Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications

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Overview

The 2009 & 2010 PEMFC cost analyses are based on updates to the bottom-up high-volume stack and BOP cost models developed in 2008.

Timeline

- Base Period: Feb 2006-May 2008
  - » 100% complete
- Option Yr 1 & 2: May 2008-Feb 2010
  - » 100% complete
- Option Yr 3: Feb 2010-Feb 2011
  - » 15% complete

Barriers

- Barriers addressed
  - » B. Cost

	Cost Targets ($/kW)		
	2009	2010	2015
Fuel Cell System	60	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
- FY08 = $50K
- FY09 = $51K
- FY10 = $92K

Partners

- Project lead: TIAX
- Collaborate with ANL on system configuration and modeling
- Yong Yang[1] : mfg. cost modeling
- Feedback from Fuel Cell Tech Team, Developers, Vendors

ANL = Argonne National Lab   [1] Austin Power Engineering LLC, Austin TX

Objectives

	Objectives
Overall	◆ Bottom-up manufacturing cost assessment of 80 kW direct-H_2 PEMFC system for automotive applications
2009	◆ High-volume (500,000 units/year) cost projection of ANL 2009 PEMFC system configuration assuming an NSTFC-based MEA and a 20 μm PFSA membrane ➢ Bottom-up manufacturing cost analysis of *both* stack and BOP ➢ Sensitivity analyses on stack and system parameters ◆ Independent peer review of cost analysis methodology and results ◆ Comprehensive report on the 2008 PEMFC cost analysis (high-volume, bottom-up stack and BOP cost)
2010	◆ Preliminary high-volume (500,000 units/year) cost projection of ANL 2010 PEMFC system configuration assuming an NSTFC-based MEA and a 20 μm reinforced PFSA membrane ➢ Metal bipolar plates ➢ Stack conditioning

BOP = Balance-of-Plant

NSTFC = Nano-Structured Thin Film Catalyst

MEA = Membrane Electrode Assembly

PFSA = Perfluorosulfonic acid

Background

Over the past year, we updated the PEMFC cost assessment based on input from ANL on the 2009 stack performance parameters.

- In 2009, we updated the system configuration, stack performance assumptions and stack and BOP component specifications based on ANL modeling results
  - Based cost assessment on ANL 2009 PEMFC system configuration assuming an NSTFC MEA and a 20 μm PFSA membrane
  - Updated bottom-up cost assessment of stack, balance of stack and stack assembly
  - Replaced EWH by planar MH for cathode air and anode fuel humidification
  - Costed HT & LT radiators, fans, coolant pumps; air precooler; flow orifice for CEM
  - Participated in independent peer-review of our cost analysis methodology and results
  - Submitted a comprehensive report to DOE on our 2008 PEMFC cost analysis
- In 2010, we are working on changes based on ANL 2010 PEMFC system:
  - NSTFC MEA with 20 μm reinforced PFSA membrane
  - Metal bipolar plates – thermal nitrided, Au-Nanoclad
  - Non-woven carbon paper GDL
  - Eliminate anode fuel humidifier, pleated planar MH for cathode air humidification
  - Other BOP updates pending ANL input
  - Stack conditioning pending funding authorization from DOE

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

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

- Radiators (HT, LT)
- Cathode Planar Membrane Humidifier (MH)
- Anode Planar MH
- Compressor-Expander-Module (CEM)
- H_2 Blower

» Develop Bill of Materials (BOM)

» Obtain raw material prices from potential suppliers

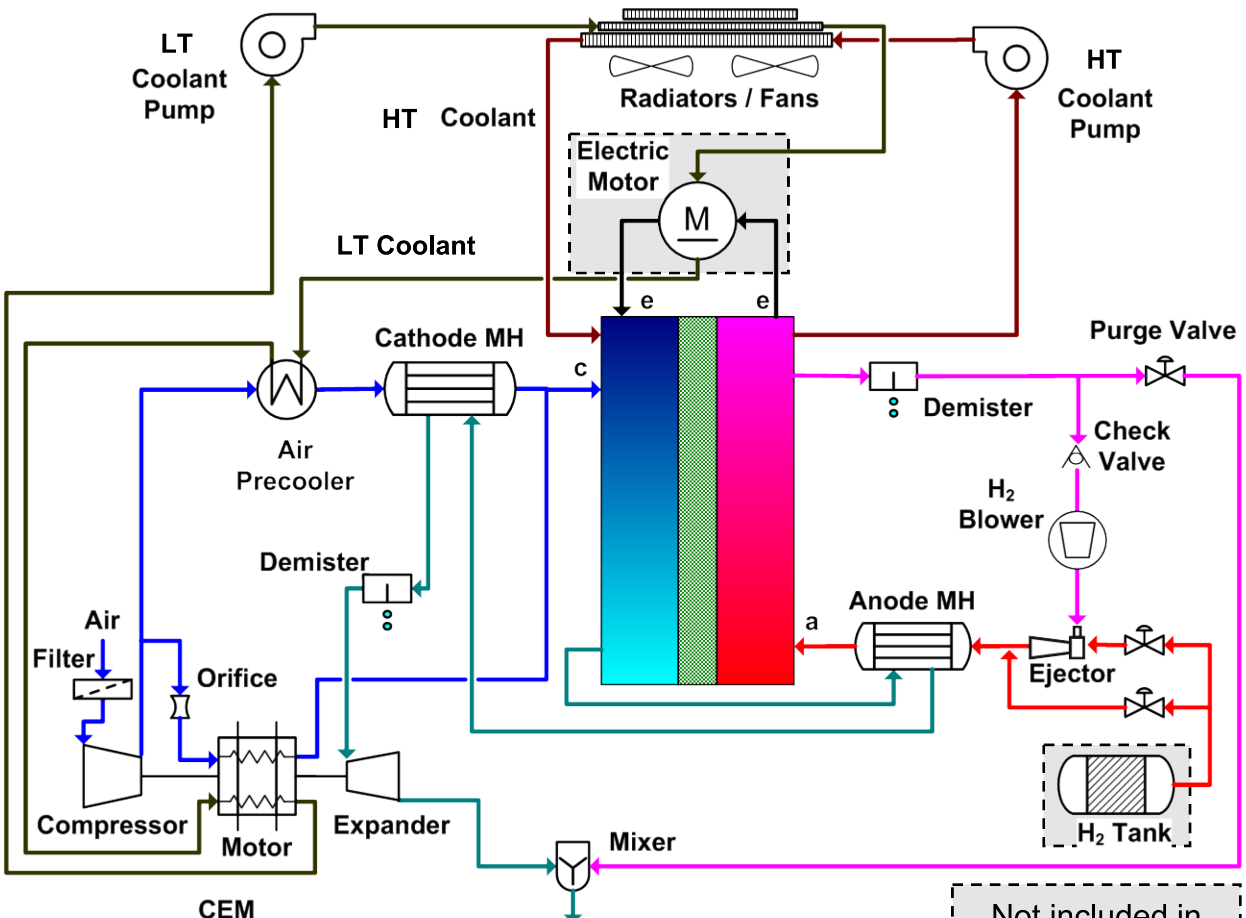
» Develop production process flow chart for key subsystems and components

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

- We used literature/experience-based estimates for stack components such as sensors, controls, control board and wire harness. We scaled quotes/catalog-based estimates for BOP components such as air precooler, flow orifice, coolant pumps, radiator fans, H_2 ejectors, valves/regulators and piping/fittings.
- We used the TIAX technology-based bottom-up cost model for the HT/LT radiators, and cathode/anode planar MH, while we used the DFMA® bottom-up manufacturing cost model for the CEM and H_2 blower.

Approach 2009 System Configuration

ANL 2009 PEMFC System Configuration



Not included in the fuel cell system cost assessment

R. K. Ahluwalia and X. Wang, Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading, July 21, 2009

Key features

Stack
- 3M NSTFC MEA
- 20 μm unsupported membrane
- 0.05 (a)/0.1 (c) mg/cm^2 Pt
- 90 °C, 2.5 atm
- Graphite bipolar plates
- Woven carbon fiber GDL

Air Management
- CEM module
- Air-cooled motor/Air-foil bearing
- 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
- Parallel ejector-pump hybrid
- 35% pump efficiency

NSTFC = Nano-Structured Thin Film Catalyst
CEM = Compressor Expander Motor
MH = Membrane Humidifier
MEA = Membrane Electrode Assembly
ANL = Argonne National Laboratory

The high-volume manufactured cost of the 2009 PEMFC stack for six scenarios[1, 2] is estimated to range between $19/kW and $40/kW.

Key Cost Assumptions		2009 Stack Scenarios[1, 2]					
		S1	S2	S3	S4	S5	S6
System net power	kW_e	80					
Stack gross power[2]	kW_e	91.5	92.1	92.3	91.6	91.8	92.1
Cell voltage (rated power)[2]	V	0.729	0.690	0.659	0.736	0.693	0.661
Stack gross power density[2]	mW/cm^2	479	658	789	451	701	886
Pt loading (total)[2]	mg/cm^2	0.25			0.15		
Stack Pt content	g/kW_{gross}	0.52	0.38	0.32	0.33	0.21	0.17
System Pt content	g/kW_{net}	0.60	0.44	0.37	0.38	0.25	0.20
Stack efficiency (rated power)[2]	% LHV	57.4	54.5	52.1	57.4	54.6	52.1
System efficiency (rated power)[2]	% LHV	50.0	47.3	45.0	50.0	47.3	45.0
System voltage (rated power)	V	300					
System active area	m^2	19.1	14.0	11.7	20.3	13.1	10.4
Stack cost[3]	**$\$/kW_{net}$**	**40.2**	**30.0**	**25.9**	**33.2**	**22.3**	**18.7**

[1] All scenarios assume a Pt cost of $1,100/tr.oz., NSTFC-based MEA, 20 µm PFSA membrane, and stack operating conditions of 90 °C and 2.5 atm.
[2] Based on stack and system modeling results by ANL for 2009 PEMFC system: R. K. Ahluwalia and X. Wang, March 6-July 21, 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).

We developed stack specifications for the 2009 baseline scenario S5, consistent with the performance predicted by ANL's stack and system modeling.

TIAX Assumptions	Units	2005[1]	2007[2,3]	2008[4]	2009[5]
Number of stacks per system	#	2	2	2	2
Number of cells per stack	#	231	221	219	217
Active area to Total area	%	85	85	85	85
Active area per cell	cm^2	323	260	277	304
Cell pitch	cells/inch (cells/cm)	9.55 (3.76)	9.75 (3.84)	9.75 (3.84)	10.57 (4.16)
System voltage (rated power)	V	300	300	300	300

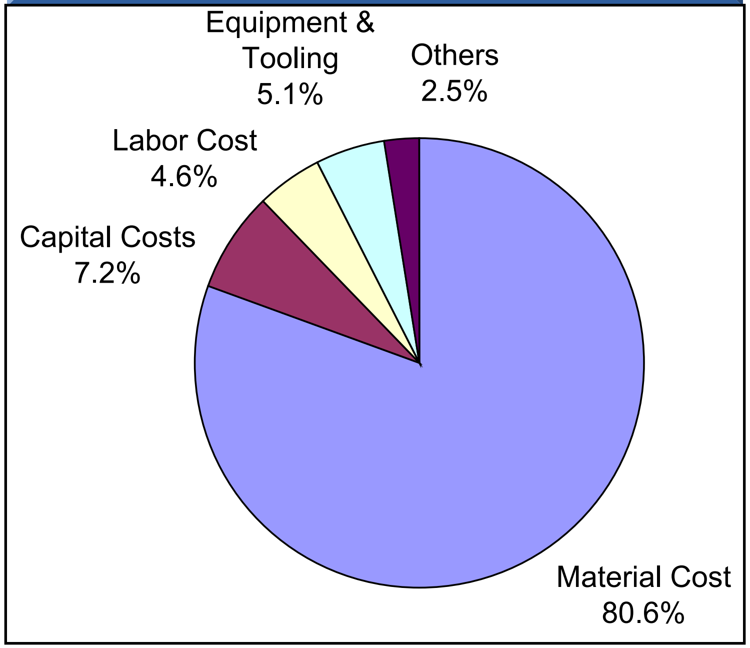
[1] E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, NREL/SR-560-39104, Sep 30, 2005
[2] R.K. Ahluwalia and X. Wang, Reference Fuel Cell System Configurations for 2007: Interim Results, ANL, Feb. 6, 2007
[3] R.K. Ahluwalia, X. Wang and R. Kumar, Fuel Cell Systems Analysis, 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
[5] R. K. Ahluwalia and X. Wang, Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading, July 21, 2009

Using S5 as the 2009 baseline scenario, we estimated that the MEA and seal together cost ~$101/m², of which material costs represent ~81%.

Manufactured Cost[1]	MEA ($/m²)	Frame Seal ($/m²)
Material *- Membrane* *- Electrode* *- GDL*	76.70 - 9.77 - 58.69 - 8.23	4.78
Capital Cost	6.18	1.14
Labor	3.85	0.81
Tooling & Equipment	4.21	0.95
Other[2]	2.03	0.45
Subtotal	**92.97**	**8.13**
Total	**101.11**	

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

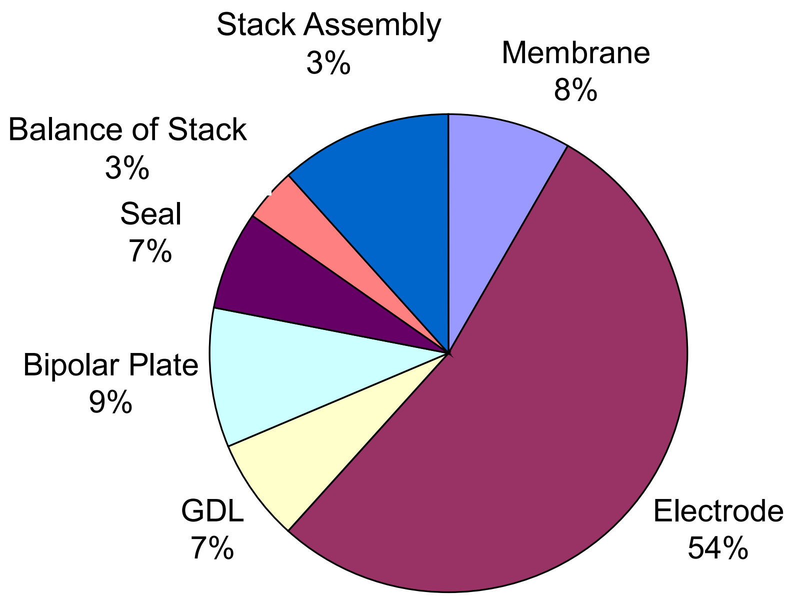
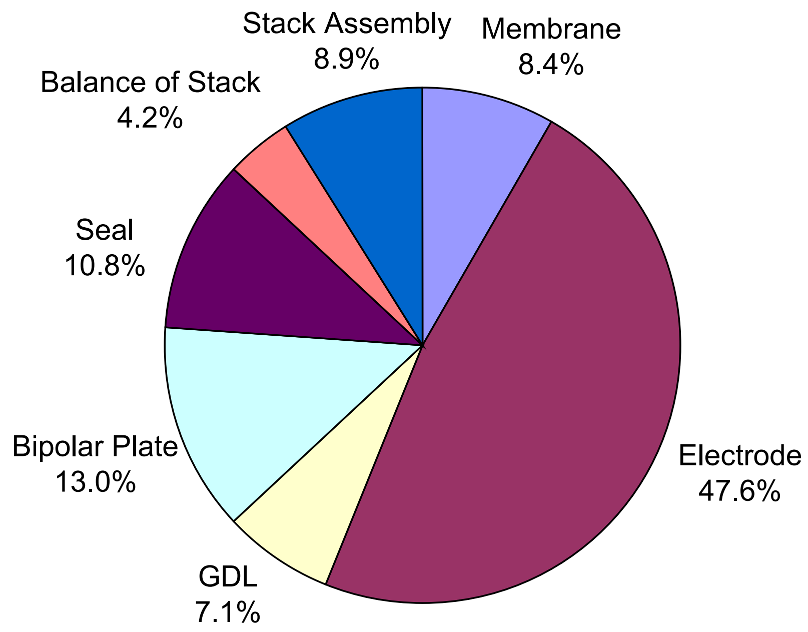
MEA/Seal Manufactured Cost ($101/m²)



In 2008, the MEA and seal cost was $140/m² due to higher material costs for the membrane (30 μm), electrodes (Pt loading = 0.25 mg/cm²) and GDL (275 μm).

The electrodes represent approximately 48% of the ~$22/kW fuel cell stack manufactured cost in 2009.

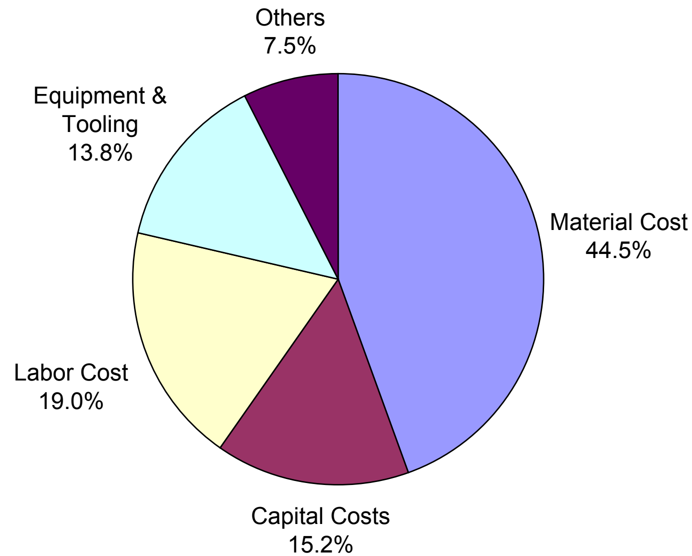
Stack Manufactured Cost – 80 kW Direct-H_2 PEMFC

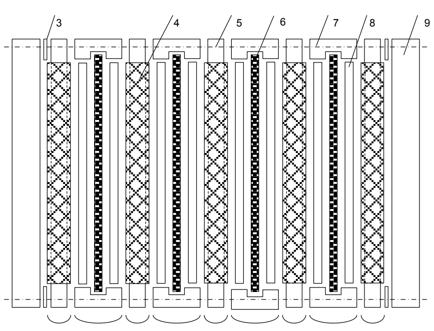
2008[1]: $29/kW; $2,320	2009[1]: $22.3/kW; $1,787
	

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

We developed bottom-up manufacturing costs for the cathode and anode planar MH based on ANL specifications[1] and other patents[2].

Cathode Planar Membrane Humidifier Manufactured Cost ($96)





Cathode Planar Membrane Humidifier Manufactured Cost ($)			
Process	**#**	**Material**	**Process**
Die Cut GDL	1	2.49	2.02
Die Cut Membrane	2	7.03	2.14
Hot Press Lamination	3	0.01	6.06
Injection Molding Frame Seal	4	0.00	4.20
Laser Cut Nickel Foam	5	15.44	17.16
Injection Molding Foam Frame	6	4.39	4.34
Injection Molding End Plate Gasket	7	0.11	0.45
Die Casting End Plate	8	9.50	1.32
Component Assembly	9	0.00	6.90
QC & Testing	10	0.00	6.80
Packaging	11	0.00	2.03
Fastener Cost	-	3.91	0.00
Total	**-**	**96**	

[1] R. K. Ahluwalia and X. Wang, Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading, July 21, 2009
[2] U.S. Patents 6,737,183; 6,835,477; 6,864,005; 7,078,117

MH = Membrane Humidifier

The water management system OEM cost[1,2] is projected to be $170.

Water Management System Cost ($)			
Component	**Factory Cost[1]**	**OEM Cost[1,2]**	**Comments**
Cathode Planar Membrane Humidifier	96	111	Bottom-up costing
Anode Planar Membrane Humidifier	52	59	Bottom-up costing
Total	**148**	**170**	

[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

The cathode and anode planar membrane humidifier costs are both estimated using bottom-up costing tools.

The thermal management system OEM cost[1,2] is projected to be $413.

Thermal Management System Cost ($)			
Component	**Factory Cost[1]**	**OEM Cost[1,2]**	**Comments**
HT Radiator	83	95	Bottom-up costing
LT Radiator	12.6	14.5	Bottom-up factory cost = $56; Scaling by LTR heat duty, 2.9/12.9*56=$12.6
Air Precooler	-	43.2	Bell Intercooler $108/unit Assuming 60% discount
HT/LT Radiator Fan - Motor - Fan	- - -	75 - 60 - 15	McMaster-Carr 5990K48, Base-mount single-phase AC motor, 0.75 HP, 3450 rpm, $152/unit Assuming 60% discount, motor costs $60/unit Aluminum fan costs ~$15/unit
HT Coolant Pump - Motor - Pump	- - -	150 - 95 - 55	McMaster-Carr 5990K53, Base-mount single-phase AC motor, 1.5 HP, 3450 rpm, $238/unit Assuming 60% discount, motor costs $95/unit Aluminum pump costs ~$55/unit
LT/Air Precooler Coolant Pump	-	30	AWECO pump, high-volume quote
Other	-	5	Two temperature sensors
Total	**399**	**413**	

[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

The air precooler, radiator fan, coolant pumps, and their motors are assumed to be purchased components; hence their price includes a markup.

The fuel management system OEM cost[1,2] is projected to be $425.

Fuel Management System Cost ($)			
Component	**Factory Cost[1]**	**OEM Cost[1,2]**	**Comments**
H_2 Blower	219.5	252	Bottom-up costing using DFMA®
H_2 Ejectors	-	40	2 ejectors assumed @ $20/unit
H_2 Demister	-	61	Parker Hannifin MN1S-6CN, 28 SCFM, ΔP=1.25 psid, rated for H_2 to 175 F, $152.50/unit Assuming 60% discount, H_2 demister costs ~$61/unit (Note: Parker Hannifin MN4S-6CN, rated for H_2 to 200+ F, ΔP=0.35 psid, $600/unit)
Solenoid Valves	-	46	2 solenoid flow control valves w/ built-in ports, McMaster-Carr 61245K1, $57.96/unit, Assuming 60% discount, solenoid valves cost ~$23/unit
Purge Valve	13	15	DFMA® bottom-up costing; DOE Chemical Hydride Storage presentation, Sept. 2005
Check valve	9	10	DFMA® bottom-up costing; DOE Chemical Hydride Storage presentation, Sept. 2005
Total	**389**	**425**	

[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

The H_2 ejectors, H_2 demister, and solenoid valves are assumed to be purchased components; hence their price includes a markup.

The air management system OEM cost[1,2] is projected to be $982.

Air Management System Cost ($)			
Component	**Factory Cost[1]**	**OEM Cost[1,2]**	**Comments**
CEM (Compressor, Expander, Motor, Motor Controller	**687**	**790**	Bottom-up costing using DFMA®; **motor controller input power updated to 9.3 kWe**
Air demister	-	156	Parker Hannifin HN4S-10CG, 226 SCFM, ΔP=2 psid, 1-¼ " NPT, 95% coalescing efficiency, $390.60/unit, Assuming 60% discount, demister costs ~$156/unit (Note: Parker Hannifin HN4L-8CG, 98.5% coalescing eff., ΔP=2 psid, $534/unit; Parker Hannifin HN5S-7CVPG, 99.5% coalescing eff., ΔP=0.5 psid, $680/unit; Parker Hannifin HN6S-7CVPG, 99.5% coalescing eff., ΔP=0.35 psid, $805/unit; Parker Hannifin HN8S-MEG, 99.95% coalescing eff., ΔP=0.35 psid, $1,235/unit; Parker Hannifin FF4-1201-6QU, 99.97% coalescing eff., ΔP=0.35 psid, $3,689/unit)
Air/H_2 mixer	-	27	Gas mixer, McMaster-Carr 3322K18, 1" pipe, $68.42, Assuming 60% discount, air/H_2 mixer costs ~$27/unit
Flow orifice	-	5	Acetal instant tube-fitting orifice, McMaster-Carr 6349T17, ½" tube, $11.29, Assuming 60% discount, flow orifice costs ~$4.5/unit
Air filter	-	4	
Total	**879**	**982**	

[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

The air demister, air/H_2 mixer, flow orifice, and air filter are assumed to be purchased components; hence their price includes a markup.

The high-volume OEM cost[1,2] for the 2009 BOP subsystems is projected to be $1,991.

