Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications

Fuel Cell Tech Team Meeting

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Overview

TIAX has performed PEMFC cost assessments for many years supported by DOE. This current project was initiated in 2006.

Timeline

- Start date: Feb 2006
- Base period: May 2008
  - » 100% complete
- Option period: May 2011

Barriers

- Barriers addressed
  - » A. Cost

	Cost Targets ($/kW)		
	2005	2010	2015
Fuel Cell System	110	45	30
Fuel Cell Stack	70	25	15

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

Budget

- Total project funding
  - » Base Period = $415K
  - » No cost share, no contractors
- FY07 = $214K
- FY08 = $26K authorized to date

Partners

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

ANL = Argonne National Lab

Objectives

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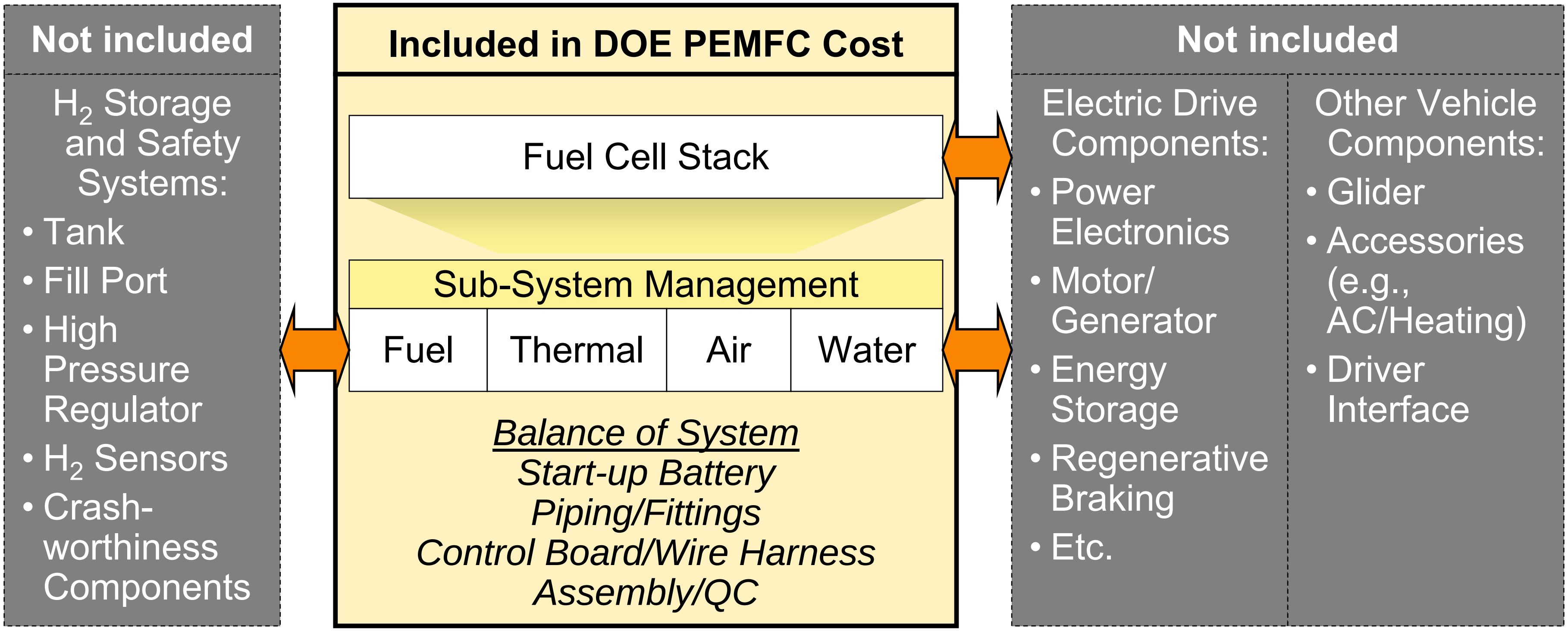
Overall	◆ Bottom-up manufacturing cost assessment of 80 kW direct-H_2 PEMFC system for automotive applications
2007	◆ High-volume (500,000 units/year) cost projection of ANL 2007 PEMFC system configuration assuming an NSTFC-based MEA and a 30 μm 3M-like membrane ◆ Bottom-up manufacturing cost analysis of BOP components (Bottom-up stack cost analysis completed in FY 2007) ◆ Sensitivity analyses on stack and system parameters ◆ EOS impacts on 2007 BOP costs (EOS analysis of 2005 stack completed in FY2006)
2008–2011	◆ Annual updates of high-volume cost projection ◆ Optional: specific analysis topics including cost implications of: » Ambient versus pressurized operation » High temperature, low humidity operation » Lower temperature, low humidity hydrocarbon membrane » Alternative PEMFC approaches including cell/stack constructions and BOP components » Other topics as the need arises

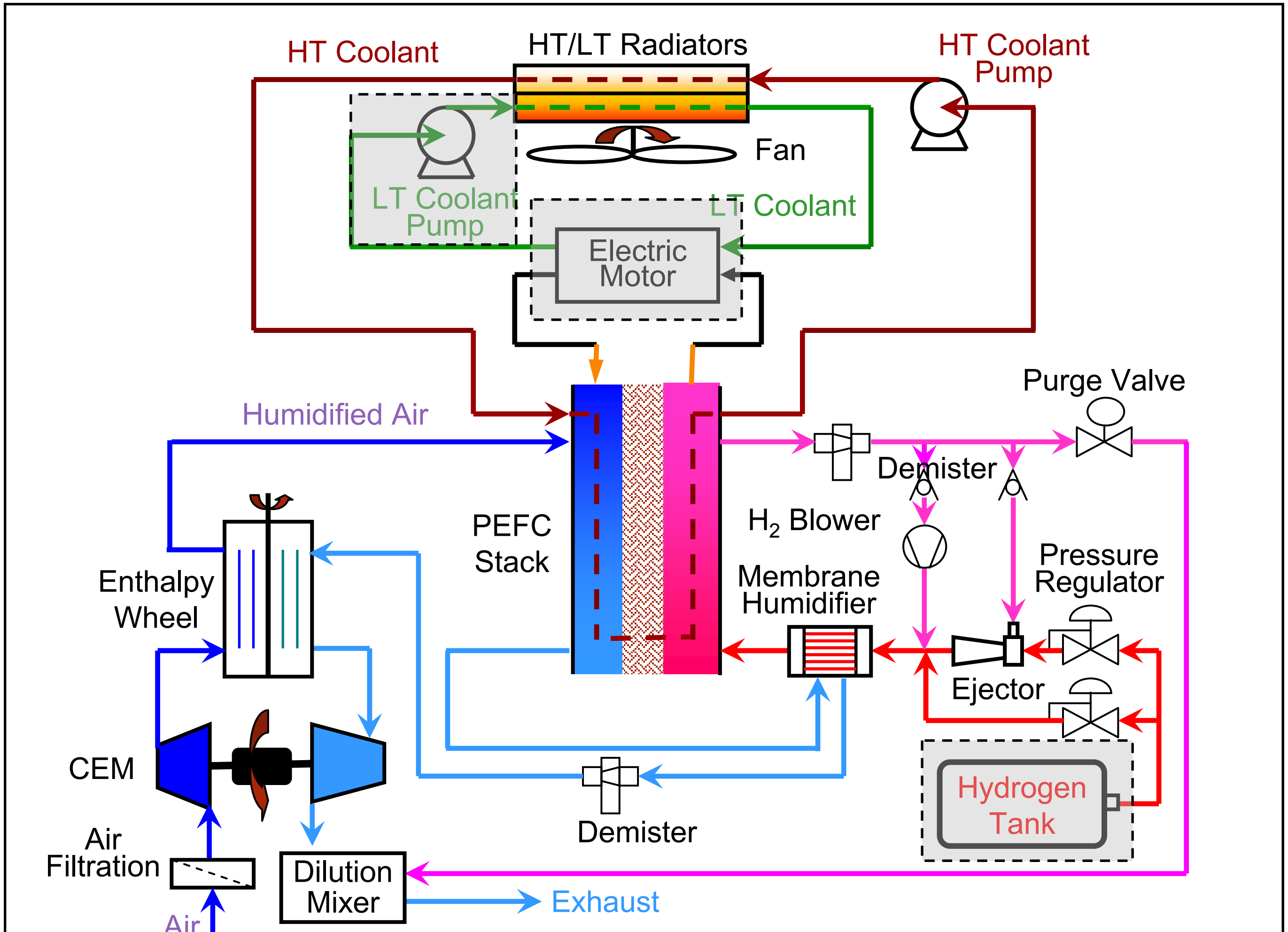
BOP = Balance-of-Plant
NSTFC = Nano-Structured Thin Film Catalyst
MEA = Membrane Electrode Assembly
EOS = Economies of Scale

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



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

We worked with Argonne National Laboratory (ANL) to define the 2007 system configuration, performance and component specifications[1].

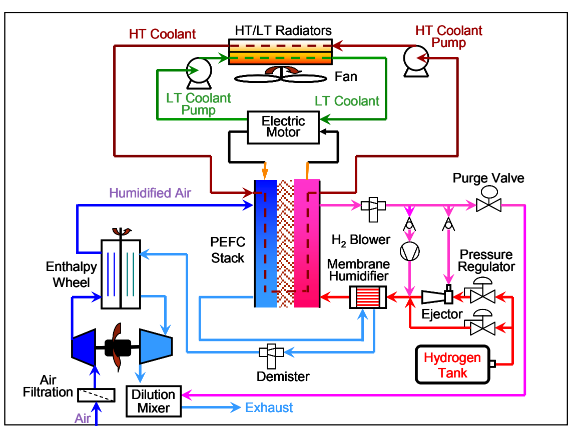


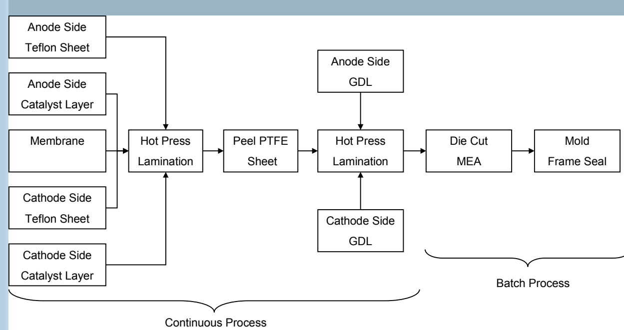
Not included in the fuel cell system cost assessment

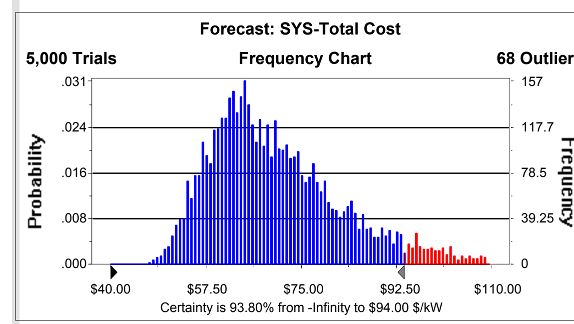
[1] R.K. Ahluwalia and X. Wang, Reference Fuel Cell System Configurations for 2007: Interim Results, ANL, Feb. 6, 2007

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

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







BOM = Bill of Materials

We used two different bottom-up costing tools to determine high-volume (500,000 units/year) manufacturing cost for the major BOP components[1].

