

# Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications

2009 DOE Hydrogen Program Review  
Arlington, VA  
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Reference: D0362

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# Overview

The 2008 PEMFC cost analysis was based on updates to the bottom-up high-volume stack and BOP cost model developed in 2007.

## Timeline

- ◆ Base period: Feb 2006-May 2008
  - » 100% complete
- ◆ Option Yr 1: May 2008-Feb 2009
  - » 100% complete
- ◆ Option Yr 2: Feb 17, 2009
  - » 10% complete

## 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
- ◆ FY07 = \$214K
- ◆ FY08 = \$50K
- ◆ FY09 = \$51K

## Partners

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



# Objectives

Objectives	
Overall	<ul style="list-style-type: none"><li>◆ Bottom-up manufacturing cost assessment of 80 kW direct-H<sub>2</sub> PEMFC system for automotive applications</li></ul>
2008	<ul style="list-style-type: none"><li>◆ High-volume (500,000 units/year) cost projection of ANL 2008 PEMFC system configuration assuming an NSTFC-based MEA and a 30 μm PFSA membrane<ul style="list-style-type: none"><li>➤ Bottom-up manufacturing cost analysis of both stack and BOP components</li><li>➤ Sensitivity analyses on stack and system parameters</li></ul></li><li>◆ Independent peer review of cost analysis methodology and results</li></ul>
2009	<ul style="list-style-type: none"><li>◆ Preliminary high-volume cost projection of ANL 2009 PEMFC system configuration assuming an NSTFC-based MEA and a 30 μm PFSA membrane</li><li>◆ Comprehensive report on the 2008 PEMFC cost analysis (high-volume, bottom-up stack and BOP cost)</li></ul>



BOP = Balance-of-Plant

NSTFC = Nano-Structured Thin Film Catalyst

PFSA = Perfluorosulfonic acid

MEA = Membrane Electrode Assembly

EOS = Economies of Scale

## Background

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### **Over the past year, we updated the 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 updated
  - Developed bottom-up manufacturing cost models for *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)
  - Based cost assessment on ANL 2008 PEMFC system configuration assuming an NSTFC-based MEA and a 30  $\mu\text{m}$  PFSA membrane
  - Revised power density and Pt loading based on ANL inputs
  - Updated bottom-up cost assessment of stack components
  - Participated in independent peer-review of our cost analysis
- In 2009, we will update the system configuration, stack performance assumptions and stack and BOP component specifications based on ANL modeling results
  - Update stack performance and system parasitics assumptions
  - Replace EWH by planar MH w/ pre-cooler for cathode air humidification
  - Include LT radiator, LT coolant pump for air pre-cooler, needle metering valve for CEM



MEA = Membrane Electrode Assembly  
EWH = Enthalpy Wheel Humidifier  
PFSA = Perfluorosulfonic acid

NSTFC = Nano-Structured Thin Film Catalyst  
MH = Membrane Humidifier

# Approach Overall Cost Assessment

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

## Technology Assessment

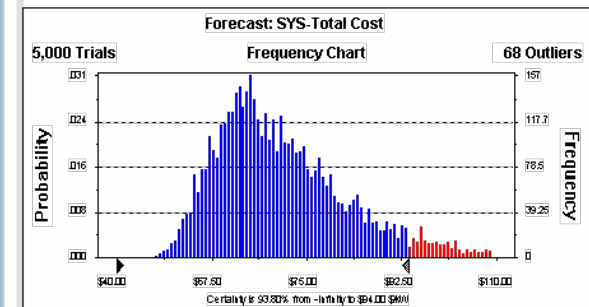
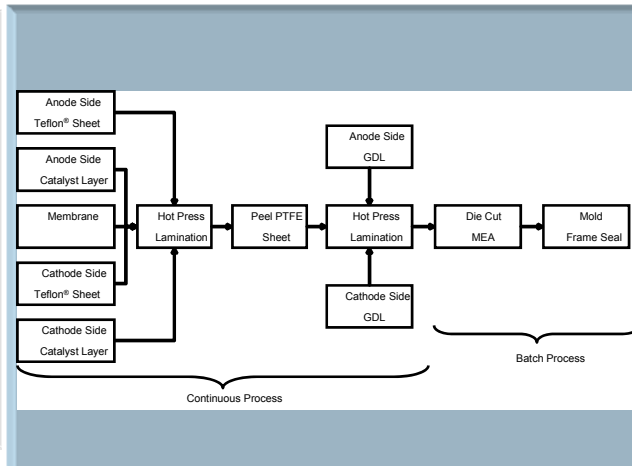
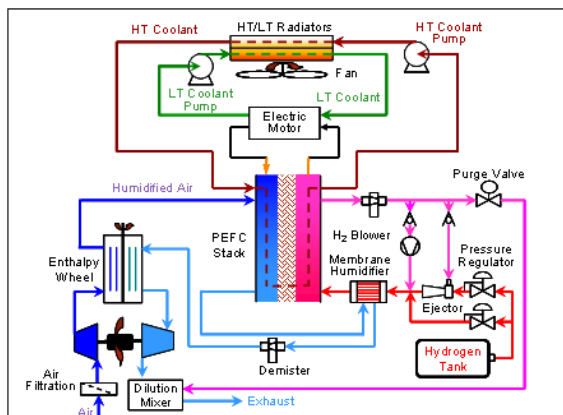
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Component Specifications
- Obtain Developer Input

## Cost Model and Estimates

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

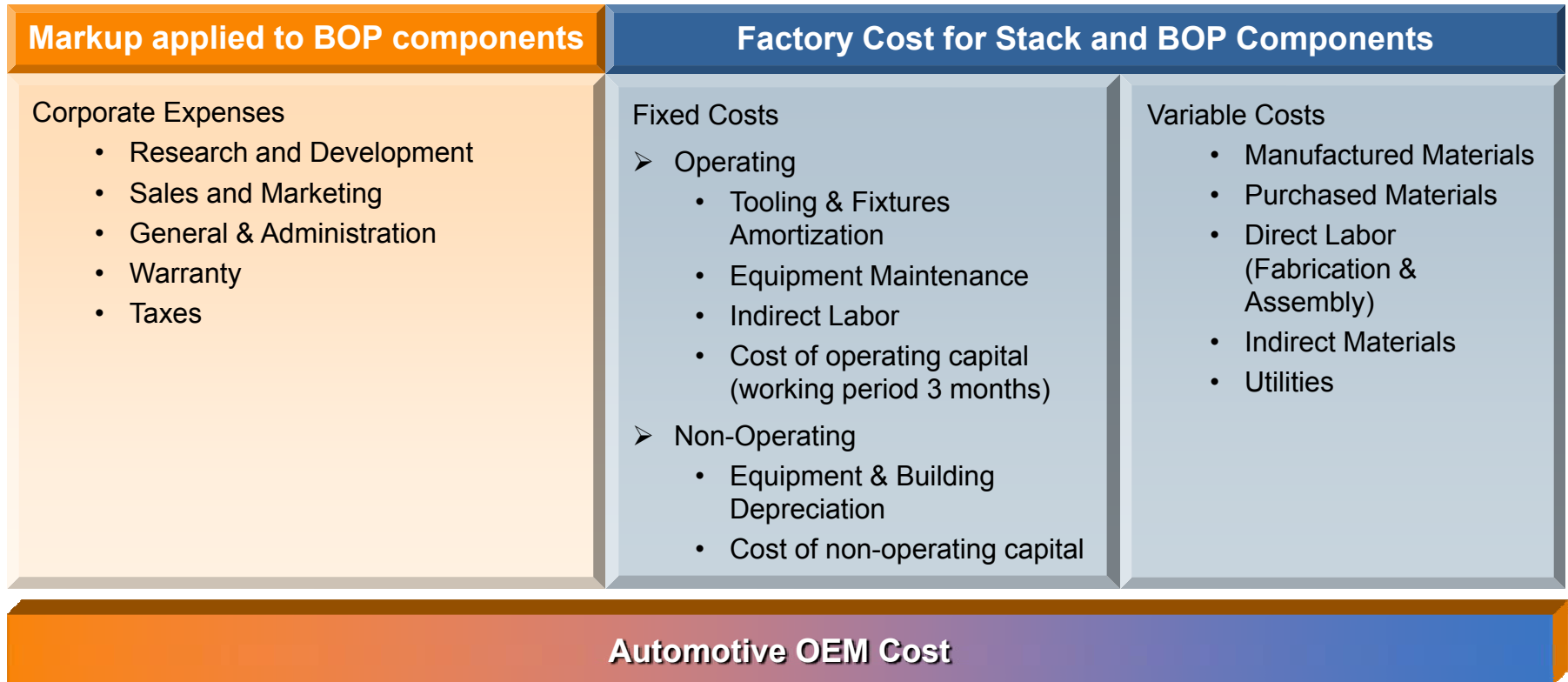
## Overall Model Refinement

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



BOM = Bill of Materials

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



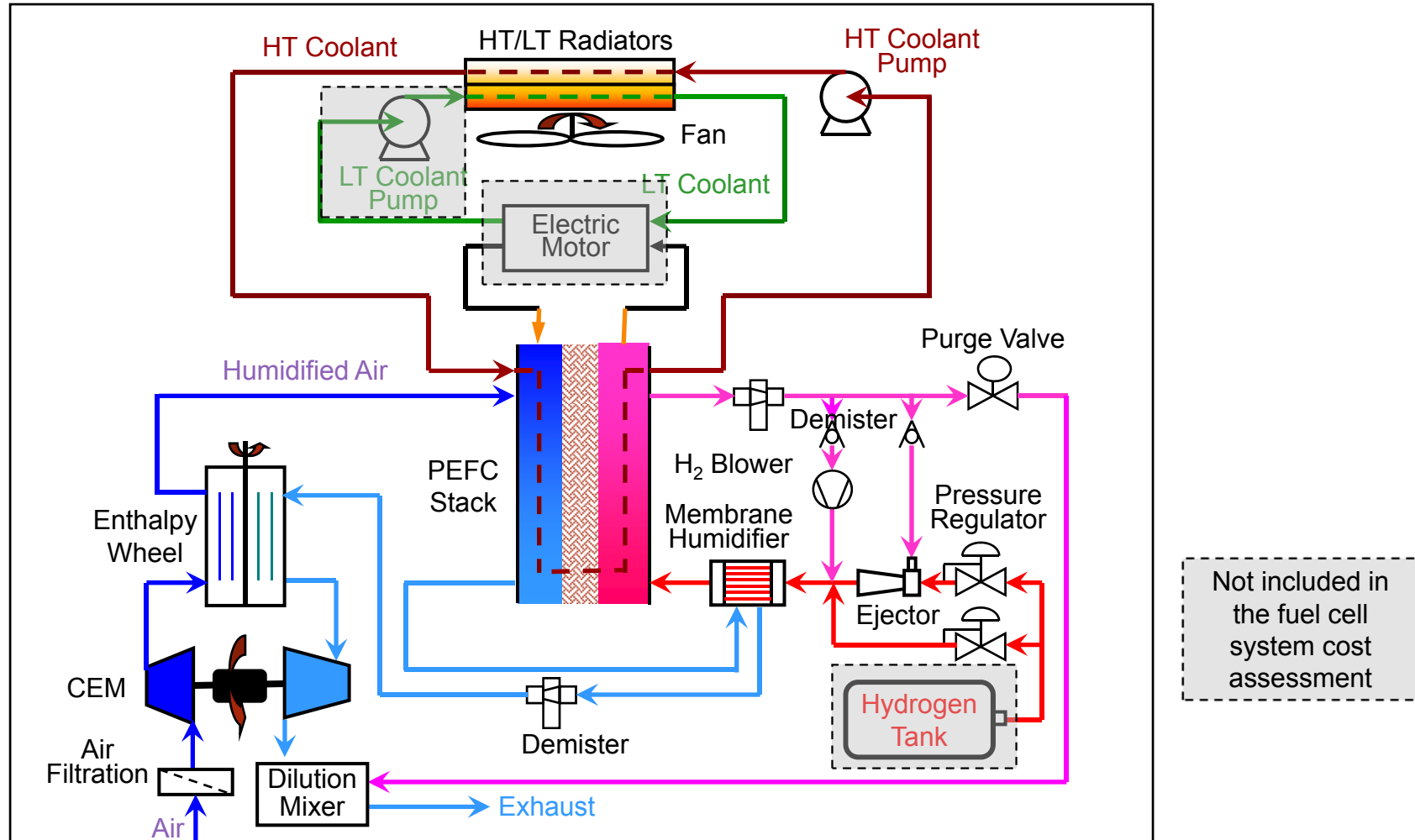
- We assume a vertically integrated process for the manufacture of the stack by the automotive OEM, so no mark-up is included on the major stack components
- Raw materials are assumed to be purchased, and therefore implicitly include supplier markup
- We assume 100% debt financed with an annual interest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



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

# Approach System Configuration

We worked with Argonne National Laboratory (ANL) to define the 2008 system configuration, performance and component specifications<sup>1</sup>.



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

**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<sub>2</sub> 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<sup>®</sup>) 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<sub>2</sub> 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<sup>®</sup> software for the CEM and H<sub>2</sub> blower.





To be consistent with the ANL stack analysis, we made the following material assumptions for the cost projection.

Component	Parameter	Selection
Membrane	Material	30 μm PFSA
	Supported	No
Electrodes (Cathode and Anode)	Catalyst	Ternary PtCo <sub>x</sub> Mn <sub>y</sub> alloy
	Type	Nano-Structured Thin Film
	Supported	PR-149 Organic whiskers
Gas Diffusion Layer (GDL)	Material	Woven carbon fiber
	Porosity	70%
Bipolar Plate	Type	Expanded graphite foil
Seal	Material	Viton®

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.

