Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: *2008 Update*

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Foreword

Energy security is fundamental to the mission of the U.S. Department of Energy (DOE) and hydrogen fuel cell vehicles have the potential to eliminate the need for oil in the transportation sector. Fuel cell vehicles can operate on hydrogen, which can be produced domestically, emitting less greenhouse gas and pollutants than conventional internal combustion engine (ICE), advanced ICE, hybrid and plug-in hybrid vehicles that are tethered to petroleum fuels. A diverse portfolio of energy sources can be used to produce hydrogen, including nuclear, coal, natural gas, geothermal, wind, hydroelectric, solar, and biomass. Thus, fuel cell vehicles offer an environmentally clean and energy-secure transportation pathway for transportation.

Fuel cell systems will have to be cost-competitive with conventional and advanced vehicle technologies to gain the market-share required to influence the environment and reduce petroleum use. Since the light duty vehicle sector consumes the most oil, primarily due to the vast number of vehicles it represents, the DOE has established detailed cost targets for automotive fuel cell systems and components. To help achieve these cost targets, the DOE has devoted research funding to analyze and track the cost of automotive fuel cell systems as progress is made in fuel cell technology. The purpose of these cost analyses is to identify significant cost drivers so that R&D resources can be most effectively allocated toward their reduction. The analyses are annually updated to track technical progress in terms of cost and indicate how much a typical automotive fuel cell system would cost if produced in large quantities (i.e. 500,000 vehicles per year).

The capacity to produce fuel cell systems at high manufacturing rates does not yet exist, and significant investments would have to be made in manufacturing development and facilities in order to enable it. Once the investment decisions are made, it will take several years to develop and fabricate the necessary manufacturing facilities. Furthermore, the supply chain will need to develop which requires negotiation between suppliers and system developer, with details rarely made public. For these reasons, the DOE has consciously decided not to analyze supply chain scenarios at this point, instead opting to concentrate its resources on solidifying the tangible core of the analysis, i.e. the manufacturing and materials costs.

The DOE uses these analyses as tools for R&D management and tracking technological progress in terms of cost. Consequently, non-technical variables are held constant to elucidate the effects of the technical variables. For example, the cost of platinum is held at $1,100 per troy ounce to insulate the study from unpredictable and erratic platinum price fluctuations. Sensitivity analysis is used to explore the effect of non-technical parameters.

To maximize the benefit of our work to the fuel cell community, DTI strives to make each analysis as transparent as possible. Through transparency of assumptions and methodology, the validity of the analysis will be strengthened. We hope that these analyses have been and will continue to be valuable tools to the hydrogen and fuel cell R&D community.

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1. Overview

This report is the second annual update of a comprehensive automotive fuel cell cost analysis[1] conducted by Directed Technologies, Inc. (DTI), under contract to the US Department of Energy (DOE). The first report, hereafter called the "2006 cost report", estimated fuel cell system cost for systems produced in the years 2006, 2010, and 2015. The 2007 Update report incorporated technology advances made in 2007 and re-appraised system costs for 2010 and 2015. It was based on the earlier report and consequently the structure and much of the approach and explanatory text was repeated. This 2008 report is another such update. The reader is directed to section 3.1 for a high-level summary of the major changes between the 2007 and 2008 updates.

In this multi-year project conducted for the US Department of Energy, DTI estimates the material and manufacturing cost of complete 80 kW_{net} direct hydrogen Proton Exchange Membrane (PEM) fuel cell systems suitable for powering light duty automobiles. The system costs were estimated for three different technology levels; one "current" system that reflects 2008 technology, one system based on predicted 2010 technology, and another system based on predicted 2015 technology. To assess the cost benefits of mass-manufacturing, five annual production rates were examined: 1,000, 30,000, 80,000, 130,000, and 500,000 systems per year.

A Design for Manufacturing and Assembly (DFMA) methodology is used to prepare the cost estimates. However, departing from DFMA standard practice, a markup rate to account for the business expenses of general and administrative (G&A), R&D, scrap, and profit, is <u>not currently included</u> in the cost estimates. Further study is planned to determine the appropriate fuel cell industry markup rates at the various system production rates. In previous system cost estimates, there was an additional 10% cost contingency, but that has not been included in this study.

In general, the system designs do not change with production rate, but material costs, manufacturing methods, and business-operational assumptions vary. Cost estimation at very low manufacturing rates (1,000 systems per year) presents particular challenges. Traditional low-cost mass-manufacturing methods are not cost-effective due to high per-unit setup and tooling costs and less defined, less automated operations are typically employed. For some repeat parts within the fuel cell stack, such as the membrane electrode assemblies (MEAs) and the bipolar flow plates, so many pieces are needed for each system that even at low system production rates (1,000/year), hundreds of thousands of individual parts are needed annually. Thus for these parts, mass-manufacturing cost reductions are achieved even at low system production rates. However, other fuel cell stack components (such as end plates and current collectors), and all balance of plant (BOP) equipment (such as blowers, hoses and valves), do not benefit from this manufacturing multiplier effect.

The 2008 system reflects the authors' best estimate of current technology and (with few exceptions[2]) is not based on proprietary information. Public presentations by fuel cell companies and other researchers along with extensive review of the patent literature have been used as the basis for much of the design and fabrication technologies. Consequently, the presented information may lag behind what is being done "behind the curtain" in fuel cell companies. Nonetheless, the current technology system provides a benchmark against which the impact of future technologies can be compared. Taken together, the analysis of these three systems provides a good sense of the range of costs that are possible for mass produced, automotive fuel cell systems and of the dependence of cost on system performance, manufacturing, and business-operational assumptions.

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[1] "Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications," Brian D. James & Jeff Kalinoski, Directed Technologies, Inc., October 2007.

[2] The bipolar plate coating method used was based on the proprietary technology of TreadStone Technologies, Inc.

2. Basic Approach

The three systems examined (2008 technology, 2010 technology, and 2015 technology) do not reflect the design of any one manufacturer but are composites of the best elements from a number of designs. All three systems were normalized to a system output power of 80 kW_{net}, although their gross powers were derived independently, based on the parasitic load from the balance of plant components, using an oxidant stoichiometry of 1.8. The stack efficiency at rated power for all three systems is pegged at 55%, to match the DOE target value. Multiplying this by the theoretical open circuit cell voltage (1.229 V) yields a cell voltage of 0.676 V at peak power. Stack pressure levels (at peak power) are projected to decrease with time, and were set at 2.3, 2.0, and 1.5 atm[3] for the 2008, 2010, and 2015 systems respectively.

The main fuel cell subsystems included in this analysis are:

- Fuel cell stacks
- Fuel supply (but not fuel storage)
- Air supply
- Humidifier and water recovery loop
- Coolant loop
- Fuel cell system controller and sensors
- Fuel cell system mounting frames

Some vehicle electrical system components explicitly excluded from the analysis include:

- Main vehicle battery or ultra capacitor[4]
- Electric traction motor (that drives the vehicle wheels)
- Traction inverter module (TIM) (for control of the traction motor)
- Vehicle frame, body, interior, or comfort related features (e.g., driver's instruments, seats, and windows).

Many of the components not included in this study are significant contributors to the total fuel cell vehicle cost, but their design and cost are not necessarily dependent on the fuel cell configuration or operating conditions. The fuel cell system is the power plant that could be used in a variety of vehicle body types and drive configurations, all of which could have a different cost structure.

As mentioned above, the costing methodology employed in this study is the Design for Manufacture and Assembly technique (DFMA). The Ford Motor Company has formally adopted the DFMA process as a systematic means for the design and evaluation of cost optimized components and systems. These techniques are powerful and are flexible enough to incorporate historical cost data and manufacturing acumen that have been accumulated by Ford since the earliest days of the company. Since fuel cell system production requires some manufacturing processes not normally found in automotive production, the formal DFMA process and DTI's manufacturing database are buttressed with budgetary and price quotations from experts and vendors in other fields. It is possible to choose cost-optimized manufacturing processes and component designs and accurately estimate the cost of the resulting products by combining historical knowledge with the technical understanding of the functionality of the fuel cell system and its component parts.

[3] The systems operate at these pressures (for both the air and hydrogen streams) at peak power. Because a centrifugal air compressor (for the 2010 and 2015 technology systems) is used to achieve air pressurization, cathode pressure is less than the full pressure at system part power.

[4] Fuel cell automobiles may be either "pure-breds" or "hybrids" depending on whether they have battery (or ultracapacitor) electrical energy storage or not. This analysis only addresses the cost of an 80 kW fuel cell power system and does not include the cost of any peak-power augmentation or hybridizing battery.

The cost for any component analyzed via DFMA techniques includes direct material cost, manufacturing cost, assembly costs, and markup. Direct material costs are determined from the exact type and mass of material employed in the component. This cost is usually based upon either historical volume prices for the material or vendor price quotations. In the case of materials not widely used at present, the manufacturing process must be analyzed to determine the probable high-volume price for the material. The manufacturing cost is based upon the required features of the part and the time it takes to generate those features in a typical machine of the appropriate type. The cycle time can be combined with the "machine rate," the hourly cost of the machine based upon amortization of capital and operating costs, and the number of parts made per cycle to yield an accurate manufacturing cost per part. The assembly costs are based upon the amount of time to complete the given operation and the cost of either manual labor or of the automatic assembly process train. The piece cost derived in this fashion is quite accurate as it is based upon an exact physical manifestation of the part and the technically feasible means of producing it as well as the historically proven cost of operating the appropriate equipment and amortizing its capital cost. Normally (though not in this report), a percentage markup is applied to the material, manufacturing, and assembly cost to account for profit, general and administrative (G&A) costs, research and development (R&D) costs, and scrap costs. This percentage typically varies with production rate to reflect the efficiencies of mass production. It also changes based on the business type and on the amount of value that the manufacturer or assembler adds to the product. (Markup rate is discussed in more detail in section 4.3)

Cost analyses were performed for mass-manufactured systems at five production rates: 1,000, 30,000, 80,000, 130,000, and 500,000 systems per year. System designs did not change with production rate, but material costs, manufacturing methods, and business-operational assumptions (such as markup rates) often varied. Fuel cell stack component costs were derived by combining manufacturers' quotes for materials and manufacturing with detailed DFMA-style analysis.

For some components (e.g. the bipolar plates and the coolant and end gaskets), multiple designs or manufacturing approaches were analyzed. The options were carefully compared and contrasted, then examined within the context of the rest of the system. The best choice for each component was included in one or more of the three baseline configurations (the 2008, 2010 and 2015 technology systems). Because of the interdependency of the various components, the selection or configuration of one component sometimes affects the selection or configuration of another. In order to handle these combinations, the model was designed with switches for each option, and logic was built in that automatically adjusts variables as needed. As such, the reader should not assume that accurate system costs could be calculated by merely substituting the cost of one component for another, using only the data provided in this report. Instead, data provided on various component options should be used primarily to understand the decision process used to select the approach selected for the baseline configurations.

3. Summary of Results

Complete fuel cell power systems were configured to allow assembly of comprehensive system Bills of Materials. A configuration summary for all three technology level systems is shown in Figure 1 below. System flow schematics for each of the systems are shown in Figure 2, Figure 3, and Figure 4. Note that for clarity, only the main system components are identified in the flow schematics. The reader is directed to the full bill of materials for a comprehensive listing of system elements.

3.1. Changes since the 2007 Update Report

This report represents the second annual update of the 2006 DTI fuel cell cost estimate report[5] under contract to the DOE. The 2006 report (dated October 2007) documented cost estimates for fuel cell systems based on projected 2006, 2010, and 2015 technologies. Like the 2007 Update before it, this annual report updates the previous work to incorporate advances made over the course of 2008. These advances include new technologies, improvements and corrections made in the cost analysis, and alterations of how the 2010 and 2015 systems are likely to develop.

Noteworthy changes from the 2007 Update report are listed below:

- **Power Density and Catalyst Loading Change:** Catalyst loading affects stack polarization performance, which in turn affects power density and stack cost. Consequently, multiple catalyst loading levels should be examined to determine which leads to lowest system cost. For the 2008 technology status, a different catalyst loading/power density design point has been selected for the cost analysis. Catalyst loading is decreased from 0.35 mgPt/cm^2 to 0.25 mgPt/cm^2 and power density is increased from 583 mW/cm^2 to 715 mW/cm^2. The combined effect of these changes was a decrease in system cost by roughly \$10/kW$_{net}$ (2008 technology, at 500,000 systems/year). The catalyst loading and power density for the 2010 and 2015 technologies are unchanged.

- **New Stainless Steel Material Selection:** The material costs were updated, and stainless steel alloy specified for the bipolar plates was switched from 310 to 316L (primarily because of cost).

- **Inclusion of Bipolar Plate Coatings:** Based on new input from the Fuel Cell Tech Team[6], bipolar plate coatings are now included in all three baseline systems. The coating method specified was based on a proprietary process from TreadStone Technologies, Inc.

- **Laser-Welding of Coolant Gaskets:** It was previously postulated that silicone gaskets were attached via insertion molding onto the bipolar plates to seal between the faces of the plates that form a cooling cell (i.e. cooling gaskets). After further investigation and consultation with fuel cell manufacturers, laser welding and screen printing were each examined as alternative gasketing methods. Both new methods are similar to one another in cost, and provide a less expensive and more practical alternative to the old injection-molded gaskets. Laser welding gaskets is a much more common practice than screen printing. However, in the event that the stainless steel bipolar plates

[5] "Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications", Brian D. James, Jeff Kalinoski, Directed Technologies Inc., October 2007.

[6] FreedomCAR and Fuel Partnership's Fuel Cell Technology Team (http://www.uscar.org/guest/view_team.php?teams_id=17) recommendation made during the September 2008 review of the DTI project.

were not used, laser welding would no longer be an option and so screen printing would be the preferred coolant gasketing method.

- **Screen-Printing of End Gaskets:** The end gaskets, which seal the first and last bipolar plates in the stack to the Lytex end plates, are now accounted for separately from the coolant gaskets. This permits the use of a different gasketing method for the end gaskets than that used for the coolant gaskets. It also facilitates the optimization of the gasketing machinery around the demands of the end gasket. As with the coolant gaskets, the end gasket manufacturing process was switched from insertion molding (to screen printing, in this case), which is cheaper & more practical than the previously selected injection-molding approach.

- **MEA Frame/Gaskets:** Unlike with the coolant and end gaskets, neither screen printing nor laser welding is a viable option for the MEA frame/gasket. However, a switch from silicone to a new liquid injection-moldable hydrocarbon material lowered costs while improving the performance characteristics of the gasket. Unfortunately, the costs savings were more than offset by correction of the amount of material used based on a more rigorous re-examination of the gasket geometry. Because the coolant and end gaskets specified in the baseline systems were thinner than the old injection-molded gaskets, the MEA frame/gaskets were left to fill in the physical gap, which dramatically increased their required thickness, and increased the cost as a result.

- **Labor Rate:** The labor rate used throughout the analysis was adjusted from $1/min down to $0.75/min ($45/hr) to better reflect the median value used in the automotive industry.

- **Wiring:** Prior to this year, the wiring costs were estimated my means of rough approximation. As the largest contributor to the Miscellaneous BOP category, the wiring costs were investigated more closely, and a detailed component specification and cost estimation were each conducted.

- **Belly Pan:** This analysis is new to the 2008 Update and replaces the rough estimation used for the belly pan cost in previous reports. It is molded via a vacuum thermoforming process, in which thin polypropylene sheets are softened with heat and sucked down on top of a one-sided mold.

- **Startup Battery:** Based on DOE input, the startup battery is no longer considered part of the fuel cell system. As such, it has been removed from the analysis, despite still being needed in the vehicle.

- **Exhaust Loop (formerly the "Low-Temperature Loop"):** It was determined that the exhaust loop performs some duties not covered in the scope of this analysis. So in a bookkeeping change similar to the startup battery's reduction to 0% inclusion in the fuel cell system, only 67% of the exhaust loop's cost is attributed to the fuel cell system (the remaining cost is attributed to the electric drive system for cooling). Because the exhaust loop is not necessary in the 2010 and 2015 technologies, this change affects the 2008 system only.

- **System Controllers:** The number of system controllers was reduced from two to one.

	2008 Technology System	2010 Technology System	2015 Technology System
Power Density (mW/cm²)	715	1,000	1,000
Total Pt loading	0.25	0.3	0.2
Operating Pressure (atm)	2.3	2	1.5
Peak Stack Temp. (°C)	70-90	99	120
Membrane Material	Nafion on ePTFE	Advanced High-Temperature Membrane	Advanced High-Temperature Membrane
Radiator/Cooling System	Aluminum Radiator, Water/Glycol coolant, DI filter	Smaller Aluminum Radiator, Water/Glycol coolant, DI filter	Smaller Aluminum Radiator, Water/Glycol coolant, DI filter
Bipolar Plates	Stamped SS 316L with Coating	Stamped SS 316L with Coating	Stamped SS 316L with Coating
Air Compression	Twin Lobe Compressor, Twin Lobe Expander	Centrifugal Compressor, Radial Inflow Expander	Centrifugal Compressor, No Expander
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous layer applied on top	Carbon Paper Macroporous Layer with Microporous layer applied on top Future options: Flexible Graphite Flake (Grafcell), Co-fab w/ Membrane/Bipolar Plate	Carbon Paper Macroporous Layer with Microporous layer applied on top Future options: Flexible Graphite Flake (Grafcell), Co-fab w/ Membrane/Bipolar Plate
Catalyst Application	Double-sided vertical die-slot coating of membrane	Double-sided vertical die-slot coating of membrane	Double-sided vertical die-slot coating of membrane
Air Humidification	Water spray injection	Polyamide Membrane	None
Hydrogen Humidification	None	None	None
Exhaust Water Recovery	SS Condenser (Liquid/Gas HX)	SS Condenser (Liquid/Gas HX)	None
MEA Containment	Injection molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E	Injection molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E	Injection molded LIM Hydrocarbon MEA Frame/Gasket around Hot-Pressed M&E
Coolant & End Gaskets	Laser Welding/Screen Printed Resin	Laser Welding/Screen Printed Resin	Laser Welding/Screen Printed Resin
Freeze Protection	Drain water at shutdown	Drain water at shutdown	Drain water at shutdown
Hydrogen Sensors	2 H_2 sensors (for FC sys), 1 H_2 sensor (for passenger cabin; not in cost estimate), 1 H_2 sensor (for fuel sys; not in cost estimate)	1 H_2 sensor (for FC sys), 1 H_2 sensor (for passenger cabin; not in cost estimate), 1 H_2 sensor (for fuel sys; not in cost estimate)	No H_2 sensors
End Plates/Compression System	Composite molded end plates with compression bands	Composite molded end plates with compression bands	Composite molded end plates with compression bands
Stack/System Conditioning	5 hours of power conditioning - from UTC's US Patent 7,078,118	4 hours of power conditioning - from UTC's US Patent 7,078,118	3 hours of power conditioning - from UTC's US Patent 7,078,118

Figure 1. Summary chart of the three different systems analyzed

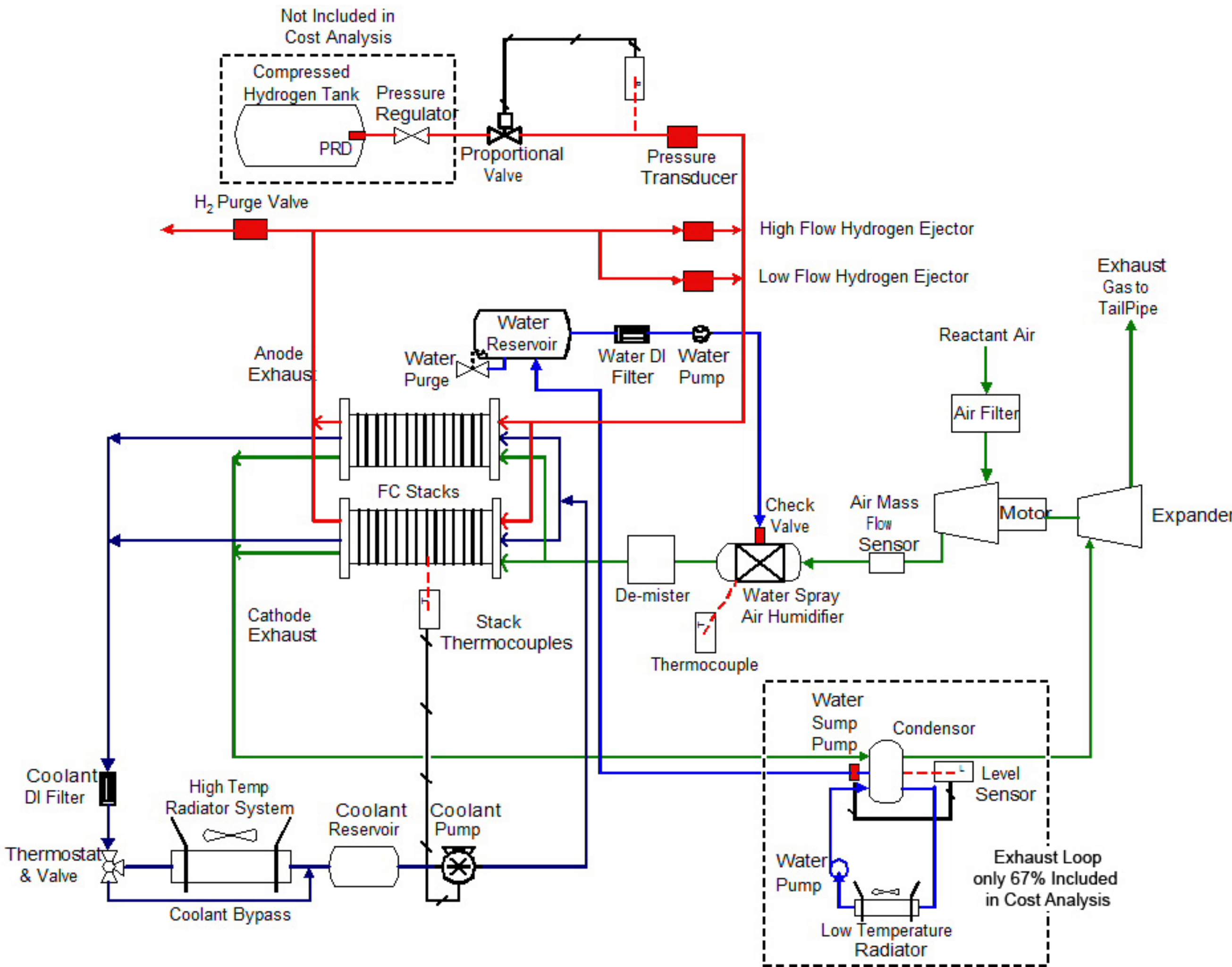

Figure 2. Flow schematic of the 2008 80 kW_{net} direct H_2 fuel cell system

The 2008 technology system is a fairly standard direct hydrogen, pressurized air fuel cell system configuration. Main features include:

- 4 separate liquid cooled fuel cell stacks, plumbed in parallel but connected electrically in series
- A twin lobe air compressor
- A twin lobe exhaust air expander
- A water spray humidifier to both humidify and cool the inlet cathode air after compression
- A liquid/gas heat exchanger to condense water in the exhaust stream for recycle to the air humidifier
- A high temperature coolant loop of water/ethylene glycol to maintain a stack temperature of ~80°C
- An exhaust loop of water/ethylene-glycol mixture to provide cooling for the exhaust air condenser
    - Only 67% of this loop is included in the system cost, because 1/3 of its function is outside of the scope of this analysis
- Twin hydrogen ejectors(high flow and low flow) to utilize the high pressure (> 300 psi) pressure in the hydrogen storage tanks to re-circulate anode hydrogen

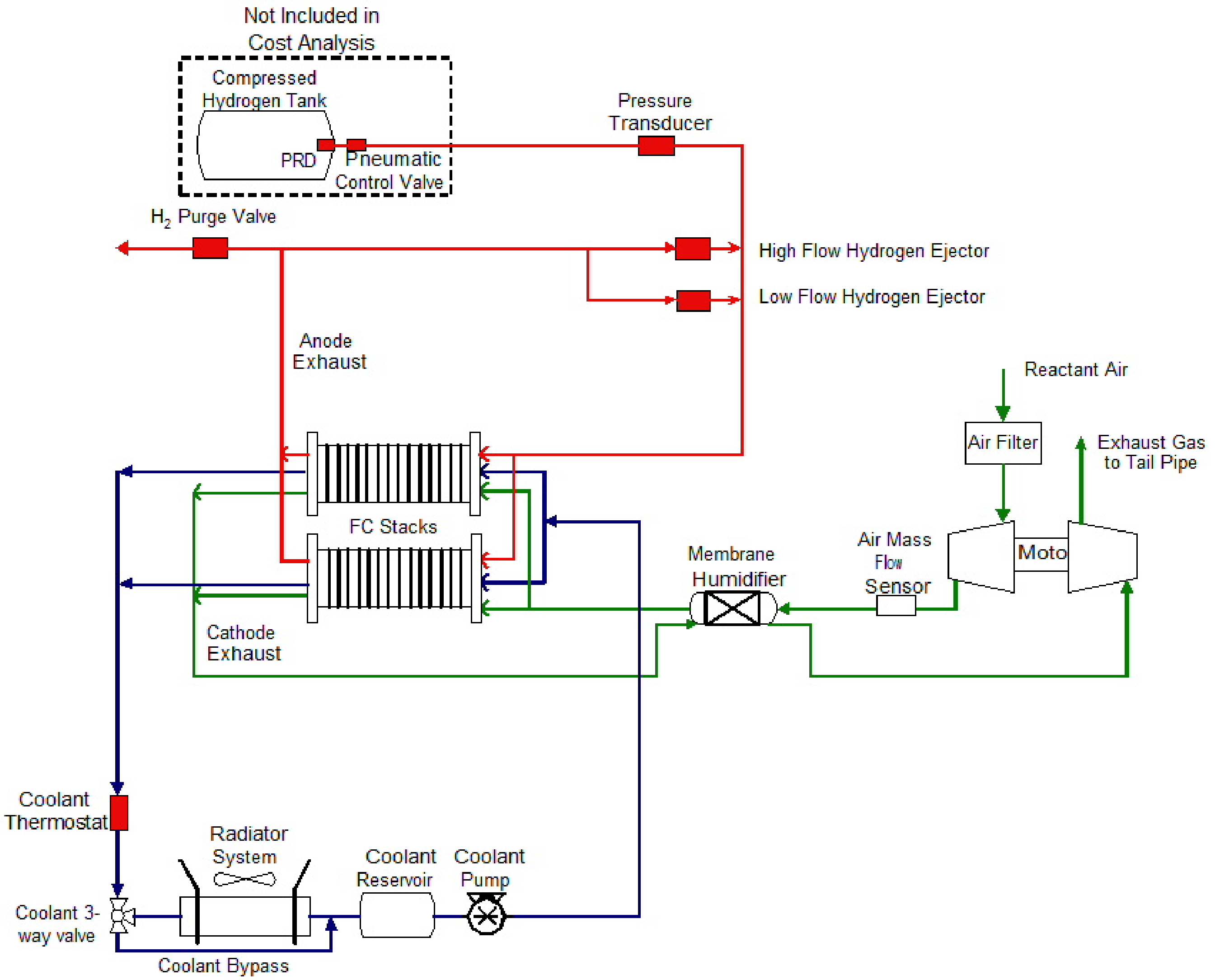

Figure 3. Flow schematic of the 2010 80 kW_{net} direct H_2 fuel cell system

The 2010 technology system was based on the 2008 configuration but with the following key differences:

- A centrifugal compressor replaces the twin lobe compressor
- A centrifugal expander replaces the twin lobe expander
- A membrane humidifier replaces the water spray humidifier
- The exhaust gas condenser is eliminated (because there is no need to capture liquid water for the water spray humidifier)
- The low temperature cooling loop is eliminated (because the condenser has been eliminated)
- The high temperature radiator is slightly smaller (because the peak operating temperature of the stack has been increased and thus there is a larger temperature difference between the coolant and the ambient temperature)

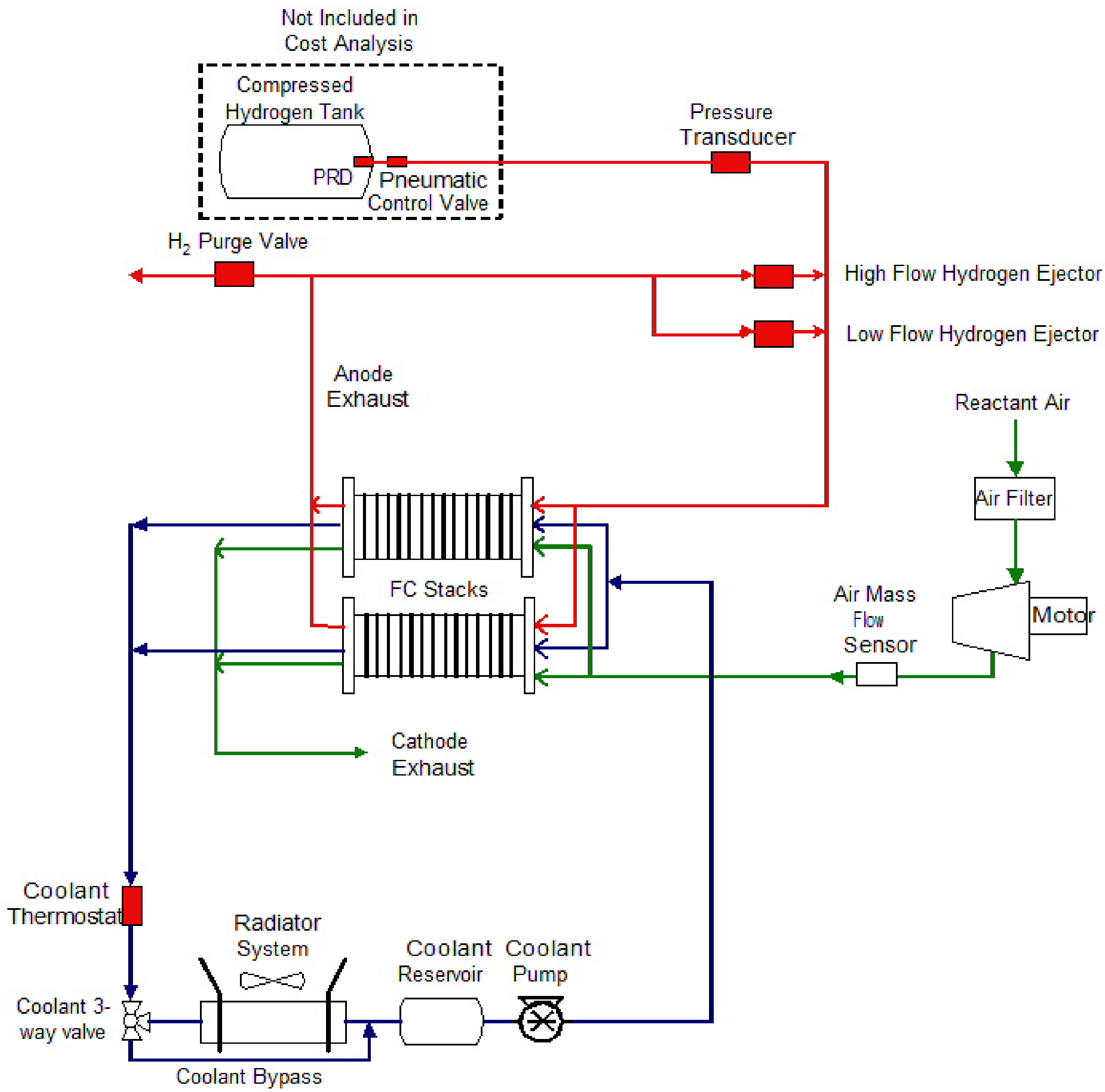

Figure 4. Flow schematic of the 2015 80 kW_{net} direct H_2 fuel cell system

The 2015 technology system is marked by the following further key configuration changes:

- The centrifugal compressor is reduced in size (because the peak cathode air pressure has been further lowered)
- The exhaust air expander is eliminated (because the overall cathode air pressure has been reduced and therefore the benefits of an expander are diminished)
- The membrane humidifier is eliminated (because an advanced PEM membrane that doesn't require humidification was assumed to be used)
- The radiator is further reduced in size (because the stack peak operating temperature has been further increased)

3.2. Cost Summary of the 2008 Technology System

Results of the cost analysis of the 2008 technology system at each of the five annual production rates are shown below. Figure 5 details the cost of the stacks, Figure 6 details the cost of the balance of plant components, and Figure 7 details the cost summation for the system.

	2008				
Annual Production Rate	**1,000**	**30,000**	**80,000**	**130,000**	**500,000**
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	90.23	90.23	90.23	90.23	90.23
Bipolar Plates (Stamped)	$898.77	$249.99	$253.83	$250.56	$249.09
MEAs					
Membranes	$2,829.02	$499.02	$313.29	$246.74	$132.43
Catalyst Ink & Application	$880.36	$659.52	$653.29	$651.79	$642.12
GDLs	$1,090.28	$706.44	$438.50	$343.06	$160.90
M & E Hot Pressing	$38.63	$9.33	$9.18	$9.42	$9.16
M & E Cutting & Slitting	$30.20	$3.59	$3.01	$2.88	$2.83
MEA Frame/Gaskets	$137.90	$247.03	$241.37	$239.85	$233.07
Coolant Gaskets (Laser Welding)	$94.31	$19.51	$15.03	$14.00	$14.14
End Gaskets (Screen Printing)	$75.69	$2.63	$1.05	$0.69	$0.31
End Plates	$69.90	$37.97	$34.02	$31.74	$23.85
Current Collectors	$13.89	$7.84	$6.79	$6.35	$5.89
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Assembly	$39.56	$20.82	$17.91	$18.31	$17.84
Stack Conditioning	$27.50	$10.93	$10.42	$10.45	$10.39
Total Stack Cost	$6,236.02	$2,482.61	$2,003.70	$1,831.35	$1,507.03
Total Cost for All Stacks	$12,472.04	$4,965.23	$4,007.39	$3,662.69	$3,014.06
Total Stack Cost ($\$/kW_{net}$)	$155.90	$62.07	$50.09	$45.78	$37.68
Total Stack Cost ($\$/kW_{gross}$)	$138.23	$55.03	$44.41	$40.59	$33.40

Figure 5. Detailed stack cost for the 2008 technology system

	2008				
Annual Production Rate	**1,000**	**30,000**	**80,000**	**130,000**	**500,000**
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	90.23	90.23	90.23	90.23	90.23
Mounting Frames	$100.00	$43.00	$33.00	$30.00	$30.00
Air Loop	$2,616.69	$1,364.16	$1,063.94	$954.11	$803.28
Humidifier & Water Recovery Loop	$535.13	$379.81	$315.54	$300.75	$273.77
Coolant Loop (High Temperature)	$528.75	$448.00	$384.25	$363.10	$331.80
Exhaust Loop (Low Temperature)	$169.18	$147.40	$130.32	$123.28	$113.90
Fuel Loop	$927.50	$747.00	$566.50	$528.40	$457.20
System Controller/Sensors	$300.00	$245.00	$230.00	$222.00	$200.00
Hydrogen Sensors	$1,700.00	$876.00	$640.00	$522.00	$200.00
Miscellaneous	$879.79	$671.68	$549.73	$523.59	$469.44
Total BOP Cost	$7,757.03	$4,922.05	$3,913.28	$3,567.24	$2,879.39
Total BOP Cost ($\$/kW_{net}$)	$96.96	$61.53	$48.92	$44.59	$35.99
Total BOP Cost ($\$/kW_{gross}$)	$85.97	$54.55	$43.37	$39.54	$31.91

Figure 6. Detailed balance of plant cost for the 2008 technology system

	2008				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	90.23	90.23	90.23	90.23	90.23
Fuel Cell Stacks	$12,472.04	$4,965.23	$4,007.39	$3,662.69	$3,014.06
Balance of Plant	$7,757.03	$4,922.05	$3,913.28	$3,567.24	$2,879.39
System Assembly & Testing	$158.84	$114.18	$112.24	$112.39	$112.01
Total System Cost	$20,387.92	$10,001.46	$8,032.91	$7,342.32	$6,005.46
Total System Cost ($/kW$_{net}$)	$254.85	$125.02	$100.41	$91.78	$75.07
Total System Cost ($/kW$_{gross}$)	$225.96	$110.85	$89.03	$81.38	$66.56

Figure 7. Detailed system cost for the 2008 technology system

3.3. Cost Summary of the 2010 Technology System

Results of the cost analysis of the 2010 technology system at each of the five annual production rates are shown below. Figure 8 details the cost of the stacks, Figure 9 details the cost of the balance of plant components, and Figure 10 details the cost summation for the system.