Costing Tools

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

TIAX Technology-Based Cost Model

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

DFMA® Concurrent Costing

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

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

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)

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

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

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

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

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

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

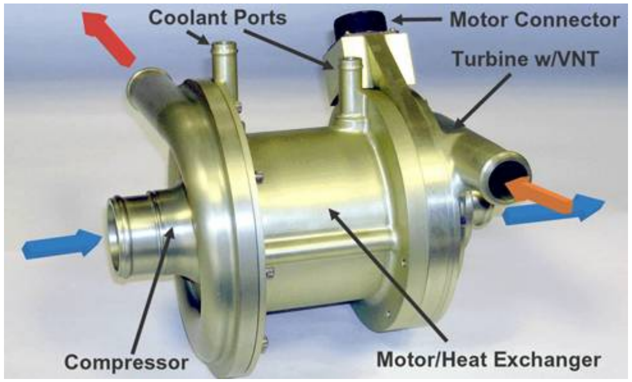
Contacted in 2005-2006

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

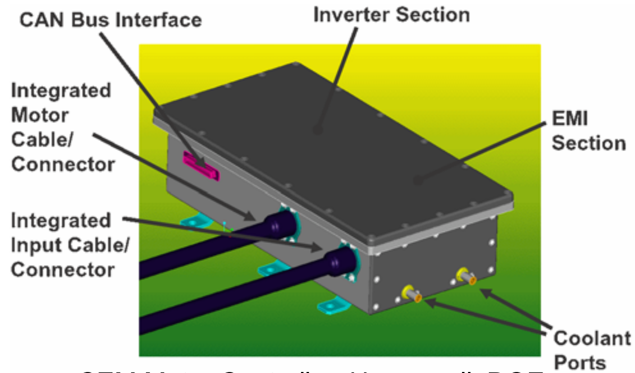
Contacted in 2007

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

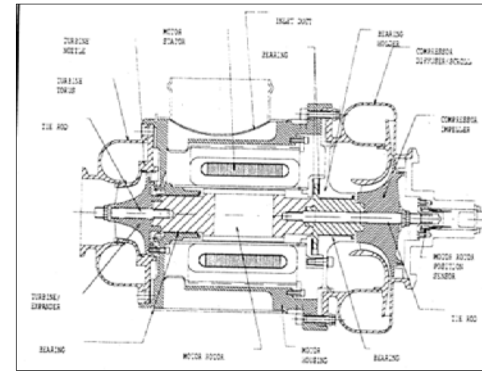
We estimated the cost of the CEM based on published presentations, reports, and patents from Honeywell.



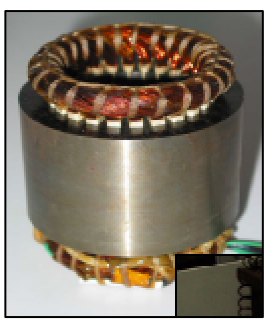
CEM: Honeywell, DOE Program Review, Progress Report & Annual Report, 2005



CEM Motor Controller: Honeywell, DOE Program Review, Progress Report & Annual Report, 2005

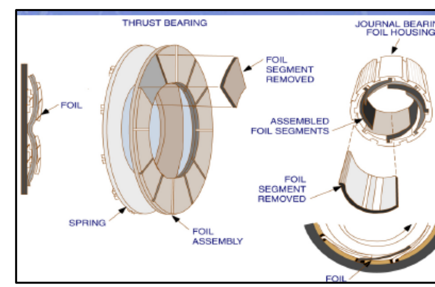


CEM Schematic: Honeywell, DOE Progress Report, 2000



Motor: Honeywell, DOE Merit Review, 2004

Turbine, Compressor, Shaft: Honeywell, DOE Merit Review, 2003



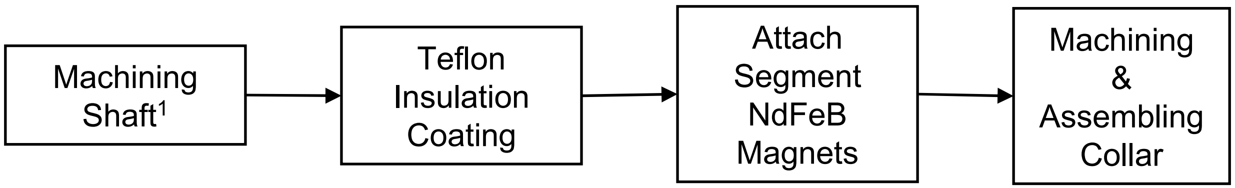
Journal Bearing: Honeywell, Fuel Cell Seminar, 2005

Volume: 15 Liters Weight: 20 kg

Unison Ring: Garrett/Honeywell, Final Report, DE-FC05-00OR22809, 2005

Unison Ring and Variable Nozzle Turbine of Garrett VNT25

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



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

Courtesy: Honeywell, DOE Merit Review 2003

CEM Motor Rotor Manufacturing Process

[1] Boothroyd Dewhurst Machining package

Results CEM Bill of Materials

The estimated CEM (including motor and motor controller) factory cost is $535 per unit[1].

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

[1] Estimates are not accurate to the number of significant figures shown.

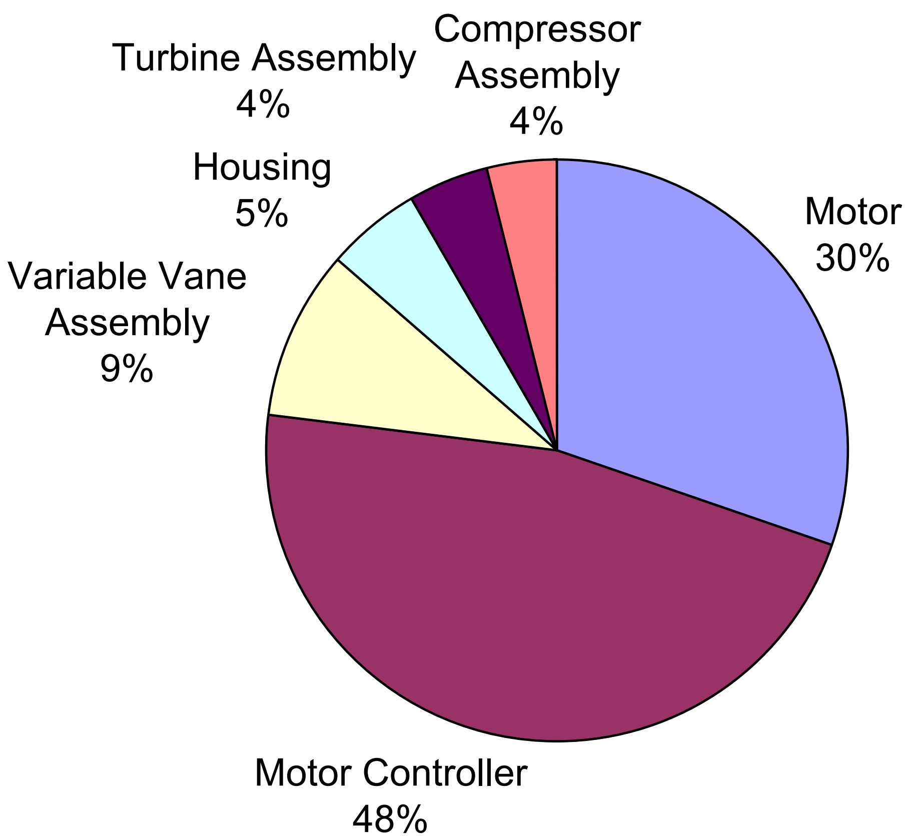
The motor assembly and motor controller are projected to cost $412, representing 77% of the CEM cost.

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

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

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

CEM Manufactured Cost ($535)

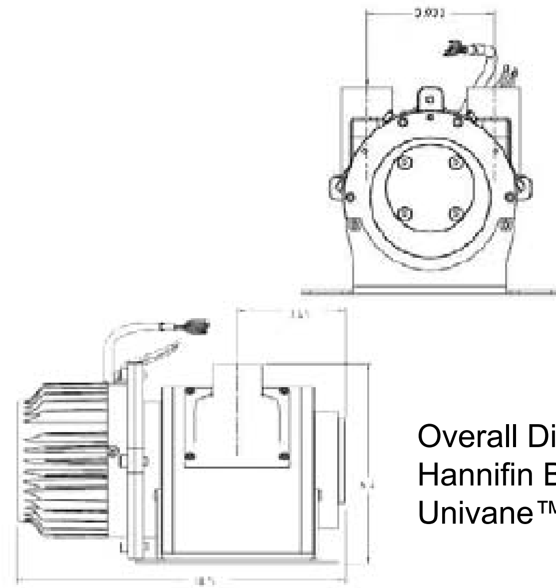


CEM Manufactured Cost ($)		
Component	Factory Cost	OEM Cost[1]
Motor	162	615
Motor Controller	251	
Variable Vane Assembly	50	
Housing	28	
Turbine Assembly	24	
Compressor Assembly	21	
Total:	**535**	

[1] Assumes 15% markup to the automotive OEM

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

Parker Hannifin Brochure for Model 55 Univane™ Compressor



Overall Dimensions from Parker Hannifin Brochure for Model 55 Univane™ Compressor

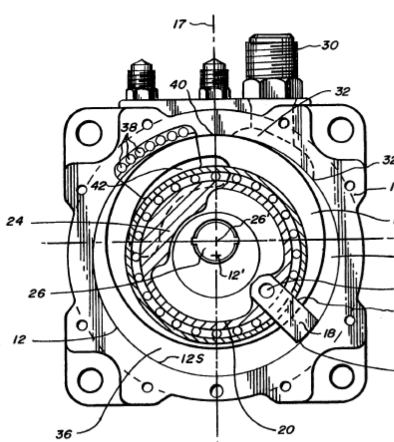


FIG. 1

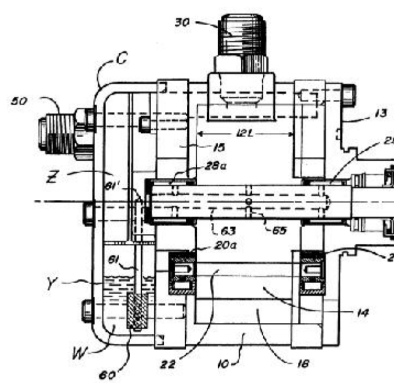


FIG. 2

US Patent: 5,374,172

Volume: 5 Liters Weight: 6.9 kg

Results H_2 Blower Process Flow

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

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

Courtesy: Parker Hannifin Brochure for Model 55 Univane™ Compressor

[1] Boothroyd Dewhurst Concurrent Costing & Machining packages

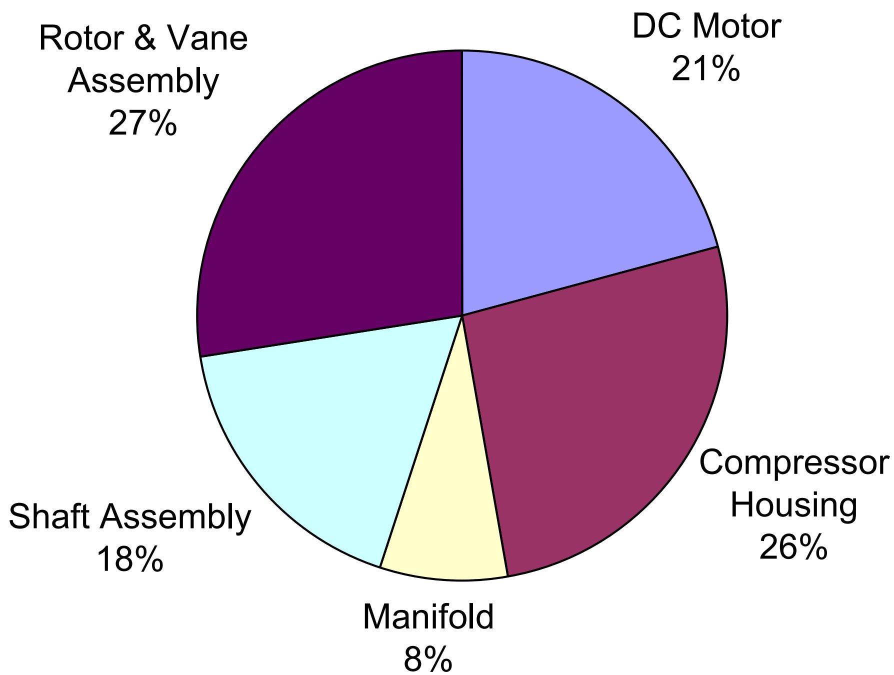
The projected H_2 blower cost is $193 per unit[1].