**Stack performance assumptions were updated by ANL based on their modeling of an NSTFC-based MEA and a 30  $\mu\text{m}$  PFSA membrane.**

Key Stack Performance Assumptions		2005 <sup>1</sup>	2007 <sup>2,3</sup>	2008 <sup>4</sup>
Net power	$\text{kW}_e$	80	80	80
Gross power	$\text{kW}_e$	<b>89.5</b>	<b>86.4</b>	<b>86.9</b>
Gross power density	$\text{mW}/\text{cm}^2$	<b>600</b>	<b>753</b>	<b>716</b>
Cell voltage (rated power)	V	0.65	0.68	0.685
Pt loading (total)	$\text{mg}/\text{cm}^2$	<b>0.75</b>	<b>0.30</b>	<b>0.25</b>
Membrane thickness	$\mu\text{m}$	50	30	30
Stack temperature	$^{\circ}\text{C}$	80	90	90
Pressure (rated power)	atm	2.5	2.5	2.5
Stack eff. (rated power)	% LHV	52	54	54

- Improvement over 2005 assumptions:
  - 67% reduction in Pt loading with an increase in power density
  - 40% thinner and less expensive membrane on an area basis
- Lower Pt loading is attributed to novel catalyst and support structure (i.e., nano-structured thin film on organic whisker support)

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

<sup>2</sup> R.K. Ahluwalia and X. Wang, Reference Fuel Cell System Configurations for 2007: Interim Results, ANL, Feb. 6, 2007

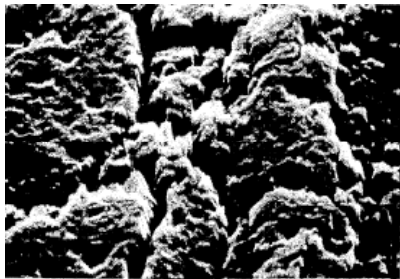
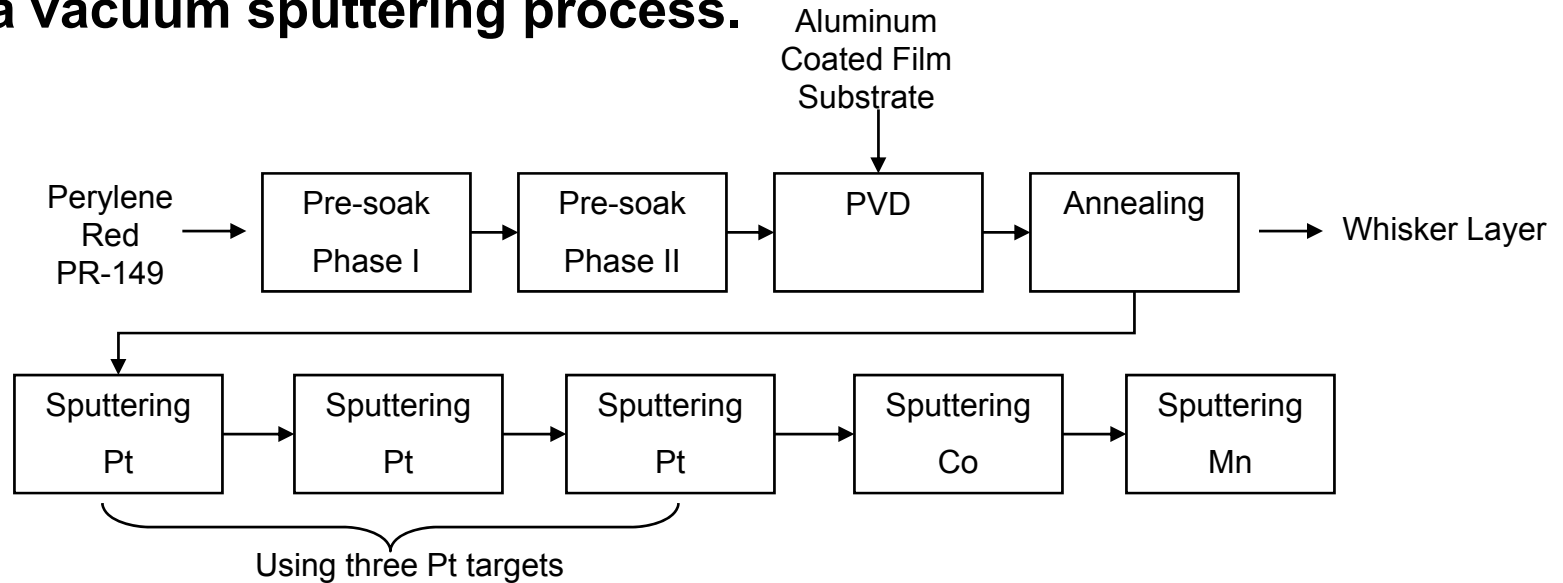
<sup>3</sup> R.K. Ahluwalia, X. Wang and R. Kumar, Fuel Cell Systems Analysis, DOE Hydrogen Program Review, May 15-18, 2007

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

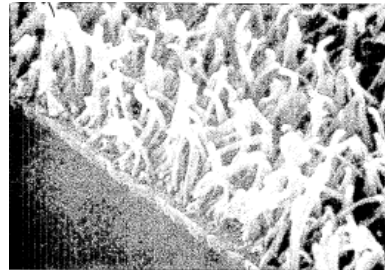
**Key assumptions in 2008 represent stack performance breakthroughs, in particular high power density with significant Pt reduction.**



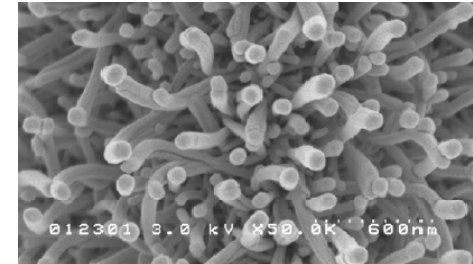
**Organic whisker support was fabricated by physical vapor deposition (PVD) with vacuum annealing process. Catalysts were coated to this layer via vacuum sputtering process.**



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



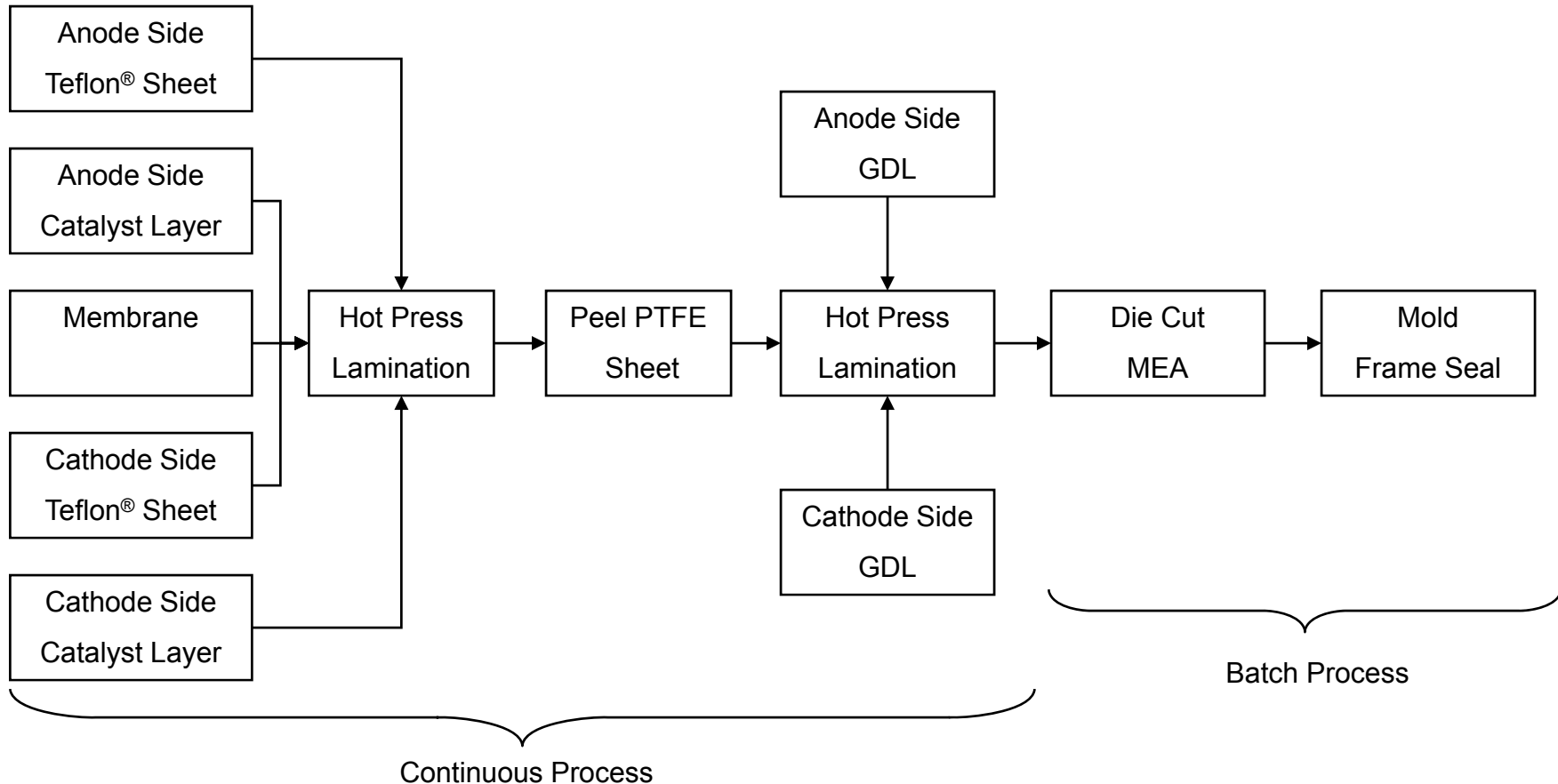
US Patent 4,812,352  
PVD coated thin film after annealing



Nanostructured Thin Film Catalyst  
before transfer to a PEM<sup>1</sup>

<sup>1</sup>M. K. Debe, Durability Aspects of Nanostructured Thin Film Catalysts for PEM Fuel Cells, ECS Transactions, 1(8) 51-66 (2006)

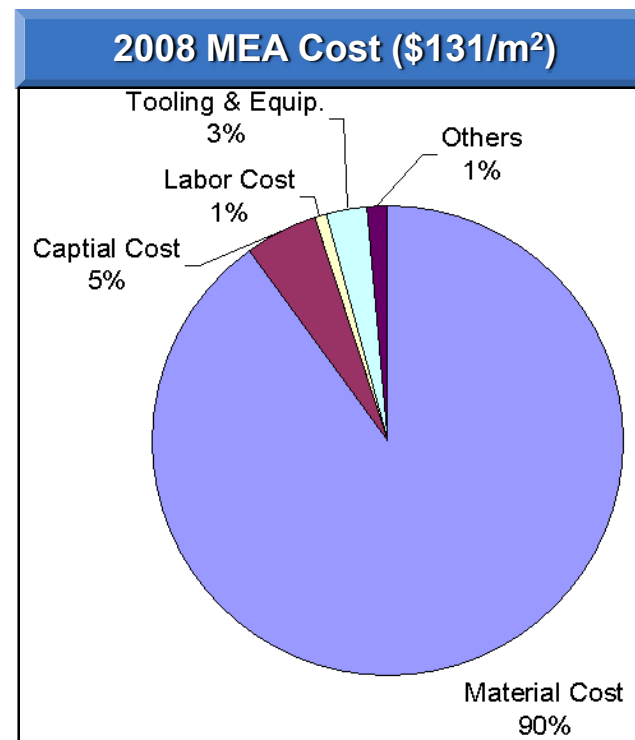
The anode and cathode organic whisker layers were hot pressed to the membrane with Teflon® backing sheets.



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.

**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 <sup>1</sup> (\$/m <sup>2</sup> )	2008 MEA <sup>1</sup> (\$/m <sup>2</sup> )
<i>Material</i>	135.48	117.71
- Membrane	- 13.89	- 13.83
- Electrode	- 109.61	- 91.90
- GDL	- 11.98	- 11.98
<i>Capital Cost</i>	7.08	6.57
<i>Labor</i>	0.99	1.02
<i>Tooling &amp; Equipment</i>	3.80	3.73
<i>Other<sup>2</sup></i>	1.73	1.71
<b>Total</b>	<b>149</b>	<b>131</b>



**In 2007, the MEA cost was higher due to higher Pt loading (0.3 mg/cm<sup>2</sup> in 2007 vs. 0.25 mg/cm<sup>2</sup> in 2008).**



<sup>1</sup> m<sup>2</sup> of active area and kW of net power

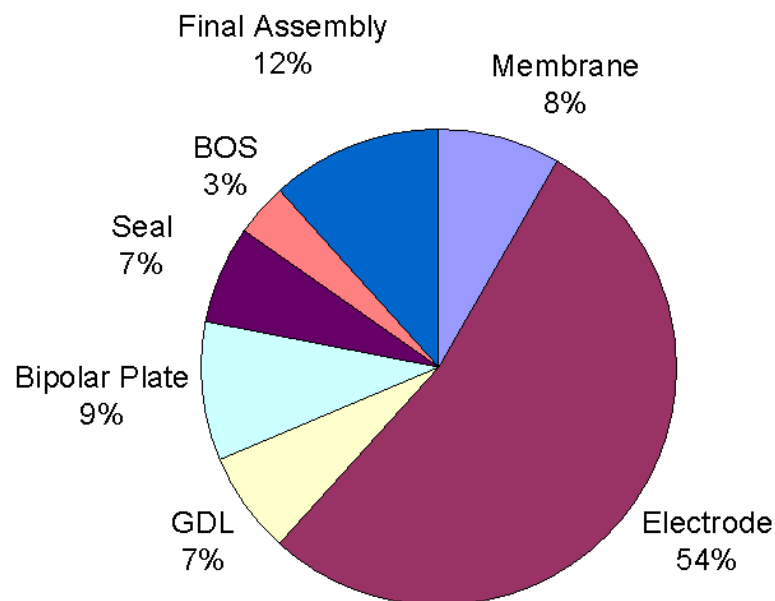
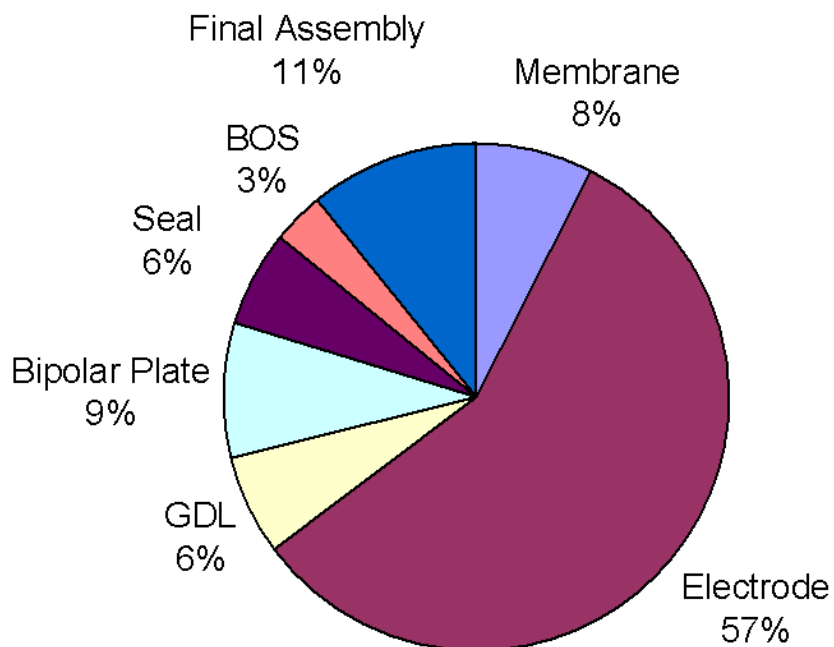
<sup>2</sup> Other costs include utilities, maintenance, and building

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

Stack Manufactured Cost – 80 kW Direct-H<sub>2</sub> PEMFC

2007<sup>1</sup>: \$31/kW, \$2,480

2008<sup>1</sup>: \$29/kW, \$2,320



<sup>1</sup> 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

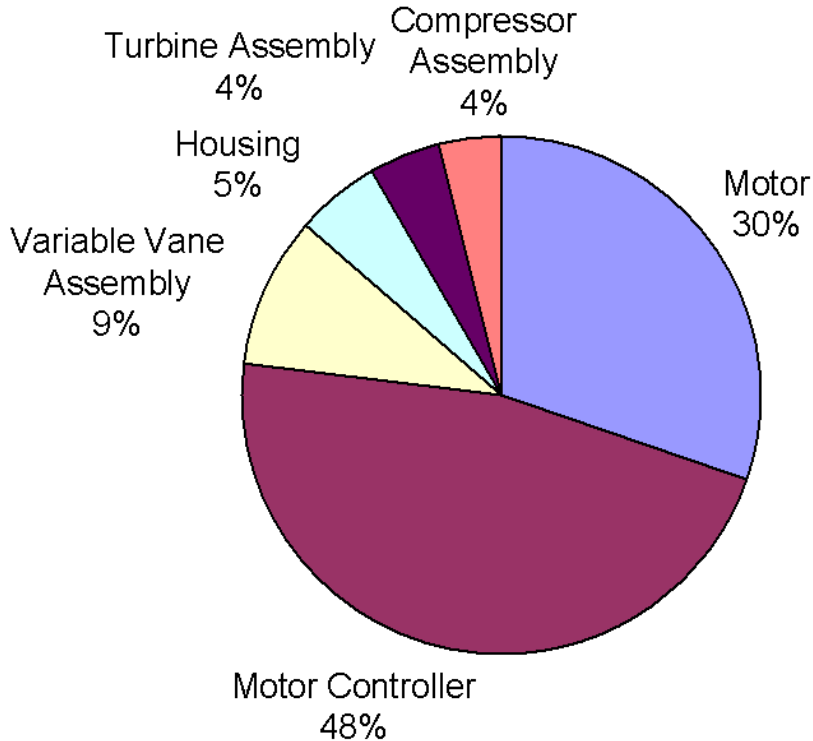
**The references used to determine the overall design and major manufacturing processes for the CEM are tabulated below.**