	2010				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	86.71	86.71	86.71	86.71	86.71
Bipolar Plates (Stamped)	$842.68	$197.28	$199.94	$196.14	$195.06
MEAs					
Membranes	$2,304.36	$415.97	$257.01	$200.55	$104.31
Catalyst Ink & Application	$760.44	$547.76	$541.92	$539.16	$531.73
GDLs	$958.30	$487.28	$306.01	$239.59	$114.48
M & E Hot Pressing	$38.01	$7.52	$7.67	$7.71	$7.55
M & E Cutting & Slitting	$30.18	$3.57	$3.00	$2.86	$2.76
MEA Frame/Gaskets	$241.26	$166.11	$162.09	$160.96	$156.32
Coolant Gaskets (Laser Welding)	$93.59	$13.30	$12.56	$12.38	$12.11
End Gaskets (Screen Printing)	$75.68	$2.62	$1.04	$0.68	$0.30
End Plates	$53.09	$25.63	$23.62	$21.55	$16.49
Current Collectors	$10.84	$5.82	$5.01	$4.68	$4.34
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Assembly	$39.56	$20.82	$17.91	$18.31	$17.84
Stack Conditioning	$26.15	$8.88	$8.54	$8.46	$8.33
Total Stack Cost	$5,484.13	$1,910.58	$1,552.34	$1,418.55	$1,176.63
Total Cost for All Stacks	$10,968.26	$3,821.15	$3,104.68	$2,837.09	$2,353.26
Total Stack Cost ($/kW$_{net}$)	$137.10	$47.76	$38.81	$35.46	$29.42
Total Stack Cost ($/kW$_{gross}$)	$126.49	$44.07	$35.80	$32.72	$27.14

Figure 8. Detailed stack cost for the 2010 technology system

	2010				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	86.71	86.71	86.71	86.71	86.71
Mounting Frames	$100.00	$43.00	$33.00	$30.00	$30.00
Air Loop	$1,887.03	$1,327.82	$1,003.72	$891.74	$754.33
Humidifier & Water Recovery Loop	$900.00	$600.00	$425.00	$350.00	$250.00
Coolant Loop (High Temperature)	$498.24	$420.54	$358.32	$338.69	$308.92
Exhaust Loop (Low Temperature)	$0.00	$0.00	$0.00	$0.00	$0.00
Fuel Loop	$927.50	$747.00	$566.50	$528.40	$457.20
System Controller/Sensors	$300.00	$245.00	$230.00	$222.00	$200.00
Hydrogen Sensors	$750.00	$367.00	$256.00	$201.00	$50.00
Miscellaneous	$827.61	$626.81	$505.90	$480.29	$427.70
Total BOP Cost	$6,190.38	$4,377.17	$3,378.45	$3,042.12	$2,478.14
Total BOP Cost ($/kW$_{net}$)	$77.38	$54.71	$42.23	$38.03	$30.98
Total BOP Cost ($/kW$_{gross}$)	$71.39	$50.48	$38.96	$35.08	$28.58

Figure 9. Detailed balance of plant cost for the 2010 technology system

	2010				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	86.71	86.71	86.71	86.71	86.71
Fuel Cell Stacks	$10,968.26	$3,821.15	$3,104.68	$2,837.09	$2,353.26
Balance of Plant	$6,190.38	$4,377.17	$3,378.45	$3,042.12	$2,478.14
System Assembly & Testing	$158.62	$113.99	$112.06	$112.21	$111.83
Total System Cost	$17,317.25	$8,312.32	$6,595.19	$5,991.42	$4,943.23
Total System Cost ($/kW$_{net}$)	$216.47	$103.90	$82.44	$74.89	$61.79
Total System Cost ($/kW$_{gross}$)	$199.71	$95.86	$76.06	$69.10	$57.01

Figure 10. Detailed system cost for the 2010 technology system

3.4. Cost Summary of the 2015 Technology System

Results of the cost analysis of the 2015 technology system at each of the five annual production rates are shown below. Figure 11 details the cost of the stacks, Figure 12 details the remaining balance of plant components, and Figure 13 details the cost summation for the system.

	2015				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	87.06	87.06	87.06	87.06	87.06
Bipolar Plates (Stamped)	$843.17	$197.75	$200.40	$196.60	$195.52
MEAs					
Membranes	$2,310.61	$417.98	$258.26	$201.53	$104.83
Catalyst Ink & Application	$567.75	$368.67	$364.24	$361.84	$356.89
GDLs	$961.34	$489.32	$307.26	$240.54	$114.88
M & E Hot Pressing	$38.01	$7.53	$7.67	$7.71	$7.55
M & E Cutting & Slitting	$30.18	$3.57	$3.00	$2.86	$2.76
MEA Frame/Gaskets	$242.10	$166.81	$162.78	$161.64	$156.98
Coolant Gaskets (Laser Welding)	$93.60	$13.30	$12.56	$12.39	$12.11
End Gaskets (Screen Printing)	$75.68	$2.62	$1.04	$0.68	$0.30
End Plates	$53.24	$25.73	$23.72	$21.64	$16.56
Current Collectors	$10.87	$5.84	$5.03	$4.70	$4.35
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Assembly	$39.56	$20.82	$17.91	$18.31	$17.84
Stack Conditioning	$24.79	$6.84	$6.40	$6.30	$6.27
Total Stack Cost	$5,300.90	$1,734.78	$1,376.28	$1,242.25	$1,001.83
Total Cost for All Stacks	$10,601.79	$3,469.55	$2,752.55	$2,484.49	$2,003.67
Total Stack Cost ($/kW$_{net}$)	$132.52	$43.37	$34.41	$31.06	$25.05
Total Stack Cost ($/kW$_{gross}$)	$121.78	$39.85	$31.62	$28.54	$23.02

Figure 11. Detailed stack cost for the 2015 technology system

	2015				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	87.06	87.06	87.06	87.06	87.06
Mounting Frames	$100.00	$43.00	$33.00	$30.00	$30.00
Air Loop	$1,378.48	$969.57	$728.45	$651.05	$553.20
Humidifier & Water Recovery Loop	$0.00	$0.00	$0.00	$0.00	$0.00
Coolant Loop (High Temperature)	$453.75	$380.50	$320.50	$303.10	$275.55
Exhaust Loop (Low Temperature)	$0.00	$0.00	$0.00	$0.00	$0.00
Fuel Loop	$927.50	$747.00	$566.50	$528.40	$457.20
System Controller/Sensors	$300.00	$245.00	$230.00	$222.00	$200.00
Hydrogen Sensors	$0.00	$0.00	$0.00	$0.00	$0.00
Miscellaneous	$812.72	$614.00	$493.40	$467.93	$415.78
Total BOP Cost	$3,972.45	$2,999.07	$2,371.84	$2,202.48	$1,931.73
Total BOP Cost ($/kW$_{net}$)	$49.66	$37.49	$29.65	$27.53	$24.15
Total BOP Cost ($/kW$_{gross}$)	$45.63	$34.45	$27.25	$25.30	$22.19

Figure 12. Detailed balance of plant cost for the 2015 technology system

	2015				
Annual Production Rate	**1,000**	**30,000**	**80,000**	**130,000**	**500,000**
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	87.06	87.06	87.06	87.06	87.06
Fuel Cell Stacks	$10,601.79	$3,469.55	$2,752.55	$2,484.49	$2,003.67
Balance of Plant	$3,972.45	$2,999.07	$2,371.84	$2,202.48	$1,931.73
System Assembly & Testing	$158.62	$113.99	$112.06	$112.21	$111.83
Total System Cost	$14,732.86	$6,582.62	$5,236.45	$4,799.18	$4,047.23
Total System Cost ($/kW$_{net}$)	$184.16	$82.28	$65.46	$59.99	$50.59
Total System Cost ($/kW$_{gross}$)	$169.24	$75.61	$60.15	$55.13	$46.49

Figure 13. Detailed system cost for the 2015 technology system

3.5. Cost Comparison of All Three Systems

The stack and system costs for all three technology levels are compared in Figure 14 and Figure 15. Stack cost is seen to range from $138/kW$_{gross}$ (1,000 systems/year in 2008) to $23/kW$_{gross}$ (500,000 systems/year in 2015). System cost is seen to range from $255/kW$_{net}$ (1,000 systems/year in 2008) to $51/kW$_{net}$ (500,000 systems/year in 2015). All three technology levels experience an initial steep drop in price with the "knee of the curve") at around 50,000 systems per year. While each technology level represents a combination of configuration and performance improvements, the system cost reductions are primarily due to balance of plant configuration changes, and the stack cost reductions are primarily due to power density and catalyst loading improvements. Consequently, the cost curves have very similar shapes but vary in amplitude according to cell performance and loading. Very little stack cost change is observed between 2010 and 2015 because stack performance and catalyst loadings are not expected to change.

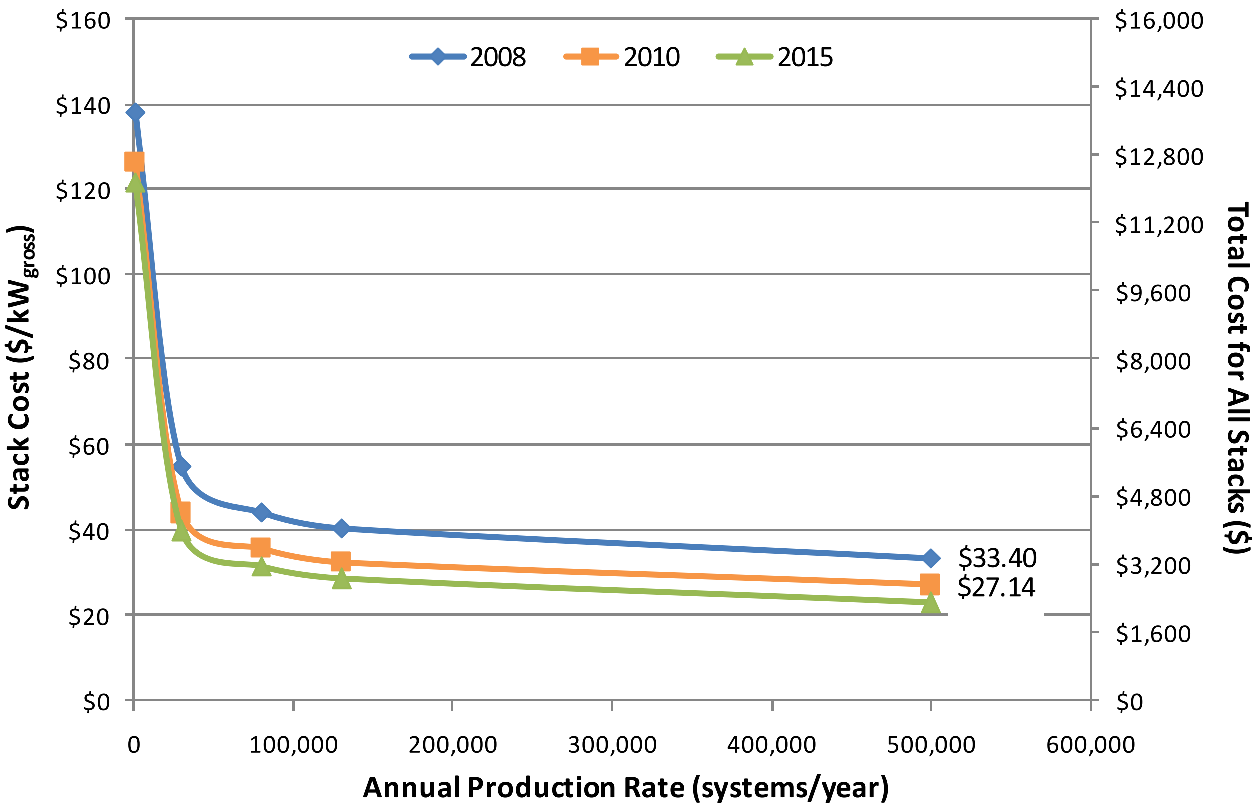

Figure 14. Gross stack cost vs. annual production rate

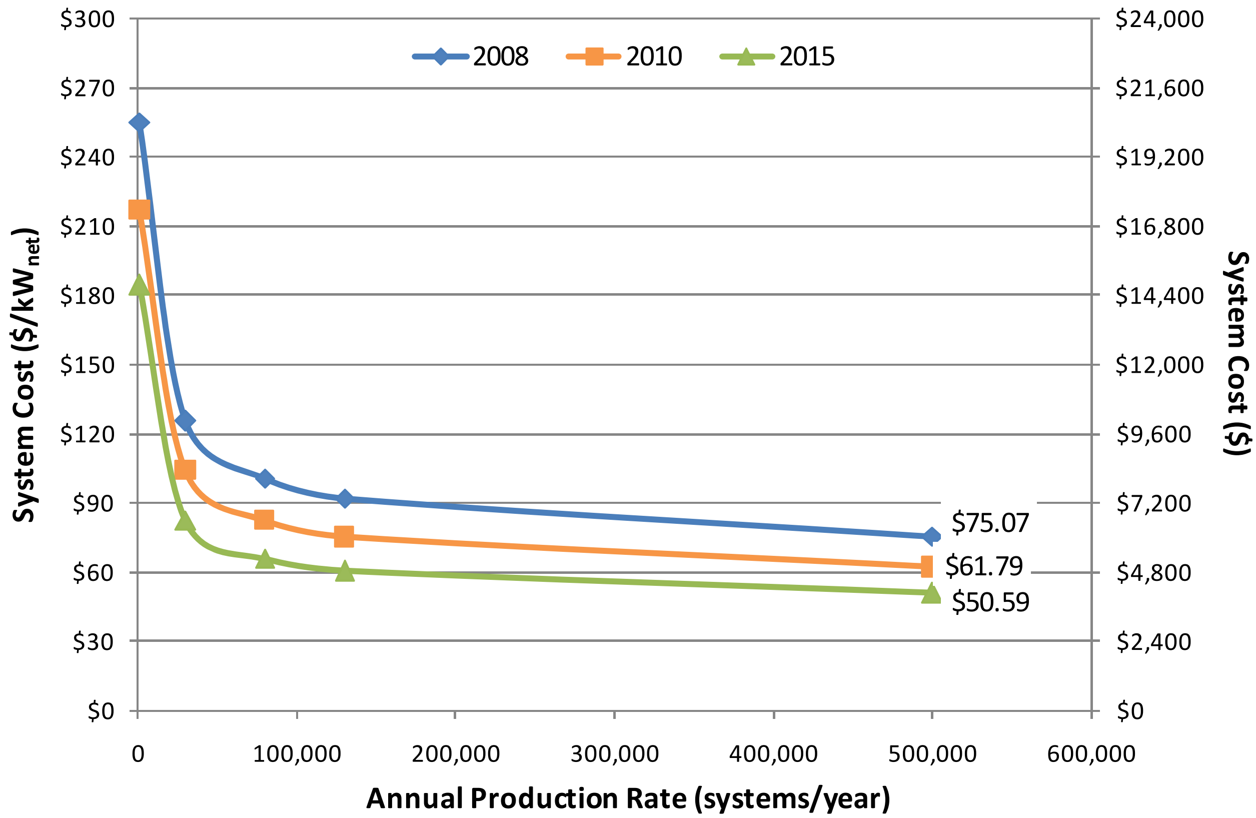

Figure 15. Net system cost vs. annual production rate

4. Detailed Assumptions

4.1. System Performance and Operation

The fuel cell stacks contained within each of the three technology level systems are identical in most design and operational parameters, differing only in active area per cell and stack gross power. However, even this variation in resulting gross power is not very large- 90.23 kW, 86.71 kW and 87.06 kW for 2008, 2010, and 2015 respectively. The differences are primarily the result of differences in the air compression load, which in turn results from different air compression approaches and levels of pressurization. Figure 16 details the efficiency, pressure and mass flow assumptions that were used to calculate expected air compressor motor power. Note that the fuel cell system needs to supply 80 kW_{net} under all conditions and thus air compression for peak system power must be evaluated at the most adverse temperature (40°C ambient). Figure 17 summarizes total system parasitic loads.

		2008	2010	2015
Compressor				
Gross Power	kW	90.23	86.71	87.06
Air Mass Flow	kg/h	304	292	293
Compression Ratio	atm	2.3	2	1.5
Compression Efficiency		65%	75%	75%
Ambient Temp	°C	40	40	40
Motor/Controller Efficiency		85%	85%	85%
Expander				
Mass Flow	kg/h	308	296	No expander in 2015 System
Compression Ratio	atm	2	1.7	
Compression Efficiency		75%	80%	
Starting Temp	°C	80	80	
Expander Shaft Power Out	kW	4.44	3.56	
Compression Alone				
Compressor Shaft Power Req	kW	11.02	7.48	4.21
Compressor Input Power Req	kW	12.96	8.80	4.96
Compressor-Expander Unit				
CMEU Input Power	kW	7.74	4.61	4.96

Figure 16. Basis of air compressor and expander power

(All values in kW)	2008	2010	2015
Fuel Cell Gross Electric Power (Output)	90.23	86.71	87.06
System Net Electrical Power (Output)	80	80	80
Air Compressor Motor	7.74	4.61	4.96
Coolant Pump	1.1	1.1	1.1
Coolant Radiator Fan	0.90	0.90	0.90
Exhaust Radiator Fan	0.38	0.00	0.00
Other (Controller, Instruments, etc.)	0.1	0.1	0.1
Total Parasitic Loads	10.23	6.71	7.06

Figure 17. Power production & loads at max. power, under peak ambient temp. operating conditions

Stack design parameters and operating conditions are summarized in Figure 18 and Figure 19. All systems operate with low single-pass hydrogen utilization but high total utilization due to a hydrogen recirculation loop.

	2008	2010	2015
Number of Stacks per System	2		
Number of Active Cells per Stack*	186		
Number of Cooling Cells per Stack*	188		
Cell Voltage at Max. Power	0.676		
Membrane Power Density at Max. Power (mW/cm^2)	715	1,000	1,000

***** This is perhaps misleading, because every plate is half active, half cooling (except for the ones that bookend the stack, which have coolant on one face, and nothing on the other)

Figure 18. Stack design parameters

	2008	2010	2015
Peak Operating Pressure (atm)	2.3	2.0	1.5
Cell Temperature (°C)	70-90	99	120
Oxygen Stoichiometry	1.8x		
Anode Gas Stream			
Hydrogen Purity	99.999% (molar basis)		
Inlet Temperature (°C)	Ambient + ~10°C		
Relative Humidity	0%		
Max (single pass) H_2 flowrate	~5.5kg/hr(~1100slpm)		
Cathode Gas Stream			
Oxygen Purity	21% (molar basis)		
Inlet Temperature (°C)	75°C		
Relative Humidity	50%		
Max (single pass) Air flowrate	~300 kg/hr (~4200slpm)		

Figure 19. Stack operation parameters

The power density (listed in Figure 18) drives the active area used in the stack geometry, so it directly affects the material quantities, thereby having a major effect on the system cost. This geometry (Figure 20) describes everything between the end plates. The table in Figure 21 lists the numerical values of these dimensions.

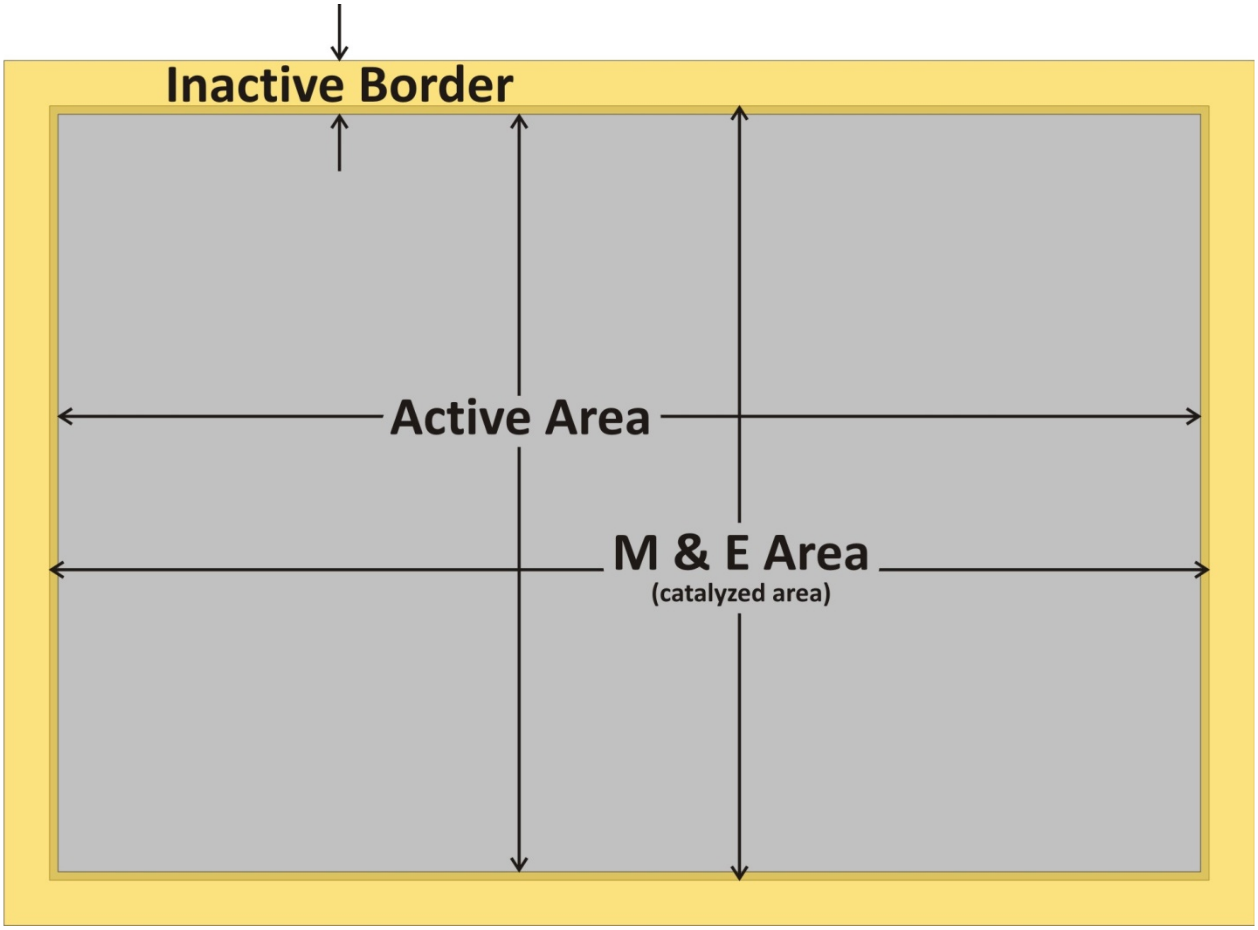

Figure 20. Cell geometry

	2008	2010	2015
Active Area (cm^2)	339.23	233.10	234.02
Active Width (cm)	22.56	18.70	18.74
Active Height (cm)	15.04	12.47	12.49
M & E (Catalyzed) Area (cm^2)	350.54	239.60	240.56
M & E (Catalyzed) Width (cm)	22.86	18.91	18.94
M & E (Catalyzed) Height (cm)	15.34	12.67	12.70
Total Area (cm^2)	424.03	291.37	292.52
Total Width (cm)	24.69	20.47	20.51
Total Height (cm)	17.17	14.24	14.26
Ratio of Width to Height	1.5	1.5	1.5
Ratio of Active Area to Total Area	0.8	0.8	0.8
Inactive Border (cm)	1.07	0.88	0.89

Figure 21. Cell dimensions

4.2. Manufacturing Cost

Manufacturing cost comprises three elements:

- Machine Costs
- Secondary Operation Costs
- Tooling Costs

It is defined as the total cost of performing a manufacturing process on a material or component. Machine cost is the total cost of operating a manufacturing machine (e.g. stamping press, injection-molding machine, lathe, etc.) and includes amortization of the machine capital cost, machine maintenance, labor and utilities to operate the machine. Secondary Operation costs are minor process costs incurred in association with a major machine operation (e.g. anodizing after metal stamping). Expendable tooling (dies, molds, etc.) costs are historically calculated separately from machine costs since manufactures often supply tooling to outside vendors[7] but pay them only for use of the processing machinery.

Machine cost is determined by multiplying machine rate (dollars per minute of machine time) times minutes of machine use. Machine rates typically range from $1.00 to $3.00 per minute, depending on the complexity of the machine, maintenance costs, and intensity of utilities. Typical DFMA methodology uses historical or actual data to determine machine rates for a given class and size of machine. For example, a 300-ton injection-molding machine might have an all-inclusive machine rate of $2.4/min, and a 1,200-ton molding machine might have a rate of $3.3/min. However, these historical machine rates assume high machine utilization, typically 14 hours per day, 240 workdays per year. Consequently, such data is of limited value to this study, as it fails to address the cost implications of low annual production rates.

To estimate machine rates at less than full machine utilizations, the machine rate is broken down into five components:

- Capital amortization
- Maintenance/Spare-part costs
- Miscellaneous Expenses
- Utility costs
- Machine labor

An overall machine rate is obtained by adding these five component costs over a year's operation and then dividing by the total minutes of actual machine run time.

Capital Amortization: The annual payment necessary to cover the initial capital cost of the machine is calculated by multiplying a fixed rate charge (FRC) times the capital cost. The fixed rate charge is merely the annual fraction of uninstalled capital cost that must be paid back adjusted for the interest rate (typically 15% to achieve a 10% after-tax return), machine lifetime (typically 7 to 15 years), corporate income tax rate (typically 40%) with further adjustment for equipment installation costs (typically 40% of machine capital cost).

Maintenance/Spare Parts: This is the fraction of uninstalled capital costs paid annually for maintenance and spare parts (typically 5-20%).

Miscellaneous Expenses: This is the fraction of uninstalled capital costs paid annually for all other expenses (typically 7%).

Utility Costs: These are the costs associated with machine electricity, natural gas, etc., typically computed by multiplying the kW of machine power times the electricity cost (typically $0.08/kWh).

Machine Labor: Cost of machine operator labor. Following automotive practices, US labor rates are generally $0.50 to $1.00 per minute depending on the level of skill required. All cases in this analysis use the median of those two values, a rate of $0.75/min ($45/hr). Prior to this 2008 Update report, the analysis used the rate of $1/min. For some processes, non-integer numbers of laborers were used per line (for instance, 0.25 is used for

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[7] Historically, automakers purchase expendable tooling separately and then supply the tooling to subcontractors. It this way, should a labor dispute develop, the automaker is (theoretically) able to retrieve the tooling and have the parts produced elsewhere.

the injection-molding process) because workers do not need to devote 100% of their time to it and can perform other tasks over the course of their workday. Note that manufacturing labor is only paid for time that the operator works. Thus if a machine is only run for an average 3 hours per day, only 3 hours per day of labor costs are incurred.

Machine Utilization: Machine utilization is determined by dividing the total runtime needed per year (including setup) by the number of simultaneous production lines needed. For example, if there is 1.5 lines worth of work, and there are two lines, each machine was assumed to run 75% of the time. Full utilization is typically defined as 14 useful hours per day, 240 workdays per year.

Machine Setup Time: The inclusion of machine setup time in determining the labor cost is a factor that contributes more significantly at lower production rates. However, due to the high number of repeat parts (such as bipolar plates or MEA gaskets) machine utilization is generally high even at low system annual production rates.

Tooling Costs: Tooling costs vary based on the rate of wear of the parts, according to the number of machine cycles required and the properties of the materials involved. Injection-molding with abrasive carbon powder fillers will wear down tooling faster than if it were neat silicone. From the total number of parts required per year, an annual cycle count is determined for the machine, and the number of tooling sets needed in the machine's lifetime can be calculated. This is divided by the machine lifetime, to determine the annual tooling cost per line. It is done this way to account for usable tooling being leftover at the start of the following year.

4.2.1. Machine Rate Validation

To demonstrate the validity of the approach for the machine rate calculation described above, Figure 22 plots the calculated injection-molding machine rate against two sets of injection-molding machine rate data. The first set of data comes from Boothroyd Dewhurst, Inc. (BDI) and is the estimated machine rate for 15 specific injection-molding machines of various sizes. The second set of data comes from Plastics Technology magazine and represents the average machine rate from a 2004 survey of injection-molders (79 respondents). Excellent agreement is achieved between the DTI machine rate calculations and the BDI data[8]. The data from Plastics Technology (PT) magazine differs substantially from both the DTI estimates and the BDI data. However, the PT data has very large error bars indicating substantially variation in the vendor reported machine rate, probably from inconsistent definition of what is included in the machine rate. It is noted that the DTI estimates are conservative for large machines, overestimating machine rate as compared to the PT survey data but underestimating rates at the lower machine sizes. The PT survey data is judged significant at low machine sizes because it represents a minimum machine rate industry receives. Consequently, to achieve conservative estimates throughout, a $25/hr minimum machine rate was imposed for all machines (not just injection-molding machines). This is consistent with previous guidance DTI has received from Ford Motor Company wherein the rule of thumb was never to let machine rate drop below $1/min (including labor) for any process.

Figure 23 plots the effective machine rate as a function of machine utilization. As shown, machine rates climb to very high levels when only used a fraction of the time[9]. This is a direct consequence of the annual capital cost repayment needing to be collected even if the machine is used infrequently.

For each component manufacturing or assembly task, the batch volume, machine setup time, and time to complete the task were computed using the above described DFMA techniques. After applying the tooling and secondary operations costs, and the labor and machine rates, the total cost for the component is calculated. A

[8] The BDI data contains one anomalously high data point at approximately 800 tons of clamping force. This point appears to be real and corresponds to the largest machine in a manufacturer's lineup.

[9] Full utilization is defined as 14 hours per day, 240 days per year.

second detailed example of machine rate calculation occurs in section 4.4.1.2 and describes the metal bipolar plate stamping costing process.