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

[1] Estimates are not accurate to the number of significant figures shown.

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

H_2 Blower Manufactured Cost ($193)

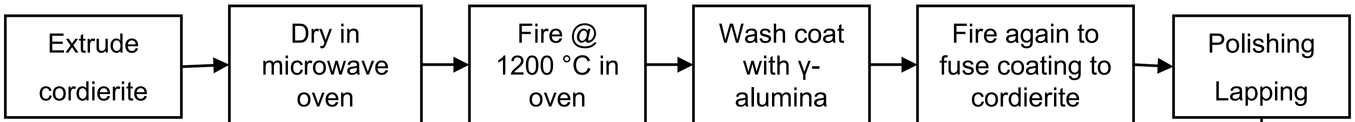


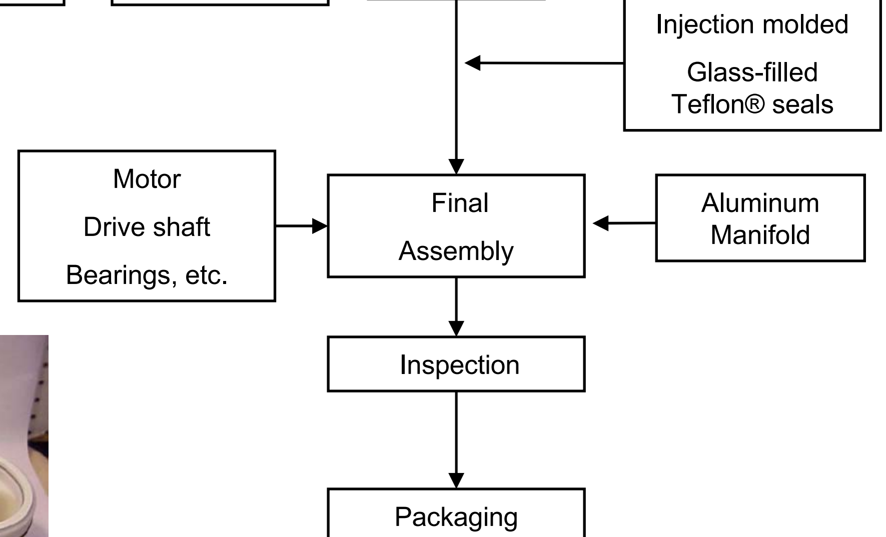
H_2 Blower Manufactured Cost ($)		
Component	Factory Cost	OEM Cost[1]
DC Motor	40	**222**
Blower Housing	51	
Manifold	15	
Shaft Assembly	34	
Rotor & Vane Assembly	53	
Total:	**193**	

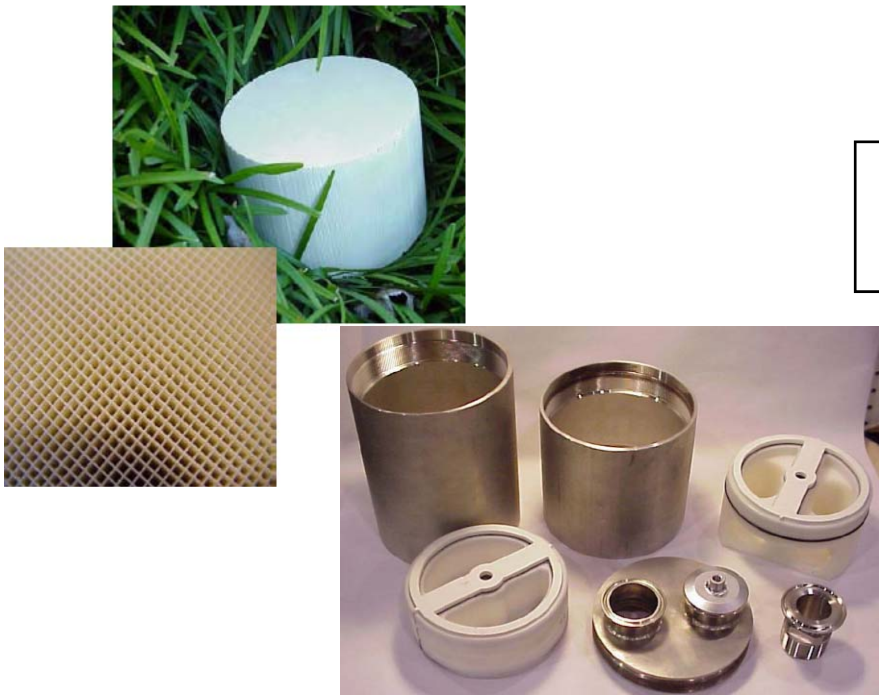
[1] Assumes 15% markup to the automotive OEM

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

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





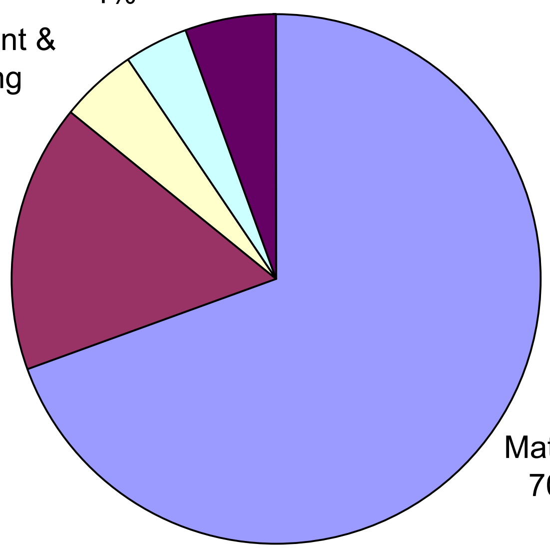


Courtesy: Emprise

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

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

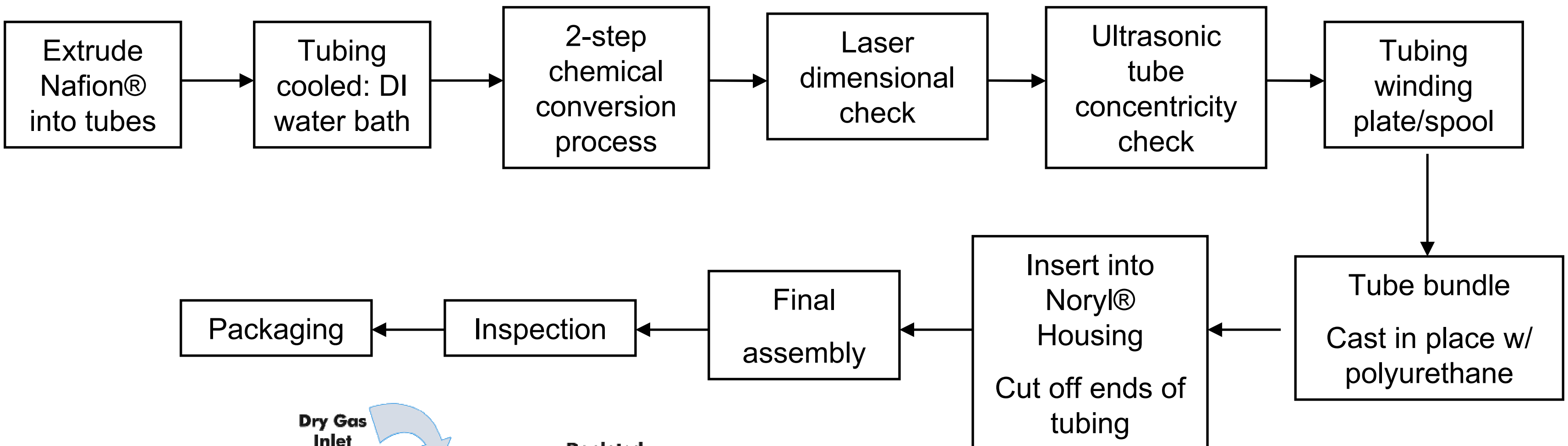
Enthalpy Wheel Humidifier Manufactured Cost ($160)

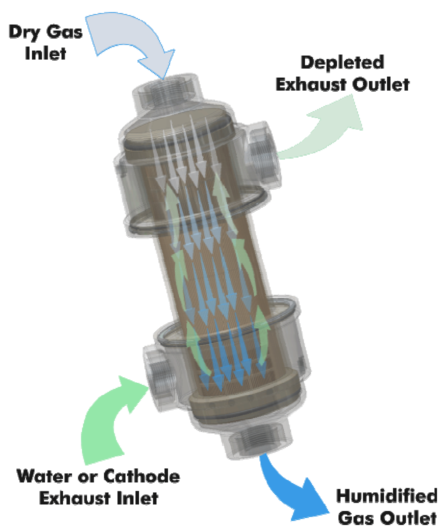


Enthalpy Wheel Humidifier Manufactured Cost[1] ($)			
Component	**#**	**Material**	**Process**
DC motor with gear box	1	50.00	0.00
Shaft	2	0.10	2.86
Wheel shaft	2	0.12	3.56
Screw	1	0.05	0.00
Bearing	2	4.30	0.00
End plate	2	10.79	1.80
Spring plate	2	1.04	1.68
Springs	26	1.30	0.00
End seal plate	2	10.79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

[1] Estimates are not accurate to the number of significant figures shown.

