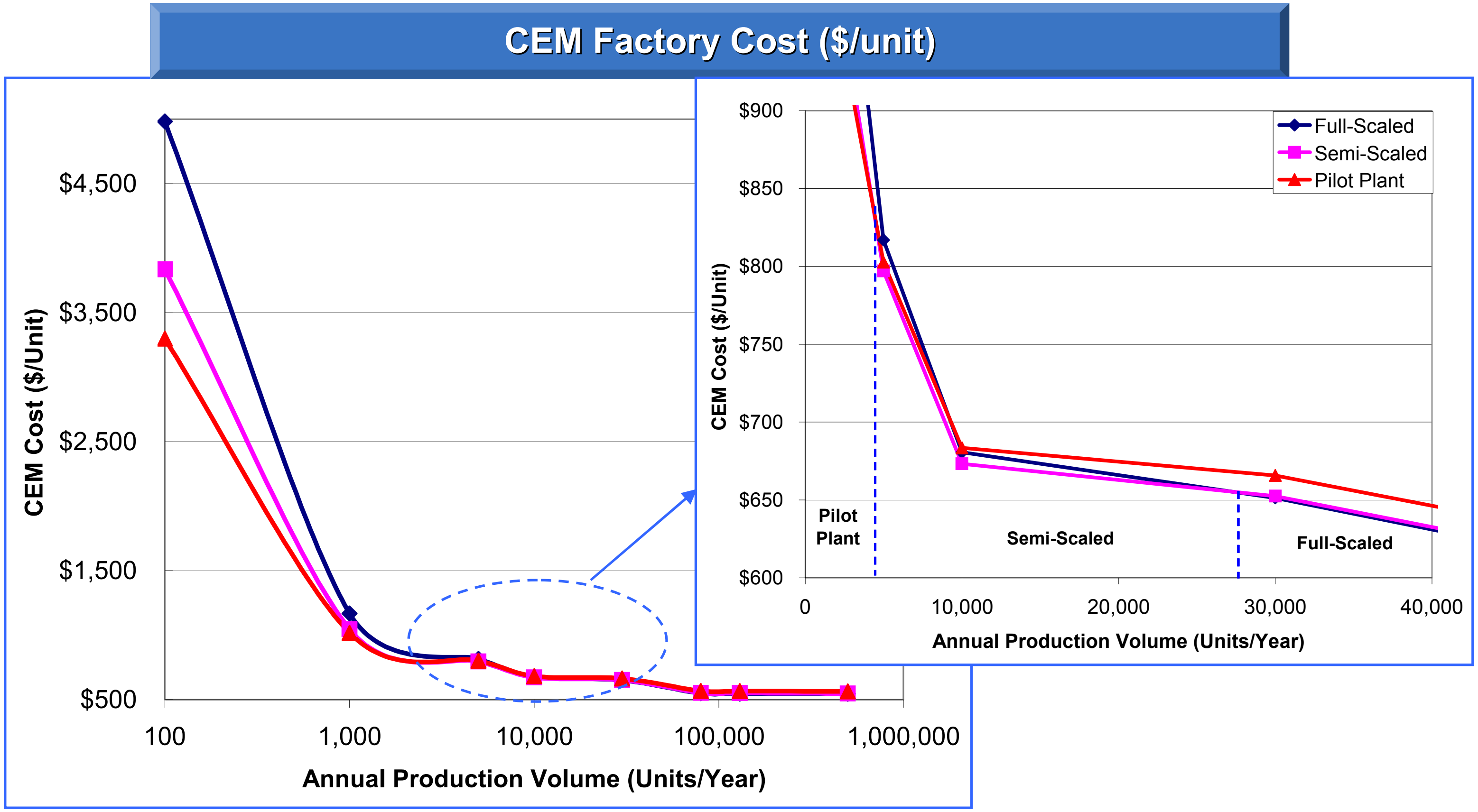
We developed process flow charts for the major CEM fabricated parts; the key manufacturing processes are tabulated below.

#	Selected Components	Material	Major Manufacturing Processes
1	Turbine Housing	Al	Casting; Turning; Drilling
2	Motor Housing	Al	Casting; Turning; Drilling
3	Compressor Housing	Al	Casting; Turning; Drilling
4	Motor connecting shaft	Steel	Turning; Heat treatment; Grinding
5	NdFeB Magnet	NdFeB	Mixing; Molding; Sintering (purchased)
6	Turbine Wheel	Al	Investment casting; Hot Isostatic Pressing (HIP)
7	Compressor Impeller	Al	Investment casting; Hot Isostatic Pressing (HIP)
8	Thrust Bearing Runner	Steel	Turning; Heat treatment; Grinding

The casting processes are varied between the three production scenarios.

Parameters		Pilot Plant	Semi-Scaled	Full-Scaled
Selected Component Processes	Turbine Housing	•Manual Sand Casting •Turning •Drilling	•Investment Casting •Turning •Drilling	•Cold Chamber Die Casting •Turning •Drilling
	Motor Housing	•Manual Sand Casting •Turning •Drilling	•Investment Casting •Turning •Drilling	•Cold Chamber Die Casting •Turning •Drilling
	Compressor Housing	•Manual Sand Casting •Turning •Drilling	•Investment Casting •Turning •Drilling	•Cold Chamber Die Casting •Turning •Drilling
	Motor Connecting Shaft	•Turning •Heat Treatment •Grinding	•Turning •Heat Treatment •Grinding	•Turning •Heat Treatment •Grinding
	Thrust Bearing Runner	•Turning •Heat Treatment •Grinding	•Turning •Heat Treatment •Grinding	•Turning •Heat Treatment •Grinding

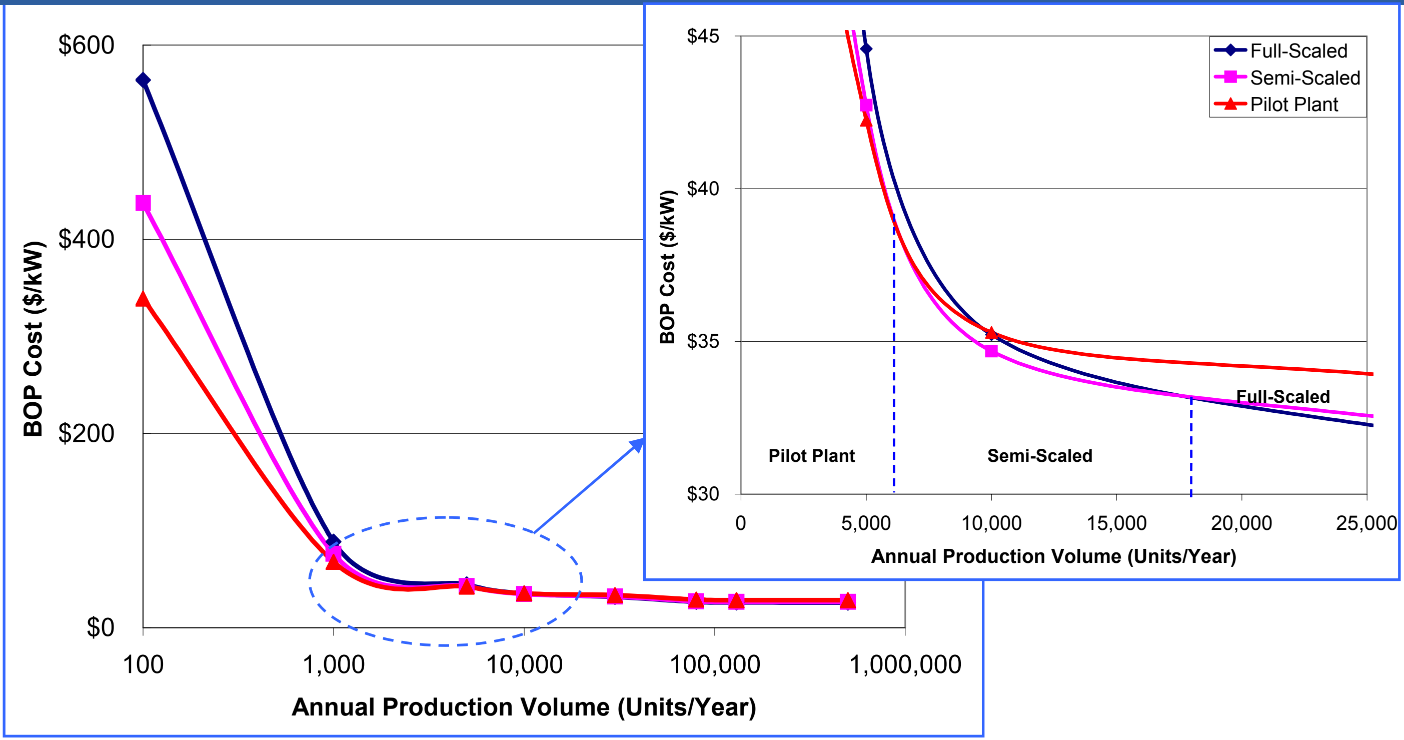
The transitions between production scenarios occur at volumes of approximately 5,000 and 28,000 units per year.



CEM Cost ($/Unit)	Annual Production Volume (Units/Year)							
	100	**1,000**	**5,000**	**10,000**	**30,000**	**80,000**	**130,000**	**500,000**
Full-Scaled	$4,982.40	$1,168.82	$816.91	$680.61	$651.28	$549.83	$548.06	$546.39
Semi-Scaled	$3,835.44	$1,046.44	$797.02	$673.26	$652.49	$553.25	$551.69	$549.62
Pilot Plant	$3,298.66	$1,018.78	$802.75	$683.43	$665.74	$568.52	$567.33	$565.92

On an overall BOP basis, the transitions between production scenarios occur at volumes of approximately 6,000 and 18,000 units per year.

BOP Factory Cost ($/kW[1])

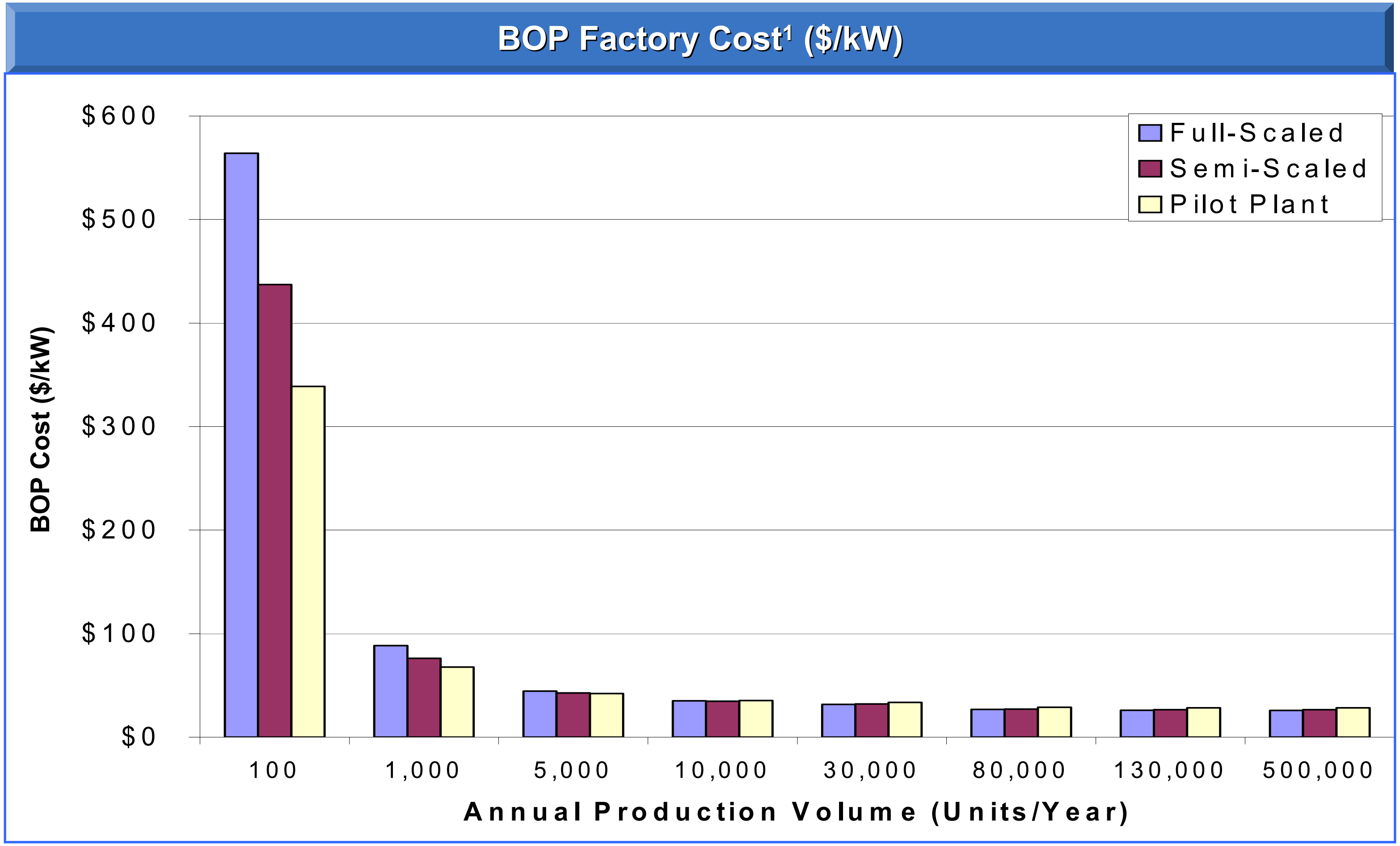


BOP Cost ($/kW[1])	Annual Production Volume (Units/Year)							
	100	1,000	5,000	10,000	30,000	80,000	130,000	500,000
Full-Scaled	$564.09	$88.52	$44.58	$35.22	$31.69	$26.65	$26.01	$25.83
Semi-Scaled	$437.26	$76.19	$42.73	$34.68	$32.09	$27.22	$26.63	$26.49
Pilot Plant	$338.92	$67.80	$42.24	$35.29	$33.57	$28.98	$28.40	$28.30

[1] PEMFC net power (80 kW) basis

Backup Slides 2007 BOP Economies of Scale *Overall BOP Cost*

As expected, at low production volumes (100 units/year), the pilot plant scenario yields the lowest BOP cost, while at volumes greater than 80,000 units/year, the full-scaled scenario yields the lowest cost.



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[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

2005/2006 Stack EOS

The 2006 EOS analysis is based on the 2005 stack specifications, with minor changes to the component material assumptions and processes.

Parameters	Units	2005 stack / 2006 EOS
Cell voltage @ rated power	V	0.65
Power density @ 0.65V	mW/cm^2	600
Total Pt Loading	mg/cm^2	0.75
Pt cost	$/g ($/tr.oz.)	29 (900)
Fuel cell net power	kW_e	80
Fuel cell gross power	kW_e	90
Stack voltage @ rated power	V	300 V @ 266 A
Number of stacks per system		2
Number of cells per stack		231
System pressure @ rated power	atm	2.5
Operating temperature	°C	80

Component	Parameter	2006 EOS Assumptions
Membrane	Material	Sulfonated fluoro-polymer
	Supported	No
	Process	Cast dispersion
	Thickness	50 µm
Electrodes (Cathode & Anode)	Catalyst	Pt
	Support	Carbon black
	Process	Screen printing / gravure coating
Gas Diffusion Layer (GDL)	Material	Non-woven carbon paper
	Process	Hydrophobic treatment
Bipolar Plate	Material	Molded graphite
	Process	Compression molding

The 2008 stack is different from the 2005 stack in that it assumes an NSTFC[1]-based MEA, a 30 µm 3M-like membrane, Pt loading=0.25 mg/cm^2 and power density=716 mW/cm^2 @ 0.685 V/cell.