Component	References
Overall System	Honeywell, DOE program review, progress report & annual report, 2005, 2004, 2003, 2000; US Patent 5,605,045
Electrical Motor	Honeywell, DOE program review, progress report & annual report 2004; US Patent 5,605,045
Motor Power Electronics	Honeywell, DOE program review, progress report & annual report, 2005; Caterpillar, DOE Contract DE-SC05-00OR-99OR22734
Turbine Variable Nozzle Vanes, 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 casting; HIP
7	Compressor Impeller	Al	Investment casting; HIP
8	Thrust Bearing Runner	Steel	Turning; Heat treatment; Grinding

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 <sup>1</sup>
Motor	162	<b>615</b>
Motor Controller <sup>2</sup>	251	
Variable Vane Assembly	50	
Housing	28	
Turbine Assembly	24	
Compressor Assembly	21	
<b>Total:</b>	<b>535</b>	

<sup>1</sup> Assumes 15% markup to the automotive OEM

<sup>2</sup> \$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

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





**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 <sup>1</sup> , \$ (without supplier markup)	OEM Cost <sup>1</sup> , \$ (with 15% supplier markup)
Water Management	Enthalpy wheel air-humidifier	Emprise	160	184
	Membrane H <sub>2</sub> -humidifier	PermaPure	58	66
	Other	-	10	10
Thermal Management	Automotive tube-fin radiator	Modine	57	65
	Radiator fan <sup>2</sup>	-	35	35
	Coolant pump <sup>3</sup>	-	120	120
	Other	-	5	5
Air Management	Compressor-Expander-Motor (CEM)	Honeywell	535	615
	Other	-	97	97
Fuel Management	H <sub>2</sub> blower	Parker Hannifin	193	222
	H <sub>2</sub> ejectors <sup>4</sup>	-	40	40
	Other	-	41	41
<b>TOTAL</b>			<b>1351</b>	<b>1500</b>

<sup>1</sup> High-volume manufactured cost based on a 80 kW net power PEMFC system.

<sup>2</sup> Assumes \$35/unit based on automotive radiator vendor catalog price, scaled for high volume production

<sup>3</sup> 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

<sup>4</sup> 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

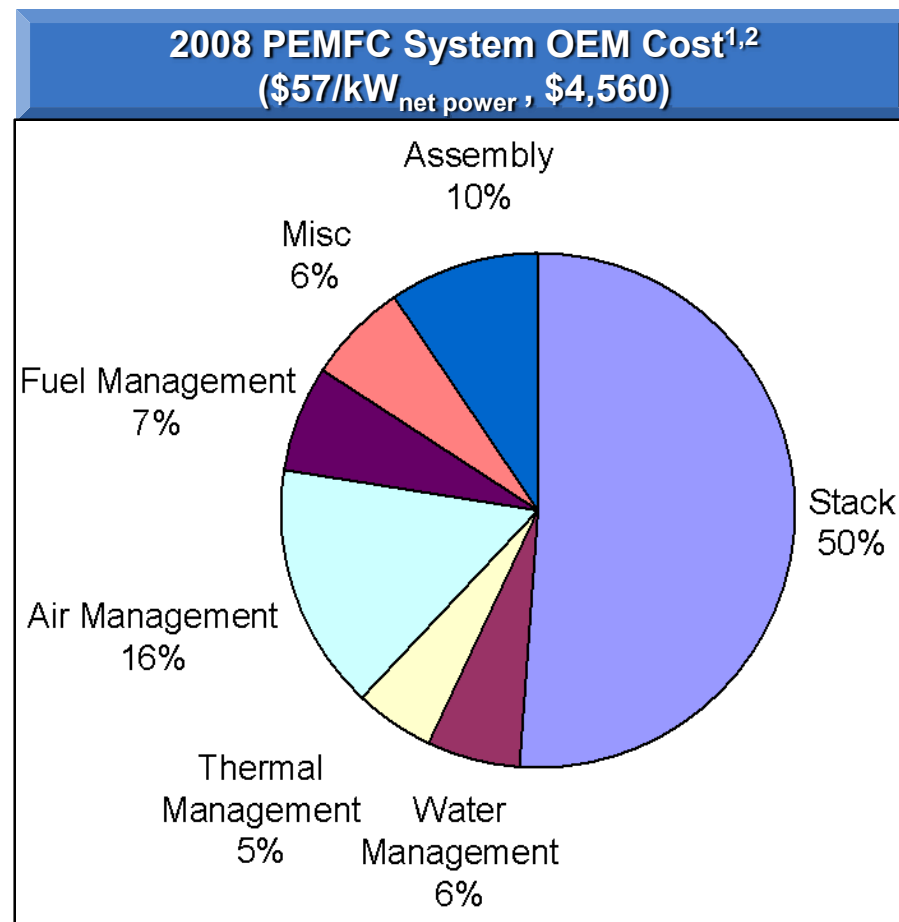


The 2008 PEMFC stack and system costs are ~15-30% higher than the DOE 2010 cost targets of \$25/kW and \$45/kW respectively.

PEMFC System Cost <sup>1</sup> (\$/kW)	2005 OEM Cost	2007 OEM Cost <sup>1,2</sup>	2008 OEM Cost <sup>1,2</sup>
<b>Stack</b>	<b>67</b>	<b>31</b>	<b>29</b>
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
<b>Total</b>	<b>108</b>	<b>59</b>	<b>57</b>

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

<sup>2</sup> Assumes 15% markup to the automotive OEM for BOP components

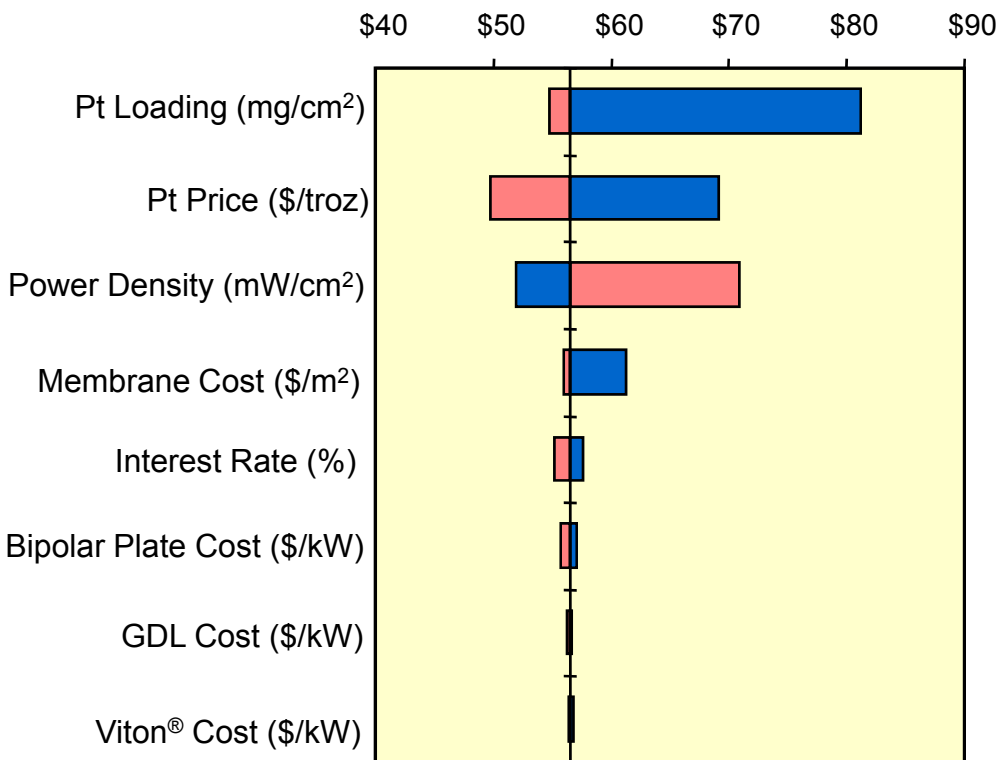


**BOP and assembly costs together represent ~50% of the PEMFC system cost in 2008, as compared to ~38% in 2005.**



## Pt loading, power density, and Pt cost are the top three drivers of the PEMFC system cost<sup>1</sup>.

2008 PEMFC System OEM Cost<sup>1</sup> (\$/kW)

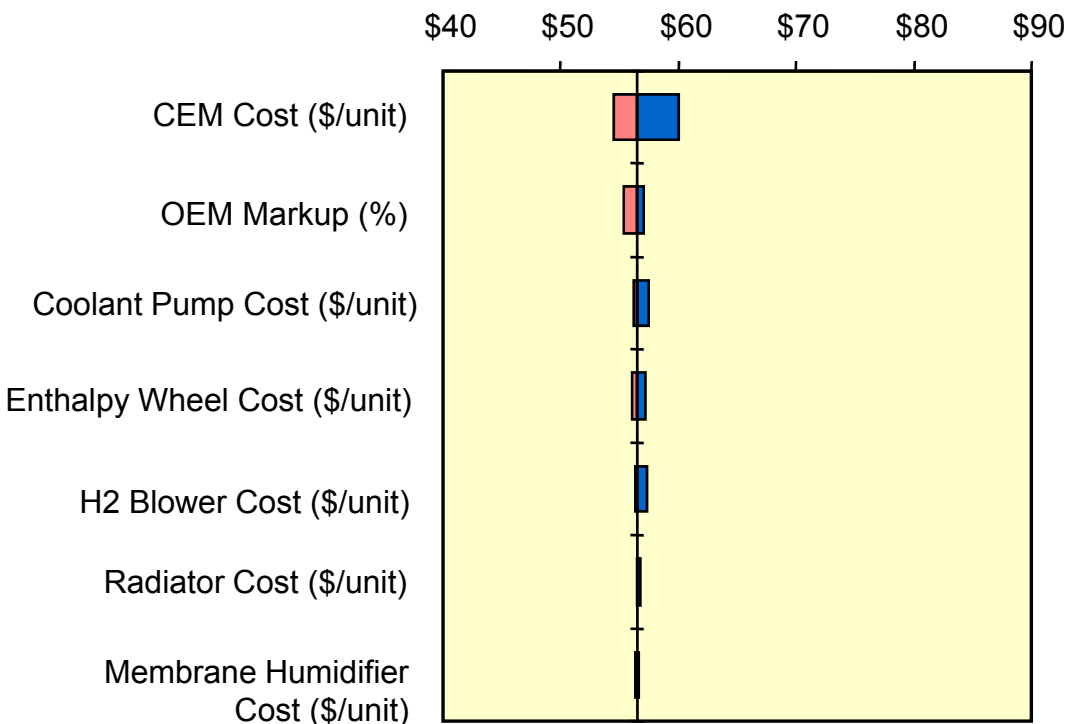


#	Variables	Min.	Max.	Base	Comments
1	Pt Loading (mg/cm <sup>2</sup> )	0.2	0.75	0.25	Minimum: DOE 2015 target <sup>2</sup> ; Maximum: TIAX 2005 report <sup>3</sup>
2	Pt Cost (\$/tr.oz.)	450	2250	1100	Minimum: ~ 108-year min. in 2007 \$ <sup>4</sup> ; Maximum: 12-month maximum LME price <sup>5</sup>
3	Power Density (mW/cm <sup>2</sup> )	350	1000	716	Minimum: industry feedback; Maximum: DOE 2015 target <sup>2</sup> .
4	Membrane Cost (\$/m <sup>2</sup> )	10	50	16	Minimum: GM <sup>6</sup> study; Maximum: DuPont <sup>7</sup> 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](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](http://www.platinum.matthey.com)
5. [www.metalprices.com](http://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

Among the BOP components, the CEM has the greatest impact on the PEMFC system cost<sup>1</sup>.

2008 PEMFC System OEM Cost<sup>1</sup> (\$/kW)

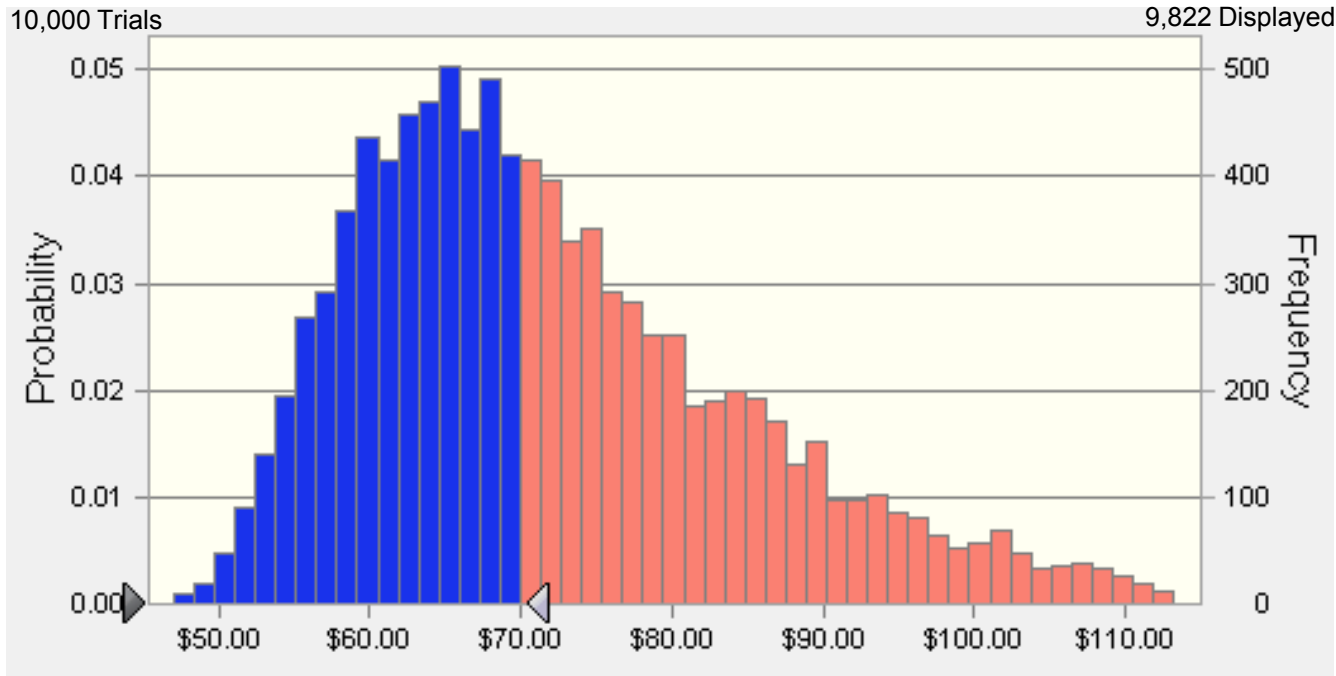


#	Variables	Min.	Max.	Base	Comments
1	CEM Cost (\$/unit)	368	808	535	Based on component single variable sensitivity analysis
2	OEM Markup	5%	20%	15%	Based on industry feedback
3	Coolant Pump Cost (\$/unit)	80	200	120	Based on industry feedback
4	Enthalpy Wheel Cost (\$/unit)	123	217	160	Based on component 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

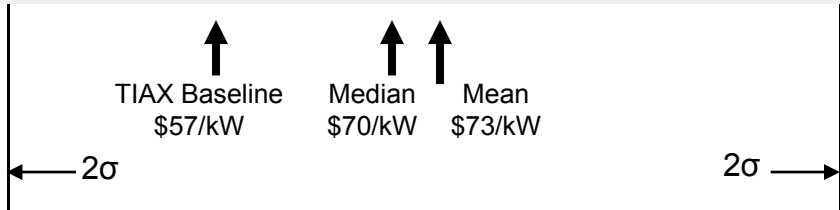
<sup>1</sup> High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Assumes a % markup to automotive OEM for BOP components.

