# Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications

## 2009 DOE Hydrogen Program Review
Arlington, VA
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Jayanti Sinha, Stephen Lasher, Yong Yang
TIAX LLC
Project ID # FC_31_Sinha

**TIAX LLC**
15 Acorn Park
Cambridge, MA
02140-2390

Tel. 617- 498-6125
**www.TIAXLLC.com**
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

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 PFSA membrane<br>➢ Bottom-up manufacturing cost analysis of both stack and BOP components<br>➢ Sensitivity analyses on stack and system parameters<br>◆ Independent peer review of cost analysis methodology and results |
| **2009** | ◆ Preliminary high-volume cost projection of ANL 2009 PEMFC system configuration assuming an NSTFC-based MEA and a 30 µm PFSA membrane<br>◆ Comprehensive report on the 2008 PEMFC cost analysis (high-volume, bottom-up stack and BOP cost) |

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

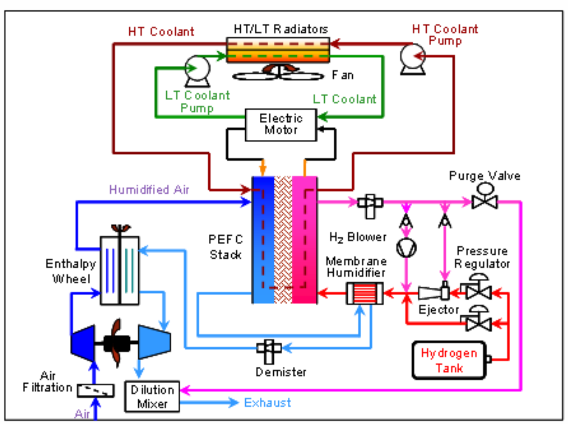
## Over the past year, we updated the PEMFC cost assessment based on input from ANL on the 2008 stack performance parameters.

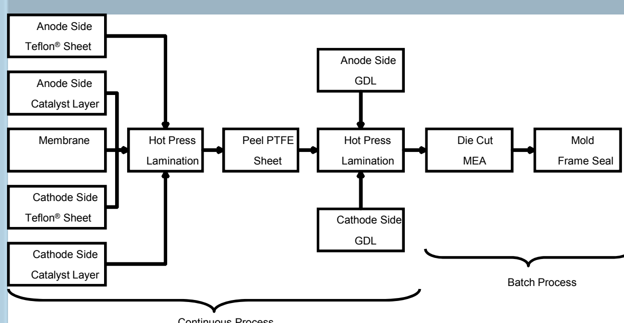
- In 2007, the PEMFC system configuration, materials, processes, performance assumptions and component specifications were updated
  - Developed bottom-up manufacturing cost models for *both* stack and BOP components
- In 2008, we updated key stack performance specifications, with no change to the system 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 μm 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/ precooler for cathode air humidification
  - Include LT radiator, LT coolant pump for air precooler, needle metering valve for CEM

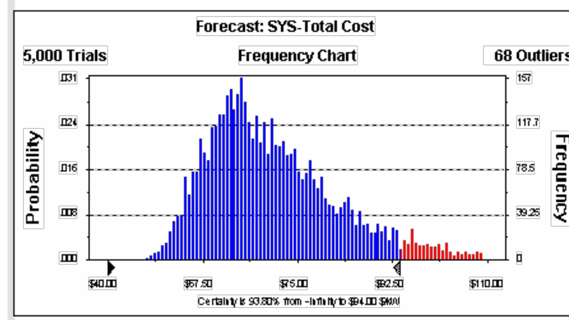
MEA = Membrane Electrode Assembly
EWH = Enthalpy Wheel Humidifier
PFSA = Perfluorosulfonic acid
NSTFC = Nano-Structured Thin Film Catalyst
MH = Membrane Humidifier

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

| Technology Assessment | Cost Model and Estimates | Overall Model Refinement |
| --- | --- | --- |
| • Perform Literature Search<br>• Outline Assumptions<br>• Develop System Requirements and Component Specifications<br>• Obtain Developer Input | • Develop Bulk Cost Assumptions<br>• Develop BOM<br>• Specify Manufacturing Processes and Equipment<br>• Determine Material and Process Costs | • Obtain Developer and Industry Feedback<br>• Revise Assumptions and Model Inputs<br>• 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.

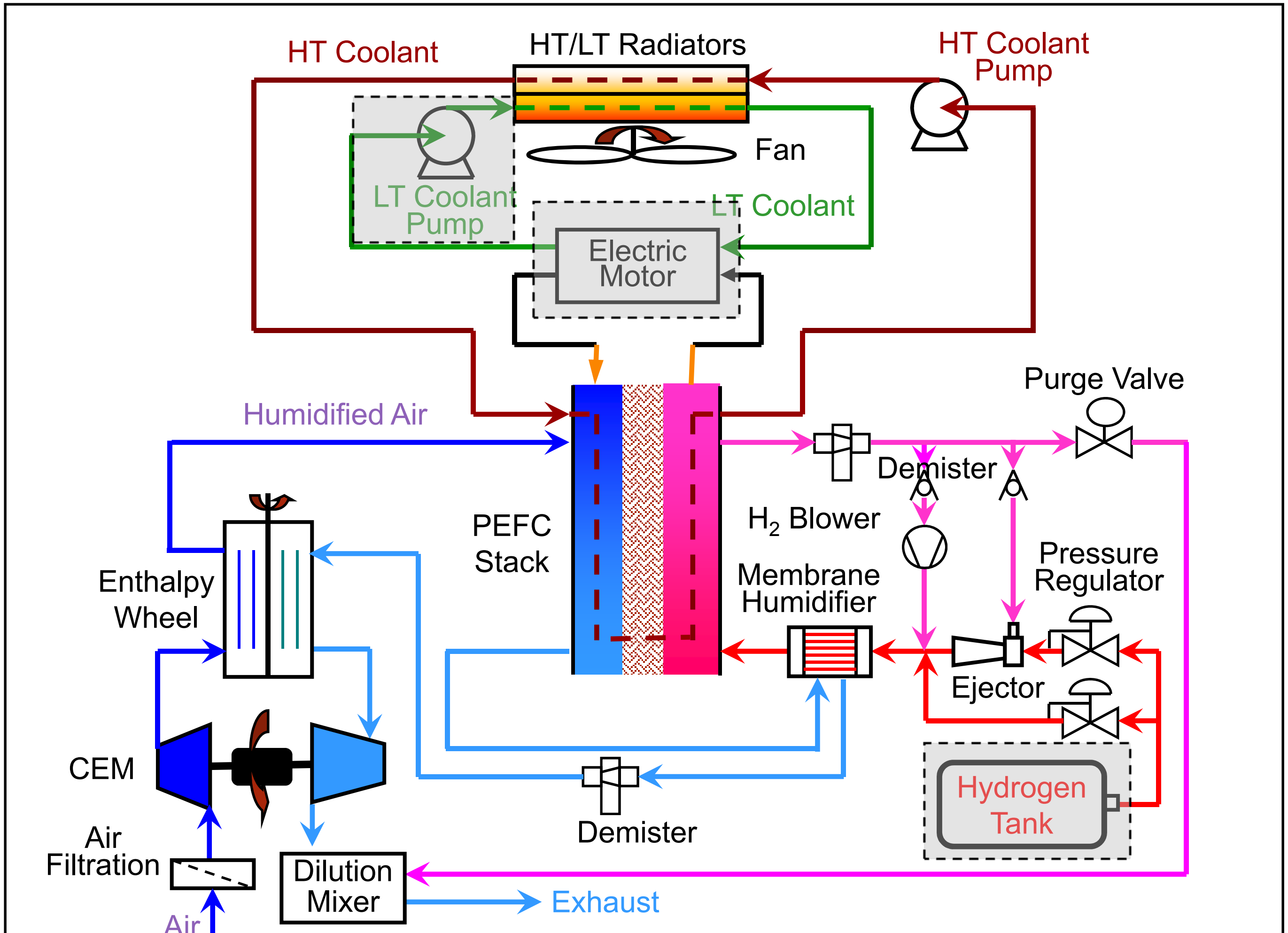
| Markup applied to BOP components | Factory Cost for Stack and BOP Components | |
|---|---|---|
| Corporate Expenses<br>• Research and Development<br>• Sales and Marketing<br>• General & Administration<br>• Warranty<br>• Taxes | Fixed Costs<br>➢ Operating<br>• Tooling & Fixtures Amortization<br>• Equipment Maintenance<br>• Indirect Labor<br>• Cost of operating capital (working period 3 months)<br>➢ Non-Operating<br>• Equipment & Building Depreciation<br>• Cost of non-operating capital | Variable Costs<br>• Manufactured Materials<br>• Purchased Materials<br>• Direct Labor (Fabrication & Assembly)<br>• Indirect Materials<br>• 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)

## 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

[1] 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 | BOP Components |
|---|---|
| • Catalyst Coated Membrane<br>• Electrodes<br>• Gas Diffusion Layer (GDL)<br>• Membrane Electrode Assembly (MEA)<br>• Bipolar Plates<br>• Seals | • Radiator<br>• Membrane Humidifier (MH)<br>• Enthalpy Wheel Humidifier (EWH)<br>• Compressor-Expander-Module (CEM)<br>• $H_2$ Blower |
| » Develop production process flow chart for key subsystems and components<br>» Obtain raw material prices from potential suppliers<br>» Estimate manufacturing costs using TIAX cost models (capital equipment, raw material costs, labor rates) | » Develop Bill of Materials (BOM)<br>» Obtain raw material prices from potential suppliers<br>» Develop production process flow chart for key subsystems and components<br>» 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.

## 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 $PtCo_xMn_y$ 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.

PFSA = Perfluorosulfonic acid

PR = Perylene Red

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

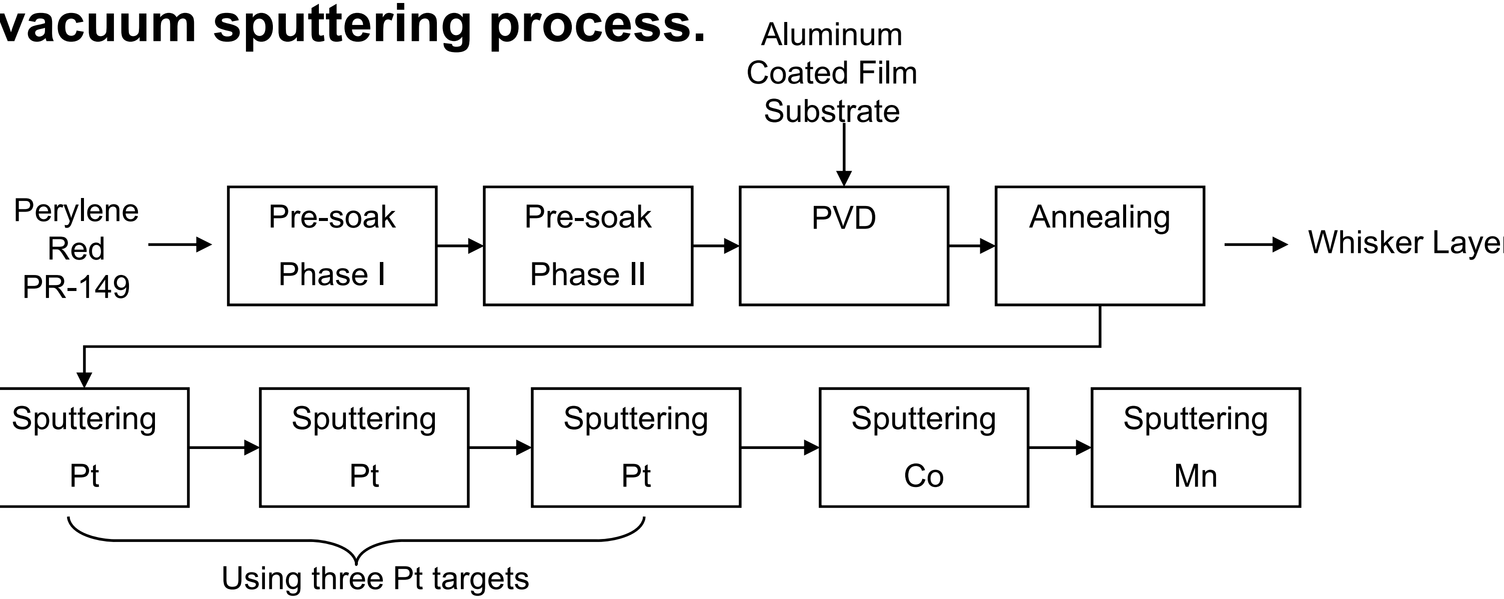
| Key Stack Performance Assumptions | | 2005[1] | 2007[2,3] | 2008[4] |
|---|---|---|---|---|
| Net power | $kW_e$ | 80 | 80 | 80 |
| Gross power | $kW_e$ | **89.5** | **86.4** | **86.9** |
| Gross power density | $mW/cm^2$ | **600** | **753** | **716** |
| Cell voltage (rated power) | V | 0.65 | 0.68 | 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 |