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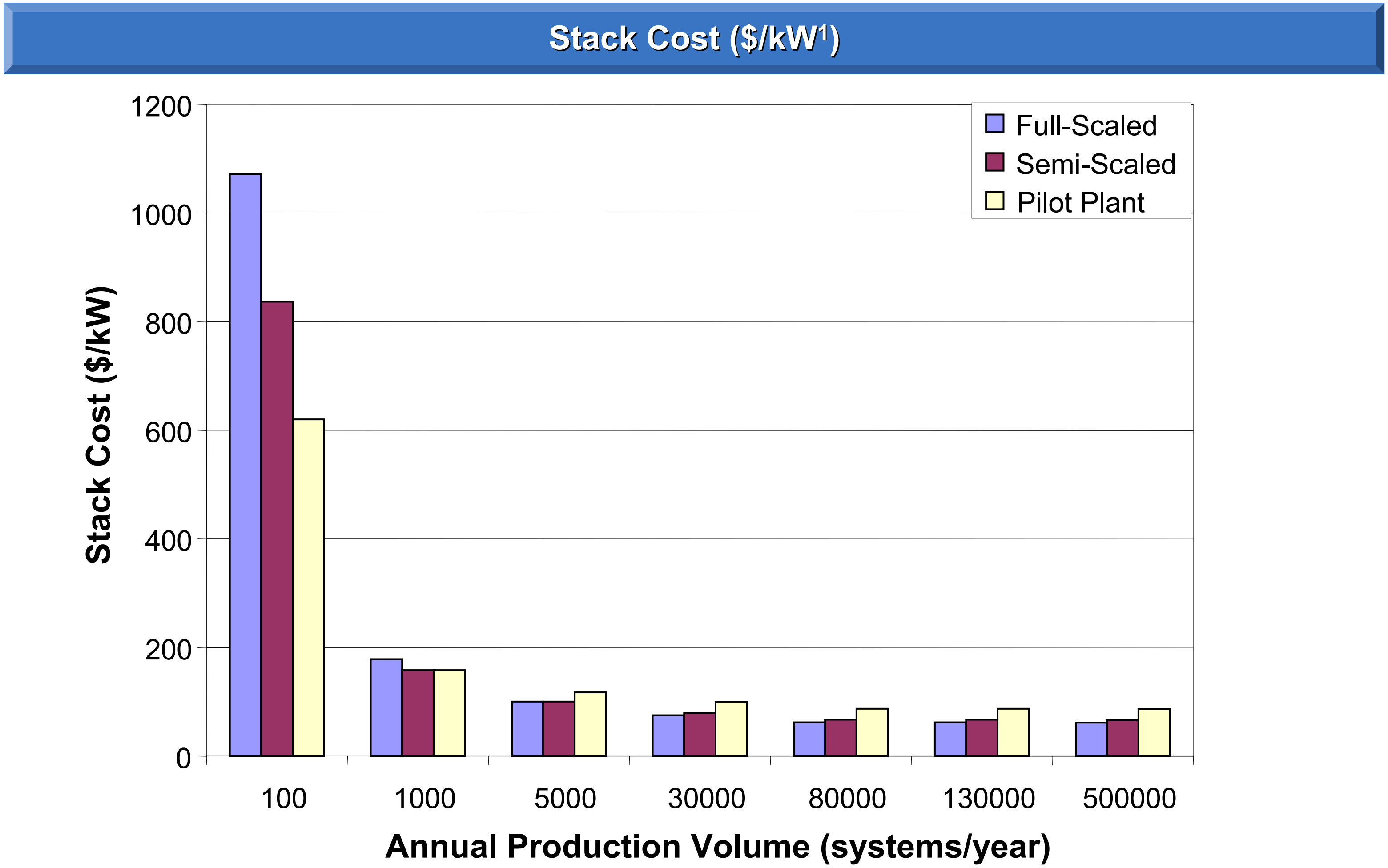
[1] Nano-Structured Thin Film Catalyst on organic whisker support

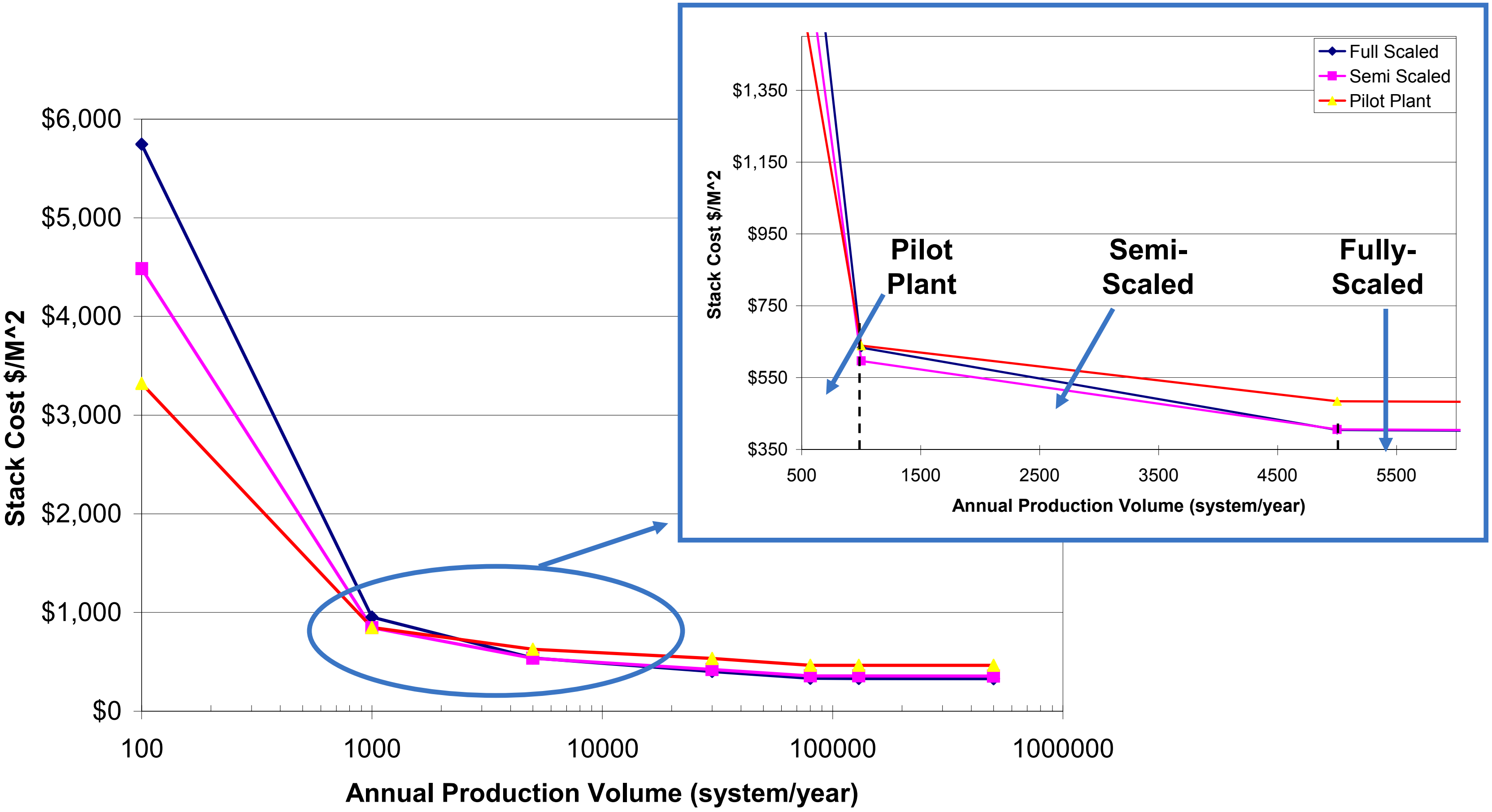
At low volumes (~100 systems/year), the pilot plant yields the lowest stack cost of ~\$610/kW[1], while at high volumes (≥ 80,000 systems/year), the full-scaled scenario yields the lowest stack cost of ~\$61/kW[1].



[1] PEMFC net power (80 kW) basis

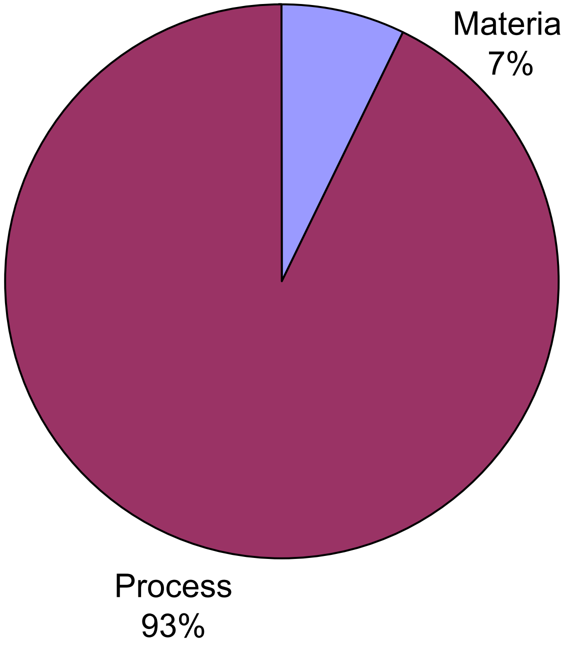
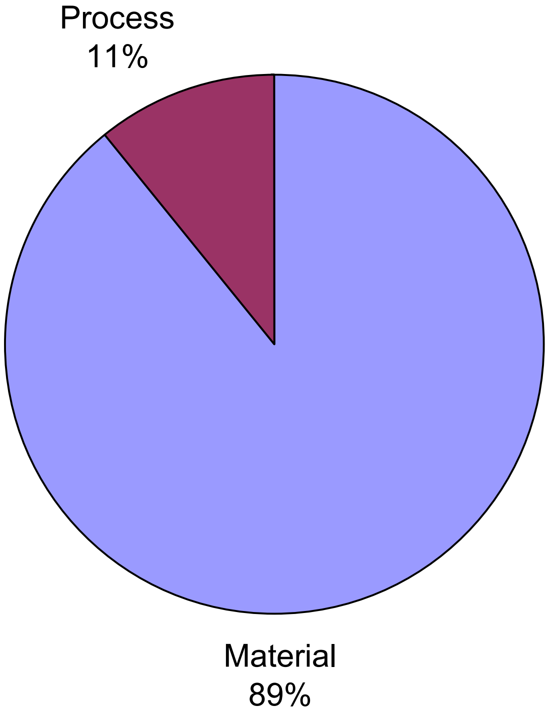
In 2006, we used a bottom-up approach to determine the impact of production volume on stack manufacturing cost.

Results – Stack Cost ($/m^2)



CAPEX controls the stack cost at low volume, while material cost dominates as the production volume increases.

Results – Stack Cost Breakout (Full-Scaled Production Scenario)

100 unit/year ($1,072/kW)	500,000 unit/year ($61/kW)
	

We coordinated with DOE, ANL, developers, and stakeholders so far this year, with additional meetings to follow.

Audience/ Reviewer	Date	Location
System Specifications Review Meeting with DOE and ANL	Feb 07	Telecon
Manufacturing Process Review Mtg. with 3M	Mar 07	Telecon
Fuel Cell Tech Team Mtg.	Apr 07	Detroit MI
National Academy of Science Review	Apr 07	Washington DC
DOE Merit Review	May 07	Washington DC
Several Work-in-Progress Mtgs. with DOE and ANL	Jun – Sep 07	Telecon
Final Presentation to HFCIT Team at DOE HQ	Nov 07	Washington DC
Fuel Cell Tech Team Mtg.	May 08	Detroit MI
DOE Annual Merit Review	June 08	Arlington VA
DOE HFCIT Review	Sep 08	Washington DC
Fuel Cell Tech Team Review	Sep 08	Telecon

We contacted developers of key stack and BOP components for their feedback on design, performance and cost assumptions.

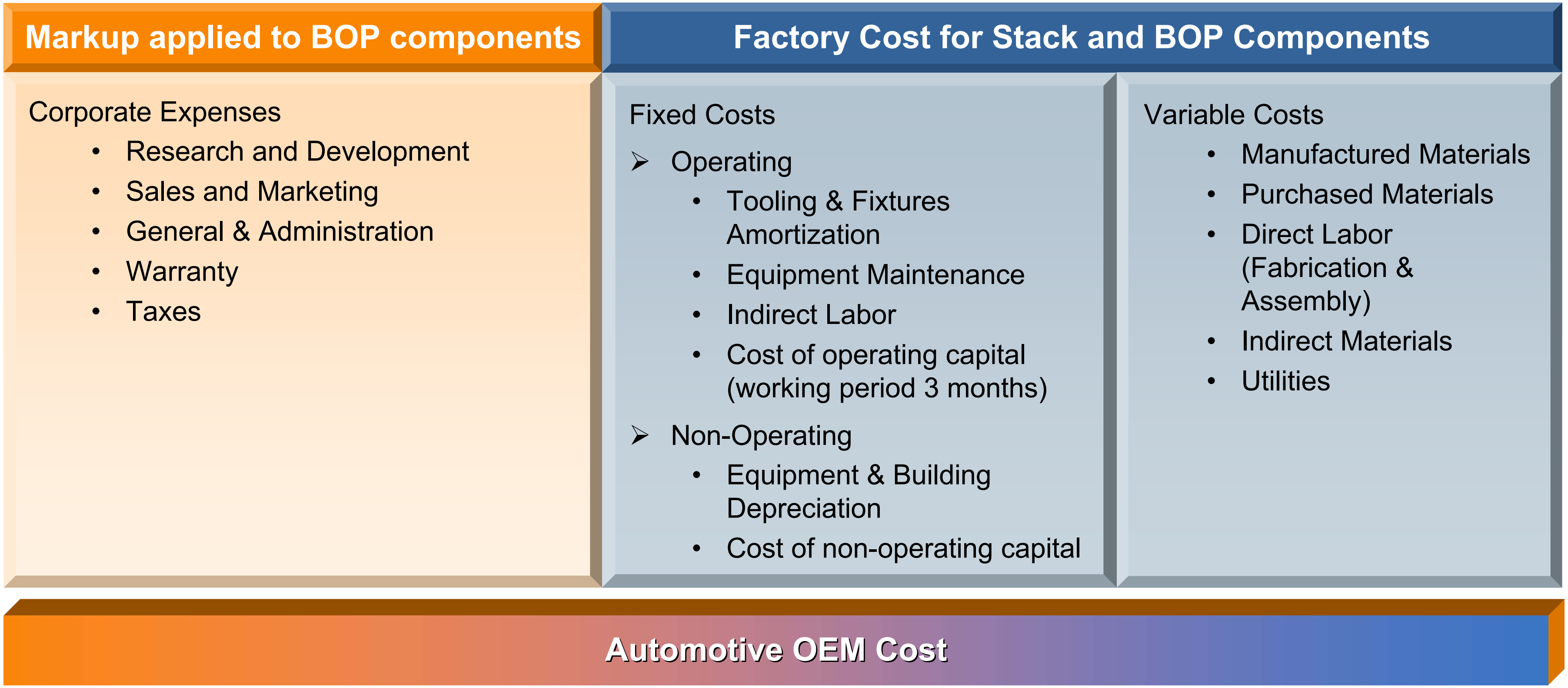
Contacted in 2005-2006

- MEA
  - 3M, DuPont, Gore
- GDL
  - E-Tek
  - SpectraCorp, Toray, SGL Carbon
- Bipolar Plates
  - Porvair, GrafTech, SGL Carbon
  - Raw Materials - Superior Graphite, Asbury Carbons
- Seals
  - Freudenberg, SGL Carbon
- Stack and System Integrators
  - Ballard
  - Tech Team (GM, Ford, Chrysler)

Contacted in 2007

- MEA
  - 3M
- Water Management
  - PermaPure (Nafion membrane-based)
  - Emprise (enthalpy wheel)
- Thermal Management
  - Modine
- Air Management
  - Honeywell (compressor-expander-motor)
- Fuel management
  - Parker Hannifin
  - H_2 Systems

We estimate an automotive OEM cost, applying no markup on stack components, and assuming a 15% markup on BOP components.