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

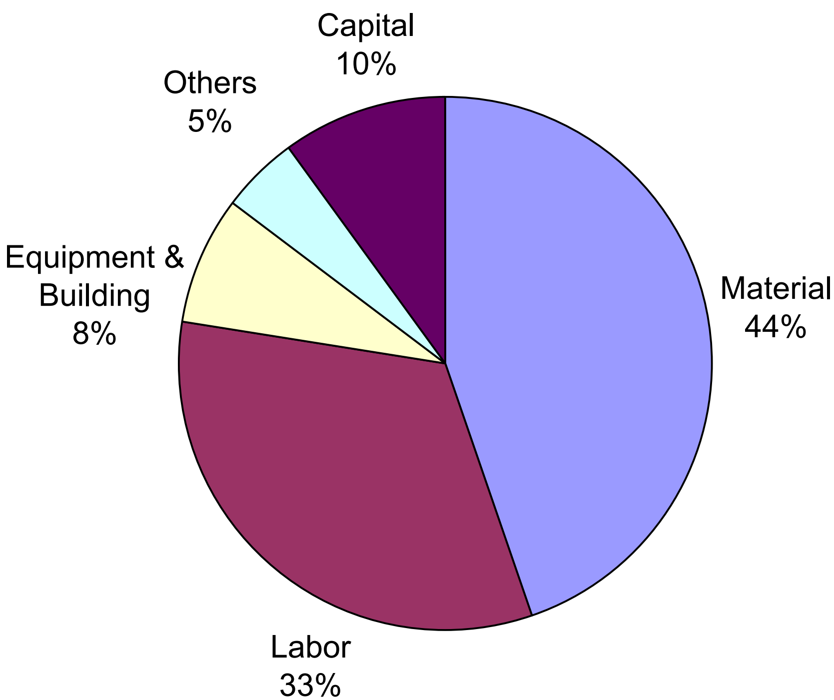




Courtesy: PermaPure

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

Membrane Humidifier Manufactured Cost ($58)



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

[1] Estimates are not accurate to the number of significant figures shown.

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

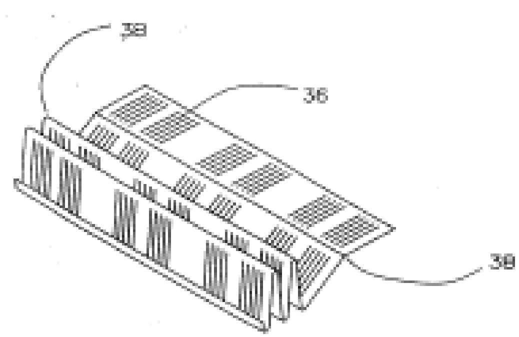
Al Tube → Cooling Core Assembly

Al Strip → Fin Fabrication → Cooling Core Assembly → CAB Brazing Oven → Electrostatic Painting → Leak Test → Packaging

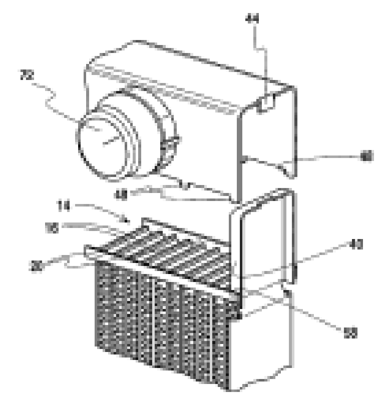
Stamp Top/Bottom Frames → Cooling Core Assembly

Stamp Inlet/Outlet Tanks → Cooling Core Assembly

Stamp Core Headers → Cooling Core Assembly

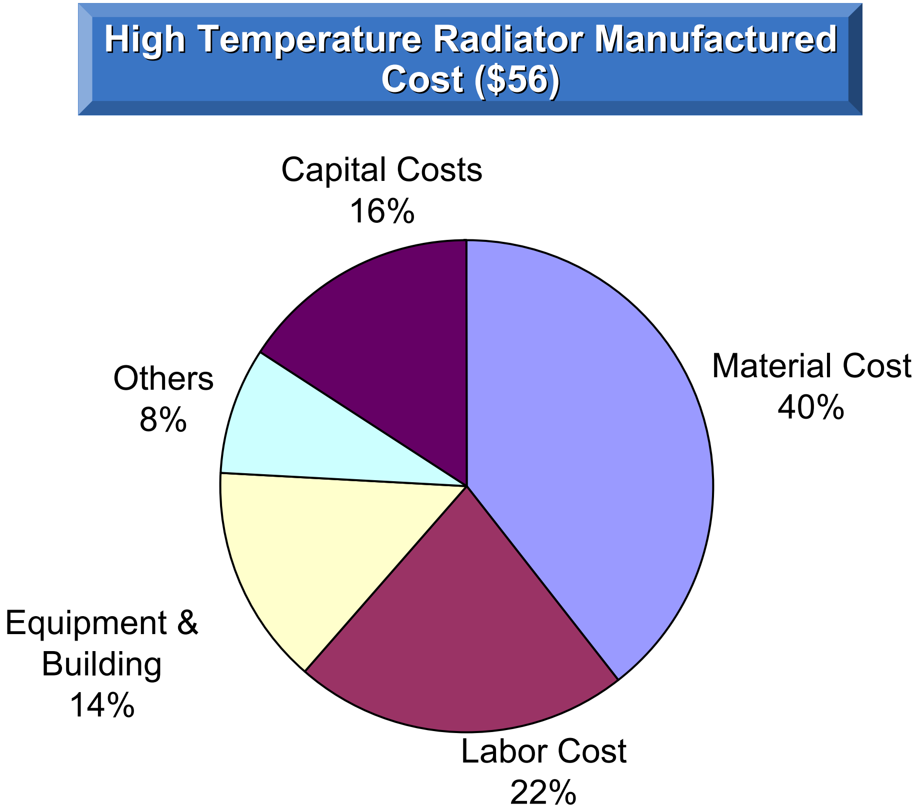


Fin Fabrication
US Patent
5,350,012



Radiator Structure
US Patent
7,032,656

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



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

[1] Assumes 15% markup to the automotive OEM

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

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

BOP Sub-system	Component	Technology Basis	Factory Cost[1], $ (without supplier markup)	OEM Cost[1], $ (with 15% supplier markup)
Water Management	Enthalpy wheel air-humidifier	Emprise	160	184
	Membrane H_2-humidifier	PermaPure	58	66
	Other	-	10	10
Thermal Management	Automotive tube-fin radiator	Modine	56	65
	Radiator fan[2]	-	35	35
	Coolant pump[3]	-	120	120
	Other	-	5	5
Air Management	Compressor-Expander-Motor (CEM)	Honeywell	535	615
	Other	-	97	97
Fuel Management	H_2 blower	Parker Hannifin	193	222
	H_2 ejectors[4]	-	40	40
	Other		41	41
TOTAL			1350	1500

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system.
[2] Assumes $35/unit based on automotive radiator vendor catalog price, scaled for high volume production
[3] Assumes $120/unit, based on 2005 PEMFC Costing Report: E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104
[4] Assumes $20/unit, and 2 ejectors, based on 2005 PEMFC Costing Report: E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104

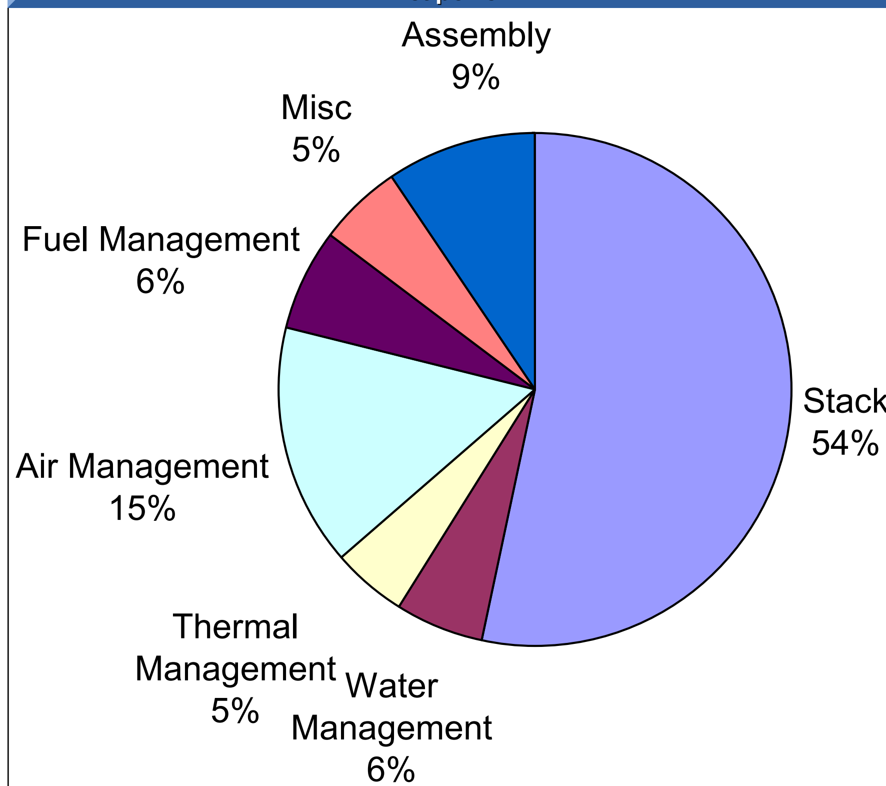
Both stack and BOP component costs are significantly reduced from the 2005 cost assessment.

PEMFC System Cost[1] ($/kW)	2005 OEM Cost	2007 Factory Cost[1]	2007 OEM Cost[1,2]
Stack	**67**	**31**	**31**
Water Management	8	2.8	3.3
Thermal Management	4	2.7	2.8
Air Management	14	7.9	8.9
Fuel Management	4	3.4	3.8
Miscellaneous	7	3.1	3.1
Assembly	4	5.5	5.5
Total	**108**	**57**	**59**

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

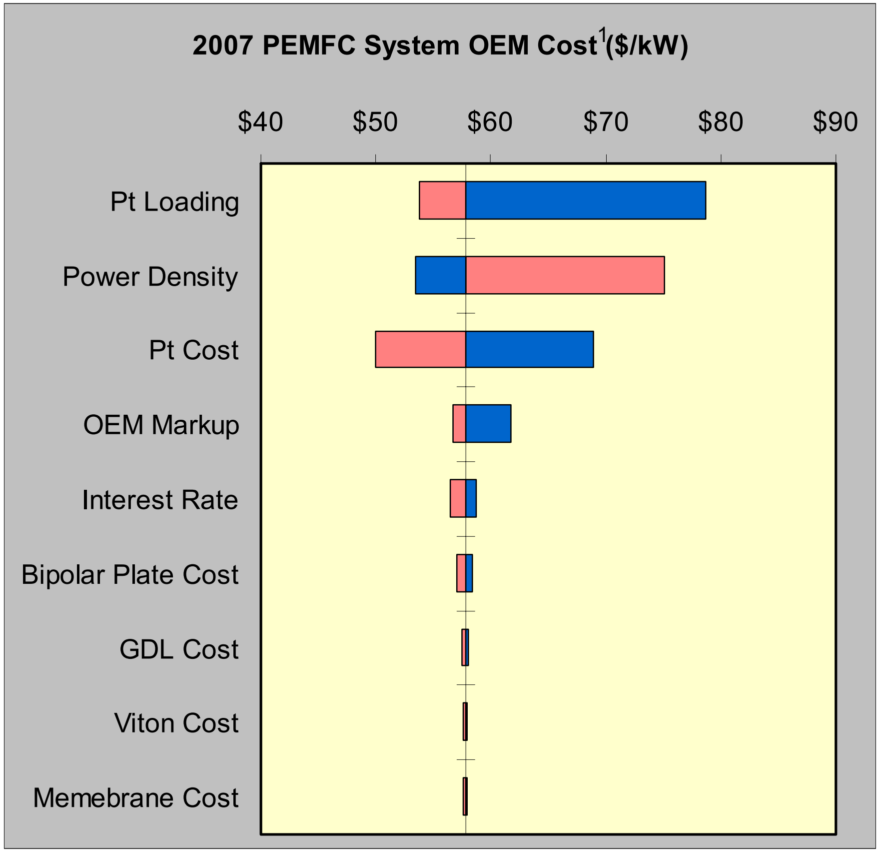
[2] Assumes 15% markup to the automotive OEM for BOP components

2007 PEMFC System OEM Cost[1,2] ($59/$kW_{net\ power}$, $4,720)



BOP component costs represent ~ 46% of the PEMFC system cost in 2007, as compared to ~ 38% in 2005.