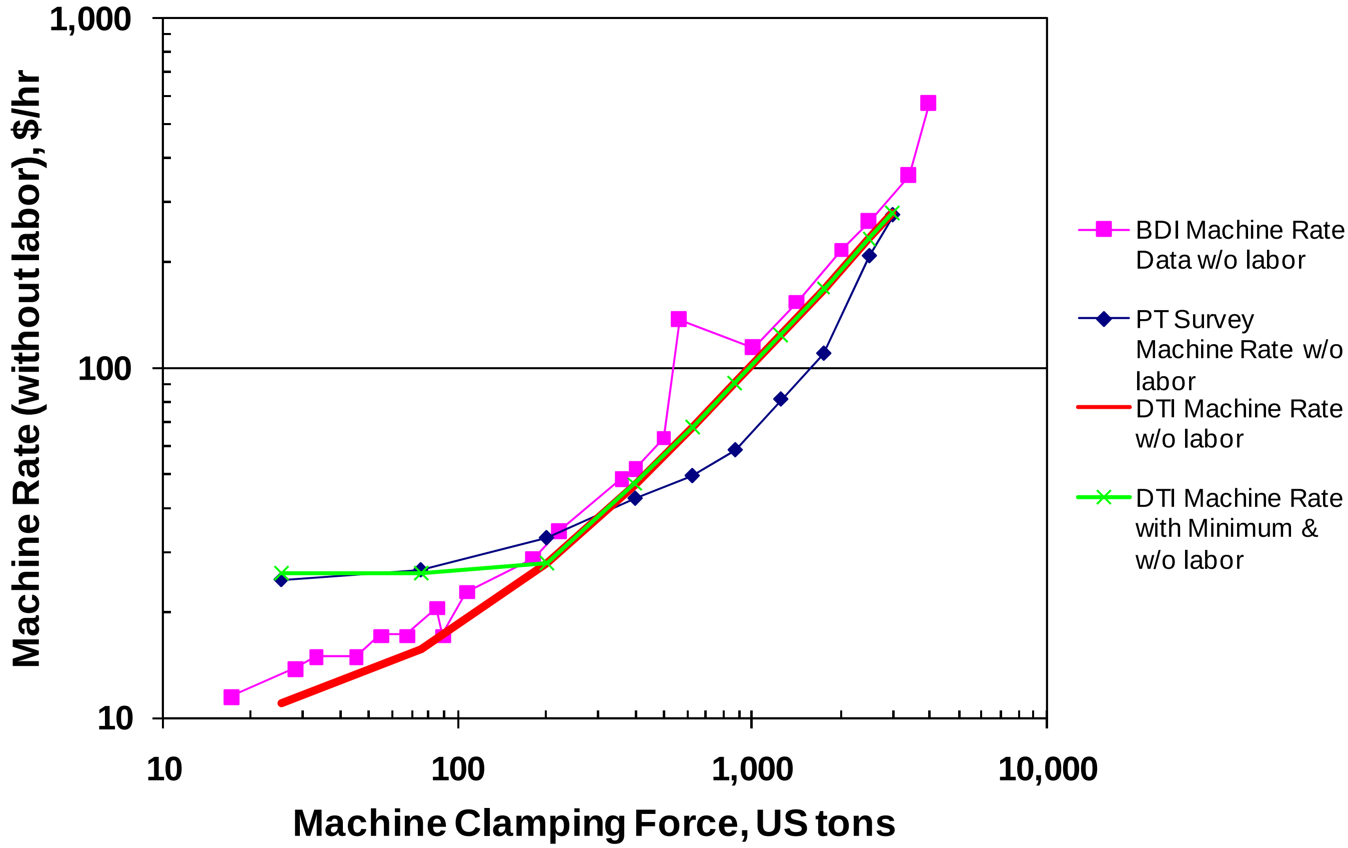

Figure 22. Injection-molding machine rate vs. machine clamping force

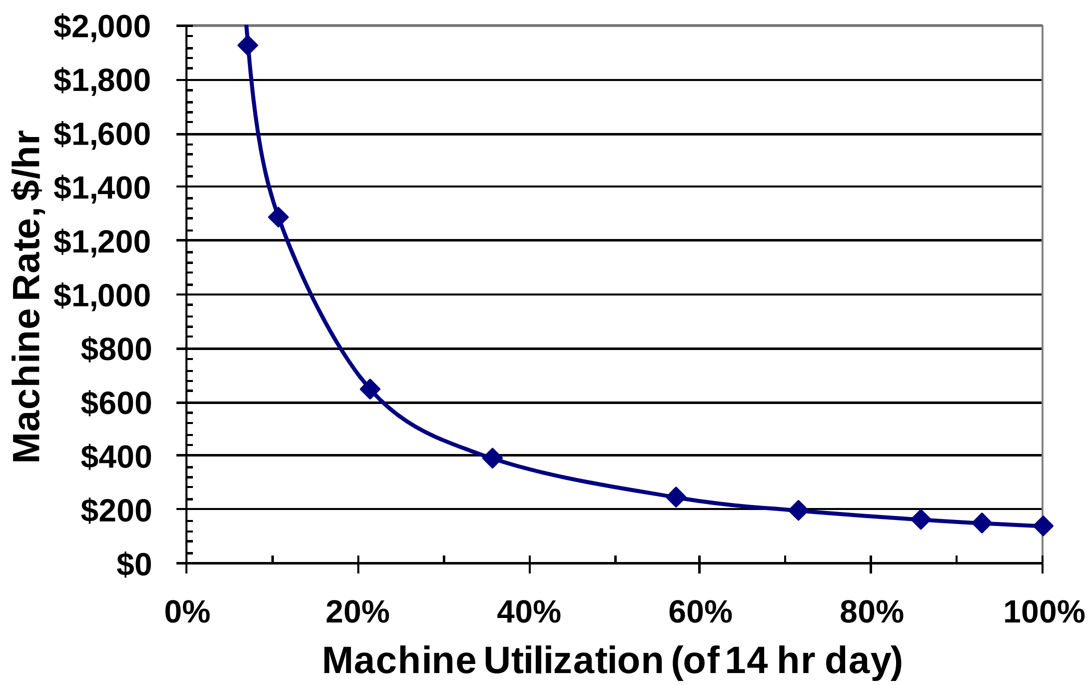

Figure 23. Machine rate vs. machine utilization

4.3. Markup Rates

Markup rates are percentage increases to the material, manufacturer and assembly cost to reflect the costs associated with profit, general and administrative (G&A) expenses, research and development (R&D) expenses, and scrap. The markup percentage varies with manufacturing rate and with what is actually being marked up. However, to provide cost estimates consistent with other cost studies conducted for the Department of Energy, no markup rates have been applied for this cost study. Thus, the costs presented are "bare" costs of manufacture and assembly. The factors that affect markup rate are discussed below to give the reader some idea of the approximate magnitude of the markup rates under various circumstances. In general, the higher the manufacturing/assembly rate, the lower the markup to reflect the increased efficiencies of business operations and ability to amortize costs over a large base of products.

Whether a company is vertically integrated or horizontally integrated affects overall markup rate. In a vertically integrated company, all production from acquisition of the base materials to final assembly is completed "in-house" by the company. In a horizontally integrated company, components and/or subassemblies are fabricated by subcontractors and typically, only the final assembly is conducted by the company. Companies are rarely 100% vertically or horizontally integrated; rather they are predominately one or the other.

Whenever a part or process is subcontracted, both the lower tier subcontractor as well as the top-level company applies a markup. This is reasonable since both companies must cover their respective costs of doing business (G&A, scrap, R&D, and profit). However, the numerical markup for each company can and should be different as they are adding different levels of value and have (potentially) different cost bases. There is a distinction made between activities adding value (such as actual manufacturing or assembly steps) as opposed to mere product "pass through"; namely, the organization earns profit on value-added activities and no-profit on mere pass-through. (An example is a firm hired to do assembly work: they justifiably earn profit on the value-adding step of assembly but not on the material cost of the components they are assembling. However, there are real costs (G&A, R&D, scrap) associated with product pass-through and the manufacturer/assembler must be compensated for these costs.)

Figure 24 displays some representative markup rates for various situations. While the figure attempts to explain how and where markups were applied, there are many exceptions to the general rule. Different markup rates were used for different components because the type and quantity of work lend themselves to lower overhead costs. MEA manufacturing markups were set at much higher rates to reflect the higher risks, both technical and business, of an evolving technology. Markups are often accumulative as the product moves from manufacturer to sub-system assembler to final assembler. However, in the case of the MEA, the car company may be assumed to supply the raw materials so that the MEA manufacturer's markup is only applied to the MEA manufacture's added-value[10] and not to the material cost.

	2008 / 2010 / 2015				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
Fuel Cell Components					
Manufacturer's Markup	27-35.5%	25-35.5%	25-35.5%	25-35.5%	25%
Integrator's Pass Through	30%	21%	20%	20%	19%
MEA Manufacturers Markup	70%	70%	60%	50%	35%
Auto Company Final Markup	37%	26.5%	23.5%	20%	15%

Figure 24. Representative markup rates (but not applied to cost estimates)

[10] This method is directed analogous to catalytic converter manufacture in the automotive industry; the auto manufacturer supplies the expensive catalyst to the catalytic converter manufacturer specifically to avoid the extra markup rate that otherwise would occur.

4.4. Fuel Cell Stack Materials, Manufacturing, and Assembly

Cost estimates for fuel cell stacks were produced using detailed, DFMA-style techniques. Each subcomponent of the stack was independently considered, with materials and manufacturing costs estimated for each. Costs were estimated for the assembly of the gasketed membrane electrode assemblies (MEAs) and the stack. Figure 25 displays an abridged view of the stack components, and Figure 26 shows a cross-sectional view of an assembled stack.

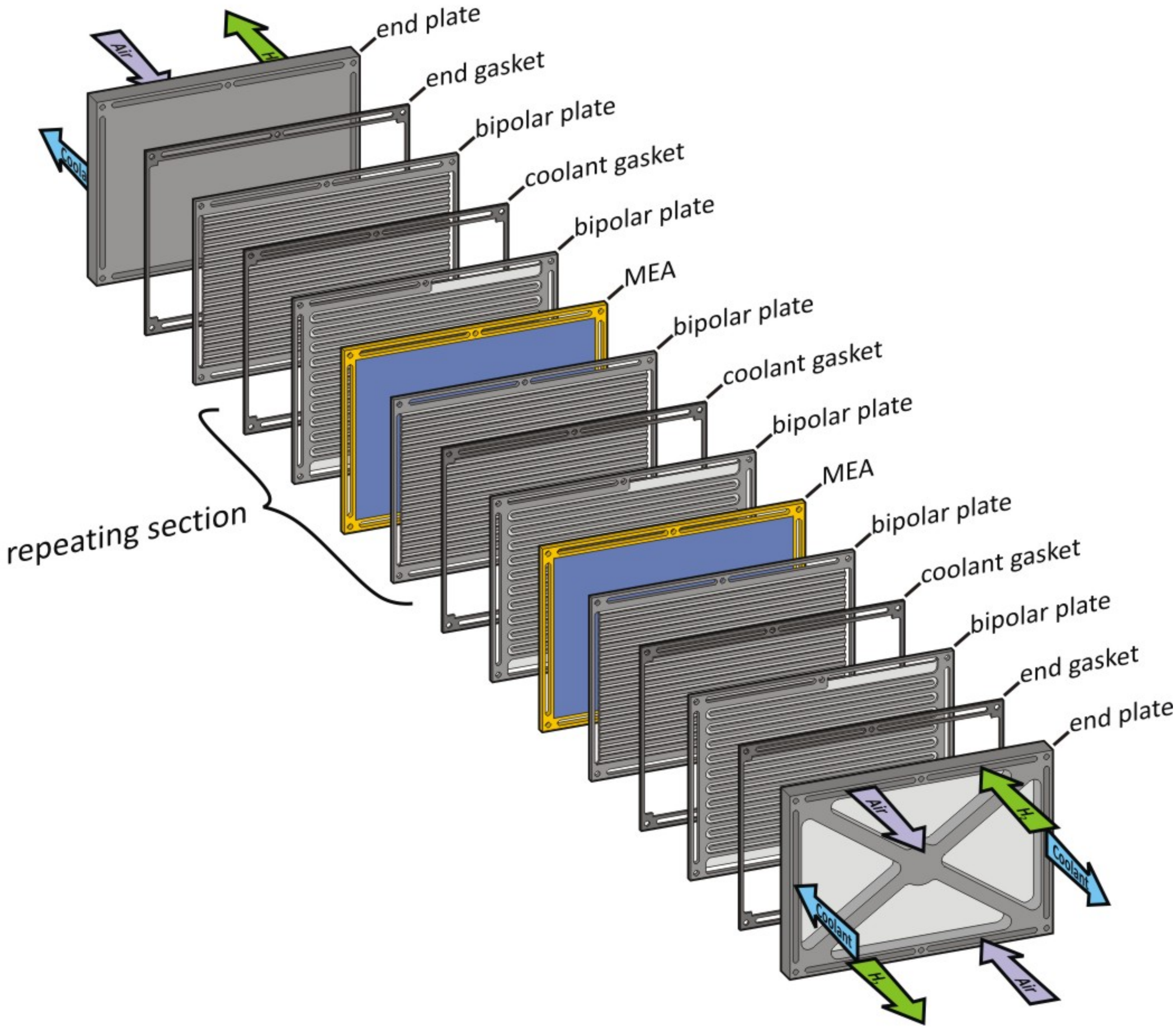

Figure 25. Exploded stack view (abridged to 2 cells for clarity)

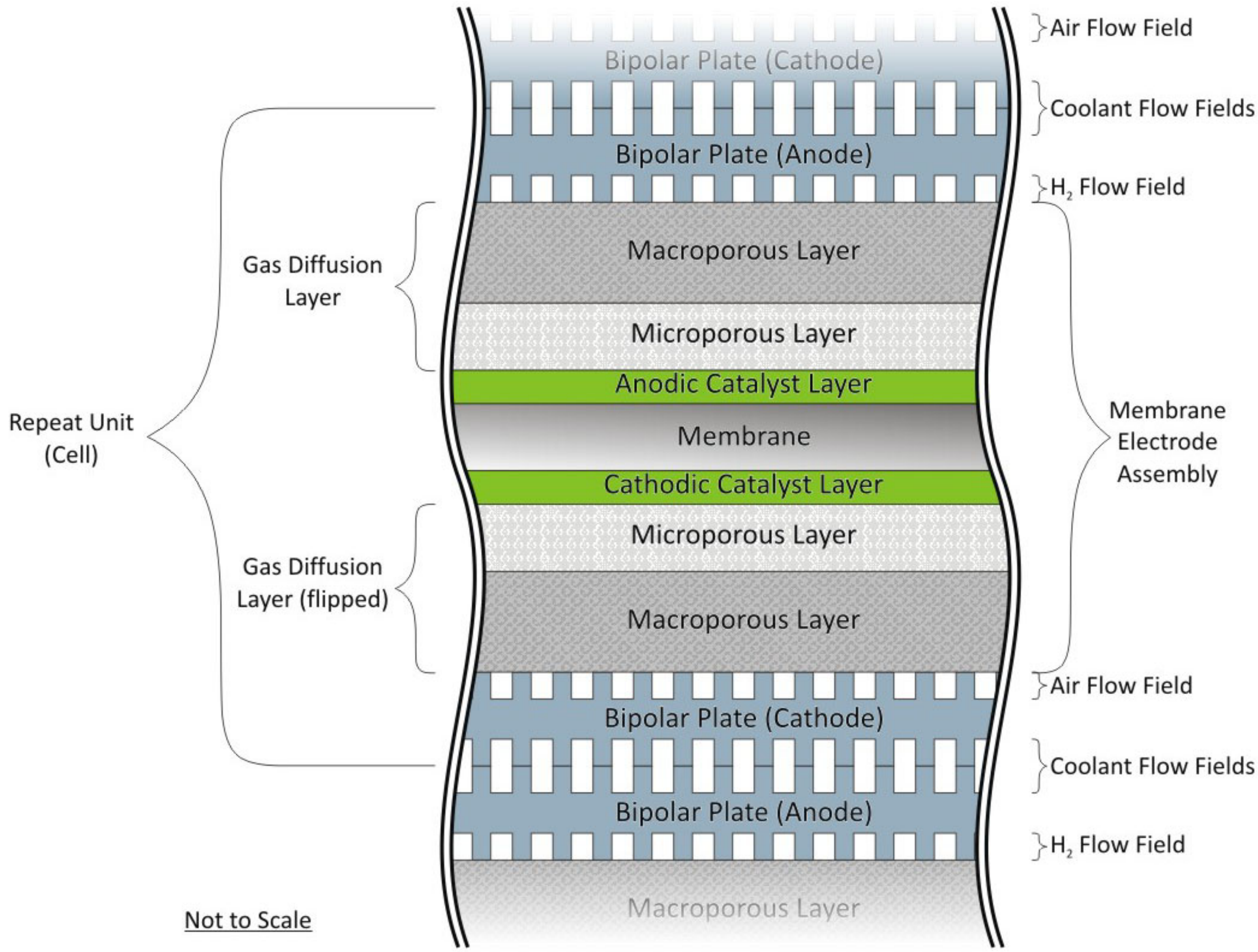

Figure 26. Stack cross-section

4.4.1. Bipolar Plates

Each stack in the system consists of 186 active cells, each of which contains two bipolar plates. A 1:1 ratio of active cells to cooling cells was assumed, in order to ensure stack temperature uniformity. Consequently, one side of bipolar plate is a cooling cell flow field and the other side is an active cell flow field. In previous estimates, the cathode and anode flow field sides of the bipolar plates were envisioned as having identical flow patterns and being symmetrical. Consequently, only one bipolar plate design was needed and the cells could be flipped 180° to alternate between cathode flow fields and anode flow fields. However, based on feedback from Ballard Power Systems, unique designs were assumed for the anode and cathode plates. An extra bipolar plate sits at each end of the stack, and is not part of the repeating cell unit. It is only half-used, as it does only cooling. End gaskets are used to block off the flow into the gas channel side of those plates. The total number of plates in a stack is therefore 374: 186 active cells * two plates per cell + two coolant-only plates. With two stacks per system, each system contains 748 bipolar plates, so even at the lowest production rate, there are hundreds of thousands of plates needed. This means that bipolar plate mass-manufacturing techniques remain appropriate across all production rates.

Two different concepts were examined for the bipolar plate: injection-molded carbon powder/polymer and stamped stainless steel. Recent industry feedback has suggested that metallic plates have as much as a 20% advantage in conductivity over carbon plates, but for now, equivalent polarization performance was assumed between the two designs. The stamped metal plates were selected because of consistent industry feedback suggesting that this is the most common approach.

4.4.1.1. Injection-Molded Bipolar Plates

Injection-molded bipolar plate costs were based on a conceptual, injection-molded manufacturing process using composite materials. Such a composite is composed of a thermoplastic polymer and one or more electrically-conductive filler materials. In this analysis, the composite is carbon powder in polypropylene at a volume ratio of 40:60 carbon:polymer. To date, similar materials have been successfully molded to form bipolar plates with sufficient conductivity for fuel cell use[11]. The primary advantage of injection molding over compression molding is a shorter cycle time, resulting in lower labor and machine costs. However, technical challenges likely exist in order to achieve adequate electrical conductivity using the assumed injection-molding process. Injection molding details are shown in Figure 27 and Figure 28.

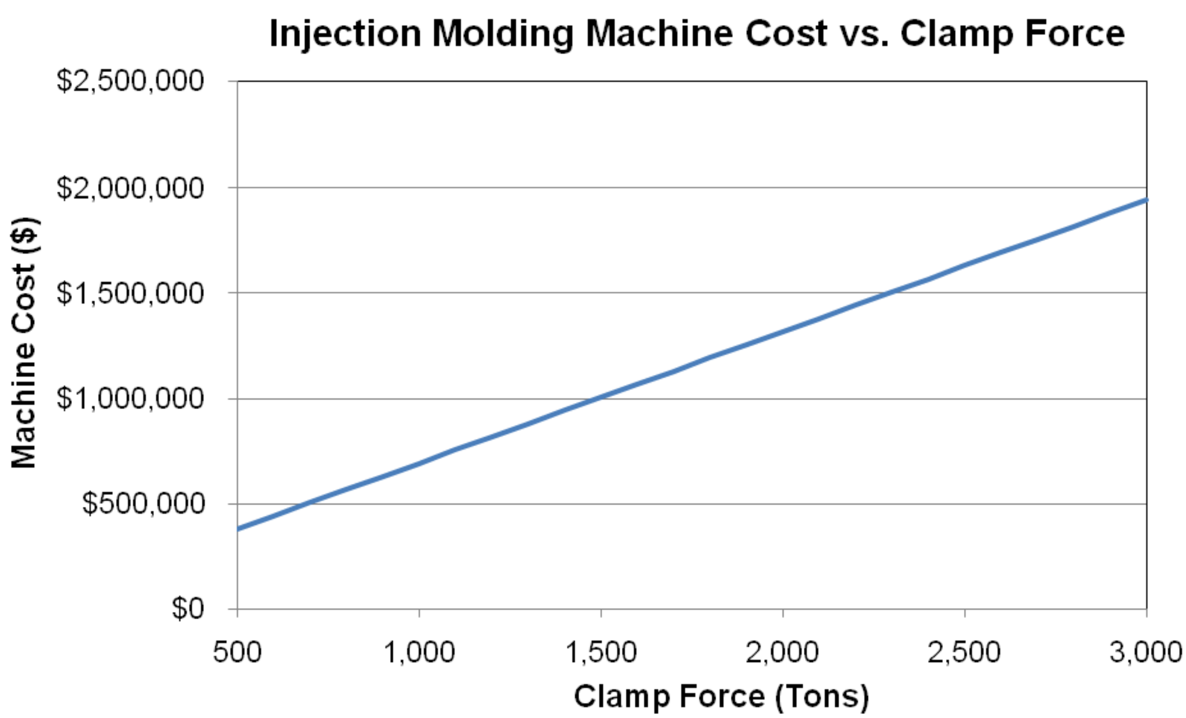

Figure 27. Injection-molding machine cost vs. clamp force

[11] Multiple companies have successfully compression and/or injection-molded of thermoset and/or /thermoplastic bipolar plates: Los Alamos National Laboratory, International Fuel Cell (IFC), Quantum injection-molding of PEMTEX thermoset material, (formerly) Energy Partners, Zentrum fur Brennstoffzellen Technik (ZBT) GmbH, and Micro Molding Technology LLC.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$815,869	$2,288,876	$2,288,876	$2,288,876	$2,288,876
	Costs per Tooling Set ($)	$38,236	$82,501	$82,501	$82,501	$82,501
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	10	27	43	166
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	90.66%	99.22%	98.00%	99.99%	99.62%
	Cycle Time (s)	29.32	32.09	32.09	32.09	32.09
	Cavities/Platen	2	6	6	6	6
	Effective Total Machine Rate ($/hr)	$141.94	$338.74	$342.73	$336.29	$337.46
	Carbon Filler Cost ($/kg)	$6.76	$6.76	$6.76	$6.76	$6.76
2010	Capital Cost ($/Line)	$585,447	$2,103,689	$2,103,689	$2,103,689	$2,103,689
	Costs per Tooling Set ($)	$38,236	$100,906	$100,906	$100,906	$100,906
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	8	20	33	125
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	90.66%	93.02%	99.22%	97.72%	99.22%
	Cycle Time (s)	29.32	32.09	32.09	32.09	32.09
	Cavities/Platen	2	8	8	8	8
	Effective Total Machine Rate ($/hr)	$105.53	$332.20	$312.66	$317.17	$312.66
	Carbon Filler Cost ($/kg)	$6.76	$6.76	$6.76	$6.76	$6.76
2015	Capital Cost ($/Line)	$587,448	$2,111,695	$2,111,695	$2,111,695	$2,111,695
	Costs per Tooling Set ($)	$38,236	$100,906	$100,906	$100,906	$100,906
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	8	20	33	125
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	90.66%	93.02%	99.22%	97.72%	99.22%
	Cycle Time (s)	29.32	32.09	32.09	32.09	32.09
	Cavities/Platen	2	8	8	8	8
	Effective Total Machine Rate ($/hr)	$105.85	$333.40	$313.79	$318.31	$313.79
	Carbon Filler Cost ($/kg)	$6.76	$6.76	$6.76	$6.76	$6.76

Figure 28. Bipolar plate injection-molding process parameters

As shown in Figure 30, costs are seen to vary between $3/kW$_{net}$ and $6/kW$_{net}$ and to be fairly level across manufacturing rate. Cost reduction for each of the advanced technology cases is due to higher power density leading to smaller plate area. Injection-molding machine cost is the main contributor accounting for ~75% of bipolar plate cost. Materials and tooling contribute ~15% and ~10% respectively. Since polypropylene is very inexpensive, the electrically conductive carbon powder filler is the main contributor to material cost. High purity carbon black was assumed as the conductive filler. Fuel cell manufacturers using polymer plates keep the exact proportions and material specifications as trade secrets but may use a mix of multiple fillers, some possible very expensive. For this analysis however, a high fill fraction (40% by volume) and medium price ($6.35/kg, based on a quote for Vulcan XC-72) were adopted as cost-representative bases for our non-proprietary cost estimates. Since the carbon black market is quite mature and substantial amounts of powder are needed even for low system production rates, a price decrease with high production rates is unlikely. Consequently, the carbon filler material cost of $6.35/kg is fixed for all production rates.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	12%	12%	12%	12%	12%
	Power Consumption (kW)	81	110	110	110	110

Figure 29. Machine rate parameters for bipolar plate injection-molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$47.04	$47.04	$47.04	$47.04	$47.04
	Manufacturing ($/stack)	$216.18	$188.22	$190.43	$186.85	$187.51
	Tooling ($/stack)	$24.22	$17.42	$17.63	$17.28	$17.35
	Total Cost ($/stack)	$287.44	$252.67	$255.11	$251.18	$251.89
	Total Cost ($/$kW_{gross}$)	$6.37	$5.60	$5.65	$5.57	$5.58
2010	Materials ($/stack)	$33.06	$33.06	$33.06	$33.06	$33.06
	Manufacturing ($/stack)	$160.73	$138.44	$130.29	$132.17	$130.29
	Tooling ($/stack)	$24.22	$16.14	$15.98	$16.22	$15.98
	Total Cost ($/stack)	$218.01	$187.65	$179.33	$181.46	$179.33
	Total Cost ($/$kW_{gross}$)	$5.03	$4.33	$4.14	$4.19	$4.14
2015	Materials ($/stack)	$33.19	$33.19	$33.19	$33.19	$33.19
	Manufacturing ($/stack)	$161.22	$138.94	$130.76	$132.65	$130.76
	Tooling ($/stack)	$24.22	$16.14	$15.98	$16.22	$15.98
	Total Cost ($/stack)	$218.62	$188.27	$179.93	$182.06	$179.93
	Total Cost ($/$kW_{gross}$)	$5.02	$4.33	$4.13	$4.18	$4.13

Figure 30. Cost breakdown for injection-molded bipolar plates

4.4.1.2. Stamped Bipolar Plates

Sheet metal stamping is an alternate method for the production of bipolar plates, suspected to be employed by General Motors for their fuel cell stacks[12]. Since 748 plates are needed per system and multiple features are required on each plate (flow fields, manifolds, etc), progressive die stamping is the logical choice. In progressive die stamping, a coil of sheet metal is fed into a stamping press having a series of die stations, each one sequentially imparting one or more feature into the part as the coil advances. The parts move through the stationary die stations by indexing and a fully formed part emerges from the last station. Figure 31 displays a simplified drawing of progressive die operations.

[12] The composition and manufacturing method for production of General Motors bipolar plates is a trade secret and is not known to the authors. However, a review of GM issued patents reveals that they are actively engaged in metallic plate research.

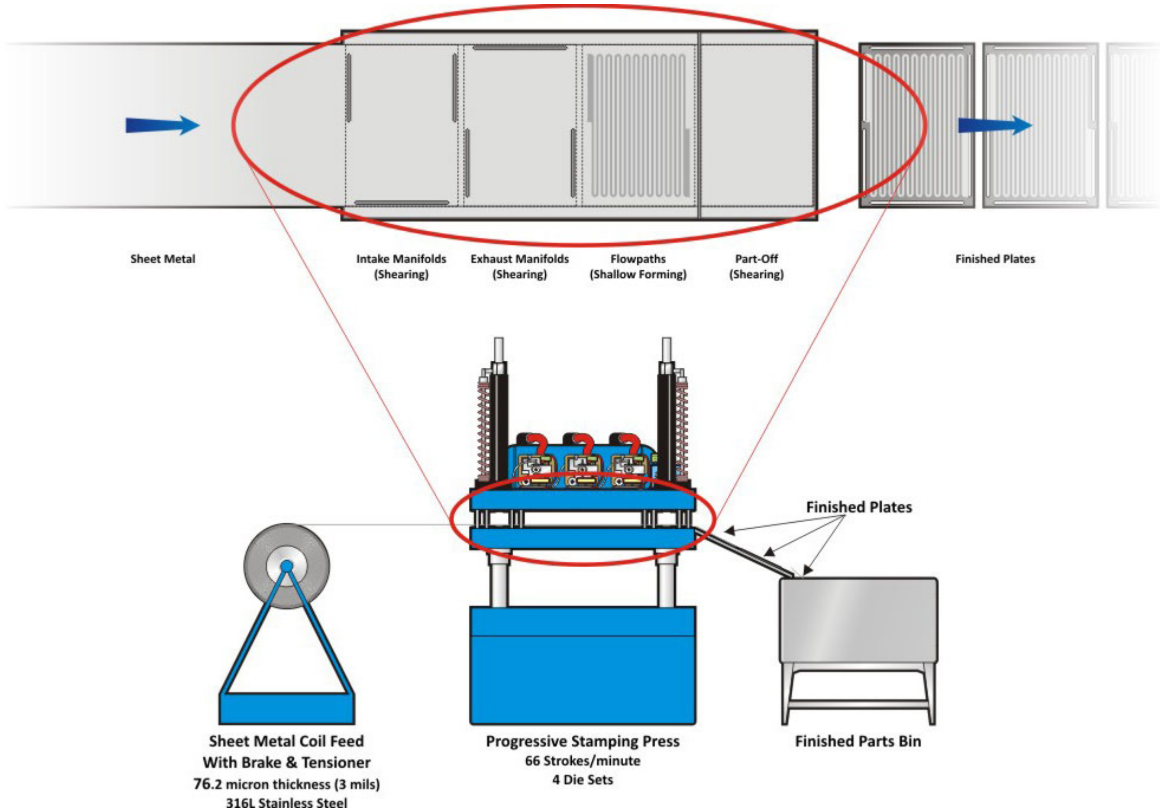

Figure 31. Bipolar plate stamping process diagram

Costs for bipolar plate progressive die stamping were obtained following the standard DTI methodology described above. In summary, capital cost, maintenance cost, and power requirements were correlated between manufacturer quotes and survey data supplied within BDI proprietary software. These data were then used to estimate true annual operating costs when operated at less than full capacity. The cost estimation process and assumptions are described more fully below.

Capital Cost and Press Tonnage: Clamping force is the primary sizing and pricing parameter of a metal forming press. For the 2006 report, price quotes and performance data for AIRAM pneumatic presses ranging from 50 tons to 210 tons were curve-fit to yield approximate purchase cost as a function of press tonnage. The cost of supporting equipment required for press operation was then added to the base press cost. Some of the supporting equipment had a fixed cost regardless of press size, while other equipment scaled in cost. A sheet metal coil feeder was judged necessary and was costed largely independent of press size. To insure part accuracy, a sheet metal straightener[13] was added, although it may prove to be ultimately unnecessary due to the thin material used (76.2 microns, or 3 mils). Typical capital costs used in the 2006 report are shown in Figure 32.

[13] Email and telephone communication with Rick Meyer of AIRAM Press Co, Covington, Ohio.

Component	Cost
Stamping Press	$49,346
Accesories	
Air Compressor	$17,696
ATC-10070 Control	$4,271
Stand	$7,406
Vibration Mounts	$1,338
Feeding Equipment	
Reel	$6,758
Loop Control	$2,245
Servo Feed	$7,405
Misc. Add-Ons	$1,106
Total Capital Cost	**$97,571** × 5 = **$487,857**

Figure 32. Capital costs breakdown for a typical bipolar plate stamping production line

In the 2006 report, it was estimated that a 65-ton press[14] was necessary to produce the bipolar plates[15]. However, it was noted that there was disagreement in the bipolar plate stamping community regarding the necessary press tonnage to form the plates[16], with one practitioner stating that a 1,000-ton press was needed.

Subsequent review by Ballard suggested that the previously estimate for total stamping system capital cost was substantially too low either due to press tonnage or supporting equipment differences. Consequently, estimated capital cost was increased five-fold to better reflect reality. The net effect of this change is relatively minor, as it only increases the system cost by about $0.2/kW$_{net}$ (at high production). This crude multiplier yields a capital cost estimate less satisfying than the itemized listing previously presented. Future investigations will be made to assess the required press tonnage and corresponding capital costs more accurately.

Press Speed: The speed of the press (in strokes per minute) varies with press size (tons): a small press is capable of higher sustained operating speeds than a large press. Press speed was correlated to press size and is shown in Figure 33.

[14] Press force figure corroborated by Dan Connors of GenCell Corporation.
[15] This press tonnage reflects the total press force of all four die stations forming a ~400 cm^2 bipolar plate.
[16] Some flow fields require increased swaging of metal to form non-uniform thickness plates whereas others require only bending of a uniform thickness plate.

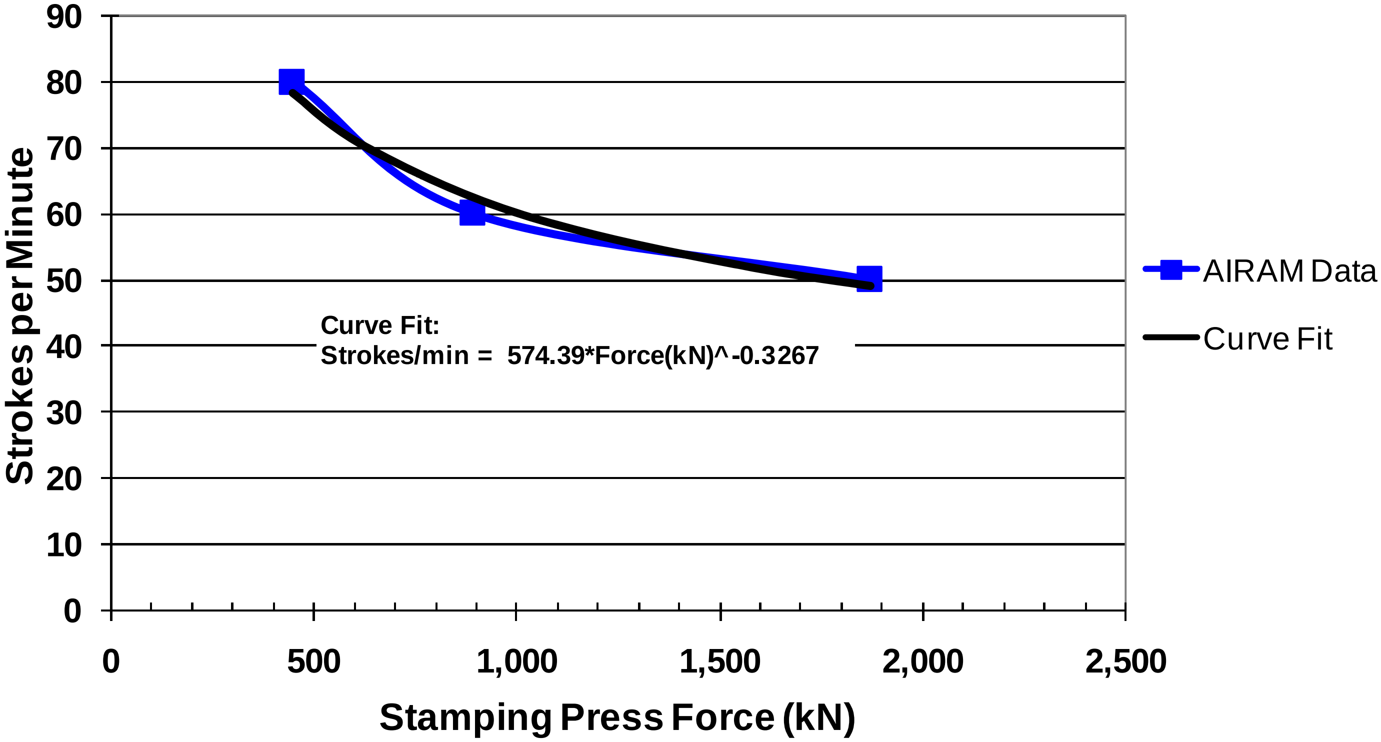

Figure 33. Press speed vs. press force

Maintenance: Given that the majority of the wear parts are shared across models, the faster operating presses tend to require maintenance more frequently. The minimal life of the set of these wear parts was estimated at 10 million cycles[17] with a total replacement cost estimated at 20-25% of complete press initial capital cost[18] depending on machine size. Since the above cycle life is the minimum number of cycles, but could be substantially more, maintenance cost of the press was estimated to be 15% of initial press capital cost every 10 million cycles. This deviates from DTI's normal methodology, which estimates maintenance costs as a percentage of initial capital per year rather than per cycle. Likewise, feeder equipment maintenance was estimated to be 5% of initial feeder capital cost every 10 million cycles[19].