Markup applied to BOP components

Corporate Expenses
- Research and Development
- Sales and Marketing
- General & Administration
- Warranty
- Taxes

Factory Cost for Stack and BOP Components

Fixed Costs
- ➢ Operating
  - Tooling & Fixtures Amortization
  - Equipment Maintenance
  - Indirect Labor
  - Cost of operating capital (working period 3 months)
- ➢ Non-Operating
  - Equipment & Building Depreciation
  - Cost of non-operating capital

Variable Costs
- Manufactured Materials
- Purchased Materials
- Direct Labor (Fabrication & Assembly)
- Indirect Materials
- Utilities

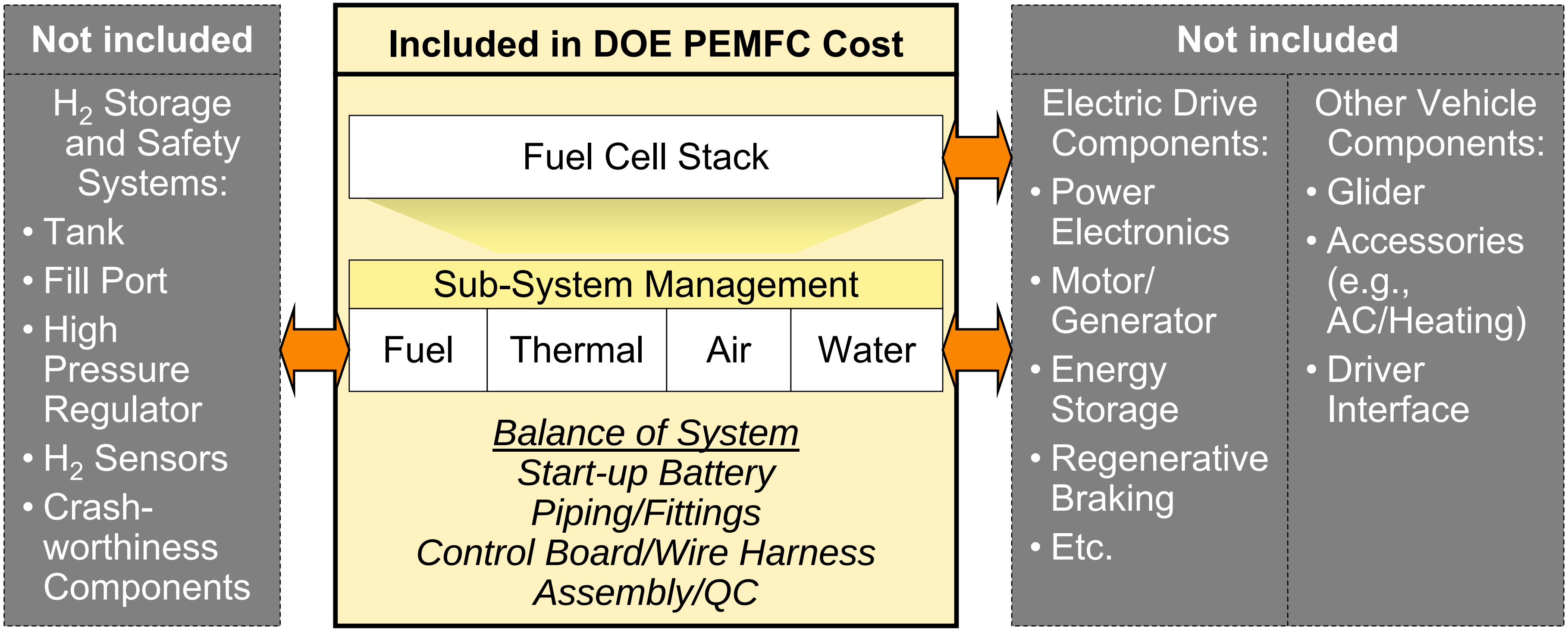
Automotive OEM Cost

- We assume a vertically integrated process for the manufacture of the stack by the automotive OEM, so no mark-up is included on the major stack components
- Raw materials are assumed to be purchased, and therefore implicitly include supplier markup
- We assume 100% debt financed with an annual interest rate of 15%, 10-year equipment life, and 25-year building life.

OEM = Original Equipment Manufacturer (i.e., car company)

Backup Slides Scope

Our cost assessment includes the fuel cell stack and related BOP subsystems, but does not include electric drive or other necessary powertrain components.



Not included

H_2 Storage and Safety Systems:

- Tank
- Fill Port
- High Pressure Regulator
- H_2 Sensors
- Crash-worthiness Components

Included in DOE PEMFC Cost

Fuel Cell Stack

Sub-System Management

Fuel	Thermal	Air	Water

<u>Balance of System</u>
Start-up Battery
Piping/Fittings
Control Board/Wire Harness
Assembly/QC

Not included

Electric Drive Components:

- Power Electronics
- Motor/ Generator
- Energy Storage
- Regenerative Braking
- Etc.

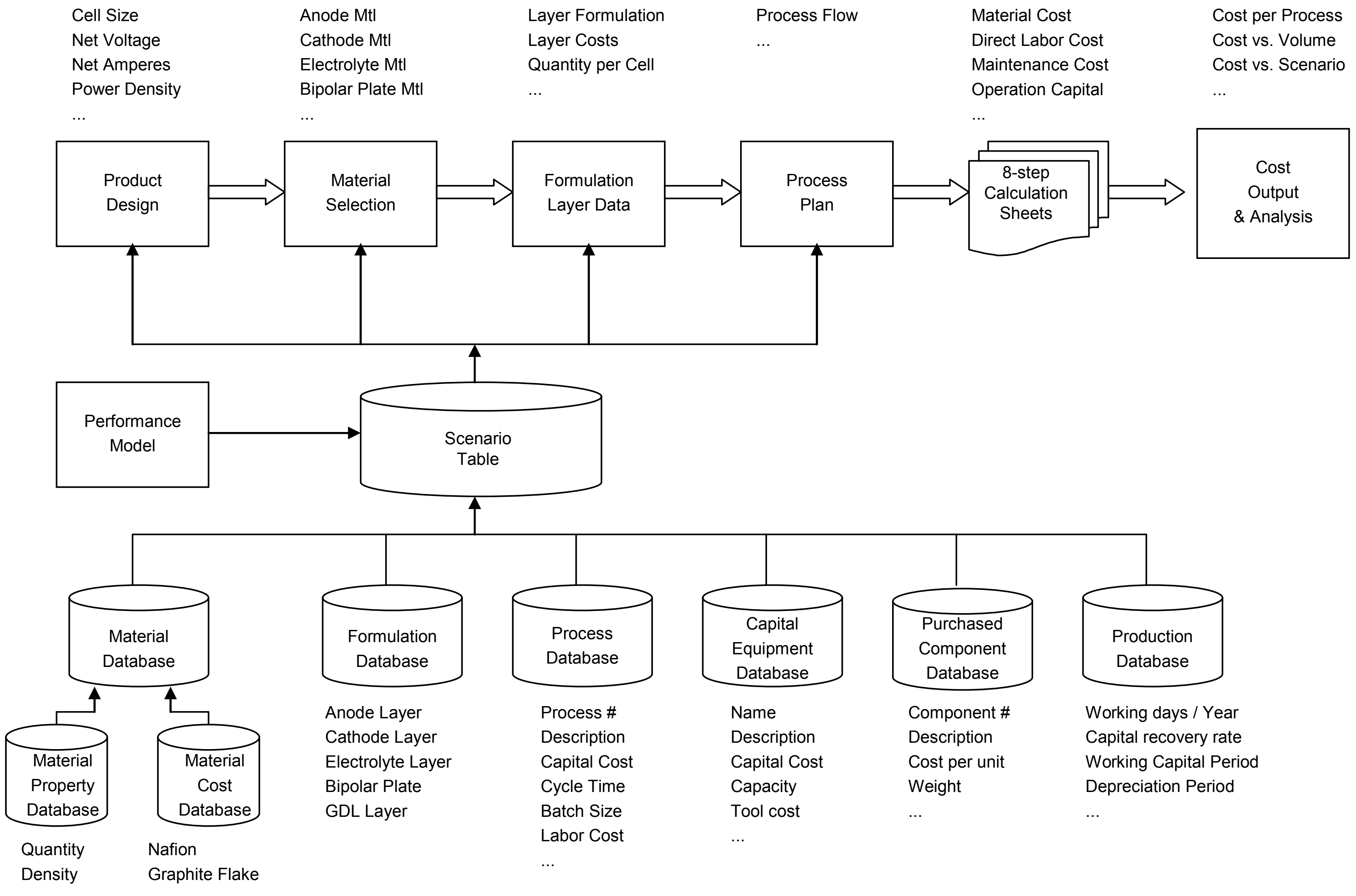
Other Vehicle Components:

- Glider
- Accessories (e.g., AC/Heating)
- Driver Interface

Quality Control (QC) includes leak and voltage tests, but does not include stack conditioning.

Backup Slides Stack Costing Approach

Our PEM stack cost model integrates expertise in materials, design, and manufacturing operations.



Cell Size
Net Voltage
Net Amperes
Power Density
...

Anode Mtl
Cathode Mtl
Electrolyte Mtl
Bipolar Plate Mtl
...

Layer Formulation
Layer Costs
Quantity per Cell
...

Process Flow
...

Material Cost
Direct Labor Cost
Maintenance Cost
Operation Capital
...

Cost per Process
Cost vs. Volume
Cost vs. Scenario
...

Product Design → Material Selection → Formulation Layer Data → Process Plan → 8-step Calculation Sheets → Cost Output & Analysis

Performance Model → Scenario Table

Material Database

Material Property Database

Quantity
Density
...

Material Cost Database

Nafion
Graphite Flake
...

Formulation Database

Anode Layer
Cathode Layer
Electrolyte Layer
Bipolar Plate
GDL Layer

Process Database

Process #
Description
Capital Cost
Cycle Time
Batch Size
Labor Cost
...

Capital Equipment Database

Name
Description
Capital Cost
Capacity
Tool cost
...

Purchased Component Database

Component #
Description
Cost per unit
Weight
...

Production Database

Working days / Year
Capital recovery rate
Working Capital Period
Depreciation Period
...

We performed single and multi- variable sensitivity analyses to examine the impact of major stack and BOP parameters on PEMFC system cost.

- Single variable stack sensitivity analysis
  - Varied one parameter at a time, holding all others constant
  - Varied overall manufacturing assumptions, economic assumptions, key stack performance parameters, and direct material cost, capital expenses and process cycle time for individual stack components
  - Assumed stack rated power, operating pressure, temperature, humidity requirements and cell voltage remained invariant
- Single variable BOP sensitivity analysis
  - Varied one parameter at a time, holding all others constant
  - Varied overall manufacturing assumptions, economic assumptions, and direct material cost, capital expenses and process cycle time for individual BOP components
  - Assumed stack rated power, operating pressure, temperature, humidity requirements and cell voltage remained invariant
- Multi-variable (Monte Carlo) system sensitivity analysis
  - Varied all stack and BOP parameters simultaneously, using triangular PDF
  - Performed Monte Carlo analysis on individual stack and BOP components, the results of which were then fed into a system-wide Monte Carlo analysis

Backup Slides Raw Material Assumptions

Raw materials for stack and BOP components are assumed to be purchased, and therefore implicitly include supplier markup.

PEMFC Sub-system	Raw Materials / Purchased Components
Stack	
Membrane	PFSA ionomer, isopropanol, silicone-treated PET film, polypropylene film, water
Electrodes	Pt, Co, Mn, perylene red (PR-149) dye, aluminum-coated film substrate, Teflon sheet
GDL	Woven carbon fiber, PTFE, carbon powder, water
Seal	Viton
Bipolar Plates	Expanded graphite flake, vinyl ester, carbon fiber, poly dimethylsiloxane (SAG), methyl ethyl ketone peroxide, cobalt naphthenate
BOS	Stack manifold, bolts, end plates, current collector
Balance of Plant	
Water management (enthalpy wheel, membrane humidifier)	Cordierite, γ-alumina, Teflon seals, enthalpy wheel motor, Nafion, Noryl®, PPS, polyurethane, O-rings
Thermal management (radiator, fan, pump)	Aluminum coil, aluminum tube, radiator fan, coolant pump
Air management (CEM, motor controller)	NdFeB magnet, steel bar stock, Teflon insulation, copper coils, steel laminations, bearings, seals, motor controller, wire harness
Fuel management (H_2 blower, H_2 ejectors)	SS316 bar, SS316 sheet, seals, H_2 blower motor, H_2 ejectors

With the exception of heat exchangers, the BOP components have not been manufactured at high volumes.

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Technology advances such as high temperature, low R.H. membranes could simplify and reduce the size/cost of some of the BOP components.

We estimated the cost of the CEM based on published presentations, reports, and patents from Honeywell.

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Backup Slides CEM References and Manufacturing Processes

The references used to determine the overall design and major manufacturing processes for the CEM are tabulated below.

Component	References
Overall System	Honeywell, DOE program review, progress report & annual report, 2005, 2004, 2003, 2000
Electrical Motor	Honeywell, DOE program review, progress report & annual report 2004; US patent 5,605,045;
Power Electronics	Honeywell, DOE program review, progress report & annual report, 2005; Caterpillar, DOE Contract DE-SC05-00OR-99OR22734
Unison Ring	US patent 6,269,642; Garrett/Honeywell, DE-FC05-00OR22809;
Journal Bearings	US patent, 2006/0153704; Honeywell 2005 fuel cell seminar;

#	Selected Components	Material	Major Manufacturing Processes
1	Turbine Housing	Al	Cold chamber die casting; Turning; Drilling
2	Motor Housing	Al	Cold chamber die casting; Turning; Drilling
3	Compressor Housing	Al	Cold chamber die casting; Turning; Drilling
4	Motor connecting shaft	Steel	Turning; Heat treatment; Grinding
5	NdFeB Magnet	NdFeB	Mixing; Molding; Sintering (purchased)
6	Turbine Wheel	Al	Investment casing; HIP
7	Compressor Impeller	Al	Investment casting; HIP
8	Thrust Bearing Runner	Steel	Turning; Heat treatment; Grinding

Backup Slides CEM Process Flow

The motor rotor manufacturing process represents the level of detail we captured in the costing of the CEM.

Machining Shaft[1] → Teflon Insulation Coating → Attach Segment NdFeB Magnets → Machining & Assembling Collar

- Cut the material from bar stock
- Thermal heat treatment (annealing)
- Machining in Lathe
  - Load Part to 3 jaw chuck
  - Face finish
  - chamber
  - Central drill & drill
  - Re-clamp the part
  - Contour turning rough
  - Reverse the part
  - face finish
  - chamber
  - Central drill and drill
  - Re- clamp the part using central holes
  - Contour turning finish
- Thermal heat treatment (hardening)
- Grinding rough
- Grinding finish

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CEM Motor Rotor Manufacturing Process

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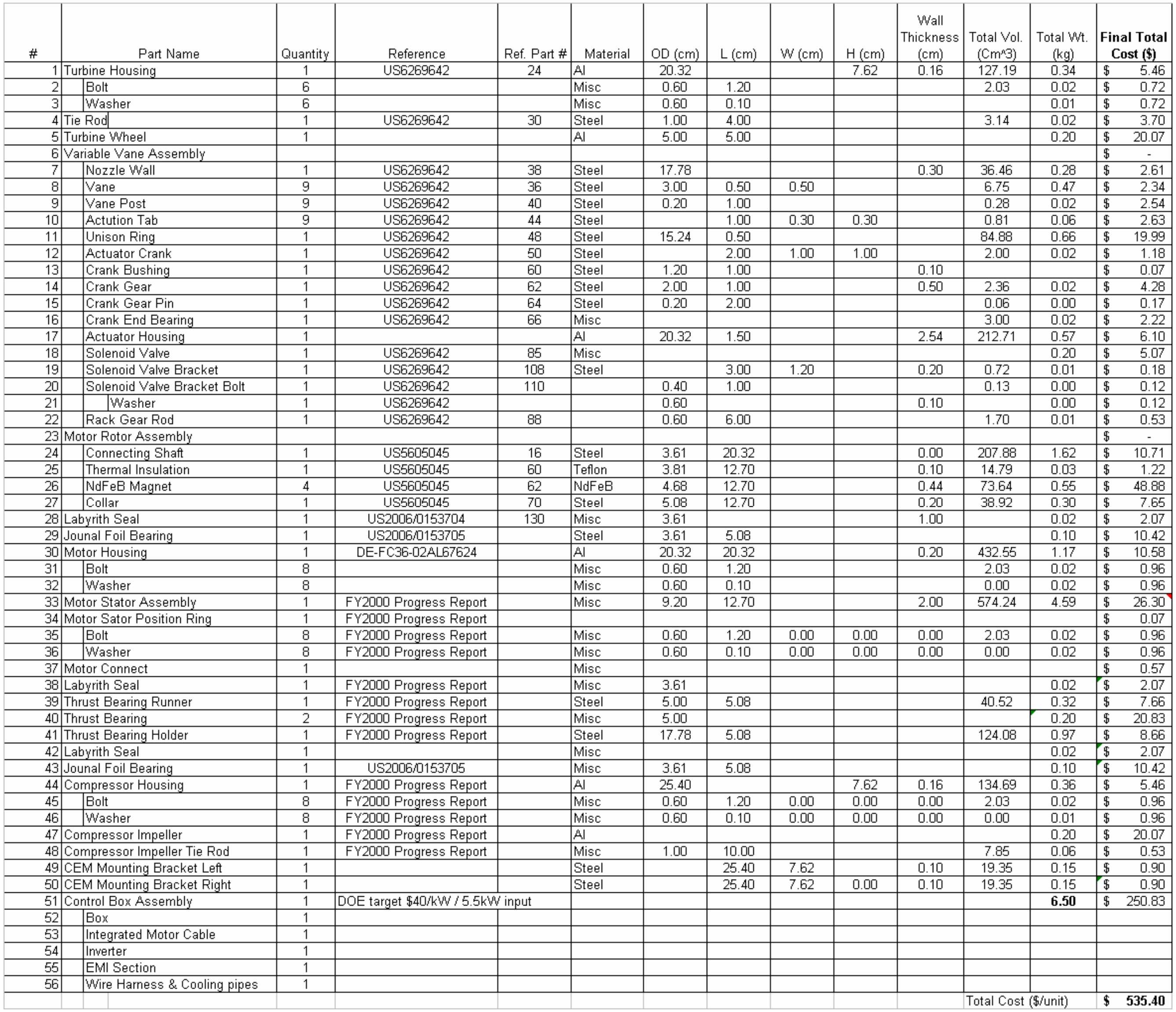
[1] Boothroyd Dewhurst Machining package

Backup Slides CEM Bill of Materials

The estimated CEM (including motor and motor controller) cost is $535 per unit.