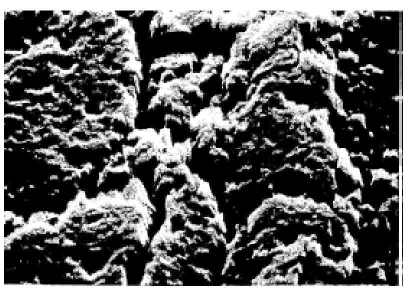
- Improvement over 2005 assumptions:
  - 67% reduction in Pt loading with an increase in power density
  - 40% thinner and less expensive membrane on an area basis
- Lower Pt loading is attributed to novel catalyst and support structure (i.e., nano-structured thin film on organic whisker support)

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

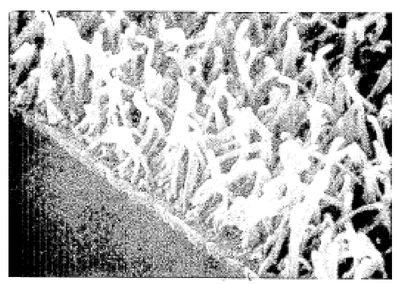
**Key assumptions in 2008 represent stack performance breakthroughs, in particular high power density with significant Pt reduction.**

# 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



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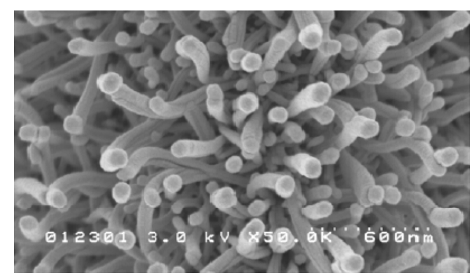
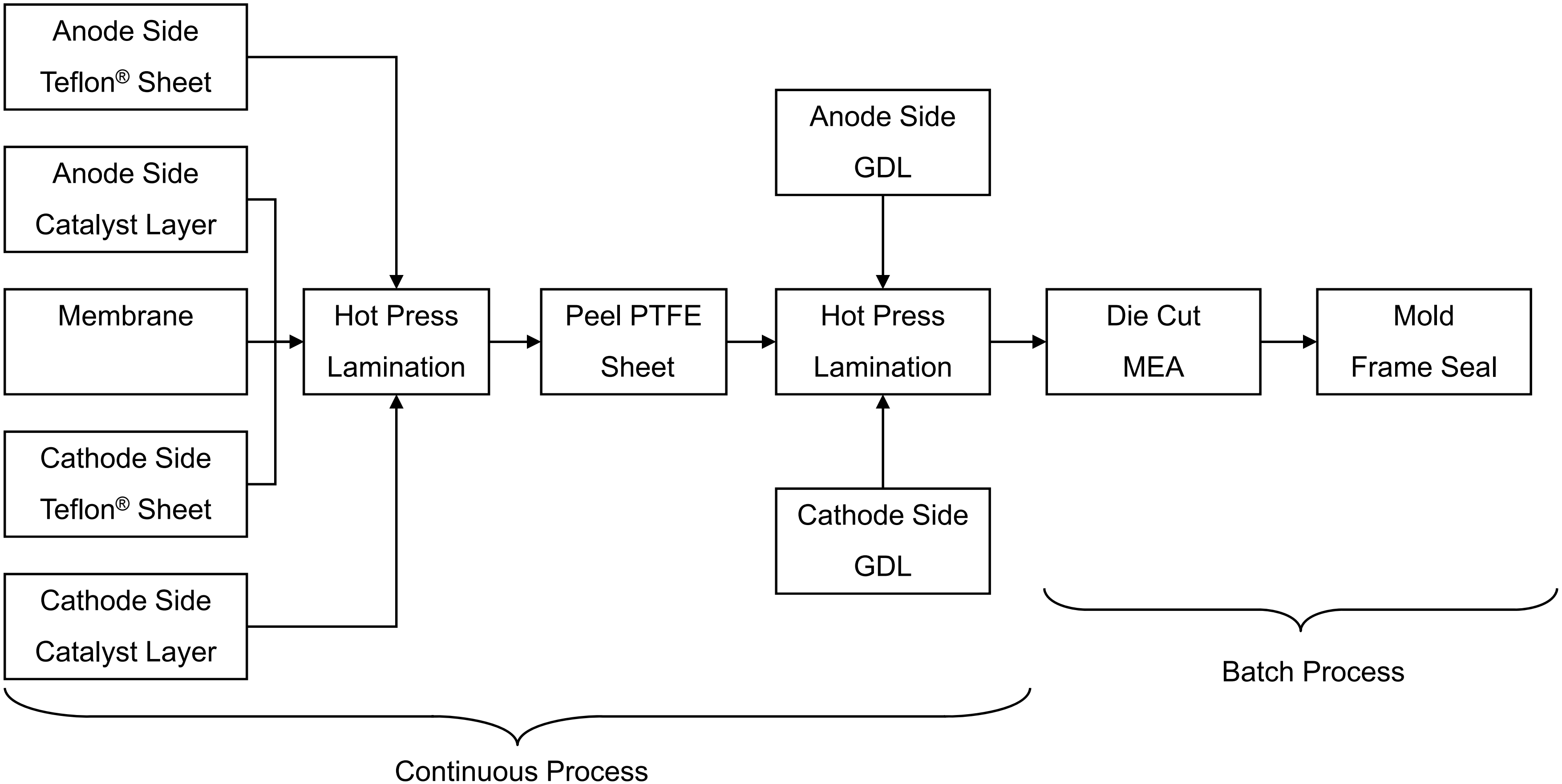



Nanostructured Thin Film Catalyst before transfer to a PEM[1]

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

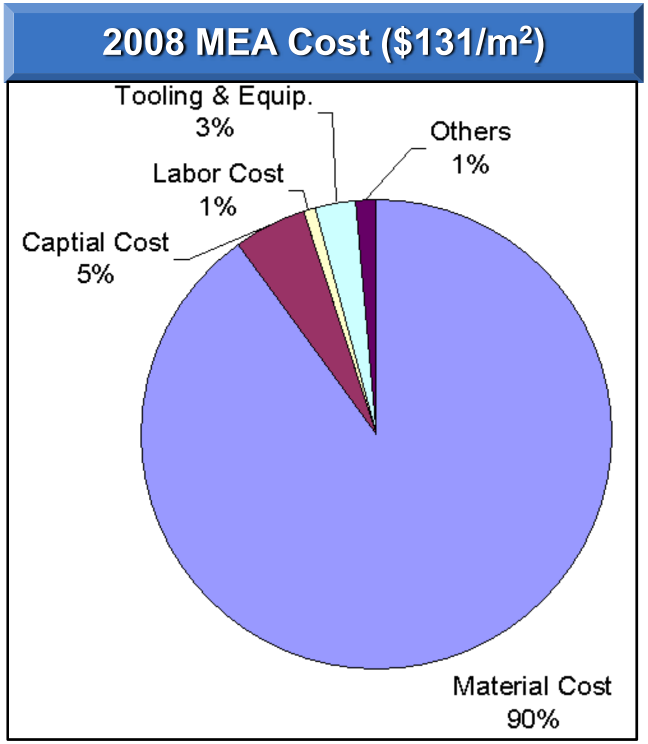
## The anode and cathode organic whisker layers were hot pressed to the membrane with Teflon® backing sheets.




## 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.

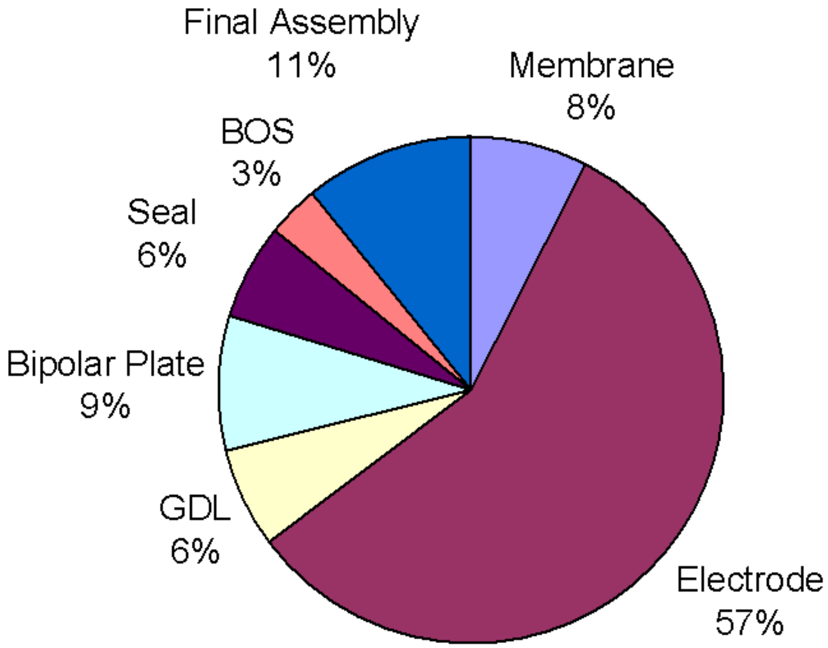
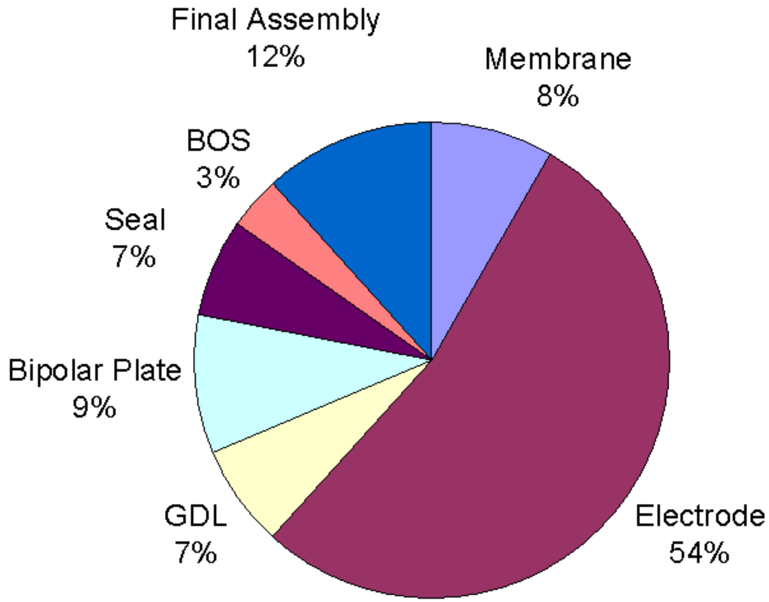
| Manufactured Cost | 2007 MEA[1] ($/m²) | 2008 MEA[1] ($/m²) |
|---|---|---|
| *Material*<br>*- Membrane*<br>*- Electrode*<br>*- GDL* | 135.48<br>- 13.89<br>- 109.61<br>- 11.98 | 117.71<br>- 13.83<br>- 91.90<br>- 11.98 |
| *Capital Cost* | 7.08 | 6.57 |
| *Labor* | 0.99 | 1.02 |
| *Tooling & Equipment*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




## 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).

[1] m² of active area and kW of net power
[2] 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-$H_2$ PEMFC | |
|---|---|
| 2007[1]: $31/kW, $2,480 | 2008[1]: $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