Monte Carlo analysis shows that the high-volume PEMFC system OEM cost<sup>1</sup> ranges between \$45/kW and \$101/kW ( $\pm 2\sigma$ ).

2008 PEMFC System OEM Cost<sup>1</sup> (\$/kW)

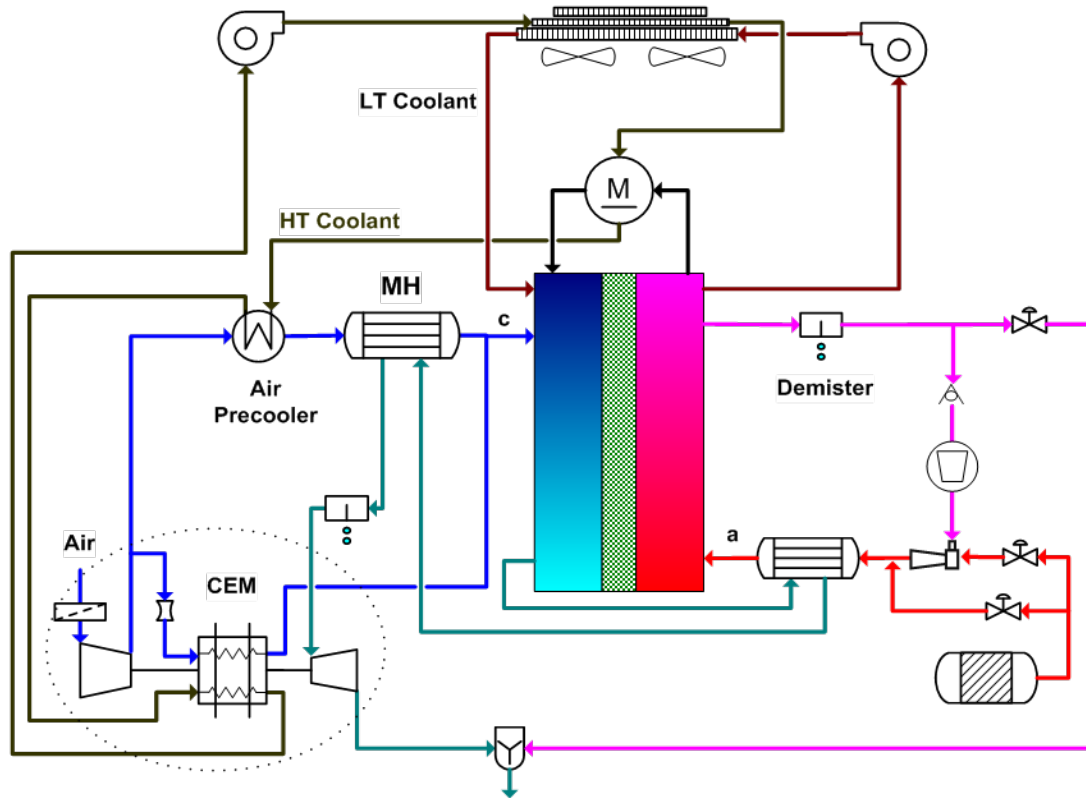


Cost <sup>1</sup>	\$/kW
Mean	73
Median	70
Std. Dev.	14
TIAX Baseline	57



<sup>1</sup> 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.





Ref: Status of Automotive Fuel Cell Systems, R. K. Ahluwalia and X. Wang, March 3, 2009

NSTFC = Nano-Structured Thin Film Catalyst  
 CEM = Compressor Expander Motor  
 MH = Membrane Humidifier

MEA = Membrane Electrode Assembly  
 AFB = Air-foil Bearing



## Key features

### Stack

- NSTFC MEA, 30  $\mu\text{m}$  membrane
- 0.1(a)/0.15(c)  $\text{mg}/\text{cm}^2$  Pt
- 90  $^\circ\text{C}$ , 2.5 atm

### Air Management

- CEM module
- Air-cooled motor/AFB
- Efficiencies at rated power: 70% compressor, 73% expander, 86% motor, 87% controller

### Water Management

- Cathode MH with precooler
- Anode MH w/o precooler

### Thermal Management

- Advanced 24-fpi louver fins
- 55% pump + 92% motor efficiency
- 45% blower + 92% motor efficiency

### Fuel Management

- Series ejector-pump hybrid
- 35% pump efficiency

**Our preliminary estimates show that the high-volume 2009 PEMFC stack cost for three scenarios<sup>1, 2</sup> ranges between \$24/kW and \$33/kW.**

Key Cost Assumptions		2009 Stack Scenarios <sup>1, 2</sup>		
		S1	S2	S3
System net power	kW <sub>e</sub>	80		
Stack gross power <sup>2</sup>	kW <sub>e</sub>	91.6	92.0	92.5
Cell voltage (rated power) <sup>2</sup>	V	0.721	0.685	0.655
Stack gross power density <sup>2</sup>	mW/cm <sup>2</sup>	640	837	966
Pt loading (total) <sup>2</sup>	mg/cm <sup>2</sup>	0.25		
Stack efficiency (rated power) <sup>2</sup>	% LHV	57.4	54.5	52.1
System efficiency (rated power) <sup>2</sup>	% LHV	50.0	47.3	45.0
System voltage (rated power)	V	300		
System active area	m <sup>2</sup>	14.3	11.0	9.6
<b>Stack cost<sup>3</sup></b>	<b>\$/kW<sub>net</sub></b>	<b>33</b>	<b>26</b>	<b>24</b>

<sup>1</sup> All scenarios assume a Pt cost of \$1,100/tr.oz., NSTFC-based MEA, 30 μm PFSA membrane, and stack operating conditions of 90 °C and 2.5 atm.

<sup>2</sup> Based on preliminary stack and system modeling results by ANL for 2009 PEMFC system: Status of Automotive Fuel Cell Systems, R. K. Ahluwalia and X. Wang, March 3, 2009

<sup>3</sup> High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).



## Summary

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### The key conclusions, accomplishments and next steps for our project are summarized below.

- Key conclusions and accomplishments:
  - The 2008 stack and system costs<sup>1</sup> of \$29/kW and \$57/kW respectively, are ~15-30% higher than the DOE 2010 cost targets.
  - Balance-of-plant and assembly costs together represent ~50% of the projected 2008 PEMFC system cost.
  - Platinum loading, power density, platinum cost, membrane cost, and CEM cost are the top five drivers of the PEMFC system cost.
  - Preliminary estimates for the high-volume 2009 PEMFC stack cost<sup>1</sup> range between \$24/kW and \$33/kW.
  - We participated in an independent peer-review of our cost analysis methodology, assumptions and resulting cost projections.
- Next steps:
  - Update and finalize high-volume cost projection of 2009 PEMFC stack and system
  - Complete a comprehensive report on the 2008 PEMFC cost analysis (high-volume, bottom-up stack and BOP cost)

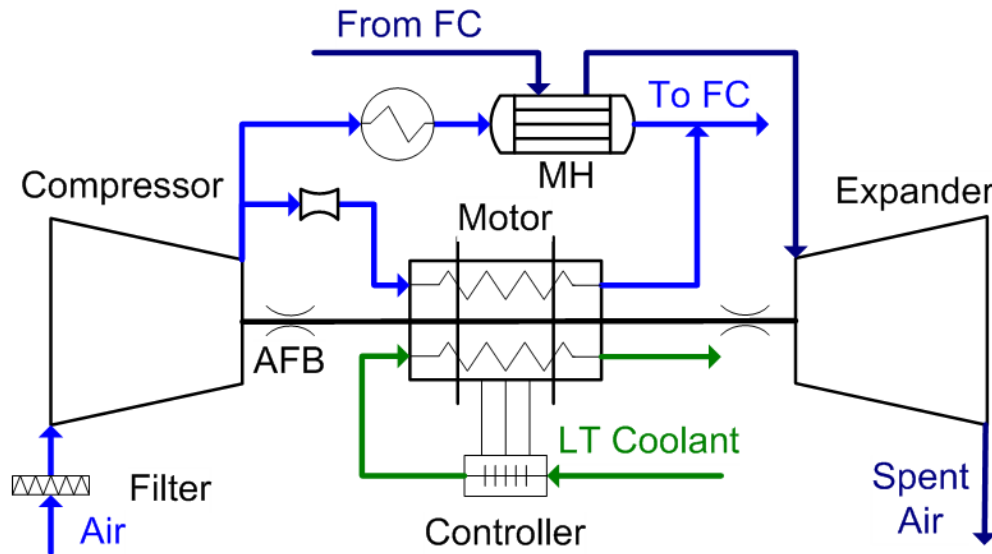


**Thank You**

**Questions?**

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

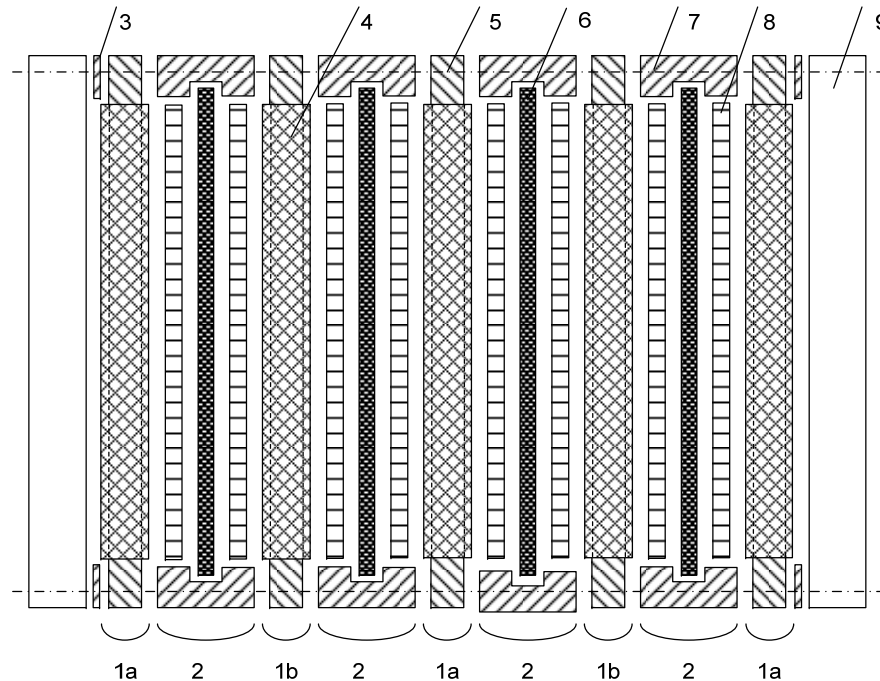
<b>Audience/ Reviewer</b>	<b>Date</b>	<b>Location</b>
<b>Fuel Cell Tech Team Mtg.</b>	May 08	Detroit MI
<b>Several Work-in-Progress Mtgs. with DOE and ANL</b>	June – Sep 08	Telecon
<b>DOE Annual Merit Review</b>	June 08	Arlington VA
<b>DOE HFCIT Review</b>	Sep 08	Washington DC
<b>Fuel Cell Tech Team Review</b>	Sep 08	Telecon
<b>Several Work-in-Progress Mtgs. with the Independent Peer Review Panel</b>	Dec 08 – present	Telecon
<b>Several Work-in-Progress Mtgs. with DOE and ANL</b>	Feb 09 – present	Telecon



- Mixed axial flow compressor
- Variable nozzle turbine
- 3-phase brushless DC motor, liquid and air cooled
- Motor controller, liquid cooled
- Air foil bearing (AFB)
- Efficiencies at rated power: 70% compressor, 73% expander, 86% motor, 87% controller

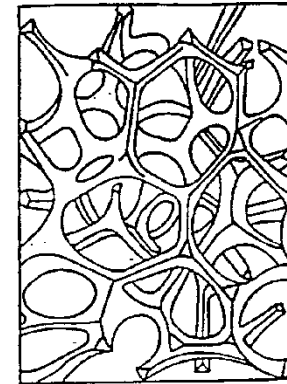
Ref: Status of Automotive Fuel Cell Systems, R. K. Ahluwalia and X. Wang, March 3, 2009

**We are developing bottom-up manufacturing costs for the planar membrane humidifier based on ANL specifications<sup>1</sup> and other patents.**



- 1a: Frame and foam unit to deliver air from fuel cell
- 1b: Frame and foam unit to deliver air to fuel cell
- 2: Gasket-GDL-Membrane unit
- 3: Endplate gasket
- 4: Metal/Carbon Foam
- 5: Frame
- 6: Membrane
- 7: Seal/Gasket
- 8: GDL
- 9: Endplate

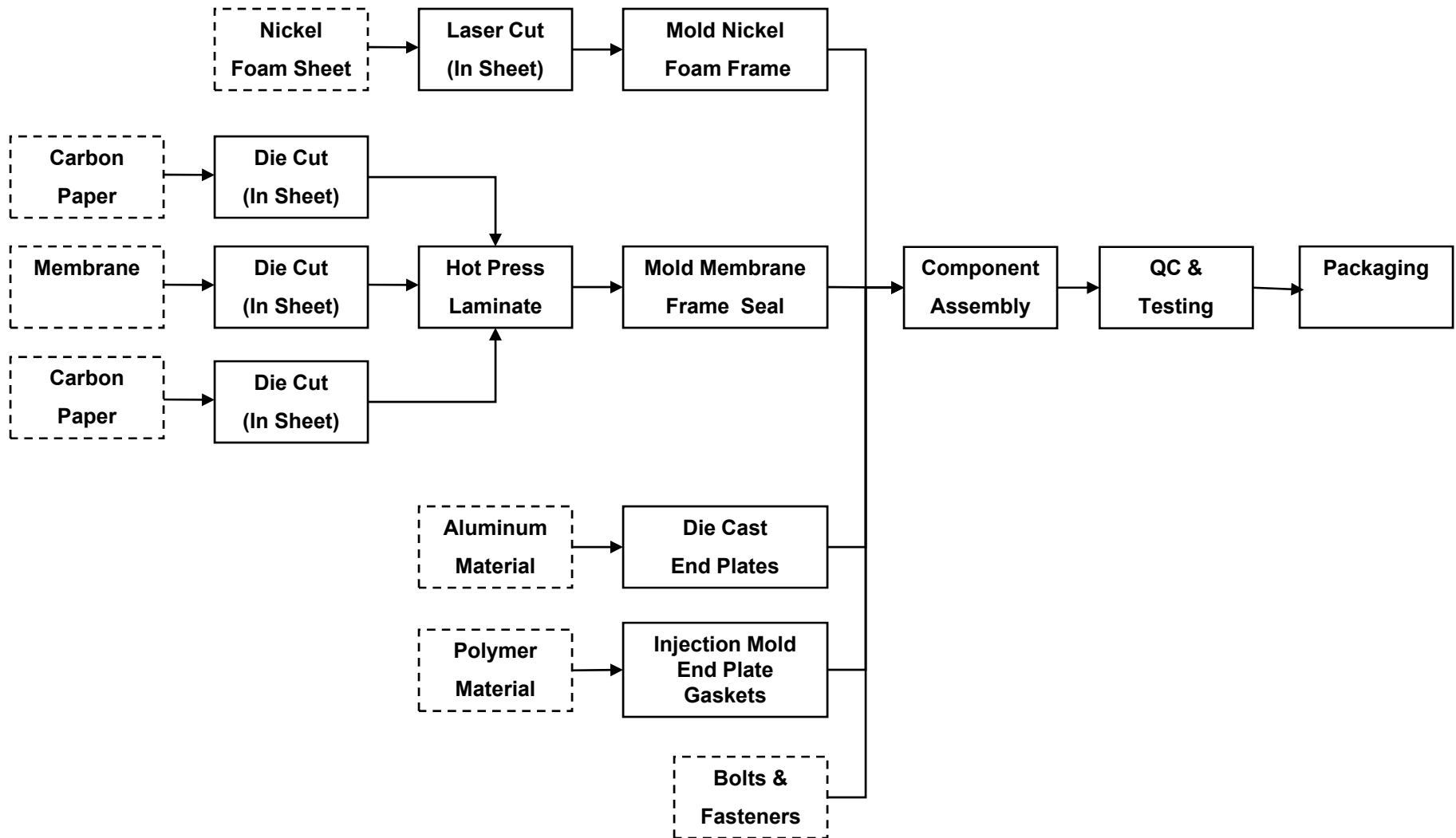
- Referenced Patents
  - U.S. Patent 6,737,183 (Nuvera)
  - U.S. Patent 6,835,477 (Nuvera)
  - U.S. Patent 6,864,005 (Ballard)
  - U.S. Patent 7,078,117 (Ballard)



Nickel foam (U.S. Patent 6,835,477)

<sup>1</sup> Status of Automotive Fuel Cell Systems, R. K. Ahluwalia and X. Wang, March 3, 2009

The preliminary cost estimate for the cathode side planar membrane humidifier is \$105 per unit, of which materials represent ~50%.