#	Part Name	Quantity	Reference	Ref. Part #	Material	OD (cm)	L (cm)	W (cm)	H (cm)	Wall Thickness (cm)	Total Vol. (Cm^3)	Total Wt. (kg)	**Final Total Cost ($)**
1	Turbine Housing	1	US6269642	24	Al	20.32			7.62	0.16	127.19	0.34	$ 5.46
2	Bolt	6			Misc	0.60	1.20				2.03	0.02	$ 0.72
3	Washer	6			Misc	0.60	0.10					0.01	$ 0.72
4	Tie Rod	1	US6269642	30	Steel	1.00	4.00				3.14	0.02	$ 3.70
5	Turbine Wheel	1			Al	5.00	5.00					0.20	$ 20.07
6	Variable Vane Assembly												$ -
7	Nozzle Wall	1	US6269642	38	Steel	17.78				0.30	36.46	0.28	$ 2.61
8	Vane	9	US6269642	36	Steel	3.00	0.50	0.50			6.75	0.47	$ 2.34
9	Vane Post	9	US6269642	40	Steel	0.20	1.00				0.28	0.02	$ 2.54
10	Actution Tab	9	US6269642	44	Steel		1.00	0.30	0.30		0.81	0.06	$ 2.63
11	Unison Ring	1	US6269642	48	Steel	15.24	0.50				84.88	0.66	$ 19.99
12	Actuator Crank	1	US6269642	50	Steel		2.00	1.00	1.00		2.00	0.02	$ 1.18
13	Crank Bushing	1	US6269642	60	Steel	1.20	1.00			0.10			$ 0.07
14	Crank Gear	1	US6269642	62	Steel	2.00	1.00			0.50	2.36	0.02	$ 4.28
15	Crank Gear Pin	1	US6269642	64	Steel	0.20	2.00				0.06	0.00	$ 0.17
16	Crank End Bearing	1	US6269642	66	Misc						3.00	0.02	$ 2.22
17	Actuator Housing	1			Al	20.32	1.50			2.54	212.71	0.57	$ 6.10
18	Solenoid Valve	1	US6269642	85	Misc							0.20	$ 5.07
19	Solenoid Valve Bracket	1	US6269642	108	Steel		3.00	1.20		0.20	0.72	0.01	$ 0.18
20	Solenoid Valve Bracket Bolt	1	US6269642	110		0.40	1.00				0.13	0.00	$ 0.12
21	Washer	1	US6269642			0.60				0.10		0.00	$ 0.12
22	Rack Gear Rod	1	US6269642	88		0.60	6.00				1.70	0.01	$ 0.53
23	Motor Rotor Assembly												$ -
24	Connecting Shaft	1	US5605045	16	Steel	3.61	20.32			0.00	207.88	1.62	$ 10.71
25	Thermal Insulation	1	US5605045	60	Teflon	3.81	12.70			0.10	14.79	0.03	$ 1.22
26	NdFeB Magnet	4	US5605045	62	NdFeB	4.68	12.70			0.44	73.64	0.55	$ 48.88
27	Collar	1	US5605045	70	Steel	5.08	12.70			0.20	38.92	0.30	$ 7.65
28	Labyrith Seal	1	US2006/0153704	130	Misc	3.61				1.00		0.02	$ 2.07
29	Jounal Foil Bearing	1	US2006/0153705		Steel	3.61	5.08					0.10	$ 10.42
30	Motor Housing	1	DE-FC36-02AL67624		Al	20.32	20.32			0.20	432.55	1.17	$ 10.58
31	Bolt	8			Misc	0.60	1.20				2.03	0.02	$ 0.96
32	Washer	8			Misc	0.60	0.10				0.00	0.02	$ 0.96
33	Motor Stator Assembly	1	FY2000 Progress Report		Misc	9.20	12.70			2.00	574.24	4.59	$ 26.30
34	Motor Sator Position Ring	1	FY2000 Progress Report										$ 0.07
35	Bolt	8	FY2000 Progress Report		Misc	0.60	1.20	0.00	0.00	0.00	2.03	0.02	$ 0.96
36	Washer	8	FY2000 Progress Report		Misc	0.60	0.10	0.00	0.00	0.00	0.00	0.02	$ 0.96
37	Motor Connect	1			Misc								$ 0.57
38	Labyrith Seal	1	FY2000 Progress Report		Misc	3.61						0.02	$ 2.07
39	Thrust Bearing Runner	1	FY2000 Progress Report		Steel	5.00	5.08				40.52	0.32	$ 7.66
40	Thrust Bearing	2	FY2000 Progress Report		Misc	5.00						0.20	$ 20.83
41	Thrust Bearing Holder	1	FY2000 Progress Report		Steel	17.78	5.08				124.08	0.97	$ 8.66
42	Labyrith Seal	1			Misc							0.02	$ 2.07
43	Jounal Foil Bearing	1	US2006/0153705		Misc	3.61	5.08					0.10	$ 10.42
44	Compressor Housing	1	FY2000 Progress Report		Al	25.40			7.62	0.16	134.69	0.36	$ 5.46
45	Bolt	8	FY2000 Progress Report		Misc	0.60	1.20	0.00	0.00	0.00	2.03	0.02	$ 0.96
46	Washer	8	FY2000 Progress Report		Misc	0.60	0.10	0.00	0.00	0.00	0.00	0.01	$ 0.96
47	Compressor Impeller	1	FY2000 Progress Report		Al							0.20	$ 20.07
48	Compressor Impeller Tie Rod	1	FY2000 Progress Report		Misc	1.00	10.00				7.85	0.06	$ 0.53
49	CEM Mounting Bracket Left	1			Steel		25.40	7.62		0.10	19.35	0.15	$ 0.90
50	CEM Mounting Bracket Right	1			Steel		25.40	7.62	0.00	0.10	19.35	0.15	$ 0.90
51	Control Box Assembly	1	DOE target $40/kW / 5.5kW input									**6.50**	$ 250.83
52	Box	1											
53	Integrated Motor Cable	1											
54	Inverter	1											
55	EMI Section	1											
56	Wire Harness & Cooling pipes	1											
											Total Cost ($/unit)		**$ 535.40**

Backup Slides CEM Motor and Controller Cost

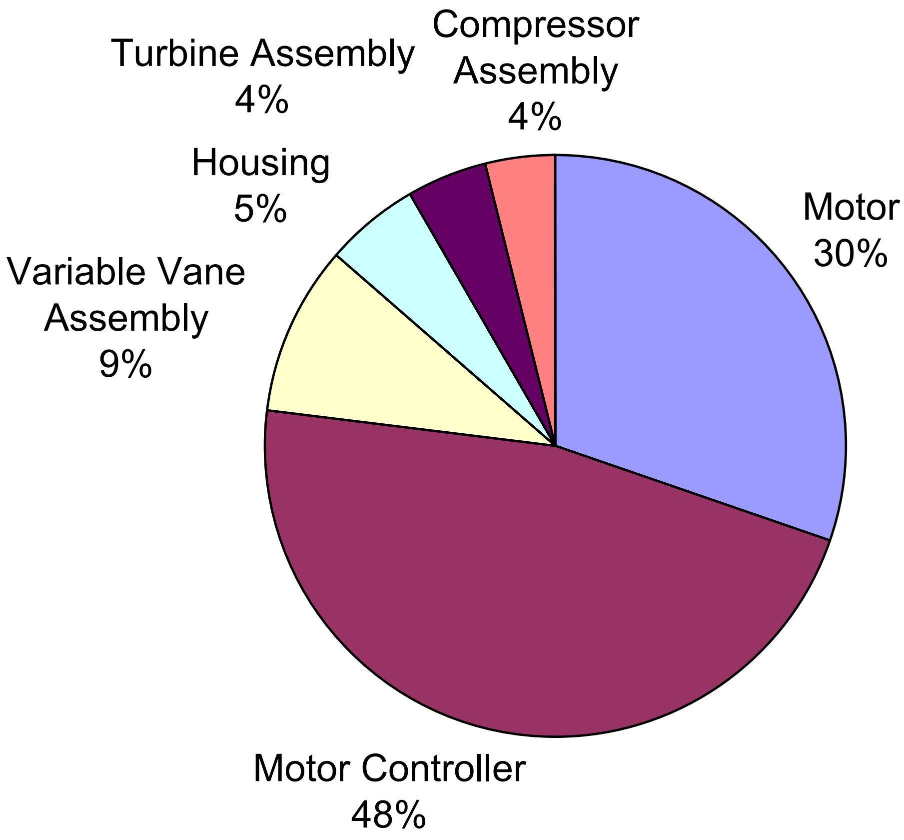
The motor assembly and motor controller are projected to cost $412, representing 77% of the CEM cost.

Motor Subsystems	Components	Manufactured Cost ($)	Comments
Stator Assembly	Copper Coils Steel Laminations	26	Assumed purchased part. The price is direct materials with a markup of 1.15. 1 kg copper coil ($7/kg) and 3.6 kg laminated steel ($4.4/kg) with a markup of 1.15.
Rotor Assembly	Shaft	11	DFMA machining package
	Magnets	49	0.55 kg NdFeB magnet with a cost of $88/kg
	Journal Foil Bearing	21	Assumed purchased part at $10 each
	Thrust Journal Bearings	21	Assumed purchased part at $10 each
	Thrust Bearing Runner	8	DFMA machining package
	Thrust Bearing Holder	9	DFMA machining package
	Seals, collar, etc.	17	Assumed purchased parts
Motor Controller	5.5 kW Inverter with DSP controller	220	$40/kW from "A Novel Bidirectional Power Controller for Regenerative Fuel Cells", Final Report for DE-FG36-04GO14329, J. Hartvigsen and S.K. Mazumder, Oct. 10, 2005
	Packaging, Wire harness, thermal management, etc	31	
Total Motor Cost ($/unit)		**412**	

The 5.5 kW inverter is projected to dominate the motor controller cost.

The CEM factory cost (without supplier markup) of $535, is the largest contributor to the overall BOP cost.

CEM Manufactured Cost ($535)



CEM Manufactured Cost ($)		
Component	**Factory Cost**	**OEM Cost[1]**
Motor	162	**615**
Motor Controller[2]	251	
Variable Vane Assembly	50	
Housing	28	
Turbine Assembly	24	
Compressor Assembly	21	
Total:	**535**	

[1] Assumes 15% markup to the automotive OEM

[2] $40/kW from “A Novel Bidirectional Power Controller for Regenerative Fuel Cells”, Final Report for DE-FG36-04GO14329, J. Hartvigsen and S.K. Mazumder, Oct. 10, 2005

Backup Slides H_2 Blower Overview

We costed the H_2 recirculating blower based on published information and patents on the Parker Hannifin Model 55 Univane™ rotary compressor.

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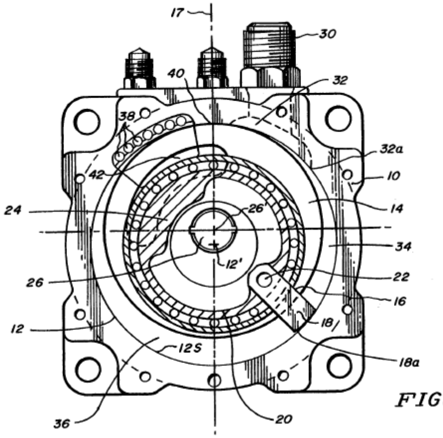


FIG. 1

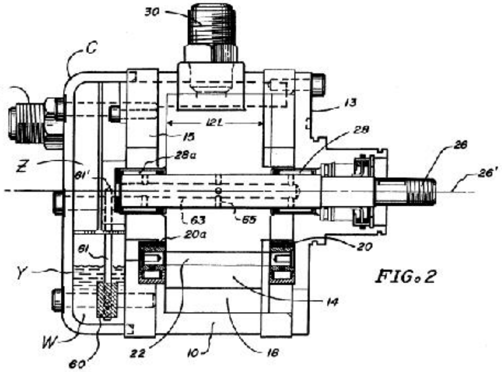


FIG. 2

US Patent: 5,374,172

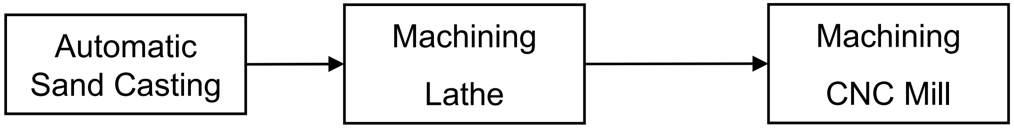
Volume: 5 Liters
Weight: 6.9 kg

The major manufacturing processes for selected components of the H_2 blower are tabulated below.

#	Selected Components	Material	Major Manufacturing Processes
1	Motor Side End Plate	SS316	Automatic sand casting; turning; drilling
2	Blower Housing	SS316	Automatic sand casting; turning; drilling
3	Inlet Manifold	SS316	Powder metallurgy
4	Outlet Manifold	SS316	Powder metallurgy
5	End Plate	SS316	Automatic sand casting; turning; drilling
6	Blower Shaft	SS316	Turning; Milling; Heat treatment; Grinding
7	Rotor	Al	Casting; Turing; Milling; Broaching
8	Vane	SS316	Hot forging; Drilling; Reaming

Backup Slides H_2 Blower Process Flow

The blower housing manufacturing process represents the level of detail we captured in the costing[1] of the H_2 blower.



- Load part to 3 jaw chuck
- Face rough
- Face finish
- chamber
- Central hole boring rough
- Central hole boring finish
- Chamber
- Reverse the part
- Face rough
- Face finish
- Chamber (inner & outer)

- Load part to fixture
- Milling the manifold connect surface rough
- Milling the manifold connect surface finish
- Drilling & tapping
- Rotate the fixture
- Milling the manifold connect surface rough
- Milling the manifold connect surface finish
- Drilling & tapping
-Load the part to vise
-Drilling & tapping
-Reverse the part (vise)
-Drilling & tapping

H_2 Blower Housing Manufacturing Process

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[1] Boothroyd Dewhurst Concurrent Costing & Machining packages

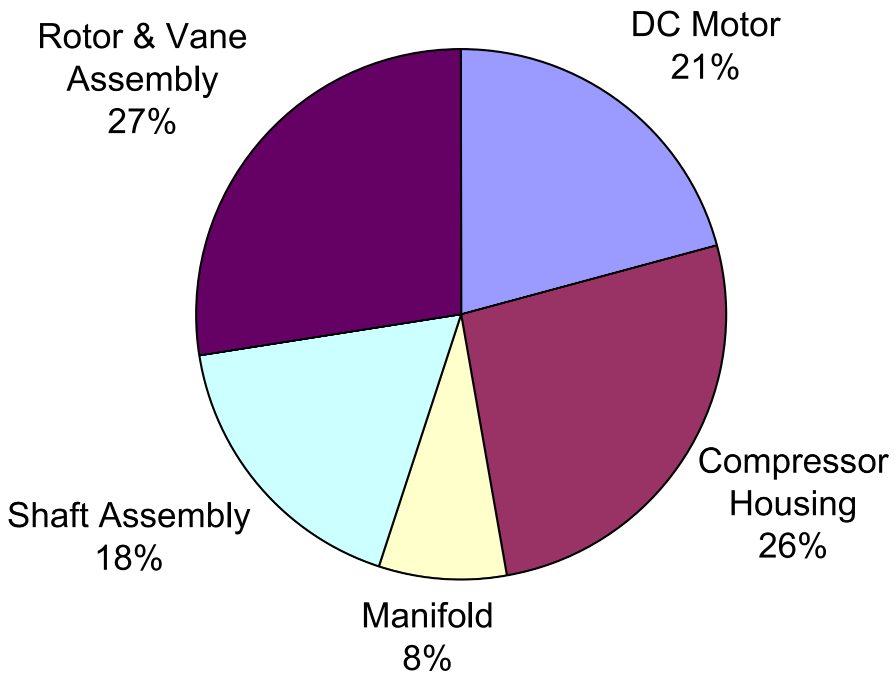
Backup Slides H$_2$ Blower Bill of Materials

The projected H$_2$ blower cost is \$193 per unit.