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

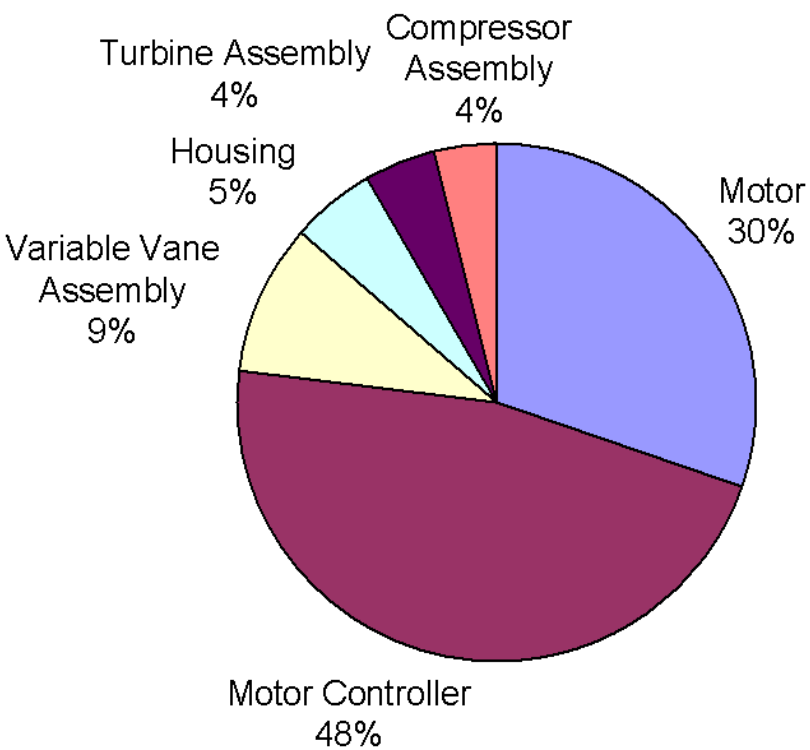
| Component | References |
|---|---|
| Overall System | Honeywell, DOE program review, progress report & annual report, 2005, 2004, 2003, 2000; US Patent 5,605,045 |
| Electrical Motor | Honeywell, DOE program review, progress report & annual report 2004; US Patent 5,605,045 |
| Motor Power Electronics | 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 |

HIP = Hot Isostatic Pressing

## 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

## 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[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

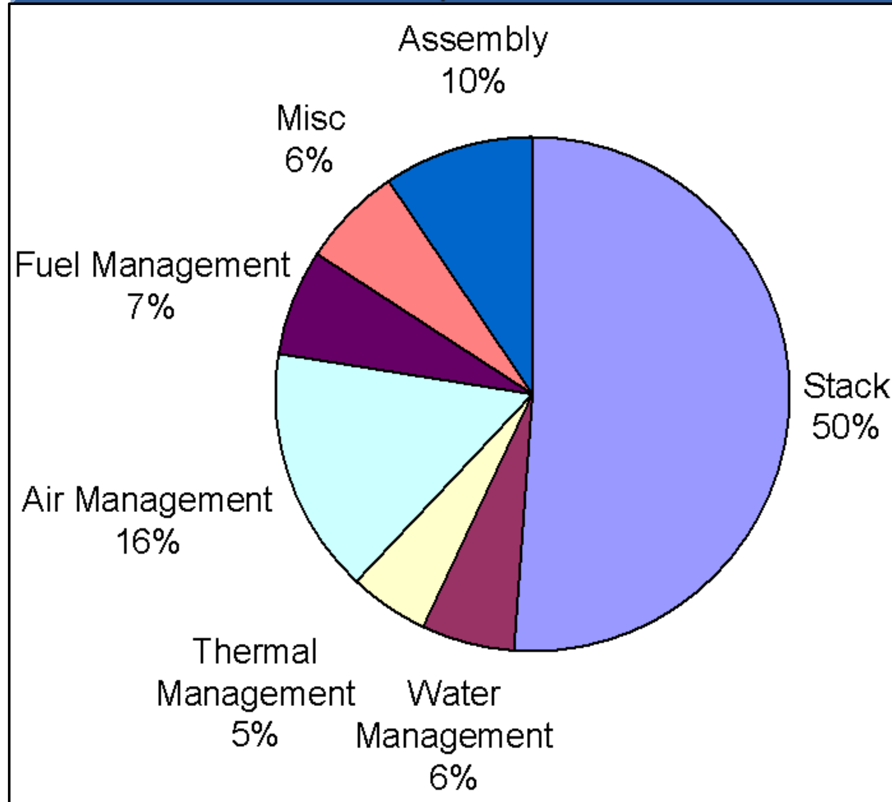
## The 2008 PEMFC stack and system costs are ~15-30% higher than the DOE 2010 cost targets of $25/kW and $45/kW respectively.

| PEMFC System Cost[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).

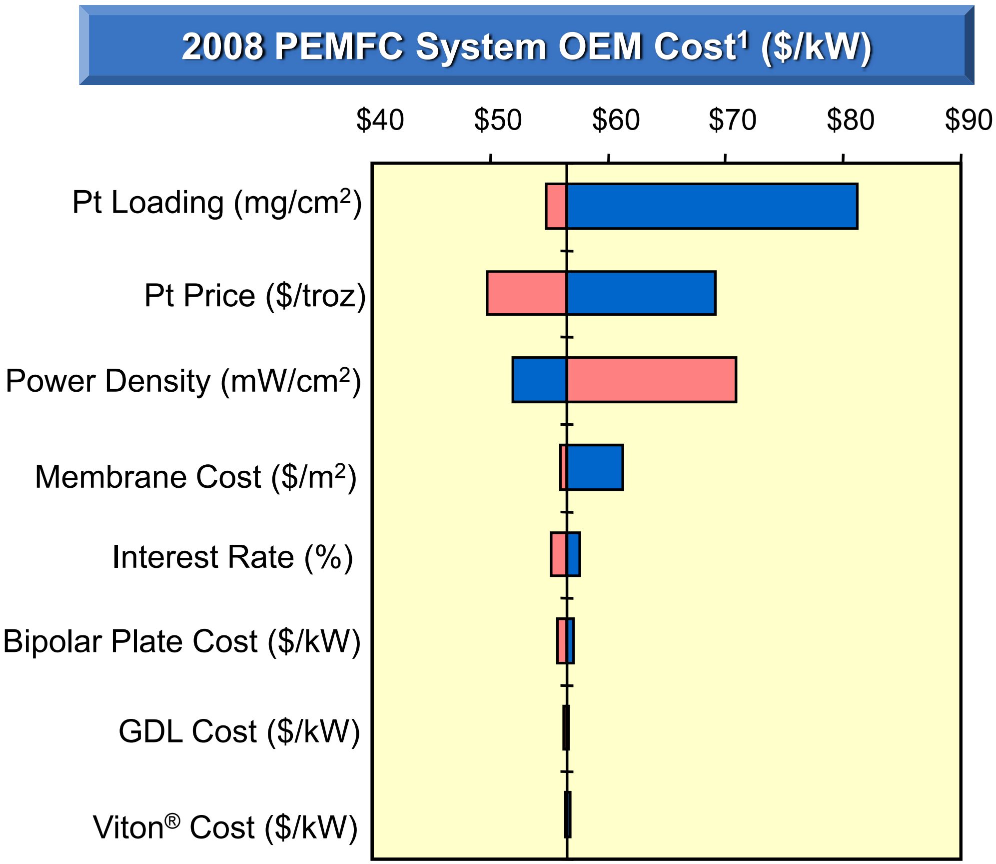
[2] Assumes 15% markup to the automotive OEM for BOP components

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




## 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[1].

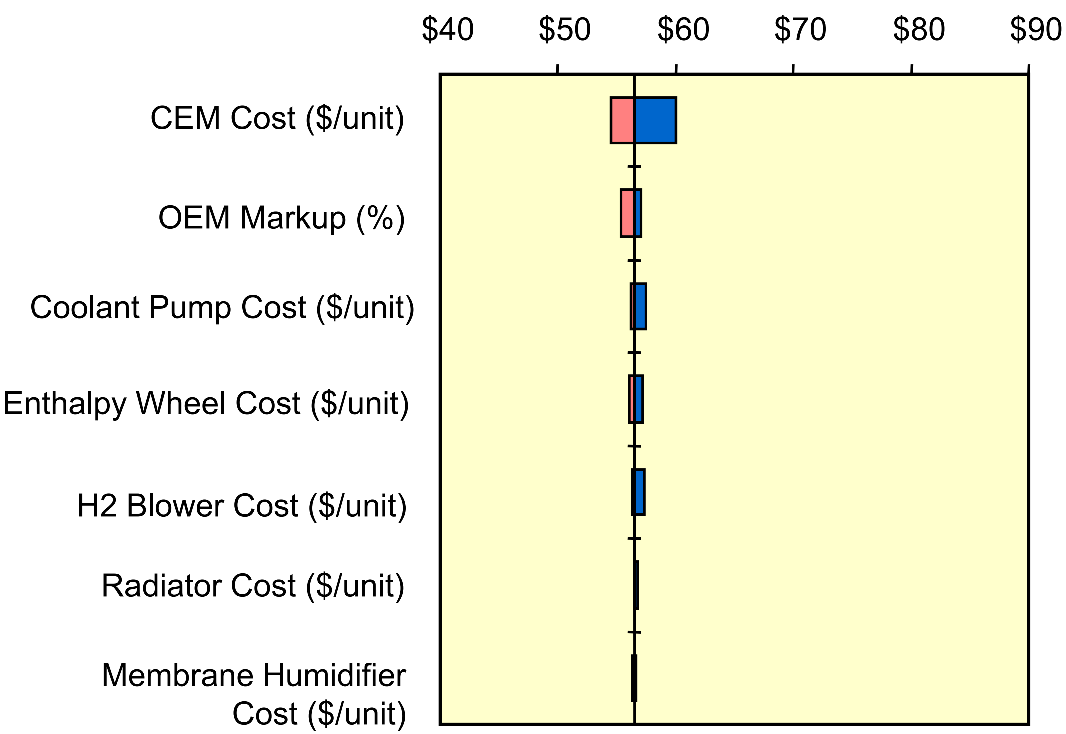



| # | Variables | Min. | Max. | Base | Comments |
|---|---|---|---|---|---|
| 1 | Pt Loading ($mg/cm^2$) | 0.2 | 0.75 | 0.25 | Minimum: DOE 2015 target[2]; Maximum: TIAX 2005 report[3] |
| 2 | Pt Cost ($/tr.oz.) | 450 | 2250 | 1100 | Minimum: ~ 108-year min. in 2007 $[4]; Maximum: 12-month maximum LME price[5] |
| 3 | Power Density ($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

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

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

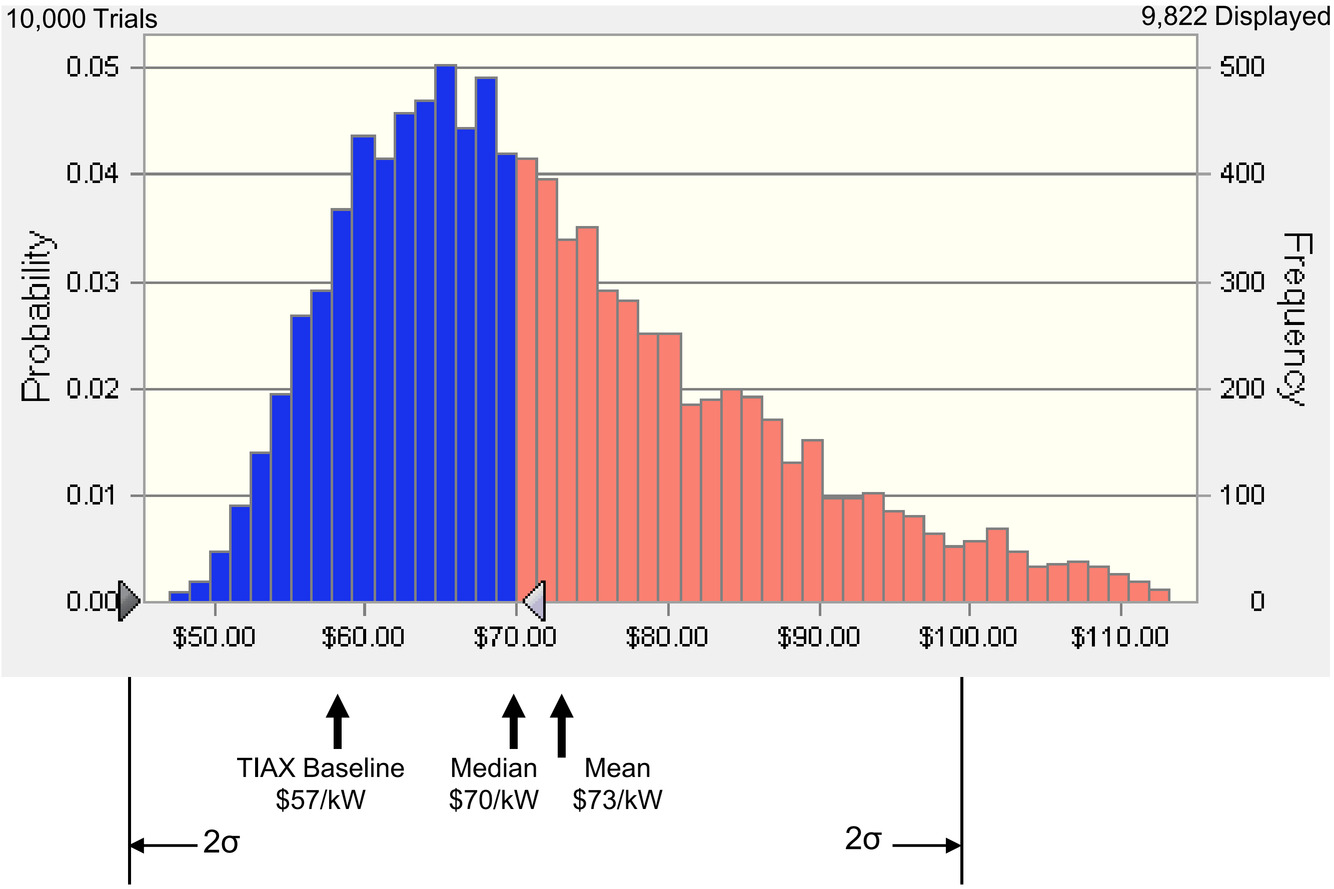



| # | Variables | Min. | Max. | Base | Comments |
|---|---|---|---|---|---|
| 1 | CEM Cost ($/unit) | 368 | 808 | 535 | Based on component single variable sensitivity analysis |
| 2 | OEM Markup | 5% | 20% | 15% | Based on industry feedback |
| 3 | Coolant Pump Cost ($/unit) | 80 | 200 | 120 | Based 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[1] ranges between $45/kW and $101/kW (± 2σ).