BOP Subsystem	Component	Technology / Cost Basis	Factory Cost[1], $	OEM Cost[1,2], $
Water Management	Cathode planar membrane humidifier (for air)	ANL	96	111
	Anode planar membrane humidifier (for H_2)	ANL	52	59
Thermal Management	HT automotive tube-fin radiator	Modine	83	95
	LT automotive tube-fin radiator	Modine	13	15
	Air precooler	Bell Intercooler	-	43
	HT/LT radiator fan	McMaster-Carr	-	75
	HT coolant pump	McMaster-Carr	-	150
	LT/Air precooler coolant pump	Aweco	-	30
	Other (2 Temperature sensors)	-	-	5
Fuel Management	H_2 blower	Parker Hannifin	219	252
	H_2 ejectors	-	-	40
	H_2 demister	Parker Hannifin	-	61
	Solenoid valves	McMaster-Carr	-	46
	Purge valve	DFMA®	13	15
	Check valve	DFMA®	9	10
Air Management	Compressor Expander Motor (CEM)	Honeywell	687	790
	Air demister	Parker Hannifin	-	156
	Air/H_2 mixer	McMaster-Carr	-	27
	Flow orifice	McMaster-Carr	-	5
	Air filter	-	-	4
TOTAL		-	**1,815**	**1,991**

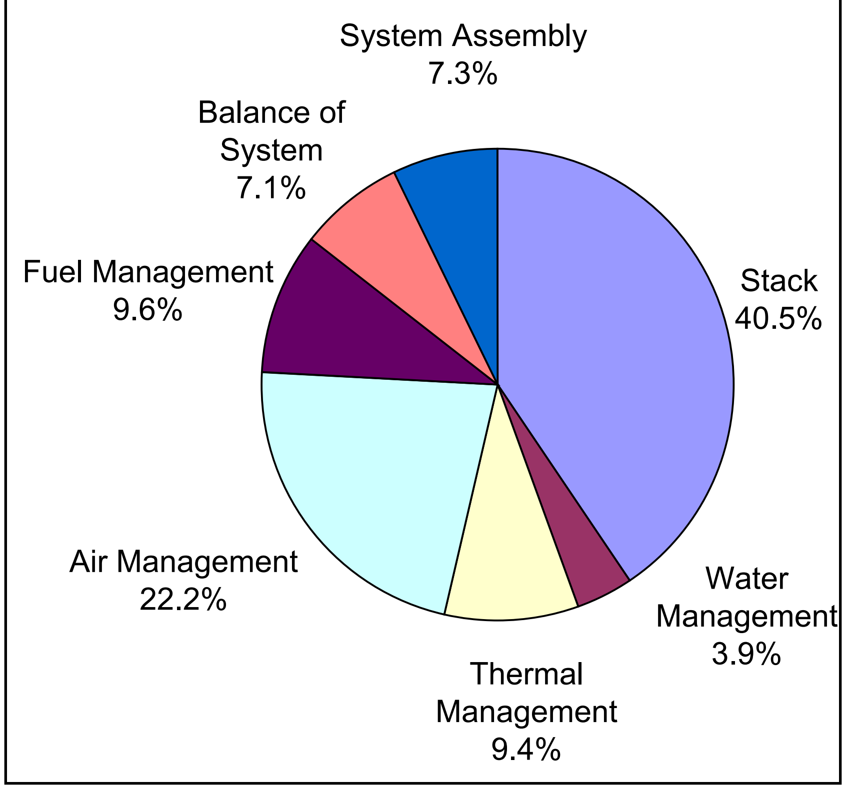
[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[2] Assumes 15% markup to the automotive OEM for BOP components

The 2009 PEMFC stack cost is lower than the DOE 2010 target of $25/kW, while the system cost is higher than the DOE 2010 target of $45/kW.

PEMFC System Cost[1] ($/kW)	2008 OEM Cost[1,2]	2009 OEM Cost[1,2]
Stack	**29.0**	**22.3**
Water Management	3.3	2.1
Thermal Management	2.8	5.2
Fuel Management	3.8	5.3
Air Management	8.9	12.3
Balance of System	3.1	4.0
System Assembly	5.5	4.0
Total	**57.0**	**55.2**

[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

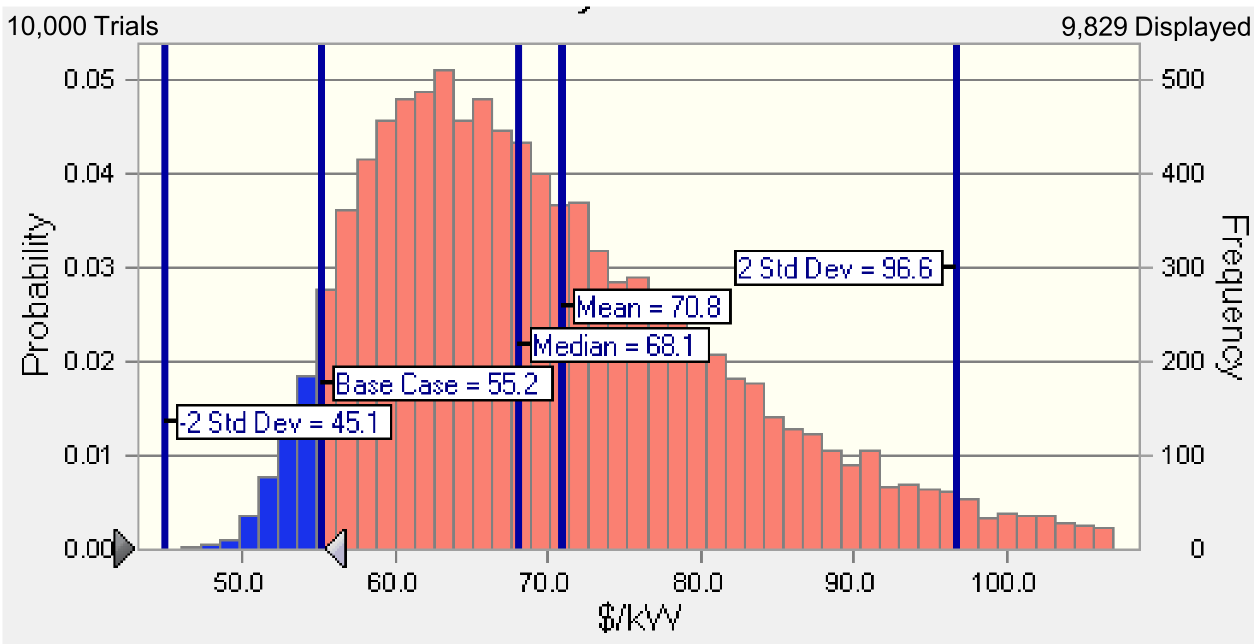
2009 PEMFC System OEM Cost[1,2] ($55.2/kW; $4,416)



BOP, balance of system and system assembly costs together represent ~60% of the PEMFC system cost in 2009, compared to ~38% in 2005.

Monte Carlo analysis shows that the high-volume 2009 PEMFC system OEM cost[1] ranges between $45/kW and $97/kW (2σ), with a mean cost of $71/kW.

2009 PEMFC System OEM Cost[1] ($/kW)

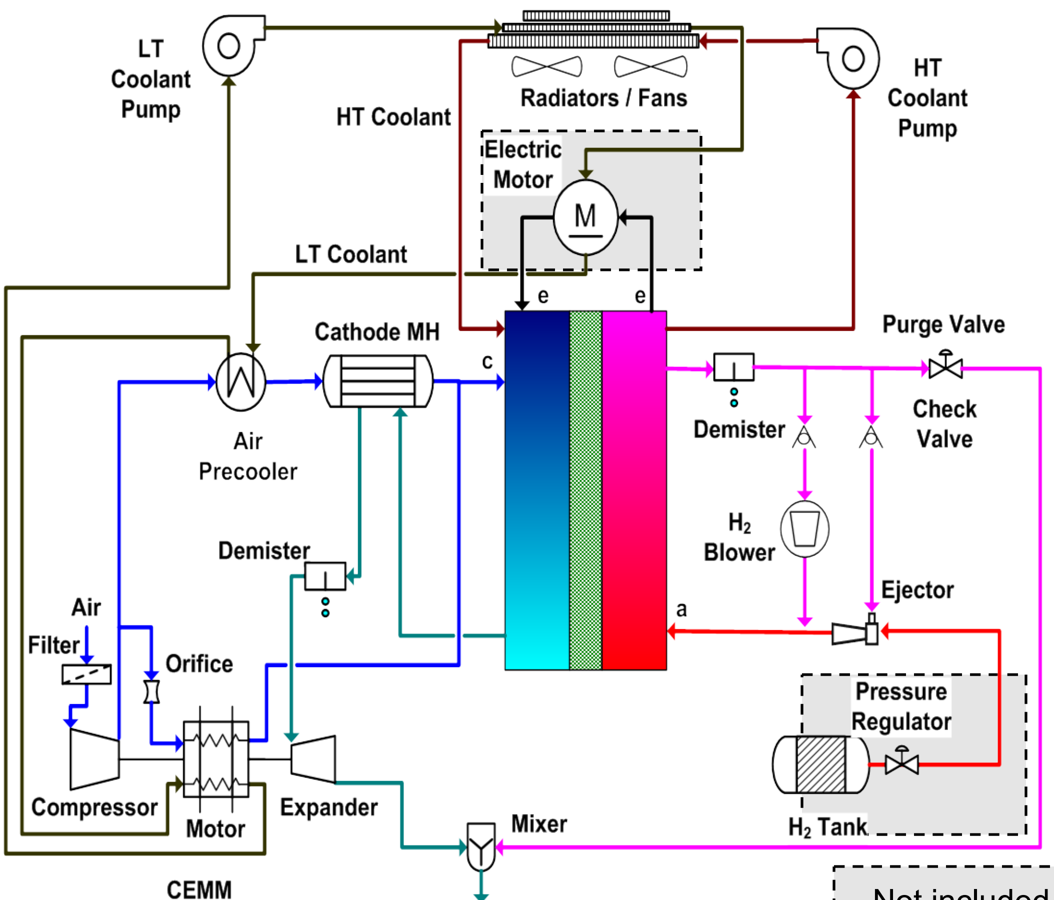


Cost[1]	$/kW
Mean	71
Median	68
Std. Dev.	13
TIAX Baseline	55

[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.

Preliminary 2010 Results

ANL 2010 PEMFC System Configuration



Not included in fuel cell system cost assessment

R. K. Ahluwalia and X. Wang, Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading, March 31, 2010

Key features

Stack
- 3M NSTFC MEA
- 20 µm reinforced membrane
- 0.05 (a)/0.1 (c) mg/cm^2 Pt
- Metal bipolar plates
- Non-woven carbon paper GDL

Air Management
- CEM module
- Air-cooled motor/Air-foil bearing

Water Management
- Cathode MH with precooler

Thermal Management
- Advanced 40-fpi microchannel fins

Fuel Management
- Parallel ejector-pump hybrid

NSTFC = Nano-Structured Thin Film Catalyst
CEM = Compressor Expander Motor
MH = Membrane Humidifier
MEA = Membrane Electrode Assembly
ANL = Argonne National Laboratory

To be consistent with ANL's stack performance model, we made the following material assumptions for the 2010 cost projection.

Component	Parameter	Selection
Membrane	Material	20 μm 3M PFSA
	Supported	**Mechanically reinforced**
Electrodes (Cathode and Anode)	Catalyst	Ternary $PtCo_xMn_y$ alloy
	Type	Nano-Structured Thin Film
	Support	PR-149 Organic whiskers
Gas Diffusion Layer (GDL)	Material	**225 μm non-woven carbon paper[1]**
	Porosity	80%
Bipolar Plate	Type[3]	**Metal w/ Nitridation surface treatment[2]**
Seal	Material	Viton®

[1] Ref: Ballard Material Products GDL with PTFE+MPL, AvCarb® GDS3250 @ 50 kPa
[2] Ref: ORNL Fe-20Cr-4V alloy with nitridation surface treatment
[3] We will evaluate Au-Nanoclad SS316 plates as an alternate scenario for metal bipolar plates in 2010

We used a Pt price of $1,100/tr.oz. for the baseline analysis and captured the impact of variation in Pt price through sensitivity analyses.

PFSA = Perfluorosulfonic acid

PR = Perylene Red

The preliminary high-volume cost of the 2010 PEMFC stack for six scenarios[1, 2, 3] is estimated to range between \$17/kW and \$33/kW.

Key Cost Assumptions		2010 Stack Scenarios[1, 2, 3]					
		S1-1	S1-2	S1-3	S2-1	S2-2	S2-3
System net power	kW_e	80					
Stack gross power[3]	kW_e	90	91	92	86	87	88
Cell voltage (rated power)[3]	V	0.721	0.650	0.590	0.685	0.622	0.563
Stack gross power density[3]	mW/cm^2	573	1059	1411	561	930	1201
Pt loading (total)[3]	mg/cm^2	0.15					
Stack Pt content	g/kW_{gross}	0.26	0.14	0.11	0.27	0.16	0.12
System Pt content	g/kW_{net}	0.29	0.16	0.12	0.29	0.18	0.14
Stack efficiency (rated power)[3]	% LHV	57	52	47	54	49	45
System efficiency (rated power)[3]	% LHV	50	45	40	50	45	40
System voltage (rated power)	V	300					
System active area	m^2	15.7	8.6	6.5	15.3	9.4	7.3
Stack cost[4]	**$\$/kW_{net}$**	**33.0**	**20.7**	**17.4**	**32.4**	**22.3**	**19.0**

[1] All scenarios assume a Pt cost of \$1,100/tr.oz., NSTFC-based MEA, and 20 μm reinforced PFSA membrane.

[2] S1: 2.5 atm, 85 C; S2: 1.5 atm, 75 C

[3] Based on stack and system modeling results by ANL for 2010 PEMFC system: R. K. Ahluwalia and X. Wang, March 31, 2010.

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

We developed specifications for the 2010 PEMFC stack scenarios consistent with the performance predicted by ANL modeling[1, 2, 3].

TIAX Assumptions		2010 Stack Scenarios[1, 2, 3]					
		S1-1	S1-2	S1-3	S2-1	S2-2	S2-3
Number of stacks per system	#	**1**					
Number of cells per stack	#	417	462	509	438	483	533
Active area to Total area[4]	%	**75%**					
Active area per cell	cm^2	377	186	128	349	195	137
Cell pitch	cells/inch (cells/cm)	19.7 (7.8)	19.7 (7.8)	19.7 (7.8)	19.7 (7.8)	19.7 (7.8)	19.7 (7.8)
System voltage (rated power)	V	300					

[1] All scenarios assume a Pt cost of $1,100/tr.oz., NSTFC-based MEA, and 20 μm reinforced PFSA membrane.

[2] S1: 2.5 atm, 85 C; S2: 1.5 atm, 75 C

[3] Based on stack and system modeling results by ANL for 2010 PEMFC system: R. K. Ahluwalia and X. Wang, March 31, 2010.

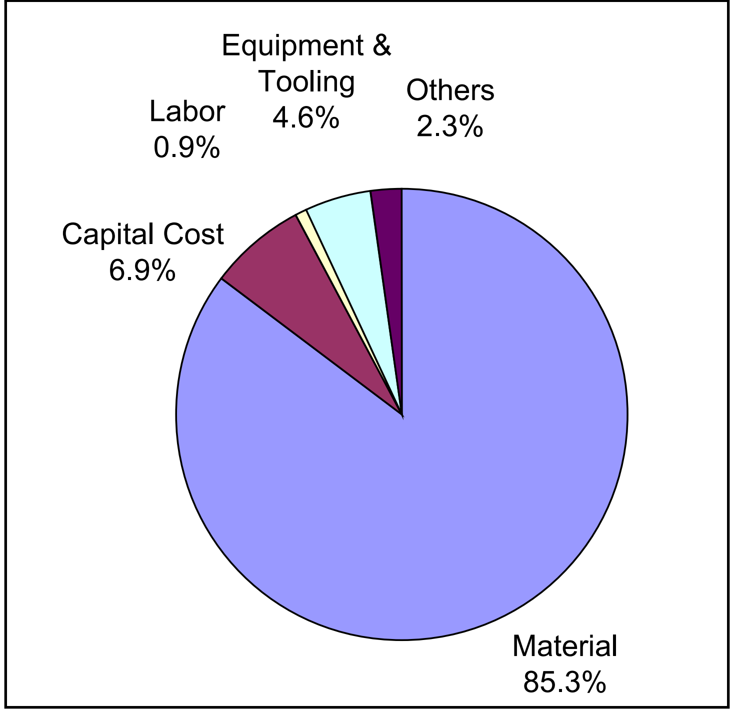
[4] Active area to Total area ratio reduced from 85% in 2009 to 75% in 2010, based on feedback from OEMs and FCTT

The reinforced 20 µm PFSA membrane is estimated to cost ~$19/m² on an active area basis, with materials representing ~85% of the cost.

Membrane Manufactured Cost[1]				
Component	Material		Process	
	($/m²)	($/kg)	($/m²)	($/kg)
Film Handling	6.33	107.64	0.33	5.67
Coating	9.64	163.83	0.42	7.10
Drying & Cooling	0.00	0.00	1.87	31.84
Quality Control	0.00	0.00	0.03	0.57
Laminating	0.00	0.00	0.05	0.89
Packaging	0.03	0.43	0.03	0.44
Subtotal	**15.99**	**2.74**	**2.74**	**46.52**
Total	**18.73 ($/m²)**			
	318.42 ($/kg)			

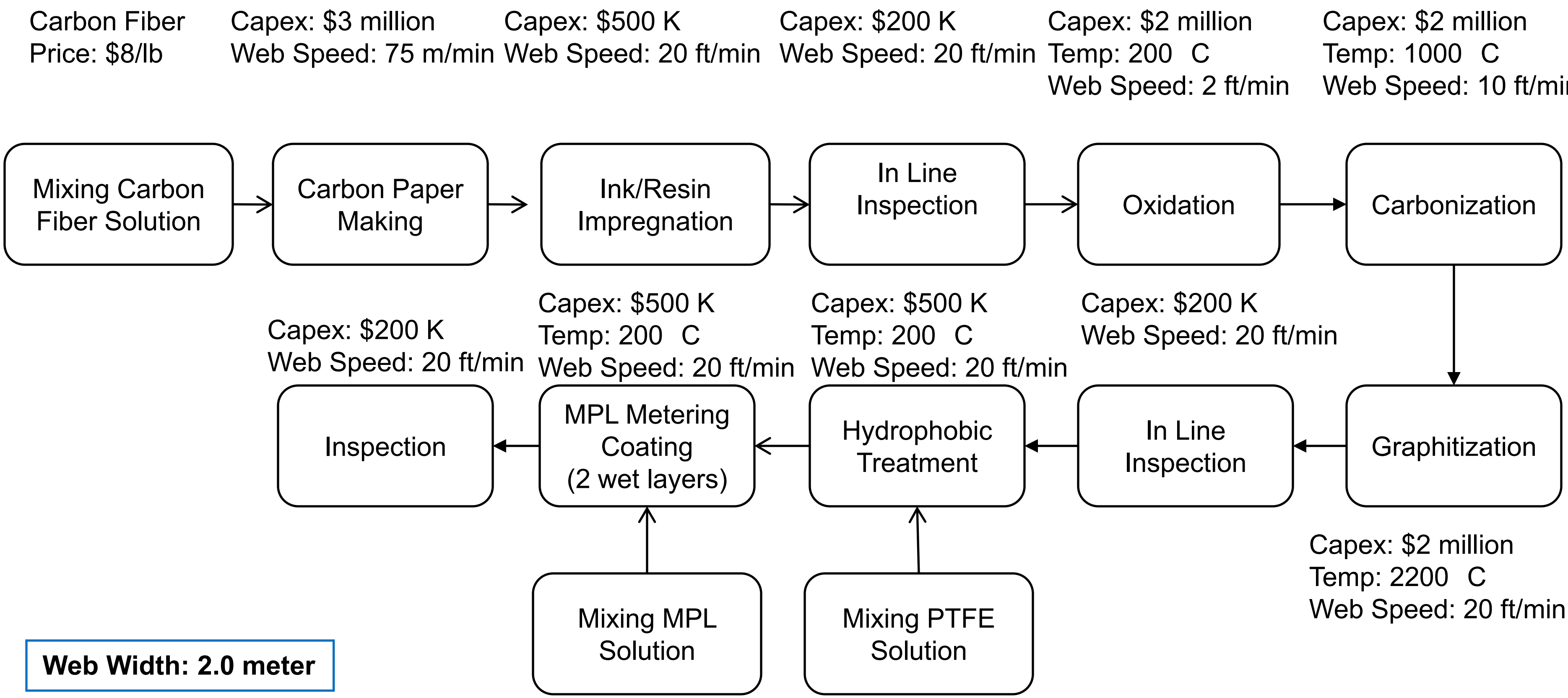
[1] Manufactured cost on an active area basis or per kg of finished membrane basis (accounts for scrap and yield)
[2] 3M PFSA ionomer cost preliminarily increased by factor of 20% over 2009 Nafion® baseline cost of $80/lb due to higher cost risk for shorter side chain PFSA ionomer: to be verified by industry feedback in 2010
[3] ePTFE cost preliminarily assumed to be $5/m²: to be verified by industry feedback in 2010

Membrane Manufactured Cost ($19/m²)



The preliminary 2010 membrane cost estimate is higher due to increased ionomer[2] and ePTFE[3] costs for the reinforced membrane.

In 2010, we costed a non-woven carbon paper GDL with PTFE+MPL.



The 2010 GDL cost is based on discussions with Ballard Material Products on their AvCarb® GDS3250, suitable for automotive applications.

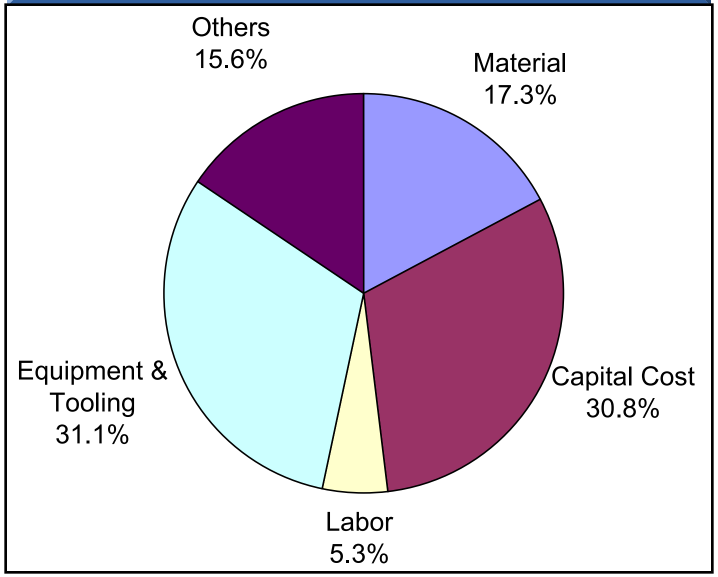
Multiple stations / lines would be required to meet the high volume production of ~19 million square meters of GDL per year)

The preliminary cost of the 2010 non-woven carbon paper GDL (for *both* anode and cathode), is ~$12/m^2, on an active area basis.

Manufactured Cost[1]	GDL ($/m^2)	GDL (Anode + Cathode) ($/m^2)
Material	1.02	2.05
Capital Cost	1.83	3.66
Labor	0.31	0.63
Tooling	1.85	3.69
Other[2]	0.92	1.84
Total	**5.94**	**11.87**

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

GDL Manufactured Cost ($12/m^2)



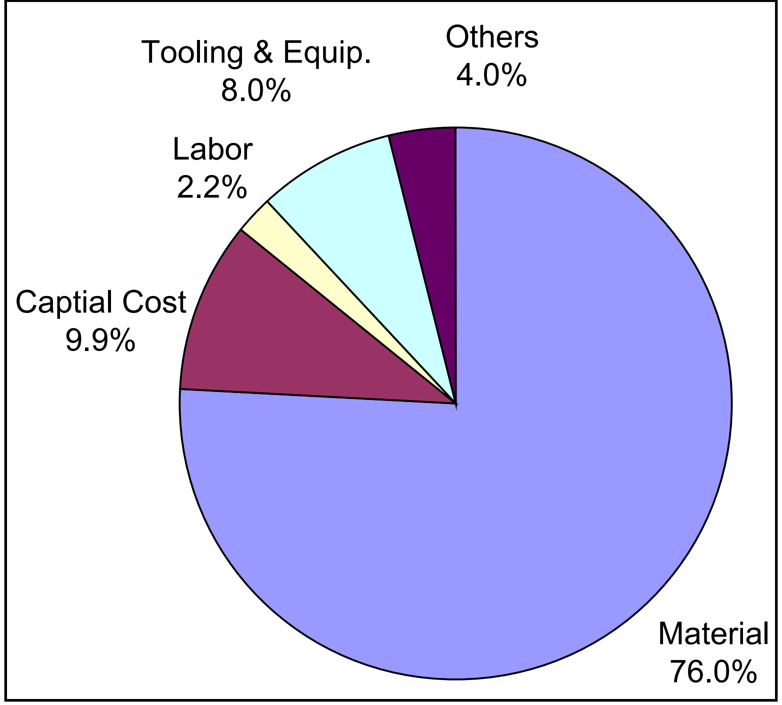
The GDL costing is changed from "buy untreated woven carbon cloth" in 2009 to "fabricate non-woven carbon paper + PTFE + MPL" in 2010.

Using S2-2 as an example scenario, the 2010 MEA and seal together are estimated to cost ~\$109/m^2.