#	Part Name	Quantity	Material	OD (cm)	L (cm)	W (cm)	Wall Thickness (cm)	Total Vol. (Cm^3)	Total Wt. (kg)	**Final Total Cost ($)**
1	100We DC Motor	1	Misc	16.51	8.89				1.00	$ 40.21
2	End Plate (motor side)	1	SS316	16.51	2.54		0.32	96.48	0.75	$ 13.33
3	Screw	4	Misc						0.02	$ 0.48
4	O-Ring	1	Misc	13.97					0.01	$ 0.57
5	Labyrith Seal (main)	1	Misc	5.08	1.27				0.02	$ 2.07
6	O-Ring		Misc	5.08					0.01	$ 0.20
7	C-Clip	1	SS316	5.08					0.01	$ 0.17
8	Labyrith Seal	1	Misc	4.45					0.02	$ 2.07
9	Blower Housing	1	SS316	15.24	8.89		0.32	106.65	0.83	$ 16.88
10	Screw	8	Misc						0.04	$ 0.96
11	O-Ring	1	Misc	13.97					0.01	$ 0.57
12	Compressor Shaft	1	SS316	1.59	12.70			25.12	0.20	$ 9.71
13	Bearing	2	SS316	3.81	2.54			28.94	0.23	$ 19.11
14	Seal	2	Misc	3.81					0.01	$ 0.54
15	Rotor	1	Al	10.16	7.62			308.73	0.83	$ 6.29
16	Vane Guide	2	SS316	7.62	1.27		1.27	32.06	0.50	$ 10.48
17	Vane Guide Bearing	2	Misc	7.62						$ 30.42
18	Vane	1	SS316		7.62	2.54	1.27	24.58	0.19	$ 2.95
19	Vane Shaft	1	SS316	0.95	9.62			6.85	0.05	$ 3.06
20	C-Clip	2	SS316	1.35					0.01	$ 0.24
21	Inlet Manifold	1	SS316	4.45	8.89		0.64	35.17	0.27	$ 5.11
22	Seal	1	Misc		5.08	3.81			0.01	$ 0.57
23	Screw	4	Misc						0.02	$ 0.48
24	Fitting	1	SS316	4.45	5.08				0.10	$ 1.07
25	O-Ring	1	Misc	2.54					0.01	$ 0.27
26	Outlet Manifold	1	SS316	4.45	8.89		0.64	35.17	0.27	$ 5.11
27	Seal	1	Misc		5.08	3.81			0.01	$ 0.57
28	Screw	4	Misc						0.02	$ 0.48
29	Fitting	1	SS316	4.45	5.08				0.10	$ 1.07
30	O-Ring	1	Misc	2.54					0.01	$ 0.27
31	End Plate	1	SS316	15.24	3.81		0.64	72.36	0.56	$ 11.69
32	Screw	8	Misc						0.04	$ 0.96
33	O-Ring	1	Misc	8.89					0.01	$ 0.57
34	End Cover	1	SS316	7.62	0.64			28.94	0.23	$ 2.00
35	Screw	4	Misc						0.02	$ 0.48
36	O-Ring	1	Misc	6.35					0.01	$ 0.27
37	Support	1	Steel		15.24	15.24	0.25	58.99	0.46	$ 2.21
								Total:	**6.88**	**$ 193.44**

The rotor & vane assembly, blower housing, and DC motor are the top three cost drivers for the H_2 blower.

H_2 Blower Manufactured Cost ($193)



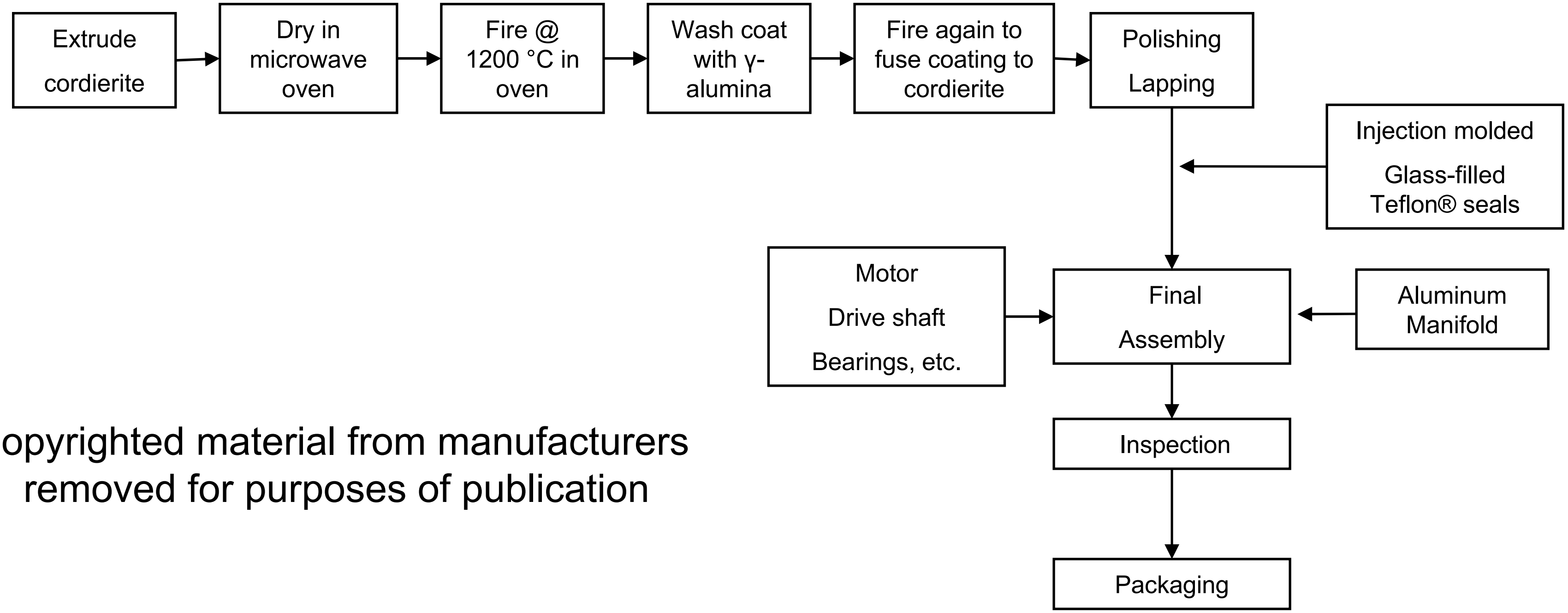
H_2 Blower Manufactured Cost ($)		
Component	**Factory Cost**	**OEM Cost[1]**
DC Motor	40	**222**
Blower Housing	51	
Manifold	15	
Shaft Assembly	34	
Rotor & Vane Assembly	53	
Total:	**193**	

[1] Assumes 15% markup to the automotive OEM

We assumed that the material for the blower housing is stainless steel 316.

Backup Slides Enthalpy Wheel Process Flow

The enthalpy wheel manufacturing process was based on discussions with Emprise on their Humidicore™ humidifier.



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The ceramic honeycomb material, Cordierite, is in mass production and is commonly used in automotive catalytic converters.

Enthalpy Wheel Humidifier Bill of Materials

The enthalpy wheel bill-of-materials was deduced from Emprise patents, white papers and personal communications.

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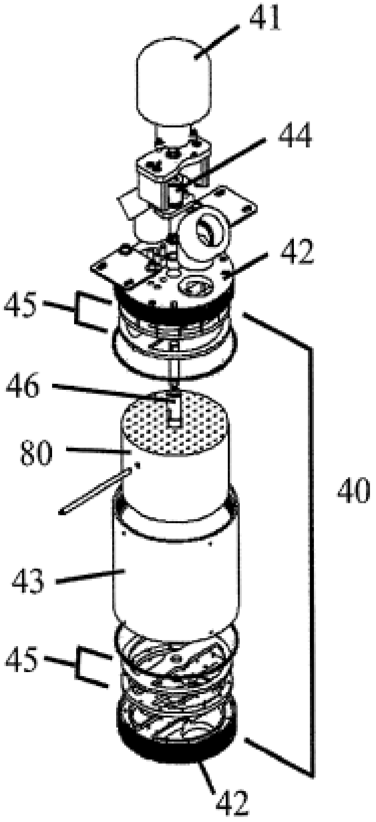
Volume: 12 liters
Weight: 8 kg



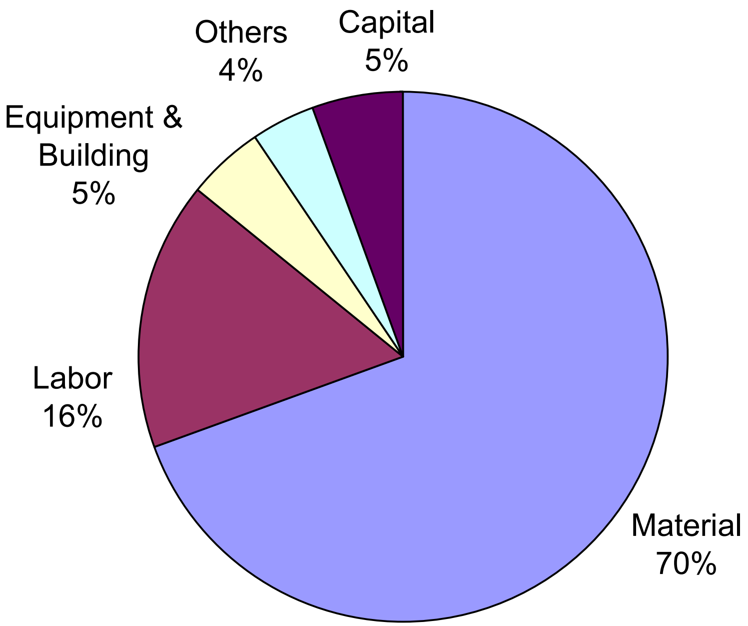
US Patent 2002/0071979

Enthalpy Wheel Humidifier			
Component	**#**	**Material**	**Size**
30 We DC motor with gear box	1	Misc.	Φ3” x 3 ¾”
Shaft	2	Steel	Φ 3/8” x 3”
Wheel shaft	2	Steel	OD:Φ1/2”, ID:Φ 3/8”, L1”
Screw	1	Misc.	Φ3/8” x ¼”
Bearing	2	Misc.	ID Φ3/8”
End plate	2	Teflon	Φ6” x ¼”
Spring plate	2	Steel	Φ6” x 1/8”
Springs	26	Misc.	Φ1/8” x ¼”
End seal plate	2	Teflon	Φ6” x ¼”
Core	1	Cordierite	Φ6” x 7”
Core pin	1	Steel	Φ¼” x 6”
Manifold (motor side)	1	Al	Φ8” x 2”
Bolts	24	Misc.	Φ¼” x 3 ½”
Main housing	1	Al	Φ8” x 9”
Bolts	4	Misc.	Φ3/8” x 10 ½”
Base manifold	1	Al	Φ8” x 2 “

Backup Slides Enthalpy Wheel Humidifier Cost

The motor is the largest contributor to the enthalpy wheel cost, followed by the cordierite core.

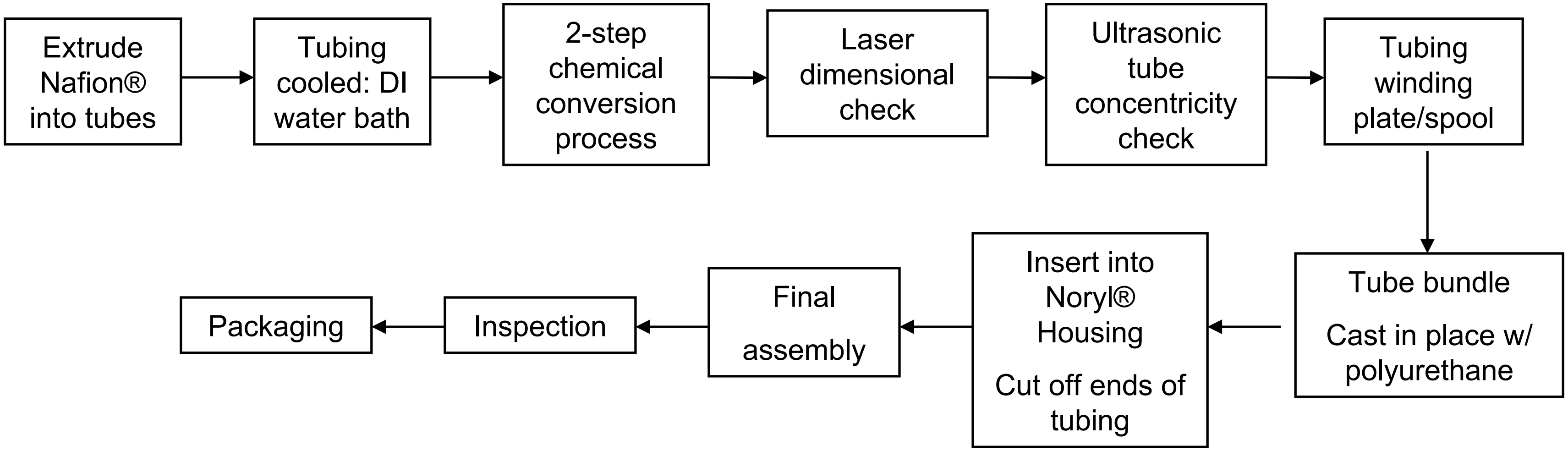
Enthalpy Wheel Humidifier Manufactured Cost ($160)



Enthalpy Wheel Humidifier Manufactured Cost ($)			
Component	**#**	**Material**	**Process**
DC motor with gear box	1	50.00	0.00
Shaft	2	0.10	2.86
Wheel shaft	2	0.12	3.56
Screw	1	0.05	0.00
Bearing	2	4.30	0.00
End plate	2	10.79	1.80
Spring plate	2	1.04	1.68
Springs	26	1.30	0.00
End seal plate	2	10.79	1.80
Core	1	8.48	20.39
Core pin	2	2.00	0.00
Manifold (motor side)	1	2.24	6.20
Bolts	12	0.60	0.00
Main housing	1	6.73	1.46
Bolts	4	0.80	0.00
Base manifold	1	2.24	6.20
Bolts	12	0.60	0.00
Packaging	1	2.00	0.00
Assembly & QC	-	-	9.95
Total	**1**	**160**	

Backup Slides Membrane Humidifier Process Flow

The Nafion tube bundle is the key component of the membrane humidifier and its manufacturing process is described below.



- Extrude Nafion® into tubes
- Tubing cooled: DI water bath
- 2-step chemical conversion process
- Laser dimensional check
- Ultrasonic tube concentricity check
- Tubing winding plate/spool
- Tube bundle

  Cast in place w/ polyurethane
- Insert into Noryl® Housing

  Cut off ends of tubing
- Final assembly
- Inspection
- Packaging

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Backup Slides Membrane Humidifier Bill of Materials

The membrane humidifier manufacturing process was based on discussions with PermaPure on their FC200-780-7PP Series™ of humidifiers.