Utilities: The principal power consumer in the progressive die process train is the air compressor for the pneumatic press and the coil feeder[20]. Compressor power is a function of the volumetric airflow requirement of each press size and was estimated to vary between 19 kW at the low end (50-ton press) and 30 kW at the high end (210-ton press). Power consumption was curve-fit to press size.

Machine Rate: Using the above information on total line capital cost, maintenance, and utilities, machine rates curves can be generated for various size presses at varying utilization. Basic input parameters are summarized in Figure 35 and Figure 36.

Die Cost: Die costing was estimated according to the equations outlined in the Boothroyd and Dewhurst section on sheet metal stamping. As expected, complex stamping operations require more intricate, and therefore more expensive, dies. The first two, and final, press steps are simple punching and sheering operations

[17] Email and telephone communication with Rick Meyer of AIRAM Press Co, Covington, Ohio.
[18] Email and telephone communication with Rick Meyer of AIRAM Press Co, Covington, Ohio.
[19] Although the anticipated longevity of the feeder equipment is much higher than that of the presses, it was assumed that feed equipment maintenance would take place concurrently with the press maintenance.
[20] The solenoid valves and controller unit each consume less than 50 watts, and are therefore negligible for costing purposes.

and therefore do not require expensive dies. The flowpath forming step involves forming a complex serpentine shape, which requires a highly complex die that is significantly more expensive than the dies for other steps in the process. This step also requires the majority of press force. The die cost figures can be seen below in Figure 34 (listed as "Tooling").

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$131.86	$131.86	$131.86	$131.86	$131.86
	Manufacturing ($/stack)	$98.21	$11.59	$11.59	$11.59	$11.02
	Tooling ($/stack)	$52.11	$46.90	$46.90	$46.90	$46.88
	Secondary Operations: Coating ($/stack)	$616.59	$59.64	$63.48	$60.21	$59.33
	Total Cost ($/stack)	$898.77	$249.99	$253.83	$250.56	$249.09
	Total Cost ($/kW$_{gross}$)	$19.92	$5.54	$5.63	$5.55	$5.52
2010	Materials ($/stack)	$90.61	$90.61	$90.61	$90.61	$90.61
	Manufacturing ($/stack)	$95.53	$11.15	$9.98	$9.71	$9.65
	Tooling ($/stack)	$48.36	$43.53	$43.53	$43.26	$43.53
	Secondary Operations: Coating ($/stack)	$608.18	$52.00	$55.83	$52.56	$51.28
	Total Cost ($/stack)	$842.68	$197.28	$199.94	$196.14	$195.06
	Total Cost ($/kW$_{gross}$)	$19.44	$4.55	$4.61	$4.52	$4.50
2015	Materials ($/stack)	$90.97	$90.97	$90.97	$90.97	$90.97
	Manufacturing ($/stack)	$95.56	$11.15	$9.98	$9.71	$9.65
	Tooling ($/stack)	$48.40	$43.56	$43.56	$43.29	$43.56
	Secondary Operations: Coating ($/stack)	$608.25	$52.07	$55.90	$52.63	$51.34
	Total Cost ($/stack)	$843.17	$197.75	$200.40	$196.60	$195.52
	Total Cost ($/kW$_{gross}$)	$19.37	$4.54	$4.60	$4.52	$4.49

Figure 34. Cost breakdown for stamped bipolar plates

<u>Die Life:</u> Over time, the repetitive use of the dies to form the metallic bipolar plates will cause these tools to wear and lose form. Consequently, the dies require periodic refurbishing or replacement depending on the severity of the wear. Based on communication with 3-Dimensional Services, Inc., dies for progressive bipolar plate stampings were estimated to last between 400,000 and 600,000 cycles before refurbishment, and may be refurbished 2 to 3 times before replacement. Thus, a die lifetime of 1.8 million cycles (3 times 600,000) was specified, with a die cost of $223,310 ($100,000 of which is from the two refurbishments, at $50,000 each).

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	13%	13%	13%	13%	13%
	Miscellaneous Expenses (% of CC)	2%	2%	2%	2%	2%
	Power Consumption (kW)	18	18	18	18	18

Figure 35. Machine rate parameters for bipolar plate stamping process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$487,857	$487,857	$487,857	$487,857	$487,857
	Costs per Tooling Set ($)	$223,310	$223,310	$223,310	$223,310	$223,310
	Tooling Lifetime (cycles)	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
	Simultaneous Lines	1	3	8	13	47
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	9.26%	92.62%	92.62%	92.62%	98.53%
	Cycle Time (s)	0.72	0.72	0.72	0.72	0.72
	Effective Total Machine Rate ($/hr)	$630.99	$74.51	$74.51	$74.51	$70.80
	Stainless Steel Cost ($/kg)	$12.99	$12.99	$12.99	$12.99	$12.99
2010	Capital Cost ($/Line)	$475,244	$475,244	$475,244	$475,244	$475,244
	Costs per Tooling Set ($)	$207,268	$207,268	$207,268	$207,268	$207,268
	Tooling Lifetime (cycles)	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
	Simultaneous Lines	1	3	7	11	42
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	8.36%	83.59%	95.53%	98.79%	99.51%
	Cycle Time (s)	0.71	0.71	0.71	0.71	0.71
	Effective Total Machine Rate ($/hr)	$680.10	$79.40	$71.05	$69.13	$68.72
	Stainless Steel Cost ($/kg)	$12.99	$12.99	$12.99	$12.99	$12.99
2015	Capital Cost ($/Line)	$475,386	$475,386	$475,386	$475,386	$475,386
	Costs per Tooling Set ($)	$207,421	$207,421	$207,421	$207,421	$207,421
	Tooling Lifetime (cycles)	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
	Simultaneous Lines	1	3	7	11	42
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	8.37%	83.66%	95.61%	98.87%	99.59%
	Cycle Time (s)	0.71	0.71	0.71	0.71	0.71
	Effective Total Machine Rate ($/hr)	$679.62	$79.37	$71.03	$69.10	$68.69
	Stainless Steel Cost ($/kg)	$12.99	$12.99	$12.99	$12.99	$12.99

Figure 36. Bipolar plate stamping process parameters

4.4.1.2.1. Alloy Selection and Corrosion Concerns

One of the challenges presented by using metallic plates is that they are more susceptible to corrosion than carbon-based plates. For this reason, alloy selection is very important. There is much uncertainty in the fuel cell community as to which alloy and surface treatments are needed to provide adequate corrosion resistance. Although some believe that suitable stainless steel alloys exist that adequately address this problem, others insist that protective coatings are necessary. If the right coating method were selected, it may be possible to use a cheaper and/or lighter (but less corrosion-resistant) material for the plates, which could help offset the cost of coating. In determining the coating method and/or plate material, consideration must be given to the different corrosion environments each plate will encounter: hydrogen and coolant for the anode plates, and oxygen and coolant for the cathode plates.

Literature and patent reviews and conversations with researchers indicate that coatings/surface treatments may not be needed and that 316L stainless steel (or another commercial alloy of similar cost) is appropriate. However, further input from the USCAR Fuel Cell Technical Team suggested that coatings *are* necessary. Because of this uncertainty, both options were examined. At the direction of the Fuel Cell Tech Team, coatings were included in the system cost for all three technology levels, and the effects of this inclusion were studied in the sensitivity analysis (page 97). The baseline system configurations specify 76.2-micron (3-mil) stainless steel 316L alloy metallic bipolar plates coated using a proprietary process from TreadStone Technologies, Inc.

The argument for uncoated plates is supported by the following two primary data sources.

Published in 2000, Davies[21] and fellow researchers at Loughborough University, UK, fabricated and tested bipolar plates of three uncoated stainless steel alloys[22] (904L, 310, and 316L). Contact resistance testing and multi-thousand hour endurance tests in a functioning cell were conducted. They concluded that 904L performs better than 310, which performs better than 316L, with the polarization differences attributable to variation in thickness of the oxide films. Analysis showed no surface deleterious effects and no evidence of corrosion. They summarized by stating that "by optimizing the chemical composition of the alloy, it would be feasible to use uncoated stainless steel bipolar plates, to provide low cost fuel cell systems with power densities approaching that observed with graphite." Recent communication with one of the co-authors[23] reveals that their 2000 paper was the last the team published in the series before forming Intelligent Energy (www.intelligent-energy.com): all current research is proprietary and hence unavailable.

Makkus[24] et al at the Netherlands Energy Research Foundation have also done comparative corrosion and performance testing of metallic bipolar plates. They examined seven alloys[25] (including 316, 317LMn, 321, 926, 3974 and two proprietary alloys). Testing revealed varying levels of corrosion and an influence of alloy pre-treatment methods. Overall, they conclude "The results indicated alloy B to be most suited for application in an SPFC, as it shows the lowest contact resistance and it yields a contaminant level comparable to alloy A." Recent communication with a co-author[26] indicates that alloy B is a commercially available, high chromium alloy (containing some Molybdenum). Additionally, the recommended "adjusted pre-treatment" is a small modification of the standard pickling[27] process wherein the acid pickling solution is heated to a temperature above 50°C.

In spite of evidence supporting the conclusion that bipolar plate coatings are not necessary when using 316L and similar alloy stainless steels, there is still some debate as to whether or not this is true. One question behind the skepticism on this issue is how the plates will perform in the long term under non-steady state conditions. C.H. Wang from TreadStone points out that even if stainless steel alloys are sufficiently corrosion resistant, they will typically have unacceptable contact resistance due to the extra chromium content required. The bipolar plate "Holy Grail," Wang said, is to find an aluminum alloy that would work, as it would be cheaper, lighter and more corrosion-resistant than any steel plate.[28]

In the absence of a definitive answer, the potential cost of applying protective coatings was examined, and at the direction of the Tech Team, this cost was included this cost in the estimates.

4.4.1.2.2. Bipolar Plate Surface Treatments and Coatings

There are a variety of methods for providing bipolar plate corrosion resistance that are either under investigation or currently being employed in the fuel cell industry. Most of these methods fall into one of the following categories:

[21] D.P. Davies, P.L. Adcock, M. Turpin, S.J. Rowen, "Stainless steel as a bipolar plate material for solid polymer fuel cells, Journal of Power Sources, 86 (2000) 237-242.

[22] An additional plate of 316 SS with a proprietary coating was also tested. This plate demonstrated superior cell polarization performance but was not tested for thousands of hours, as were the other samples.

[23] Private communication, P.L. Adcock, April 2007.

[24] Robert D. Makkus, Arno H.H. Janssen, Frank A de Bruijn, Ronald K.A.M. Mallant, "Use of stainless steel for cost competitive bipolar plates in the SPFC", Netherlands Energy Research Foundation, Journal of Power Sources 86 (2000) 274-282.

[25] A coated plated was also partially tested. However, only initial performance results, as opposed to performance after 3,000 hours of operation, were reported. Consequently, the conclusions in the Davies paper focus on the uncoated alloy results since a more comprehensive view of performance was obtained.

[26] Private communication, Robert Makkus, Netherlands Energy Research Foundation, April 2007.

[27] Standard pickling treatment is defined as a room temperature bath of a sulfuric acid, hydrochloric acid, and HF solution.

[28] Private communication, C.H. Wang, TreadStone Technologies, Inc., November 2008.

- **Nitriding:** surface diffusion of nitrogen into steel surface typically via nitrogen or ammonia at ~550°C to form chromium nitride (or aluminum nitride, in the case of aluminum plates)

- **Physical vapor depositions (PVD):** use of ion-beams or magnetron sputtering to create a charged molecular vapor cloud of coating material (gold, TiN, etc.) which then settles and adheres to the bipolar plate surface

- **Electroplating:** use of an electric current to deposit a metal layer onto the surface of the bipolar plate immersed in an aqueous metallic ion bath

- **Pickling:** treatment of the bipolar plate surface with an acid mixture (typically hydrochloric and sulfuric) in order to remove impurities (rust, scale, etc.).

There are a large number of non-corrosive, highly conductive materials that are well-suited as coatings for stainless steel bipolar plates[29]. Gold is often considered one of the most effective; however, its cost is usually prohibitive. Alternately, Fonk[30] from GM states: "most preferably, the [coating] particles will comprise carbon or graphite (i.e. hexagonally crystallized carbon)."

No quantitative judgment was made as to the fuel cell performance of one surface treatment method over another. From a general perspective however, the most important aspects are application speed and the ability to deliver a thin coating of reliable thickness, with sufficient surface smoothness to cover the plate surface uniformly. Methods such as ion-beam assisted physical vapor deposition[31] are able to achieve excellent uniformity and low layer thickness (10 nanometer layers of gold with near perfect flatness) but are capital-intensive and suffer from slow application speed if relatively thick layers are proven necessary. Consequently, a brief cost analysis was conducted for three surface treatment options (electroplating, magnetron sputtering (titanium nitriding), and thermally-grown chromium nitriding). In addition, a detailed cost analysis was conducted for TreadStone's proprietary process, which was included in the stack costs for the baseline system configurations.

Based on conversations with industry, an electroplating cost was estimated as approximately $1.50/kW, (or 2.5 cents per 100 cm^2 of surface area), plus material costs. Electroplating provides a consistently reliable coating to a minimum thickness of 12.7 microns (0.5 mils). Assuming this minimum coating thickness, only 1.1 cm^3 of coating material is needed per plate. Consequently, material cost can rise to $30-54/kg before it adds $1/kW to stack cost. If carbon power is used as the coating material, the total material-and-application cost is estimated at under $1.75/kW.

Additionally, a preliminary analysis was conducted for aluminum plates with a titanium-nitride surface treatment via magnetron sputtering. A 1997 GM patent states that a preferred embodiment is an aluminum bipolar plate (6061-T6), coated with a 10-micron layer of stainless steel (Al-6XN), and topped with a 0.3-micron layer of titanium nitride. Consultation with magnetron sputtering experts suggests that these are surprisingly thick layers to deposit and could take up to 60 minutes of sputtering time[32]. Since the patent is over 10 years old, a shorter deposition time was postulated, which is consistent with using thinner layers (or a single layer).

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[29] "Gold, platinum, graphite, carbon, nickel, conductive metal borides, nitrides and carbides (e.g. titanium nitride, titanium carbide, and titanium diboride), titanium alloyed with chromium and/or nickel, palladium, niobium, rhodium, rare earth metals, and other noble metals." (Fonk et al, US Patent 6,372,376, p.4)

[30] US Patent #6,372,376 titled "Corrosion resistant PEM fuel cell"

[31] US Patent #6,866,958 titled "Ultra-low loadings of AU for stainless steel bipolar plates"

[32] 60 minutes is only a rough estimate, based on a 150 nm/min sputtering rate. A detailed analysis would have to be conducted to determine the exact duration and system configuration.

Preliminary analysis[33] indicates a total bipolar plate cost of $5-11/kW for production rates of 30,000 to 500,000 systems per year. (Analysis at the 1,000 systems per year rate was not conducted since alternate equipment would be required and therefore fell outside the scope of the preliminary analysis.) Cost variation with manufacturing rate is low with the two-to-one cost variation resulting from uncertainty in deposition time (varied from two to ten minutes). Overall, titanium-nitrided aluminum stamped plates represents a potential $2/kW to $8/kW cost adder compared to uncoated stainless steel stamped plates.

The thermally-grown chromium nitriding process examined for this study (see Figure 37) was based on the work of Mike Brady at Oak Ridge National Laboratory. Unlike the titanium nitriding process mentioned previously, this is not a deposited coating, but a surface conversion. The plates are placed into a nitrogen-rich environment and heated to 800-1,000°C for approximately 2 hours. The high temperature favors the reaction of all exposed metal surfaces, and forms a chromium nitride layer with the chromium in the stainless steel. This process does not leave any pinhole defects, and is amenable to complex geometries (such as flow field grooves), while allowing the simultaneous "coating" of both sides of the plates.

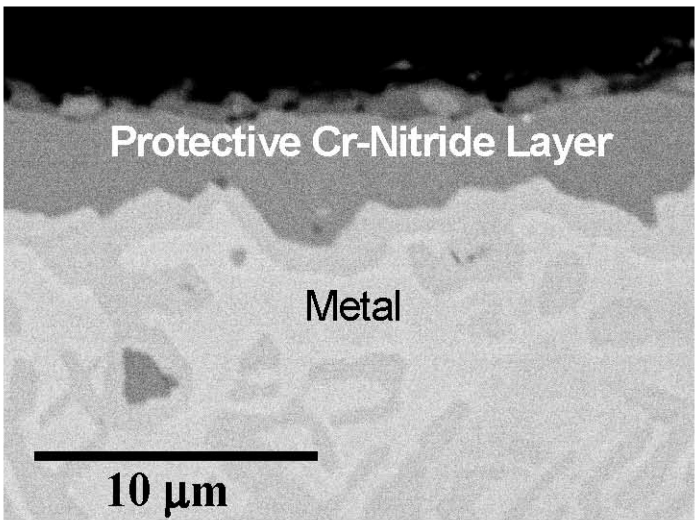

Figure 37. Magnified chromium nitride surface conversion

Conventional nitriding is currently conducted in large automated facilities, and is relatively cheap. The anticipated process for bipolar plates is similar, but simpler and faster. The plates would be batch-processed, and could feasibly be handled in a "lights out" facility, meaning there would be zero human operators (not counting maintenance). Because of the long processing time (1-3 hrs), it is important to fit the maximum number of plates in each batch. As such, the spacing between the plates becomes a critical factor in the processing cost. Figure 38 shows a parametric analysis of the relationship between plate spacing and nitriding cost for batch times of 1 and 3 hours.

[33] Based on $6/kg Aluminum material cost, standard plate forming costs as defined elsewhere in this report, $200/kg Titanium material cost, a 10 micron TiN layer, $1.2M magnetron sputtering system, 600 kW electrical consumption, 60 plates processed per batch, 2-10 minute sputtering time.

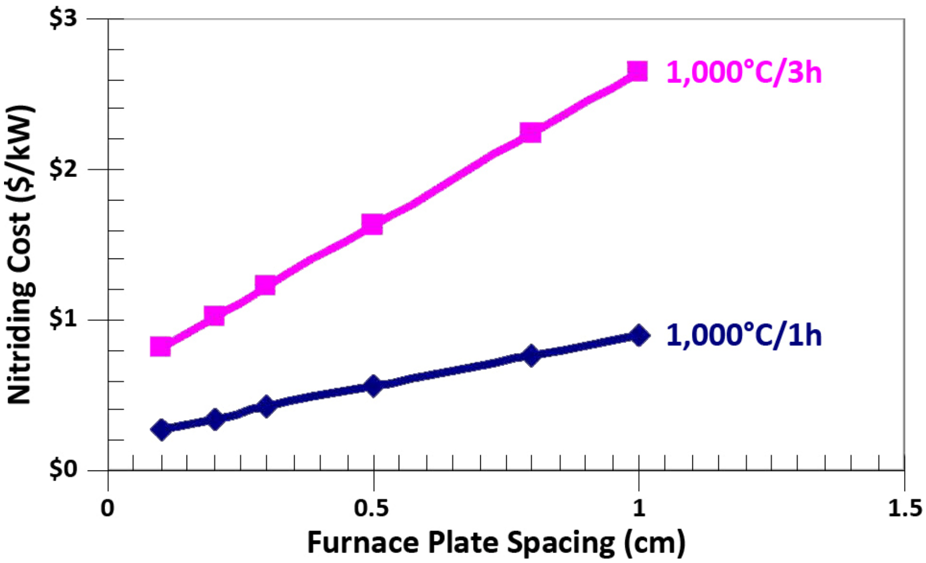

Figure 38. Impact of plate spacing on nitriding cost

Based on discussions with Brady, it was estimated that the coating would likely cost about $0.75/kW. However, if an optimistic combination of a short batch time and high packing density can be achieved, it may be possible to get the cost down around $0.25/kW.

Alternatively, it may be possible to nitride the plates in a matter of seconds by using a pulsed plasma arc lamp. In this method, fewer plates would simultaneously be processed, but the dramatically higher throughput would still yield a hefty cost savings, more than offsetting the extremely high capital costs (~$1-2 million per line). DTI estimates suggest that this method could lower the costs down to between $0.16 and $0.44/kW.

The fourth coating method examined for this analysis was TreadStone's proprietary process. A DFMA analysis was conducted based on information from TreadStone's patent US 7,309,540, as well as that transferred under a non-disclosure agreement, with close collaboration with C.H. Wang and Gerry DeCuollo of TreadStone Technologies, Inc.

According to the patent, the coating consists of "one or more resistant layers, comprising conductive vias through the resistant layer(s)"[34] (see Figure 39). The resistant layer provides excellent corrosion protection, while the vias provide sufficient electrical conduction to improve overall conductivity through the plate.

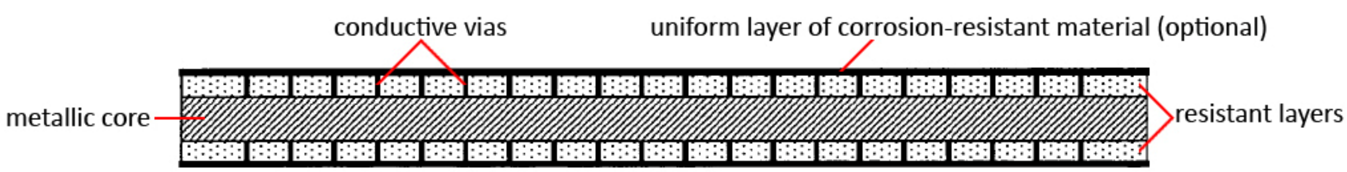

Figure 39. Conductive vias shown in US patent 7,309,540

The resistant layer is applied via a physical vapor deposition process. Details of the manufacturing process are considered proprietary, so no further explanation is provided. The cost breakdown for the TreadStone process is shown in Figure 40.

[34] US Patent 7,309,540 titled "Electrical Power Source Designs and Components"

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$24.06	$24.06	$24.06	$24.06	$24.06
	Manufacturing ($/stack)	$592.53	$35.59	$39.42	$36.15	$35.27
	Total Cost ($/stack)	$616.59	$59.64	$63.48	$60.21	$59.33
	Total Cost ($/kW$_{gross}$)	$13.67	$1.32	$1.41	$1.33	$1.32
2010	Materials ($/stack)	$16.53	$16.53	$16.53	$16.53	$16.53
	Manufacturing ($/stack)	$591.65	$35.47	$39.30	$36.04	$34.75
	Total Cost ($/stack)	$608.18	$52.00	$55.83	$52.56	$51.28
	Total Cost ($/kW$_{gross}$)	$14.03	$1.20	$1.29	$1.21	$1.18
2015	Materials ($/stack)	$16.59	$16.59	$16.59	$16.59	$16.59
	Manufacturing ($/stack)	$591.66	$35.47	$39.30	$36.04	$34.75
	Total Cost ($/stack)	$608.25	$52.07	$55.90	$52.63	$51.34
	Total Cost ($/kW$_{gross}$)	$13.97	$1.20	$1.28	$1.21	$1.18

Figure 40. Cost breakdown for TreadStone bipolar plate coating process

4.4.2. Membrane

4.4.2.1. Membrane Material & Structure (Nafion® on ePTFE)

The PEM membrane is widely acknowledged as one of the more costly stack components and one needing to be reduced in cost to achieve a cost competitive fuel cell system. Nafion®, a perfluorinated sulfonic acid (PFSA) from DuPont originally developed as chloro-alkali membrane, is the main membrane chemistry used in PEM fuel cells. However, multiple other PFSA variants are in use, including membranes from Dow, Asahi, Gore, and GEFC. Multiple other membrane chemistries are under development[35], including partially fluorinated (PVDF) and non-fluorinated (BAM3G, S-PPBP, MBS-PBI, MBS-PPTA, S-PEK). Additionally, membranes may be homogenous, composites[36], or placed on a substrate for mechanical reinforcement.

For purposes of this study, the approach selected was Nafion® on a porous expanded polytetrafluoroethylene[37] (ePTFE) substrate. This approach is modeled on the W.L. Gore approach as understood by a review of Gore PEMSelect product literature, patents, and discussions with Gore engineers. While alternate approaches (such as homogenous cast or extruded membranes) have the potential for lower cost by obviating the expense of the ePTFE substrate, the Gore-like approach was selected since it should theoretically supply substantially better mechanical properties and is thereby inherently better suited for roll-to-roll processing. Mechanical strength is an important characteristic in roll-to-roll processing (also known as web converting) and roll-to-roll processing appears to offer the best opportunity for very fast (and thus lowest cost) membrane formation. Alternate membrane formation techniques were not considered in detail for this study. Basic parameters of the selected approach are shown in Figure 41.

Membrane Ionomer	Nafion™ (PFSA)
Substrate	ePTFE
Substrate Porosity	95%
Substrate Density	0.098 g/cc
Membrane Thickness	25.4 microns
Nafion Density	1.979 g/cc

Figure 41. Basic membrane characteristics

35 "Review and analysis of PEM fuel cell design and manufacturing", Miral Mehta, Joyce Smith Cooper, Journal of Power Sources 114 (2003) 32-53.

36 PFSA membranes used in the chloro-alkali production process are typically composed of 5-9 layers of tailored membranes.

37 PTFE is most commonly known as Teflon™ and is used as a non-stick coating for frying pans, etc. Expanded PTFE is most commonly known as Gore-Tex™ and is used as a "breathable" but water resistant layer in sportswear.

4.4.2.2. Membrane Material Cost

The membrane material system is quite simple and consists of only two elements: the Nafion® ionomer and the ePTFE substrate. Expanded PTFE is used extensively in the textile industry where the production quantities dwarf even the highest demands from the automotive sector. Conversations with apparel makers confirm that the price of ePTFE is unlikely to change appreciable between the low and high fuel cell system demands. Consequently, the cost of ePTFE is set at $5/m^2$ for all membrane production levels.

The cost of Nafion® ionomer greatly affects overall membrane cost even though the membrane is very thin[38]. Based on vendor quotes of Nafion®, quotes for products similar to Nafion®, and on discussion with industry experts, it was projected that Nafion® ionomer costs would drop by roughly 95% from low to high production (~$2,000/kg to $112/kg). Figure 42 displays the assumed cost of Nafion® ionomer used in this cost study. Since Nafion® cost is a major driver of overall membrane cost, the Nafion® $/kg is a prime candidate for further exploration in a sensitivity analysis.

As discussed below, there are appreciable cutting losses[39] associated with the roll-to-roll manufacturing process, which directly affect the membrane material costs. The same yield rates were applied to the materials as were applied to the manufacturing process (50-80% depending on production rate) but it was further assumed that a portion of ionomer in the scrap membrane was able to be recycled. Consequently, it was assumed for costing purposes that the ionomer material wastage rate was half that of the overall membrane areal scrap rate.

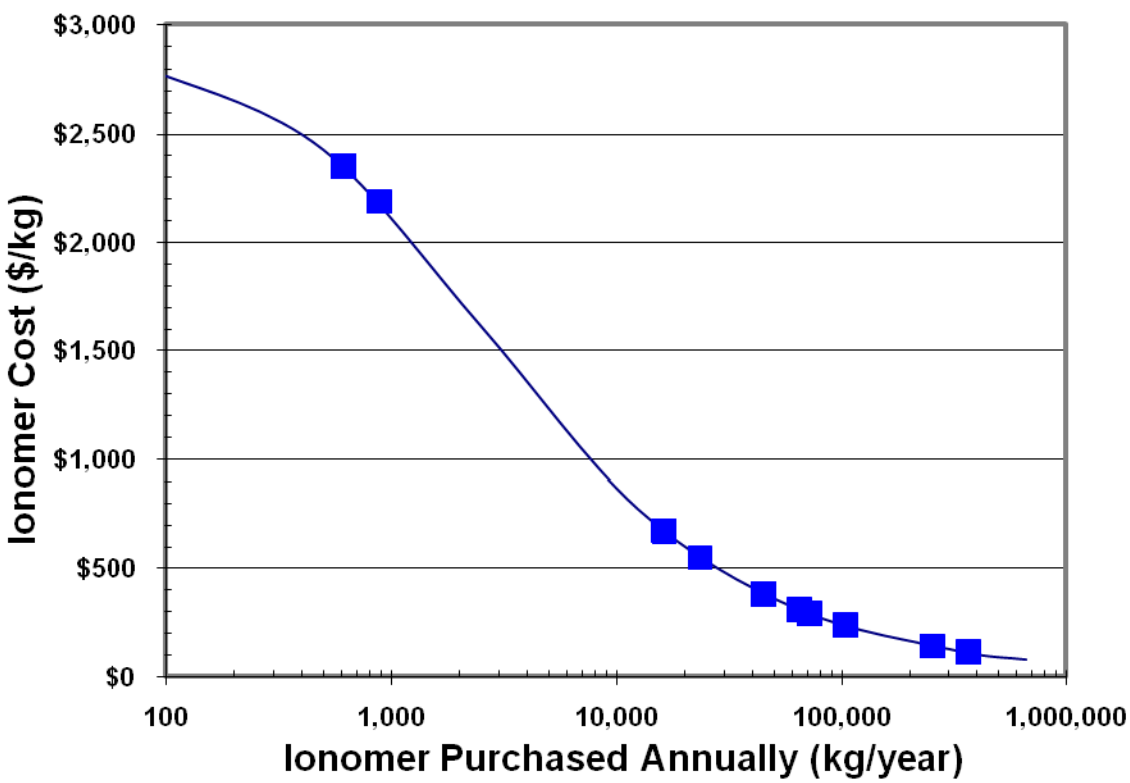

Figure 42. Ionomer material cost

[38] Even at 25 microns, approximately 50 grams of Nafion® is contained in a square meter of membrane. At $1,000/kg, this equals $50/m^2$.

[39] These losses are meant to capture the total difference between gross and net material usage. Thus, they encompass losses associated with trimming, cutting, startup/shutdown, and improper ionomer application.

4.4.2.3. Membrane Manufacturing Cost

At low and intermediate production rates, the processing cost to manufacture the membrane remains a major, if not dominant, cost element. In 1998, DTI analyzed[40] the cost of a Gore-like[41] PEM membrane of 90%-by-volume Nafion® ionomer in an expanded-polytetrafluoroethylene (ePTFE) matrix. Multiple generations of similar Gore membranes have achieved industry leading membrane performance, and Gore maintains a publicly stated commitment to lowering membrane costs to automotive competitive levels. The authors previously analyzed manufacturing costs using DFMA techniques based on automated roll-to-roll processing. The major steps of the process trains included: unwinding of previously manufactured ePTFE, occlusion of ionomer into the ePTFE web, IR drying of the ionomer, de-ionized water rinse, catalyst ink deposition via rollers, IR drying, boiling water hydration, air drying, and finished membrane winding with tension control throughout. The membrane manufacturing cost was estimated at $0.83/m^2 at high production rates (500,000 systems per year), but to achieve these levels, very aggressive assumptions were made regarding ionomer material cost, processing speed, technical feasibility, and capital cost.

In 2001, Directed Technologies revisited the membrane forming process[42]. Processing parameter were modified and capital costs of the web processing equipment was estimated by vendor quotes from USWebcon. Multiple variants on the process train were considered including alteration of the starting ionomer form to eliminate the boiling water hydration step, multiple passes on the occlusion/dipping step to ensure pinhole free coverage, and multiple rewind stations to reduce the continuous length of the process train.

In 2005, DTI again refined the membrane fabrication process[43] based on further discussion with industry experts. Industry feedback suggested the following cost modeling changes:

- Substantially increase capital cost.
- Decrease membrane yield rates.
- Decrease plant life[44] from 10 years to 5 years.
- Plan for significant plant underutilization[45] (assume plant to function at 67% capacity for the low and moderate production rates (1,000-30,000 units/year) and 81% capacity at high production (500,000 units/year))

These changes had the cumulative effect of significantly increasing membrane cost, particularly at the low production rates. This is not surprising since the web processing equipment was selected specifically for its high volume capacity, thus it can be expected to shine at high volume but have poor scale-down attributes.

The 2008 analysis was based strongly on the 2005 assessment. As schematically detailed in Figure 43, the membrane fabrication process consists of eight main steps:

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[40] Franklin D. Lomax, Jr., Brian D. James, George N. Baum, C.E. “Sandy” Thomas, “Detailed Manufacturing Cost Estimates for Polymer Electrolyte Membrane (PEM) Fuel Cells for Light Duty Vehicles”, Directed Technologies Inc., prepared for Ford Motor Company under DOE contract, August 1998.

[41] W. L. Gore & Associates manufactures a number of membrane products based on ePTFE fabric as a support structure for polymer electrolyte. 18 microns reflects the membrane thickness of the Gore Series 57 membrane produced specifically for automotive application.

[42] Brian D. James, “DFMA Cost Estimation of Low/Mid/High Production Fuel Cell/Reformer Systems”, Project Review Meeting, Directed Technologies, Inc., prepared under DOE contract, February 2001.

[43] Gregory D. Ariff, Duane B. Myers, Brian D. James, “Baseline PEM Fuel Cell Power System Cost Assessment for a 50 kW Automotive System”, Directed Technologies, Inc., prepared under DOE contract, January 2005.

[44] Because mass-manufacturing of membrane is a rapidly evolving technology, a 5 year plant useful life was thought appropriate not because the equipment would wear out but because it would rapidly become technologically obsolete.

[45] The 67% capacity was based on 5-year average utilization of a plant with 25% annual production increases. The 81% capacity was based on a 10-year average utilization of a plant with 5% annual production increases.

1. **Unwinding:** An unwind stand with tensioners to feed the previously procured ePTFE substrate into the process line. Web width was selected as the optimal width to match an integer number of cells and thereby minimize waste. A web width of ~ 1m was deemed feasible for both the membrane fabrication line and the subsequent catalyzation and MEA hot-pressing lines.

2. **First Ionomer Bath:** The ePTFE substrate is dipped into an ionomer/solvent bath to partially occlude the pores.

3. **First Infra-red Oven Drying:** The web dries via infra-red ovens. A drying time of 30 seconds was postulated. Since the web is traveling quickly, considerable run length is required. The ovens may be linear or contain multiple back-and-forth passes to achieve the total required dwell time.

4. **Second Ionomer Bath:** The ionomer bath dipping process is repeated to achieve full occlusion of the ePTFE pores and an even thickness, pinhole-free membrane.

5. **Second Infra-red Oven Drying:** The web is drying after the second ionomer bath.

6. **Boiling Water Hydration:** The web is held in boiling water for 5 minutes to fully hydrate the ionomer. Optimal selection of the ionomer may reduce or eliminate this boiling step.

7. **Air Dryer:** High velocity air is used to dry the web after the hydration step.