**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 <sup>1</sup> , \$/kW	2005	2007	2008	2010 DOE Target	Cost drivers / Comments
Membrane	4	2	2	10	Power density changed from 600 mW/cm <sup>2</sup> (2005), to 753 mW/cm <sup>2</sup> (2007), to 716 mW/cm <sup>2</sup> (2008) Pt loading decreased from 0.75 mg/cm <sup>2</sup> (2005), to 0.3 mg/cm <sup>2</sup> (2007), to 0.25 mg/cm <sup>2</sup> (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
<b>Total<sup>2</sup></b>	<b>67</b>	<b>31</b>	<b>29</b>	<b>25</b>	

<sup>1</sup> 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.

<sup>2</sup> Results may not appear to calculate due to rounding of the 2005, 2007, and 2008 cost results.

**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 <sup>1</sup> (\$/m <sup>2</sup> )	2007 Cost <sup>1</sup> (\$/m <sup>2</sup> )	2008 Cost <sup>1</sup> (\$/m <sup>2</sup> )	Cost drivers / Comments
Membrane	23	16	16	30 µm unsupported membrane; DOE 2010 target = \$20/m <sup>2</sup>
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/cm <sup>2</sup> (2005) to 0.3 mg/cm <sup>2</sup> (2007) to 0.25 mg/cm <sup>2</sup> (2008); power density changed from 600 mW/cm <sup>2</sup> (2005), to 753 mW/cm <sup>2</sup> (2007), to 716 mW/cm <sup>2</sup> (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
<b>Total</b>	<b>361</b>	<b>210</b>	<b>191</b>	

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



<sup>1</sup> Manufactured cost on an active area basis

## Detailed results of 2008 fuel cell stack cost breakdown.

Stack Costs <sup>2</sup>		Active Area Basis <sup>1</sup>				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 <sup>2</sup> (\$/kW)
		Mtl Cost (\$/m <sup>2</sup> )	Process Cost (\$/m <sup>2</sup> )	Total Cost (\$/m <sup>2</sup> )	Unit Cell Weight/Area (g/cm <sup>2</sup> )					
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
<b>MEA Total</b>		<b>\$117.7</b>	<b>\$13.1</b>	<b>\$130.8</b>	<b>0.05</b>	<b>7</b>	<b>\$1,429</b>	<b>\$159</b>	<b>\$1,588</b>	<b>\$20</b>
Bipolar Coolant Plate		\$10.2	\$7.7	\$17.9	0.10	24	\$124	\$93	\$218	\$3
Bipolar Interconnect <sup>2</sup>		\$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
<b>Total Unit Cell</b>		<b>\$127.9</b>	<b>\$20.8</b>	<b>\$148.7</b>	<b>0.22</b>	<b>40</b>	<b>\$1,676</b>	<b>\$638</b>	<b>\$2,314</b>	<b>\$29</b>

<sup>1</sup> Manufactured cost on an active area basis

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



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

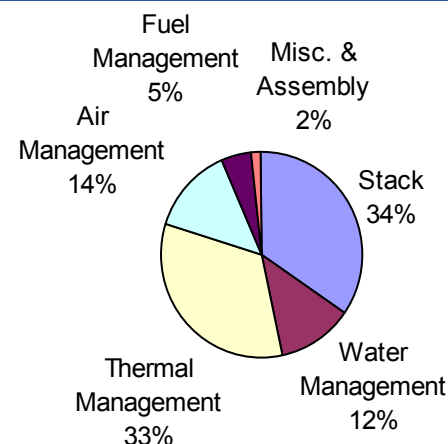
PEMFC Sub-System	Volume <sup>1</sup> (L)	Weight (kg)	DOE 2010 Target
<b>Stack</b>	<b>41</b>	<b>44</b>	
Power density <sup>1,2</sup> ( $W_e/L$ )	1,940		2,000
Specific power <sup>2</sup> ( $W_e/kg$ )	1,803		2,000
<b>Balance of Plant</b>	<b>79</b>	<b>71</b>	
Water management (enthalpy wheel, membrane humidifier)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

<sup>1</sup> Does not include packing factor, which would lower volumetric power density.

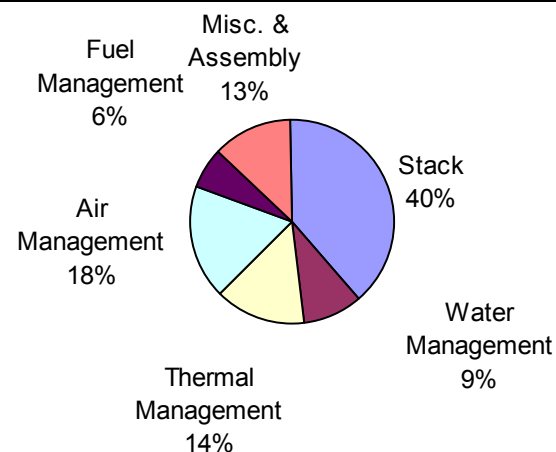
<sup>2</sup> Based on stack net power output of 80 kW, and **not** on the gross power output of 86.9 kW

<sup>3</sup> The radiator fan and coolant pump were in the Misc. category in 2005 and 2007

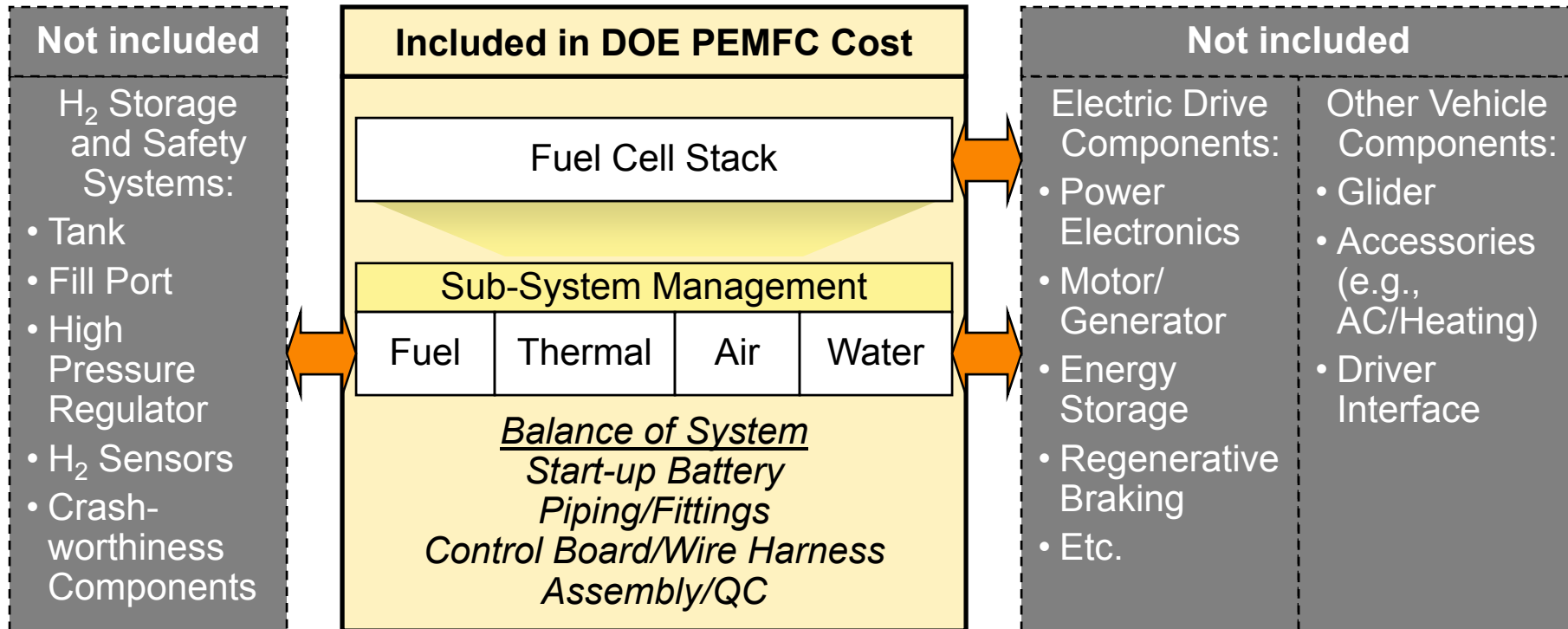
**2008 PEMFC System Volume (120 L)**



**2008 PEMFC System Weight (115 kg)**

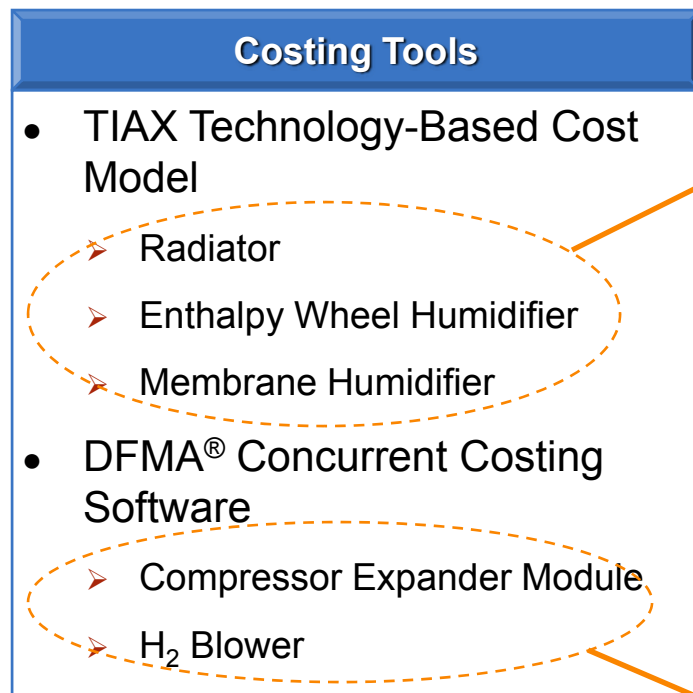


**Our cost assessment includes the fuel cell stack and related BOP subsystems, but does not include electric drive or other necessary powertrain components.**



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

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



### 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<sup>®</sup> 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

<sup>1</sup> We used experience-based estimates (as opposed to bottom-up costing) for components such as the enthalpy wheel motor, H<sub>2</sub> ejectors, radiator fan, coolant pump, valves and regulators.

### **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

**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
<b>Stack</b>	
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
<b>Balance of Plant</b>	
Water management (enthalpy wheel, membrane humidifier)	Cordierite, $\gamma$ -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 <sub>2</sub> blower, H <sub>2</sub> ejectors)	SS316 bar, SS316 sheet, seals, H <sub>2</sub> blower motor, H <sub>2</sub> ejectors

**We developed stack specifications consistent with the performance assumptions.**

TIAX Assumptions	Units	2005 <sup>1</sup>	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 per system	#	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 <sup>2</sup>	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

<sup>1</sup> 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.**

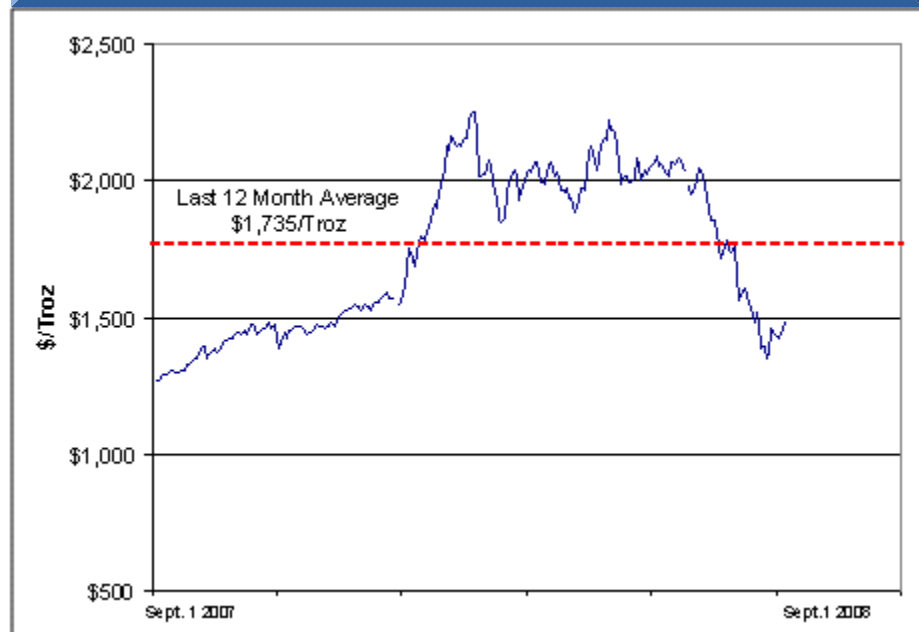


**Platinum at \$1,100/tr.oz. is close to the average price (\$1,059/tr.oz.) over the last five years.**

**Last Five Years' Platinum Price**



**Last Twelve Months' Platinum Price**



**The Pt price averaged over the 12 month period from Sep 2007 to Sep 2008 is ~ \$1,735/tr.oz.**

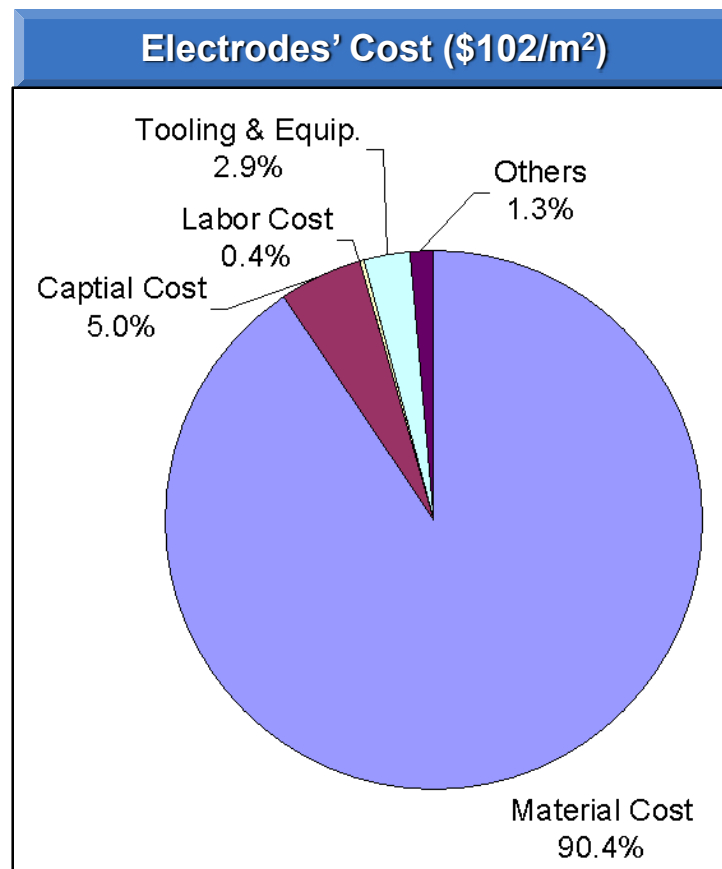


**Platinum price dominates the electrode costs. We have assumed Pt price to be \$1,100/tr.oz. or \$35.4/g.**

Manufactured Cost	Anode <sup>1</sup> (\$/m <sup>2</sup> )	Cathode <sup>1</sup> (\$/m <sup>2</sup> )	Total <sup>1</sup> (\$/m <sup>2</sup> )
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 <sup>2</sup>	0.510	0.79	1.329
<b>Total</b>	<b>35</b>	<b>67</b>	<b>102</b>