Manufactured Cost[1]	MEA (\$/m^2)	Frame Seal (\$/m^2)
Material *- Membrane* *- Electrode* *- GDL*	77.19 - 15.99 - 59.14 - 2.05	5.99
Capital Cost	9.09	1.75
Labor	1.15	1.27
Tooling & Equipment	7.32	1.50
Other[2]	3.51	0.71
Subtotal	**98.26**	**11.22**
Total	**109.49**	

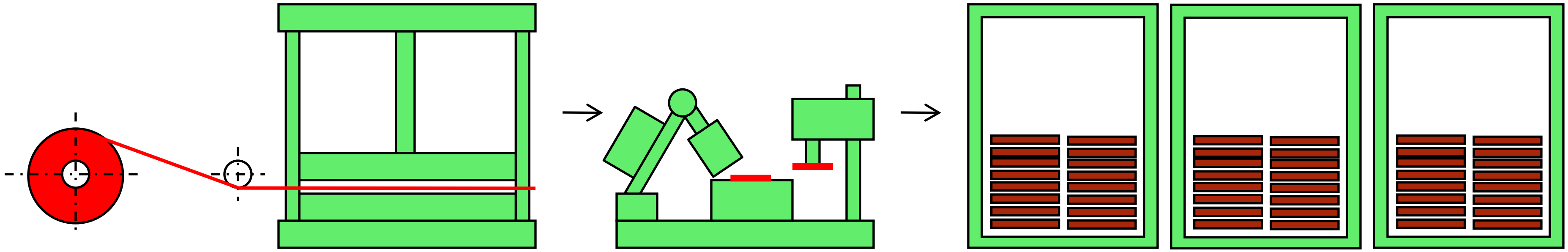
[1] Manufactured cost on a per m^2 of active area basis
[2] Other costs include utilities, maintenance, and building
[3] Active area to Total area ratio reduced from 85% in 2009 to 75% in 2010, based on feedback from OEMs and FCTT

MEA & Seal Manufactured Cost (\$109/m^2)



The preliminary estimate for the 2010 MEA & seal cost is higher due to increased ionomer and ePTFE costs for the reinforced membrane, the reduction in active area ratio[3] from 85% to 75%, reduction in MEA utilization from 100% to 95%, and refinement of GDL costing.

The metal bipolar plate cost is based on discussions with ORNL on their thermal nitriding process[1] for specific alloys, e.g. Fe-20Cr-4V.



$Fe_{20}Cr_4V$ Foil
0.1 mm thick

Price: $5/lb

Stamping
Seven-Stage
Progressive Die[2]

Cycle Time: 30 parts/minute
Capex: $400,000, 300 ton Press + Coil feeding
Tooling: $300 K [3]

Laser
Welding (Anode & Cathode Plate Edges)

Cycle Time: 0.25 minute
Capex: $200,000

Heat up Vacuum Furnace
Cycle Time: 30 minutes
Capex: $1,200,000
Temp: 950 °C
Packing Capacity: 1m³ (1,500 plates)

Thermal Nitridation [4]
Cycle Time: 90 minutes
Capex: $1,200,000
Temp: 950 °C
Packing Capacity: 1m³ (1,500 plates)

Cool Down Furnace
Cycle Time: 60 minutes
Capex: $300,000
Packing Capacity: 1m³ (1,500 plates)

- Stamping: The anode side plate and the cathode side plate are stamp pressed by a seven stage progressive die which forms the micro flow channels, punches the main flow channels, bolt holes, and trims the edges.
- Welding: The anode and cathode side plate edges are welded together using laser welding.
- Thermal Nitridation: The bipolar plate is heated for 1.5 hours at 950 °C degree in a vacuum nitridation furnace. It takes 0.5 hour to heat up and 1 hour to cool down.

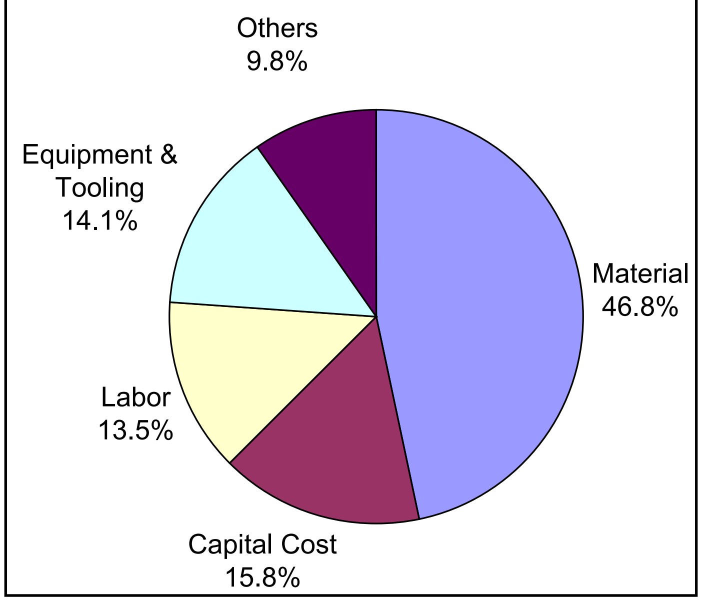
1. Nitrided metallic bipolar plates, M.P. Brady, et al., ORNL, DOE Merit Review presentation, May 2009
2. US 20090081520 (Hitachi)
3. Discussion with Minster Press Inc., April 2010
4. Preferential thermal nitridation to form pin-hole free Cr-nitrides to protect proton exchange membrane fuel cell metallic bipolar plates, M.P. Brady, et al., Scripta Materialia 50 (2004) 1017-1022

The preliminary cost of the nitrided Fe-20Cr-4V metal bipolar plates is estimated to be ~$53/m^2 or ~$6/kW in 2010.

	Bipolar Plate Manufactured Cost[1] ($/m^2)		Bipolar Plate Manufactured Cost[2] ($/kW)	
Component	Material	Process	Material	Process
Stamping	24.75	10.70	2.91	1.26
Laser Welding	0.00	7.05	0.00	0.83
Nitridation	0.00	10.40	0.00	1.22
Subtotal	**24.75**	**28.14**	**2.91**	**3.31**
Total	**52.89**		**6.22**	

[1] Manufactured cost on an active area basis
[2] Manufactured cost on a kW_{net} basis

Bipolar Plate Manufactured Cost ($53/m^2)



The base metal foil thickness[1] is 0.1 mm and the overall bipolar plate thickness is 0.9 mm. We will also evaluate Au-Nanoclad SS316 bipolar plates in 2010.

1. Discussion with ORNL, April 2010

Preliminary 2010 stack (S2-2) manufactured costs on an active area basis are higher than the 2009 stack costs, due to the reduction in active area ratio from 85% (in 2009) to 75% (in 2010).

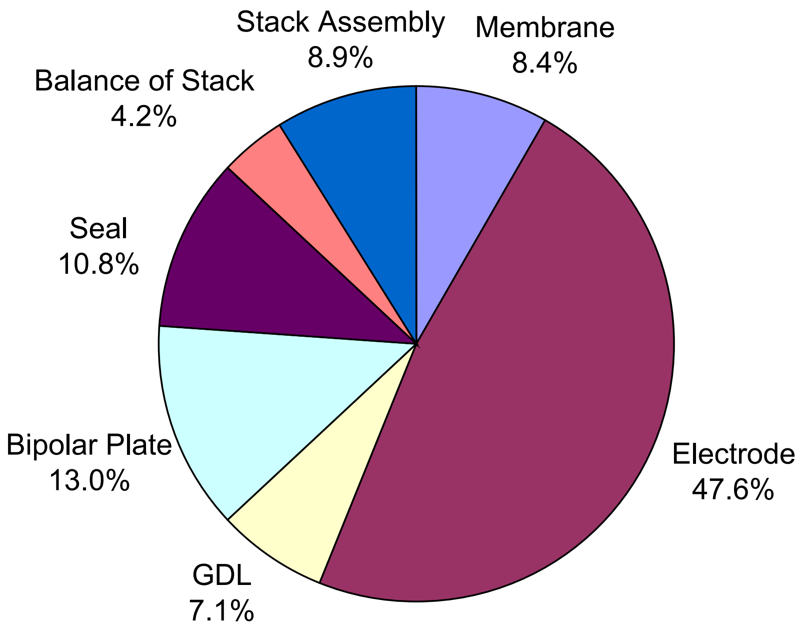
Stack Manufactured Cost[1], $/m^2$	2009	2010 S2-2[2, 3, 4]	Δ%	Comments
Membrane	11	19	+70%	3M PFSA ionomer (1.2*$80/lb) & ePTFE ($5/m^2) included in 2010
Electrodes	65	68	+4%	MEA utilization rate decreased from 100% in 2009 to 95% in 2010
GDL	10	12	+8%	
Seals	15	18	+22%	Active area decreased from 13.1 m^2 in 2009 to 9.4 m^2 in 2010
Bipolar plates	18	53	+194%	Nitrided metallic plate in 2010
Balance of Stack (Stack manifold, tie bolts, end plates, current collectors, electrical insulators)	6	5	-20%	1 stack per system in 2010 vs. 2 stacks per system in 2009
Stack Assembly[5, 6]	12	15	+25%	Active area decreased from 13.1 m^2 in 2009 to 9.4 m^2 in 2010
Total Stack[7]	**136**	**189**	**+39%**	

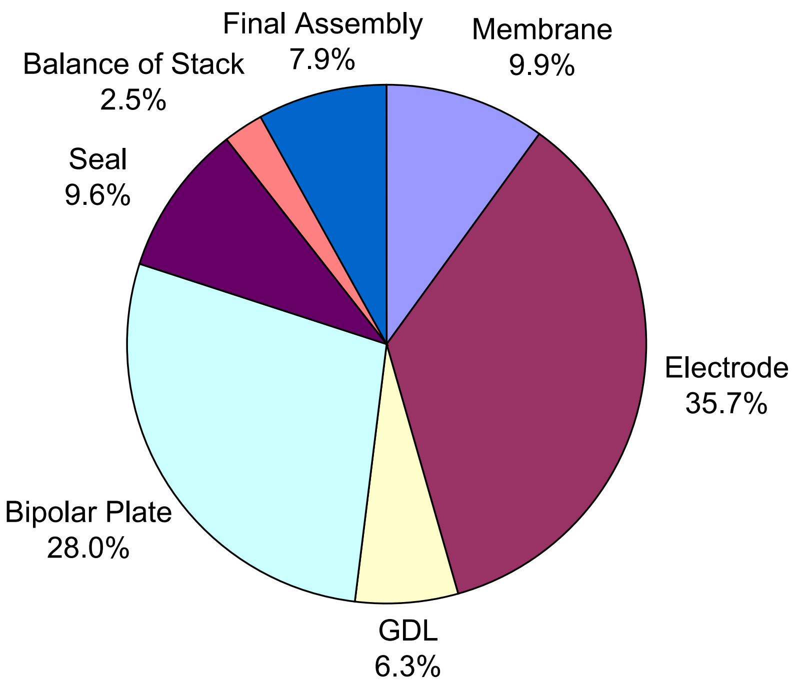
[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[2] Based on stack and system modeling results by ANL for 2010 PEMFC system: R. K. Ahluwalia and X. Wang, March 31, 2010.
[3] Assumes a Pt cost of $1,100/tr.oz., NSTFC-based MEA, and 20 μm reinforced PFSA membrane.
[4] S2: stack inlet pressure @ rated power = 1.5 atm, stack temperature = 75 °C
[5] Stack Assembly cost includes QC but not Stack Conditioning; QC includes visual inspection, and leak tests for fuel loop, air loop and coolant loop
[6] Task to “Estimate High-Volume Costs of Stack Conditioning” is planned to be completed in 2010, pending funding authorization from DOE
[7] Results may not appear to calculate due to rounding of the component cost results.

The preliminary cost estimate for the 2010 stack (S2-2) is ~$22/kW, which is similar to the 2009 stack cost.

Stack Manufactured Cost – 80 kW Direct-H_2 PEMFC

2009[1]: $22.3/kW; $1,787	2010 S2-2[1, 2, 3, 4]: $22.3/kW; $1,787





[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] Based on stack and system modeling results by ANL for 2010 PEMFC system: R. K. Ahluwalia and X. Wang, March 31, 2010.
[3] Assumes a Pt cost of $1,100/tr.oz., NSTFC-based MEA, and 20 μm reinforced PFSA membrane.
[4] S2: stack inlet pressure @ rated power = 1.5 atm, stack temperature = 75 °C

Preliminary 2010 stack (S2-2) manufactured costs on a net kW basis are similar to the 2009 stack costs.

Stack Manufactured Cost[1], $/kW	2009	2010 S2-2[2, 3, 4]	Δ%	Comments	2010 DOE Target
Membrane	1.9	2.2	+18%	3M PFSA ionomer (1.2*$80/lb) & ePTFE ($\$5/m^2$) included in 2010	10
Electrodes	10.6	8.0	-25%	Power density is higher for same Pt loading in 2010[2]; 2010: 930 mW/cm^2, 2009: 701 mW/cm^2	
GDL	1.6	1.4	-12%		
Seals	2.4	2.1	-11%		
Bipolar plates	2.9	6.2	+115%	Nitrided metallic plate in 2010	5
Balance of Stack (Stack manifold, tie bolts, end plates, current collectors, electrical insulators)	0.9	0.6	-39%	Power density is higher for same Pt loading in 2010[2]; 2010: 930 mW/cm^2, 2009: 701 mW/cm^2	
Stack Assembly[5, 6]	1.8	1.8	-11%		
Total Stack[7]	**22.3**	**22.3**	**0%**		**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).
[2] Based on stack and system modeling results by ANL for 2010 PEMFC system: R. K. Ahluwalia and X. Wang, March 31, 2010.
[3] Assumes a Pt cost of $1,100/tr.oz., NSTFC-based MEA, and 20 μm reinforced PFSA membrane.
[4] S2: stack inlet pressure @ rated power = 1.5 atm, stack temperature = 75 °C
[5] Stack Assembly cost includes QC but not Stack Conditioning; QC includes visual inspection, and leak tests for fuel loop, air loop and coolant loop
[6] Task to “Estimate High-Volume Costs of Stack Conditioning” is planned to be completed in 2010, pending funding authorization from DOE
[7] Results may not appear to calculate due to rounding of the component cost results.

The preliminary high-volume OEM cost of the 2010 PEMFC system for six scenarios[1, 2, 3] is estimated to range between $49/kW and $65/kW.

PEMFC System Cost[1] ($/kW)	2009 OEM Cost[4, 5]	2010 Stack Scenarios[1, 2, 3]					
		S1-1	S1-2	S1-3	S2-1	S2-2	S2-3
Stack[4]	**22.3**	**33.0**	**20.7**	**17.4**	**32.4**	**22.3**	**19.0**
Water Management[5, 6, 7]	**2.1**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**
Thermal Management[5, 7]	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Fuel Management[5, 7]	5.3	5.3	5.3	5.3	5.3	5.3	5.3
Air Management[5, 7, 8]	**12.3**	**12.2**	**12.4**	**12.9**	**9.9**	**10.4**	**10.6**
Balance of System[5, 7]	4.0	4.0	4.0	4.0	4.0	4.0	4.0
System Assembly	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Total System[4, 5, 6, 7]	**52.4**	**65.0**	**52.9**	**50.0**	**62.2**	**52.4**	**49.4**

[1] All scenarios assume a Pt cost of $1,100/tr.oz., NSTFC-based MEA, and 20 μm reinforced PFSA membrane.
[2] S1: 2.5 atm, 85 C; S2: 1.5 atm, 75 C
[3] Based on stack and system modeling results by ANL for 2010 PEMFC system: R. K. Ahluwalia and X. Wang, March 31, 2010.
[4] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[5] Assumes 15% markup to the automotive OEM for BOP components
[6] Water Management in 2010 preliminarily assumes cathode planar membrane humidifier and no anode humidifier
[7] Using 2009 cost numbers for BOP subsystems' preliminary cost; all BOP costs pending ANL input, are planned to be updated in 2010
[8] CEM motor controller cost varies based on preliminary modeling by ANL, of CEM parasitic power, for different scenarios

Summary

Preliminary 2010 Results

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

- Key conclusions and accomplishments:
  - The 2009 PEMFC stack cost[1] was estimated to range between $19/kW and $40/kW over six different scenarios.
  - The PEMFC stack and system costs[1, 2] were estimated to be $22/kW and $55/kW respectively, for the 2009 baseline scenario.
  - BOP, balance-of-system and system assembly costs together represented ~60% of the projected PEMFC system cost, for the 2009 baseline scenario.
  - Monte Carlo analysis shows that the 2009 PEMFC system OEM cost[1, 2] ranges between $45/kW and $97/kW (2σ), with a mean cost of $71/kW.
  - We participated in an independent peer-review of our cost analysis, and submitted a comprehensive report to DOE on our 2008 PEMFC cost analysis
  - Preliminary estimates for the manufactured cost[1] of the 2010 PEMFC stack, ranged between $17/kW and $33/kW over six different scenarios.
  - Preliminary estimates for the OEM cost[1, 2] of the 2010 PEMFC system, ranged between $49/kW and $65/kW over six different scenarios.
- Next steps:
  - Finalize baseline scenario for 2010 PEMFC system, and develop BOP cost estimates
  - Finalize reinforced membrane, non-woven GDL and metal bipolar plate (thermal nitrided and Au-Nanoclad) cost estimates for baseline scenario for 2010 PEMFC stack
  - Develop bottom-up cost projection for stack conditioning[3]
  - Perform single-variable and Monte Carlo sensitivity analyses on stack and system costs

[1] High-volume manufactured cost based on a 80 kW net power PEMFC net power system.
[2] 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.
[3] Task to "Estimate High-Volume Costs of Stack Conditioning" is planned to be completed in 2010, pending funding authorization from DOE

Acknowledgement

We would like to thank the DOE for supporting this project over the past five years, and acknowledge valuable discussions with OEMs, FCTT, developers, national labs, and equipment manufacturers.

- Key discussions this year to date include:
  - Ballard Material Products
  - Ford Motor Co.
  - Oak Ridge National Laboratory
  - Argonne National Laboratory
  - Several equipment manufacturers
  - Independent Peer Review Panel

Thank You!

Supplemental Slides

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 – Mar 09	Telecon
Several Work-in-Progress Mtgs. with DOE and ANL	Feb 09 – Sep 09	Telecon
DOE Annual Merit Review	May 09	Arlington VA
Fuel Cell Tech Team Review	Aug 09	Telecon
Several Telecons & Mtgs. with Ford, Ballard Material Products, ORNL, ANL, and others	Feb 10 – present	Telecon
DOE Annual Merit Review	June 10	Washington DC

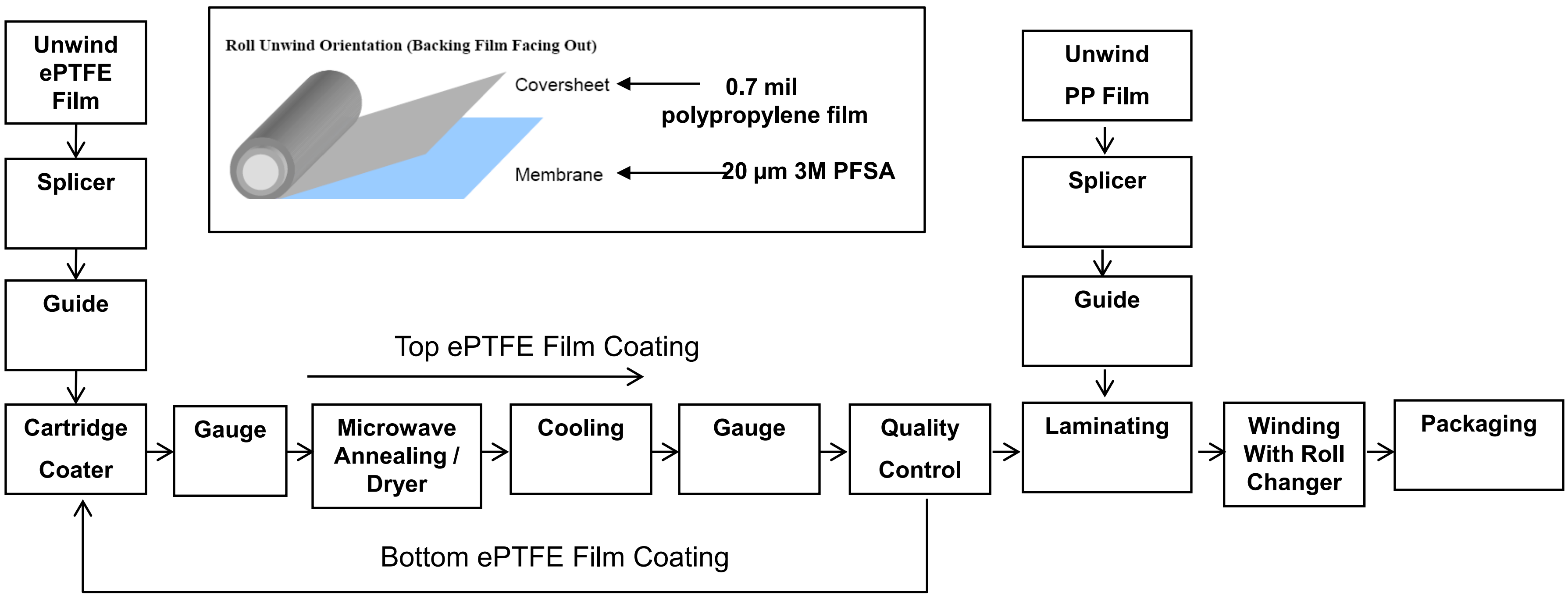
ANL modeled a 3M PFSA membrane, with a Gore-Select® type of support, and total thickness of 20 microns.

	ePTFE	3M PFSA ionomer Supported Membrane
Thickness (µm)	20	20
Porosity (%)	95%	-
Bulk Density (g/cm^3)	0.098	1.97

- Impregnation of ePTFE layer with liquid ionomer solution is not suitable for a high-volume manufacturing process because both the ePTFE and ionomer film are hydrophobic. Impregnation times can be unacceptably long and repeated impregnations are needed.
  - US 6156451 (Dupont)
  - S. Ahn, Y. Lee, H. Ha, S. Hong, I. Oh, Properties of the reinforced composite membranes formed by melt-soluble ion-conducting polymer resins for PEMFCs, Electrochim. Acta 50 (2004) 571–575.
  - T.Yu,H. Lin, K. Shen, L. Huang,Y. Chang, G. Jung, J. Huang, Nafion/PTFE composite membranes for fuel cell applications, J. Polym. Res. 11 (2004)
- A double-side dispersion coating process is used in our analysis
  - US 2008/0269409 (Dupont)

We assumed a double-side dispersion coating process for membrane fabrication.

We used US 2008/0269409 to adapt our existing 3M PFSA membrane fabrication process to an ePTFE-supported membrane process.



We assumed a double-side dispersion coating process for membrane fabrication.

Progress 2010 Stack S2-2 *GDL Configuration*

Preliminary 2010 Results

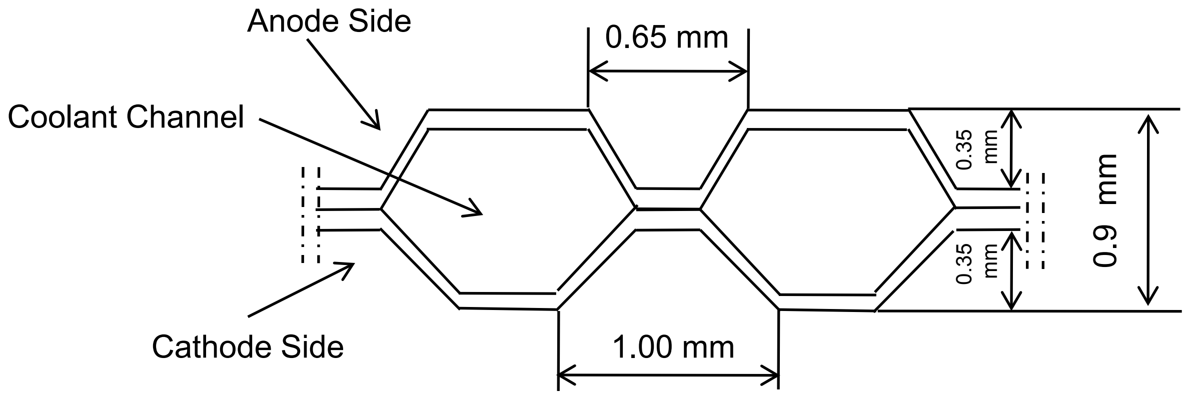
In 2010, we costed a non-woven carbon paper GDL with PTFE+MPL.

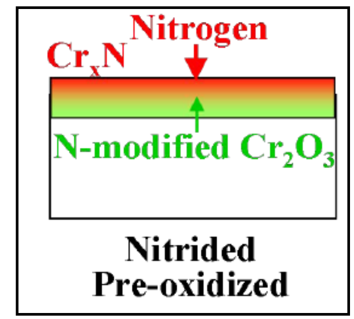
• Bill of Materials	• Process
2009 GDL: Woven carbon cloth MPL: 47% PTFE, 53% Carbon black **2010 GDL**: We developed a separate BOM for bare GDL+ PTFE+MPL GDL: non-woven carbon fiber paper, 10 wt% PTFE MPL: 50% PTFE, 50% Carbon black	**2009 GDL**: Purchase untreated woven carbon cloth Coat hydrophobic PTFE and MPL together **2010 GDL**: Fabricate non-woven carbon paper Hydrophobic treatment MPL coating

Material	Pressure (kPa)	Bare GDL	GDL with PTFE Treatment	GDL with PTFE Treatment + MPL
Thickness (µm)	50	185		225
Porosity (%)	250	90%	88%	80%
Areal Weight (g/m^2)		40	44	75
Materials		Carbon Fiber loading: 15 g/m^2 Ink/Resin loading: 25 g/m^2	10 wt% PTFE treatment PTFE loading: 4 g/m^2	PTFE loading: 15 g/m^2 Carbon black loading: 16 g/m^2
Comments		AvCarb® EP40 Assume that process starts with PAN-precursor commercial-grade carbon fiber Carbon fiber price: $8/lb	PTFE Cost: $9.41/lb	AvCarb® GDS3250 Carbon Black Cost: $1.52/lb

In 2009 and previous years, we combined the GDL hydrophobic coating and MPL coating together and treated them as a single process step.