8. **Rewind:** The finished membrane is wound onto a spool for transport to the catalyzation process line.

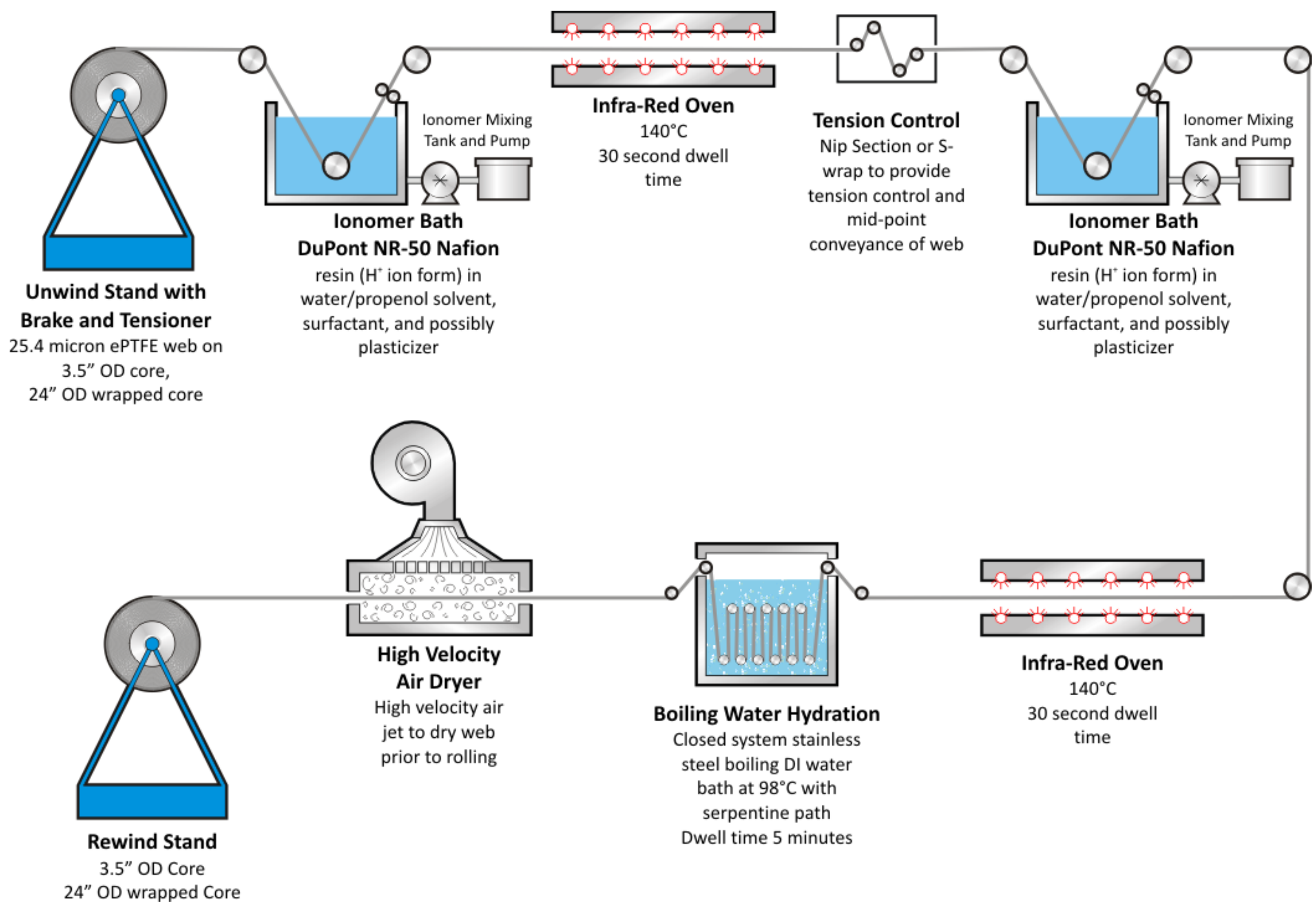

Figure 43. Membrane fabrication process diagram

Details of the membrane fabrication cost analysis are shown in Figure 44. Two roll-to-roll plants were postulated: a "low-speed plant" (5 m/min) and a "high-speed" plant (35 m/min). Run at part load, they cover the full span of membrane production requirements (1,000 to 500,000 vehicles/year). Key assumptions are noted below.

Capital Cost: Capital costs were coarsely estimated based on industry input and are significantly greater than the element-by-element summation based on component price quotes.

Web speed: Even the "high-speed" web (35 m/min) is very slow by converting machinery standards where speeds of 100 m/min are often achieved[46]. This is a nod toward cost conservativeness and a reflection that the upper bound of membrane web speed is not known at this time.

Discount Rate: The discount rate is increased to 20% to reflect the increased business risk of a membrane production line.

Production for Simultaneous Product Lines: In virtually all other components of the fuel cell stack system, it was assumed that there was vertical integration and dedicated component production for a single vehicle product. For the membrane however, it is likely that a separate company will fabricate the membrane for multiple car companies or, at least, that the membrane plant will produce membrane for more than one line of vehicles. Consequently, a multiplier on the yearly membrane demand was included to reflect supply to multiple vehicle product lines. This multiplier is not constant as production rate increases since the plant at is some point limited by capacity. The non-constant nature of the multiplier leads to unevenness in the resulting $\$/m^2$ cost projections.

Peak Equipment Utilization: DTI conversations with a membrane supplier led to limiting the utilization of the plant as a means of reflecting rapid demand growth. Utilization (at most manufacturing rates) was limited to 67% to reflect the five-year average utilization assuming 25% per year demand growth. For the 500,000 vehicles per year case, plant utilization was allowed to increase to 80% to reflect a more stable production scenario.

Production/Cutting Yield: Further conversations with a membrane supplier led to the postulation of a substantial loss rate in membrane production. Per supplier input, a 50% yield was assumed up to 25% plant utilization, with an 80% yield above 80% utilization, and a linear variance in between.

Workdays and Hours: The maximum plant operating hours were assumed to be 20 hours per day, 240 days per year. Actual hours vary based on actual plant utilization.

Cost Markup: The standard methodology throughout the analysis had been not to apply manufacturer markups, in keeping with the vertically-integrated manufacturing assumption, and the directives of the DOE on this costing project. However, since it is likely that the membrane producer will not be vertically integrated, a markup was included in our membrane cost estimate. Furthermore, because the membrane is a critical component of the stack, significantly higher margins were allocated than are typical to the automotive industry where there is a large supplier base with virtually interchangeable products competing solely on price.

[46] Several factors influence web speed selection: the inherent mechanical strength of the web as it endures high-speed processing, the complexity/number-of-turns required in a particular element to allow adequate dwell time when moving at high–speed, and the web material losses resulting from a malfunction. If the web requires 30 seconds to dry and moves at 100 m/min, the drying section must be 300 m long. If something should break or not perform adequately, many meters of web product are lost during a shut-down because of the inertia of the rollers.

Revenue: Annual membrane fabricator revenue was not an input in the analysis. Rather it was an output. However, it is worth noting that even at high membrane production rates, company revenues are still only about $33M per year. This is a modest company size and supports the notion of allowing higher than average markups as a means to entice people into the business.

		2008/ 2010/ 2015				
Annual Veh Prod. (1 product line)	**veh/year**	**1,000**	**30,000**	**80,000**	**130,000**	**500,000**
Capital Amortization						
Capital Cost (Membrane Fabrication)	$	$15,000,000	$15,000,000	$25,000,000	$25,000,000	$30,000,000
Machine Lifetime	years	10	10	10	10	10
Discount Rate	%	20%	20%	20%	20%	20%
Corporate Income Tax Rate	%	40%	40%	40%	40%	40%
Capital Recovery Factor (CRF)		0.331	0.331	0.331	0.331	0.331
Labor Costs						
Min. Mfg. Labor Staff (Simul. on 1 Shift)	FTE	5	25	50	50	50
Labor Rate	$/min	1	1	1	1	1
Machine Costs						
Maint./Spare Parts (% of inst. C.C./year)	%	5%	5%	5%	5%	5%
Miscellaneous Expenses	%	5%	5%	5%	5%	5%
Total Power Consumption	kW	200	250	350	350	350
Electrical Utility Cost	$/kWh	0.07	0.07	0.07	0.07	0.07
Membrane Production Parameters						
Simul. Prod. Lines to Which Mem. is		4.5	1.5	3	2.15	1
Vehicle Annual Production	veh/year	4,500	45,000	240,000	279,500	500,000
m² per Vehicle	m²/vehicle	13.95	13.95	13.95	13.95	13.95
Peak Equipment Utilization Due to Growth	%	67%	67%	67%	67%	80%
Production/Cutting Yield	%	50%	70%	64%	67%	80%
Prod/Cutting Yield (to avoid circular logic)	%	50%	70%	65%	68%	80%
Gross Production @ 100% Utilization (plant)	m²/year	187,388	1,338,486	7,807,836	8,685,732	10,898,438
Gross Production (plant)	m²/year	125,550	896,786	5,231,250	5,819,440	8,718,750
Net Production (plant)	m²/year	62,775	627,750	3,348,000	3,899,025	6,975,000
Net Production of 1 Line	m²/year	13,950	418,500	1,116,000	1,813,500	6,975,000
Design Web Speed	m/min	5	5	35	35	35
Web Width	m	1	1	1	1	1
Work Days per Year	days/year	240	240	240	240	240
Plant Utilization (of 20 hr days)	%	8.7%	62.3%	51.9%	57.7%	86.5%
Hours per Year of Production	hrs/year	419	2,989	2,491	2,771	4,152
Hours per Day of Production	hrs/day	1.74	12.46	10.38	11.55	17.30
Annual Cost Summation						
Capital Recovery Cost	$/year	$4,963,069	$4,963,069	$8,271,782	$8,271,782	$9,926,138
Labor Cost	$/year	$576,000	$4,483,929	$7,473,214	$8,313,486	$12,455,357
Maintenance/Spares Cost	$/year	$750,000	$750,000	$1,250,000	$1,250,000	$1,500,000
Miscellaneous Expenses	$/year	$750,000	$750,000	$1,250,000	$1,250,000	$1,500,000
Utility Cost	$/year	$5,859	$52,313	$61,031	$67,893	$101,719
Effective Machine Rate	$/min	$281	$61	$122	$115	$102
Total Mfg. Cost per m² (Pre-Markup)	$/m²	$112	$18	$5	$5	$4
Manufacturing Cost Markup %	%	100%	100%	75%	50%	30%
Gross Margin	%	50%	50%	43%	33%	23%
Annual Revenue	$/year	$14,089,856	$21,998,620	$32,035,547	$28,729,742	$33,128,178
Total Manufacturing Cost (Incl. Markup)*	**$/m²**	**$224.45**	**$35.04**	**$9.57**	**$7.37**	**$4.75**

* Note that because these numbers are used only to obtain a curve-fit, the manufacturing costs shown here differ slightly from the actual manufacturing costs used (shown in Figure 40.) [47]

Figure 44. Simplified membrane manufacturing cost analysis assumptions

[47] Note that because these numbers are used only to obtain a curve fit, the manufacturing costs shown here differ slightly from the actual manufacturing costs used (shown in Figure 47).

Membrane manufacturing cost is plotted against membrane annual volume in Figure 45 below. Membrane material cost is not included. Note that annual membrane volume has two potential definitions depending on the assumption of either a single product line or multiple product lines. When all membrane production goes toward a single product line, membrane volume is total production volume. When multiple product lines are assumed, membrane volume represents annual sales volume (to a single customer). Thus, in essence, the cost curve is shifted to the left due to economies of scale made possible by pooling multiple demands. The cost curve is seen to be uneven due to this effect. To aid in numerical calculation, a power curve was curve-fit to each relationship, and the less expensive, multiple-product-line curve was utilized in subsequent power system cost computations.

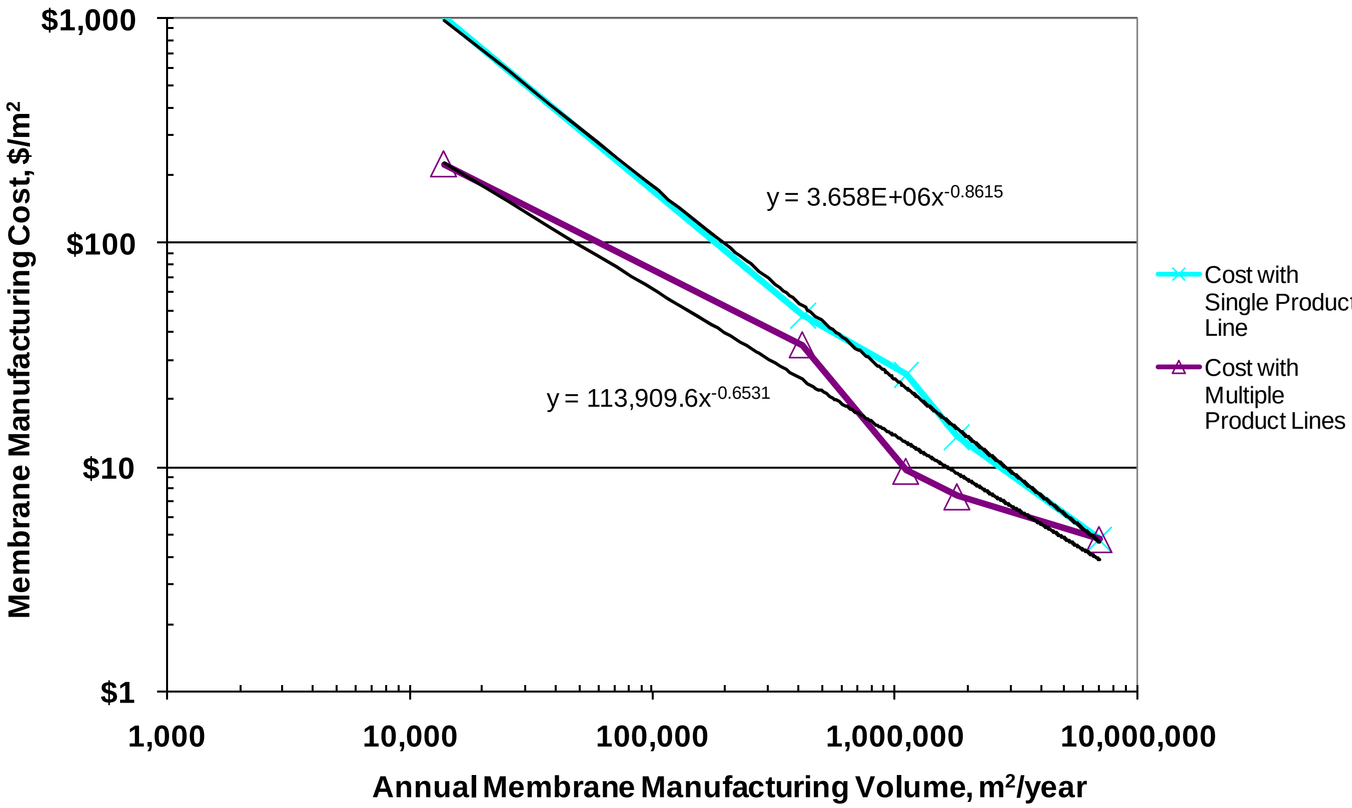

Figure 45. Membrane manufacturing cost vs. annual membrane manufacturing volume

4.4.2.4. Total Membrane Cost and Comparison to Other Estimates

Total membrane cost used in this study is shown in Figure 46 below along with 2005 membrane estimates[48] from DuPont and GM. The DuPont and GM estimates were for 25 micron thick, homogeneous PFSA membranes whereas the DTI estimates were for ePTFE-supported 25 micron membranes. All estimates represent membrane fabrication and materials cost alone and do not include any catalyst or catalyst application cost. Overall, the estimates were in excellent agreement although they represent two distinctly different fabrication methods using the same ionic material. Figure 47 details the material and manufacturing costs of the uncatalyzed membrane. Note that unlike most elements in the cost analysis, membrane manufacturer markup has been added to the membrane cost, as the membrane is likely to be produced by an outside vendor rather than made in-house by the fuel cell fabricator.

[48] "Two Fuel Cell Cars In Every Garage?", Mark F. Mathias, Rohit Makharia, Hubert A Gasteiger, Jason J. Conley, Timothy J. Fuller, Craig J. Gittleman, Shyam S. Kocha, Daniel P. Miller, Corky K. Mittelsteadt, Tao Xie, Susan G. Yan, Paul T. Yu (all from GM's Fuel Cells Activities Division or Giner Electrochemical Systems), The Electrochemical Society Interface, Fall 2005, pg 24-35.

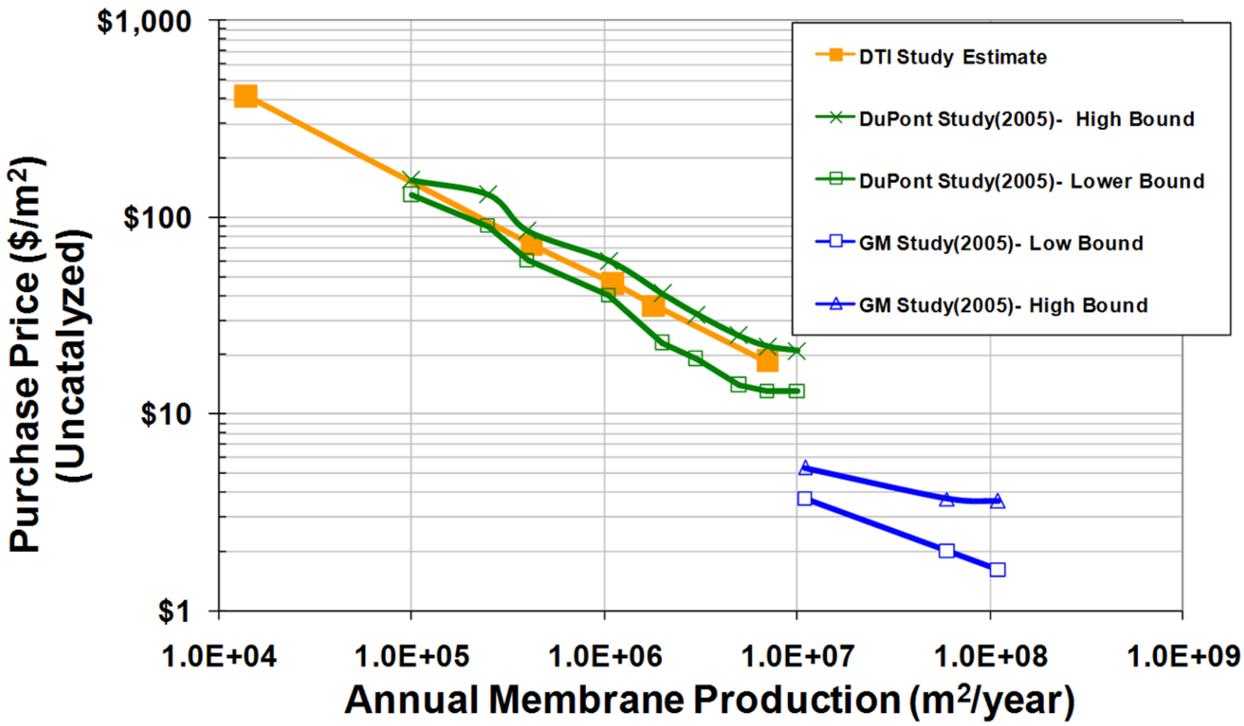

Figure 46. Membrane (material + manufacturing) cost, compared to previous analysis and vendor quotes

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/m²)	$188.33	$48.66	$33.04	$26.79	$15.53
	Manufacturing ($/m²)	$227.36	$24.66	$13.00	$9.46	$3.93
	Total Cost ($/m²)	$415.69	$73.33	$46.03	$36.26	$19.46
	Total Cost ($/stack)	$2,829.02	$499.02	$313.29	$246.74	$132.43
	Total Cost ($/kW$_{gross}$)	$62.71	$11.06	$6.94	$5.47	$2.94
2010	Materials ($/m²)	$201.22	$57.20	$38.20	$30.67	$17.22
	Manufacturing ($/m²)	$289.84	$31.44	$16.57	$12.07	$5.01
	Total Cost ($/m²)	$491.05	$88.64	$54.77	$42.74	$22.23
	Total Cost ($/stack)	$2,304.36	$415.97	$257.01	$200.55	$104.31
	Total Cost ($/kW$_{gross}$)	$53.15	$9.59	$5.93	$4.63	$2.41
2015	Materials ($/m²)	$201.39	$57.37	$38.30	$30.75	$17.26
	Manufacturing ($/m²)	$289.11	$31.36	$16.53	$12.03	$4.99
	Total Cost ($/m²)	$490.49	$88.73	$54.82	$42.78	$22.25
	Total Cost ($/stack)	$2,310.61	$417.98	$258.26	$201.53	$104.83
	Total Cost ($/kW$_{gross}$)	$53.08	$9.60	$5.93	$4.63	$2.41

Figure 47. Cost breakdown for un-catalyzed membrane

4.4.3. Catalyst Ink

The catalyst layer is formed by applying a catalyst ink to the membrane as described in the next section. The catalyst ink was based on a slurry of platinum, Vulcan XC-72 carbon powder, and 5% wt ionomer solution, with an aqueous methanol solution for a solvent. The platinum is dispersed on the carbon powder via a chloroplatinic acid (CPA) precipitation method[49]. The overall catalyst ink preparation process is described in Figure 48.

[49] Process based parameters based on personal communication with E-TEK.

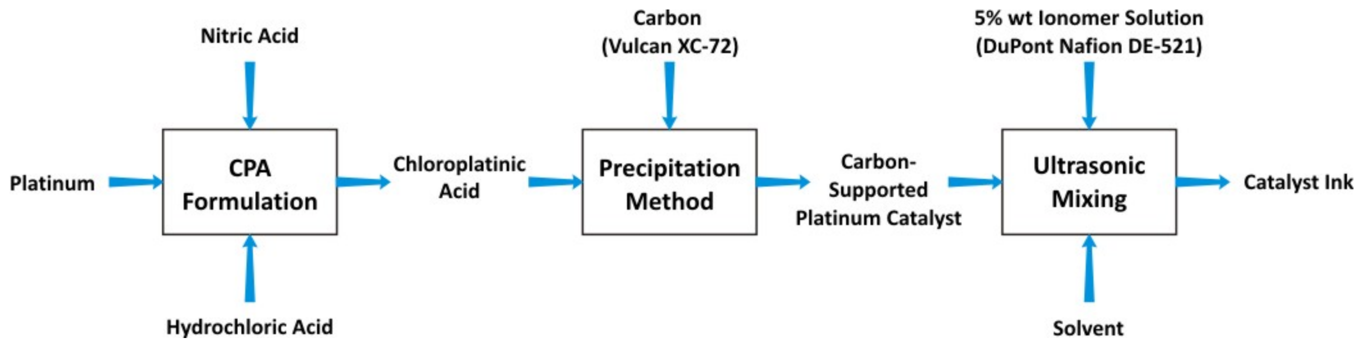

Figure 48. Catalyst ink preparation

Preparing the CPA involves dissolving platinum sponge into a 4:1 mix of hydrochloric and nitric acids, called "aqua regia," via the reaction:

$$Pt + 4\ HNO_3 + 6\ HCl \rightarrow H_2PtCl_6 + 4\ NO_2 + 4\ H_2O$$

The CPA (H_2PtCl_6) is brownish-red, and is isolated by evaporating the solution to a syrup. It is then precipitated onto the carbon powder such that the mass ratio[50] is 60% carbon, 40% Pt.

Cost of the CPA was obtained by combining Pt material cost with CPA preparation cost. CPA preparation cost was obtained by price quote from J&J Materials, an independent toll-manufacturer and chemical synthesis lab in Neptune, NJ. Further costs associated with precipitating the CPA onto the platinum were obtained using our DFMA-style analysis. This carbon-supported platinum catalyst is then combined with a 5% (by weight) ionomer solution and a solvent (a 50/50 blend (by weight) of methanol and de-ionized water).

WET	Vulcan XC-72	Platinum	Nafion	Solvent	Methanol	DI water
	60%	40%	5%	95%	50%	50%
	C-Supported Pt		Nafion soln DE-521		Solvent	
	15%		72%		13%	
DRY	Vulcan XC-72		Platinum		Nafion	
	48.4%		32.3%		19.4%	

Figure 49. Catalyst ink composition

Figure 49 details the composition of the catalyst ink as specified in US Patent 7,141,270 to Umicore. After combining the ingredients, the slurry is mixed with an ultrasonic processor, which homogenizes the ink so it coats smoothly and evenly across the membrane. When the catalyst ink is dry, the solvent was assumed to have dissolved completely, leaving a coating that's 19% Nafion®, 32% Platinum, and 48% Vulcan XC-72.

The raw material cost of platinum is the major cost element of the catalyst ink. At the direction of the DOE, a platinum cost of $1,100 per troy ounce was selected. Using this value ensures consistency with other DOE projects, and provides some insulation for the model from the wild fluctuations of the platinum market. As shown in Figure 50, platinum cost varied greatly in 2008, with the daily trading values reaching an annual (and all-time) peak of $2,280/tr.oz. on March 4, 2008, and a low of $782/tr.oz on October 27.[51]

[50] Maria Inman of Faraday Technology Inc. (*Low-Cost Manufacturing of PEM Fuel Cells: Catalyzation of the MEA*) reports that increasing the Pt/C ratio decreases the Pt surface area, which results in a performance decrease (lower utilization at higher loadings). Other sources listed 20% and 45% Pt/C (by weight, wet). 40% was selected for costing purposes.

[51] Platinum prices found at http://www.platinum.matthey.com/prices/price_charts.html

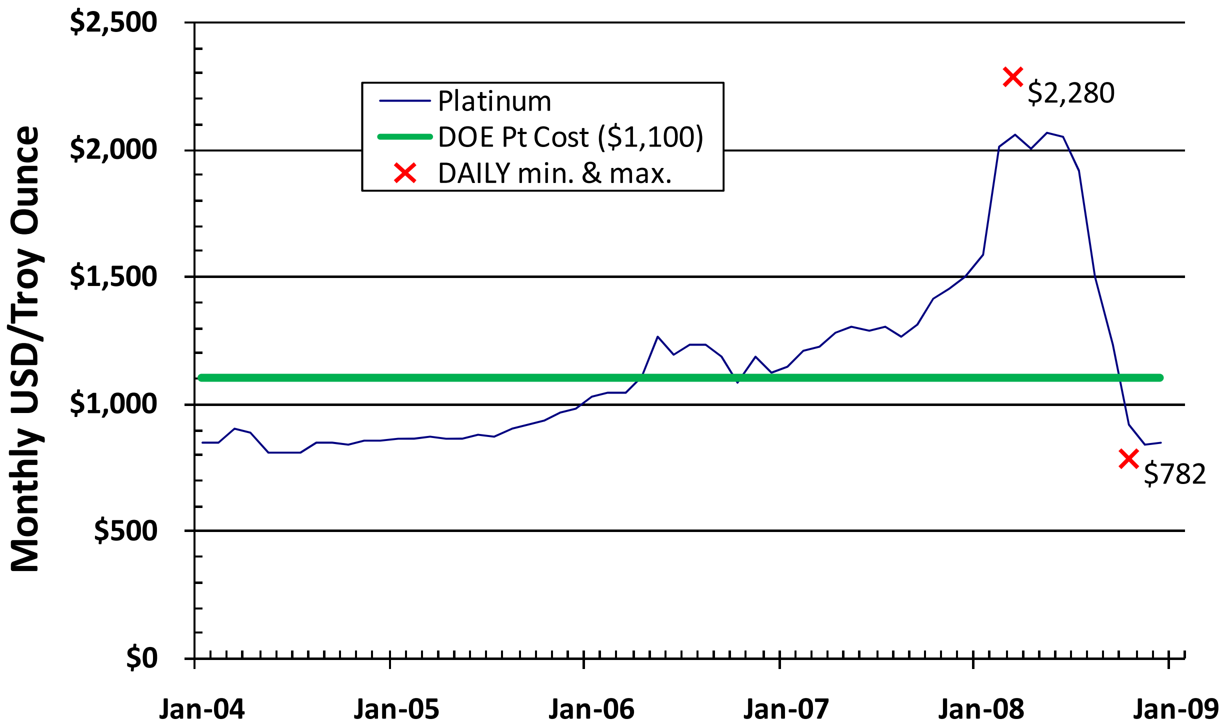

Figure 50. Five-year graph of monthly platinum prices

While this may have been an anomalously turbulent year in the market, the five-year average cost is $1,156/tr.oz., which is very close to the $1,100 value provided by the DOE. Careful consideration should be paid to this, as changes in platinum cost will dramatically affect the system cost[52]. Assumptions and catalyst ink costs are summarized in Figure 51 and Figure 52.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	7%	7%	7%	7%	7%
	Power Consumption (kW)	2	2	2	2	2

Figure 51. Machine rate parameters for ultrasonic mixing process

[52] See section 5 ("Sensitivity Analysis") for the effect that platinum cost and other parameters have on the system cost.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Platinum ($/stack)	$601.71	$601.71	$601.71	$601.71	$601.71
	Other Materials ($/stack)	$22.50	$5.77	$3.33	$2.58	$1.32
	Manufacturing ($/stack)	$83.77	$45.87	$43.52	$43.10	$35.56
	Total Cost ($/stack)	$707.99	$653.36	$648.56	$647.39	$638.59
	Total Cost ($/kW$_{gross}$)	$15.69	$14.48	$14.38	$14.35	$14.16
2010	Platinum ($/stack)	$497.88	$497.88	$497.88	$497.88	$497.88
	Other Materials ($/stack)	$19.98	$5.80	$3.36	$2.60	$1.32
	Manufacturing ($/stack)	$70.28	$37.99	$36.02	$35.67	$29.42
	Total Cost ($/stack)	$588.14	$541.68	$537.27	$536.16	$528.63
	Total Cost ($/kW$_{gross}$)	$13.57	$12.49	$12.39	$12.37	$12.19
2015	Platinum ($/stack)	$333.20	$333.20	$333.20	$333.20	$333.20
	Other Materials ($/stack)	$13.38	$3.90	$2.26	$1.75	$0.89
	Manufacturing ($/stack)	$48.87	$25.48	$24.13	$23.89	$19.70
	Total Cost ($/stack)	$395.45	$362.58	$359.59	$358.84	$353.78
	Total Cost ($/kW$_{gross}$)	$9.09	$8.33	$8.26	$8.24	$8.13

Figure 52. Catalyst ink cost summary

4.4.4. Catalyst Application

Approximately 60% of the fuel cell community applies catalyst ink to the GDL rather than directly to the membrane[53]. However, both are valid approaches and membrane coating was selected for this analysis, which allows simultaneous application of both the anode and the cathode layers, simplifying the overall process and reducing cost.

The anode and cathode each have different catalyst loadings for each technology level (0.07, 0.09, and 0.04 mg/cm^2 for the anode, and 0.18, 0.21, and 0.16 mg/cm^2 for the cathode). The ink formula (see section 4.4.3) is identical for both sides, which simplifies the ink preparation process, but a thicker catalyst layer is applied on the cathode side to achieve a higher platinum loading[54].

A vertical coating process was selected, to apply catalyst to both sides simultaneously. The machine (modeled here as the Coatema VertiCoater, see Figure 53) employs dual die slot coaters[55] on either side of the vertically moving membrane. The unit contains an integrated drying zone, as well as spool management for tension control. The feedstocks are rolls of uncatalyzed membrane, and platinum catalyst ink.

[53] Personal communication with Thomas Kolbusch of Coatema Coating Machinery GmbH, September 2006.
[54] Alternately, separate anode and cathode catalyst ink formulations could be prepared differing in C/Pt ratio so that catalyst layer thickness could be independently controlled. Such an approach would not add substantially to cost.
[55] A variety of slurry application devices are compatible with the Coatema VertiCoater, such as the knife, commabar, engraved roller, and multi-roller systems.

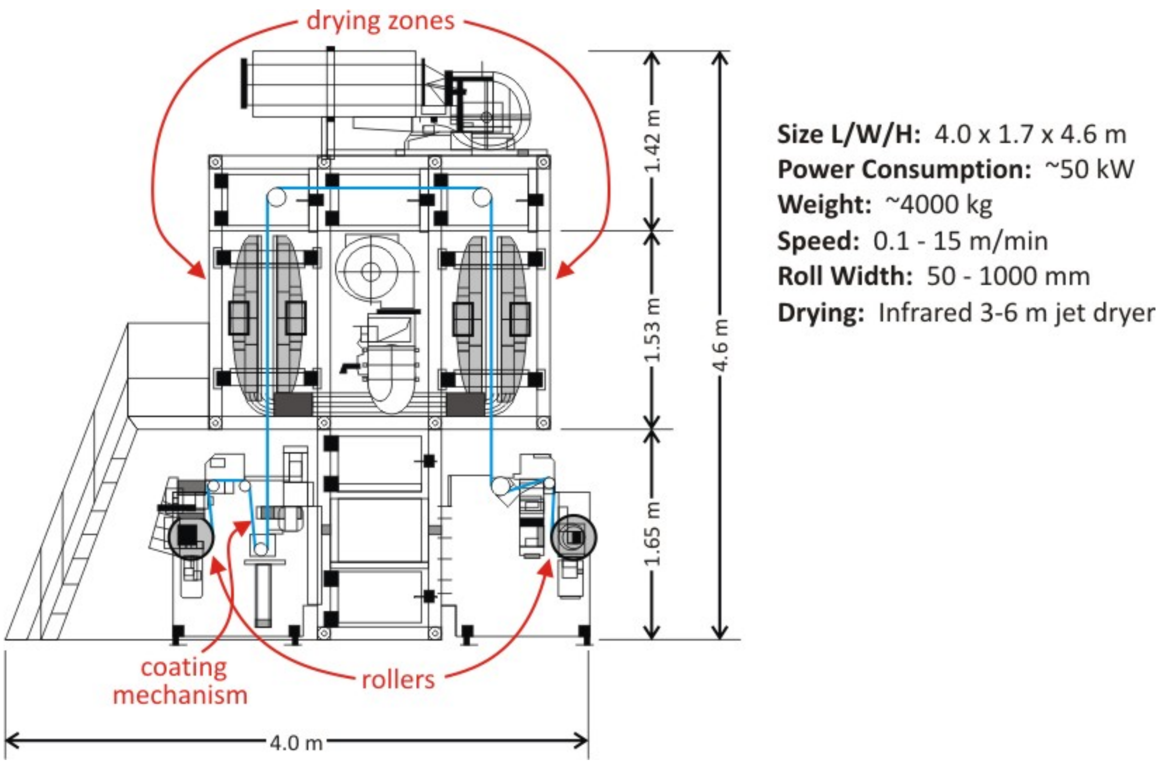

Figure 53. Coatema VertiCoater

The VertiCoater runs at a maximum rate of 15 meters per minute, but after consultation with Bob Sandbank of Eurotec, USA, a distributor of Coatema machinery, the speed was dialed back to 10 meters per minute, because of the delicate nature of the membrane[56]. While the VertiCoater can handle web widths of up to 1 m, the width was limited to 50 cm in this analysis, so as to match the maximum width of other components in the fabrication process[57].