<sup>1</sup> m<sup>2</sup> of active area

<sup>2</sup> Other costs include utilities, maintenance, and building



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

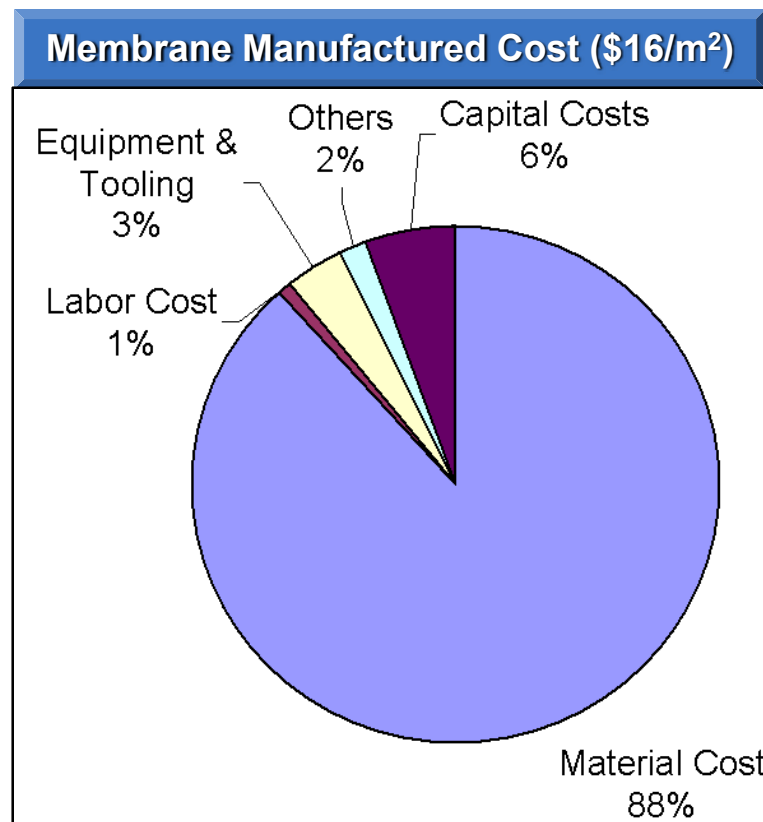




The estimated membrane cost on an active area basis is \$16/m<sup>2</sup>, with material cost representing about 88% of the total cost.

Membrane Manufactured Cost <sup>1</sup>				
Component	Material		Process	
	(\$/m <sup>2</sup> )	(\$/kg)	(\$/m <sup>2</sup> )	(\$/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
<b>Subtotal</b>	<b>13.83</b>	<b>301.85</b>	<b>1.85</b>	<b>40.15</b>
<b>Total</b>	<b>15.68 (\$/m<sup>2</sup>)</b>			
	<b>340.85 (\$/kg)</b>			

<sup>1</sup> Manufactured cost on an active area basis or per kg of finished membrane basis (accounts for scrap and yield)



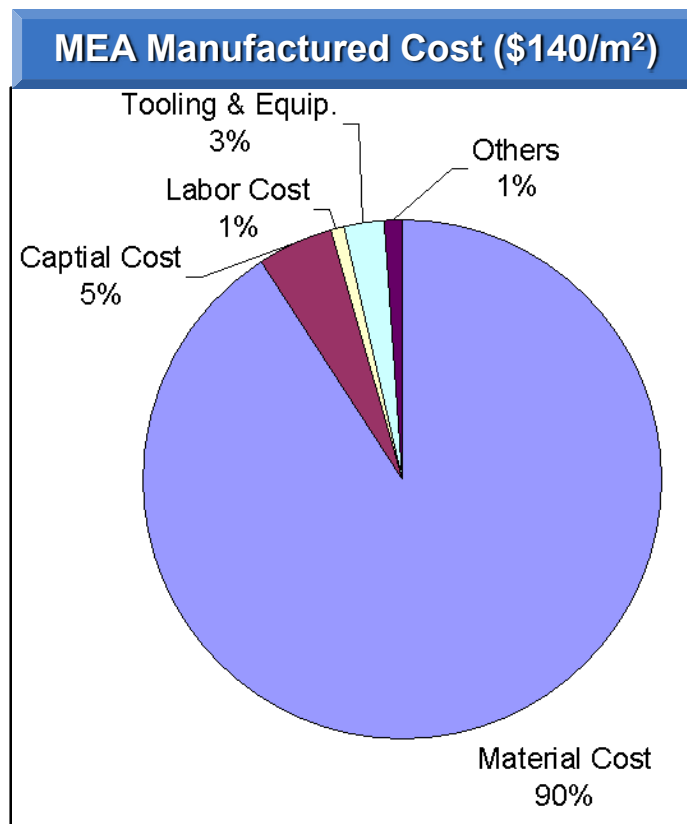
In 2005, the membrane cost was \$23/m<sup>2</sup> due to higher material costs (2 mil) and higher process costs (double pass required for coating).

On an active area basis, the MEA and seal together cost \$140/m<sup>2</sup>.

Manufactured Cost <sup>1</sup>	MEA (\$/m <sup>2</sup> )	Frame Seal (\$/m <sup>2</sup> )
<i>Material</i>	117.71	
- Membrane	- 13.89	5.03
- Electrode	- 91.90	
- GDL	- 11.98	
<i>Capital Cost</i>	6.57	1.27
<i>Labor</i>	1.02	0.93
<i>Tooling &amp; Equipment</i>	3.73	1.10
<i>Other<sup>2</sup></i>	1.71	0.50
<b>Subtotal</b>	<b>130.74</b>	<b>8.83</b>
<b>Total</b>	<b>139.57</b>	

<sup>1</sup> Manufactured cost on an active area basis

<sup>2</sup> Other costs include utilities, maintenance, and building



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

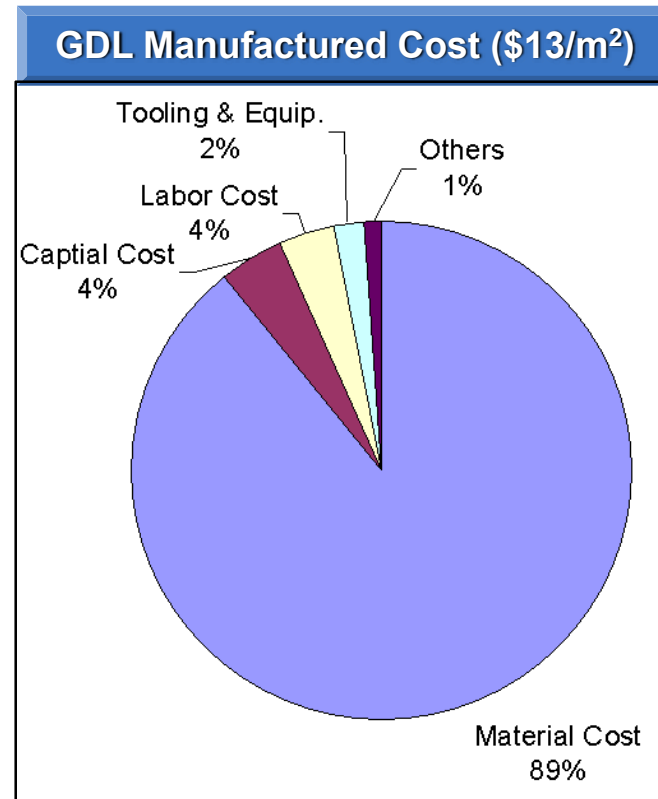


The anode GDL has the same cost as the cathode GDL, of ~ \$13/m<sup>2</sup>.

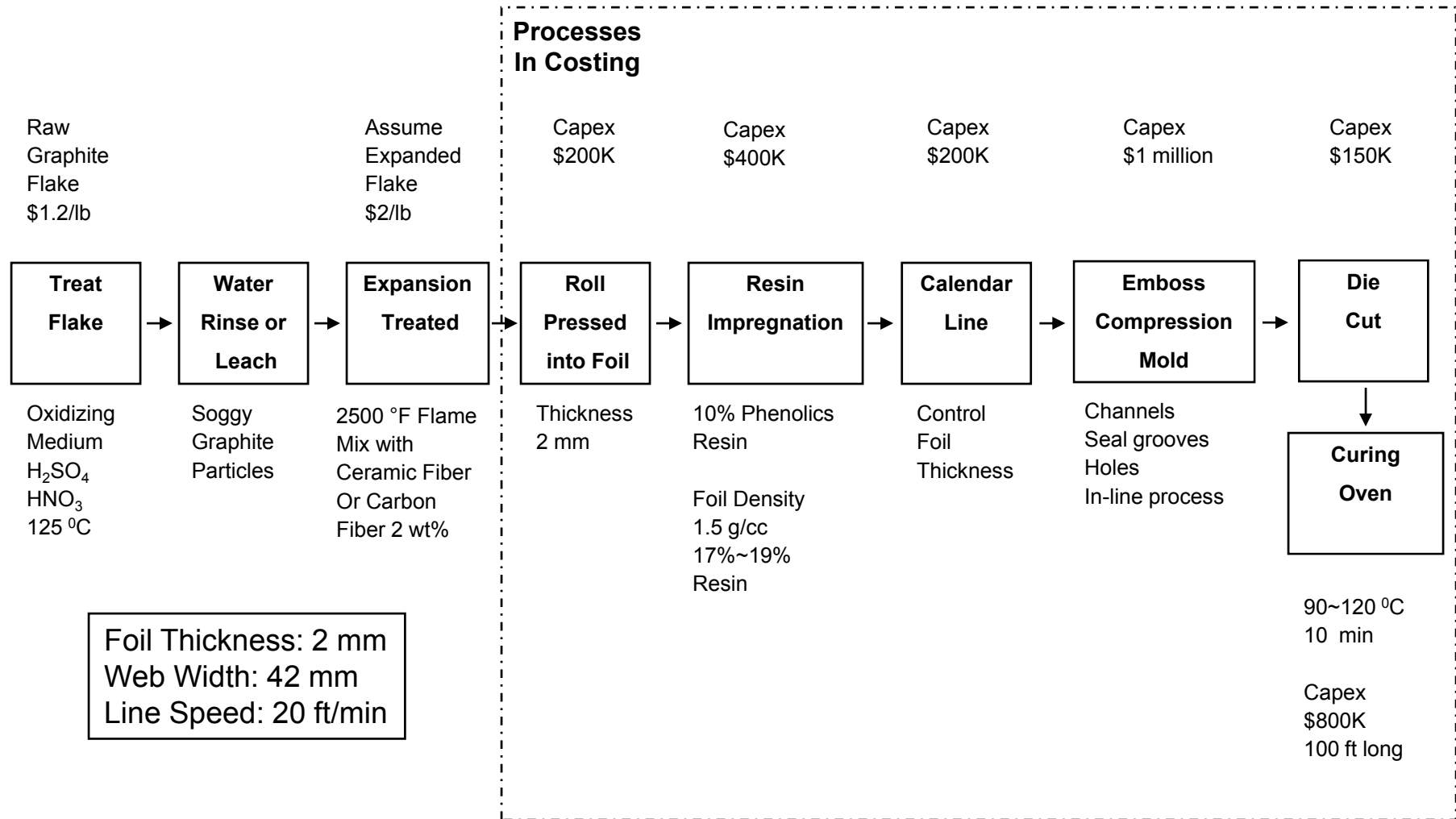
Manufactured Cost <sup>1</sup>	GDL (\$/m <sup>2</sup> )
Material	11.98
Capital Cost	0.57
Labor	0.52
Tooling	0.24
Other <sup>2</sup>	0.16
<b>Total</b>	<b>13.47</b>

<sup>1</sup> Manufactured cost on an active area basis

<sup>2</sup> Other costs include utilities, maintenance, and building

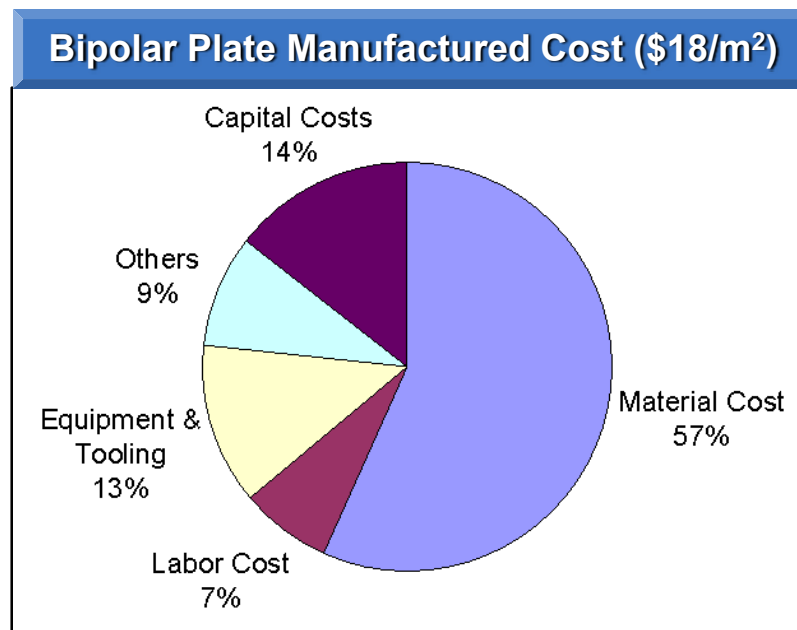


**Our process flow for the expanded graphite bipolar plate is based on a GrafTech® process chart and related patents.**



**We estimate the expanded graphite foil bipolar plate cost is \$18/m<sup>2</sup> at high volume.**

Bipolar Plate Manufactured Cost <sup>1</sup> (\$/m <sup>2</sup> )		
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
<b>Subtotal</b>	<b>10.24</b>	<b>7.70</b>
<b>Total</b>	<b>17.94</b>	