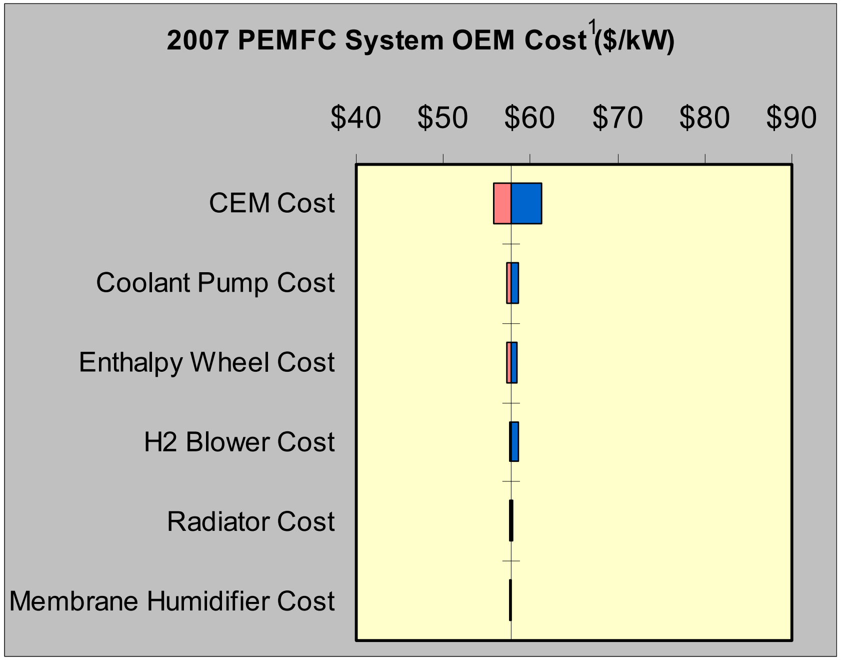
Pt loading, power density, and Pt cost are the top three cost drivers of the PEMFC system cost[1].



#	Variables	Minimum	Maximum	Base	Comments
1	Pt Loading (mg/cm^2)	0.2	0.75	0.3	Minimum: DOE 2015 target[2]; Maximum: TIAX 2005 study[3]
2	Power Density (mW/cm^2)	350	1000	753	Minimum: industry feedback; Maximum: DOE 2015 target[2].
3	Pt Cost ($/tr.oz.)	450	2000	1100	Minimum: historical average[4]; Maximum: current LME price[5]
4	OEM Markup	5%	20%	15%	Based on industry feedback
5	Interest Rate	8%	20%	15%	Based on industry feedback
6	Bipolar Plate Cost ($/kW)	1.8	3.4	2.6	Based on component single variable sensitivity analysis
7	GDL Cost ($/kW)	1.7	2.2	1.9	Based on component single variable sensitivity analysis
8	Viton Cost ($/kg)	39	58	48	Based on industry feedback
9	Membrane Cost ($/m^2)	10	50	16	Minimum: GM study[6]; Maximum: DuPont projection[7]

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

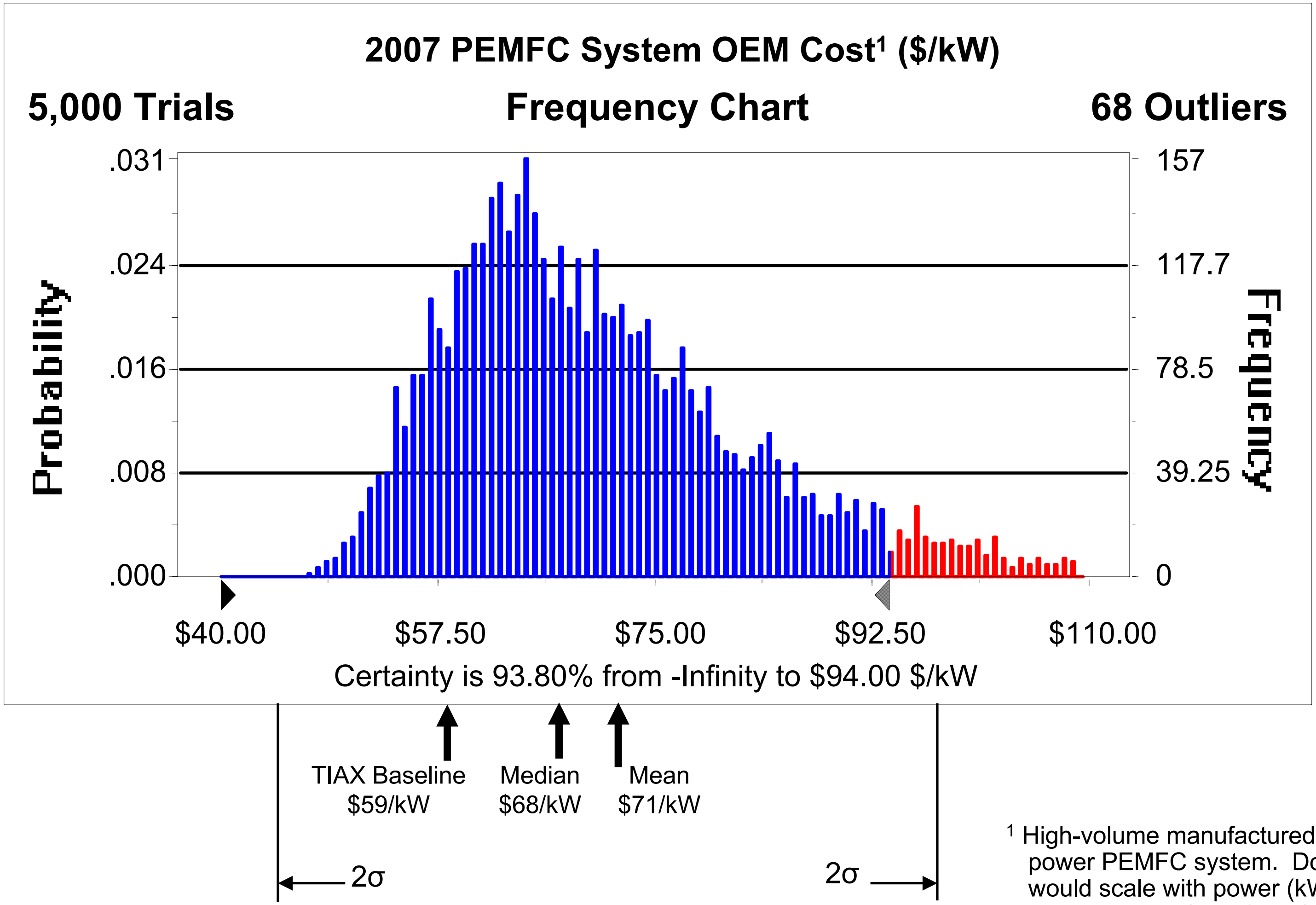
Among the BOP components, the CEM has the greatest impact on the PEMFC system cost[1].



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

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

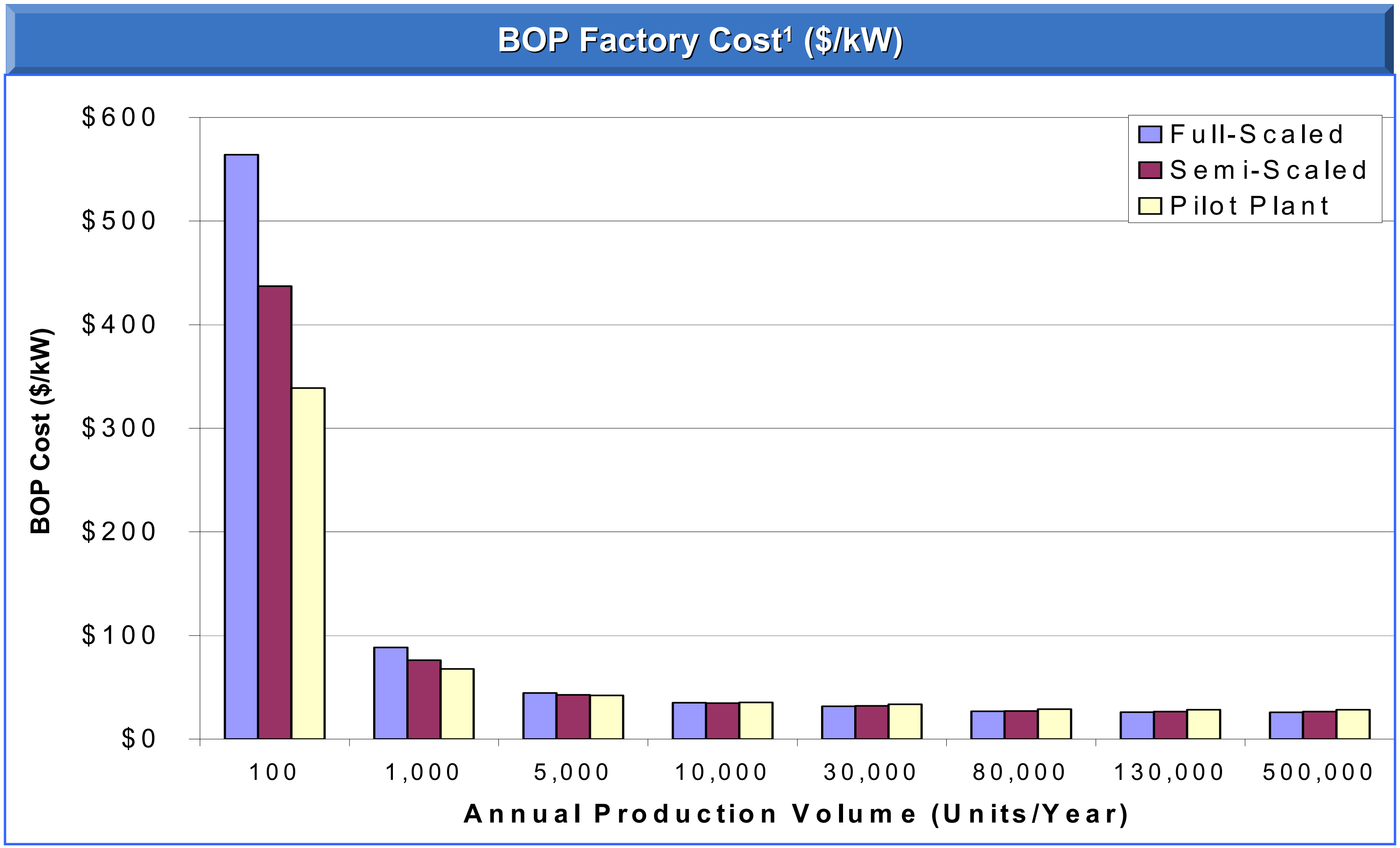
Monte Carlo analysis shows that the PEMFC system OEM cost ranges between $45/kW and $97/kW (± 2σ) at a production volume of 500,000 units per year.