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	7%	7%	7%	7%	7%
	Power Consumption (kW)	50	50	50	50	50

Figure 54. Machine rate parameters for catalyst application process

56 As discussed in the membrane section (section 4.4.2, page 37), both homogeneous and substrate reinforced membrane are commonly used in the fuel cell stacks. However, homogeneous Nafion® membrane is historically known for its low tensile strength and has often been likened to "wet tissue paper." In contrast, substrate reinforced membranes exhibit much higher mechanical strength. Consequently, the stronger, Gore-like membrane was selected, for which the membrane has an expanded polytetrafluoroethylene (ePTFE) substrate, occluded with Nafion® ionomer. This style of membrane has a significantly higher tensile strength, and thus lends itself more easily to roll-to-roll processing where the membrane web must be supported in tension from the edges.

57 The inputs of one process are often the outputs of another, so roll widths for all related processes must be identical, and thus the roll width for all the membrane and electrode processes is limited to 50 cm.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$829,499	$829,499	$829,499	$829,499	$829,499
	Simultaneous Lines	1	1	2	3	9
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	1.71%	50.95%	67.93%	73.59%	94.34%
	Effective Total Machine Rate ($/hr)	$5,990.67	$215.99	$165.79	$154.20	$123.60
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
2010	Capital Cost ($/Line)	$829,499	$829,499	$829,499	$829,499	$829,499
	Simultaneous Lines	1	1	2	2	8
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	1.41%	42.10%	56.13%	91.22%	87.70%
	Effective Total Machine Rate ($/hr)	$7,286.58	$258.19	$197.44	$127.32	$131.81
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
2015	Capital Cost ($/Line)	$829,499	$829,499	$829,499	$829,499	$829,499
	Simultaneous Lines	1	1	2	2	8
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	1.41%	42.19%	56.24%	91.39%	87.87%
	Effective Total Machine Rate ($/hr)	$7,274.83	$257.71	$197.09	$127.10	$131.59
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17

Figure 55. Catalyst application process parameters

Machine rate and process assumptions are displayed in Figure 54 and Figure 55. Capital costs for a single line are estimated at $750,000 for all manufacturing rates, but the majority of the costs for the catalyzed membrane come from the materials. This is largely due to the skyrocketing cost of platinum, and the cost of Nafion®.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Manufacturing ($/stack)	$172.37	$6.16	$4.73	$4.40	$3.53
	Total Cost ($/stack)	$172.37	$6.16	$4.73	$4.40	$3.53
	Total Cost ($/kW$_{gross}$)	$3.82	$0.14	$0.10	$0.10	$0.08
2010	Manufacturing ($/stack)	$172.29	$6.09	$4.65	$3.00	$3.11
	Total Cost ($/stack)	$172.29	$6.09	$4.65	$3.00	$3.11
	Total Cost ($/kW$_{gross}$)	$3.97	$0.14	$0.11	$0.07	$0.07
2015	Manufacturing ($/stack)	$172.29	$6.09	$4.66	$3.00	$3.11
	Total Cost ($/stack)	$172.29	$6.09	$4.66	$3.00	$3.11
	Total Cost ($/kW$_{gross}$)	$3.96	$0.14	$0.11	$0.07	$0.07

Figure 56. Cost breakdown for catalyst application

Ballard, 3M and others have proposed advanced catalyst deposition techniques designed to enhance performance and lower precious metal loadings simultaneously. In 2005, Ballard[58] anticipated the future use (after 2010) of chemical vapor deposition (CVD) nanoparticle dispersions of catalyst to achieve < 0.3 mgPt/cm^2 loadings on non-carbon, corrosion free supports. This type of catalyst application, as opposed to the die slot techniques postulated for the cost analysis, may prove necessary to achieve uniform deposition at very low loadings. However, what is clear from the cost analysis is that roller application is so inexpensive (~$0.10/kW) that future advanced deposition techniques will not be able to offer any cost reduction- indeed, future techniques (if necessary) may actually increase catalyst application costs.

[58] Ballard Power Corp. presentation to the Fifth International Partnership for the Hydrogen Economy (IPHE) Conference http://www.iphe.net/IPHErestrictedarea/5th%20IPHE%20SC%20mtg/Final%20Presentations/Host%20Country%20Presentations/7.6_Ballard.pdf.

4.4.5. Gas Diffusion Layer

Figure 57 displays a cross-sectional diagram of the modeled gas diffusion layer (GDL). Consistent with recent research,[59] the GDL was assumed to be a dual-layer sheet, with macroporous & microporous layers. The 0.28 mm thick macroporous layer was assumed to be a non-woven carbon substrate (based on SGL Carbon's GDL 34BA) to which a hydrophobic 0.04 mm thick microporous layer of PTFE and Vulcan XC-72 is applied. A full DFMA analysis of the GDL was not conducted[60]. Rather, a price quote was obtained for the base macroporous layer and the costs of the microporous layer material and application were added to it.

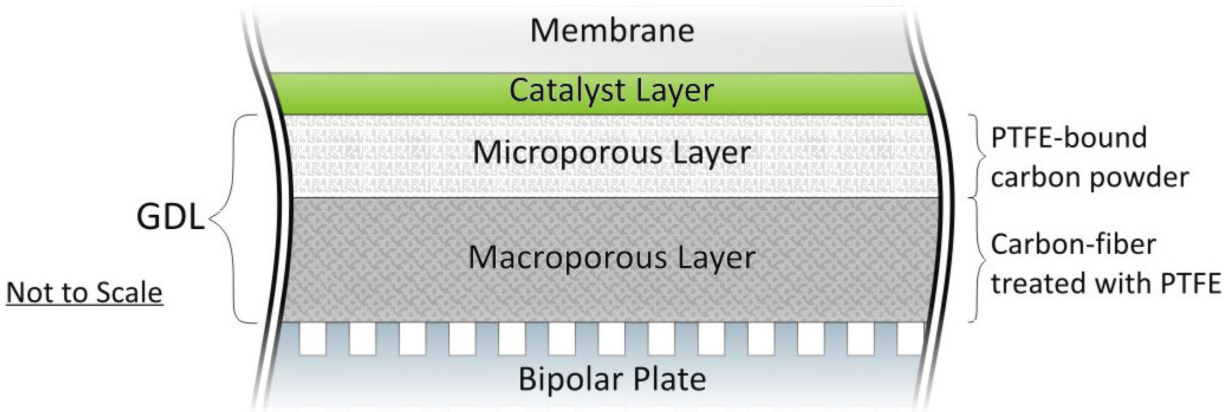

Figure 57. Cross-section of gas diffusion layer in stack

Figure 58 schematically portrays the dual-layer GDL process train. Major steps in the process train include:

- Unrolling of the macroporous layer
- Application of a PTFE coating via dipping in a PTFE/solvent bath
- Drying of the PTFE coating in an IR oven
- Spray deposition of the microporous layer
- Drying of the PTFE coating in an IR oven
- Drying of the microporous coating in an IR oven
- Cure of the microporous coating
- Rewind of the finished dual-layer GDL

[59] *Development and Characterizations of Microporous Layer for PEM Fuel Cells*, Sehkyu Park, Jong-Won Lee, Branko N. Popov (University of South Carolina), Robert E. Mammarella, Kimiaki K. Miyamoto (Greenwood Research Laboratory)

[60] A ground-up analysis of the macroporous GDL layer is planned for a later stage of this project.

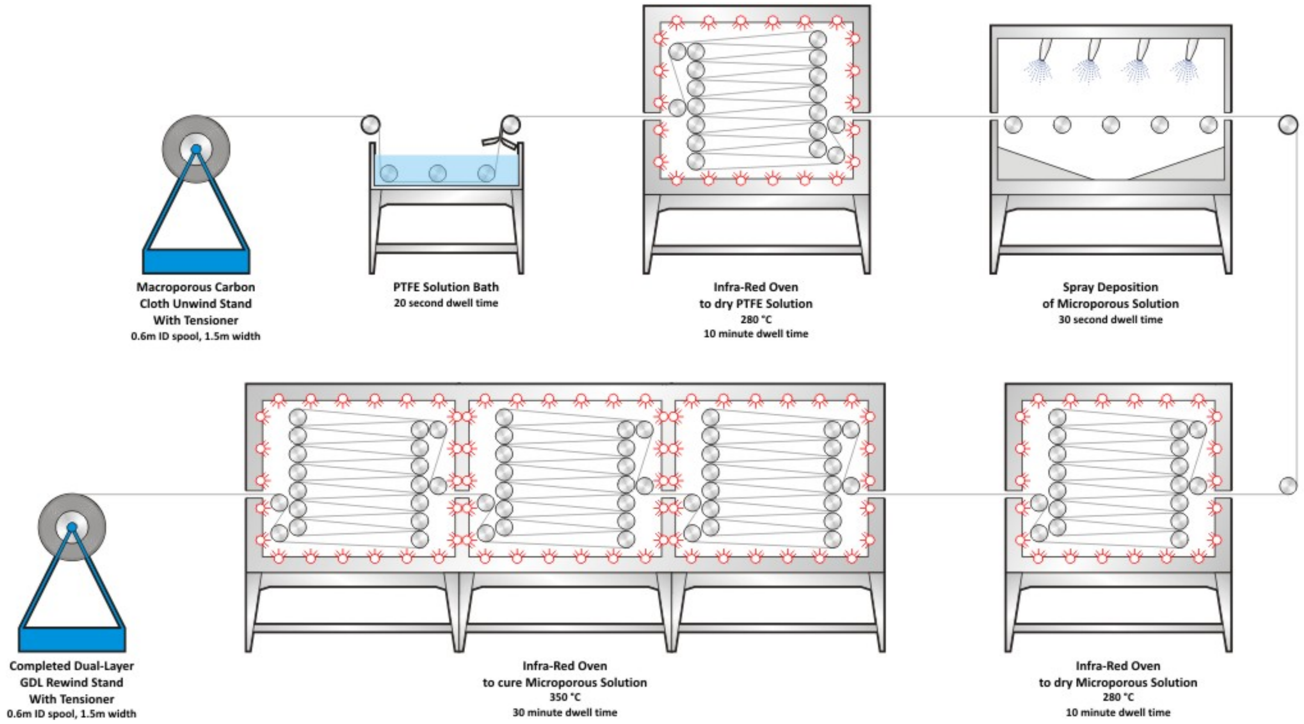

Figure 58. Dual-layer GDL process diagram

Component	Cost
Unwind Stand w/ Tensioner	$27,650
Dipper	$82,950
Oven 1 (Macroporous Layer)	$158,420
VCF1500HV Ultrasonic Mixer	$26,799
Sprayer for Microporous Solution	$331,800
Oven 2 (Microporous Layer Stage 1)	$158,420
Oven 3 (Microporous Layer Stage 2)	$475,259
Rewind Stand w/Tensioner	$27,650
Total Capital Cost	$1,288,947

Figure 59. Capital cost breakdown for a typical microporous layer application line

Figure 60 and Figure 61 report the key process parameters for the GDL manufacturing process, including the cost of the macroporous layer in $\$/m^2$ of material purchased (**not** per active area of membrane). One of the benefits of applying the catalyst to the membrane rather than the GDL's is that the anode and cathode GDL's are identical and thus do not need separate processing. Figure 62 however, shows the purchased cost of the macroporous layer independent of the material or manufacturing costs for the rest of the GDL, as it inherently includes both. Overall, the GDL contributes approximately $3-24/kW to the cost of the fuel cell stack. The range is large because of high material cost and low line utilization at 1,000 systems per year.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$429,649	$1,288,947	$1,288,947	$1,288,947	$1,288,947
	Simultaneous Lines	1	3	6	10	36
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	7.09%	70.76%	94.34%	91.98%	98.27%
	Effective Total Machine Rate ($/hr)	$797.50	$274.02	$217.84	$222.17	$211.10
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
	Macroporous Layer Cost ($/m^2)	$72.78	$49.16	$29.97	$22.92	$9.63
2010	Capital Cost ($/Line)	$1,288,947	$1,288,947	$1,288,947	$1,288,947	$1,288,947
	Simultaneous Lines	1	2	5	8	30
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.85%	87.71%	93.55%	95.01%	97.45%
	Effective Total Machine Rate ($/hr)	$2,767.41	$230.59	$219.26	$216.65	$212.47
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
	Macroporous Layer Cost ($/m^2)	$72.78	$49.16	$29.97	$22.92	$9.63
2015	Capital Cost ($/Line)	$1,288,947	$1,288,947	$1,288,947	$1,288,947	$1,288,947
	Simultaneous Lines	1	2	5	8	30
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.87%	87.93%	93.79%	95.25%	97.69%
	Effective Total Machine Rate ($/hr)	$2,757.77	$230.13	$218.83	$216.22	$212.05
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
	Macroporous Layer Cost ($/m^2)	$72.78	$49.16	$29.97	$22.92	$9.63

Figure 60. GDL manufacturing process parameters (microporous layer addition only)

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	7%	7%	7%	7%	7%
	Power Consumption (kW)	493	491	491	491	491

Figure 61. Machine rate parameters for GDL manufacturing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Purchased Macroporous Layer ($/kW$_{gross}$)	$21.96	$14.83	$9.04	$6.91	$2.91
	Other Materials ($/kW$_{gross}$)	$0.10	$0.10	$0.10	$0.10	$0.10
	Manufacturing ($/kW$_{gross}$)	$2.10	$0.72	$0.57	$0.59	$0.56
	Total Cost ($/kW$_{gross}$)	$24.17	$15.66	$9.72	$7.60	$3.57
2010	Purchased Macroporous Layer ($/kW$_{gross}$)	$15.76	$10.64	$6.49	$4.96	$2.09
	Other Materials ($/kW$_{gross}$)	$0.07	$0.07	$0.07	$0.07	$0.07
	Manufacturing ($/kW$_{gross}$)	$6.27	$0.52	$0.50	$0.49	$0.48
	Total Cost ($/kW$_{gross}$)	$22.10	$11.24	$7.06	$5.53	$2.64
2015	Purchased Macroporous Layer ($/kW$_{gross}$)	$15.76	$10.65	$6.49	$4.96	$2.09
	Other Materials ($/kW$_{gross}$)	$0.07	$0.07	$0.07	$0.07	$0.07
	Manufacturing ($/kW$_{gross}$)	$6.25	$0.52	$0.50	$0.49	$0.48
	Total Cost ($/kW$_{gross}$)	$22.09	$11.24	$7.06	$5.53	$2.64

Figure 62. Cost breakdown for gas diffusion layers

4.4.6. MEA Gaskets and MEA Assembly

The MEA gasket was based on insertion molding a silicone frame around the catalyzed membrane and GDL's. The gasketed MEA is formed in three steps. First is the hot-pressing, which is done in an indexed roll-to-roll process. The second is cutting & slitting of the hot-pressed membrane and electrode into individual rectangular pieces. Then the pieces are manually inserted into a mold, and the frame/gasket is insertion-molded around it. This frame has features to hold the GDL and membrane as well as a "lip" which folds over and captures the sheets for easy handling.

4.4.6.1. Hot-Pressing the Membrane and GDLs

The hot-pressing process (see Figure 63) starts with three rolls; two of GDL and one of catalyzed membrane. Because of the decision to catalyze the membrane instead of the electrode, the two rolls of GDL are identical. Each of the three corresponding unwind stands is equipped with a brake and a tensioner. These three rolls merge at a set of rollers, and then travel through the hot press. On the other side of the press, a single rewind stand collects the hot-pressed membrane and electrode.

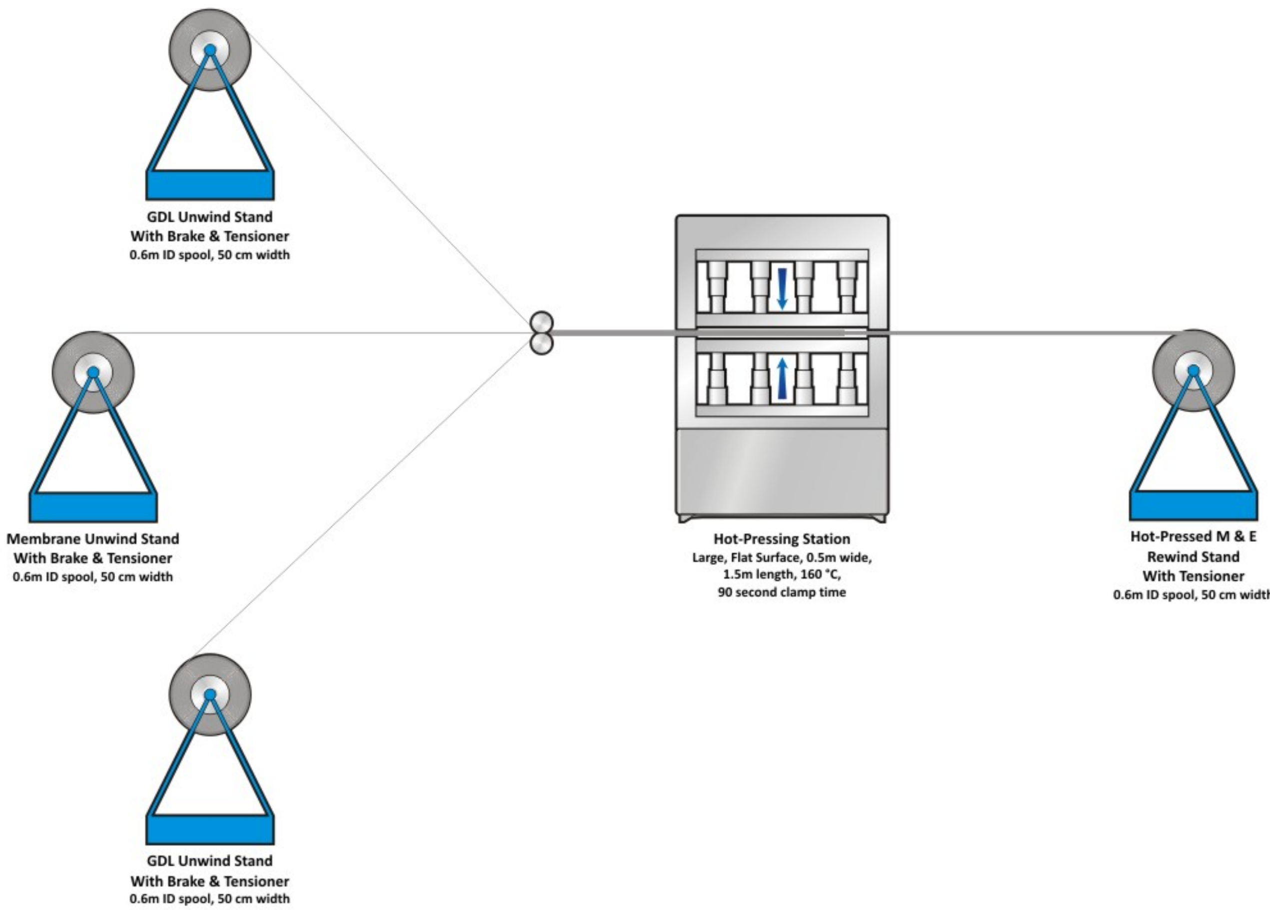

Figure 63. Hot-pressing process diagram

The press is heated to 160°C, and is indexed with a press time of 90 seconds. It takes 3 seconds to open the press, advance the roll to the next section, and re-close the press, making the cycle time 93 seconds. The section advance time could be quicker, but because of the limited tensile strength of the materials, 3 seconds is appropriate. Furthermore, 3 seconds is only 1/30th of the press time, and for an already-inexpensive process, the savings in speeding up the section advance would be minimal. The press is 50 cm wide by 150 cm in length, so approximately 18 to 22 cells get hot-pressed at a time, depending on the cell geometry. Processing parameters are further defined in Figure 64.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$191,282	$191,282	$191,282	$191,282	$191,282
	Costs per Tooling Set ($)	$11,060	$11,060	$11,060	$11,060	$11,060
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	5	13	22	81
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	16.18%	96.98%	99.46%	95.51%	99.77%
	Effective Total Machine Rate ($/hr)	$140.79	$33.90	$33.37	$34.23	$33.31
	Index Time (s)	93.00	93.00	93.00	93.00	93.00
2010	Capital Cost ($/Line)	$191,282	$191,282	$191,282	$191,282	$191,282
	Costs per Tooling Set ($)	$11,060	$11,060	$11,060	$11,060	$11,060
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	4	11	18	67
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	13.23%	99.17%	96.17%	95.50%	98.68%
	Effective Total Machine Rate ($/hr)	$169.41	$33.43	$34.08	$34.24	$33.54
	Index Time (s)	93.00	93.00	93.00	93.00	93.00
2015	Capital Cost ($/Line)	$191,282	$191,282	$191,282	$191,282	$191,282
	Costs per Tooling Set ($)	$11,060	$11,060	$11,060	$11,060	$11,060
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	4	11	18	67
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	13.23%	99.19%	96.18%	95.51%	98.69%
	Effective Total Machine Rate ($/hr)	$169.39	$33.43	$34.08	$34.23	$33.53
	Index Time (s)	93.00	93.00	93.00	93.00	93.00

Figure 64. Hot-pressing process parameters

Hot pressing cost is summarized in Figure 66. Because of the simplicity of the process, the cost is quite low, especially at high manufacturing rates. Since the press is flat, tool wear is minimal. Material costs are zero since the cost of membrane and GDL were accounted for elsewhere.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	5%	5%	5%	5%	5%
	Miscellaneous Expenses (% of CC)	7%	7%	7%	7%	7%
	Power Consumption (kW)	16	16	16	16	16

Figure 65. Machine rate parameters for hot-pressing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Manufacturing ($/stack)	$38.26	$9.21	$9.06	$9.30	$9.04
	Tooling ($/stack)	$0.37	$0.12	$0.12	$0.12	$0.12
	Total Cost ($/stack)	$38.63	$9.33	$9.18	$9.42	$9.16
	Total Cost ($/kW$_{gross}$)	$0.86	$0.21	$0.20	$0.21	$0.20
2010	Manufacturing ($/stack)	$37.64	$7.43	$7.57	$7.61	$7.45
	Tooling ($/stack)	$0.37	$0.10	$0.10	$0.10	$0.10
	Total Cost ($/stack)	$38.01	$7.52	$7.67	$7.71	$7.55
	Total Cost ($/kW$_{gross}$)	$0.88	$0.17	$0.18	$0.18	$0.17
2015	Manufacturing ($/stack)	$37.64	$7.43	$7.57	$7.61	$7.45
	Tooling ($/stack)	$0.37	$0.10	$0.10	$0.10	$0.10
	Total Cost ($/stack)	$38.01	$7.53	$7.67	$7.71	$7.55
	Total Cost ($/kW$_{gross}$)	$0.87	$0.17	$0.18	$0.18	$0.17

Figure 66. Cost breakdown for hot-pressing process

4.4.6.2. Cutting & Slitting

As shown in Figure 67, the rolls of hot-pressed membrane and GDL are next fed through cutters and slitters to achieve the desired dimensions for insertion into the MEA frame. The 50 cm wide input roll is slit into ribbon streams of the appropriate width (again, depending on cell geometry). The streams continue through to the cutters, which turn the continuous material into individual rectangles. These rectangles are then sorted into magazine racks.

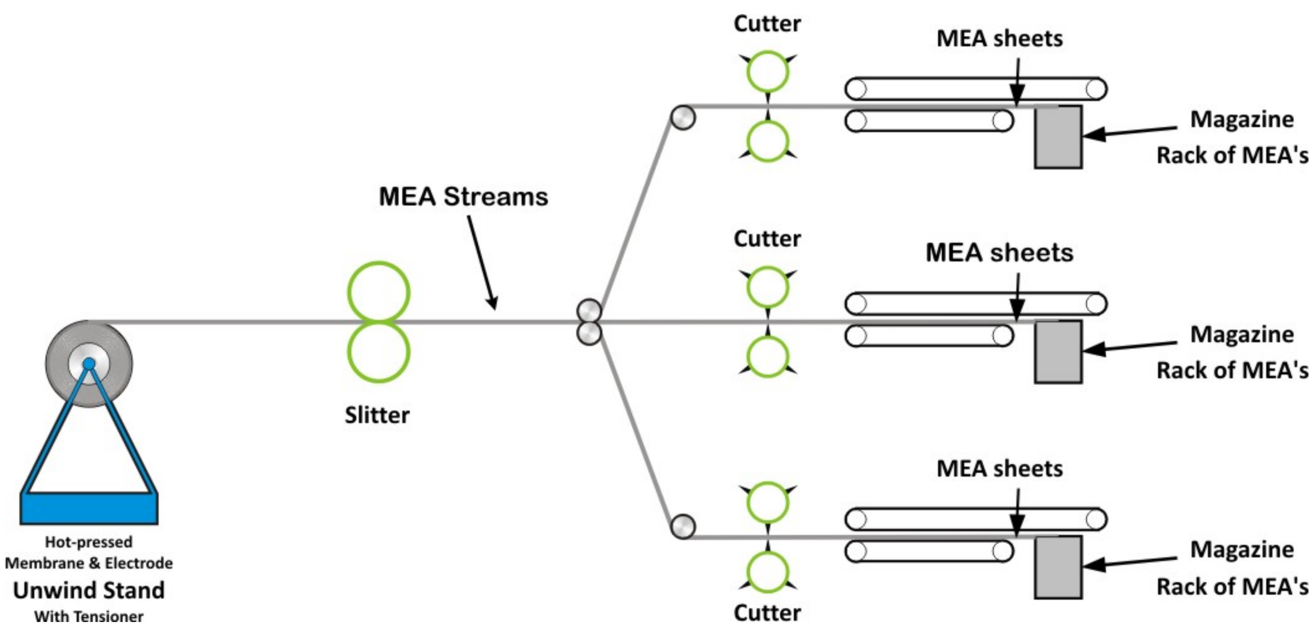

Figure 67. Cutting & slitting process diagram

Figure 69 further details the process parameters. Machine utilization at 1,000 systems per year is extremely poor (as low as 0.43%). However, costs associated with manual cutting are comparable to the automated system running at poor utilization. Consequently, for simplicity that process is present as being automated at all production rates. Figure 71 summarizes the overall cost of the cutting and slitting operation.

Component	Cost
Unwind Stand w/ Tensioner	$27,650
Cutter/Slitter	$94,010
Stacker	$11,060
Total Capital Cost	$132,720

Figure 68. Capital cost breakdown for the cutting and slitting process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$132,720	$132,720	$132,720	$132,720	$132,720
	Costs per Tooling Set ($)	$5,530	$5,530	$5,530	$5,530	$5,530
	Tooling Lifetime (cycles)	200,000	200,000	200,000	200,000	200,000
	Simultaneous Lines	1	1	1	1	3
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.53%	13.80%	36.80%	59.80%	76.65%
	Effective Total Machine Rate ($/hr)	$3,082.10	$131.22	$57.09	$39.97	$33.95
	Line Speed (m/s)	1.00	1.33	1.33	1.33	1.33
2010	Capital Cost ($/Line)	$132,720	$132,720	$132,720	$132,720	$132,720
	Costs per Tooling Set ($)	$5,530	$5,530	$5,530	$5,530	$5,530
	Tooling Lifetime (cycles)	200,000	200,000	200,000	200,000	200,000
	Simultaneous Lines	1	1	1	1	2
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.43%	11.41%	30.41%	49.42%	95.02%
	Effective Total Machine Rate ($/hr)	$3,794.39	$156.12	$66.43	$45.72	$29.82
	Line Speed (m/s)	1.00	1.33	1.33	1.33	1.33
2015	Capital Cost ($/Line)	$132,720	$132,720	$132,720	$132,720	$132,720
	Costs per Tooling Set ($)	$5,530	$5,530	$5,530	$5,530	$5,530
	Tooling Lifetime (cycles)	200,000	200,000	200,000	200,000	200,000
	Simultaneous Lines	1	1	1	1	2
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.43%	11.43%	30.47%	49.52%	95.20%
	Effective Total Machine Rate ($/hr)	$3,791.08	$155.82	$66.34	$45.66	$29.79
	Line Speed (m/s)	1.00	1.33	1.33	1.33	1.33

Figure 69. Cutting & slitting process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	7%	7%	7%	7%	7%
	Power Consumption (kW)	17	17	17	17	17

Figure 70. Machine rate parameters for cutting & slitting process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Manufacturing ($/stack)	$27.62	$1.01	$0.44	$0.31	$0.26
	Tooling ($/stack)	$2.58	$2.57	$2.57	$2.57	$2.57
	Total Cost ($/stack)	$30.20	$3.59	$3.01	$2.88	$2.83
	Total Cost ($/kW$_{gross}$)	$0.67	$0.08	$0.07	$0.06	$0.06
2010	Manufacturing ($/stack)	$27.60	$1.00	$0.42	$0.29	$0.19
	Tooling ($/stack)	$2.58	$2.57	$2.57	$2.57	$2.57
	Total Cost ($/stack)	$30.18	$3.57	$3.00	$2.86	$2.76
	Total Cost ($/kW$_{gross}$)	$0.70	$0.08	$0.07	$0.07	$0.06
2015	Manufacturing ($/stack)	$27.60	$1.00	$0.42	$0.29	$0.19
	Tooling ($/stack)	$2.58	$2.57	$2.57	$2.57	$2.57
	Total Cost ($/stack)	$30.18	$3.57	$3.00	$2.86	$2.76
	Total Cost ($/kW$_{gross}$)	$0.69	$0.08	$0.07	$0.07	$0.06

Figure 71. Cost breakdown for cutting & slitting process

4.4.6.3. Insertion-Molding the Frame/Gasket

The final step in creating the membrane electrode assembly (MEA) is insertion molding the frame/gasket. Its purpose is twofold:

- Provide sealing and proper manifolding around the periphery of the MEA
- Provide a rigid structure to the MEA for ease of handling during assembly

Based on a 2003 patent from Ballard Power Systems (see Figure 72), the rectangular hot-pressed membrane/GDL is inserted into an injection-molding machine, and the gasket is molded into place around it.

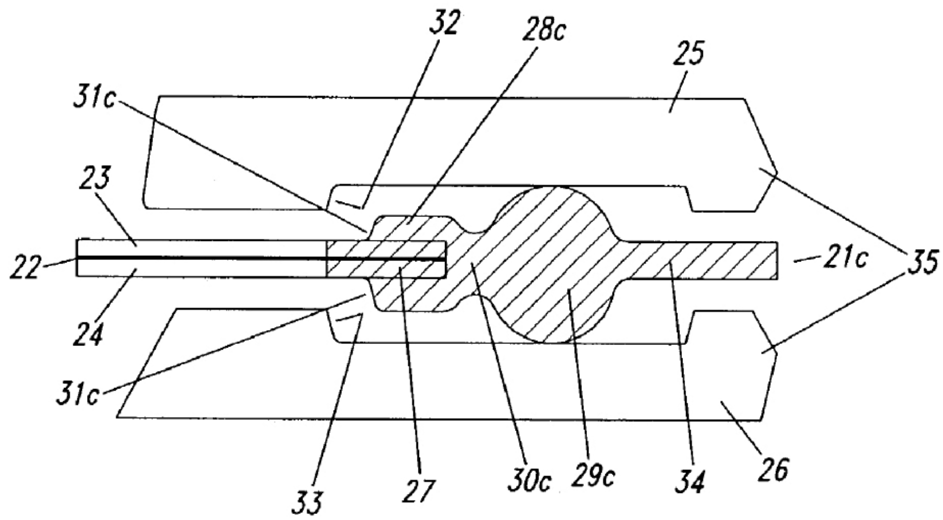

Figure 72. Insertion-molded frame/gasket concept, US patent 7,070,876

This process is similar to the insertion molding of the coolant & end gaskets (pages 65 & 72, respectively), but has different manifolds, and is molded around the hot-pressed membrane & electrode, rather than onto the face of a bipolar plate or an end plate. Because the membrane is sensitive to temperature, this limits the molding temperature to 130°C, or 150°C if the process is fast enough. This requirement greatly limits the material choices for the gasket.

Prior to the 2008 Update, the material specified was a generic silicone. After reviewing DTI work, Jason Parsons from UTC highlighted some durability problems with using silicone, as well as the fact that the silicone cost used in the analysis was too low.

Several new materials were investigated as alternatives, including several types of DuPont's Viton® material, and a new liquid injection-moldable (LIM) hydrocarbon material from Henkel Loctite (see Figure 73). Although it costs more than the old (erroneous) silicone cost, this new material is cheaper than the updated silicone cost, and exhibits dramatically better durability performance. Although DuPont's Viton® GF-S has a lower material cost (in $/kg) than the LIM hydrocarbon, the Viton® requires a higher injection-molding pressure, and takes three times longer to mold. Furthermore, the density of the Viton® is almost double that of the other materials, so a greater material mass is needed to fill the required gasket volume, meaning the gaskets weigh more, and the per-volume costs are actually the highest. These factors all made the selection of the LIM hydrocarbon an easy choice.

		Generic Silicone (2007 Analysis)	Henkel Loctite Silicone 5714	DuPont Viton® GBL-600S	DuPont Viton® GF-S	Henkel Loctite LIM Hydrocarbon
Density	g/cc	1.4	1.05	1.84	1.92	1.05
Cost	$/kg	$14.33	$56.70	$36.87	$36.87	$43.37
Cost	$/L	$20.06	$59.54	$67.84	$70.79	$45.54
Cure Time	s	150	540	420	180	60
Cure Temp	°C	127	130	177	187	130
Durability	hrs	~5,000	~5,000	~15,000	~15,000	~10,000
Inj. Mold Pressure		low	low	mid-to-high	mid-to-high	low

Figure 73. MEA frame/gasket materials comparison[61]

In the injection-molding process, each part is required to have a shot mass greater than the part mass, to account for material lost in the sprue and cooling channels. In the 2008 design for example, the part mass is 14.5 grams, and the shot mass is 20.4.