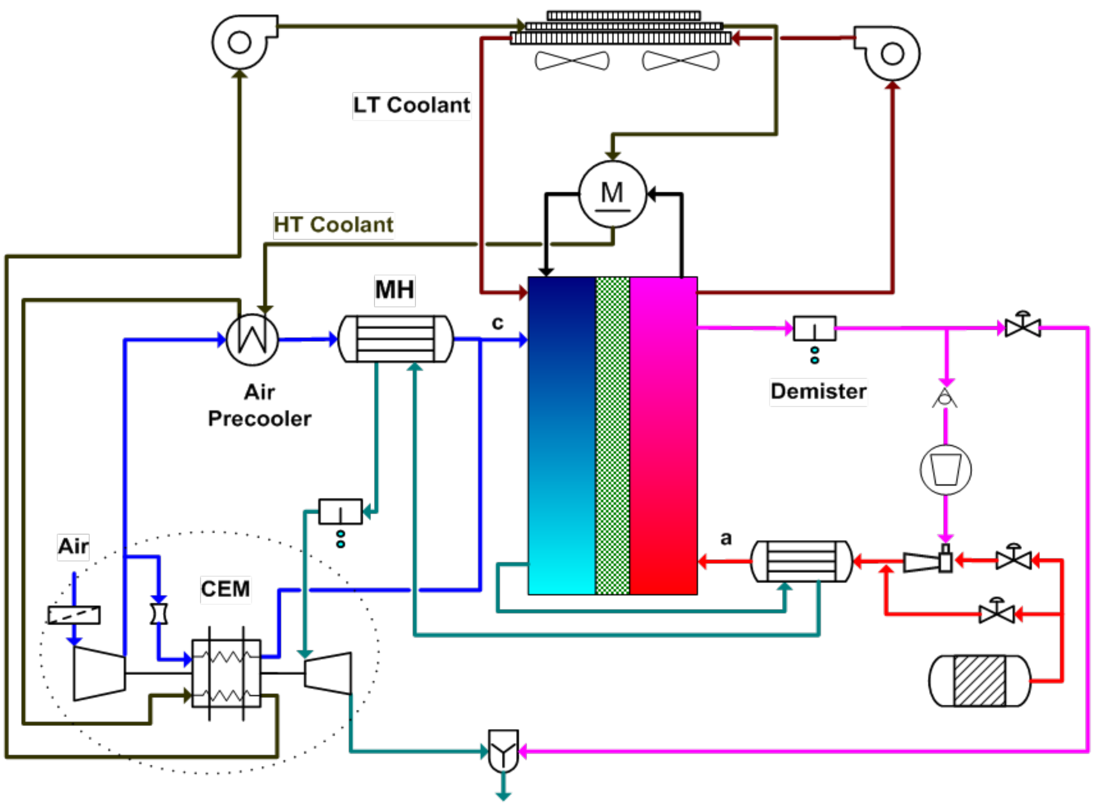
## 2008 PEMFC System OEM Cost[1] ($/kW)




| 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.

## **Future Work** 2009 ANL System




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 μm membrane
- 0.1(a)/0.15(c) mg/cm$^2$ Pt
- 90 °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[1, 2] ranges between $24/kW and $33/kW.

| Key Cost Assumptions | | 2009 Stack Scenarios[1, 2] | | |
|---|---|---|---|---|
| | | S1 | S2 | S3 |
| System net power | $kW_e$ | 80 | | |
| Stack gross power[2] | $kW_e$ | 91.6 | 92.0 | 92.5 |
| Cell voltage (rated power)[2] | V | 0.721 | 0.685 | 0.655 |
| Stack gross power density[2] | $mW/cm^2$ | 640 | 837 | 966 |
| Pt loading (total)[2] | $mg/cm^2$ | 0.25 | | |
| Stack efficiency (rated power)[2] | % LHV | 57.4 | 54.5 | 52.1 |
| System efficiency (rated power)[2] | % LHV | 50.0 | 47.3 | 45.0 |
| System voltage (rated power) | V | 300 | | |
| System active area | $m^2$ | 14.3 | 11.0 | 9.6 |
| **Stack cost[3]** | **$/kW$_{net}$** | **33** | **26** | **24** |

[1] 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.

[2] 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

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

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

- Key conclusions and accomplishments:
  - The 2008 stack and system costs[1] 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[1] 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)

[1] PEMFC net power (80 kW) basis

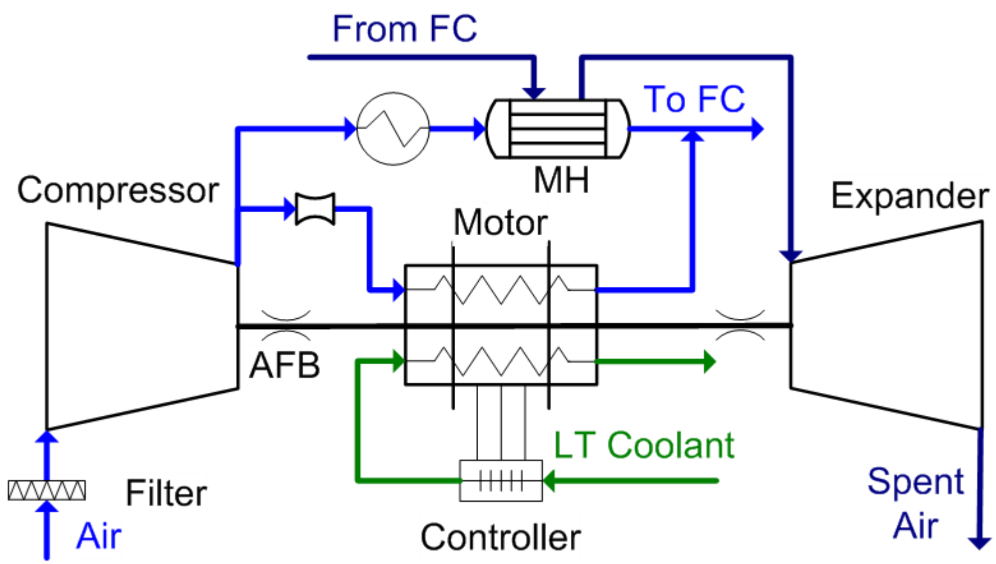
# Acknowledgement

Thank You

Questions?

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

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

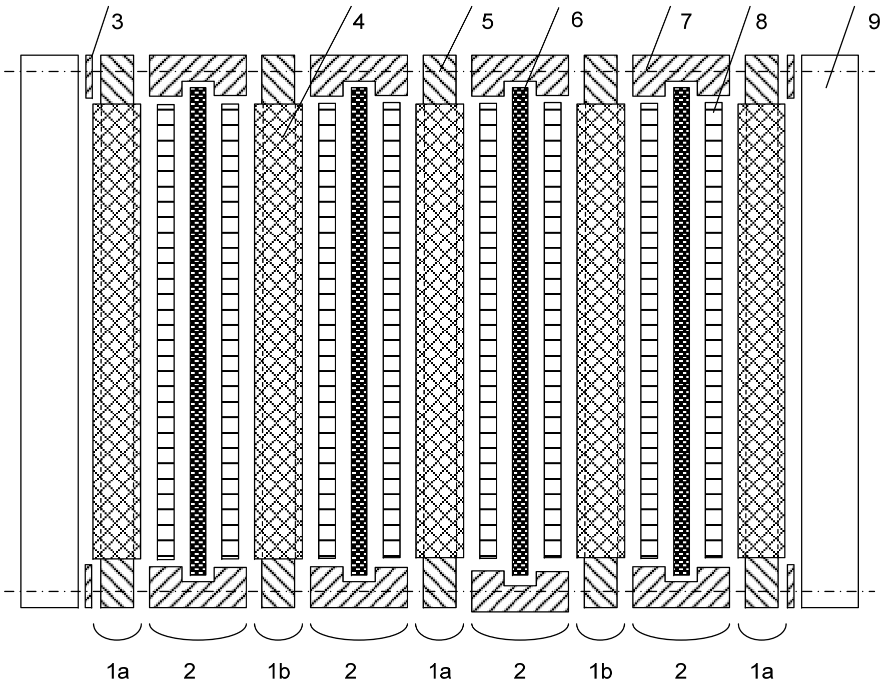



- Mixed axial flow compressor
- Variable nozzle turbine
- 3-phase brushless DC motor, liquid and air cooled
- Motor controller, liquid cooled
- Air foil bearing (AFB)
- Efficiencies at rated power: 70% compressor, 73% expander, 86% motor, 87% controller

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

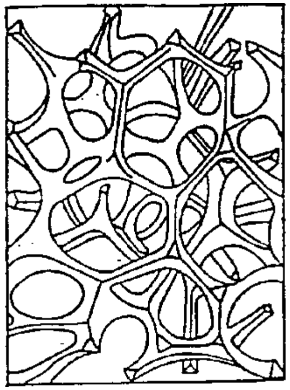
CEM = Compressor Expander Motor
MH = Membrane Humidifier
AFB = Air-foil Bearing
LT = Low-Temperature

# We are developing bottom-up manufacturing costs for the planar membrane humidifier based on ANL specifications[1] 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

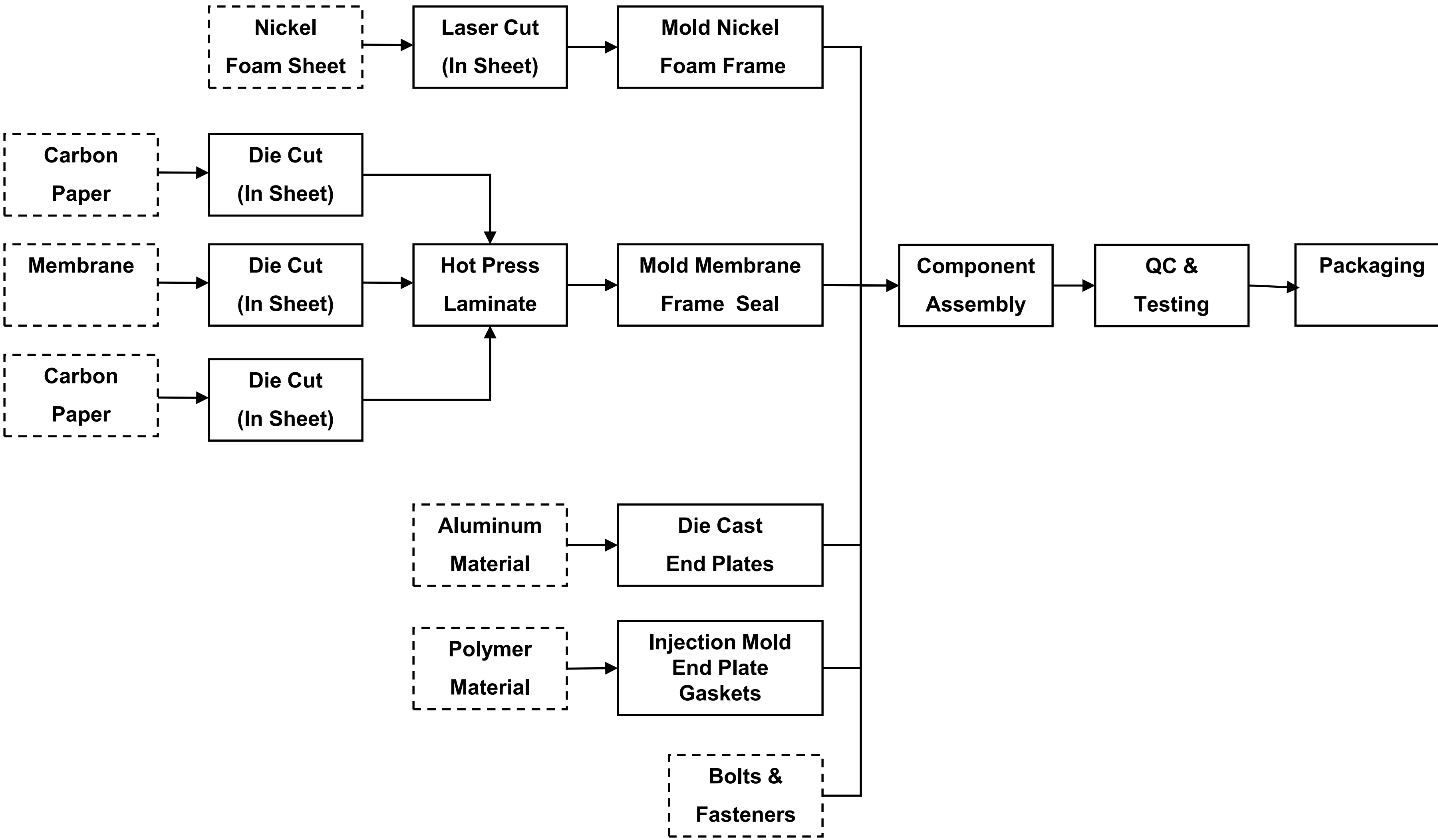
- Referenced Patents
  - U.S. Patent 6,737,183 (Nuvera)
  - U.S. Patent 6,835,477 (Nuvera)
  - U.S. Patent 6,864,005 (Ballard)
  - U.S. Patent 7,078,117 (Ballard)