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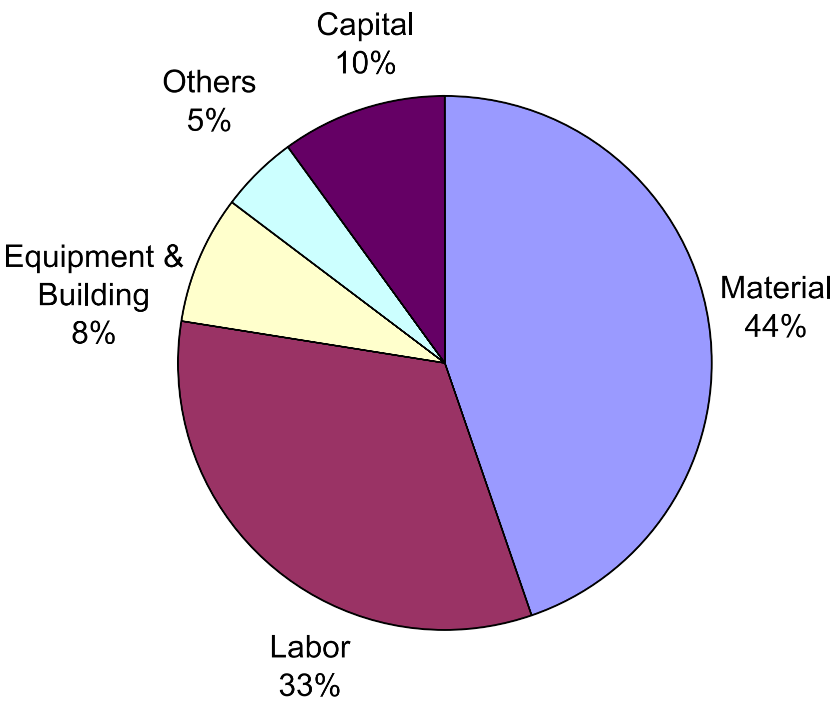
Volume: 2 liters
Weight: 2 kg

Membrane Humidifier			
Component	**#**	**Material**	**Size**
Right side housing	1	Polyphenylsulfone (PPS)	OD 3 3/4”, Length 4”
Small O-ring	2	Viton	OD 3”
Big O-ring	2	Viton	OD 3 1/2”
C-clip	2	Steel	OD 3 1/2”
Nafion tubes	960	Nafion	ID 1mm, OD 1.12 mm, Length 178 mm
Nafion tube housing	1	Noryl® (Modified Polyphenylene Oxide)	OD 3 1/2”, Length 7”
Nafion tube header	2	Polyurethane	OD 3 1/2”, Length 1”
Mesh filter	2	Nylon	Width 2”, length 2”
Left side housing	1	Polyphenylsulfone (PPS)	OD 3 3/4” Length 4”

Material costs represent approximately 44% of the membrane humidifier cost projection.

Membrane Humidifier Manufactured Cost ($58)



Membrane Humidifier Manufactured Cost ($)			
Component	**#**	**Material**	**Process**
Right side housing	1	2.62	0.84
Small O-ring	2	1.00	0.00
Big O-ring	2	1.00	0.00
C-clip	2	0.20	0.00
Nafion tubes	960	14.19	22.42
Nafion tube housing	1	1.30	0.88
Nafion tube header	2	0.20	0.00
Mesh filter	2	0.20	0.00
Left side housing	1	2.85	0.85
Assembly & packaging	-	2.05	6.93
Subtotal	-	25.85	31.93
Total	**-**	**58**	

We developed a manufacturing process flow chart for the radiator based on Modine patents and in-house experience.

Al Tube

Al Strip

Fin Fabrication

Cooling Core Assembly

CAB Brazing Oven

Electrostatic Painting

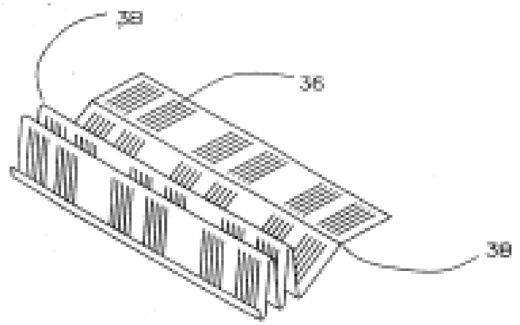
Leak Test

Packaging

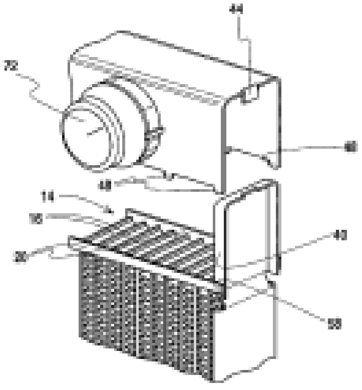
Stamp Top/Bottom Frames

Stamp Inlet/Outlet Tanks

Stamp Core Headers



Fin Fabrication
US Patent
5,350,012



Radiator Structure
US Patent
7,032,656

Backup Slides Radiator Bill of Materials

We used a Modine all-aluminum automobile radiator structure as our baseline design.

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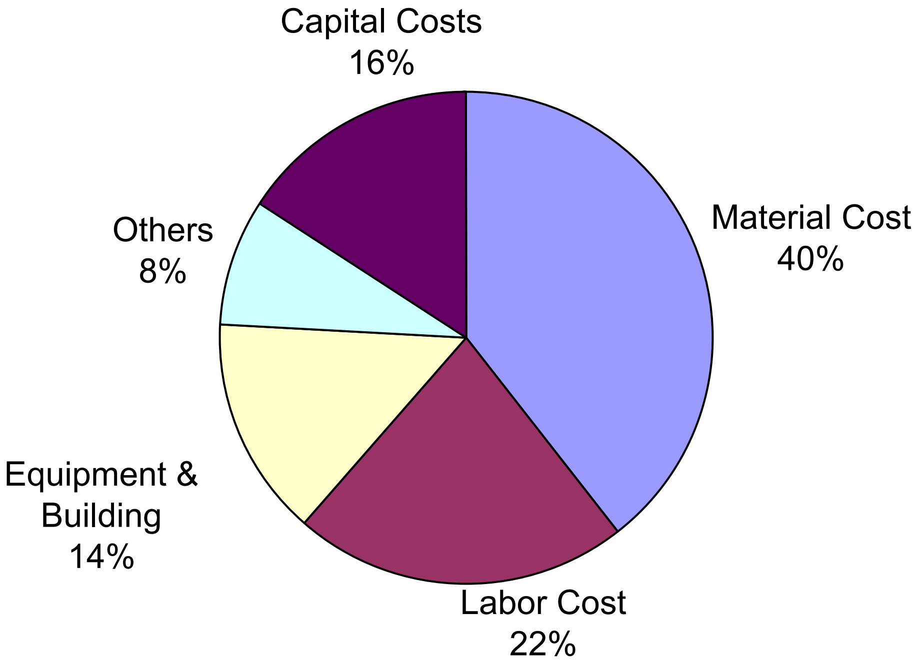
#	Components	#	Mtl.	Size (L x W x H) (mm)
1	Serpentine Louvered Fin	38381	A3003	28.00 x 7.94 x 0.08
2	Core Tube	64	A3003	600.00 x 28.00 x 2.76
3	Inlet Header, Solder Well Type	1	A3003	500.00 x 68.00 x 1.80
5	Outlet Header, Solder Well Type	1	A3003	500.00 x 68.00 x 1.80
8	Top Side Piece	1	A3003	600.00 x 68.00 x 1.80
9	Bottom Side Piece	1	A3003	600.00 x 68.00 x 1.80
10	Inlet Tank	1	A3003	500.00 x 140.00 x 1.80
11	Inlet Hose Connection	1	A3003	50.40
12	Outlet Tank	1	A3003	500.00 x 140.00 x 1.80
13	Outlet Hose Connection	1	A3003	50.40
14	Filler neck/Overflow Tub	1	A3003	25.40
15	Drain Fitting	1	A3003	25.40
16	Heater Return Line Connection	1	A3003	25.40
17	Coolant Level Indicator Fitting	1	A3003	25.40

Volume: 25 Liters
Weight: 5 kg

The radiator manufactured cost is projected to be $56, with an overall OEM cost for the thermal management system of $220 assuming a 15% markup.

High Temperature Radiator Manufactured Cost ($56)



Thermal Management System Cost ($)		
Component	**Factory Cost**	**OEM Cost[1]**
Radiator	56	65
Radiator Fan	-	35
Coolant Pump	-	120
Total	**-**	**220**

[1] Assumes 15% markup to the automotive OEM

The radiator fan and coolant pump are assumed to be purchased components, hence their price includes a markup.

Backup Slides Membrane Process Flow

We estimated the membrane manufacturing cost assuming a coater-laminator line, with line rate of 20 ft/min.

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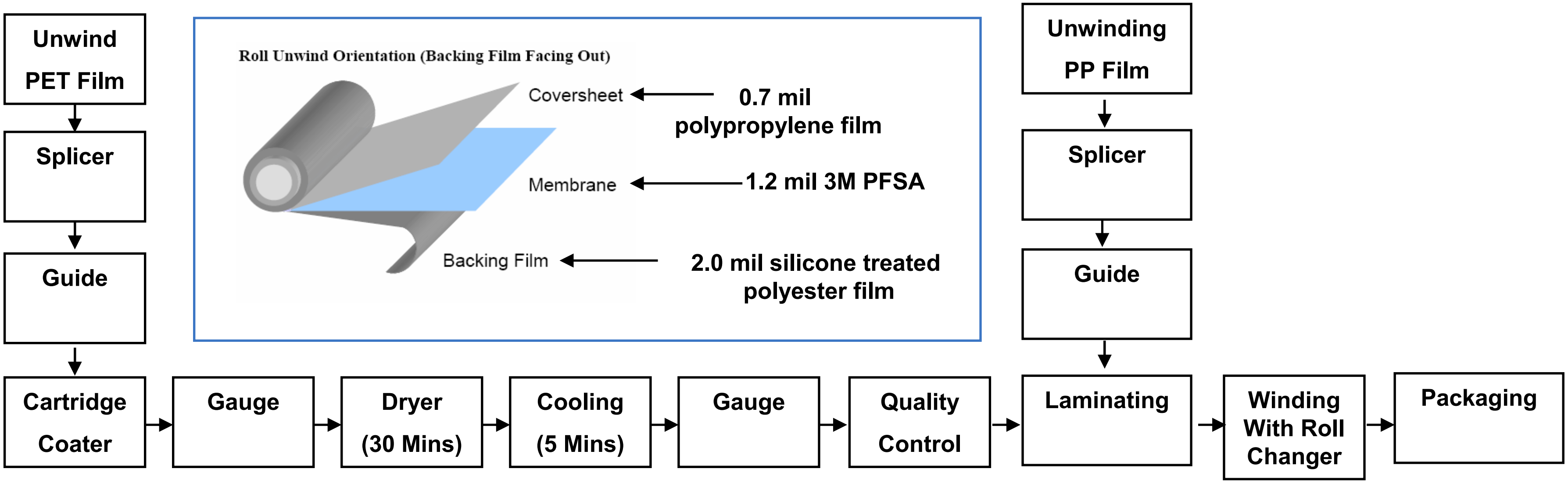


0.7 mil polypropylene film

1.2 mil 3M PFSA

2.0 mil silicone treated polyester film

Unwind PET Film → Splicer → Guide → Cartridge Coater → Gauge → Dryer (30 Mins) → Cooling (5 Mins) → Gauge → Quality Control → Laminating → Winding With Roll Changer → Packaging

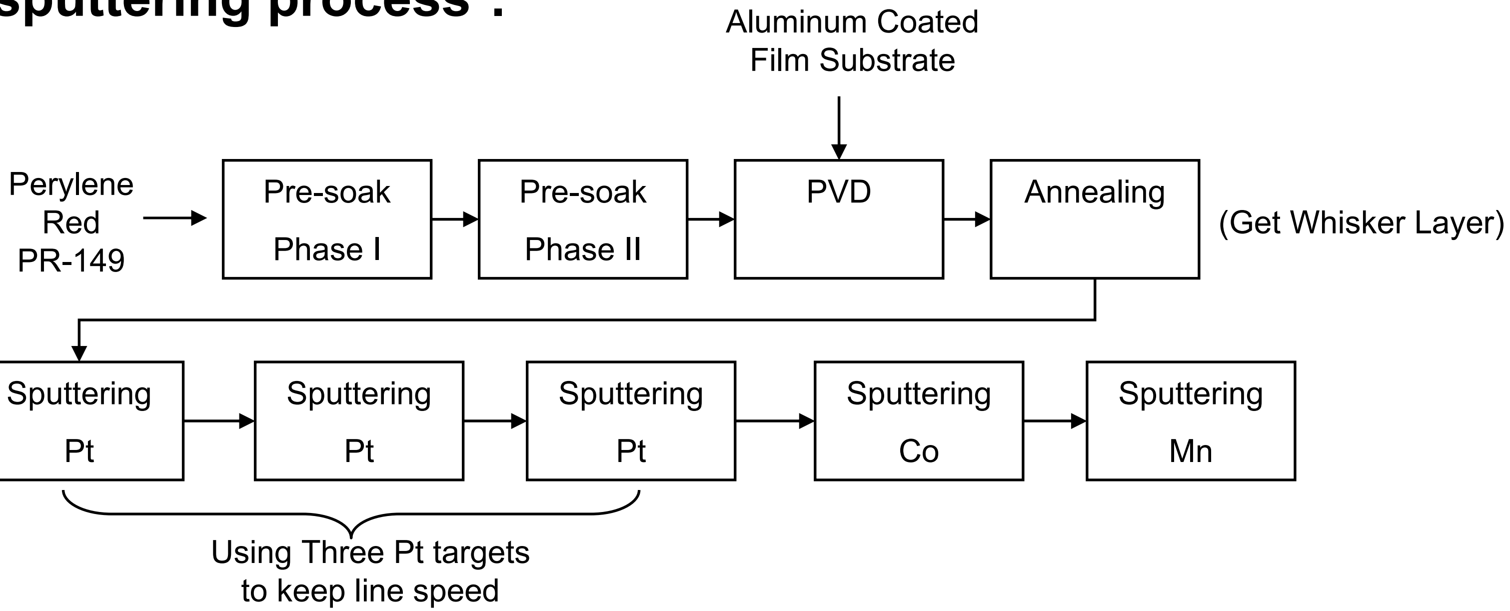
Unwinding PP Film → Splicer → Guide → Laminating

We assumed the use of a "cast dispersion" process to prepare the membrane.

- The coating solution is a dispersion of 40 wt.% 3M PFSA in 30% water and 30% isopropanol
- The roll coating process deposits a 3 mil wet film thickness to produce a 1.2 mil dry film thickness
- The coating is applied to 2.0 mil silicone-treated PET (6 ft wide) backing film
- The preferred coating arrangement is "knife over roll"
  - An alternative coating arrangement is "reverse roll coating"
- The drying process is a "two-stage oven"
  - First Stage dry for 30 minutes at 50^{o}C
  - Full dry for 15 min. at 110^{o}C
  - Forced air cooling for 5 minutes at 20^{o}C
  - Catalytic combustor used to burn solvent
- The membrane is laminated with a 0.7 mil polypropylene coversheet
- A "Class 10,000" clean room environment was assumed in this estimate

Backup Slides Membrane Catalyst Coating

Organic whisker layer was fabricated by physical vapor deposition (PVD) with vacuum annealing process. Catalysts were coated to this layer via sputtering process[1].