Fe-20Cr-4V was picked as the base metal alloy, with nitridation surface treatment.





Ref.1

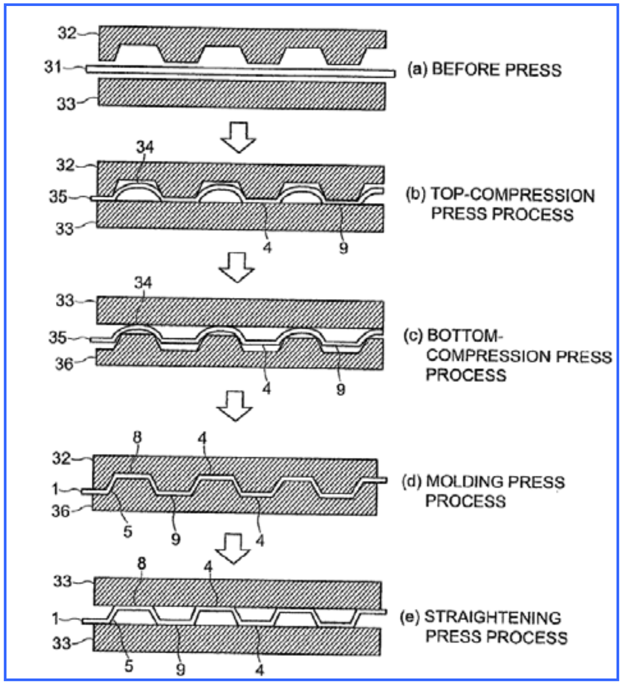
Parameter	Specifications
Bipolar Plate Area (cm^2)	260
Base Material Thickness[3] (mm)	0.1
Base Material	Fe-20Cr-4V
Base Material Surface Treatment	Pre-oxidation + Nitridation
# of Tiles in a Bipolar Plate	2
Cooling Channels?	Yes
Joint Method	Laser Welding Edge

Parameter	Dimensions
Anode Side Channel Width[2] (mm)	0.65
Anode Side Channel Depth[2] (mm)	0.35
Anode Side Flow Channel Area as % of Active Area	50%
Cathode Side Channel Width[2] (mm)	1.00
Cathode Side Channel Depth[2] (mm)	0.35
Total Thickness (mm)	1.10
Cathode Side Flow Channel Area as % of Active Area	75%
Overall Active Area	75%
Cavity as % of Active Area	73%
Cavity as % of non Active Area	87%

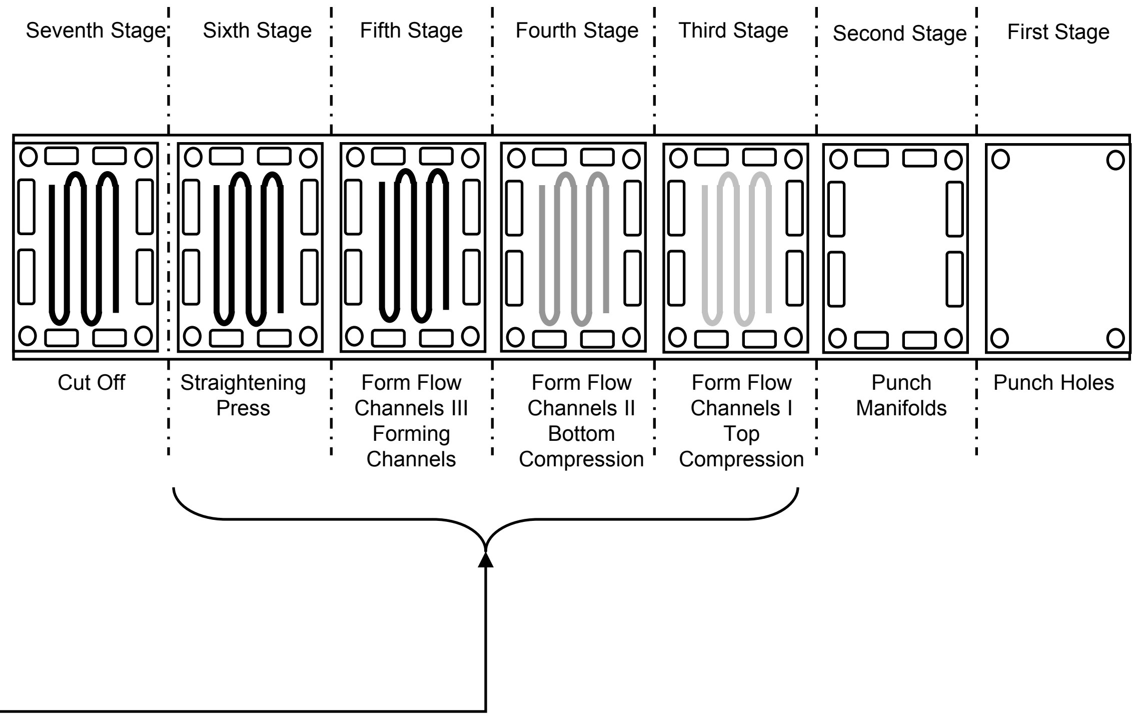
The base metal foil thickness is 0.1 mm and the overall bipolar plate thickness is 0.9 mm.

1. Nitrided metallic bipolar plates, M.P. Brady, et al., ORNL, DOE Merit Review presentation, May 2009
2. GM patents: US 20070082252; US 7,291,414; US 20090186253
3. Discussion with ORNL, April 2010

A seven-stage progressive die is assumed, in order to prevent cracks during the thin metal forming process. The tooling cost is ~$300,000[1].



US Patent: 20090081520 (Hitachi)

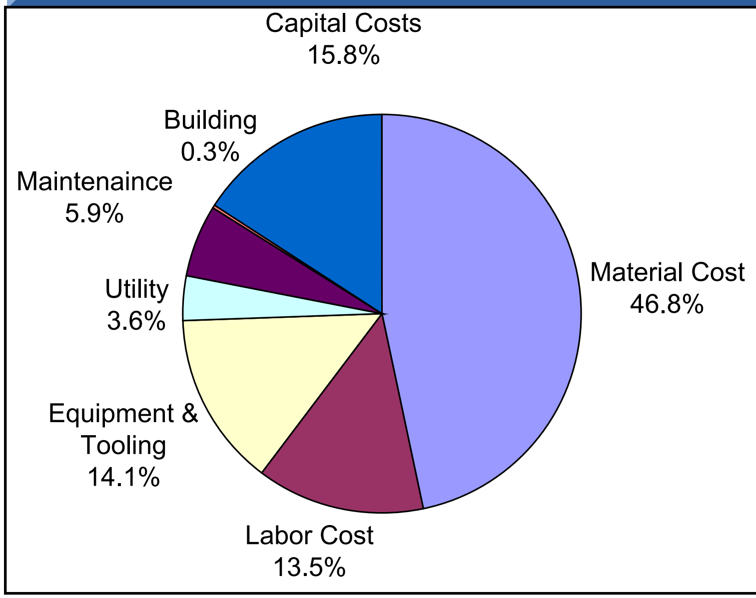


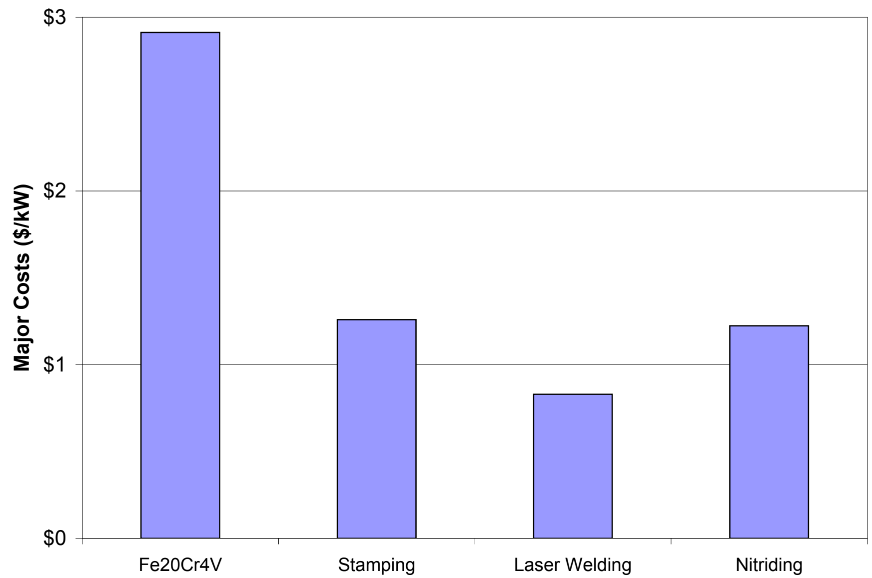
A 300 ton press with a coil feed line are assumed, with a production rate of 30 parts per minute[1].

1. Discussion with Minster Press Inc., April 2010

The preliminary cost of the 2010 nitrided metal bipolar plates is estimated to be ~$6/kW. The substrate alloy, stamping process, and nitriding process are the major cost drivers.

Metal Bipolar Plate Manufactured Cost ($6.2/kW)





Cost of Metal Foil	Bipolar Plate Cost ($/kW)
$3/lb Foil	5.0
$5/lb Foil (baseline)	6.2
$7/lb Foil	7.4

A quartz lamp nitriding process will be considered as a path to cost reduction, due to much reduced cycle time of ~10 minutes.

US 20070082252; US 7,291,414 (GM)

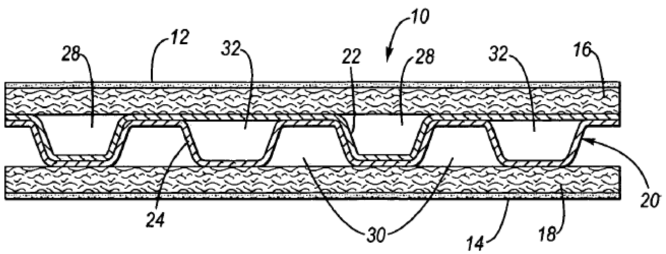


Fig. 1

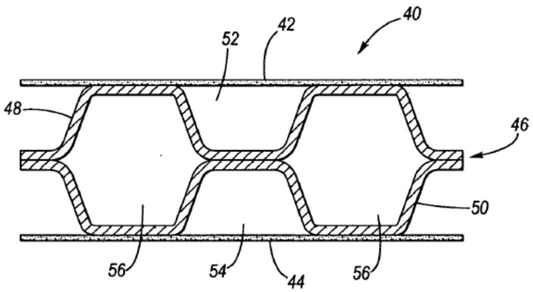


Fig. 2

TABLE I

Parameter	Nested[1]	Non-Nested[2]	Nested[3]
Cathode channel depth (mm)	0.34	0.35	0.34
Anode channel depth (mm)	—	0.31	—
Feed channel depth (mm)	0.17	—	0.17
Repeat distance (mm)	0.97	1.29	0.97
Anode ΔP (kPa)	13	13	30
Cathode ΔP (kPa)	30	30	85
Coolant ΔP (kPa)	57	22	106
Power density (kW/l)	6.0	4.8	6.3
Thermal mass (kJ/K)	20	27	19

[1]Nested in active feed region, non-nested in inactive feed regions, and with no diffusion media in the inactive feed regions.
[2]Non-nested, and no inactive feed regions.
[3]Nested in active feed region, and non-nested in inactive feed regions, with diffusion media in the inactive feed regions.

[0038] Table I below provides a comparison of various parameters discussed above for a nested plate design according to the present invention having no diffusion media in the inactive feed regions, a non-nested plate design, and a nested plate design having diffusion media in the inactive feed regions. This data is from a fuel cell stack including a 360 cm^2 active area, 200 cells, 66 kW output power, 1.5 A/cm^2 current density and a low pressure. The nested designs are smaller than the non-nested designs, have a higher power density (higher kW/liter), and have an even greater reduction in thermal mass from 27 to 19-20 kJ/kilogram due to the reduced coolant volume. The nested plate design having diffusion media in the inactive feed regions produces very shallow feed channels in the inactive feed regions and leads to an unacceptably high pressure drop (85 kPa vs. 30 kPa on the cathode side).

US 20090186253 (GM): 0.55 mm wide, 0.29 mm deep channels

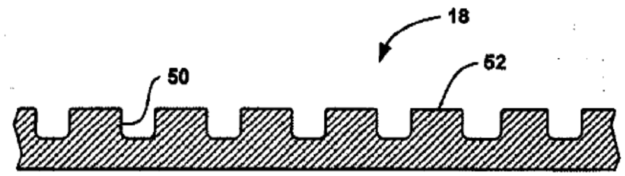


FIGURE 2
PRIOR ART

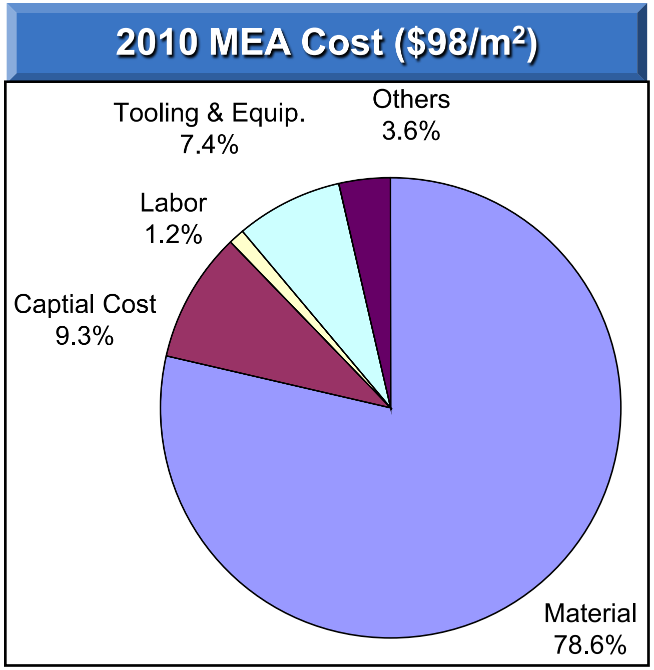
[0012] Current fuel cell stack designs typically focus on achieving high volumetric power density by reducing the active area of the fuel cell and increasing the current density. The key enabling design features of the bipolar plate **18** for this purpose include elimination of serpentine flow channels on the cathode side **12** to avoid accumulation of liquid water in the U-bends of the channels **50**, and the reduction of the channel-to-channel pitch to maximize the utilization of the catalyst layer **22** under the lands **52** in the absence of a significant channel-to-channel pressure gradient. In this design, the cathode side bipolar plate **18** includes 108 nearly rectangular channels **50** with a width of 0.55 mm and a depth of 0.29 mm and a land width of 0.65 mm. These flow field plates provide operation above 600 mV at 1.5 A/cm^2. One example of such a flow field plate is disclosed in U.S. patent application Ser. No. 10/669,479, titled Flow Field Plate Arrangement For A Fuel Cell, filed Sep. 24, 2003.

Progress 2010 Stack S2-2 *MEA Cost*

Preliminary 2010 Results

Using S2-2 as an example scenario, we determined the cost breakout for the MEA; materials represent ~79% of the $98/m^2 MEA cost in 2010.

Manufactured Cost	2009 MEA[1] ($/m^2)	2010 MEA[1] ($/m^2)
Material *- Membrane* *- Electrode* *- GDL*	76.70 - 9.77 - 58.69 - 8.23	77.19 - 15.99 - 59.14 - 2.05
Capital Cost	6.18	9.09
Labor	3.85	1.15
Tooling & Equipment	4.21	7.32
Other[2]	2.03	3.51
Total	**93**	**98**



The preliminary estimate for the 2010 MEA cost is higher due to increased ionomer and ePTFE costs for the reinforced membrane, the reduction in active area ratio[3] from 85% to 75%, reduction in MEA utilization from 100% to 95%, and refinement of GDL costing.

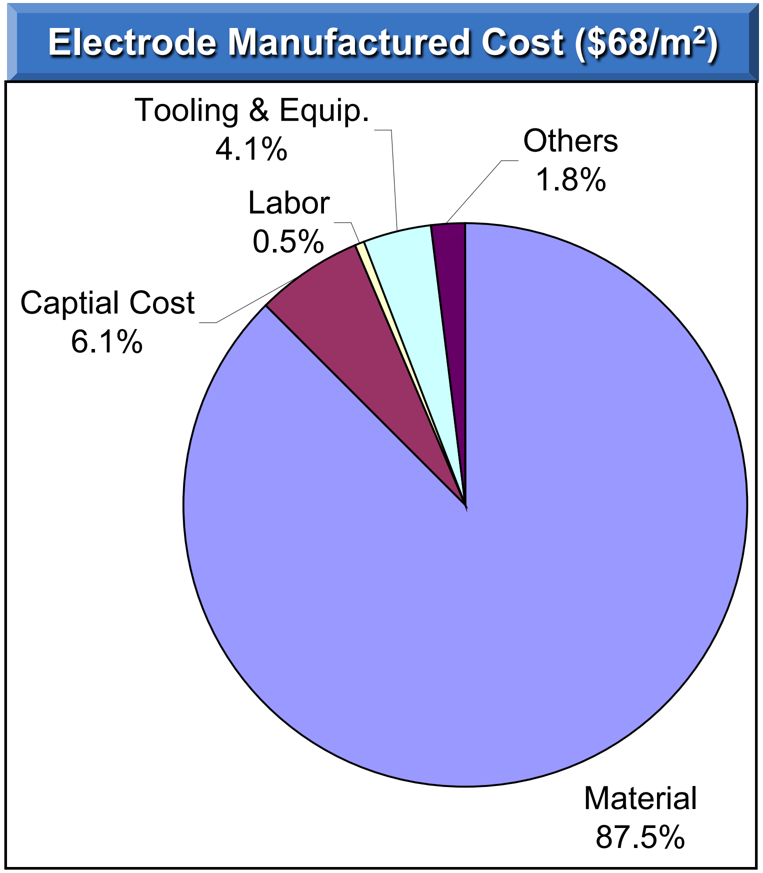
TIAX

[1] m^2 of active area and kW of net power
[2] Other costs include utilities, maintenance, and building

Platinum price dominates the preliminary 2010 electrode cost estimate of $68/m². 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	20.25	38.89	59.14
Capital Cost	1.58	2.56	4.14
Labor	0.16	0.19	0.35
Tooling	1.12	1.65	2.77
Other[2]	0.50	0.72	1.22
Total	**23.61**	**44.02**	**67.63**

[1] m² of active area
[2] Other costs include utilities, maintenance, and building



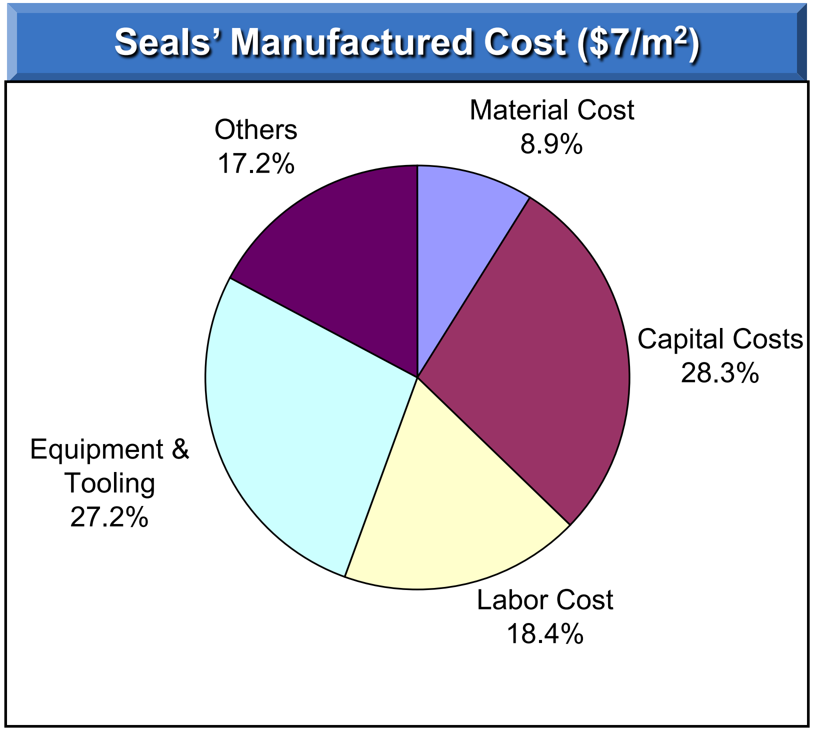
Platinum at $1,100/tr.oz. is close to the average price ($1,096/tr.oz.) over the last year.

Progress 2010 Stack S2-2 *Seal Cost*

The preliminary cost of the 2010 seals is estimated to be ~$7/m².

Manufactured Cost[1]	Seals ($/m²)
Material	0.63
Capital Cost	1.99
Labor	1.30
Tooling	1.92
Other[2]	1.22
Total	**7.05**

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



Transfer molding is used to fabricate the seals between the MEA and bipolar/cooling plate. The seal material is Viton® which costs ~$20/lb.

Progress 2010 Stack S2-2 *Cost Breakdown*

Preliminary results of 2010 PEM fuel cell stack (S2-2) cost breakdown.

Stack Costs		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 ($)	Total Fuel Cell Module Cost ($/kW)
		Mtl Cost ($/m²)	Process Cost ($/m²)	Total Cost ($/m²)	Unit Cell Weight/Area (g/cm²)					
MEA	Anode GDL	$1.0	$4.9	$5.9	$0.0	$1.8	$9.7	$46.3	$56.0	$0.7
	Anode Active Layer	$20.2	$3.4	$23.6	$0.0	$0.0	$190.6	$31.6	$222.2	$2.8
	Electrolyte	$16.0	$2.7	$18.7	$0.0	$0.3	$150.6	$25.8	$176.3	$2.2
	Cathode Active Layer	$38.9	$5.1	$44.0	$0.0	$0.0	$366.1	$48.3	$414.4	$5.2
	Cathode GDL	$1.0	$4.9	$5.9	$0.0	$1.8	$9.7	$46.3	$56.0	$0.7
MEA Total		**$77.2**	**$21.1**	**$98.3**	**0.04**	**4**	**$727**	**$198**	**$925**	**$12**
Bipolar Coolant Plate		$24.8	$28.1	$52.9	$0.1	$20.1	$233.0	$264.9	$497.9	$6.2
Bipolar Interconnect[2]		$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Gaskets						$1.2	$59.3	$112.6	$171.9	$2.1
End Plates						$0.7	$2.9	$1.2	$4.1	$0.1
Current Collector						$0.4	$1.0	$0.5	$1.6	$0.0
Insulator						$0.3	$6.3	$0.4	$6.8	$0.1
Outer Wrap						$1.8	$5.5	$2.4	$7.9	$0.1
Tie Bolts						$2.9	$23.3	$1.8	$25.1	$0.3
Final Assy								$141.3	$141.3	$1.8
Total Unit Cell		**$101.9**	**$49.2**	**$151.2**	**0.11**	**31**	**$1,058**	**$724**	**$1,781**	**$22.3**

1 High-volume manufactured cost on an active area basis, for a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
2 Based on stack and system modeling results by ANL for 2010 PEMFC system: R. K. Ahluwalia and X. Wang, March 31, 2010.
3 Assumes a Pt cost of $1,100/tr.oz., NSTFC-based MEA, and 20 μm reinforced PFSA membrane.
4 S2: stack inlet pressure @ rated power = 1.5 atm, stack temperature = 75 °C
5 Stack Assembly cost includes QC but not Stack Conditioning ; QC includes visual inspection, and leak tests for fuel loop, air loop and coolant loop
6 Task to "Estimate High-Volume Costs of Stack Conditioning" is planned to be completed in 2010, pending funding authorization from DOE

Stack performance assumptions were updated by ANL based on their modeling of an NSTFC-based MEA and a 20 μm PFSA membrane.

Key Stack Performance Assumptions		2005[1]	2007[2,3]	2008[4]	2009[5]
Net power	kW_e	80	80	80	80
Gross power	kW_e	**89.5**	**86.4**	**86.9**	**92.1**
Gross power density	mW/cm^2	**600**	**753**	**716**	**701**
Cell voltage (rated power)	V	0.65	0.68	0.685	0.693
Pt loading (total)	mg/cm^2	**0.75**	**0.30**	**0.25**	**0.15**
Membrane thickness	μm	50	30	30	20
Stack temperature	ºC	80	90	90	90
Pressure (rated power)	atm	2.5	2.5	2.5	2.5
Stack eff. (rated power)	% LHV	52	54	54	55

[1] E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, NREL/SR-560-39104, Sep 30, 2005
[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
[5] R. K. Ahluwalia and X. Wang, Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading, July 21, 2009

Key assumptions in 2009 represent ANL's inclusion of new performance data from 3M at the cell/short-stack level, and from Honeywell on the CEM parasitic power.