<sup>1</sup> Manufactured cost on an active area basis

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

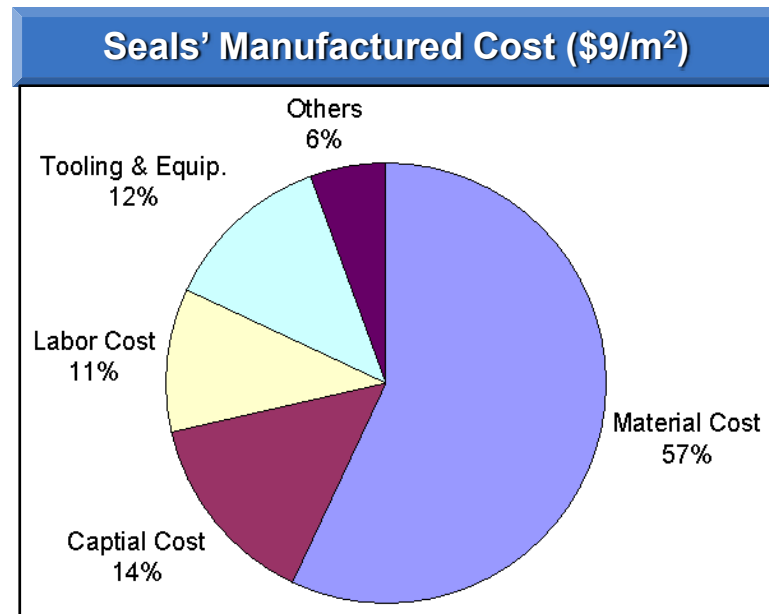


**Transfer molding is used to fabricate the seals between the MEA and bipolar plate (cooling plate).**

Manufactured Cost <sup>1</sup>	Seals (\$/m <sup>2</sup> )
<i>Material</i>	5.03
<i>Capital Cost</i>	1.27
<i>Labor</i>	0.93
<i>Tooling</i>	1.10
<i>Other<sup>2</sup></i>	0.50
<b>Total</b>	<b>8.83</b>

<sup>1</sup> Manufactured cost on an active area basis

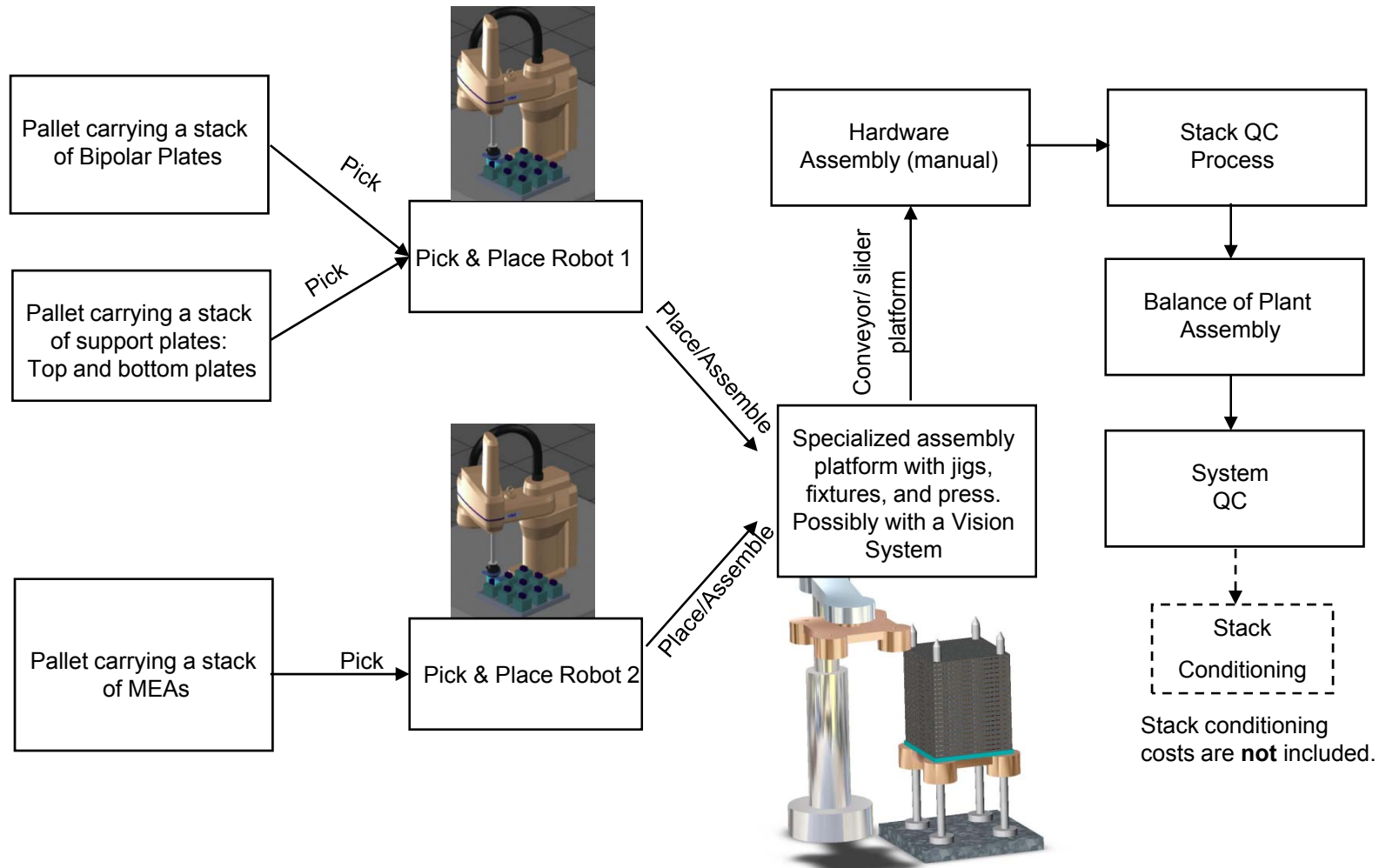
<sup>2</sup> Other costs include utilities, maintenance, and building



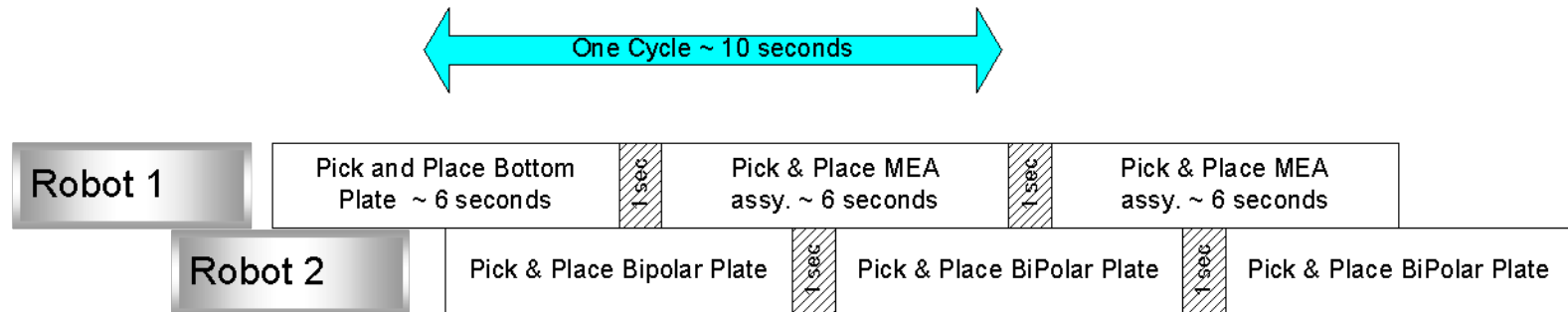
**The seal material is Viton® which costs about \$20/lb.**



**A pair of robots in a specialized assembly station with a vision system is assumed to assemble the stack.**



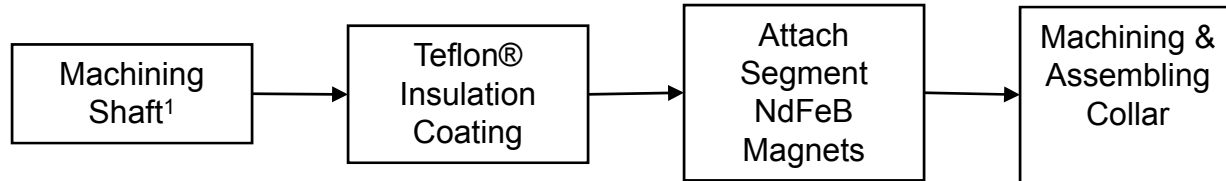
**Assuming a two-robot assembly station, we estimate that a complete PEMFC system is assembled in approximately two hours.**



Stack assembly step	Time	Comments
<b>Pick &amp; place a single repeat unit</b>	~ 10 seconds	Based on two robot setup
<b>Assemble a single stack</b>	~ 38 mins.	For 220 MEAs and bipolar plates
<b>Assemble balance of stack (BOS)</b>	~ 10 mins.	BOS includes endplates, endplate insulators, outer wrap, stack manifold, current collectors, tie bolts
<b>Stack quality control</b>	~ 15 mins.	Stack burn-in / conditioning time is not included



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



- 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



Courtesy: Honeywell, DOE Merit Review 2003

CEM Motor Rotor Manufacturing Process

# 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. (Cm³)	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	Actuation 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	Labyrinth Seal	1	US2006/0153704	130	Misc	3.61				1.00		0.02	\$ 2.07
29	Journal 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	Labyrinth 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	Labyrinth Seal	1			Misc							0.02	\$ 2.07
43	Journal 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



**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	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.
	Steel Laminations		
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	
<b>Total Motor Cost (\$/unit)</b>		<b>412</b>	

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

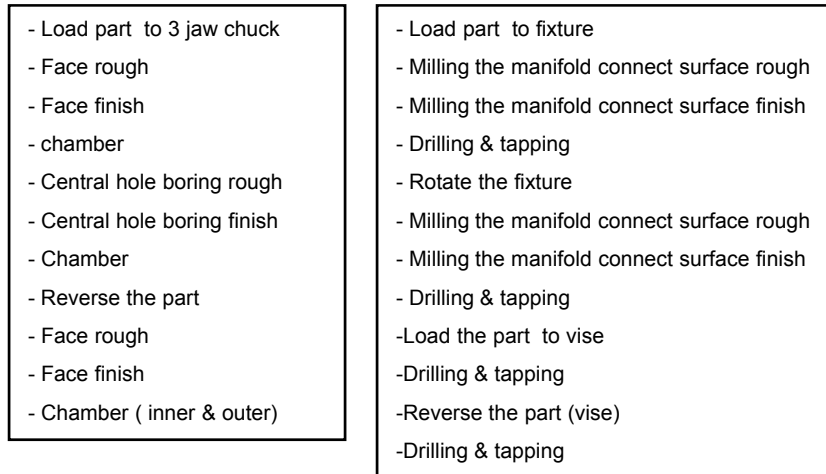
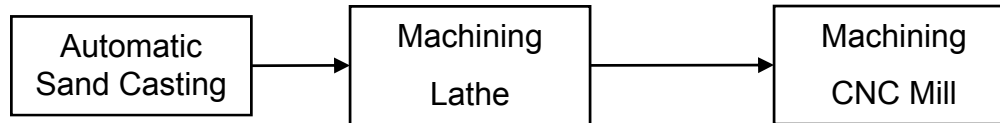


**The rotor and single vane structure in the Parker Hannifin Model 55 Univane H<sub>2</sub> blower are referenced from US patent 5,374,172.**

#	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; Turning; Milling; Broaching
8	Vane	SS316	Hot forging; Drilling; Reaming

**The major manufacturing processes for selected components of the H<sub>2</sub> blower are tabulated above.**

The blower housing manufacturing process represents the level of detail we captured in the costing<sup>1</sup> of the H<sub>2</sub> blower.



H<sub>2</sub> Blower Housing Manufacturing Process

# Backup Slides H<sub>2</sub> Blower Bill of Materials

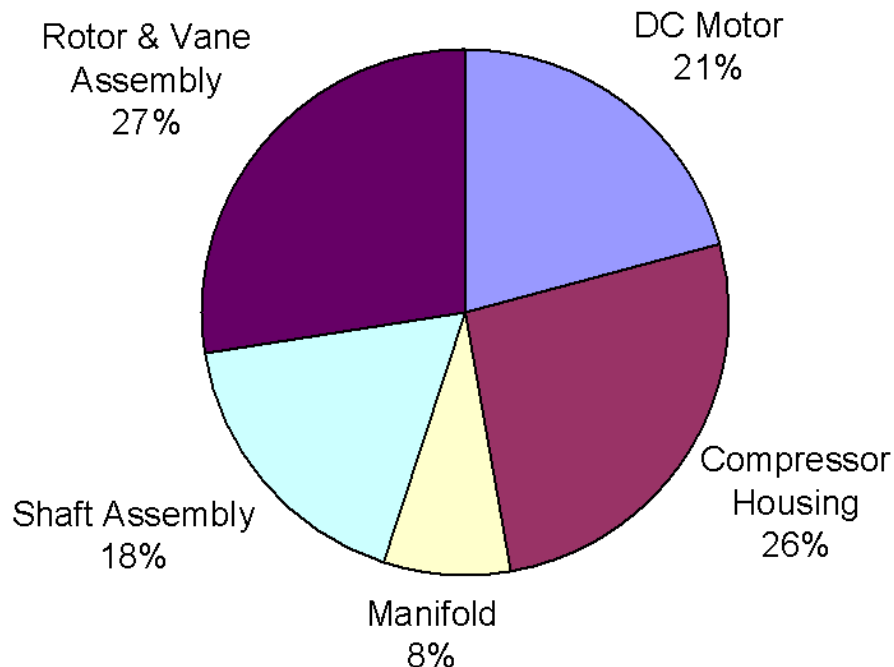
The projected H<sub>2</sub> blower cost is \$193 per unit.

#	Part Name	Quantity	Material	OD (cm)	L (cm)	W (cm)	Wall Thickness (cm)	Total Vol. (Cm <sup>3</sup> )	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	Labyrinth 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	Labyrinth 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
<b>Total:</b>									<b>6.88</b>	<b>\$ 193.44</b>



The rotor & vane assembly, blower housing, and DC motor are the top three cost drivers for the H<sub>2</sub> blower.