Cost[1]	$/kW
Mean	71
Median	68
Std. Dev.	13
TIAX Baseline	59

[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.

At low production volumes (100 units/year), the pilot plant scenario yields the lowest BOP cost of $340/kW, while at high volumes (≥ 80,000 units/year), the full-scaled scenario yields the lowest BOP cost of $26/kW.



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

The 2007 PEMFC stack and system costs are ~ 25-30% higher than the DOE 2010 cost targets.

PEMFC Sub-System	Factory Cost[1], $/kW (without supplier markup)	OEM Cost[1,2], $/kW (with 15% supplier markup)	DOE 2010 Cost Target[3], $/kW
Stack	**31**		**25**
Balance of Plant	**26**	**28**	**20**
Water management (enthalpy wheel, membrane humidifier)	2.8	3.3	
Thermal management (radiator, fan, pump)	2.7	2.8	
Air management (CEM, motor controller)	7.9	8.9	5
Fuel management (H_2 blower, H_2 ejectors)	3.4	3.8	
Miscellaneous and assembly	8.6		
Total System	**57**	**59**	**45**

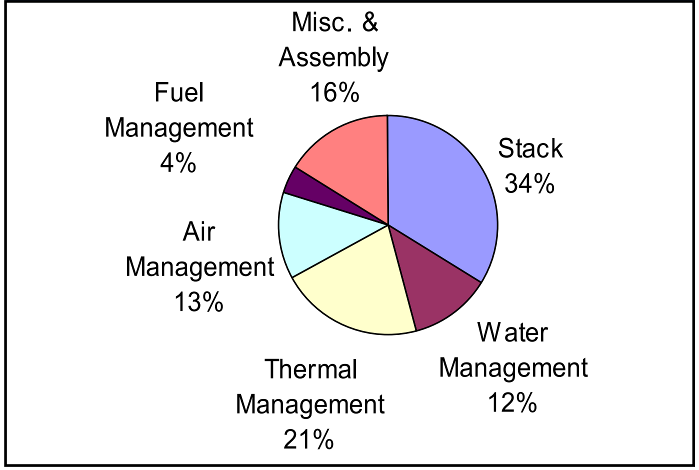
[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW).
[2] Assumes 15% markup to the automotive OEM for BOP components
[3] FreedomCAR targets are $20/kW for the stack and $35/kW for the total system.

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

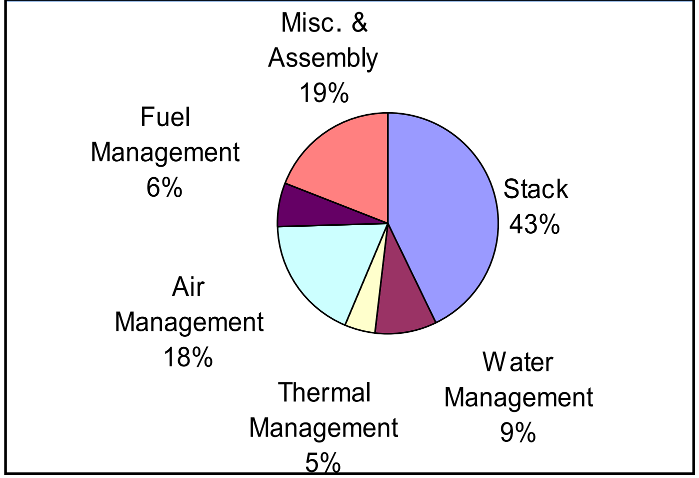
PEMFC Sub-System	Volume[1] (L)	Weight (kg)	DOE 2010 Target
Stack	**40**	**47**	
Power density[2] (W_e/L)	2,000		2,000
Specific power[2] (W_e/kg)	1,702		2,000
Balance of Plant	**78**	**63**	
Water management (enthalpy wheel, membrane humidifier)	14	10	
Thermal management (radiator, fan, pump)	25	5	
Air management (CEM, motor controller)	15	20	
Fuel management (H_2 blower, H_2 ejectors)	5	7	
Miscellaneous and assembly	19	21	
Total System	**118**	**110**	
Power density[2] (W_e/L)	678		650
Specific power[2] (W_e/kg)	727		650

[1] Does not include packing factor, which would lower volumetric power density.
[2] Based on stack net power output of 80 kW, and **not** on the gross power output of 86.5 kW

2007 PEMFC System Volume (118 L)



2007 PEMFC System Weight (110 kg)



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

- Interview developers and stakeholders for feedback on performance and cost assumptions and overall results
  - 2006 Stack economies-of-scale
  - 2007 System high-volume cost
  - 2007 BOP economies-of-scale
- Incorporate feedback into stack and BOP bottom-up cost models.
- Prepare a comprehensive report on the 2007 PEMFC cost analysis (high-volume, bottom-up stack and BOP cost)

Acknowledgement

Thank You

Questions?

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

Audience/ Reviewer	Date	Location
DOE Merit Review	May 06	Washington DC
Kickoff Mtg. with DOE	May 06	Washington DC
Coordination Mtg. with DOE and ANL	Oct 06	Washington DC
Fuel Cell Tech Team Mtg.	Aug 06	Detroit MI
System Specifications Review Meeting with DOE and ANL	Feb 07	Telecon
Manufacturing Process Review Mtg. with 3M	Mar 07	Telecon
Fuel Cell Tech Team Mtg.	Apr 07	Detroit MI
National Academy of Science Review	Apr 07	Washington DC
DOE Merit Review	May 07	Washington DC
Several Work-in-Progress Mtgs. with DOE and ANL	Jun – Sep 07	Telecon
Final Presentation to Dr. JoAnn Milliken	Nov 07	Washington, DC
Fuel Cell Tech Team Mtg.	May 08	Detroit MI

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

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

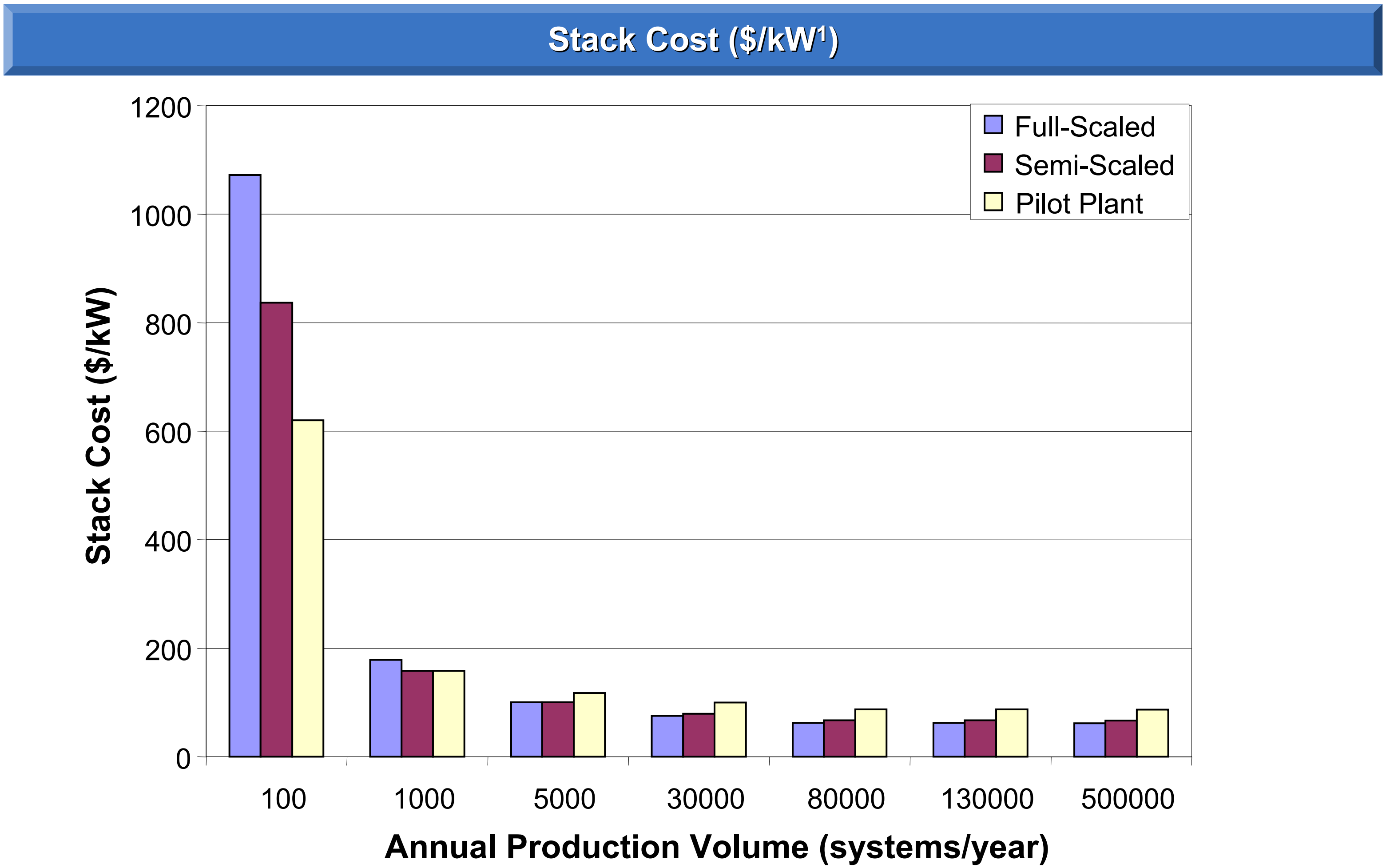
Component	Parameter	2006 EOS Assumptions
Membrane	Material	Sulfonated fluoro-polymer
	Supported	No
	Process	Cast dispersion
	Thickness	50 µm
Electrodes (Cathode & Anode)	Catalyst	Pt
	Support	Carbon black
	Process	Screen printing / gravure coating
Gas Diffusion Layer (GDL)	Material	Non-woven carbon paper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

The 2007 stack is different from the 2005 stack in that it assumes an NSTFC[1]-based MEA, a 30 µm 3M-like membrane, Pt loading=0.3 mg/cm^2 and power density = 753 mW/cm^2 @ 0.68 V/cell.