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

[1] 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[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)<br>Pt loading decreased from 0.75 $mg/cm^2$ (2005), to 0.3 $mg/cm^2$ (2007), to 0.25 $mg/cm^2$ (2008)<br>Woven carbon fiber cost decreased from $30/kg (2005) to $20/kg (2007 & 2008)<br>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).

[1] Manufactured cost on an active area basis

# 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 ($/m²) | Process Cost ($/m²) | Total Cost ($/m²) | Unit Cell Weight/Area (g/cm²) | | | | | |
| 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

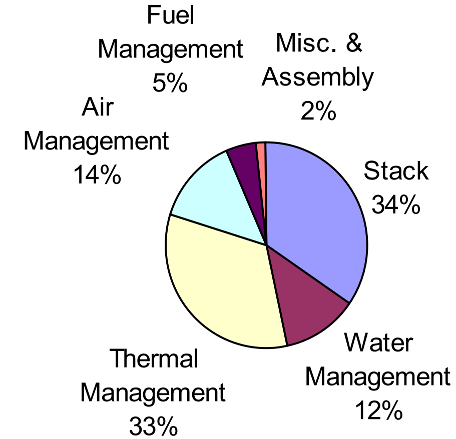
[2] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

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

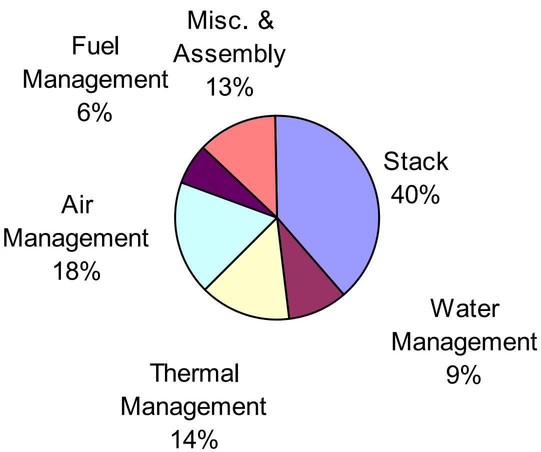
| PEMFC Sub-System | Volume[1] (L) | Weight (kg) | DOE 2010 Target |
|---|---|---|---|
| **Stack** | **41** | **44** | |
| Power density[1,2] ($W_e$/L) | 1,940 | | 2,000 |
| Specific power[2] ($W_e$/kg) | 1,803 | | 2,000 |
| **Balance of Plant** | **79** | **71** | |
| Water management (enthalpy wheel, 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

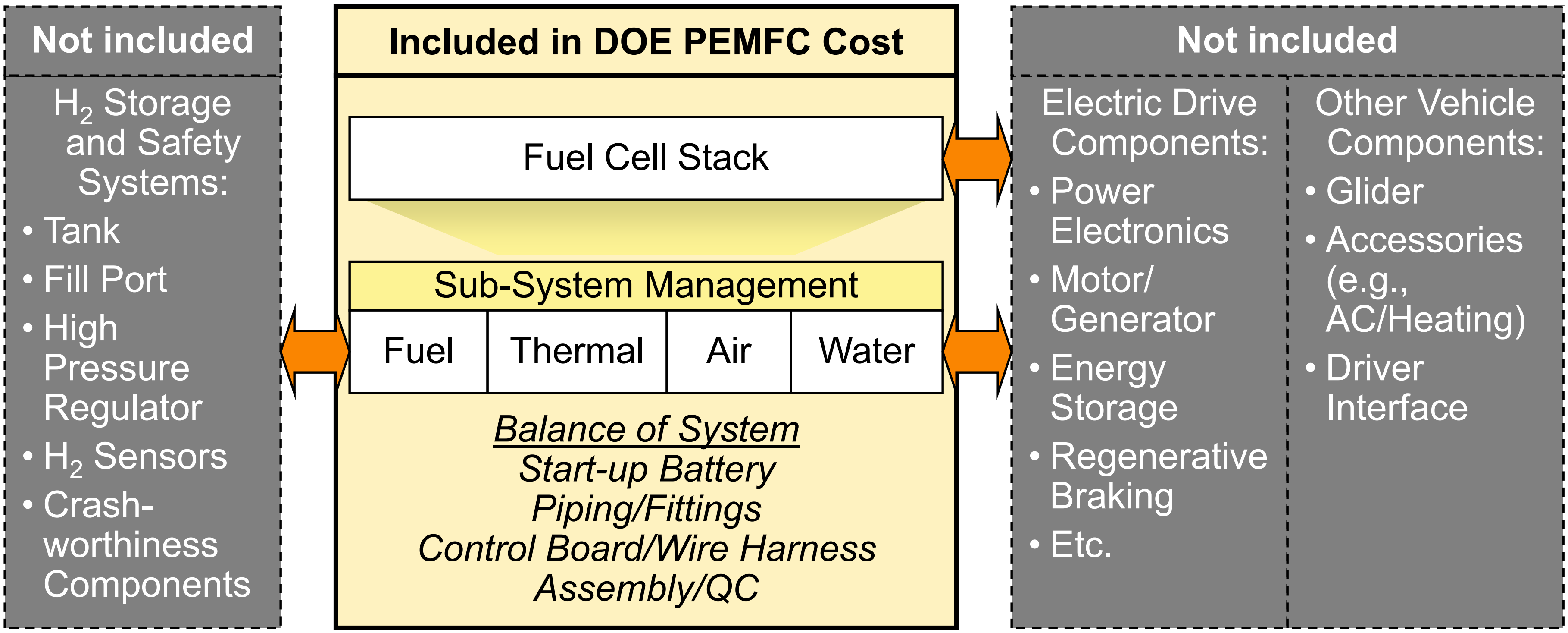
**2008 PEMFC System Volume (120 L)**




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



## 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.

**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.

## 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 |
|---|---|
| **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, $\gamma$-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 ($H_2$ blower, $H_2$ ejectors) | SS316 bar, SS316 sheet, seals, $H_2$ blower motor, $H_2$ ejectors |

# 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 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 | $cm^2$ | 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 |

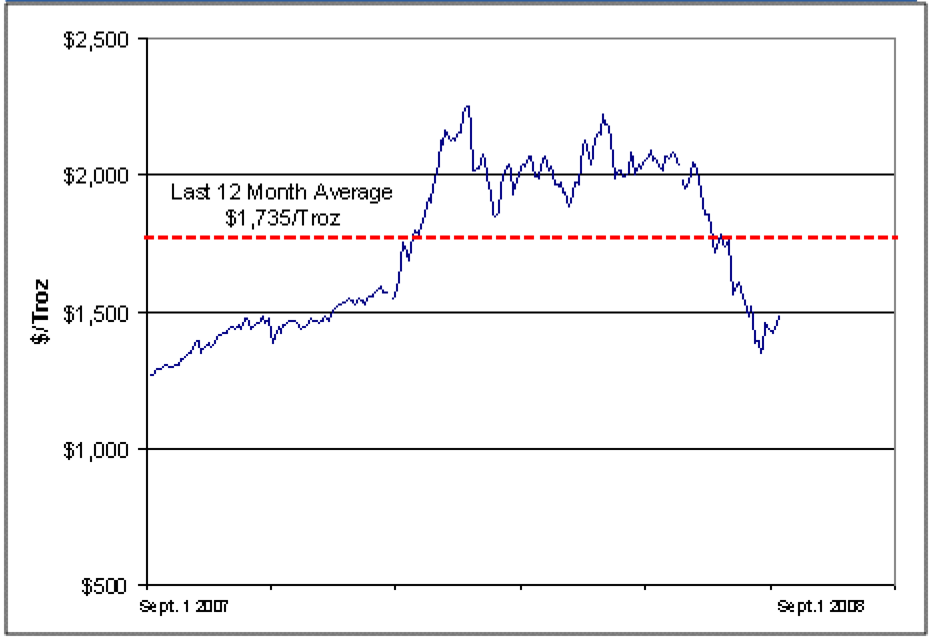
[1] E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104

# 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**



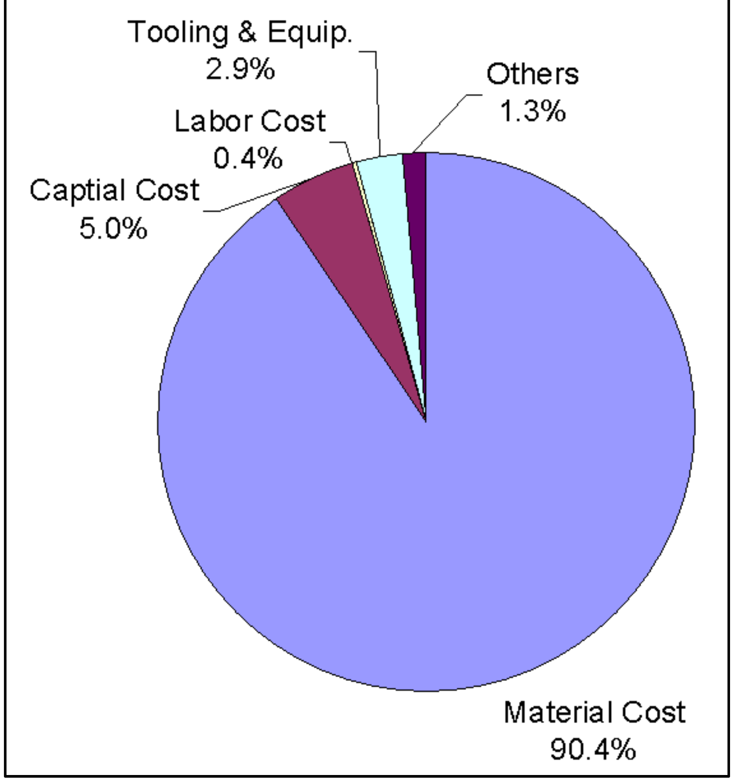

## The Pt price averaged over the 12 month period from Sep 2007 to Sep 2008 is ~ $1,735/tr.oz.

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

| Manufactured Cost | Anode[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)**