Aluminum Coated
Film Substrate

Perylene
Red
PR-149

Pre-soak
Phase I

Pre-soak
Phase II

PVD

Annealing

(Get Whisker Layer)

Sputtering
Pt

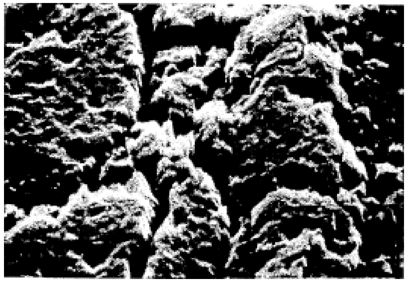
Sputtering
Pt

Sputtering
Pt

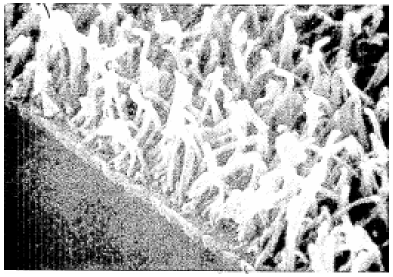
Sputtering
Co

Sputtering
Mn

Using Three Pt targets
to keep line speed



US Patent 4,812,352
PVD coated thin film before annealing



US Patent 4,812,352
PVD coated thin film after annealing

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journal paper removed
for purposes of publication

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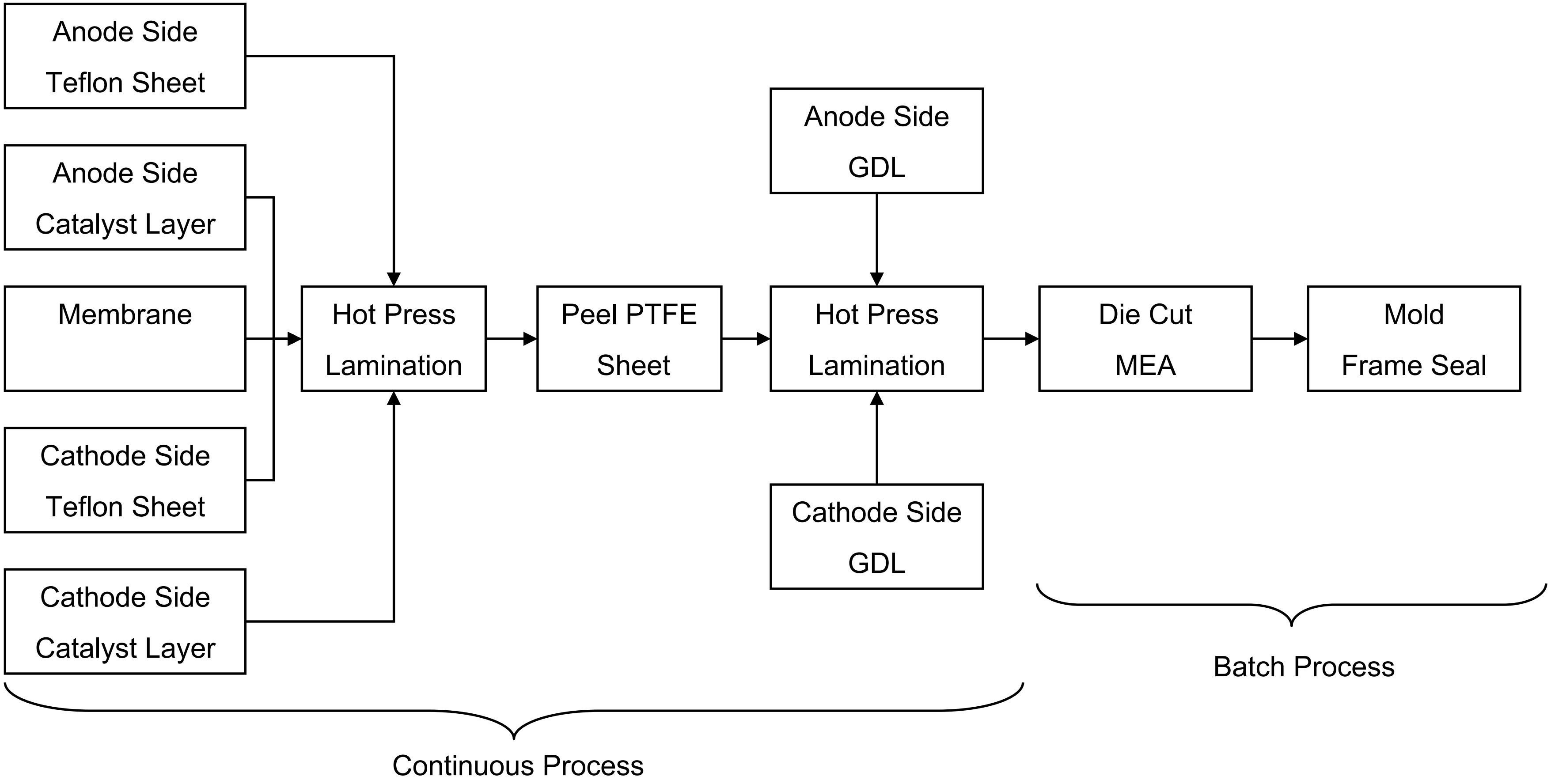
[1] M. K. Debe, Nano-Structured Thin Film Catalysts (NSTFC) for Next Generation PEM Fuel Cells, Northern Nano Workshop, November 2006

The anode and cathode organic whisker layers were hot pressed to the membrane with Teflon backing sheets.



The catalyst coated membrane and GDL layers were laminated to form an MEA in roll good form; the MEA was cut into sheets and molded with a frame seal.

Backup Slides Bipolar Plate Process Flow

Our process flow for the expanded graphite bipolar plate is based on a GrafTech® process chart and related patents.

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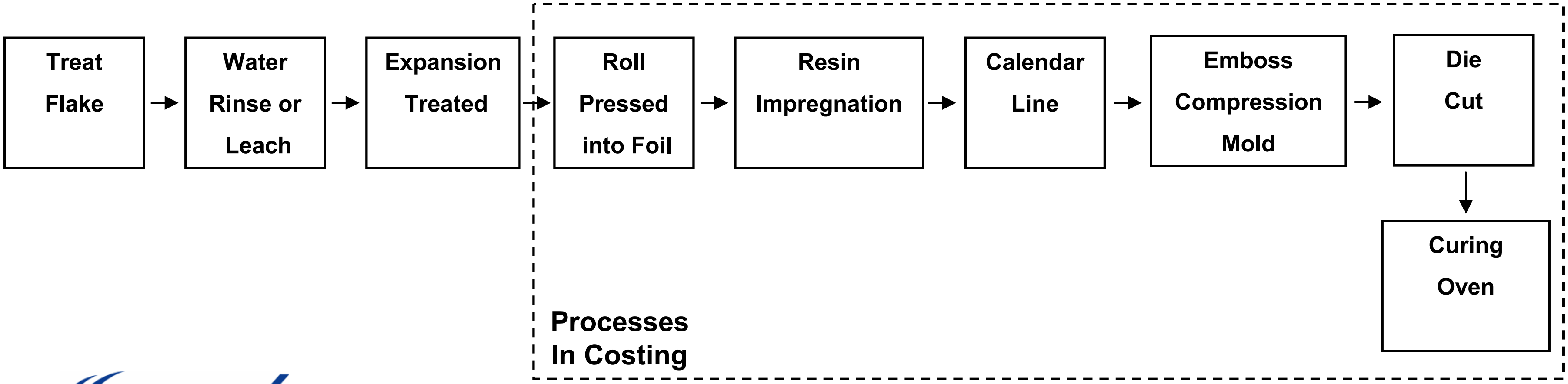
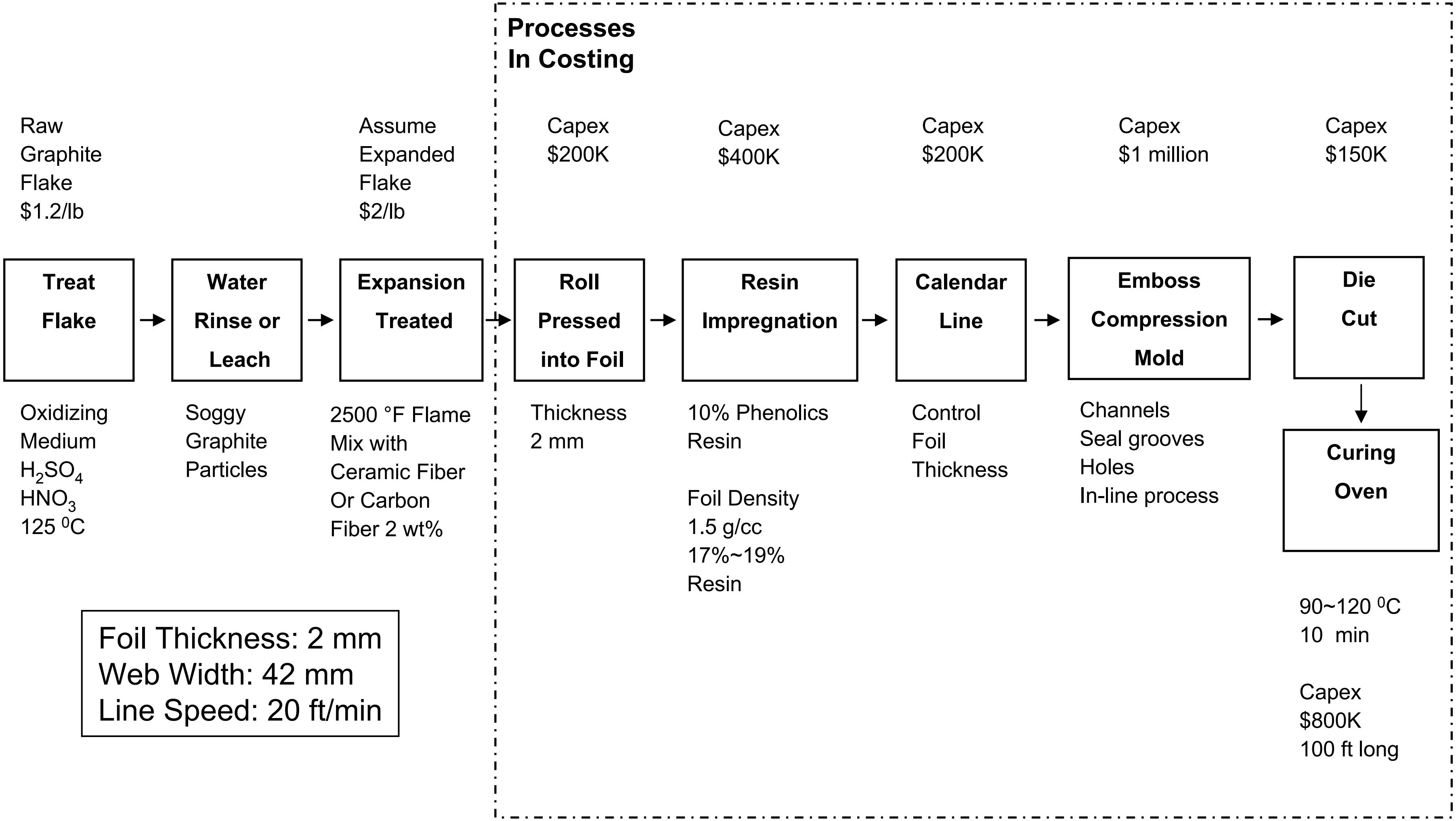

Treat Flake → Water Rinse or Leach → Expansion Treated → Roll Pressed into Foil → Resin Impregnation → Calendar Line → Emboss Compression Mold → Die Cut → Curing Oven

Processes In Costing

Our process flow for the expanded graphite bipolar plate is based on a GrafTech® process chart and related patents.



Processes In Costing

Raw Graphite Flake $1.2/lb

Treat Flake

Oxidizing Medium
H_2SO_4
HNO_3
125 ^{0}C

→ **Water Rinse or Leach**

Soggy Graphite Particles

→ Assume Expanded Flake $2/lb

Expansion Treated

2500 °F Flame
Mix with Ceramic Fiber Or Carbon Fiber 2 wt%

→ Capex $200K

Roll Pressed into Foil

Thickness 2 mm

→ Capex $400K

Resin Impregnation

10% Phenolics Resin

Foil Density 1.5 g/cc
17%~19% Resin

→ Capex $200K

Calendar Line

Control Foil Thickness

→ Capex $1 million

Emboss Compression Mold

Channels
Seal grooves
Holes
In-line process

→ Capex $150K

Die Cut

↓ **Curing Oven**

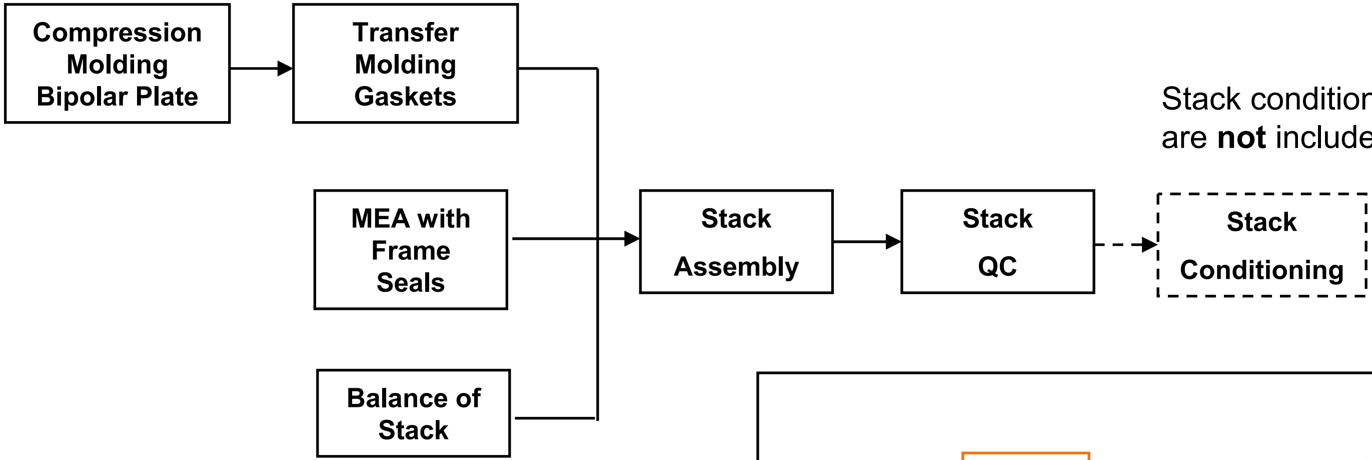
90~120 ^{0}C
10 min

Capex $800K
100 ft long

Foil Thickness: 2 mm
Web Width: 42 mm
Line Speed: 20 ft/min

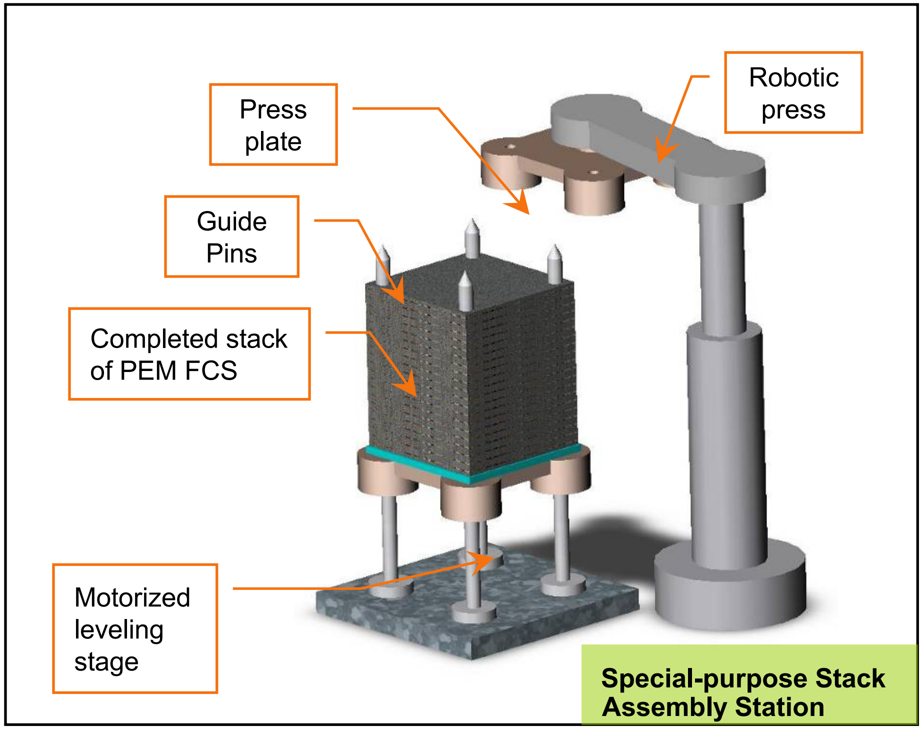
Backup Slides Stack Assembly Process Flow

Top-level process flow diagram for the stack assembly.



Stack conditioning costs are **not** included.