2009 stack costs on a per kW basis are lower than the 2008 stack costs primarily due to the lower Pt loading, thinner membrane, and reduced stack assembly time.

Stack Manufactured Cost[1], $/kW	2005	2007	2008	2009	2010 DOE Target
Membrane	4	2	2	2	10
Electrodes	52	18	16	11	
GDL	3	2	2	2	
Seals	1	2	2	2	
Bipolar plates	3	3	3	3	5
Balance of Stack (Stack manifold, tie bolts, end plates, current collectors, electrical insulators)	1	1	1	1	
Stack Assembly[2]	2	3	3	2	
Total[3]	**67**	**31**	**29**	**22**	**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).
[2] Stack Assembly cost in 2005 includes neither QC nor Stack Conditioning, while in 2007-2009, it includes QC but not Stack Conditioning.
[3] Results may not appear to calculate due to rounding of the component cost results.

2009 stack costs on an active area basis are lower than the 2008 stack costs primarily due to the lower Pt loading, thinner membrane, and reduced stack assembly time.

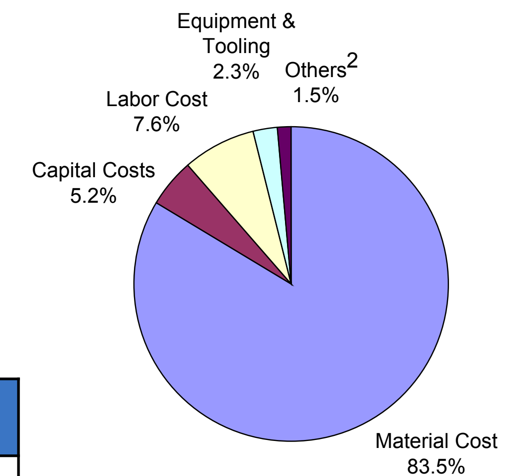
Stack Manufactured Cost[1], $/m²	2005	2007	2008	2009
Membrane	23	16	16	11
Electrodes	279	120	102	65
GDL	18	13	13	10
Seals	6	13	13	15
Bipolar plates	17	18	18	18
Balance of Stack (Stack manifold, tie bolts, end plates, current collectors, electrical insulators)	6	6	6	6
Stack Assembly[2]	10	23	23	12
Total[3]	**361**	**210**	**191**	**136**

[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] Stack Assembly cost in 2005 includes neither QC nor Stack Conditioning, while in 2007-2009, it includes QC but not Stack Conditioning.
[3] Results may not appear to calculate due to rounding of the component cost results.

Material costs represent ~84% of the Balance of Stack cost because the components have relatively simple, mature manufacturing processes.

Balance of Stack Cost[1] ($)	
Component	**Cost ($)**
Current Collectors	3.7
Insulators	18.2
End Plates	10.2
Tie Bolts	21.4
Stack Manifold / Outer Wrap	21.2
Total	**74.7**

Balance of Stack Cost[1] ($75/system)



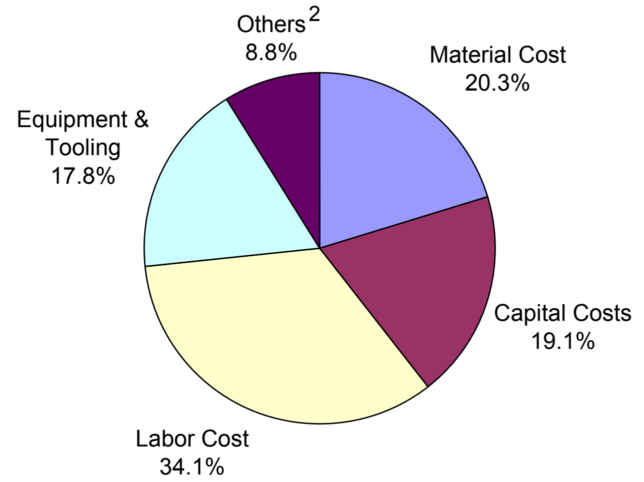
Process Name	Capex Per Station ($)	# of Stations	Labor Per Station	Cycle Time (sec/unit)	Required Space (m^2)	Equipment Power (kW)
Die Cast Endplate	300,000	1	1	10	40	10
Die Cut Endplate Insulator	40,000	2	1	5	10	5
Cut T- Bolt	20,000	3	0.5	30	20	5
Wrap Manufacturing - Shear Stock	40,000	5	1	0.5	10	3
Wrap Manufacturing - Turret Punch	250,000	1	0.5	28	40	5
Wrap Manufacturing - Bend	105,000	1	1	65	160	5

[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] Other costs include utilities, maintenance, and building

The assembly of the stack repeat units is assumed to be robotic, while the assembly of the balance of stack components is a manual process.

Stack Assembly Cost[1] ($)	
Component/Process	**Cost ($)**
Repeat parts (robotic)	131.3
Non-repeat parts (manual)	5.2
Stack Quality Control[3]	22.4
Total	**158.9**

Stack Assembly Cost[1] ($159/system)



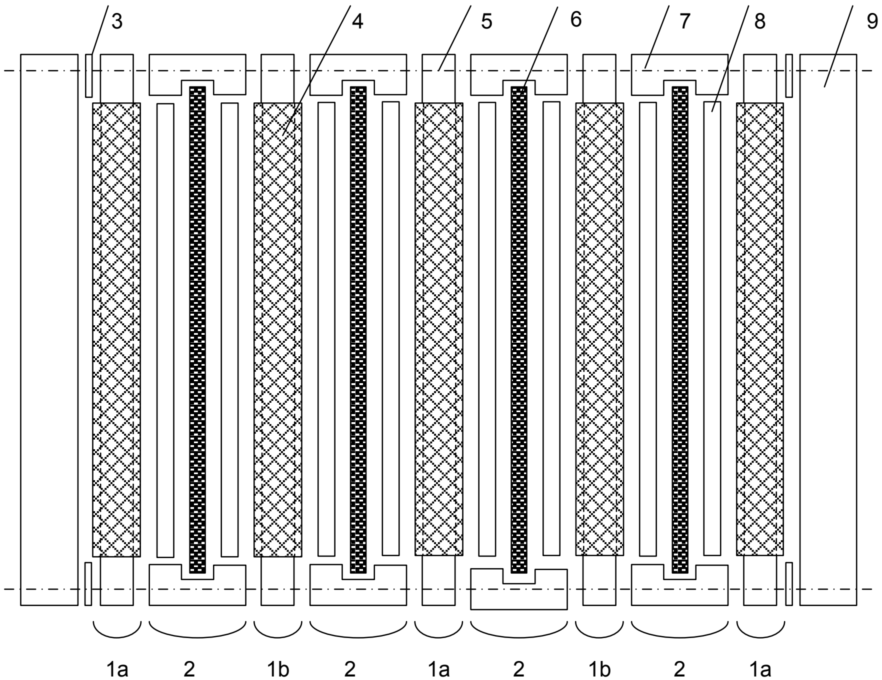
Process Name	Capex Per Station ($)	# of Stations	Labor Per Station	Cycle Time (sec/unit)	Required Space (m^2)	Equipment Power (kW)
Stack Assembly	400,000	83	0.2	1,135	20	10
Balance of Stack Assembly	20,000	44	0.2	600	20	5
Stack QC[3]	300,000	66	0.2	900	20	5

[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] Other costs include utilities, maintenance, and building
[3] Stack QC includes visual inspection, and leak tests for fuel loop, air loop and coolant loop
[4] Task to "Estimate High-Volume Costs of Stack Conditioning" is planned to be completed in 2010, pending funding authorization from DOE

We estimate that 2 stacks and the BOS are assembled in ~1 hour. Stack assembly cost includes stack QC[3], but not stack conditioning / burn-in costs[4].

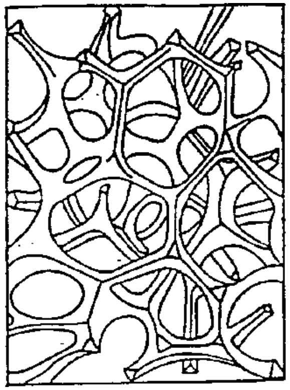
BOS = Balance of Stack QC = Quality Control

We developed 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

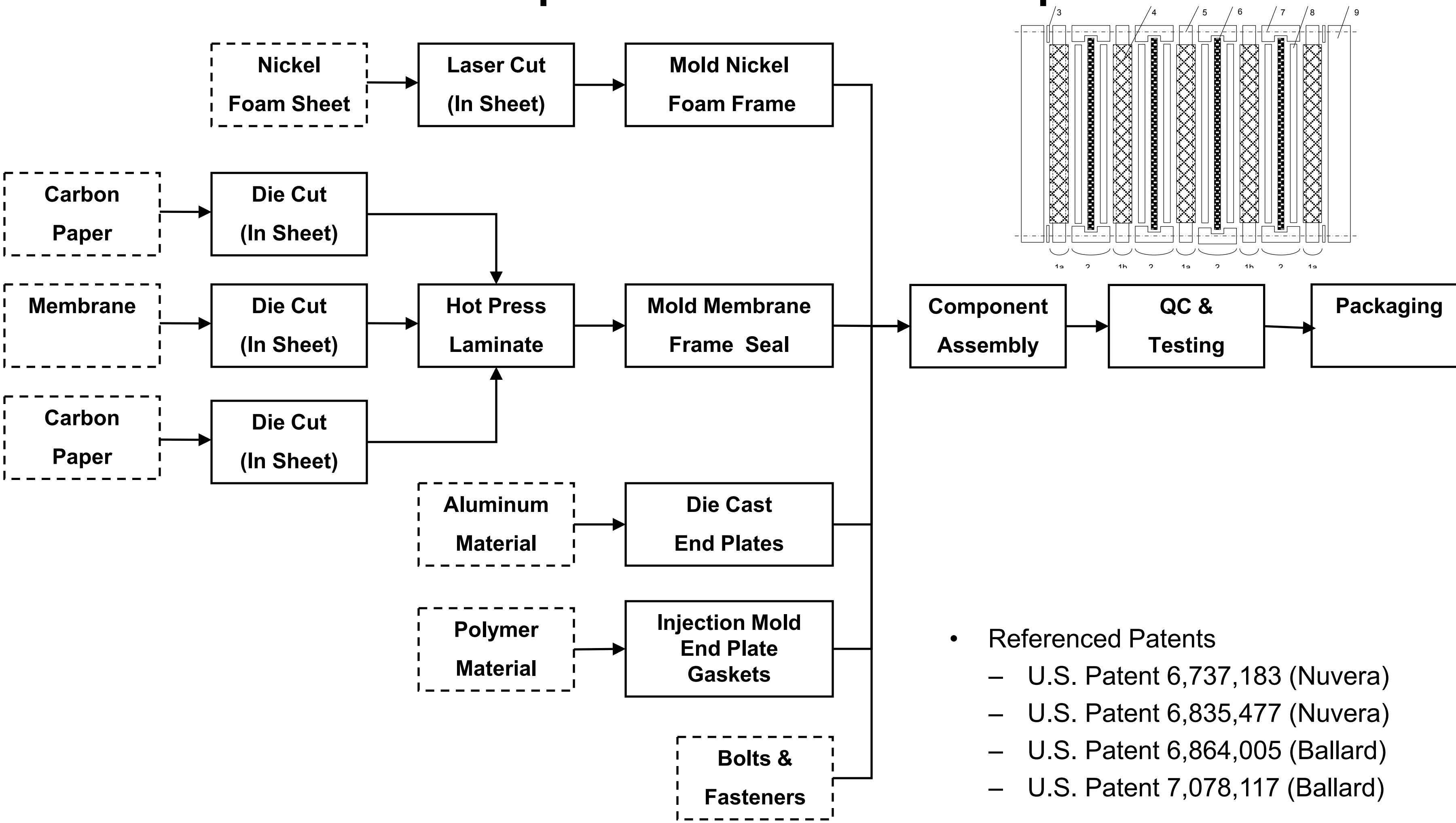
- Referenced Patents
  - U.S. Patent 6,737,183 (Nuvera)
  - U.S. Patent 6,835,477 (Nuvera)
  - U.S. Patent 6,864,005 (Ballard)
  - U.S. Patent 7,078,117 (Ballard)



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

[1] R. K. Ahluwalia and X. Wang, Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading, July 21, 2009

We developed bottom-up manufacturing costs for the planar membrane humidifier based on ANL specifications[1] and other patents.



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

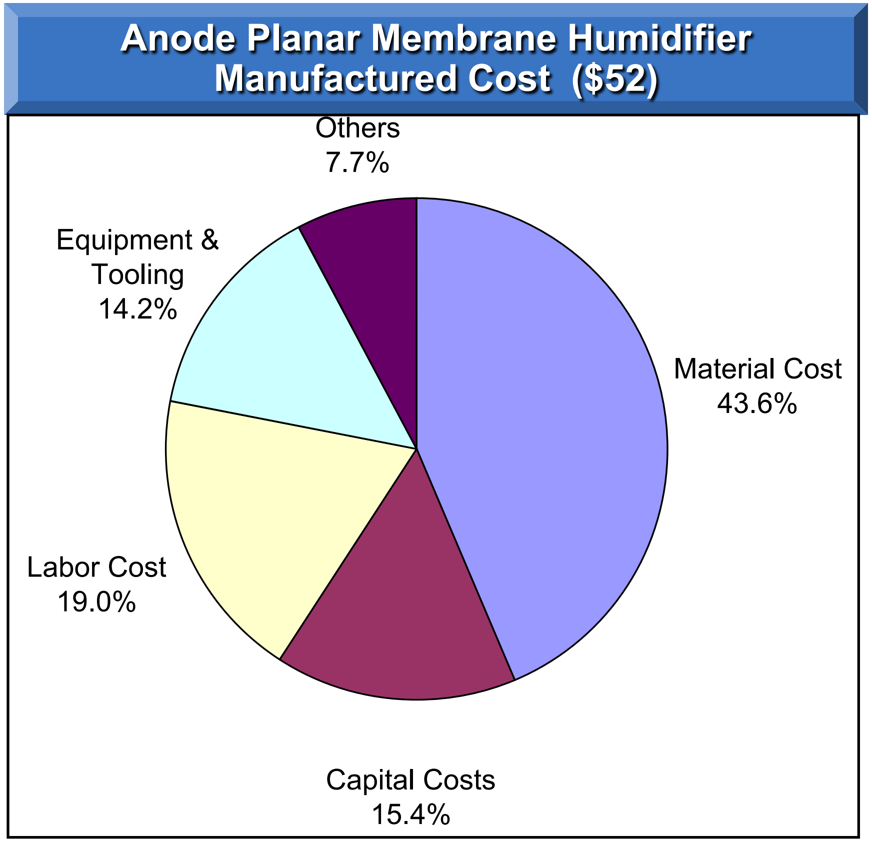
[1] R. K. Ahluwalia and X. Wang, Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading, July 21, 2009

Bill of Materials for the cathode/anode planar membrane humidifiers

Cathode Planar Membrane Humidifier			
Component	**#**	**Material**	**Size (mm)**
Membrane	42	Nafion®	400 (length), 140 (width), 0.03 (thickness)
GDL	84	Woven carbon fiber	300 (length), 120 (width), 0.1 (thickness)
Nickel Foam	43	Nickel foam	300 (length), 120 (width), 1.5 (thickness)
Frame	43	HDPE	400 (length), 140 (width), 1.5 (thickness)
Membrane Gasket	42	Nitrile rubber	400 (length), 140 (width), 0.22 (thickness)
End Plate	2	Al	400 (length), 140 (width), 20 (thickness)
End Plate Gasket	2	Nitrile rubber	400 (length), 140 (width), 0.22 (thickness)
Bolt	4	Misc.	101 (length), 10 (OD)
Washer	4	Misc.	-
Nut	4	Misc.	-

Anode Planar Membrane Humidifier			
Component	**#**	**Material**	**Size (mm)**
Membrane	22	Nafion®	350 (length), 120 (width), 0.03 (Thickness)
GDL	44	Woven carbon fiber	250 (length), 100 (width), 0.1 (thickness)
Nickel Foam	23	Nickel foam	250 (length), 100 (width), 1.5 (thickness)
Frame	23	HDPE	350 (length), 120 (width), 1.5 (thickness)
Membrane Gasket	42	Nitrile rubber	350 (length), 120 (width), 0.22 (thickness)
End Plate	2	Al	350 (length), 120 (width), 20 (thickness)
End Plate Gasket	2	Nitrile rubber	350 (length), 120 (width), 0.22 (thickness)
Bolt	4	Misc.	68 (length), 10 (OD)
Washer	4	Misc.	-
Nut	4	Misc.	-

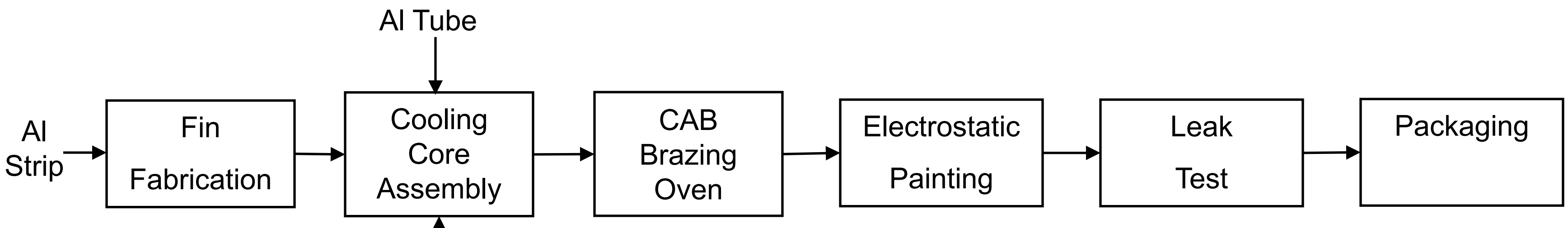
Material costs represent approximately 44% of the anode planar membrane humidifier manufactured cost of $52.

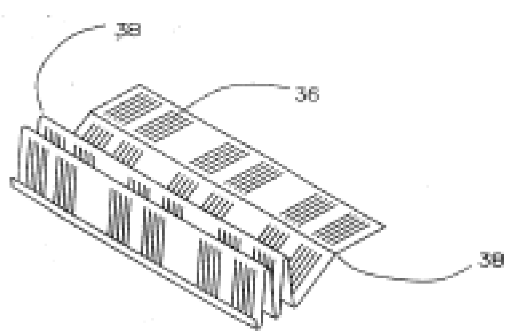


Anode Planar Membrane Humidifier Manufactured Cost ($)			
Process	**#**	**Material**	**Process**
Die Cut GDL	1	0.91	1.05
Die Cut Membrane	2	3.68	1.12
Hot Press Lamination	3	0.00	3.18
Injection Molding Frame Seal	4	0.00	2.20
Laser Cut Nickel Foam	5	5.74	9.09
Injection Molding Foam Frame	6	2.35	2.47
Injection Molding End Plate Gasket	7	0.09	0.45
Die Casting End Plate	8	7.11	1.26
Component Assembly	9	0.00	3.62
QC & Testing	10	0.00	3.56
Packaging	11	0.00	1.06
Fastener Cost	-	2.63	0.00
Total	**-**	**52**	

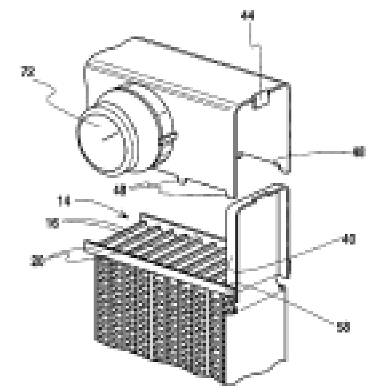
The high-volume manufactured cost of the cathode planar membrane humidifier is estimated to be $96.

We developed a manufacturing process flow chart for the HT and LT radiators 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 for developing a Bill of Materials for the HT/LT radiators.

High-Temperature (HT) Radiator

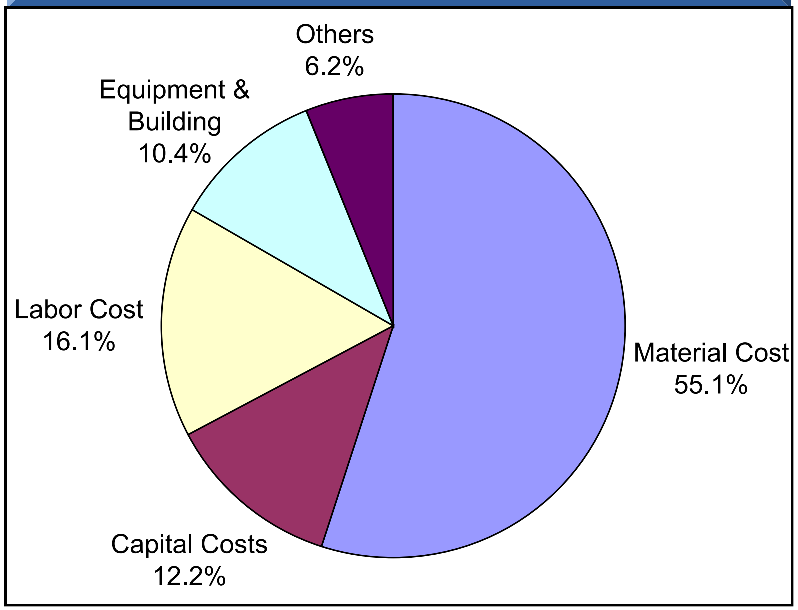
#	Components	#	Mtl.	Size (L x W x H) (mm)
1	Serpentine Louvered Fin	39208	Al 3003	59.70 x 4.44 x 0.10
2	Core Tube	61	Al 3003	700.00 x 59.70 x 2.80
3	Inlet Header, Solder Well Type	1	Al 3003	546.00 x 99.70 x 1.80
5	Outlet Header, Solder Well Type	1	Al 3003	546.00 x 99.70 x 1.80
8	Top Side Piece	1	Al 3003	720.00 x 99.70 x 1.80
9	Bottom Side Piece	1	Al 3003	720.00 x 99.70 x 1.80
10	Inlet Tank	1	Al 3003	446.00 x 140.00 x 1.80
11	Inlet Hose Connection	1	Al 3003	50.40
12	Outlet Tank	1	Al 3003	446.00 x 140.00 x 1.80
13	Outlet Hose Connection	1	Al 3003	50.40
14	Filler neck/Overflow Tub	1	Al 3003	25.40
15	Drain Fitting	1	Al 3003	25.40
16	Heater Return Line Connection	1	Al 3003	25.40
17	Coolant Level Indicator Fitting	1	Al 3003	25.40

Low-Temperature (LT) Radiator

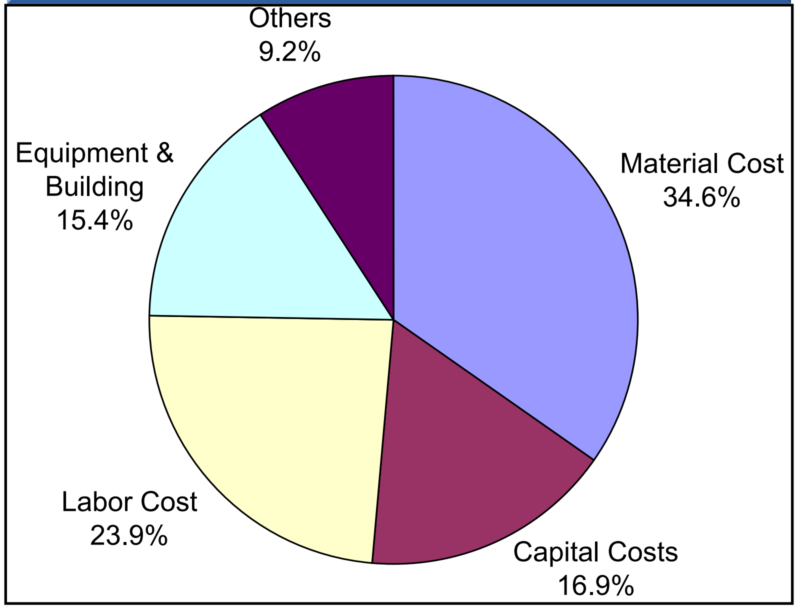
#	Components	#	Mtl.	Size (L x W x H) (mm)
1	Serpentine Louvered Fin	38381	Al 3003	17.00 x 4.04 x 0.08
2	Core Tube	64	Al 3003	700.00 x 17.00 x 2.80
3	Inlet Header, Solder Well Type	1	Al 3003	523.80 x 57.00 x 1.80
5	Outlet Header, Solder Well Type	1	Al 3003	523.80 x 57.00 x 1.80
8	Top Side Piece	1	Al 3003	720.00 x 57.00 x 1.80
9	Bottom Side Piece	1	Al 3003	720.00 x 57.00 x 1.80
10	Inlet Tank	1	Al 3003	423.80 x 140.00 x 1.80
11	Inlet Hose Connection	1	Al 3003	50.40
12	Outlet Tank	1	Al 3003	423.80 x 140.00 x 1.80
13	Outlet Hose Connection	1	Al 3003	50.40
14	Filler neck/Overflow Tub	1	Al 3003	25.40
15	Drain Fitting	1	Al 3003	25.40
16	Heater Return Line Connection	1	Al 3003	25.40
17	Coolant Level Indicator Fitting	1	Al 3003	25.40

The HT radiator manufactured cost is projected to be $83, while the LT radiator manufactured cost is projected to be $56.