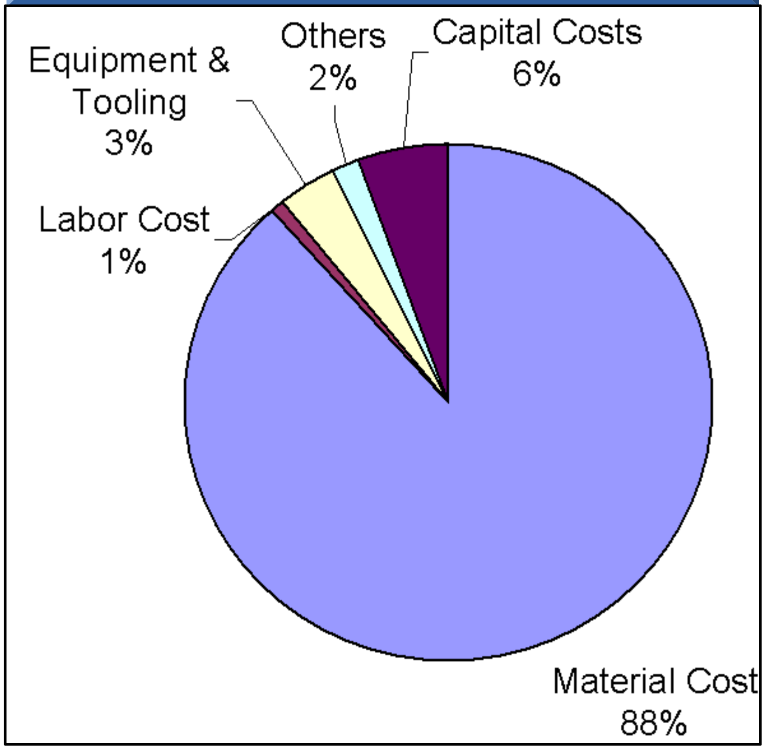

## Platinum at $1,100/tr.oz. is close to the average price ($1,059/tr.oz.) over the last five years.

## The estimated membrane cost on an active area basis is $16/m², with material cost representing about 88% of the total cost.

| Membrane Manufactured Cost[1] | | | | |
|---|---|---|---|---|
| Component | Material | | Process | |
| | ($/m²) | ($/kg) | ($/m²) | ($/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 ($/m²)** | | | |
| | **340.85 ($/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/m²)**



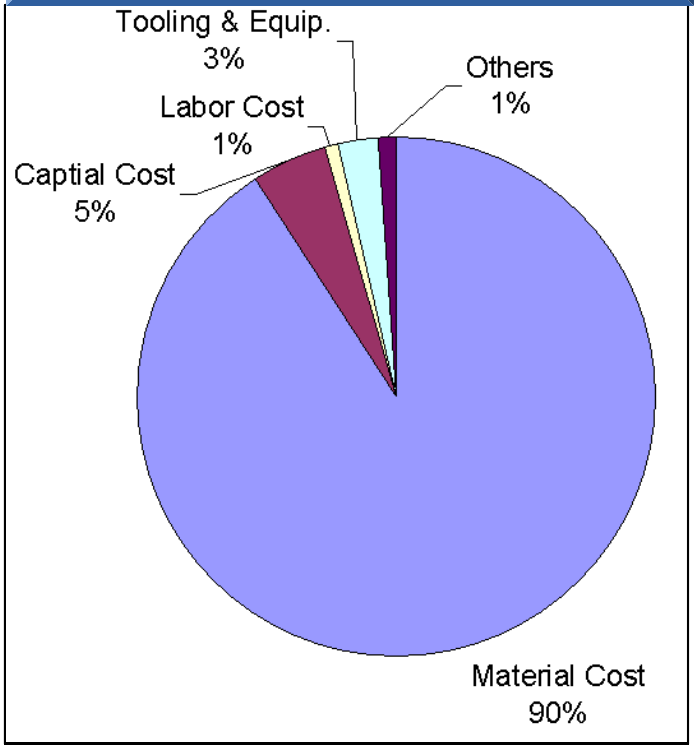

## In 2005, the membrane cost was $23/m² due to higher material costs (2 mil) and higher process costs (double pass required for coating).

# On an active area basis, the MEA and seal together cost $140/m$^2$.

| Manufactured Cost[1] | MEA ($/m$^2$) | Frame Seal ($/m$^2$) |
|---|---|---|
| *Material*<br>*- Membrane*<br>*- Electrode*<br>*- GDL* | 117.71<br>- 13.89<br>- 91.90<br>- 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

**MEA Manufactured Cost ($140/m$^2$)**

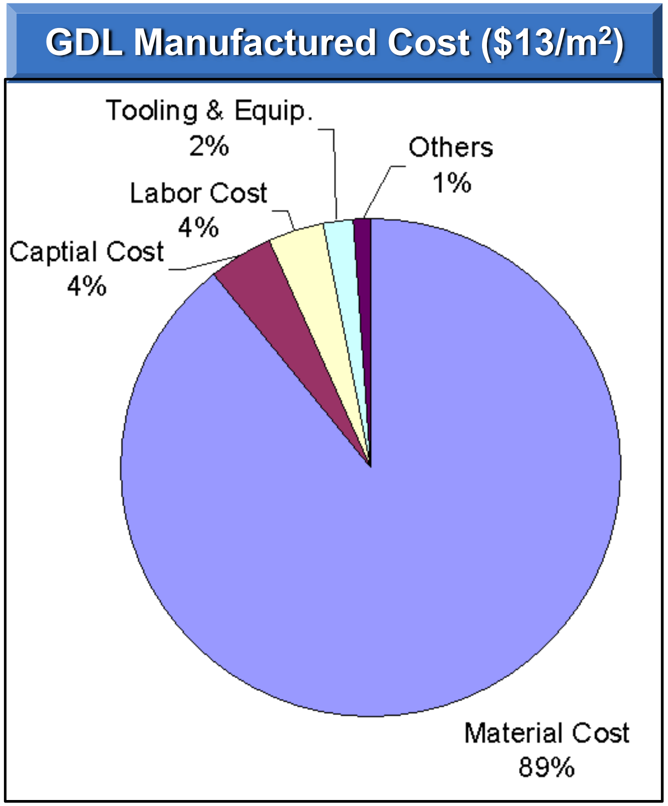



## In 2005, the MEA and seal cost was $325/m$^2$ due to higher material costs for the membrane (2 mil), electrodes (Pt loading = 0.75 mg/cm$^2$) and GDL (woven carbon fiber = $30/kg).

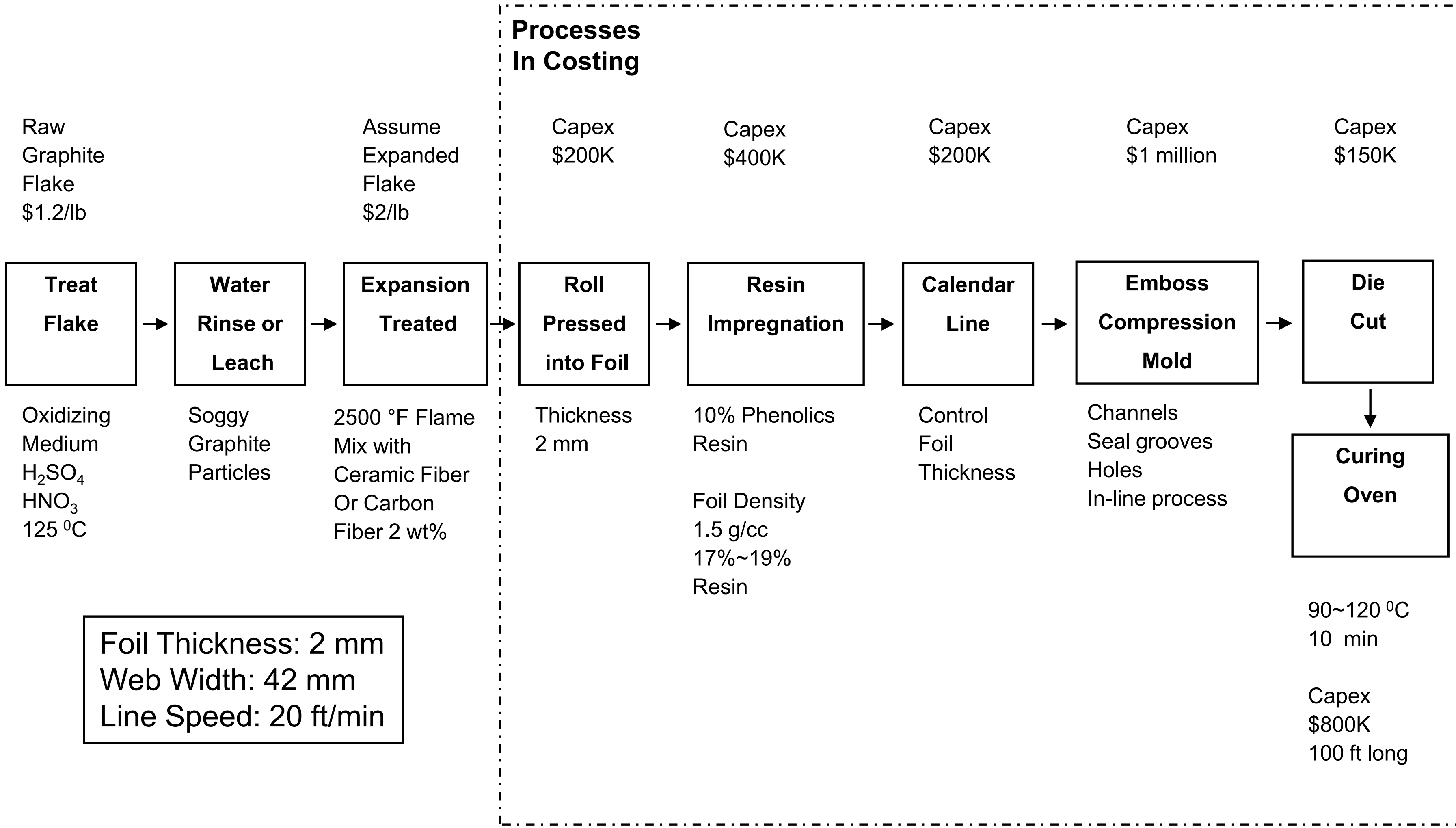
# The anode GDL has the same cost as the cathode GDL, of ~ $13/m^2$.