As shown in Figure 74, the optimal number of cavities per platen ranges from 6 to 16, as determined by lowest overall cost. The necessary clamping force ranges from 640 to 1300 tons, and the injection pressure is a constant 1,379 bar (20,000 psi) for each case.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$332,075	$620,057	$702,337	$661,197	$661,197
	Costs per Tooling Set ($)	$70,334	$120,843	$133,575	$127,277	$127,277
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	11	26	45	171
	Laborers per Line	1.00	0.33	0.33	0.33	0.33
	Line Utilization	69.32%	98.73%	99.74%	98.72%	99.92%
	Cycle Time (s)	135	153	158	156	156
	Cavities/Platen	6	13	15	14	14
	Effective Total Machine Rate ($/hr)	$116.40	$109.17	$120.18	$115.19	$114.08
	Material Cost ($/kg)	$51.29	$46.79	$45.57	$44.98	$43.37
2010	Capital Cost ($/Line)	$283,224	$455,115	$478,976	$478,976	$478,976
	Costs per Tooling Set ($)	$86,025	$133,575	$139,748	$139,748	$139,748
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	10	25	41	155
	Laborers per Line	1.00	0.33	0.33	0.33	0.33
	Line Utilization	53.94%	97.24%	98.81%	97.90%	99.60%
	Cycle Time (s)	140	158	161	161	161
	Cavities/Platen	8	15	16	16	16
	Effective Total Machine Rate ($/hr)	$122.30	$85.89	$88.39	$89.01	$87.86
	Material Cost ($/kg)	$51.90	$47.34	$46.11	$45.51	$43.88
2015	Capital Cost ($/Line)	$284,288	$457,097	$481,088	$481,088	$481,088
	Costs per Tooling Set ($)	$86,025	$133,575	$139,748	$139,748	$139,748
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	10	25	41	155
	Laborers per Line	1.00	0.33	0.33	0.33	0.33
	Line Utilization	53.94%	97.24%	98.81%	97.90%	99.60%
	Cycle Time (s)	140	158	161	161	161
	Cavities/Platen	8	15	16	16	16
	Effective Total Machine Rate ($/hr)	$122.58	$86.19	$88.71	$89.33	$88.17
	Material Cost ($/kg)	$51.89	$47.34	$46.10	$45.50	$43.88

Figure 74. MEA frame/gasket insertion-molding process parameters

[61] The prices listed are for 2008 technology, 500,000 systems/year.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	12%	12%	12%	12%	12%
	Power Consumption (kW)	67	95	101	98	98

Figure 75. Machine rate parameters for MEA frame/gasket insertion-molding process

The cost summary for the MEA frame/gasket molding process is shown in Figure 76.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$194.77	$177.68	$173.03	$170.78	$164.68
	Manufacturing ($/stack)	$135.56	$66.39	$65.45	$66.13	$65.49
	Tooling ($/stack)	$2.34	$2.95	$2.89	$2.94	$2.90
	Total Cost ($/stack)	$137.90	$247.03	$241.37	$239.85	$233.07
	Total Cost ($/kW$_{gross}$)	$3.06	$5.48	$5.35	$5.32	$5.17
2010	Materials ($/stack)	$127.56	$116.37	$113.33	$111.85	$107.86
	Manufacturing ($/stack)	$110.83	$46.77	$45.85	$46.17	$45.57
	Tooling ($/stack)	$2.87	$2.97	$2.91	$2.94	$2.89
	Total Cost ($/stack)	$241.26	$166.11	$162.09	$160.96	$156.32
	Total Cost ($/kW$_{gross}$)	$5.56	$3.83	$3.74	$3.71	$3.61
2015	Materials ($/stack)	$128.15	$116.90	$113.85	$112.37	$108.35
	Manufacturing ($/stack)	$111.09	$46.94	$46.01	$46.34	$45.73
	Tooling ($/stack)	$2.87	$2.97	$2.91	$2.94	$2.89
	Total Cost ($/stack)	$242.10	$166.81	$162.78	$161.64	$156.98
	Total Cost ($/kW$_{gross}$)	$5.56	$3.83	$3.74	$3.71	$3.61

Figure 76. Cost breakdown for MEA frame/gasket insertion molding

4.4.7. End Plates

In a typical PEM fuel cell stack, the purposes of an end plate are threefold:

- Evenly distribute compressive loads across the stack
- Cap off and protect the stack
- Interface with the current collector

Normally there is also a separate insulator plate at each end to electrically insulate the stack from the rest of the vehicle. However our end plate design, based on a UTC patent (see Figure 77), eliminates the need for separate insulators. Thus, our end plates also serve a fourth function: electrically insulate the ends of the stack.

Made from a compression-molded composite (LYTEX 9063), the end plate is strong enough (455 MPa) to withstand the required compressive loading, while also being sufficiently electrically non-conductive ($3x10^{14}$ ohm-cm volume resistivity). Using this material allows for an end plate with lower cost and lower thermal capacity than the typical metal end plates, with the additional benefit of having no susceptibility to corrosion. The benefits of lower cost and corrosion resistance are obvious, and the low thermal capacity limits the thermal energy absorbed during a cold start, effectively accelerating the start-up period.

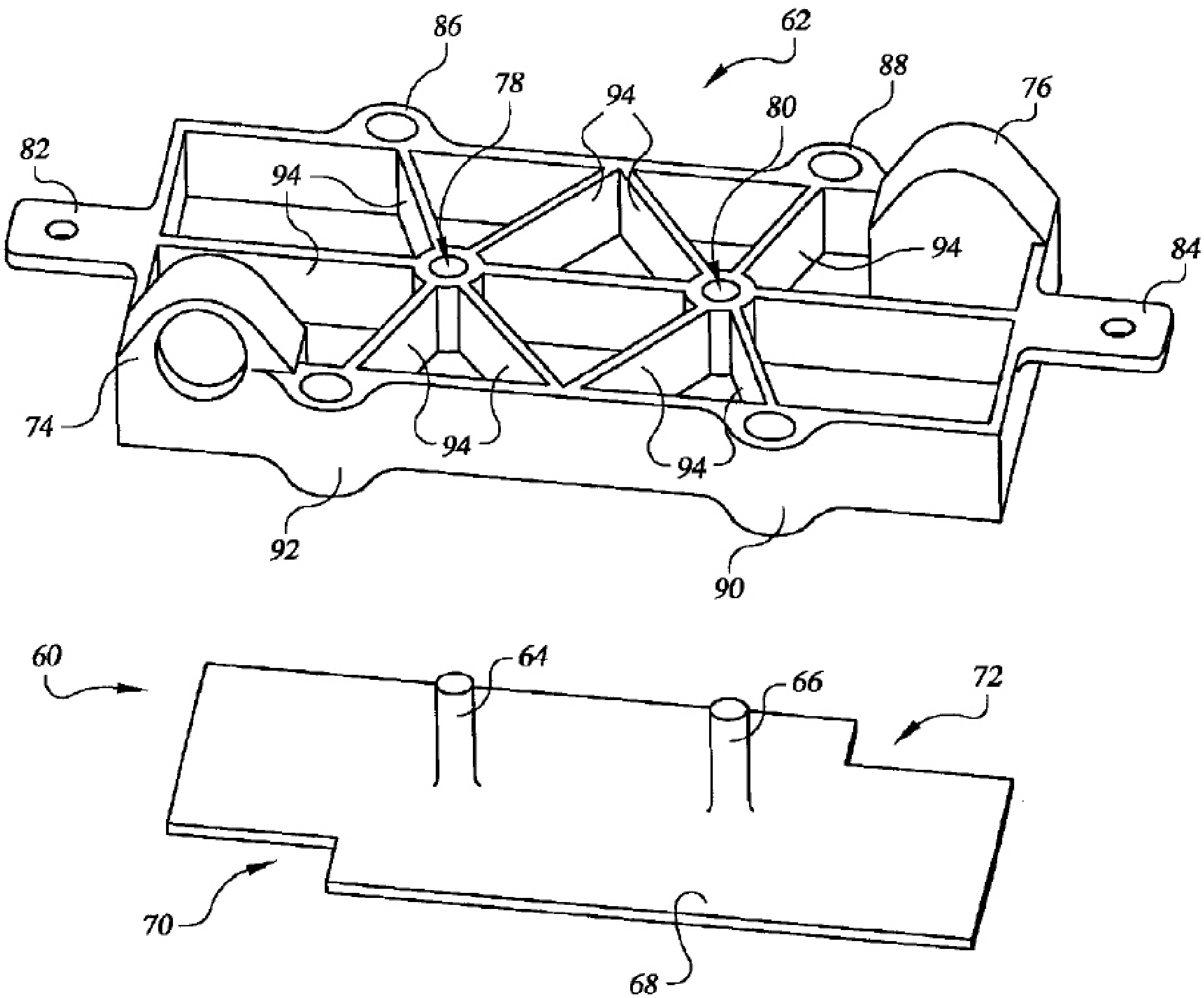

Figure 77. End plate concept, US patent 6,764,786

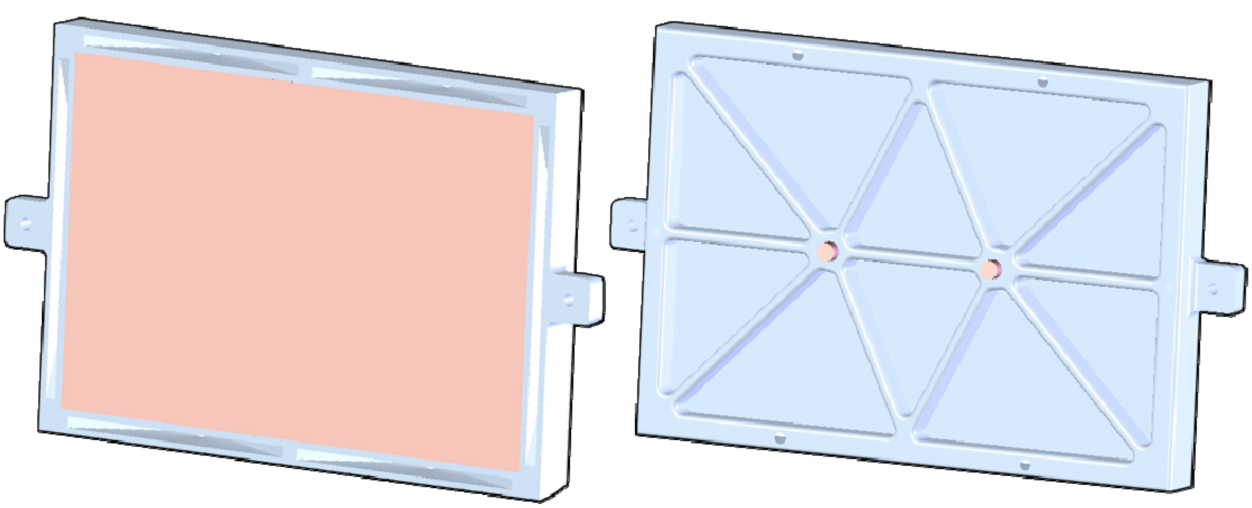

Figure 78. End plate & current collector

LYTEX 9063 is a high performance engineered structural composite (ESC) molding compound consisting of epoxy and glass fiber reinforcement. It is designed for military and aerospace structural applications requiring excellent mechanical properties, retention of properties at elevated temperatures, good chemical resistance and excellent electrical properties. For all of these reasons, it is ideally suited for this application.

The end plates are manufactured via compression molding. A summary of the procedure is as follows[62]:

1. Remove enough LYTEX from cold storage for one day's usage. Allow it to warm to room temperature.
2. Clean mold thoroughly. Apply a uniform thin coating of a mold release. (Note: Once the mold is conditioned for LYTEX, only periodic reapplications are required.)
3. Adjust mold temperature to 300°F (148°C).
4. Adjust molding pressure on the material to 1500 psi (105 kg/cm).
5. Remove protective film completely from both sides of the LYTEX.
6. Cut mold charge so the LYTEX covers approximately 80% of the mold area and is about 105% of the calculated part weight.
7. Dielectrically preheat the LYTEX quickly to 175°F (80°C).
8. Load material into mold and close the mold.
9. Cure for 3 minutes
10. Remove part from mold. Because of low shrinkage and high strength, the part may fit snugly in the mold.
11. Clean up mold and begin again.
12. Re-wrap unused LYTEX and return to cold storage.

[62] Based on Quantum Composites recommended procedures for LYTEX molding.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$120,190	$304,813	$331,188	$331,188	$383,937
	Costs per Tooling Set ($)	$27,626	$79,172	$85,232	$85,232	$96,834
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	1	1	2	5
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.13%	38.11%	92.80%	75.40%	99.47%
	Cycle Time (s)	310	346	351	351	361
	Cavities/Platen	2	9	10	10	12
	Effective Total Machine Rate ($/hr)	$337.35	$126.06	$65.03	$76.42	$69.45
	LYTEX Cost ($/kg)	$19.36	$17.07	$15.85	$14.63	$10.97
2010	Capital Cost ($/Line)	$103,686	$176,179	$176,179	$212,425	$212,425
	Costs per Tooling Set ($)	$27,626	$59,608	$59,608	$72,906	$72,906
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	1	2	2	8
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.13%	54.64%	72.86%	91.52%	88.00%
	Cycle Time (s)	310	330	330	341	341
	Cavities/Platen	2	6	6	8	8
	Effective Total Machine Rate ($/hr)	$292.61	$58.66	$47.52	$46.62	$47.90
	LYTEX Cost ($/kg)	$19.36	$17.07	$15.85	$14.63	$10.97
2015	Capital Cost ($/Line)	$103,830	$176,609	$176,609	$212,999	$212,999
	Costs per Tooling Set ($)	$27,626	$59,608	$59,608	$72,906	$72,906
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	1	2	2	8
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.13%	54.64%	72.86%	91.52%	88.00%
	Cycle Time (s)	310	330	330	341	341
	Cavities/Platen	2	6	6	8	8
	Effective Total Machine Rate ($/hr)	$293.00	$58.78	$47.60	$46.71	$48.00
	LYTEX Cost ($/kg)	$19.36	$17.07	$15.85	$14.63	$10.97

Figure 79. End plate compression molding process parameters

As seen in Figure 81, the material represents the majority of the end plate costs, ranging from 51% to 96%, depending on the production rate.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	4.0	4.0	5.0	7.0	14.0
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	12%	12%	12%	12%	12%
	Power Consumption (kW)	27	54	57	57	63

Figure 80. Machine rate parameters for compression molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$39.92	$35.19	$32.68	$30.16	$22.62
	Manufacturing ($/stack)	$29.06	$2.69	$1.27	$1.49	$1.16
	Tooling ($/stack)	$0.92	$0.09	$0.07	$0.09	$0.06
	Total Cost ($/stack)	$69.90	$37.97	$34.02	$31.74	$23.85
	Total Cost ($/$kW_{gross}$)	$1.55	$0.84	$0.75	$0.70	$0.53
2010	Materials ($/stack)	$26.96	$23.77	$22.07	$20.37	$15.28
	Manufacturing ($/stack)	$25.21	$1.80	$1.45	$1.10	$1.13
	Tooling ($/stack)	$0.92	$0.07	$0.10	$0.07	$0.08
	Total Cost ($/stack)	$53.09	$25.63	$23.62	$21.55	$16.49
	Total Cost ($/$kW_{gross}$)	$1.22	$0.59	$0.54	$0.50	$0.38
2015	Materials ($/stack)	$27.07	$23.87	$22.16	$20.46	$15.34
	Manufacturing ($/stack)	$25.24	$1.80	$1.46	$1.10	$1.14
	Tooling ($/stack)	$0.92	$0.07	$0.10	$0.07	$0.08
	Total Cost ($/stack)	$53.24	$25.73	$23.72	$21.64	$16.56
	Total Cost ($/$kW_{gross}$)	$1.22	$0.59	$0.54	$0.50	$0.38

Figure 81. Cost breakdown for end plates

4.4.8. Current Collectors

The job of the current collectors is to channel the current that is distributed across the active area of the stack down to the positive and negative terminals. In our design, based on the UTC patent (Figure 77) and shown in Figure 78, two copper current studs protrude through the end plates to connect to a copper sheet in contact with the last bipolar plate.

The current collectors were designed to fit snugly within the end plate. A shallow (0.3 mm) cavity in the end plate provides room for the 1 mm thick copper sheet, sized to the active area of the cells. The remaining 0.7 mm of the sheet thickness protrudes from the end plate, and the end plate gasket seals around the edges.

The face of the current collector is pressed against the coolant side of the last bipolar plate in the stack. With the compression of the stack, it makes solid electrical contact with the bipolar plate, and thus can collect the current generated by the stack.

The other side of the current collector is flush against the inner face of the end plate. Two copper studs protrude through their corresponding holes in the end plate, where they are brazed to the current collector sheet. On the outside of the end plate, these studs serve as electrical terminals to which power cables may be attached.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Manufacturing Process	Manual	Auto	Auto	Auto	Auto
	Costs per Tooling Set ($)	$1,911	$1,911	$1,911	$1,911	$1,911
	Tooling Lifetime (cycles)	400,000	400,000	400,000	400,000	400,000
	Capital Cost ($/Line)	$24,777	$69,743	$69,743	$69,743	$69,743
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.00	0.00	0.00	0.00	0.00
	Line Utilization	0.11%	0.88%	2.34%	3.79%	14.58%
	Effective Total Machine Rate ($/hr)	$2,596	$942	$363	$228	$69
	Index Time (s)	0.00	0.00	0.00	0.00	0.00
	Copper Cost ($/kg)	$11.06	$11.06	$11.06	$11.06	$11.06
2010	Manufacturing Process	Manual	Auto	Auto	Auto	Auto
	Costs per Tooling Set ($)	$1,729	$1,729	$1,729	$1,729	$1,729
	Tooling Lifetime (cycles)	400,000	400,000	400,000	400,000	400,000
	Capital Cost ($/Line)	$21,611	$65,802	$65,802	$65,802	$65,802
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.00	0.00	0.00	0.00	0.00
	Line Utilization	0.11%	0.79%	2.09%	3.41%	13.09%
	Effective Total Machine Rate ($/hr)	$2,271	$991	$381	$239	$71
	Index Time (s)	0.00	0.00	0.00	0.00	0.00
	Copper Cost ($/kg)	$11.06	$11.06	$11.06	$11.06	$11.06
2015	Manufacturing Process	Manual	Auto	Auto	Auto	Auto
	Costs per Tooling Set ($)	$1,731	$1,731	$1,731	$1,731	$1,731
	Tooling Lifetime (cycles)	400,000	400,000	400,000	400,000	400,000
	Capital Cost ($/Line)	$21,641	$65,837	$65,837	$65,837	$65,837
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.00	0.00	0.00	0.00	0.00
	Line Utilization	0.11%	0.79%	2.10%	3.41%	13.10%
	Effective Total Machine Rate ($/hr)	$2,274	$992	$381	$239	$71
	Index Time (s)	0.00	0.00	0.00	0.00	0.00
	Copper Cost ($/kg)	$11.06	$11.06	$11.06	$11.06	$11.06

Figure 82. Current collector manufacturing process parameters

Manufacturing the current collectors is a fairly simple process. A roll of 1 mm thick copper sheeting is stamped to size, and 8 mm diameter copper rod is cut to 2.43 cm lengths. The ends of the rods are then brazed to one face of the sheet. At low production (1,000 systems per year), a manual cutting process is used. All other manufacturing rates use an automated process that cuts parts from a roll of copper sheet stock.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	25	25	30	39	66
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	13%	13%	13%	13%	13%
	Miscellaneous Expenses (% of CC)	2%	2%	2%	2%	2%
	Power Consumption (kW)	16	16	16	16	16

Figure 83. Machine rate parameters for current collector manufacturing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$8.32	$6.84	$6.08	$5.70	$5.32
	Manufacturing ($/stack)	$4.98	$0.46	$0.18	$0.11	$0.03
	Tooling ($/stack)	$0.06	$0.01	$0.01	$0.01	$0.01
	Total Cost ($/stack)	$13.89	$7.84	$6.79	$6.35	$5.89
	Total Cost ($/kW$_{gross}$)	$0.31	$0.17	$0.15	$0.14	$0.13
2010	Materials ($/stack)	$5.90	$4.85	$4.31	$4.04	$3.77
	Manufacturing ($/stack)	$4.35	$0.44	$0.17	$0.11	$0.03
	Tooling ($/stack)	$0.06	$0.01	$0.01	$0.01	$0.01
	Total Cost ($/stack)	$10.84	$5.82	$5.01	$4.68	$4.34
	Total Cost ($/kW$_{gross}$)	$0.25	$0.13	$0.12	$0.11	$0.10
2015	Materials ($/stack)	$5.92	$4.87	$4.33	$4.06	$3.79
	Manufacturing ($/stack)	$4.36	$0.44	$0.17	$0.11	$0.03
	Tooling ($/stack)	$0.06	$0.01	$0.01	$0.01	$0.01
	Total Cost ($/stack)	$10.87	$5.84	$5.03	$4.70	$4.35
	Total Cost ($/kW$_{gross}$)	$0.25	$0.13	$0.12	$0.11	$0.10

Figure 84. Cost breakdown for current collector manufacturing process

4.4.9. Coolant Gaskets

The coolant gaskets allow coolant from the coolant manifolds to flow across the bipolar plates, while keeping the air and hydrogen manifolds sealed off. They seal between the facing coolant-flow sides of the bipolar plates, around the perimeter of the flow fields. Because there is a coolant gasket in every repeat unit, plus an extra at the end of the stack (see Figure 25), there are 187 coolant gaskets needed per stack.

There are several different methods of manufacturing and applying coolant gaskets. The first of these is an insertion-molding process, which is what was specified for the baseline systems prior to this 2008 Update. Two more methods have since been examined: laser-welding and screen-printing. After an initial selection of screen-printing, the laser-welding process was ultimately selected. Figure 85 shows a comparison between the costs of the three methods.

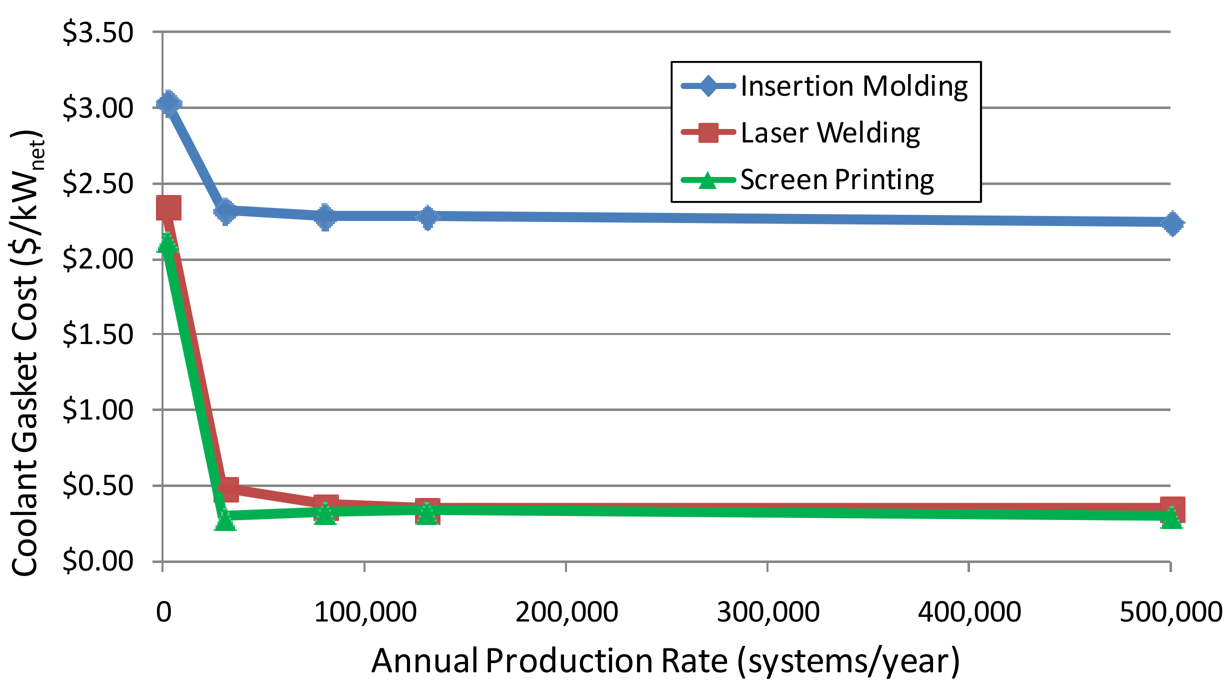

Figure 85. Coolant gasket manufacturing method cost comparison (for 2008 technology)

4.4.9.1. Insertion-Molded Coolant Gaskets

In this process, the bipolar plates are inserted into an injection-molding machine prior to each cycle, and the gaskets are molded directly onto the plates. This is preferable to making stand-alone gaskets because they are so thin that they lack the structural integrity to stand on their own, which would make the assembly process exceedingly difficult.

Prior to the 2008 Update, the material specified was a generic silicone. As with the MEA frame/gasket, this material specification has been changed to a new liquid injection-moldable hydrocarbon material from Henkel Loctite. More on the material selection can be found in the section on the MEA Frame/Gasket (section 4.4.6.3).

Unfortunately, the insertion-molding process has a relatively high manufacturing cost, owing mainly to the slow cycle time of the molding process. Figure 86 details the process parameters and Figure 88 summarizes the gasket costs.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$259,943	$539,478	$642,348	$574,420	$609,362
	Costs per Tooling Set ($)	$61,907	$120,843	$139,748	$127,277	$133,575
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	5	13	16	14	15
	Total Cycle Time (s)	132.7	153.0	160.6	155.6	158.1
	Simultaneous Lines	1	11	25	45	163
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	82.06%	99.26%	99.34%	99.25%	99.97%
	Effective Total Machine Rate ($/hr)	$59.51	$93.15	$108.07	$98.25	$102.74
	Material Cost ($/kg)	$51.29	$46.79	$45.57	$44.98	$43.37
2010	Capital Cost ($/Line)	$210,768	$401,385	$421,664	$421,664	$421,664
	Costs per Tooling Set ($)	$70,334	$133,575	$139,748	$139,748	$139,748
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	6	15	16	16	16
	Total Cycle Time (s)	135	158	161	161	161
	Simultaneous Lines	1	10	25	41	156
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	69.69%	97.77%	99.34%	98.43%	99.50%
	Effective Total Machine Rate ($/hr)	$57.04	$73.72	$75.81	$76.36	$75.72
	Material Cost ($/kg)	$51.90	$47.34	$46.11	$45.51	$43.88
2015	Capital Cost ($/Line)	$211,433	$403,037	$423,424	$423,424	$423,424
	Costs per Tooling Set ($)	$70,334	$133,575	$139,748	$139,748	$139,748
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	6	15	16	16	16
	Total Cycle Time (s)	135	158	161	161	161
	Simultaneous Lines	1	10	25	41	156
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	69.69%	97.77%	99.34%	98.43%	99.50%
	Effective Total Machine Rate ($/hr)	$57.18	$73.97	$76.07	$76.62	$75.98
	Material Cost ($/kg)	$51.89	$47.34	$46.10	$45.50	$43.88

Figure 86. Gasket insertion-molding process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	12%	12%	12%	12%	12%
	Power Consumption (kW)	58	87	96	90	93

Figure 87. Machine rate parameters for gasket insertion-molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$36.30	$33.11	$32.25	$31.83	$30.69
	Manufacturing ($/stack)	$82.04	$56.95	$56.36	$56.71	$56.25
	Tooling ($/stack)	$4.13	$2.95	$2.91	$2.94	$2.90
	Total Cost ($/stack)	$122.46	$93.02	$91.52	$91.48	$89.84
	Total Cost ($/$kW_{gross}$)	$2.71	$2.06	$2.03	$2.03	$1.99
2010	Materials ($/stack)	$22.08	$20.15	$19.62	$19.36	$18.67
	Manufacturing ($/stack)	$66.79	$40.36	$39.54	$39.82	$39.49
	Tooling ($/stack)	$2.34	$2.97	$2.91	$2.94	$2.91
	Total Cost ($/stack)	$91.22	$63.48	$62.07	$62.12	$61.07
	Total Cost ($/$kW_{gross}$)	$2.10	$1.46	$1.43	$1.43	$1.41
2015	Materials ($/stack)	$22.20	$20.26	$19.73	$19.47	$18.77
	Manufacturing ($/stack)	$66.95	$40.50	$39.67	$39.96	$39.63
	Tooling ($/stack)	$2.34	$2.97	$2.91	$2.94	$2.91
	Total Cost ($/stack)	$91.50	$63.72	$62.31	$62.37	$61.31
	Total Cost ($/$kW_{gross}$)	$2.10	$1.46	$1.43	$1.43	$1.41

Figure 88. Cost breakdown for gasket insertion-molding

4.4.9.2. Laser-Welded Coolant Gaskets

Laser welding is an option that only applies to use with metallic bipolar plates. The idea of welding two plates together to form a seal is a popular approach in the fuel cell industry, an alternative to injection-molding with potential for increased production rates. Conversations with Richard Trillwood of Electron Beam Engineering of Anaheim, California indicated that grade 316L stainless steel is exceptionally well-suited to laser welding. Additionally, the thinness of the plates allows welding from above, which is significantly quicker and cheaper than welding around the perimeter. Figure 89 shows the key process parameters.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$400,000	$800,000	$800,000	$800,000	$800,000
	Gaskets Welded Simultaneously	1	3	3	3	3
	Runtime per Gasket (s)	6.70	2.2	2.2	2.2	2.2
	Simultaneous Lines	1	3	6	9	35
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	20.72%	69.07%	92.10%	99.77%	98.67%
	Effective Total Machine Rate ($/hr)	$270.92	$168.11	$129.55	$120.65	$121.84
	Material Cost ($/kg)	$0.00	$0.00	$0.00	$0.00	$0.00
2010	Capital Cost ($/Line)	$400,000	$800,000	$800,000	$800,000	$800,000
	Gaskets Welded Simultaneously	1	3	3	3	3
	Runtime per Gasket (s)	6	2	2	2	2
	Simultaneous Lines	1	2	5	8	30
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	17.63%	88.14%	94.02%	95.49%	97.94%
	Effective Total Machine Rate ($/hr)	$316.02	$134.74	$127.18	$125.44	$122.65
	Material Cost ($/kg)	$0.00	$0.00	$0.00	$0.00	$0.00
2015	Capital Cost ($/Line)	$400,000	$800,000	$800,000	$800,000	$800,000
	Gaskets Welded Simultaneously	1	3	3	3	3
	Runtime per Gasket (s)	6	2	2	2	2
	Simultaneous Lines	1	2	5	8	30
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	17.66%	88.29%	94.18%	95.65%	98.10%
	Effective Total Machine Rate ($/hr)	$315.51	$134.53	$126.99	$125.25	$122.47
	Material Cost ($/kg)	$0.00	$0.00	$0.00	$0.00	$0.00

Figure 89. Coolant gasket laser welding process parameters

Laser welding provides a number of distinct advantages compared to traditional gasketing methods. The welds are extremely consistent and repeatable, and do not degrade over time as some gaskets do. It also has extremely low power requirements, and very low maintenance and material costs. The consumables include argon gas, compressed air and a cold water supply. Maintenance involves lamp replacement every three months, lens cleaning, and general machine repair. Trillwood suggested that the welding speed is limited to a range of 60 to 100 inches per minute, with a maximum of three parts being welded simultaneously. However, according to *Manufacturing Engineering & Technology*,[63] laser welding speeds range from 2.5m/min to as high as 80 m/min. Taking a guess at a conservative value in the middle, 15 m/min (0.25m/s) was selected.

The impact this has on the cycle time proved the process' most limiting factor. Although it is quicker than injection molding, it is still slower than screen printing. However, the capital costs are low enough that laser welding is cost-competitive with screen printing most production rates, while providing a more consistent, durable, and reliable seal. Figure 90 shows the machine rate parameters, and Figure 91 shows the cost breakdown.

[63] *Manufacturing Engineering & Technology*, by Kalpakjian & Schmid (5th edition), p. 957

2008/ 2010/ 2015	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
	Equipment Lifetime	20	20	20	20	20
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.162	0.162	0.162	0.162	0.162
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	12%	12%	12%	12%	12%
	Power Consumption (kW)	34	34	34	34	34

Figure 90. Machine rate parameters for gasket laser-welding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Manufacturing ($/stack)	$94.31	$19.51	$15.03	$14.00	$14.14
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$94.31	$19.51	$15.03	$14.00	$14.14
	Total Cost ($/kW$_{gross}$)	$2.09	$0.43	$0.33	$0.31	$0.31
2010	Materials ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Manufacturing ($/stack)	$93.59	$13.30	$12.56	$12.38	$12.11
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$93.59	$13.30	$12.56	$12.38	$12.11
	Total Cost ($/kW$_{gross}$)	$2.16	$0.31	$0.29	$0.29	$0.28
2015	Materials ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Manufacturing ($/stack)	$93.60	$13.30	$12.56	$12.39	$12.11
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$93.60	$13.30	$12.56	$12.39	$12.11
	Total Cost ($/kW$_{gross}$)	$2.15	$0.31	$0.29	$0.28	$0.28

Figure 91. Cost breakdown for coolant gasket laser welding

4.4.9.3. Screen-Printed Coolant Gaskets

Preliminary research revealed that screen printing outperformed laser welding in both cycle time and cost efficiency. Although updates to the laser welding analysis tipped the scale towards that process, screen printing the gaskets is still a useful approach to have analyzed, and is actually slightly cheaper than welding at most production rates. Conversations with DEK International confirmed initial DTI assumptions, and various screen printers were examined for their efficacy at five production levels. To screen print a seal onto a bipolar plate, a single plate, or a pallet holding several plates, is first fed into the machine by conveyor. Once in the screen printer, it is locked into place and cameras utilize fiduciary markers on either the plate itself or the pallet for appropriate alignment. A precision emulsion screen is placed over the plates, allowing a wiper to apply the sealing resin. After application, the resin must be UV cured to ensure adequate sealing.

Two different scenarios were examined in the screen printing process. In the first, one plate would be printed at a time, reducing costs by halving the need for handling robots to align plates. It would also avoid the necessity of a pallet to align multiple plates in the screen printer. The second scenario requires two handling robots to place four plates onto prefabricated self-aligning grooves in a pallet, ensuring proper alignment in the screen printer. The advantage of this technique is reduced cycle time per plate. However, it would result in increased capital costs due to more expensive screen printers, increased necessity for handling robots and precise mass-manufacture of pallets. Small variations in the grooves of pallets would lead to failure of the screen printer to align properly or apply the resin appropriately.