H<sub>2</sub> Blower Manufactured Cost (\$193)



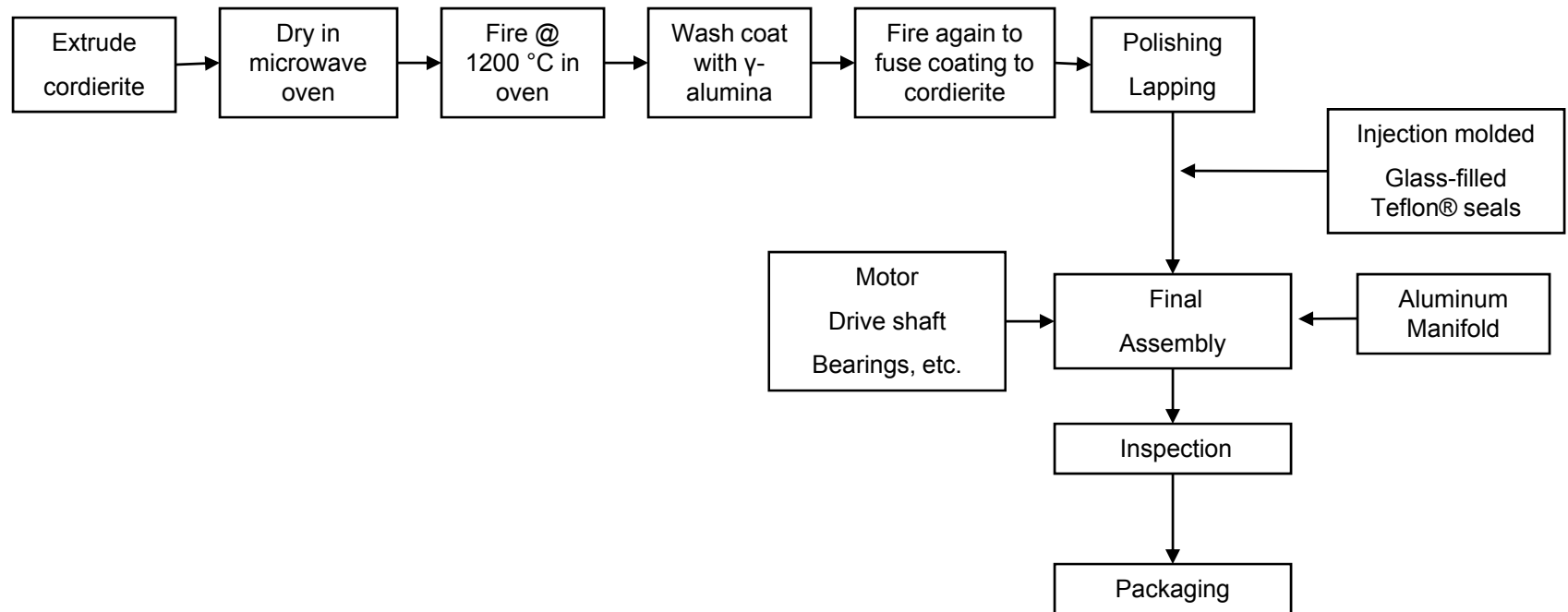
H <sub>2</sub> Blower Manufactured Cost (\$)		
Component	Factory Cost	OEM Cost <sup>1</sup>
DC Motor	40	<b>222</b>
Blower Housing	51	
Manifold	15	
Shaft Assembly	34	
Rotor & Vane Assembly	53	
<b>Total:</b>	<b>193</b>	

<sup>1</sup> Assumes 15% markup to the automotive OEM

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



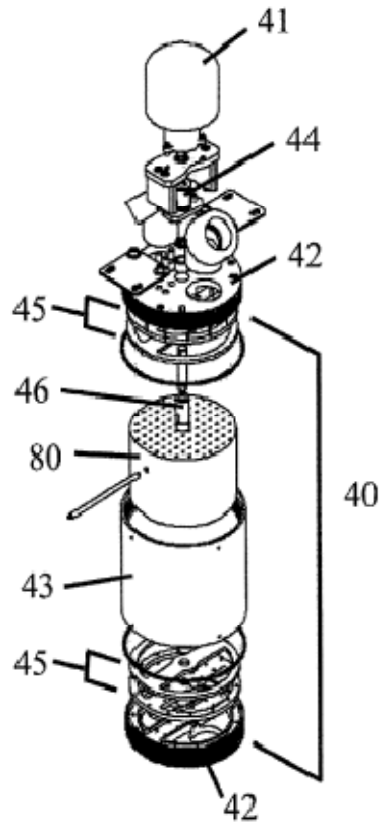
The enthalpy wheel manufacturing process was based on discussions with Emprise on their Humidicore™ humidifier.



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



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

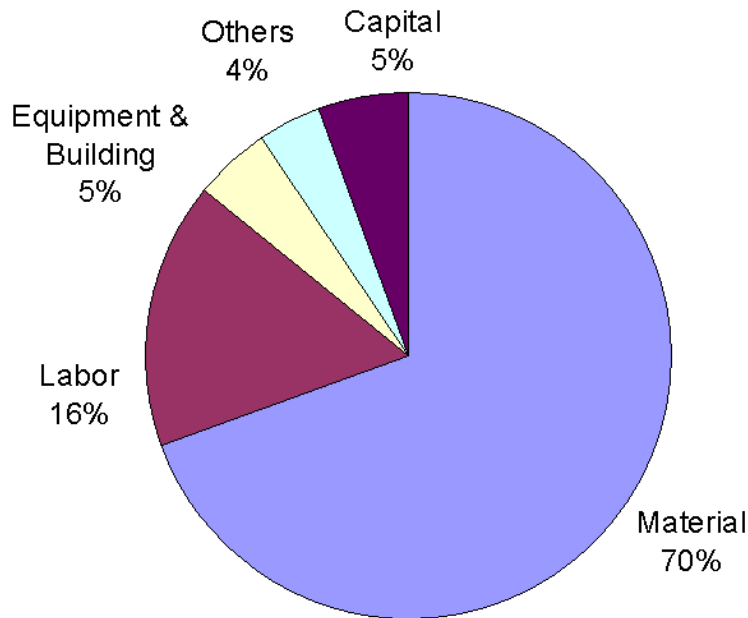


US Patent 2002/0071979

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 "

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

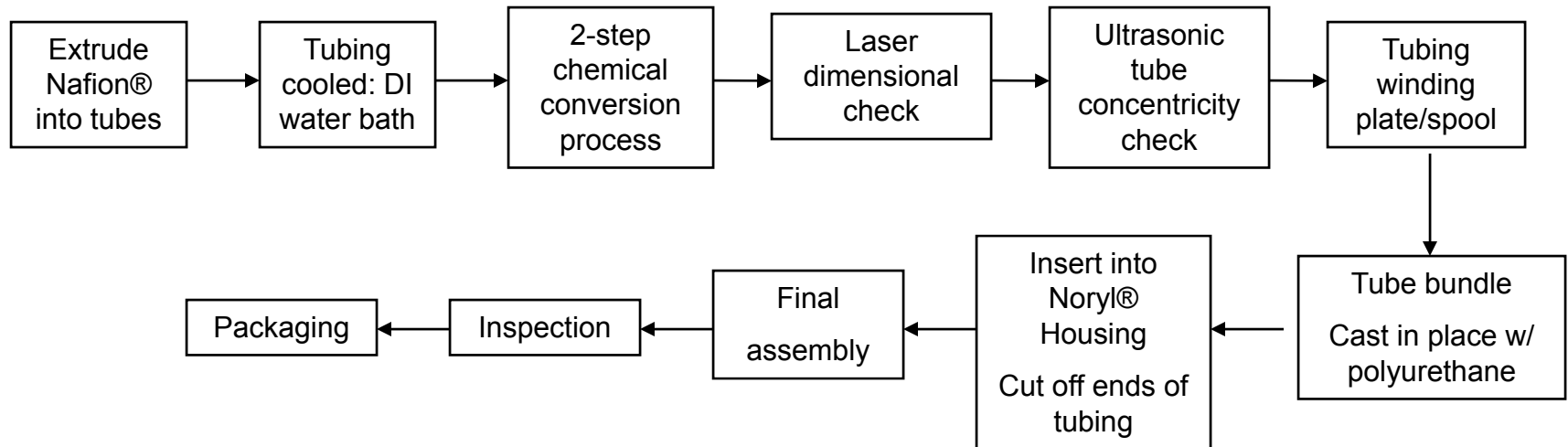
**Enthalpy Wheel Humidifier Manufactured Cost (\$160)**



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
<b>Total</b>	<b>1</b>	<b>160</b>	



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

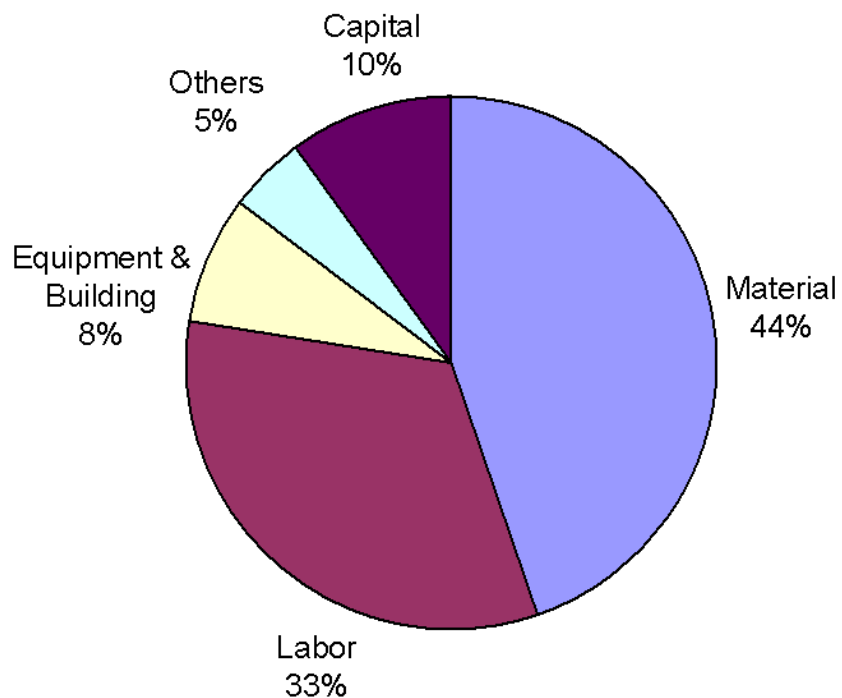


The membrane humidifier manufacturing process was based on discussions with PermaPure on their FC200-780-7PP Series™ of humidifiers.

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"

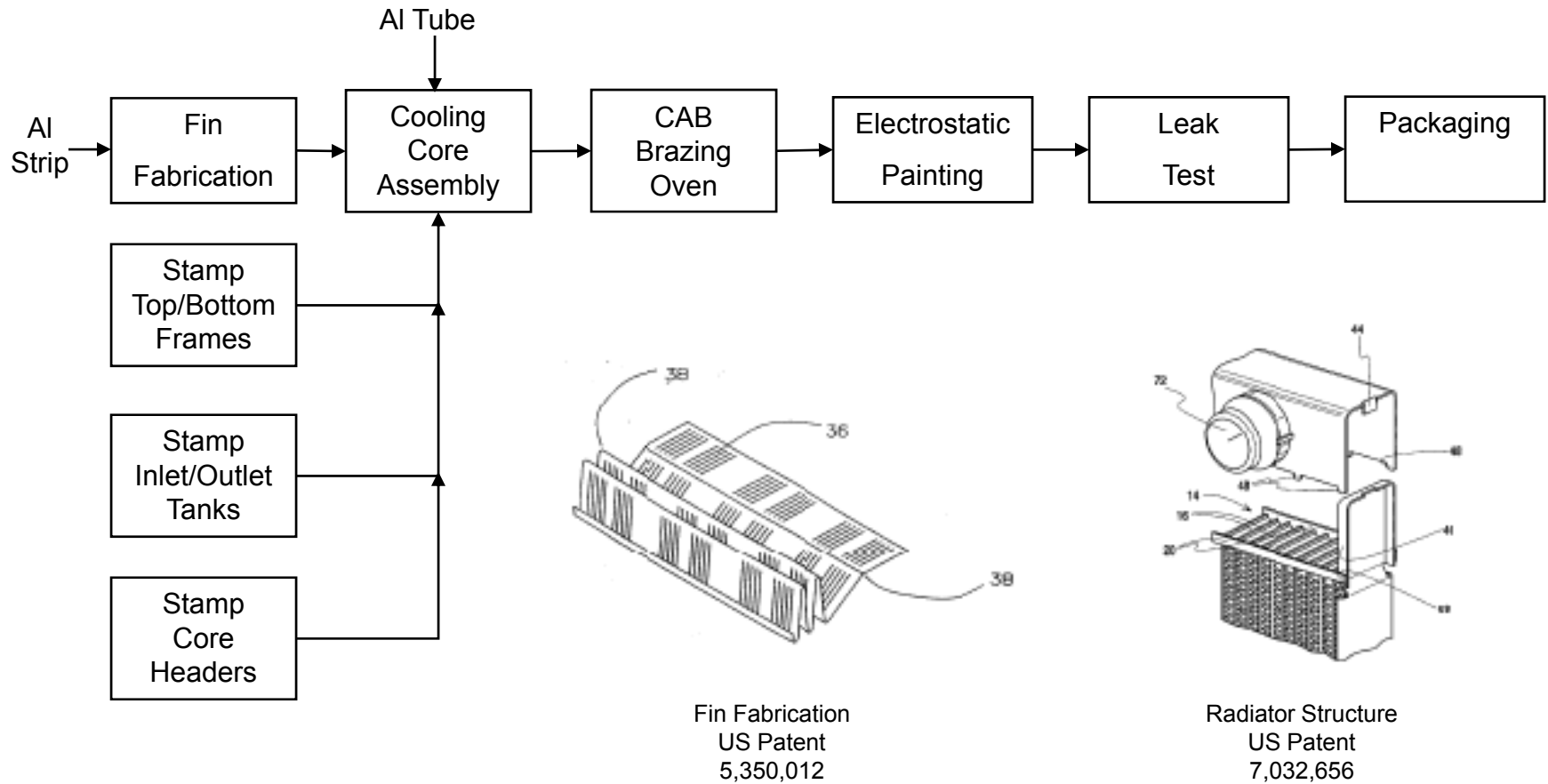
**Material costs represent approximately 44% of the membrane humidifier cost projection.**

**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
<b>Total</b>	-	<b>58</b>	

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

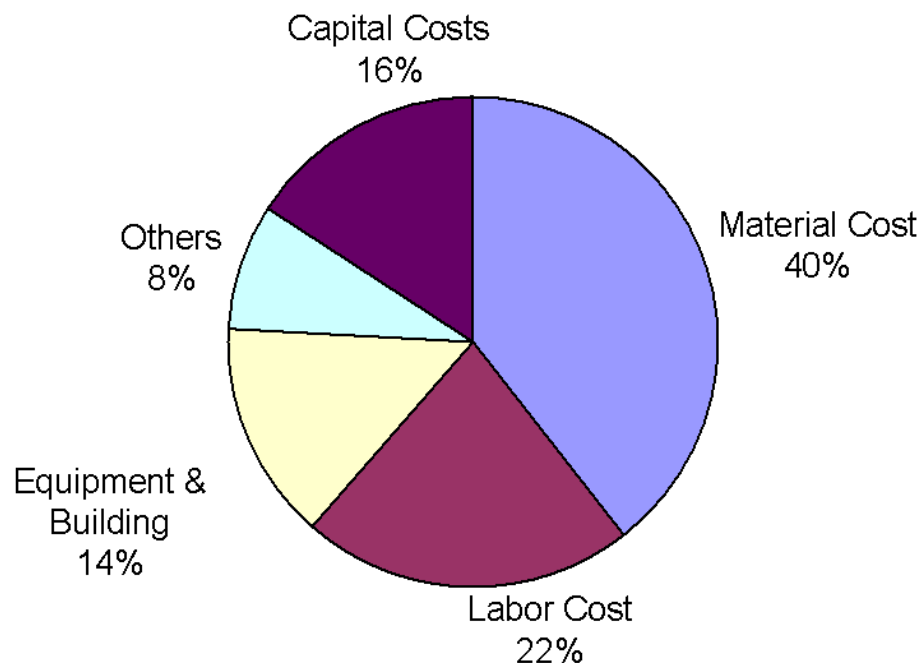


**We used a Modine all-aluminum automobile radiator structure as our baseline design.**

#	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

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 <sup>1</sup>
Radiator	56	65
Radiator Fan	-	35
Coolant Pump	-	120
<b>Total</b>	-	<b>220</b>

<sup>1</sup> 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.