HT Radiator Manufactured Cost ($83)



LT Radiator Manufactured Cost ($56)



Since the electric drive motor accounts for 10 kW of the 12.9 kW heat duty of the LT radiator, we account for ~22.5% of the $56/unit cost of the LTR within the scope of the Fuel Cell System cost.

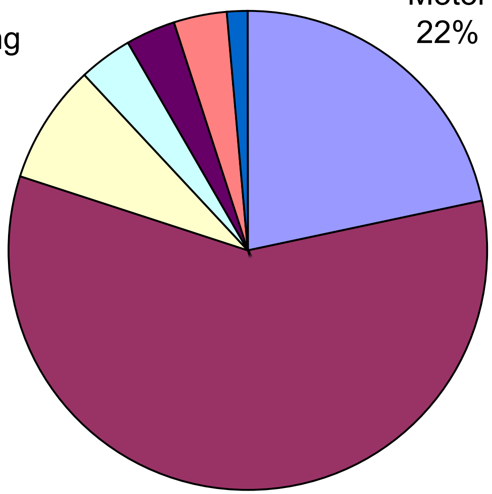
The motor assembly and motor controller are projected to cost $564, representing 82% of the CEM manufactured cost.

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	**9.3 kW_e Inverter with DSP controller**	**372**	$40/kW from "A Novel Bidirectional Power Controller for Regenerative Fuel Cells", Final Report for DE-FG36-04GO14329, J. Hartvigsen and S.K. Mazumder, Oct. 10, 2005
	Packaging, Wire harness, thermal management, etc	30	
Total Motor Cost ($/unit)		**564**	

The 9.3 kW_e inverter is projected to dominate the motor controller cost.

The CEM manufactured cost of $687, is the single largest cost contributor to the overall BOP cost.

CEM Manufactured Cost ($687)



CEM Cost ($)		
Component	**Factory Cost[1]**	**OEM Cost[1,2]**
Motor	162	**790**
Motor Controller[3]	402	
Variable Vane Assembly	50	
Housing	28	
Turbine Assembly	24	
Compressor Assembly	21	
Total:	**687**	

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

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

[3] $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

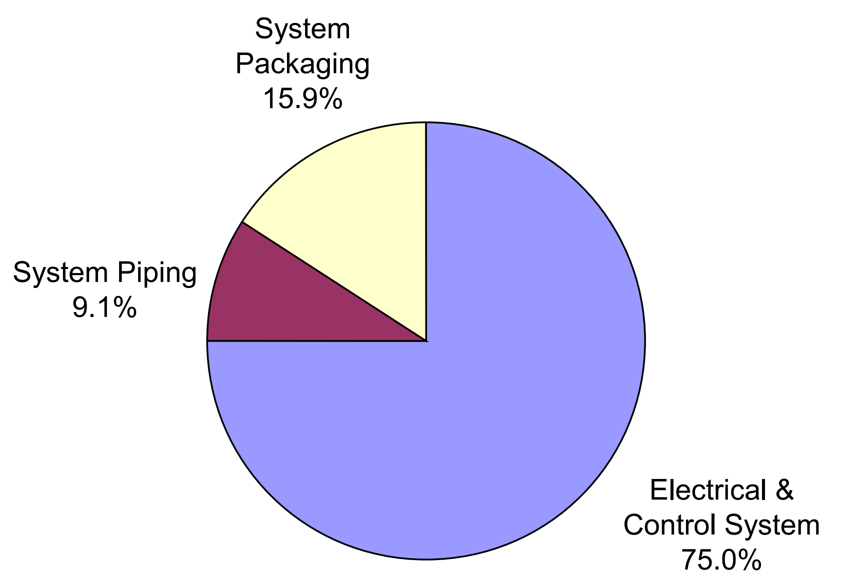
The motor assembly and motor controller (9.3 kW_e) are projected to cost $564, representing 82% of the CEM manufactured cost.

The balance of system includes the electrical & controls system, system piping, and system packaging.

Balance of System Cost[1] ($)

Balance of System	#	$315.38
Startup Power	0	
Startup Battery	0	
Switching Regulator for recharging (on MB)	0	
Electrical & Controls System	1	**$236.58**
Main Control Board	1	$6.00
Control Power Regulator	1	$6.00
Control Power Circuit Breaker	1	$2.00
Distributed Processors	3	$6.00
On/off Power FET to control solenoid valves	3	$3.00
Pre Cooler Fan Motor Relay	1	$2.00
Sensor Signal Conditioning	1	$10.00
Memory chip for history	1	$10.00
Main Wiring Harness		
RTD Sensor Wiring	12	$7.02
Other Sensor Wiring	24	$14.05
On/Off Valve Wiring	4	$3.51
Motor Control Wiring	24	$14.05
Connectors	18	$6.58
Power Wiring	8	$19.20
Safety Contactor	1	$30.00
Sensors		
Humidity	1	$8.36
Flow Rate	1	$10.00
Differential Pressure	2	$18.80
Temperature	2	$5.00
H_2 sensor for anode exhaust	1	$45.00
Prestack CO sensor	1	$10.00
System Piping		**$28.80**
Piping		$4.80
Fittings (Ts/ends)		$24.00
System Packaging	1	**$50.00**

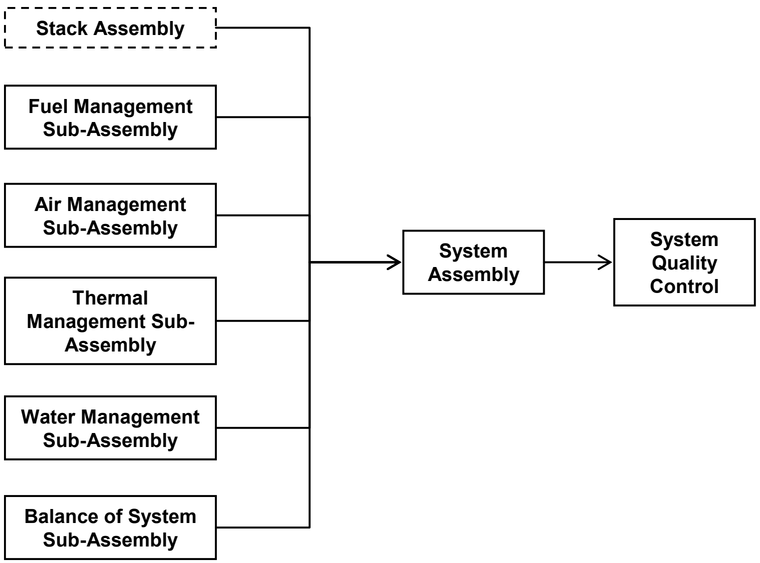
Balance of System Cost[1] ($315/system)



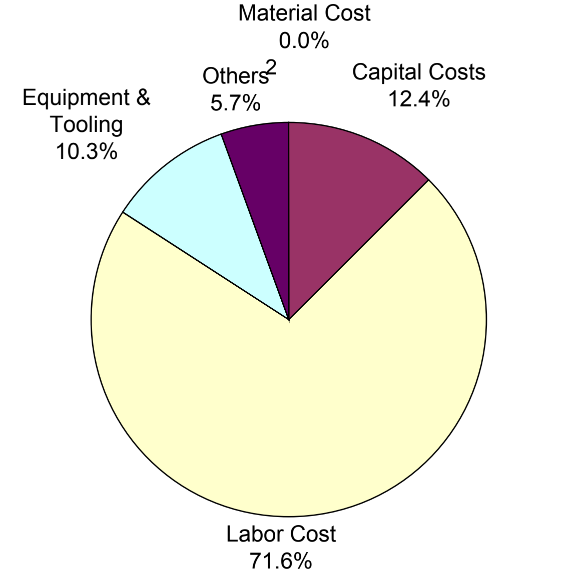
[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).

A complete 80 kW_{net} PEMFC system (including two stacks, balance-of-stack, BOP subsystems, balance-of-system, stack QC, and system QC) is estimated to be assembled in ~ 5 hours.

Process Name	Capex Per Station ($)	# of Stations	Labor Per Station	Cycle Time (min/unit)	Required Space (m^2)	Equipment Power (kW)
System Assembly[3]	200,000	462	1	213	20	10
System QC[4]	300,000	33	2	15	20	10



System Assembly Cost[1,3] ($323/system)



[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] Other costs include utilities, maintenance, and building
[3] System Assembly category includes BOP subsystem assembly, balance-of-system assembly, and final system assembly
[4] System QC includes visual inspection, leakage tests, and power-on/voltage test

System Quality Control[4] cost is included, while system conditioning / break-in is not included.

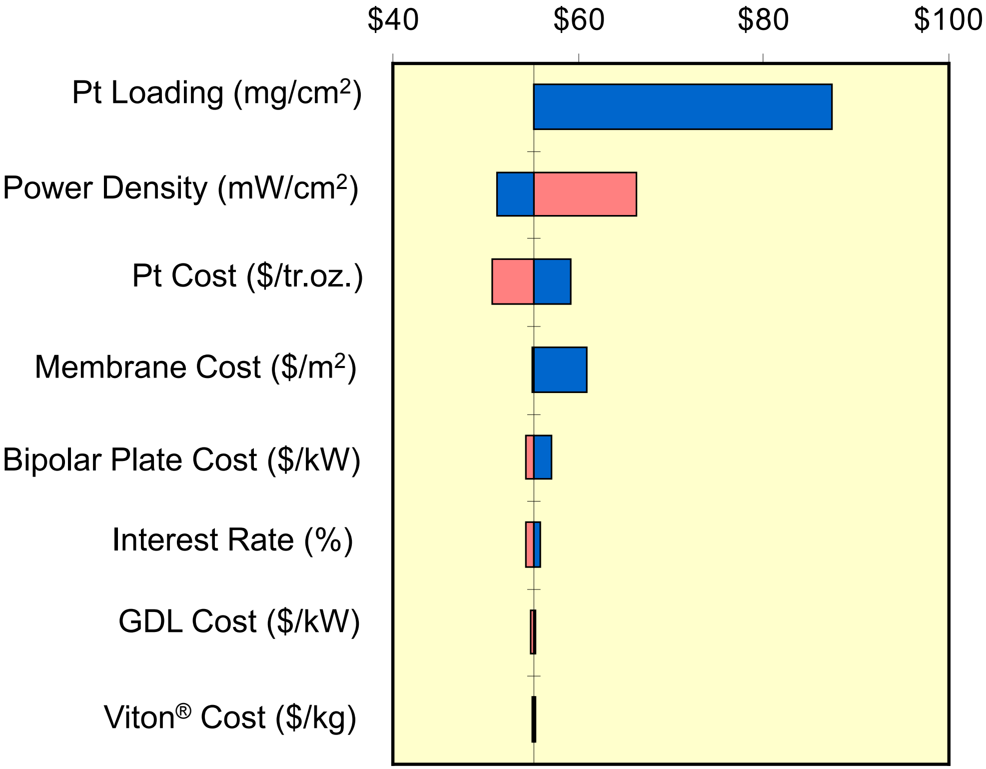
TIAX

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

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

2009 PEMFC System OEM Cost[1] ($/kW)

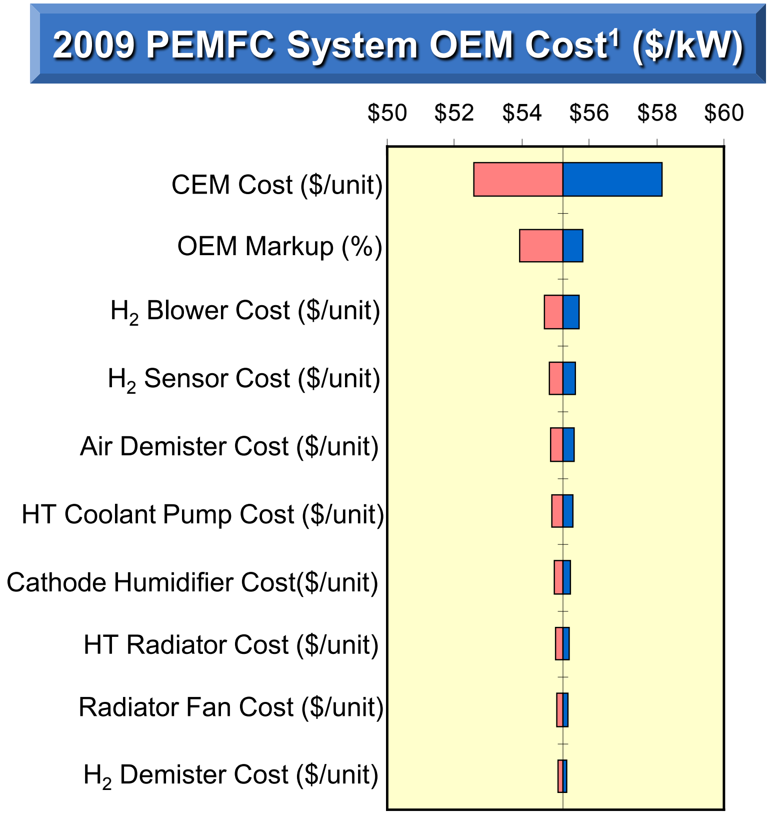


#	Variables	Min	Max	Base	Comments
1	Pt Loading (mg/cm^2)	0.15	0.75	0.15	Minimum: 2009 status; Maximum: TIAX 2005 report[2]
2	Power Density (mW/cm^2)	350	1000	701	Minimum: industry feedback; Maximum: DOE 2015 target[3].
3	Pt Cost ($/tr.oz.)	450	1675	1100	Minimum: ~ 108-year min. in 2007 $[4]; Maximum: 12-month maximum LME price[5]
4	Membrane Cost ($\$/m^2$)	10	50	11.4	Minimum:GM[6] study; Maximum: DuPont[7] projection from 2002
5	Bipolar Plate Cost ($/kW)	1.8	5.0	2.9	Minimum: Based on component single variable sensitivity analysis; Maximum: DOE 2010 target[3]
6	Interest Rate (%)	8%	20%	15%	Based on industry feedback
7	GDL Cost ($/kW)	1.3	1.9	1.6	Minimum: 80% of the baseline; Maximum: 120% of the baseline
8	Viton® Cost ($/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. Carlson, E.J. et al., "Cost Analysis of PEM Fuel Cell Systems for Transportation", Sep 30, 2005, NREL/SR-560-39104
3. http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf
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

TIAX

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



#	Variables	Min	Max	Base	Comments
1	CEM Cost ($/unit)	472	925	687	Based on component single variable sensitivity analysis
2	OEM Markup (%)	5%	20%	15%	Based on industry feedback
3	H_2 Blower Cost ($/unit)	177	259	219	Based on component single variable sensitivity analysis
4	H_2 Sensor Cost ($/unit)	10	80	45	UTRC Final Report[2]
5	Air Demister Cost ($/unit)	125	187	156	Min. & Max: 20% of the base
6	HT Coolant Pump Cost ($/unit)	120	180	150	Min. & Max: 20% of the base
7	Cathode Humidifier Cost ($/unit)	77	116	96	Min. & Max: 20% of the base
8	HT Radiator Cost ($/unit)	66	99	83	Min. & Max: 20% of the base
9	HT/LT Radiator Fan Cost ($/unit)	60	90	75	Min. & Max: 20% of the base
10	H_2 Demister Cost ($/unit)	49	73	61	Min. & Max: 20% of the base
11	Anode Humidifier Cost ($/unit)	41	62	52	Min. & Max: 20% of the base
12	System Packaging Cost ($/unit)	40	60	50	Min. & Max: 20% of the base
13	Fuel Solenoid Valve Cost ($/unit)	37	56	46	Min. & Max: 20% of the base
14	Air Precooler Cost ($/unit)	35	52	43	Min. & Max: 20% of the base
15	LT Coolant Pump Cost ($/unit)	24	36	30	Min. & Max: 20% of the base
16	Power System Safety Contactor Cost ($/unit)	24	36	30	Min. & Max: 20% of the base
17	Air/H_2 Mixer Cost ($/unit)	22	33	27	Min. & Max: 20% of the base
18	H_2 Purge Valve Cost ($/unit)	10	16	13	Min. & Max: 20% of the base
19	H_2 Check Valve Cost ($/unit)	7	11	9	Min. & Max: 20% of the base

[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.

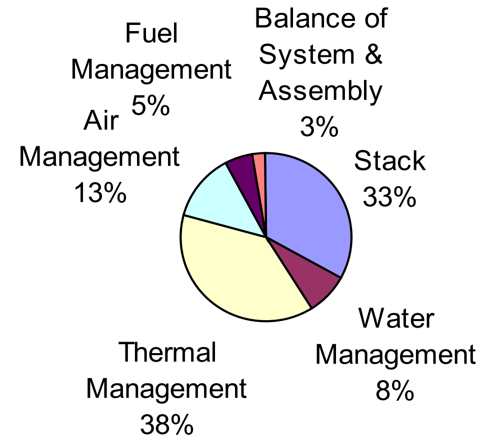
[2] Knight, B., Clark, T. et al., "Development of Sensors for Automotive PEM-based Fuel Cells", DE-FC04-02AL67616, Dec. 2005

The power density and specific power of the 2009 stack and system do not meet the DOE 2010 targets.

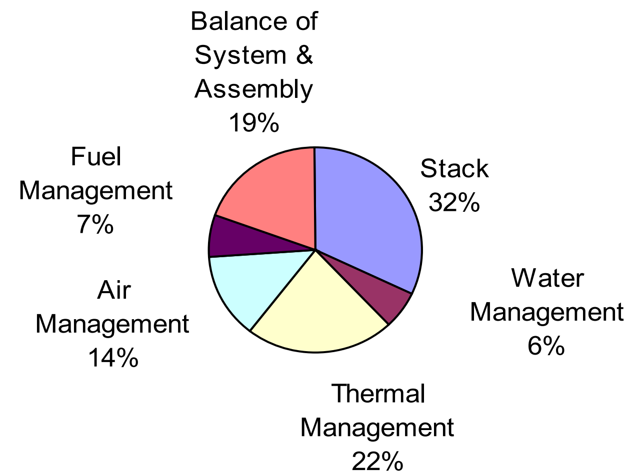
PEMFC Subsystem	Volume[1] (L)	Weight (kg)	DOE 2010 Target
Stack	**42**	**45**	
Membrane	0.3	0.4	
Electrodes	0.0	0.0	
GDL	4.8	4.8	
Seals	0.9	1.8	
Bipolar plates	31.0	26.2	
Balance of Stack	4.5	11.9	
Power Density[1,2] (W_e/L)	**1,905**		**2,000**
Specific Power[2] (W_e/kg)	**1,778**		**2,000**
Balance of Plant	**84**	**96**	
Water Management	10	8	
Thermal Management	48	31	
Fuel Management	6	10	
Air Management	17	19	
Balance of System & System Assembly	3	27	
Total System	**126**	**141**	
Power Density[1,2] (W_e/L)	**635**		**650**
Specific Power[2] (W_e/kg)	**567**		**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

2009 PEMFC System Volume (126 L)



2009 PEMFC System Weight (141 kg)



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

Technology Assessment

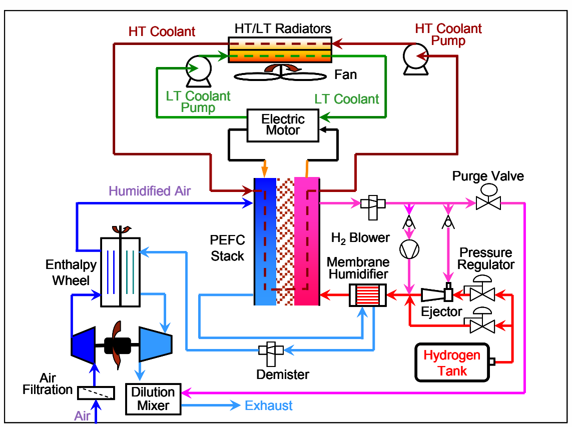
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Component Specifications
- Obtain Developer Input

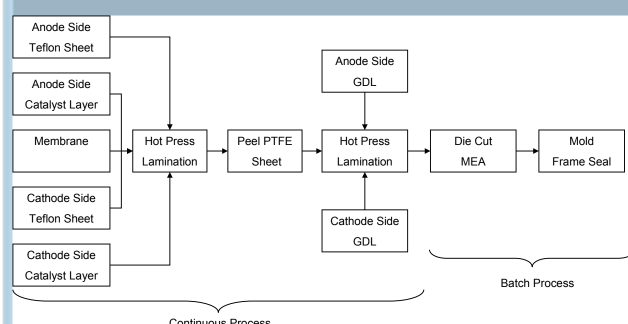
Cost Model and Estimates

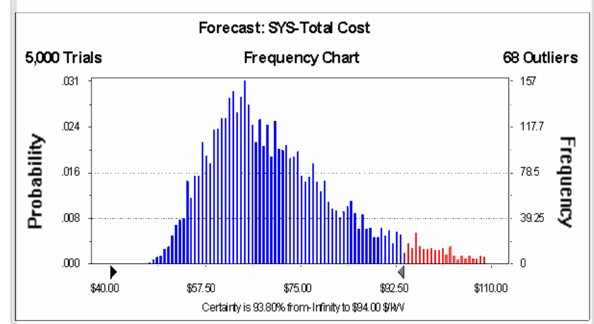
- Develop Bulk Cost Assumptions
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Process Costs

Overall Model Refinement

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



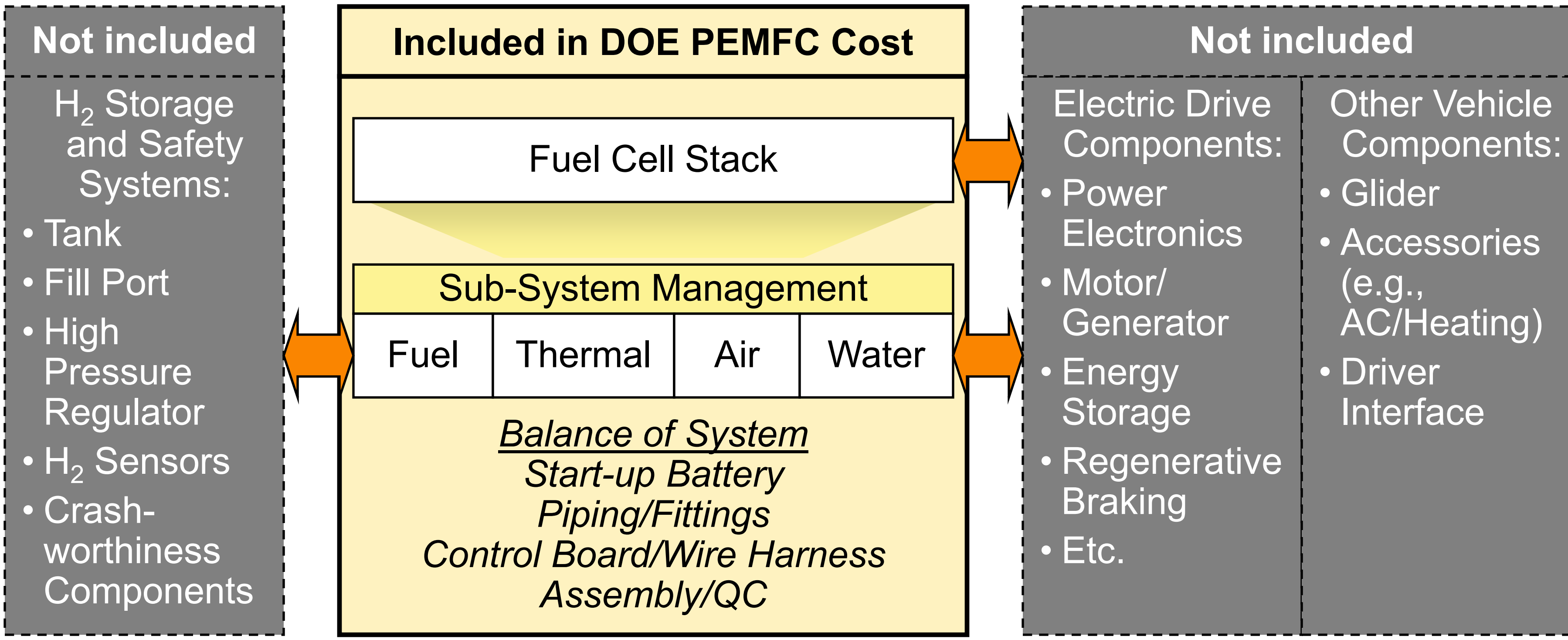




BOM = Bill of Materials

Teflon is a registered trademark of E.I. du Pont de Nemours and Company

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[1].