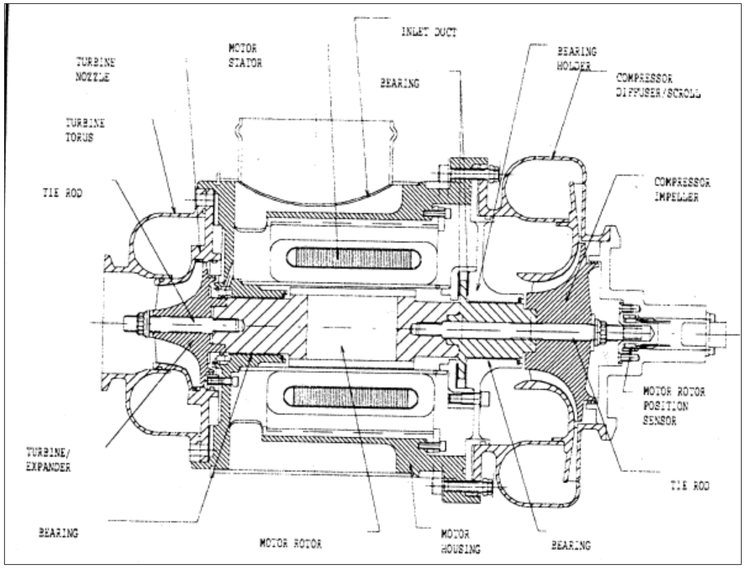
Stack Assembly Station conceptualized by TIAX ⇨

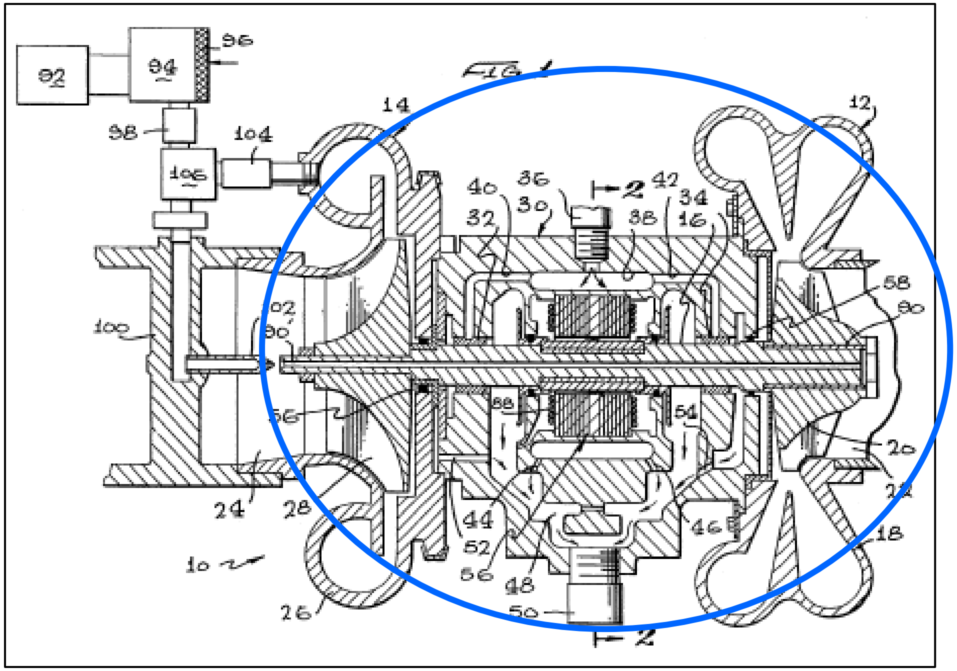


Special-purpose Stack Assembly Station

Backup Slides CEM Patents

The overall compressor/expander design is referenced from Honeywell DOE project presentations[1] and US patent 5,605,045.





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[1] Mark Gee, "Turbocompressor for PEM Fuel Cells," Progress Report, DOE Hydrogen, Fuel Cells, and Infrastructure Technologies Program, 2000.

The major sub-assemblies (e.g., variable nozzle vanes, motor, air bearing) are referenced from US patents, other public materials, and TIAX experience.

The turbine variable nozzle vanes and control assembly are referenced from US patent 6,269,642.

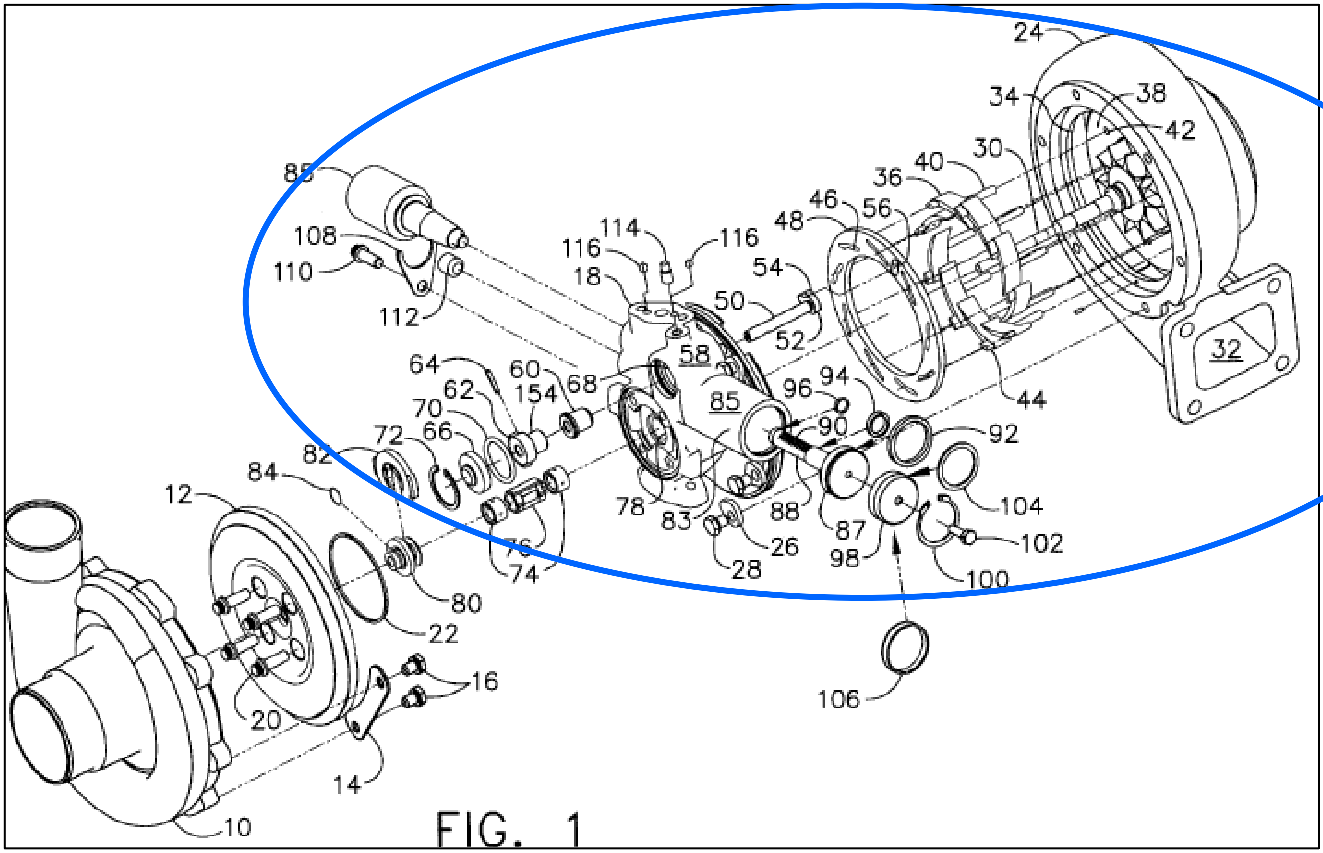
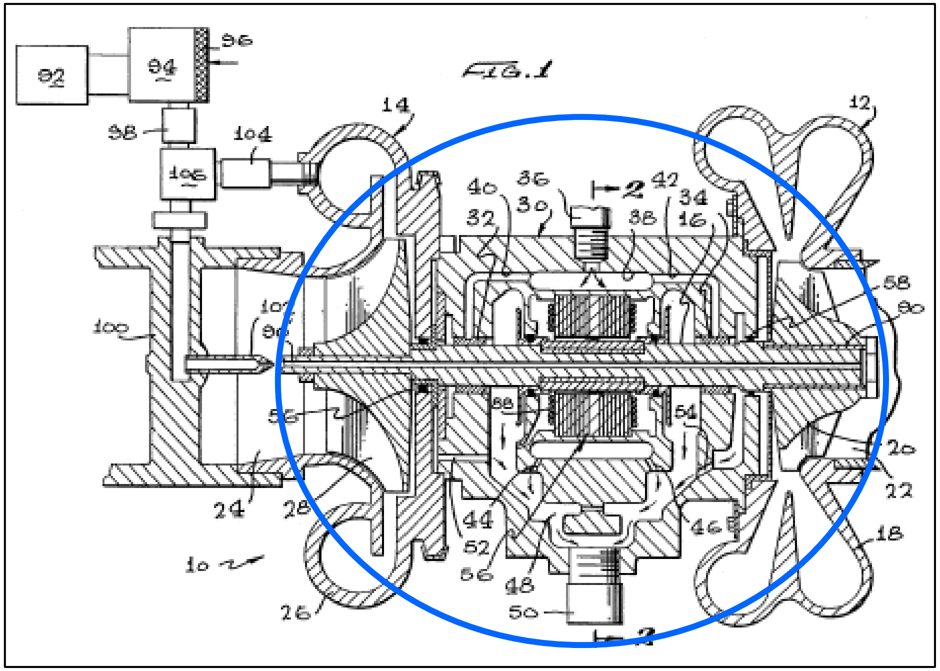
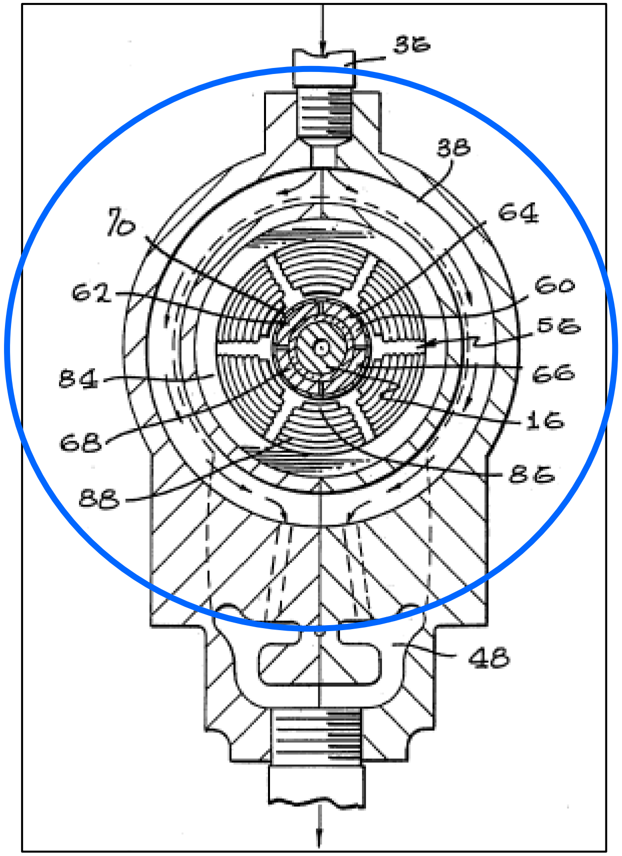


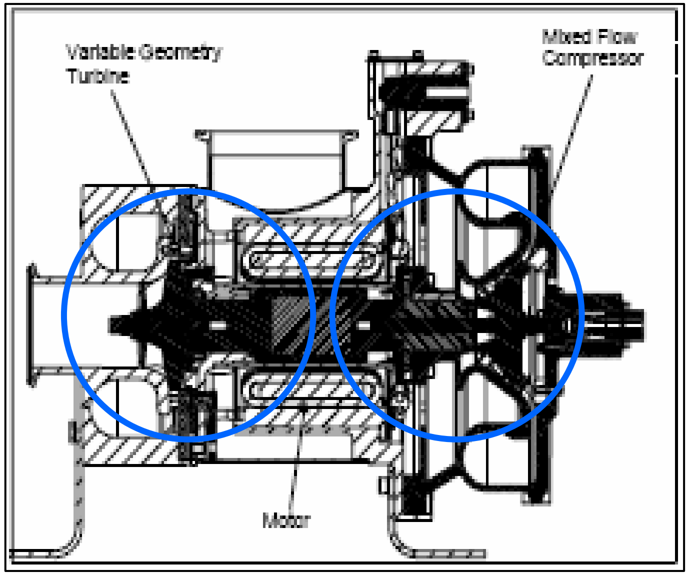
FIG. 1

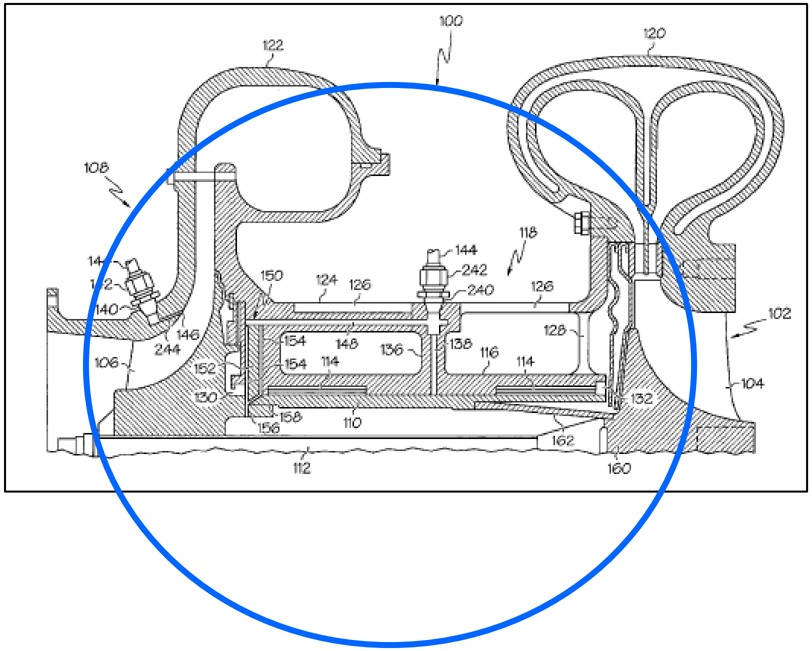
The CEM motor stator and rotor assembly are referenced from US patent 5,605,045.





The journal air bearing assemblies are referenced from Honeywell DOE project presentations[1] and US patent 2006/0153704.





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[1] Mark Gee, "Turbocompressor for PEM Fuel Cells," Progress Report, DOE Hydrogen, Fuel Cells, and Infrastructure Technologies Program, 2002.

The rotor and single vane structure in the Parker Hannifin Model 55 Univane H_2 blower are referenced from US patent 5,374,172.

FIG. 3

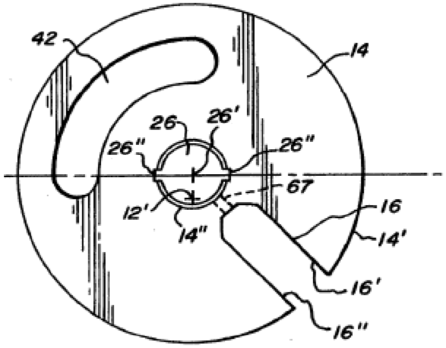
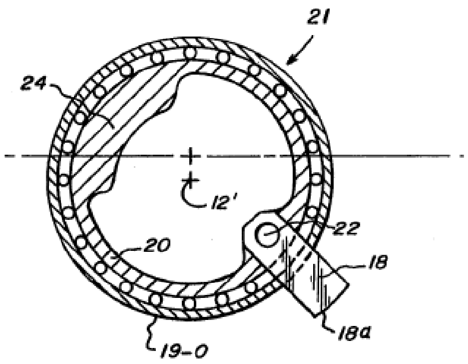


FIG. 4



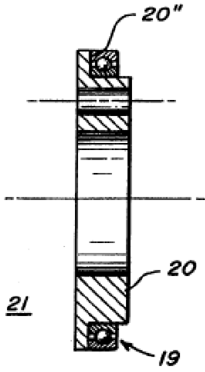


FIG. 5C

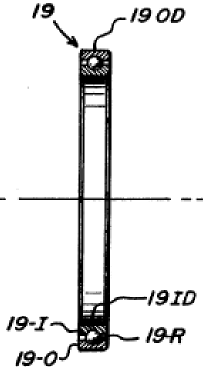


FIG. 5A

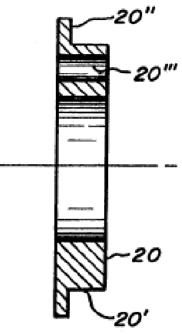


FIG. 5B

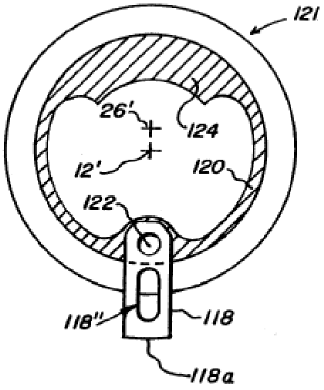


FIG. 6