| 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



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

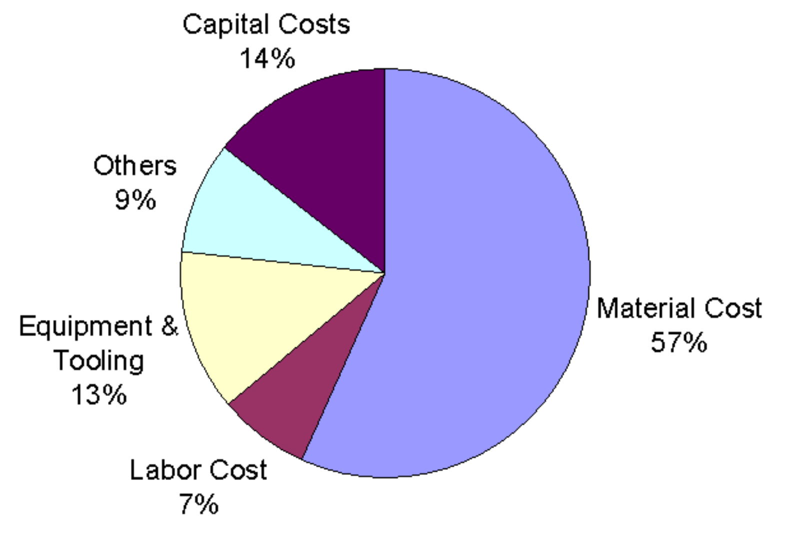


# We estimate the expanded graphite foil bipolar plate cost is $18/m² at high volume.

| 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)**

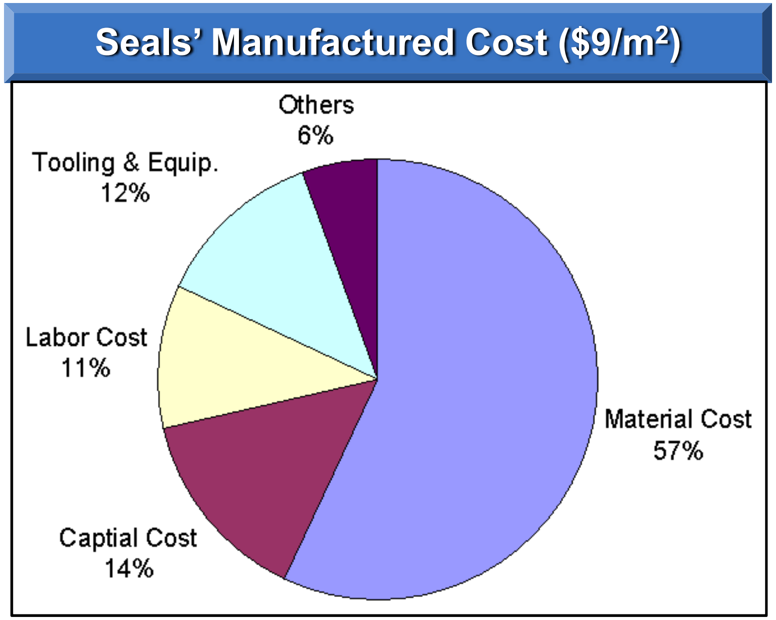



# We assumed a raw graphite flake cost of $1.2/lb and expanded graphite flake cost of $2/lb.

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

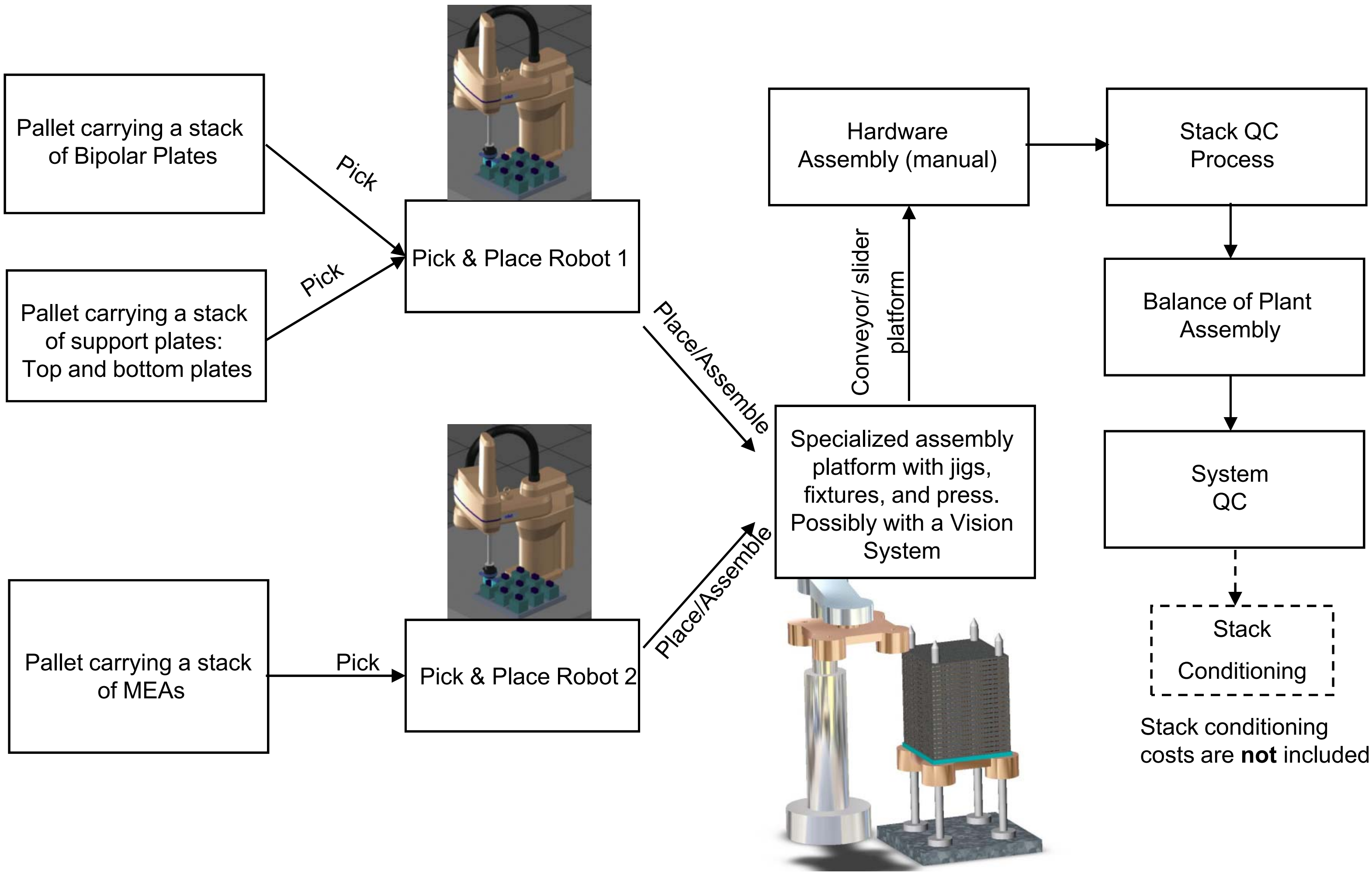
| Manufactured Cost[1] | Seals ($/m²) |
|---|---|
| *Material* | 5.03 |
| *Capital Cost* | 1.27 |
| *Labor* | 0.93 |
| *Tooling* | 1.10 |
| *Other*[2] | 0.50 |
| ***Total*** | **8.83** |

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

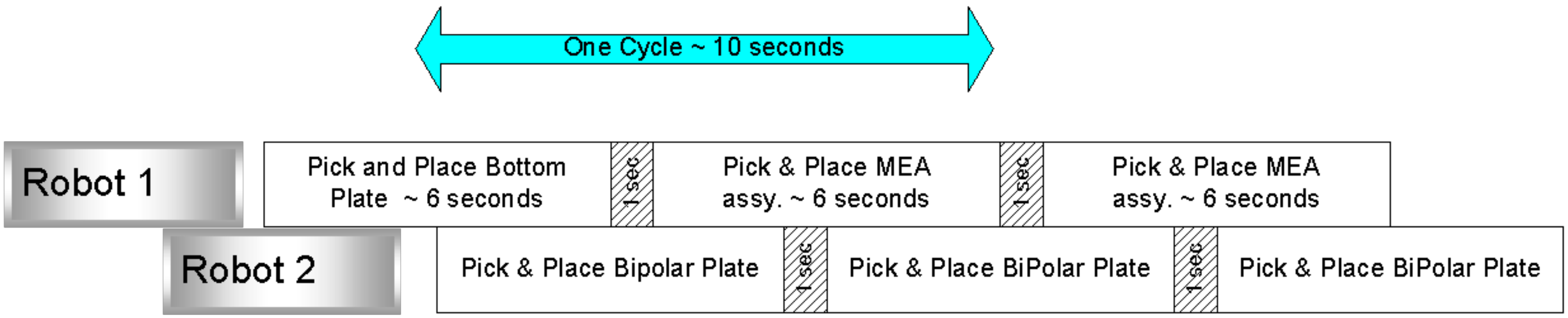



## The seal material is Viton® which costs about $20/lb.

# 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 |
|---|---|---|
| **Pick & place a single repeat unit** | ~ 10 seconds | Based on two robot setup |
| **Assemble a single stack** | ~ 38 mins. | For 220 MEAs and bipolar plates |
| **Assemble balance of stack (BOS)** | ~ 10 mins. | BOS includes endplates, endplate insulators, outer wrap, stack manifold, current collectors, tie bolts |
| **Stack quality control** | ~ 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.

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

Courtesy: Honeywell, DOE Merit Review 2003

CEM Motor Rotor Manufacturing Process

[1] Boothroyd Dewhurst Machining package

# 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** |

# 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 | $40/kW from "A Novel Bidirectional Power Controller for Regenerative Fuel Cells", Final Report for DE-FG36-04GO14329, J. Hartvigsen and S.K. Mazumder, Oct. 10, 2005 |
| | Packaging, Wire harness, thermal management, etc | 31 | |
| **Total Motor Cost ($/unit)** | | **412** | |

## 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 $H_2$ 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; Turing; Milling; Broaching |
| 8 | Vane | SS316 | Hot forging; Drilling; Reaming |

**The major manufacturing processes for selected components of the $H_2$ blower are tabulated above.**

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

Automatic Sand Casting → Machining Lathe → Machining CNC Mill

**Machining Lathe:**

- 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)

**Machining CNC Mill:**

- 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

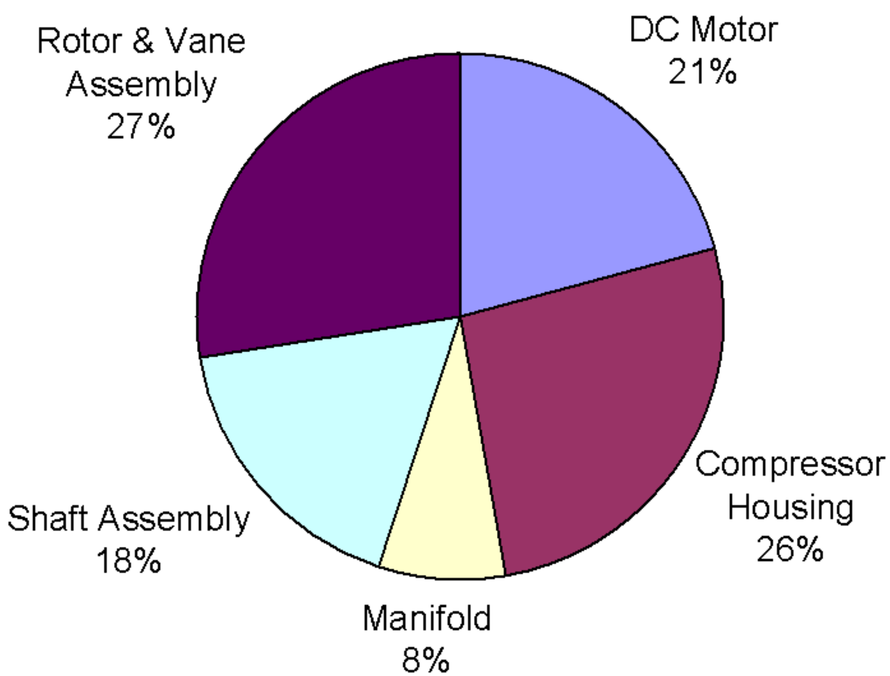
[1] Boothroyd Dewhurst Concurrent Costing & Machining packages

# 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)**

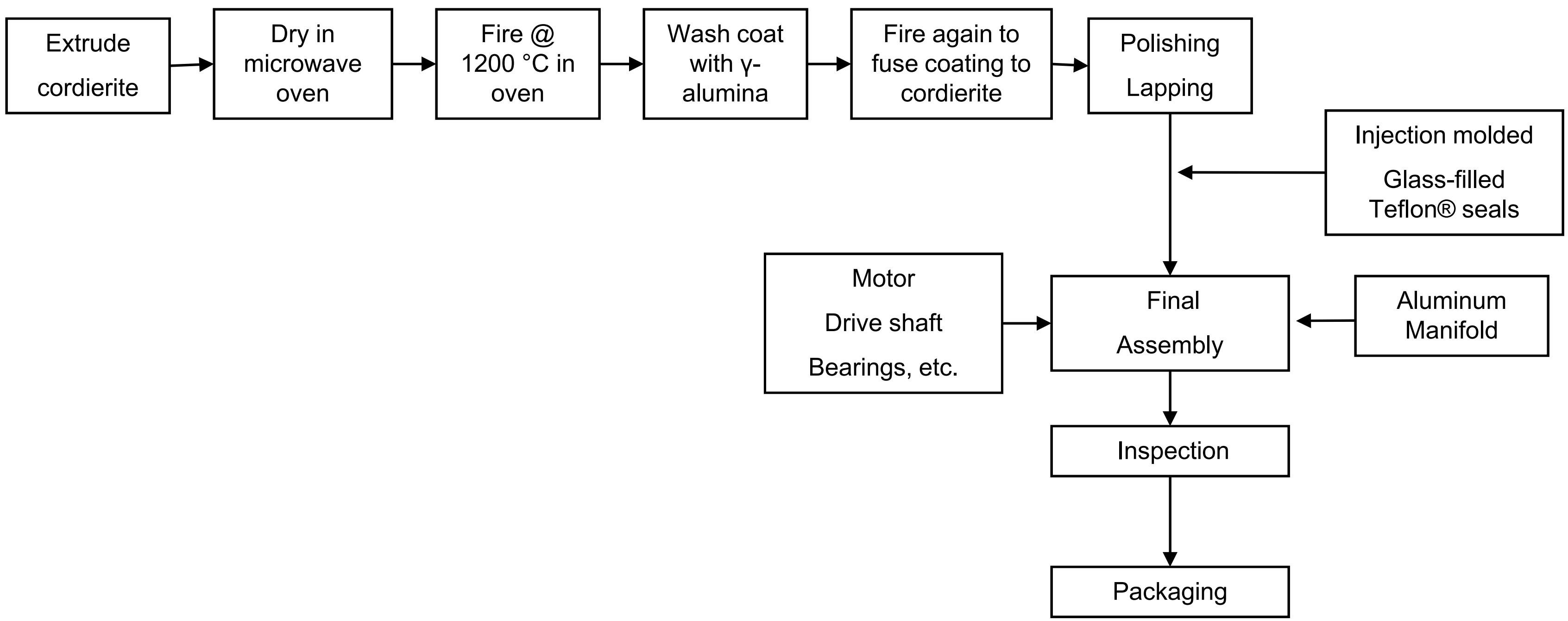



| $H_2$ Blower Manufactured Cost ($) | | |
|---|---|---|
| **Component** | **Factory Cost** | **OEM Cost[1]** |
| DC Motor | 40 | **222** |
| Blower Housing | 51 | |
| Manifold | 15 | |
| Shaft Assembly | 34 | |
| Rotor & Vane Assembly | 53 | |
| **Total:** | **193** | |

[1] Assumes 15% markup to the automotive OEM

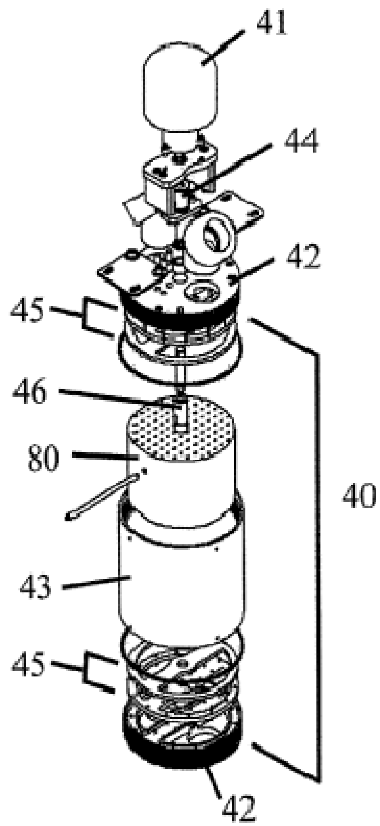
# We assumed that the material for the blower housing is stainless steel 316.