TIAX

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

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



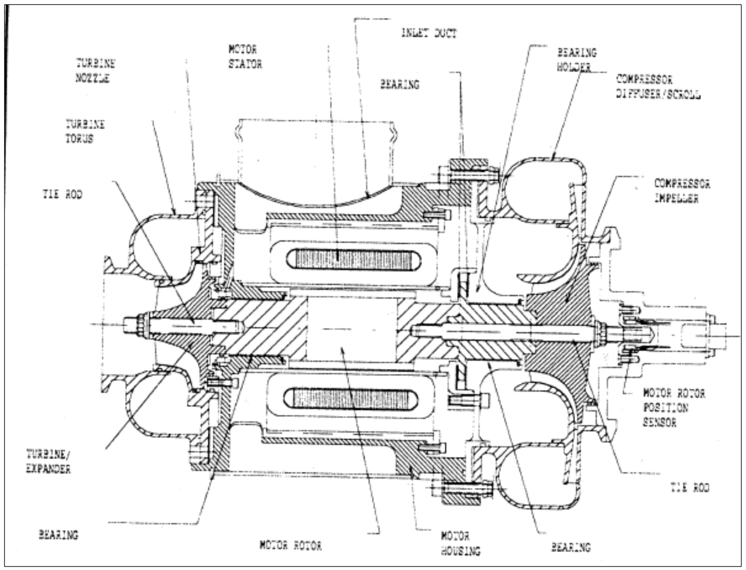
[1] PEMFC net power (80 kW) basis

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

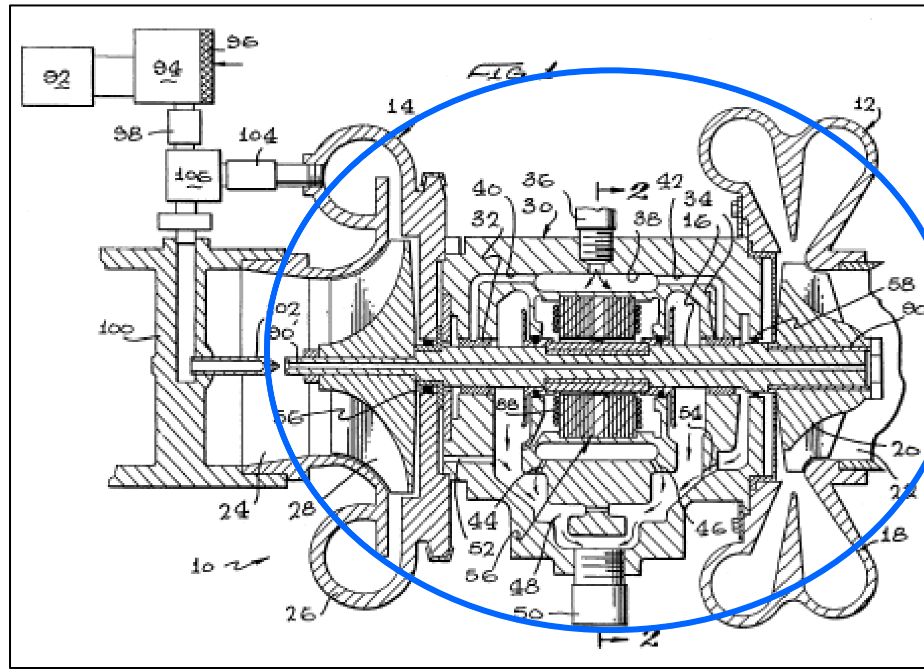
Component	References
Overall System	Honeywell, DOE program review, progress report & annual report, 2005, 2004, 2003, 2000
Electrical Motor	Honeywell, DOE program review, progress report & annual report 2004; US patent 5,605,045;
Power Electronics	Honeywell, DOE program review, progress report & annual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

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

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



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



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

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

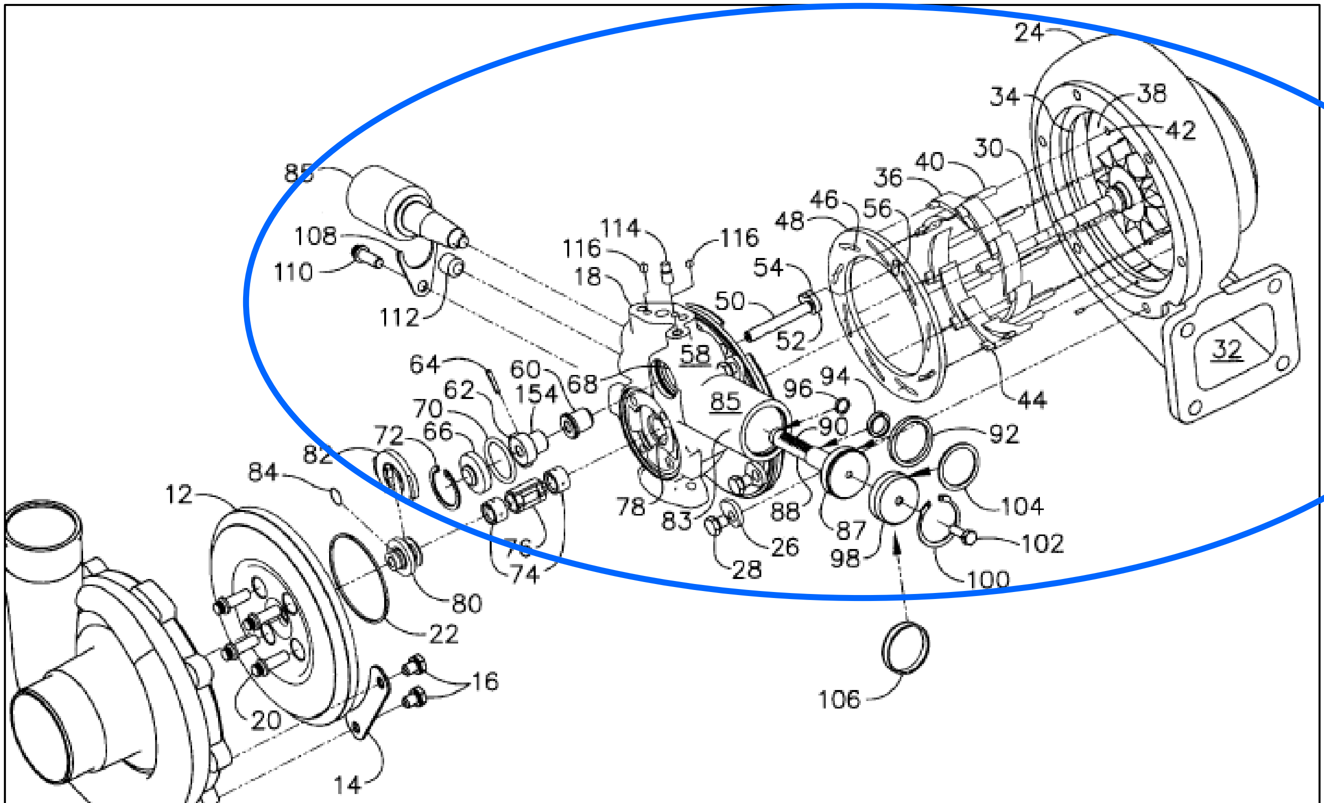
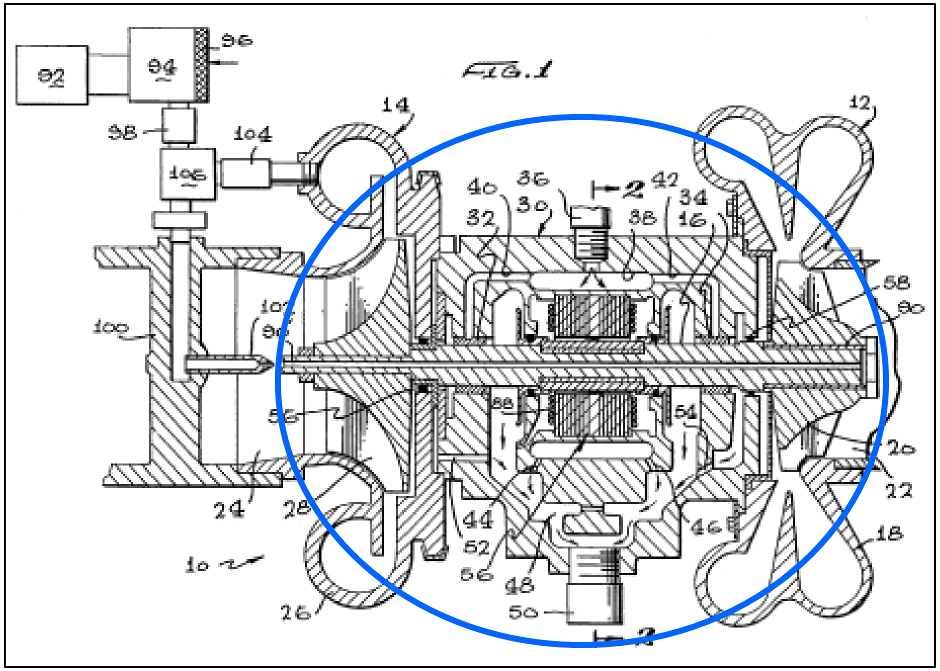
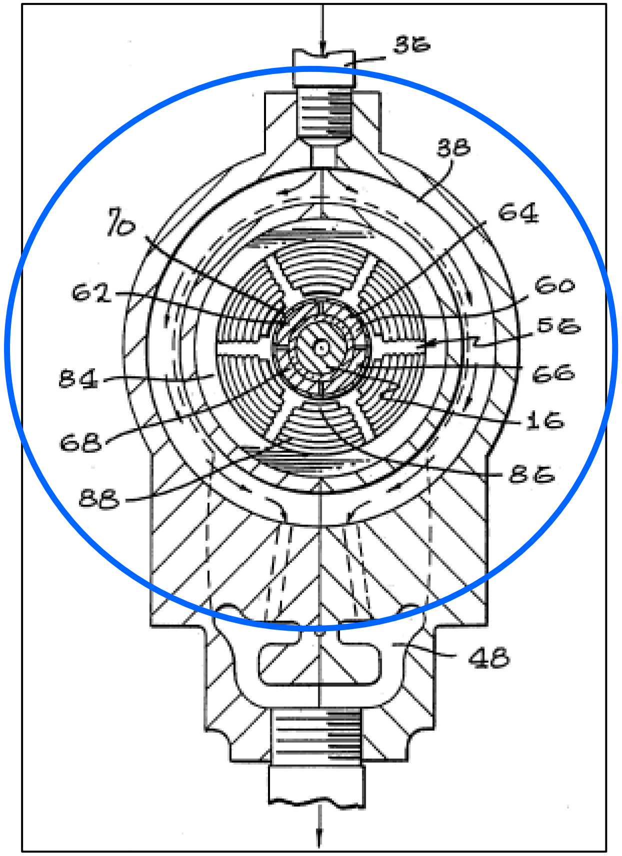