[1] Task to "Estimate High-Volume Costs of Stack Conditioning" is planned to be completed in 2010, pending funding authorization from DOE

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 • Research and Development • Sales and Marketing • General & Administration • Warranty • Taxes	Fixed Costs ➢ Operating • Tooling & Fixtures Amortization • Equipment Maintenance • Indirect Labor • Cost of operating capital (working period 3 months) ➢ Non-Operating • Equipment & Building Depreciation • Cost of non-operating capital	Variable Costs • Manufactured Materials • Purchased Materials • Direct Labor (Fabrication & Assembly) • Indirect Materials • Utilities
Automotive OEM Cost		

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

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

We used two different bottom-up costing tools to estimate the high-volume cost of the major BOP components[1].

Bottom-up Manufacturing Costing Tools

- TIAX Technology-Based Cost Model
  - Radiators – HT, LT
  - Cathode Planar MH
  - Anode Planar MH
- 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 scaled quotes/catalog-based estimates for BOP components such as air precooler, needle metering valve, coolant pumps, radiator fans, H_2 ejectors, valves/regulators and piping/fittings.

To be consistent with ANL's stack performance model, we made the following material assumptions for the 2009 cost projection.

Component	Parameter	Selection
Membrane	Material	20 μm PFSA
	Supported	No mechanical reinforcement; assumed to be chemically stabilized
Electrodes (Cathode and Anode)	Catalyst	Ternary $PtCo_xMn_y$ alloy
	Type	Nano-Structured Thin Film
	Support	PR-149 Organic whiskers
Gas Diffusion Layer (GDL)	Material	180 μm Woven carbon fiber
	Porosity	70%
Bipolar Plate	Type	Expanded graphite foil
Seal	Material	Viton®

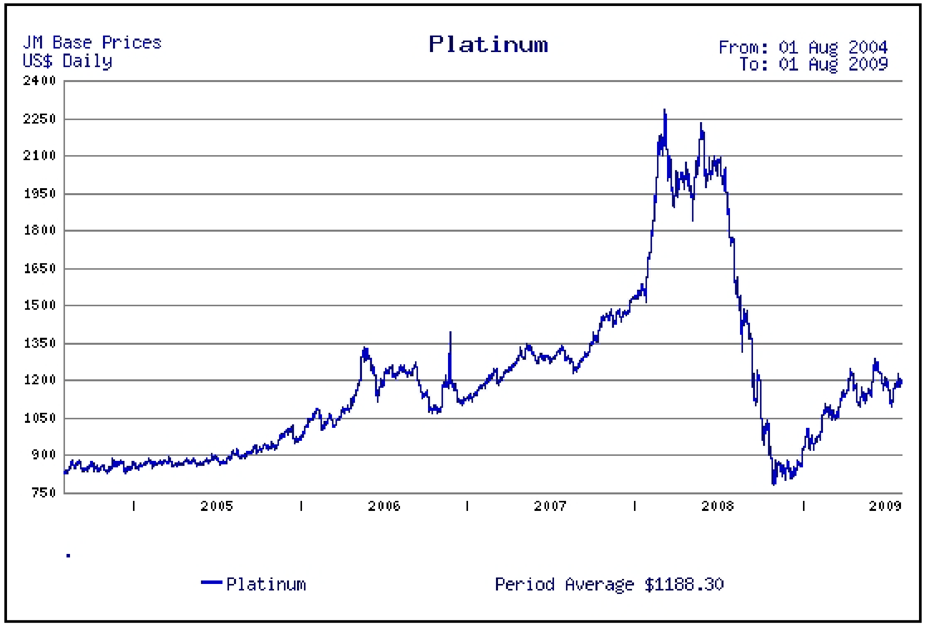
We used a Pt price of $1,100/tr.oz. for the baseline analysis and captured the impact of variation in Pt price through sensitivity analyses.

PFSA = Perfluorosulfonic acid

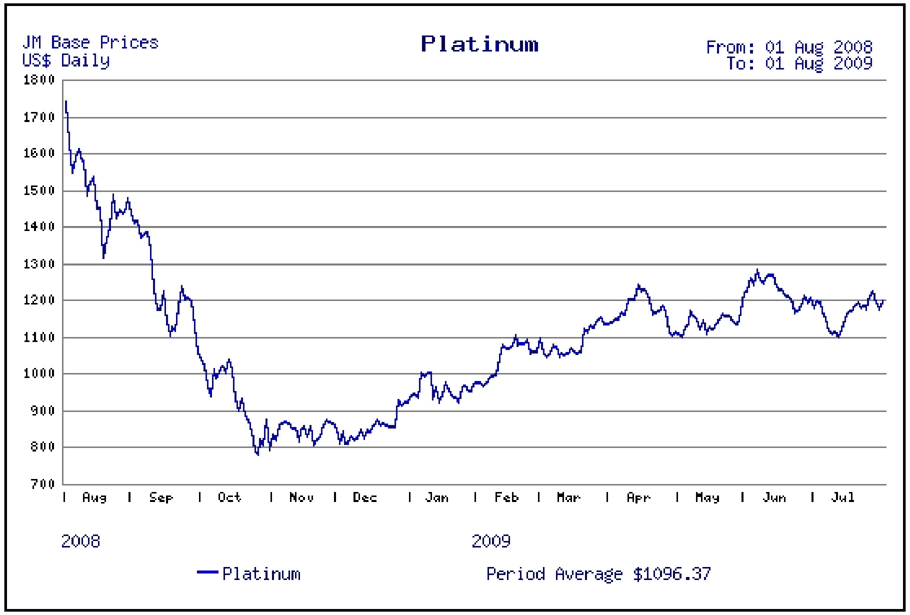
PR = Perylene Red

Platinum at $1,100/tr.oz. is close to the average price ($1,096/tr.oz.) over the 12 month period from Aug. 2008 to Aug. 2009.

Last Five Years' Platinum Price



Last Twelve Months' Platinum Price



The Pt price averaged over the last five years is ~$1,188/tr.oz.

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
Balance of Stack	Stack manifold, tie bolts, end plates, current collectors, electrical insulators
Balance of Plant	
Water Management	Nickel foam, Nafion®, nitrile rubber, aluminum, HDPE, woven carbon fiber
Thermal Management	Aluminum coil, aluminum tubing, radiator fan, coolant pumps, air precooler, temperature sensors
Air Management	NdFeB magnet, steel bar stock, Teflon® insulation, copper coils, steel laminations, bearings, seals, motor controller, wire harness, air demister, air/H_2 mixer, flow orifice, air filter
Fuel Management	SS316 bar, SS316 sheet, seals, H_2 blower motor, H_2 ejectors, H_2 demister, solenoid valves, purge valve, check valve

Progress 2009 PEMFC Stack *Cost Breakdown*

Detailed results of 2009 PEM fuel cell stack cost breakdown.

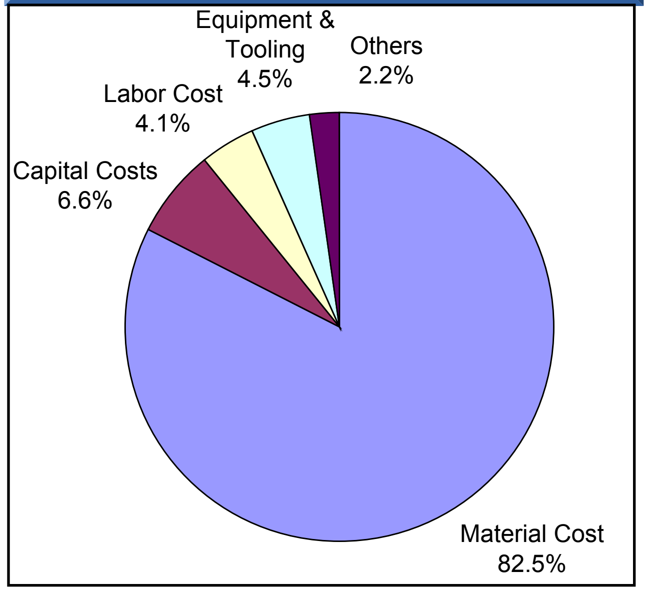
2009 PEMFC Stack Costs[2]		Active Area Basis[1] Material Cost[1] ($/m^2)	Process Cost[1] ($/m^2)	Total Cost[1] ($/m^2)	Unit Cell Weight/Area (g/cm^2)	Stack Module Weight (kg)	Stack Module Material Cost[2] ($)	Stack Module Process Cost[2] ($)	Stack Module Cost[2] ($)	Stack Module Cost[2] ($/kW)
MEA	Anode GDL	$4.12	$0.72	$4.84	0.02	2.37	$54.21	$9.50	$63.71	$0.80
	Anode Active Layer	$19.28	$3.15	$22.43	0.00	0.01	$253.95	$41.52	$295.47	$3.69
	Electrolyte	$9.77	$1.67	$11.44	0.00	0.40	$128.74	$21.96	$150.70	$1.88
	Cathode Active Layer	$36.97	$5.14	$42.11	0.00	0.00	$486.97	$67.67	$554.64	$6.93
	Cathode GDL	$4.12	$0.72	$4.84	0.02	2.37	$54.21	$9.50	$63.71	$0.80
MEA Total		**$74.26**	**$11.40**	**$85.66**	**0.04**	**5.16**	**$978.08**	**$150.15**	**$1,128.23**	**$14.10**
Bipolar Coolant Plate		$10.25	$7.35	$17.60	0.10	26.17	$135.00	$96.83	$231.83	$2.90
Seals						1.81	$79.09	$114.55	$193.64	$2.42
End Plates						1.97	$3.91	$6.33	$10.24	$0.13
Current Collectors						1.23	$1.40	$2.26	$3.67	$0.05
Insulators						0.80	$8.62	$9.56	$18.18	$0.23
Stack Manifold/Outer Wrap						5.40	$8.13	$13.09	$21.22	$0.27
Tie Bolts						2.49	$19.68	$1.72	$21.40	$0.27
Stack Assembly								$158.87	$158.87	$1.99
Total Unit Cell		**$84.51**	**$18.75**	**$103.26**	**0.21**	**45.02**	**$1,233.93**	**$553.35**	**$1,787.27**	**$22.34**

[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).

Material costs dominate the manufactured cost of the stack components. For example, materials make up ~83% of the MEA cost in 2009.

Manufactured Cost	2008 MEA[1] ($/m^2)	2009 MEA[1] ($/m^2)
Material *- Membrane* *- Electrode* *- GDL*	117.71 - 13.83 - 91.90 - 11.98	76.70 - 9.77 - 58.69 - 8.23
Capital Cost	6.57	6.18
Labor	1.02	3.85
Tooling & Equipment	3.73	4.21
Other[2]	1.71	2.03
Total	**131**	**93**

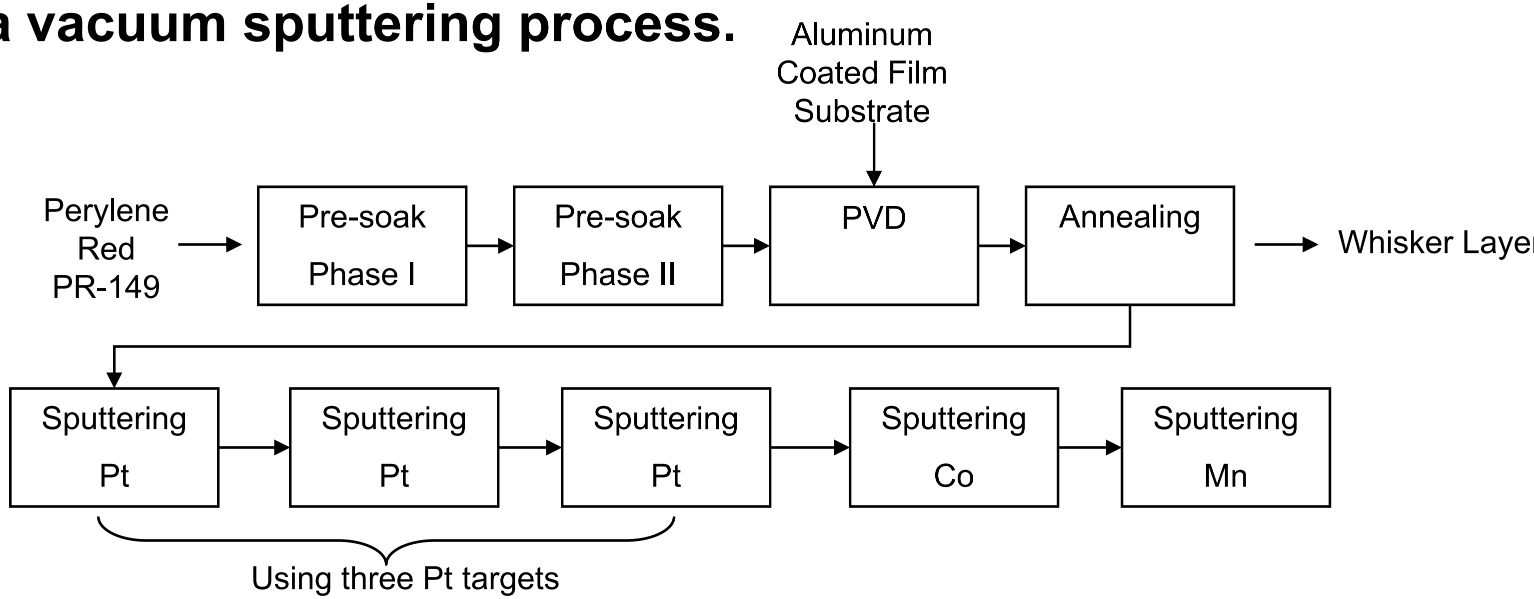
2009 MEA Cost ($93/m^2)

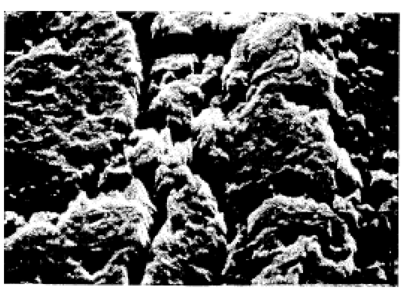


In 2009, the MEA cost was lower due to lower material costs for the membrane (20 μm), electrodes (Pt loading = 0.15 mg/cm^2) and GDL (180 μm).

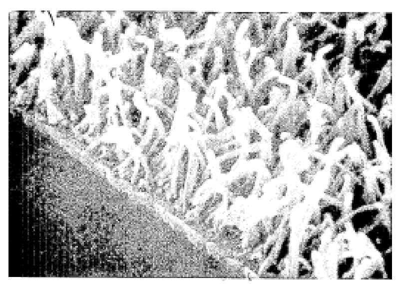
[1] m^2 of active area and kW of net power
[2] Other costs include utilities, maintenance, and building

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

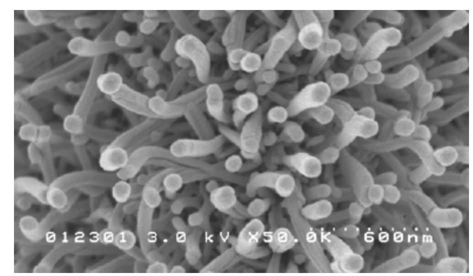




US Patent 4,812,352
PVD coated thin film before annealing



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

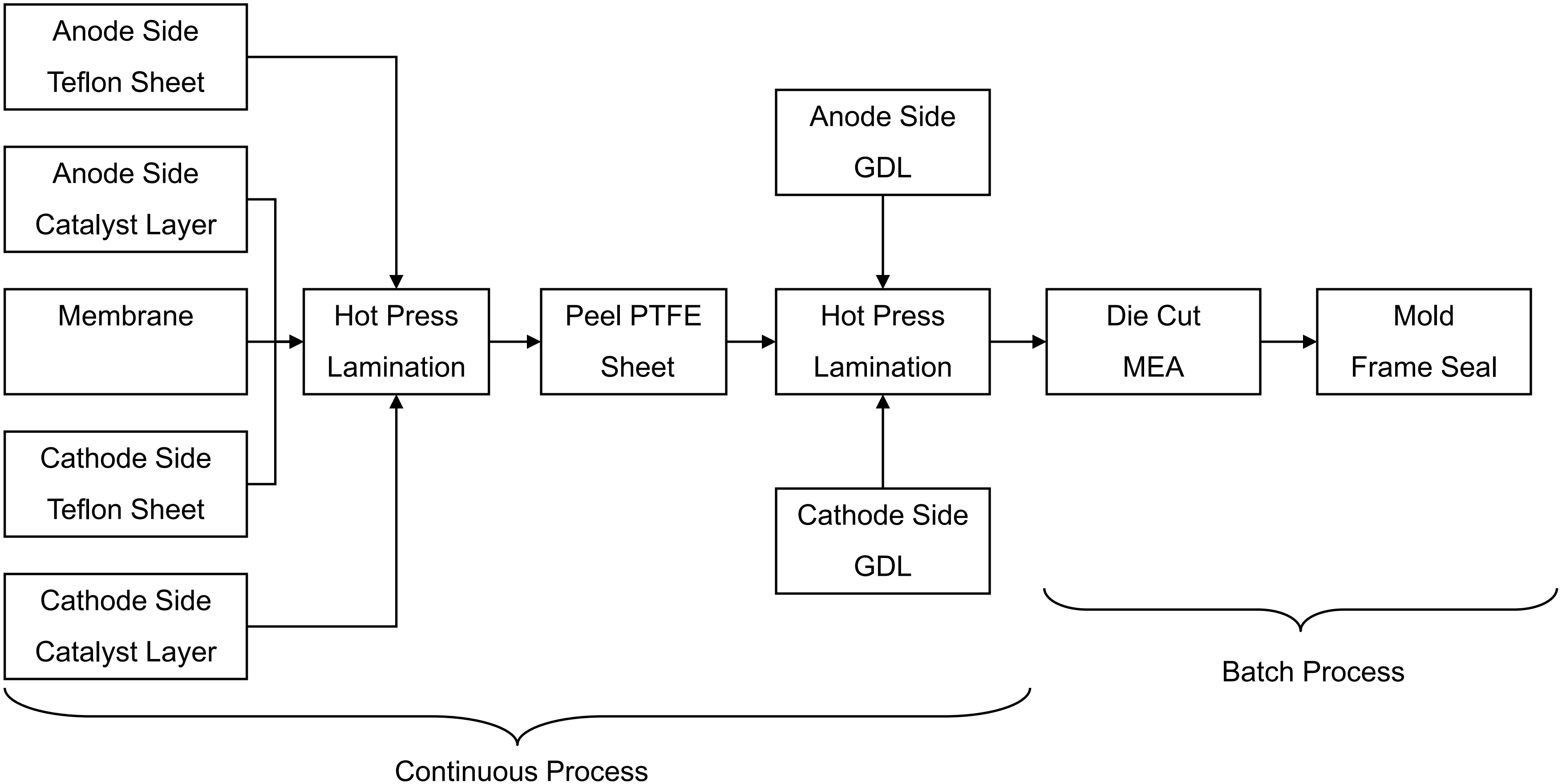


Nanostructured Thin Film Catalyst before transfer to a PEM[1]

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

TIAX

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



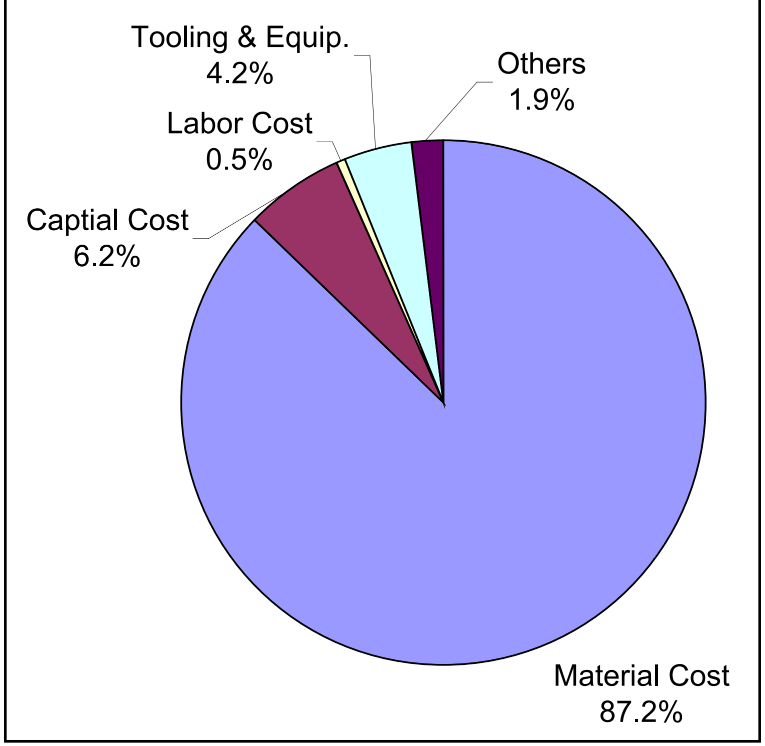
The catalyst coated membrane and GDL layers were laminated to form an MEA in roll good form; the MEA was cut into sheets and molded with a frame seal.

Platinum price dominates the electrode cost of $64/m². 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	19.28	36.97	56.25
Capital Cost	1.49	2.54	4.02
Labor	0.16	0.19	0.35
Tooling	1.04	1.68	2.72
Other[2]	0.47	0.73	1.20
Total	**22**	**42**	**64**

[1] m² of active area
[2] Other costs include utilities, maintenance, and building

Electrode Manufactured Cost ($64/m²)



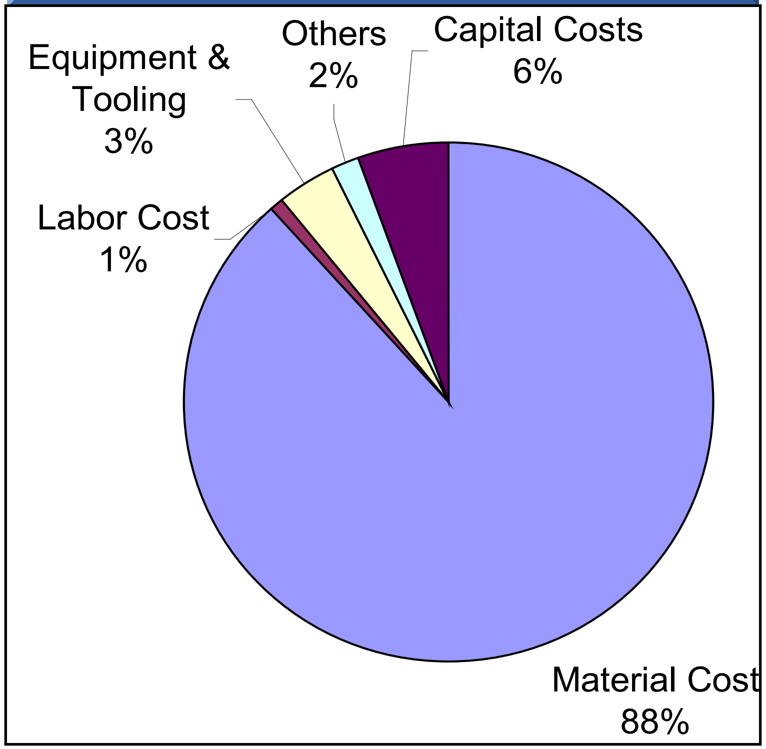
Platinum at $1,100/tr.oz. is close to the average price ($1,096/tr.oz.) over the last year.

The estimated membrane cost on an active area basis is $11/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	5.25	0.22	3.71
Coating	7.80	132.62	0.29	4.90
Drying & Cooling	0.00	0.00	1.00	17.02
Quality Control	0.00	0.00	0.04	0.60
Laminating	0.00	0.00	0.06	0.94
Packaging	1.66	28.29	0.07	1.16
Subtotal	**9.77**	**166.16**	**1.67**	**28.34**
Total	**11.44 ($/m²)**			
	194.50 ($/kg)			

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

Membrane Manufactured Cost ($11/m²)



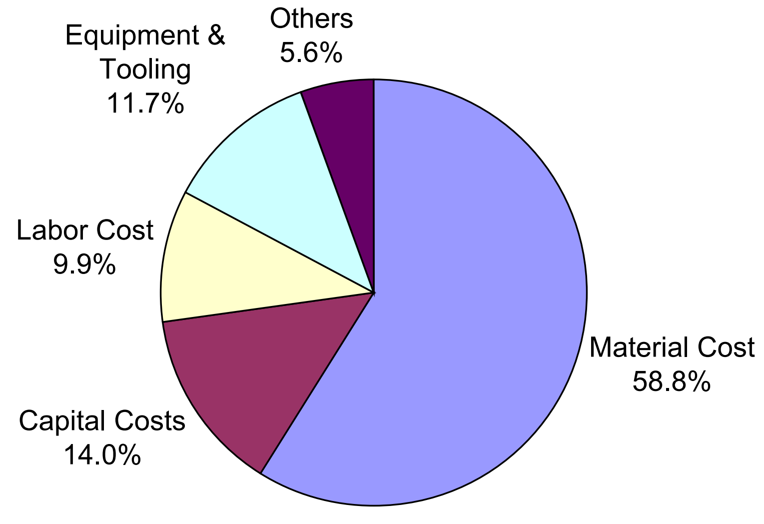
In 2008, the membrane cost was $16/m² due to higher material costs associated with a thicker 30 μm membrane.