## 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.

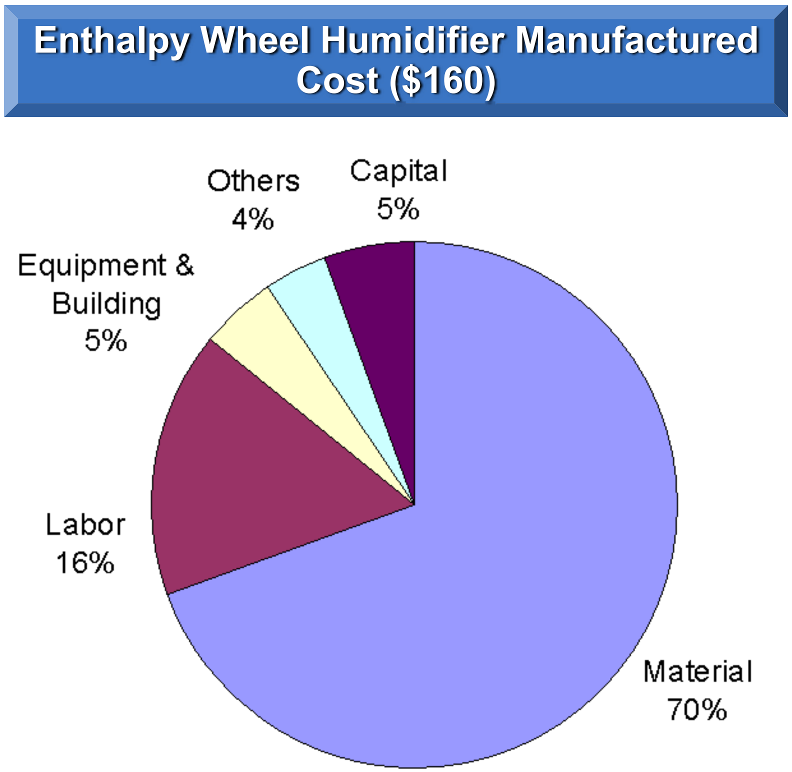
# The enthalpy wheel bill-of-materials was deduced from Emprise patents, white papers and personal communications.




US Patent 2002/0071979

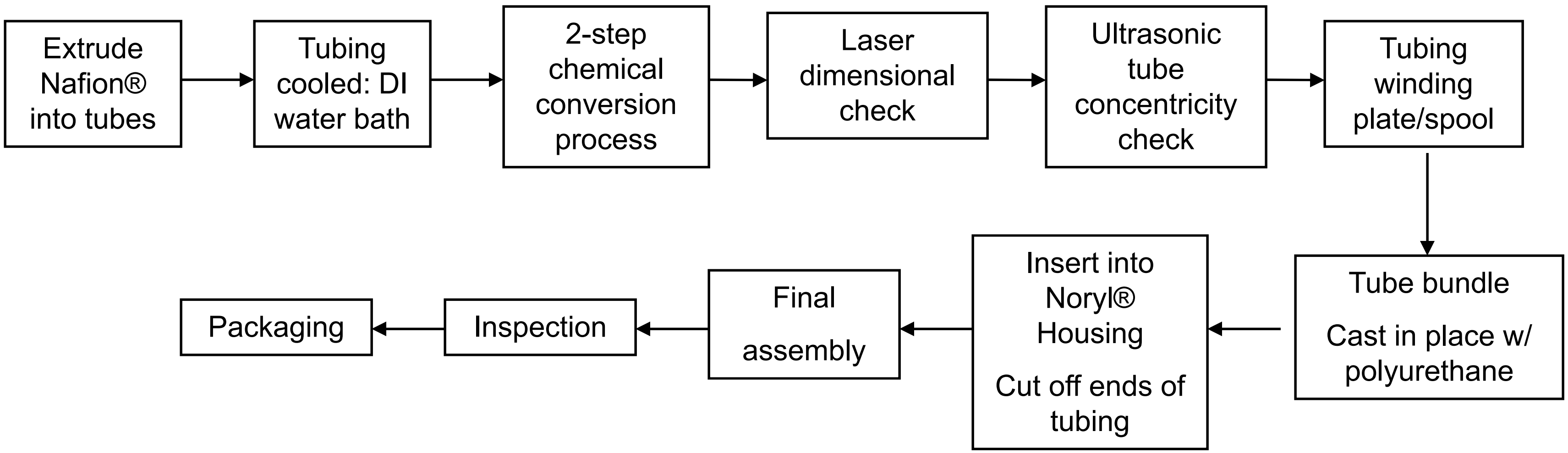
| Enthalpy Wheel Humidifier | | | |
|---|---|---|---|
| **Component** | **#** | **Material** | **Size** |
| 30 We DC motor with gear box | 1 | Misc. | Φ3” x 3 ¾” |
| Shaft | 2 | Steel | Φ 3/8” x 3” |
| Wheel shaft | 2 | Steel | OD:Φ1/2”, ID:Φ 3/8”, L1” |
| Screw | 1 | Misc. | Φ3/8” x ¼” |
| Bearing | 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 ($) | | | |
|---|---|---|---|
| **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** | |

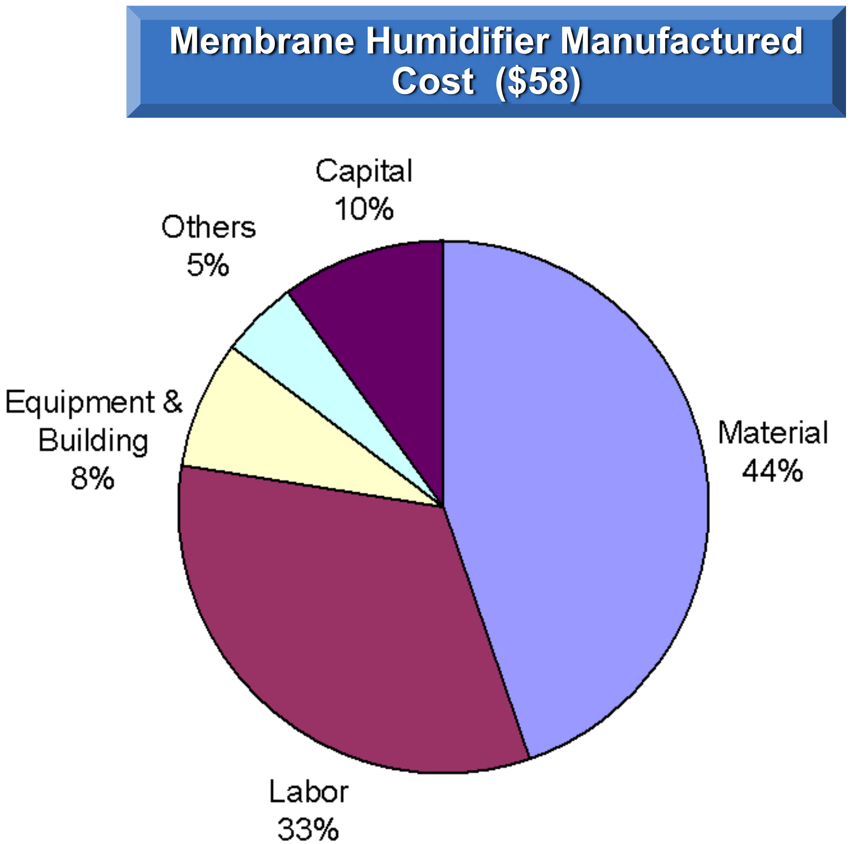
# The Nafion® tube bundle is the key component of the membrane humidifier and its manufacturing process is described below.



# 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” |

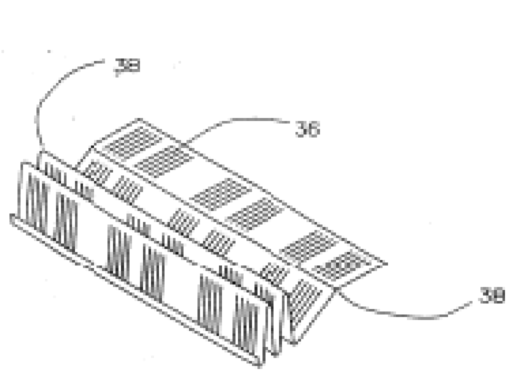
# Material costs represent approximately 44% of the membrane humidifier cost projection.



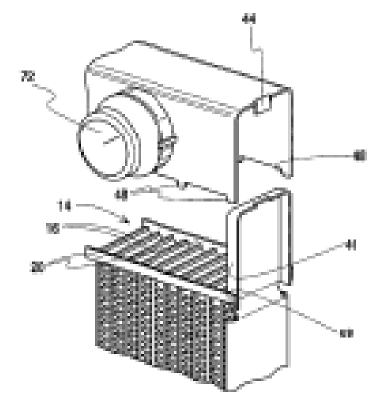

| Membrane Humidifier Manufactured Cost ($) | | | |
|---|---|---|---|
| **Component** | **#** | **Material** | **Process** |
| Right side housing | 1 | 2.62 | 0.84 |
| Small O-ring | 2 | 1.00 | 0.00 |
| Big O-ring | 2 | 1.00 | 0.00 |
| C-clip | 2 | 0.20 | 0.00 |
| Nafion® tubes | 960 | 14.19 | 22.42 |
| 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.






Fin Fabrication
US Patent
5,350,012



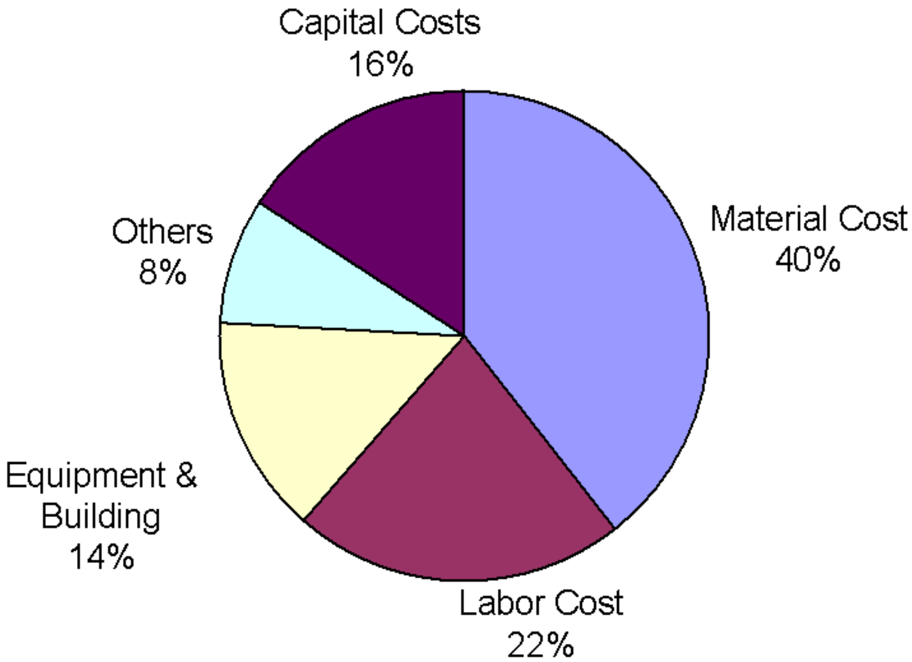
Radiator Structure
US Patent
7,032,656

# 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[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.