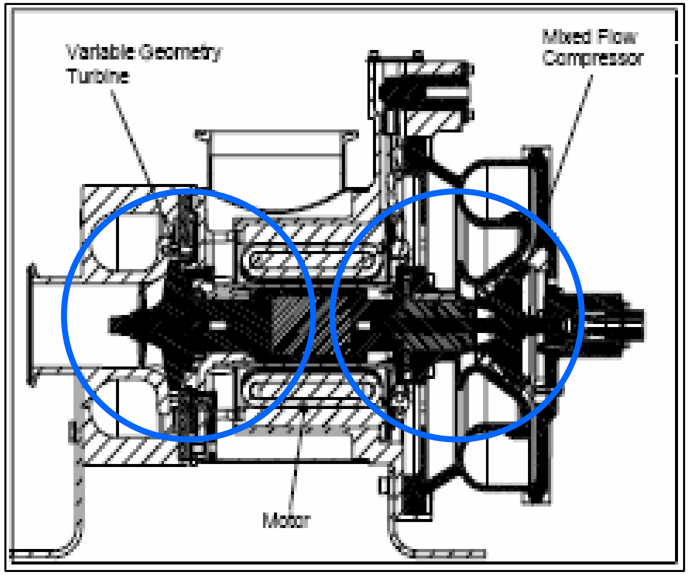
FIG. 1

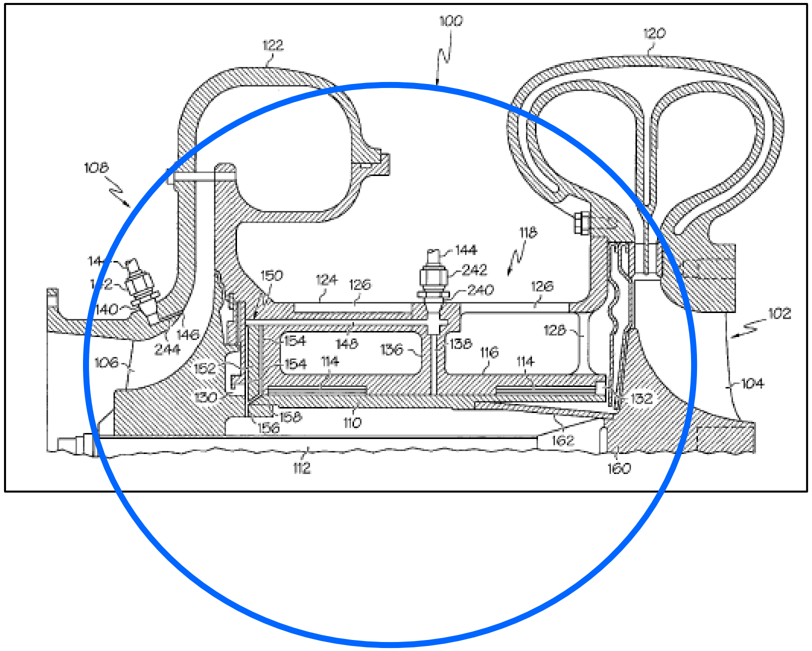
The CEM motor stator and rotor assembly are referenced from US patent 5,605,045.





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





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

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

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

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

FIG. 3

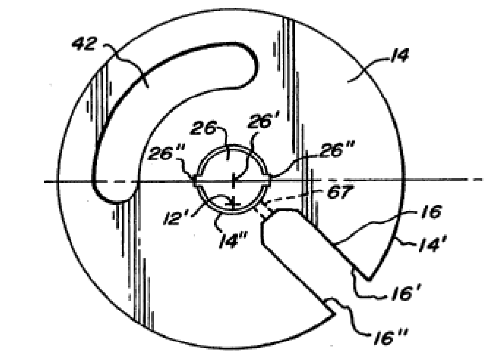
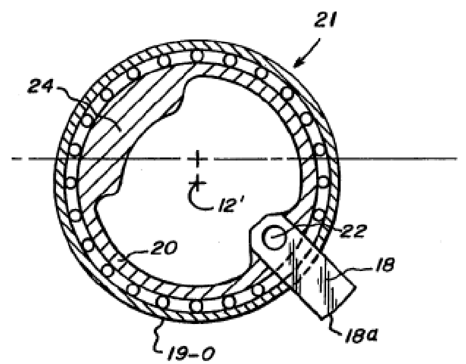


FIG. 4



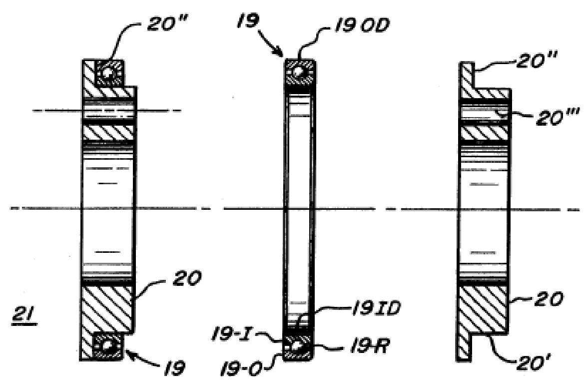


FIG. 5C FIG. 5A FIG. 5B

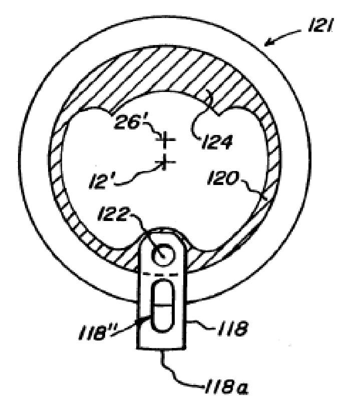


FIG. 6

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

Stack performance assumptions were provided by ANL based on their modeling of a 3M-like stack.

- Improvement over 2005 assumptions:
  - 60% reduction in Pt loading with an increase in power density
  - 40% thinner and less expensive membrane on an area basis
- Platinum (Pt) loading and power density are critical parameters that influence stack cost
- Lower Pt loading is attributed to novel catalyst and support structure (i.e., nano-structured thin film on organic whisker support)
- We reviewed the performance assumptions with 3M, ANL and the FC Tech Team, but we did not assess other developers' state-of-the-art performance attributes

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

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

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

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

Key assumptions in 2007 represent stack performance breakthroughs, in particular high power density with significant Pt reduction.

We developed material cost assumptions and additional stack specifications consistent with the new performance assumptions.

TIAX Assumptions	Units	2005[1]	2007
Production volume	units/yr	500,000	500,000
Pt cost	$/g ($/tr.oz.)	29.0 (900)	35.4 (1100)
Pt conversion cost	% Pt cost	20%	10%
Number of stacks	#	2	2
Number of cells per stack	#	231	221
Active cell area:Total cell area	%	85%	85%
Active area per cell	cm^2	323	269
Cell pitch	cells/inch (cells/cm)	9.55 (3.76)	10.00 (3.85)
Stack voltage (rated power)	V	300	300

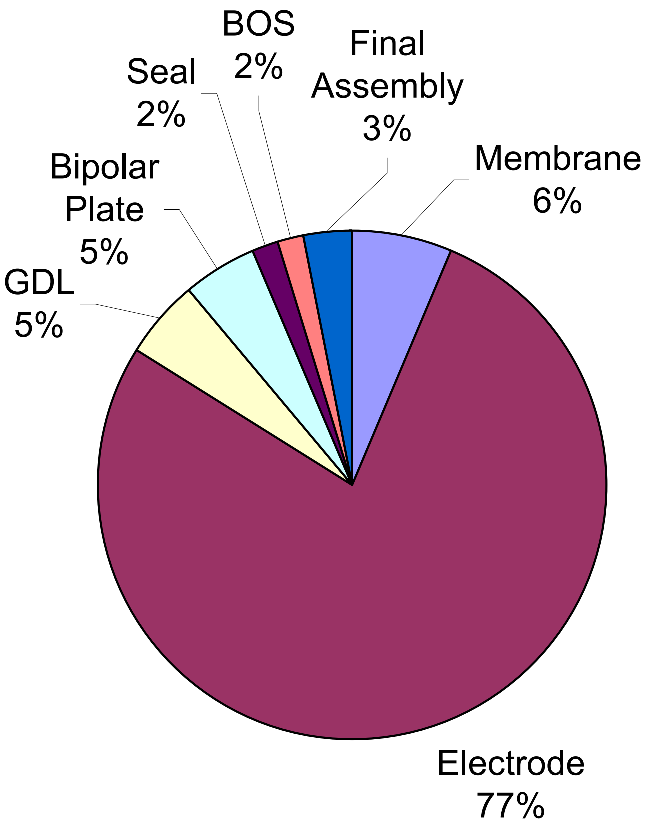
[1] E.J. Carlson et al., Cost Analysis of PEM Fuel Cell Systems for Transportation, Sep 30, 2005, NREL/SR-560-39104

Most 2007 assumptions are consistent with our 2005 cost assessment, except an increase in Pt cost to reflect current (high) prices.

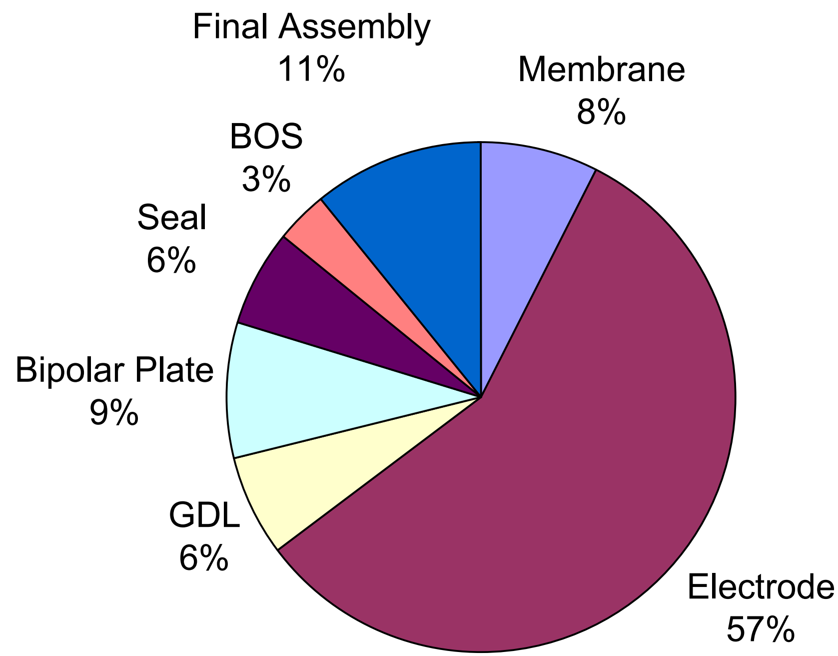
The electrodes represent approximately 57% of the $31/kW fuel cell stack cost in 2007.

Stack Manufactured Cost – 80 kW Direct-H_2 PEMFC

2005[1]: $67/kW, $5,360



2007[1]: $31/kW, $2,480



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

BOS = Balance-of-Stack

Stack costs on a per kW basis are 54% lower than the 2005 costs primarily due to higher power density with decreased Pt loading.

Manufactured Cost[1], $/kW	2005	2007	% change[2]	2010 DOE Target	Cost drivers / Comments
Membrane	4	2	-46%	10	Power density increased from 600 mW/cm^2 to 753 mW/cm^2 Pt loading decreased from 0.75 mg/cm^2 to 0.3 mg/cm^2 Woven carbon fiber cost decreased from $30/kg to $20/kg Changed window frame from nitrile rubber ($5/lb) to Viton® ($20/lb)
Electrodes	52	18	-66%		
GDL	3	2	-42%		
Seal	1	2	73%		
Bipolar plates	3	3	-17%	5	
BOS	1	1	-13%		Includes stack manifold, bolts, end plates, current collector
Final Assembly	2	3	75%		2007 cost includes QC but not conditioning, while 2005 cost includes neither
Total[2]	**67**	**31**	**- 54%**	**25**	

[1] High-volume manufactured cost based on a 80 kW net power PEMFC system. Does not represent how costs would scale with power (kW). Estimates are not accurate to the number of significant figures shown.
[2] Results may not appear to calculate due to rounding of the 2005 and 2007 cost results.

BOS = Balance-of-Stack