Transfer molding is used to fabricate the seals between the MEA and bipolar/cooling plate. The seal cost is ~$8/m^2.

Manufactured Cost[1]	Seals ($/m^2)
Material	4.78
Capital Cost	1.14
Labor	0.81
Tooling	0.95
Other[2]	0.45
Total	**8.13**

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

Seals' Manufactured Cost ($8/m^2)

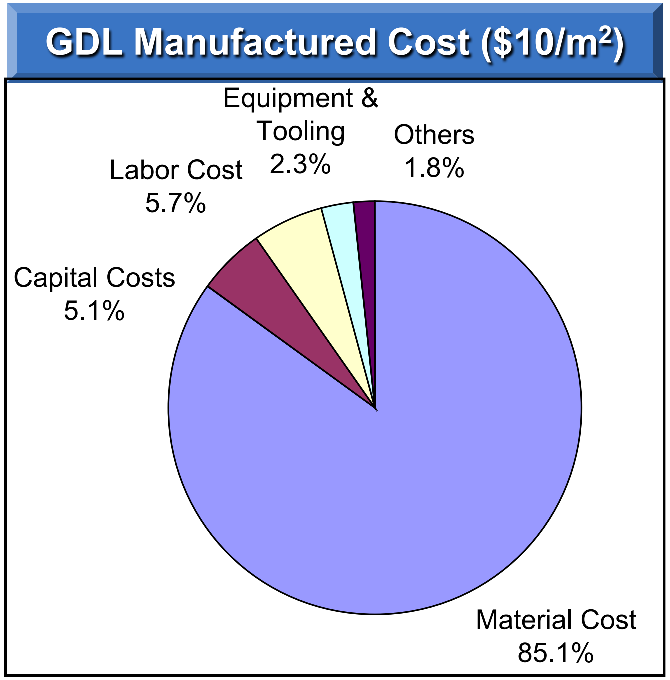


The seal material is Viton® which costs ~$20/lb.

The estimated high-volume cost of the woven carbon fiber GDL (for *both* anode and cathode), is ~$10/m^2, on an active area basis.

Manufactured Cost[1]	GDL ($/m^2)
Material	8.23
Capital Cost	0.50
Labor	0.55
Tooling	0.22
Other[2]	0.17
Total	**9.67**

[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.

Raw Graphite Flake $1.2/lb

Assume Expanded Flake $2/lb

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

- **Treat Flake**: Oxidizing Medium, H_2SO_4, HNO_3, 125 ^{0}C
- **Water Rinse or Leach**: Soggy Graphite Particles
- **Expansion Treated**: 2500 F Flame, Mix with Ceramic Fiber Or Carbon Fiber 2 wt%

Processes In Costing

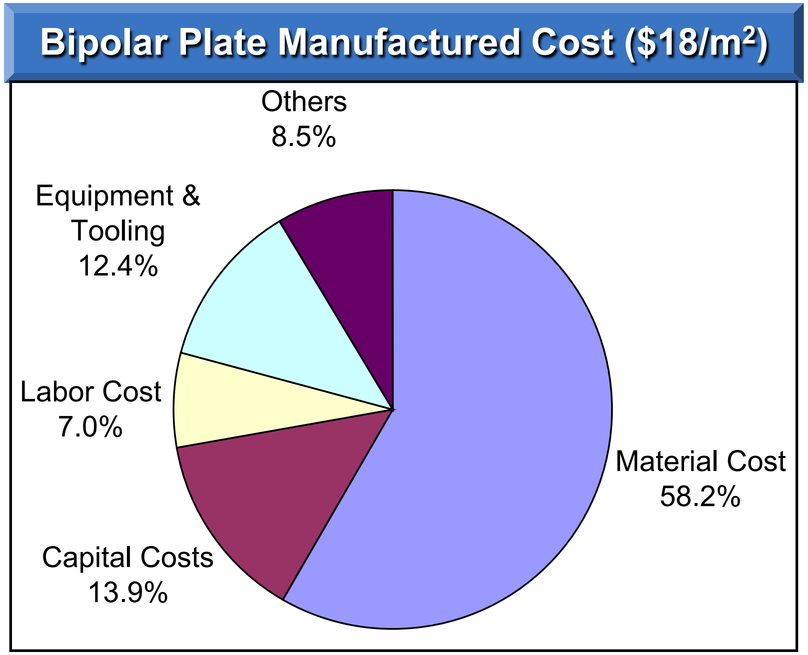
- **Roll Pressed into Foil**: Capex $200K; Thickness 2 mm
- **Resin Impregnation**: Capex $400K; 10% Phenolics Resin; Foil Density 1.5 g/cc, 17%~19% Resin
- **Calendar Line**: Capex $200K; Control Foil Thickness
- **Emboss Compression Mold**: Capex $1 million; Channels, Seal grooves, Holes, In-line process
- **Die Cut**: Capex $150K
- **Curing Oven**: 90~120 ^{0}C, 10 min; Capex $800K, 100 ft long

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

We estimate the expanded graphite foil bipolar plate cost is $18/m^2 at high volume.

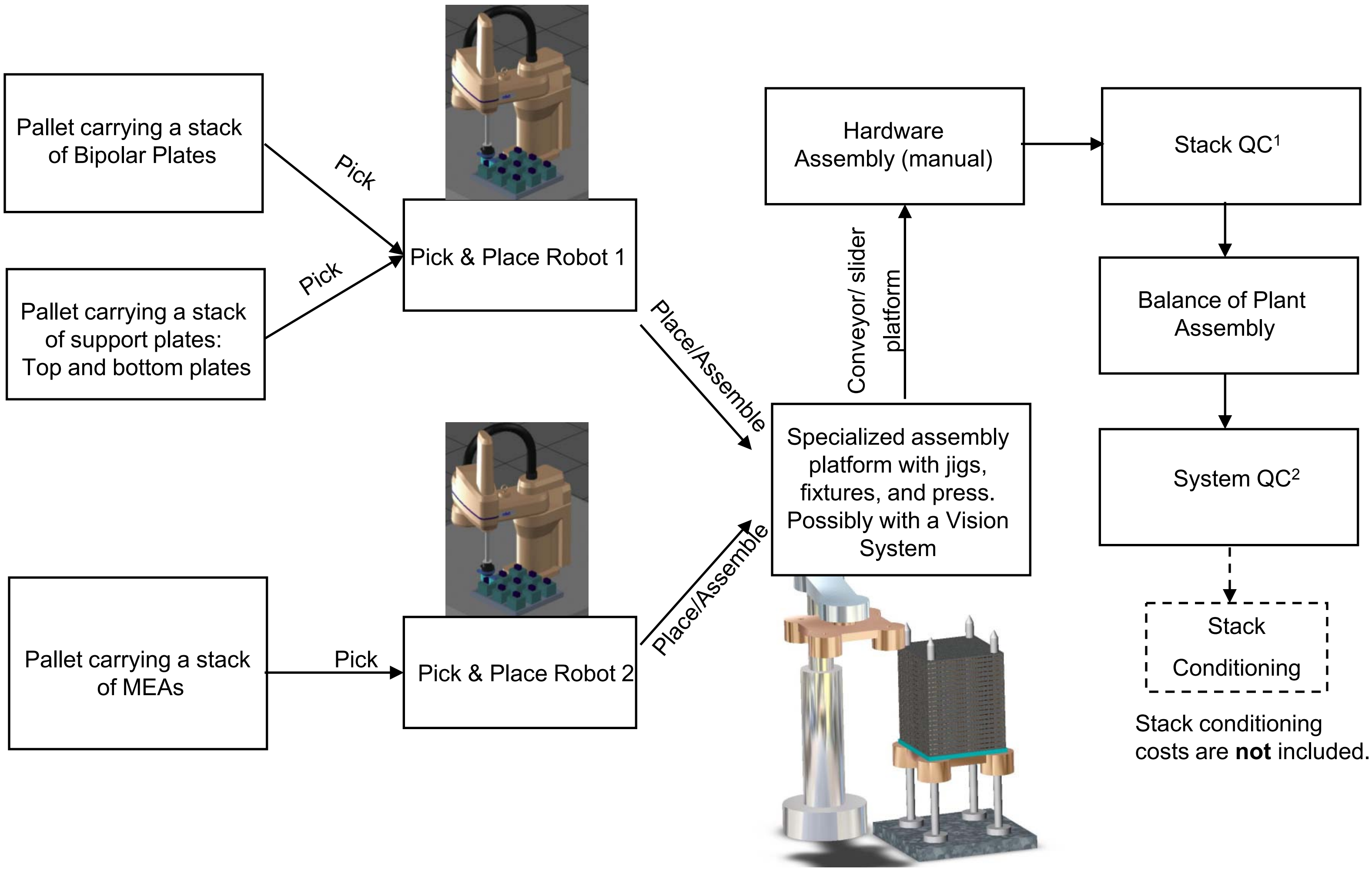
Bipolar Plate Manufactured Cost[1] ($/m^2)		
Component	**Material**	**Process**
Roll Form	10.25	0.92
Impregnation		1.03
Calendar		0.66
Compression Molding		2.15
Die Cut		0.57
Curing		2.01
Subtotal	**10.25**	**7.35**
Total	**17.60**	

[1] 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.

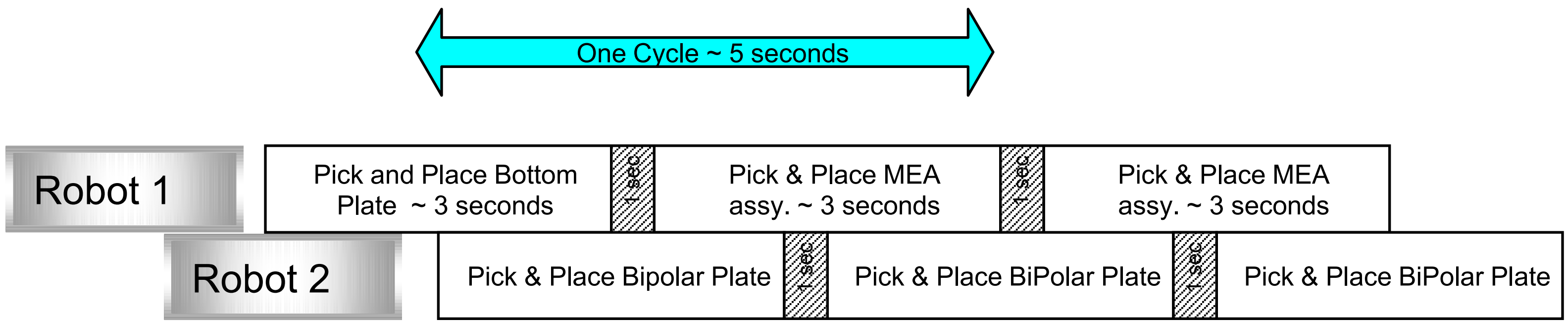
A pair of robots in a specialized assembly station with a vision system is assumed to assemble the stack.



[1] Stack QC includes visual inspection, and leak tests for fuel loop, air loop and coolant loop
[2] System QC includes visual inspection, leakage tests, and power-on/voltage test

Progress 2009 Stack Assembly *Cycle Time*

Assuming a two-robot assembly station, we estimate that two stacks[1] and the Balance of Stack are assembled in ~ 1 hour.



Stack assembly step	Time	Comments
Pick & place a single repeat unit	~ 5 seconds	Based on two-robot setup
Assemble a single stack[1]	~ 19 minutes	For 217 MEAs and bipolar plates
Assemble balance of stack (BOS)	~ 10 minutes	BOS includes endplates, electrical insulators, outer wrap/stack manifold, current collectors, tie bolts
Stack Quality Control[2]	~ 15 minutes	Stack burn-in / conditioning time is not included

[1] We assume two stacks per 80 kW_{net} PEMFC system
[2] Stack QC includes visual inspection, and leak tests for fuel loop, air loop and coolant loop

The rotor and single vane structure in the Parker Hannifin Model 55 Univane H_2 blower are referenced from U.S. 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_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

Progress 2009 PEMFC System *H_2 Blower BOM*

The projected H_2 blower manufactured cost is $219 per unit.

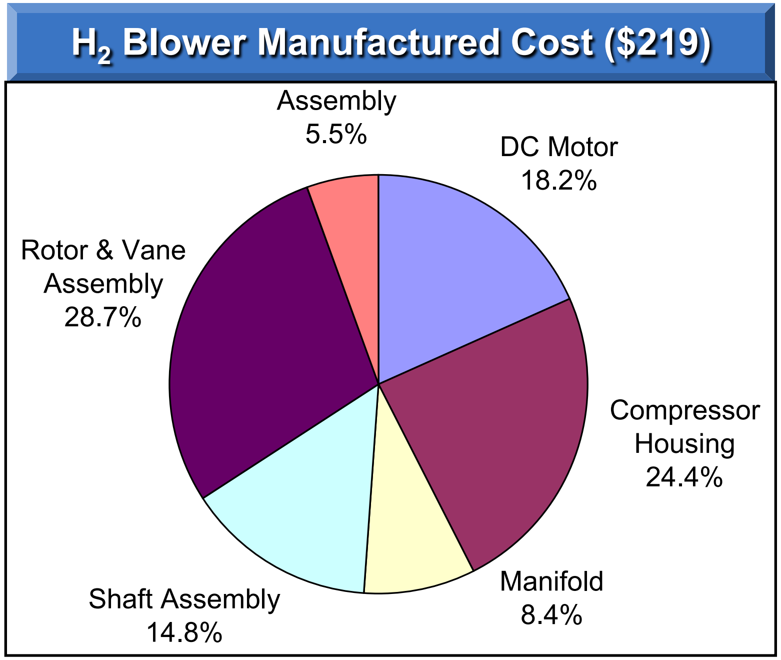
#	Part Name	Quantity	Material	OD (cm)	L (cm)	W (cm)	Wall Thickness (cm)	Total Vol. (Cm^3)	Total Wt. (kg)	TIAX Model Total (unit Cost)
1	100We DC Motor	1	Misc	16.51	8.89			1902.24	1.00	40.00
2	End Plate (motor side)	1	SS316	16.51	2.54		0.32	96.48	0.75	$13.75
3	Screw	4	Misc	0.64	2.54			0.80	0.02	0.20
4	O-Ring	1	Misc	13.97					0.01	0.50
5	Labyrith Seal (main)	1	Misc	5.08	1.27				0.02	2.00
6	O-Ring	1	Misc	5.08					0.01	0.20
7	C-Clip	1	SS316	5.08					0.01	0.10
8	Labyrith Seal	1	Misc	4.45					0.02	2.00
9	Blower Housing	1	SS316	15.24	8.89		0.32	106.65	0.83	$19.66
10	Screw	8	Misc	0.64					0.04	0.40
11	O-Ring	1	Misc	13.97					0.01	0.50
12	Compressor Shaft	1	SS316	1.59	12.70			25.12	0.20	$9.17
13	Bearing	2	SS316	3.81	2.54			28.94	0.23	18.70
14	Seal	2	Misc	3.81					0.01	0.40
15	Rotor	1	Al	10.16	7.62			308.73	0.83	$9.40
16	Vane Guide	2	SS316	7.62	1.27		1.27	32.06	0.50	$15.60
17	Vane Guide Bearing	2	Misc	7.62	1.60			61.62	0.48	30.00
18	Vane	1	SS316		7.62	2.54	1.27	24.58	0.19	$3.82
19	Vane Pin	1	SS316	0.95	9.62			6.85	0.05	4.00
20	C-Clip	2	SS316	1.35					0.01	0.10
21	Inlet Manifold	1	SS316	4.45	8.89		0.64	35.17	0.27	$7.33
22	Seal	1	Misc		5.08	3.81			0.01	0.50
23	Screw	4	Misc	0.32					0.02	0.20
24	Fitting	1	SS316	4.45	5.08				0.10	1.00
25	O-Ring	1	Misc	2.54					0.01	0.20
26	Outlet Manifold	1	SS316	4.45	8.89		0.64	35.17	0.27	$7.33
27	Seal	1	Misc		5.08	3.81			0.01	0.50
28	Screw	4	Misc						0.02	0.20
29	Fitting	1	SS316	4.45	5.08				0.10	1.00
30	O-Ring	1	Misc	2.54					0.01	0.20
31	End Plate	1	SS316	15.24	3.81		0.64	72.36	0.56	$11.97
32	Screw	8	Misc						0.04	0.40
33	O-Ring	1	Misc	8.89					0.01	0.50
34	End Cover	1	SS316	7.62	0.64			28.94	0.23	$5.21
35	Screw	4	Misc						0.02	0.20
36	O-Ring	1	Misc	6.35					0.01	0.20
37	Support	1	Steel		15.24	15.24	0.25	58.99	0.46	0.00

SubTotal: **$207.44**

Assembly: **$12.00**

Total: **$219.44**

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

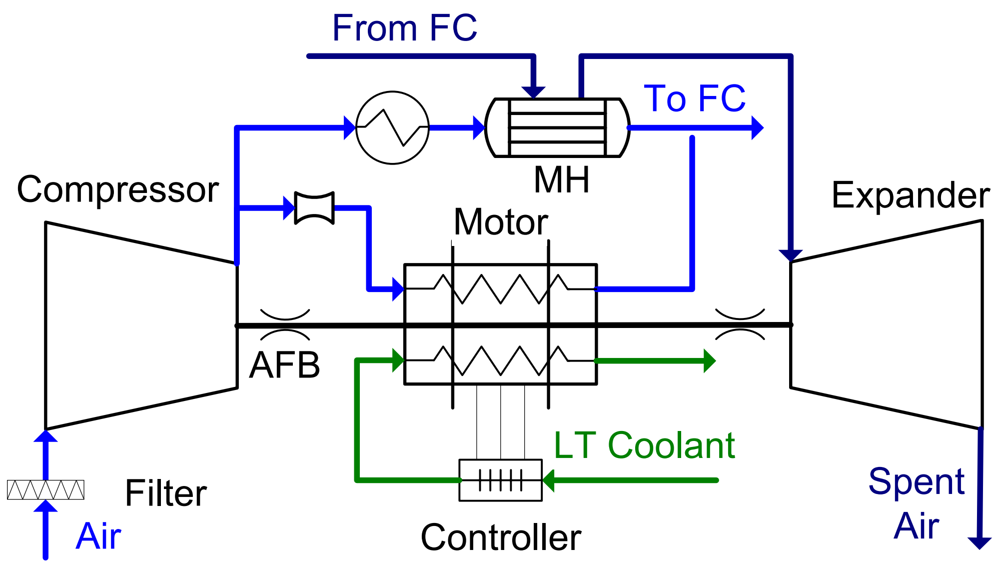


H_2 Blower Cost ($)		
Component	**Factory Cost[1]**	**OEM Cost[1,2]**
DC Motor	40	
Blower Housing	53	
Manifold	18	
Shaft Assembly	33	
Rotor & Vane Assembly	63	
Assembly	12	
Total:	**219**	**252**

[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

Progress 2009 PEMFC System *CEM*



- 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

R. K. Ahluwalia and X. Wang, Automotive Fuel Cell System with NSTFC Membrane Electrode Assemblies and Low Pt Loading, July 21, 2009

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

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; U.S. Patent 5,605,045
Electrical Motor	Honeywell, DOE program review, progress report & annual report 2004; U.S. 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	U.S. Patent 6,269,642; Garrett/Honeywell, DE-FC05-00OR22809
Journal Bearings	U.S. 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 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

Ref: 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 $687 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)	TIAX Model Total (unit Cost)
1	Turbine Housing	1	US6269642	24	Al	20.32			7.62	0.16	127.19	0.34	$5.39
2	Bolt	6			Misc	0.60	1.20				2.03	0.02	$0.30
3	Washer	6			Misc	1.00	0.10					0.01	$0.30
4	Tie Rod	1	US6269642	30	Steel	1.00	4.00				3.14	0.02	$3.72
5	Turbine Wheel	1			Al	5.00	5.00				0.07	0.20	$20.00
6	Variable Vane Assembly												$0.00
7	Nozzle Wall	1	US6269642	38	Steel	17.78				0.30	36.46	0.28	$2.54
8	Vane	9	US6269642	36	Steel	3.00	0.50	0.50			6.75	0.47	$15.39
9	Vane Post	9	US6269642	40	Steel	0.20	1.00				0.28	0.02	$0.00
10	Actution Tab	9	US6269642	44	Steel		1.00	0.30	0.30		0.81	0.06	$0.00
11	Unison Ring	1	US6269642	48	Steel	15.24	0.50				84.88	0.66	$16.88
12	Actuator Crank	1	US6269642	50	Steel		2.00	1.00	1.00		2.00	0.02	$1.11
13	Crank Bushing	1	US6269642	60	Steel	1.20	1.00			0.10	0.35	0.00	$0.05
14	Crank Gear	1	US6269642	62	Steel	2.00	1.00			0.50	2.36	0.02	$4.21
15	Crank Gear Pin	1	US6269642	64	Steel	0.20	2.00				0.06	0.00	$0.10
16	Crank End Bearing	1	US6269642	66	Misc						3.00	0.02	$2.15
17	Actuator Housing	1			Al	20.32	1.50			2.54	212.71	0.57	$6.03
18	Solenoid Valve	1	US6269642	85	Misc							0.20	$5.00
19	Solenoid Valve Bracket	1	US6269642	108	Steel		3.00	1.20		0.20	0.72	0.01	$0.01
20	Solenoid Valve Bracket Bolt	1	US6269642	110		0.40	1.00				0.13	0.00	$0.05
21	Washer	1	US6269642			0.60				0.10		0.00	$0.05
22	Rack Gear Rod	1	US6269642	88	Steel	0.60	6.00				1.70	0.01	$0.46
23	Motor Rotor Assembly												$0.00
24	Motor Shaft	1	US5605045	16	Steel	3.31	20.32			0.00	115.21	0.90	$10.64
25	Thermal Insulation	1	US5605045	60	Teflon	3.81	12.70			0.25	35.49	0.07	$1.47
26	NdFeB Magnet	4	US5605045	62	NdFeB	4.68	12.70			0.44	73.64	0.55	$48.60
27	Collar	1	US5605045	70	Steel	5.08	12.70			0.20	38.92	0.30	$7.58
28	Labyrith Seal	1	US2006/0153704	130	Misc	5.31				1.00		0.02	$2.00
29	Jounal Foil Bearing	1	US2006/0153705		Steel	3.31	5.08					0.10	$10.00
30	Motor Housing	1	DE-FC36-02AL67624		Al	20.32	20.32			0.20	432.55	1.17	$12.26
31	Bolt	8			Misc	0.60	1.20				2.03	0.16	$0.40
32	Washer	8			Misc	1.00	0.10				0.00	0.04	$0.40
33	Motor Stator Assembly	1	FY2000 Progress Report		Misc	9.20	12.70			1.50	460.59	2.95	$17.91
34	Motor Sator Position Ring	1	FY2000 Progress Report										$0.50
35	Bolt	8	FY2000 Progress Report		Misc	0.60	1.20	0.00	0.00	0.00	2.03	0.16	$0.40
36	Washer	8	FY2000 Progress Report		Misc	1.00	0.10	0.00	0.00	0.00	0.00	0.04	$0.40
37	Motor Connector	1			Misc								$0.50
38	Labyrith Seal	1	FY2000 Progress Report		Misc	5.31						0.02	$2.00
39	Thrust Bearing Runner	1	FY2000 Progress Report		Steel	8.00	5.08			0.50	25.00	0.20	$7.59
40	Thrust Bearing	2	FY2000 Progress Report		Misc	8.00						0.20	$20.00
41	Thrust Bearing Holder	1	FY2000 Progress Report		Steel	10.00	1.00			0.50	50.00	0.39	$8.59
42	Labyrith Seal	1			Misc								$0.00
43	Jounal Foil Bearing	1	US2006/0153705		Misc	3.31	5.08					0.10	$10.00
44	Compressor Housing	1	FY2000 Progress Report		Al	25.40			7.62	0.16	134.69	0.36	$5.39
45	Bolt	8	FY2000 Progress Report		Misc	0.60	1.20	0.00	0.00	0.00	2.03	0.02	$0.40
46	Washer	8	FY2000 Progress Report		Misc	1.00	0.10	0.00	0.00	0.00	0.00	0.01	$0.40
47	Compressor Impeller	1	FY2000 Progress Report		Al	5.00	5.00					0.20	$20.00
48	Compressor Impeller Tie Rod	1	FY2000 Progress Report		Misc	1.00	10.00				7.85	0.06	$3.91
49	CEM Mounting Bracket Left	1			Steel		25.40	7.62		0.10	19.35		$0.00
50	CEM Mounting Bracket Right	1			Steel		25.40	7.62	0.00	0.10	19.35		$0.00
51	Control Box Assembly	1	DOE target $40/kW / 5.5kW input									**6.50**	$402.00
52	Box	1											$0.00
53	Integrated Motor Cable	1											$0.00
54	Inverter	1											$0.00
55	EMI Section	1											$0.00
56	Wire Harness & Cooling pipes	1											$0.00
57	Final Assembly												$9.65
													$686.73