Printers: Three different screen printer models were examined as recommended by representatives from the DEK Corporation. The Horizon 01i machine was suggested for one-plate printing. The Europa VI and the PV-1200 were both evaluated for four plate printing. Comparison of the screen printers can be seen in Figure 92. After cost-analysis, it was determined that, despite the increased capital cost of the PV-1200 machines, their reduced cycle time (12.26 second to 4 seconds) led to significant savings at high volumes. Of the five different production levels examined, the PV-1200 was cheapest and most effective for all except the smallest, 1,000 systems per year, scenario. Due to low utilization, the Horizon machine is the cheapest alternative at this production level. Figure 93 details the cost per kW of each screen printer at the different production levels.

		Screen Printers (DEK)		
Machine		Horizon	Europa VI	PV-1200
Cycle Time	s	9.63	12.26	4
Cost	$	$150,000	$200,000	$1,000,000
Power Consumption	kW	3.5	3.5	0.7
Print Area	in^2	400	841	841

Figure 92. Screen printer comparison

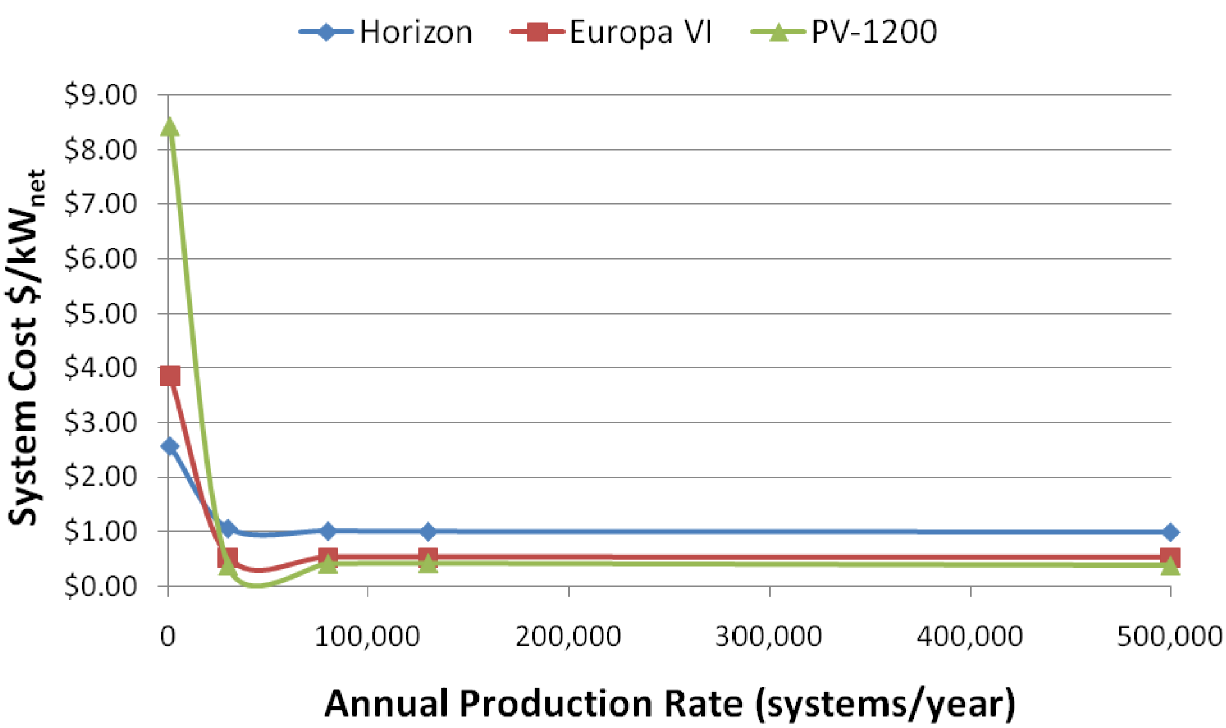

Figure 93. Screen printer cost vs. annual production rate

Resin: Our resin formula was based upon information gleaned from the Dana Corporation US patent 6,824,874. The patent outlines several resins that would be suitable to provide an effective seal between bipolar plates and resin "A" was selected for its formulaic simplicity. However, any of the other recommended resins could be substituted with negligible changes in cost and performances.

UV Curing: Following printing, a short conveyor is needed to transfer the printed plate to a UV curing system. Consultation with representatives from UV Fusion Systems Inc. of Gaithersburg, Maryland, along with information from the Dana Corporation resin patent indicated that the VPS 1250 lamp carrying 350 watt type D and type H+ bulbs would be adequate to cure the resin. If it is only necessary to cure a single plate, then one seven inch type D, and one seven inch type H+ bulb should be used. In order to ensure full UV coverage, for a 24 inch pallet holding four plates, three side-by-side ten inch bulbs of both types would be employed.

Patent research indicates that roughly two seconds of exposure for each type of lamp is sufficient for curing. When using the PV-1200 screen printer the curing time for both lamps matches the cycle time for the screen printer. If using the Horizon printer, the cure time is less than half the cycle time for the printer, yet in both situations the plates could be indexed to match the screen printer cycle time. A shutter would be built into the lamp to block each bulb for half of the time the plate is within the system to ensure adequate exposure of both light types. Rapidly turning the bulbs on and off is more destructive to the bulb life than continuous operation, making a shutter the preferred method of alternating light sources.

Cost estimation for UV curing system includes cost of lamps, bulbs, power supply rack, light shield to protect operators, and blowers for both lamp operation and heat reduction.

Figure 94 shows the key process parameters, as selected for the model. The capital cost includes the cost of the screen printer, plus a UV curing system, plate handling robots, and a conveyor belt.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$387,201	$1,438,201	$1,438,201	$1,438,201	$1,438,201
	Gaskets Printed Simultaneously	1	4	4	4	4
	Runtime per Gasket (s)	9.78	1.0	1.0	1.0	1.0
	Simultaneous Lines	1	1	3	5	17
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	30.22%	96.25%	85.55%	83.41%	94.36%
	Effective Total Machine Rate ($/hr)	$164.85	$189.30	$209.95	$214.71	$192.60
	Material Cost ($/kg)	$13.21	$13.21	$13.21	$13.21	$13.21
2010	Capital Cost ($/Line)	$387,201	$1,438,201	$1,438,201	$1,438,201	$1,438,201
	Gaskets Printed Simultaneously	1	4	4	4	4
	Runtime per Gasket (s)	10	1	1	1	1
	Simultaneous Lines	1	1	3	5	16
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	30.14%	95.65%	85.02%	82.90%	99.63%
	Effective Total Machine Rate ($/hr)	$165.24	$190.33	$211.11	$215.90	$183.68
	Material Cost ($/kg)	$13.21	$13.21	$13.21	$13.21	$13.21
2015	Capital Cost ($/Line)	$387,201	$1,438,201	$1,438,201	$1,438,201	$1,438,201
	Gaskets Printed Simultaneously	1	4	4	4	4
	Runtime per Gasket (s)	10	1	1	1	1
	Simultaneous Lines	1	1	3	5	16
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	30.15%	95.65%	85.03%	82.90%	99.64%
	Effective Total Machine Rate ($/hr)	$165.24	$190.32	$211.10	$215.89	$183.67
	Material Cost ($/kg)	$13.21	$13.21	$13.21	$13.21	$13.21

Figure 94. Coolant gasket screen-printing process parameters

__Maintenance:__ Communication with DEK has indicated that, if properly cared for, the screen printers have a lifetime of twenty years, but on average are replaced after only eight years due to poor maintenance practices. The lifetime was specified as ten years. Regular maintenance, including machine repair, cleaning, and replacement of screens every 10,000 cycles costs an estimated $10,000 per year.

Figure 95 shows the assumed machine rate parameters.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	3%	1%	1%	1%	1%
	Miscellaneous Expenses (% of CC)	12%	12%	12%	12%	12%
	Power Consumption (kW)	61	166	166	166	166

Figure 95. Machine rate parameters for coolant gasket screen printing process

Utilities: Relatively little power is used by the printers. A belt-drive system that collects and releases parts is the primary power consumer of the screen printers. Additional consumption comes from the alignment system, the wiper blade and the screen controls. Depending on the specifications of the individual printer, power consumption varies from 0.7 to 3.5 kW. On the other hand, the UV curing system has higher power demand. Power usage, from 50 to 100 kW, is primarily for powering the lamps, but also necessary for the exhaust blowers, modular blowers for the lamp, and the systems built in conveyor. Figure 96 shows the cost breakdown for the process.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$1.70	$1.70	$1.70	$1.70	$1.70
	Manufacturing ($/stack)	$83.70	$10.20	$11.32	$11.57	$10.38
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$85.40	$11.90	$13.01	$13.27	$12.08
	Total Cost ($/$kW_{gross}$)	$1.89	$0.26	$0.29	$0.29	$0.27
2010	Materials ($/stack)	$1.02	$1.02	$1.02	$1.02	$1.02
	Manufacturing ($/stack)	$83.68	$10.19	$11.31	$11.56	$9.84
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$84.70	$11.22	$12.33	$12.59	$10.86
	Total Cost ($/$kW_{gross}$)	$1.95	$0.26	$0.28	$0.29	$0.25
2015	Materials ($/stack)	$1.03	$1.03	$1.03	$1.03	$1.03
	Manufacturing ($/stack)	$83.68	$10.19	$11.31	$11.56	$9.84
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$84.71	$11.22	$12.33	$12.59	$10.87
	Total Cost ($/$kW_{gross}$)	$1.95	$0.26	$0.28	$0.29	$0.25

Figure 96. Cost breakdown for coolant gasket screen printing

4.4.10. End Gaskets

The end gaskets are very similar to the coolant gaskets (section 4.4.9, but are sandwiched between the last bipolar plate and the end plate, rather than between two bipolar plates. This means that welding is not an option, as the end plates are non-metallic. They also have slightly different geometry than the coolant gaskets, because they manifold the reactant gasses rather than the coolant. Like the coolant gaskets, they were initially modeled using insertion molding, but were switched to a screen printing approach for the 2008 Update. The largest difference between coolant and end gaskets is simply the number of gaskets needed- at only two end gaskets per stack (four per system), there are far fewer of them than the coolant gaskets. Although the same methodology was still applied to their manufacture, the processes were optimized from those used for the coolant gaskets, in order to account for the lower quantities. Figure 97 shows a comparison between the costs of the two end gasket production methods. Because of the lower production quantities, the screen printing method yields a far smaller savings over the insertion-molding method than it does for the coolant gaskets.

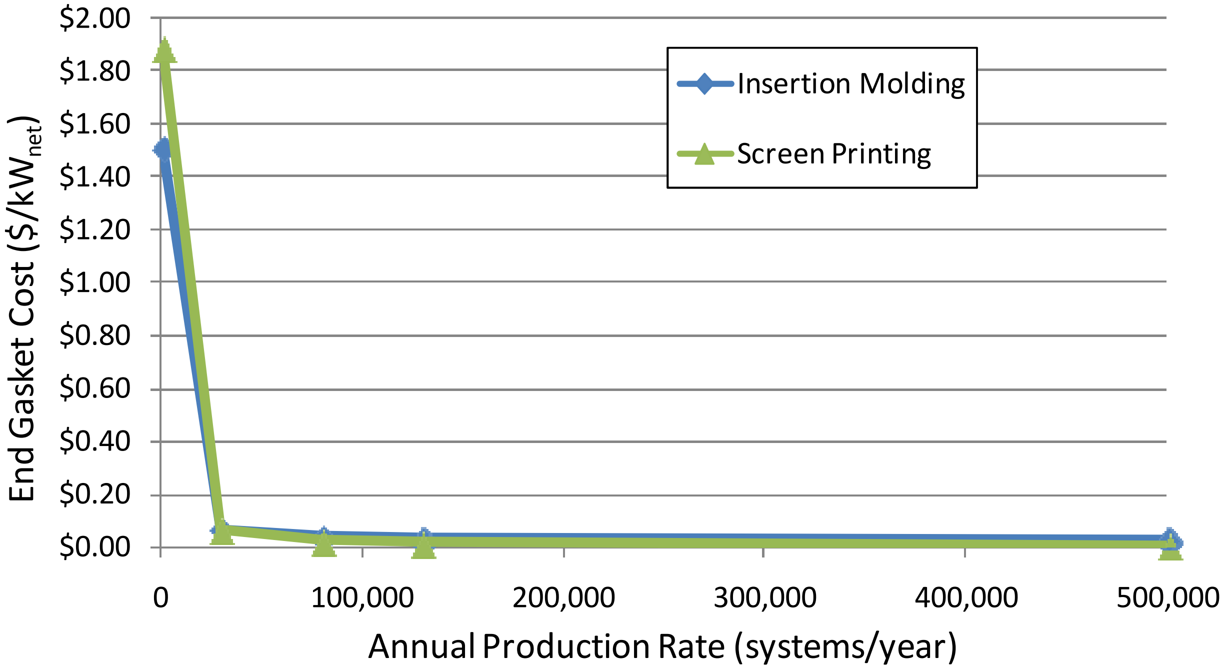

Figure 97. End gasket manufacturing method cost comparison (for 2008 technology)

4.4.10.1. Insertion-Molded End Gaskets

The methodology for insertion molding the end gaskets is identical to that of the insertion-molded coolant gaskets (section 4.4.9.1). Thus, only the data tables are presented in this section, and the reader is directed to the coolant gasket section for more details.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$249,794	$245,883	$287,023	$371,259	$659,241
	Costs per Tooling Set ($)	$52,954	$52,954	$61,907	$78,348	$127,277
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	4	4	5	7	14
	Total Cycle Time (s)	132.7	153.0	160.6	155.6	158.1
	Simultaneous Lines	1	1	1	1	2
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	1.10%	37.95%	84.99%	95.53%	93.36%
	Effective Total Machine Rate ($/hr)	$3,163.73	$105.22	$62.73	$70.51	$116.46
	Material Cost ($/kg)	$51.29	$46.79	$45.57	$44.98	$43.37
2010	Capital Cost ($/Line)	$181,295	$179,674	$205,156	$279,982	$429,633
	Costs per Tooling Set ($)	$52,954	$52,954	$61,907	$86,025	$127,277
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	4	4	5	8	14
	Total Cycle Time (s)	135	158	161	161	161
	Simultaneous Lines	1	1	1	1	2
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	1.12%	39.21%	84.99%	86.32%	94.86%
	Effective Total Machine Rate ($/hr)	$2,256.86	$78.32	$48.59	$60.80	$79.86
	Material Cost ($/kg)	$51.90	$47.34	$46.11	$45.51	$43.88
2015	Capital Cost ($/Line)	$181,827	$180,202	$205,818	$281,039	$431,481
	Costs per Tooling Set ($)	$52,954	$52,954	$61,907	$86,025	$127,277
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	4	4	5	8	14
	Total Cycle Time (s)	135	158	161	161	161
	Simultaneous Lines	1	1	1	1	2
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	1.12%	39.21%	84.99%	86.32%	94.86%
	Effective Total Machine Rate ($/hr)	$2,263.44	$78.51	$48.71	$60.98	$80.14
	Material Cost ($/kg)	$51.89	$47.34	$46.10	$45.50	$43.88

Figure 98. End gasket insertion-molding process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	12%	12%	12%	12%	12%
	Power Consumption (kW)	57	57	62	71	98

Figure 99. Machine rate parameters for end gasket insertion-molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$0.47	$0.42	$0.41	$0.41	$0.39
	Manufacturing ($/stack)	$58.31	$2.24	$1.12	$0.87	$0.73
	Tooling ($/stack)	$1.77	$0.06	$0.03	$0.04	$0.03
	Total Cost ($/stack)	$60.54	$2.72	$1.56	$1.32	$1.16
	Total Cost ($/kW$_{gross}$)	$1.34	$0.06	$0.03	$0.03	$0.03
2010	Materials ($/stack)	$0.28	$0.26	$0.25	$0.25	$0.24
	Manufacturing ($/stack)	$42.39	$1.72	$0.87	$0.68	$0.51
	Tooling ($/stack)	$1.77	$0.06	$0.03	$0.02	$0.03
	Total Cost ($/stack)	$44.44	$2.04	$1.14	$0.95	$0.78
	Total Cost ($/kW$_{gross}$)	$1.02	$0.05	$0.03	$0.02	$0.02
2015	Materials ($/stack)	$0.28	$0.26	$0.25	$0.25	$0.24
	Manufacturing ($/stack)	$42.52	$1.72	$0.87	$0.68	$0.51
	Tooling ($/stack)	$1.77	$0.06	$0.03	$0.02	$0.03
	Total Cost ($/stack)	$44.56	$2.04	$1.15	$0.95	$0.78
	Total Cost ($/kW$_{gross}$)	$1.02	$0.05	$0.03	$0.02	$0.02

Figure 100. Cost breakdown for end gasket insertion molding

4.4.10.2. Screen-Printed End Gaskets

As with the insertion-molded end gaskets, the screen-printed end gaskets share an identical methodology to their coolant gasket counterpart, but have been optimized according to their production volume. For more details on this process, see section 4.4.9.3. The data tables are presented below.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$387,201	$387,201	$387,201	$387,201	$638,201
	Gaskets Printed Simultaneously	1	1	1	1	4
	Runtime per Gasket (s)	9.78	9.78	9.78	9.78	3.10
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.32%	9.70%	25.86%	42.02%	51.31%
	Effective Total Machine Rate ($/hr)	$13,932.93	$479.90	$189.97	$123.06	$164.56
	Material Cost ($/kg)	$13.21	$13.21	$13.21	$13.21	$13.21
2010	Capital Cost ($/Line)	$387,201	$387,201	$387,201	$387,201	$638,201
	Gaskets Printed Simultaneously	1	1	1	1	4
	Runtime per Gasket (s)	10	10	10	10	3
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.32%	9.67%	25.79%	41.91%	51.20%
	Effective Total Machine Rate ($/hr)	$13,969.65	$481.13	$190.43	$123.34	$164.85
	Material Cost ($/kg)	$13.21	$13.21	$13.21	$13.21	$13.21
2015	Capital Cost ($/Line)	$387,201	$387,201	$387,201	$387,201	$638,201
	Gaskets Printed Simultaneously	1	1	1	1	4
	Runtime per Gasket (s)	10	10	10	10	3
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.32%	9.67%	25.79%	41.91%	51.20%
	Effective Total Machine Rate ($/hr)	$13,969.30	$481.11	$190.42	$123.34	$164.85
	Material Cost ($/kg)	$13.21	$13.21	$13.21	$13.21	$13.21

Figure 101. End gasket screen printing process parameters

2008/ 2010/ 2015	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
	Equipment Lifetime	15	15	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	3%	3%	3%	3%	2%
	Miscellaneous Expenses (% of CC)	12%	12%	12%	12%	12%
	Power Consumption (kW)	61	61	61	61	162

Figure 102. Machine rate parameters for end gasket screen printing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/stack)	$0.02	$0.02	$0.02	$0.02	$0.02
2008	Manufacturing ($/stack)	$75.66	$2.61	$1.03	$0.67	$0.28
2008	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
2008	Total Cost ($/stack)	$75.69	$2.63	$1.05	$0.69	$0.31
2008	Total Cost ($/$kW_{gross}$)	$1.68	$0.06	$0.02	$0.02	$0.01
2010	Materials ($/stack)	$0.01	$0.01	$0.01	$0.01	$0.01
2010	Manufacturing ($/stack)	$75.66	$2.61	$1.03	$0.67	$0.28
2010	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
2010	Total Cost ($/stack)	$75.68	$2.62	$1.04	$0.68	$0.30
2010	Total Cost ($/$kW_{gross}$)	$1.75	$0.06	$0.02	$0.02	$0.01
2015	Materials ($/stack)	$0.01	$0.01	$0.01	$0.01	$0.01
2015	Manufacturing ($/stack)	$75.66	$2.61	$1.03	$0.67	$0.28
2015	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
2015	Total Cost ($/stack)	$75.68	$2.62	$1.04	$0.68	$0.30
2015	Total Cost ($/$kW_{gross}$)	$1.74	$0.06	$0.02	$0.02	$0.01

Figure 103. Cost breakdown for end gasket screen printing

4.4.11. Stack Compression

Traditional PEM fuel cells use tie-rods, nuts and Belleville washers to supply axial compressive force to ensure fluid sealing and adequate electrical connectivity. However, the use of metallic compression bands was assumed, as used by Ballard Power Systems and described in US Patent 5,993,987 (Figure 104). Two stainless steel bands of 2 cm width are wrapped axially around the stack and tightened to a pre-determined stack compressive loading, and then the ends of the bands are tack welded to each other. The end plates' low conductivity allows them to act as insulators, to prevent shorting of the stack. Custom recesses in the end plates are used to provide a convenient access to the lower surface of the bands to enable welding. The edges of the bipolar plates do not contact the compressive bands. The costs are reported as part of the stack assembly section, as shown in Figure 108.

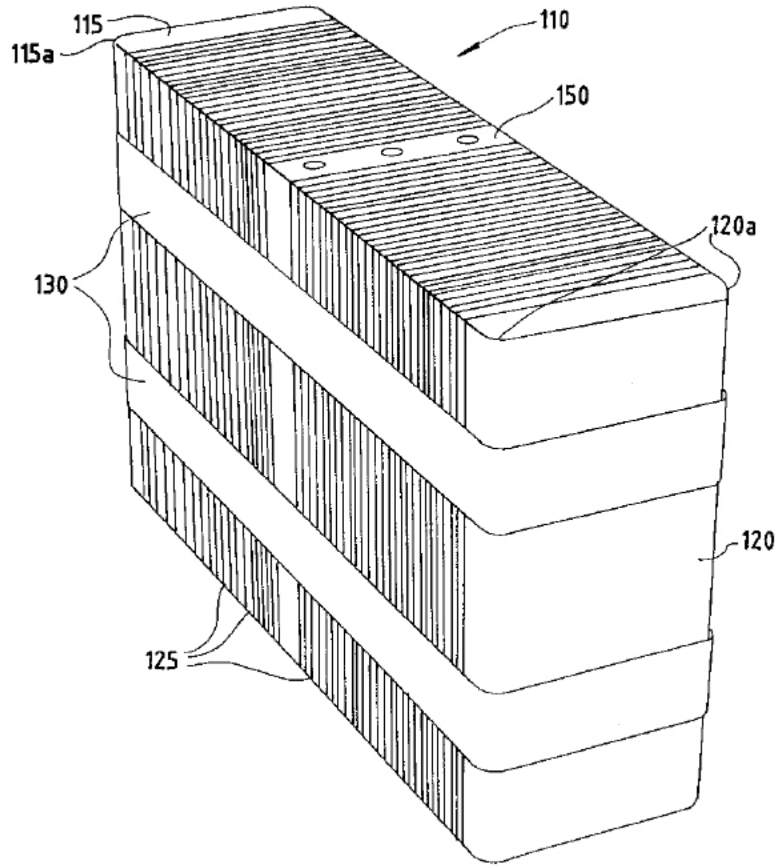

Figure 104. Stack compression bands concept, US patent 5,993,987

4.4.12. Stack Assembly

Stack assembly costs were based on the amortized workstation costs and the estimated times to perform the required actions. Two methods of stack assembly were analyzed: manual and semi-automated.

At the lowest production rate of 1,000 systems per year (2,000 stacks/year), manual assembly was selected. Manual assembly consists of workers using their hands to individually acquire and place each element of the stack: end-plate, insulator, current collector, bipolar plate, gasketed MEA, bipolar plate, and so on. An entire stack is assembled at a single workstation. The worker sequentially builds the stack (vertically) and then binds the cells with metallic compression bands. The finished stacks are removed from the workstation by conveyor belt.

At higher production levels, stack assembly is semi-automatic, requiring less time and labor and ensuring superior quality control. This is termed “semi-automatic” because the end components (end plates, current conductors, and initial cells) are assembled manually but the 186 active cell repeat units are assembled via automated fixture. Figure 105 details the layout of the assembly workstations and Figure 106 lists additional processing parameters.

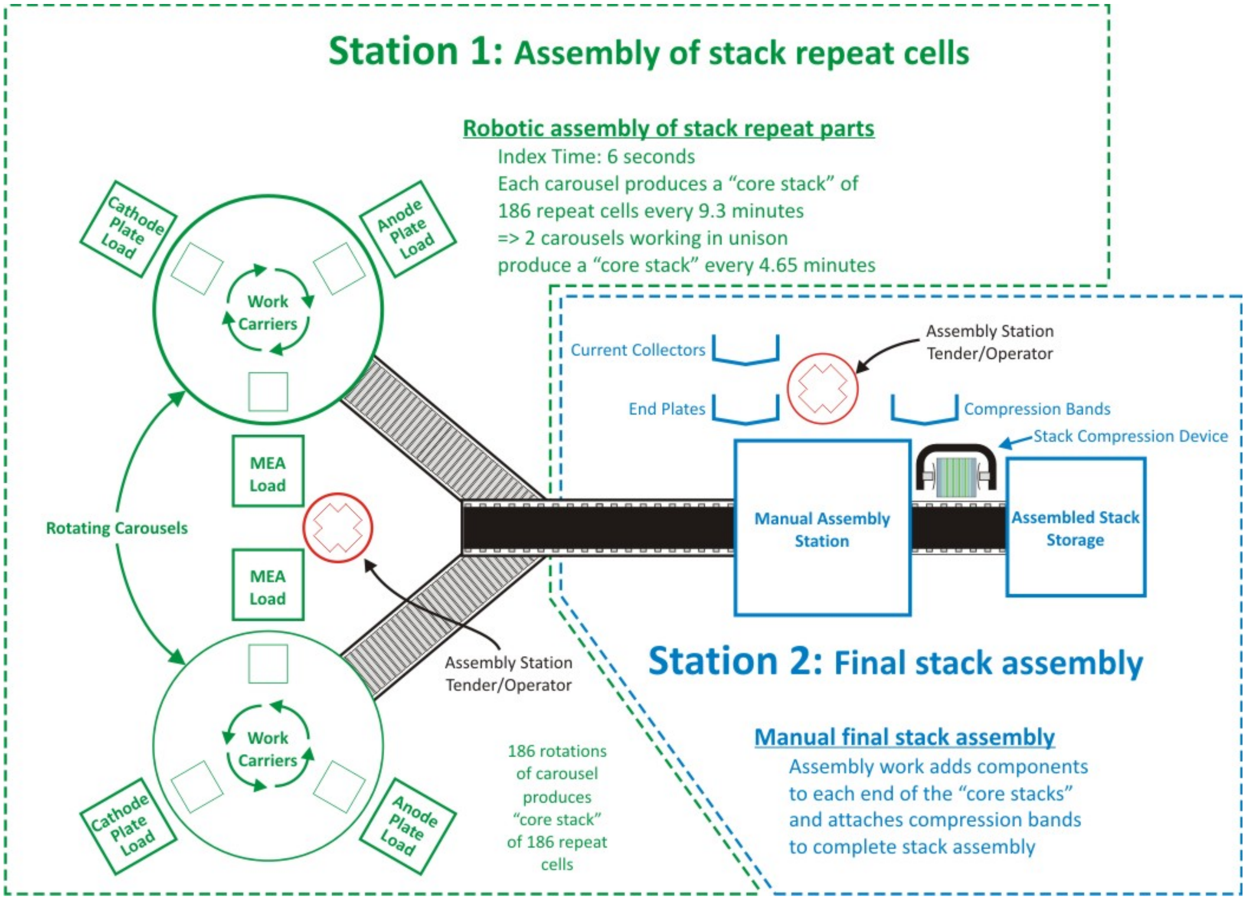

Figure 105. Semi-automated stack assembly work flow diagram

Following assembly, each stack is transported to a leak-check station where the three sets of fluid channels (hydrogen, air, and coolant) are individually pressurized with gas and monitored for leaks. This test is very brief and meant only to verify gas and liquid sealing. Full performance testing of the stack will occur during stack conditioning.

As shown in Figure 108, stack assembly is quite inexpensive, ranging from \$1.14 /kW_{gross} at the most (2010, 1,000 systems per year) to only \$0.51 /kW_{gross} (2008, 500,000 systems per year). The only material costs are those of the compressive metal bands.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Assembly Method	Manual	Semi-Auto	Semi-Auto	Semi-Auto	Semi-Auto
	Capital Cost ($/Line)	$11,060	$810,171	$810,171	$810,171	$810,171
	Simultaneous Lines	1	4	9	15	56
	Laborers/Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	48.76%	83.41%	98.86%	96.39%	99.30%
	Effective Total Machine Rate ($/hr)	$48.29	$111.43	$95.86	$98.02	$95.49
	Index Time (min)	49.2	11.2	11.2	11.2	11.2
2010	Assembly Method	Manual	Semi-Auto	Semi-Auto	Semi-Auto	Semi-Auto
	Capital Cost ($/Line)	$11,060	$810,171	$810,171	$810,171	$810,171
	Simultaneous Lines	1	4	9	15	56
	Laborers/Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	48.76%	83.41%	98.86%	96.39%	99.30%
	Effective Total Machine Rate ($/hr)	$48.29	$111.43	$95.86	$98.02	$95.49
	Index Time (min)	49.2	11.2	11.2	11.2	11.2
2015	Assembly Method	Manual	Semi-Auto	Semi-Auto	Semi-Auto	Semi-Auto
	Capital Cost ($/Line)	$11,060	$810,171	$810,171	$810,171	$810,171
	Simultaneous Lines	1	4	9	15	56
	Laborers/Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	48.76%	83.41%	98.86%	96.39%	99.30%
	Effective Total Machine Rate ($/hr)	$48.29	$111.43	$95.86	$98.02	$95.49
	Index Time (min)	49.2	11.2	11.2	11.2	11.2

Figure 106. Stack assembly process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	24,777	24,777	24,777	24,777	24,777
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.306	0.175	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	7%	7%	7%	7%	7%
	Power Consumption (kW)	1	7	7	7	7

Figure 107. Machine rate parameters for stack assembly process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Compression Bands ($/stack)	$10.00	$8.00	$6.00	$5.50	$5.00
	Assembly ($/stack)	$39.56	$20.82	$17.91	$18.31	$17.84
	Total Cost ($/stack)	$49.56	$28.82	$23.91	$23.81	$22.84
	Total Cost ($/kW$_{gross}$)	$1.10	$0.64	$0.53	$0.53	$0.51
2010	Compression Bands ($/stack)	$10.00	$8.00	$6.00	$5.50	$5.00
	Assembly ($/stack)	$39.56	$20.82	$17.91	$18.31	$17.84
	Total Cost ($/stack)	$49.56	$28.82	$23.91	$23.81	$22.84
	Total Cost ($/kW$_{gross}$)	$1.14	$0.66	$0.55	$0.55	$0.53
2015	Compression Bands ($/stack)	$10.00	$8.00	$6.00	$5.50	$5.00
	Assembly ($/stack)	$39.56	$20.82	$17.91	$18.31	$17.84
	Total Cost ($/stack)	$49.56	$28.82	$23.91	$23.81	$22.84
	Total Cost ($/kW$_{gross}$)	$1.14	$0.66	$0.55	$0.55	$0.52

Figure 108. Cost breakdown for stack assembly

4.4.13. Stack Conditioning and Testing

PEM fuel cell stacks have been observed to perform better in polarization tests if they first undergo "stack conditioning". Consequently, a series of conditioning steps were modeled based on a regulation scheme discussed in UTC Fuel Cell's US patent 7,078,118. The UTC Fuel Cell patent describes both a voltage variation and a fuel/oxidant variation regime for conditioning. The voltage variation method was selected since it requires marginally less fuel consumption and allows easier valving of reactants. The conditioning would occur immediately after stack assembly at the factory. Because the conditioning is effectively a series of controlled polarization tests, the conditioning process also serves a stack quality control purpose and no further system checkout is required.

Figure 109 details the stack conditioning steps. The UTC patent states that while prior art conditioning times were 70+ hours, the UTC accelerated break-in methodology is able to achieve 95% of the performance benefit in 5 hours and typically maximum performance in 13.3 hours[64]. A declining conditioning duration (5 hours for 2008 technology, 4 hours for 2010, and 3 hours for 2015) was selected , consistent with the patent's assertion that "the required number will be dependent on the formulation and processing conditions used to fabricate the fuel cells" and an expectation of process improvement in the future.

	Step	Gas on Anode	Gas on Cathode	Primary Load Switch	DC Power Supply Positive Terminal	Electrode Potential	Current Density
Cathode Filling Cycles	1	4% H_2-N_2	N_2	Open	Connected to Cathode	Cathode 0.04V to 1.04V	Low
	2	4% H_2-N_2	N_2	Open	Connected to Cathode	Cathode 0.04V to 1.04V	Low
	3	Repeat Step #1					Low
	4	Repeat Step #2					Low
	5	Repeat Step #1					Low
	6	Repeat Step #2					Low
Anode Filling Cycles	7	N_2	4% H_2-N_2	Open	Connected to Anode	Anode 0.04V to 1.04V	Low
	8	N_2	4% H_2-N_2	Open	Connected to Anode	Anode 0.04V to 1.04V	Low
	9	Repeat Step #7					Low
	10	Repeat Step #8					Low
	11	Repeat Step #7					Low
	12	Repeat Step #8					Low
Performance Calibrations	13	H_2	Air	Closed	Not Connected	Depends on Current Density	0-1600 mA/cm^2
	14	Repeat step #13 up to 10 times					

Figure 109. Stack conditioning process based on US patent 7,078,118 ("Applied Voltage Embodiment")

Conditioning cost was calculated by estimating the capital cost of a programmable load bank to run the stacks up and down the polarization curve according to the power conditioning regimen. The fuel cells load banks were assumed to condition five stacks simultaneously. Since the five stacks can be staggered in starting time, peak power can be considerably less than 10 times the individual stack rated power of 40 kW. It was estimated that simultaneous peak power would be approximately 50 kW and cost approximately $100,000[65]. Hydrogen usage

[64] The UTC Fuel Cell patents does not overtly state 13.3 hours to maximum performance but that duration is suggested by their specification of test procedure, 10 cycles of polarization testing for maximum performance, $100mA/cm^2$ increments, and 5 minute increment hold times.

[65] Cost of the programmable load bank is modeled loosely on the AeroVironment ABC-150, a common load bank for fuel cell testing which costs about $100,000. However, the desired load bank would be lower total power but must be able to

was estimated based on 50% fuel cell efficiency and \$3/kg hydrogen. DTI's standard machine rate methodology yields machine rates of approximately \$0.52/min for each load bank. Total costs for stack conditioning are shown in Figure 112. Note that considerable power is generated and rather than dumping the load to a resistor bank, it may be advantageous to sell the electricity back to the grid. This would require considerable electrical infrastructure and is expected to be only a relatively small benefit[66]; sale of electricity to the grid is not included in our cost estimates.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Capital Cost ($/Line)	$110,600	$110,600	$110,600	$110,600	$110,600
	Simultaneous Lines	1	6	14	23	87
	Laborers per Line	0.10	0.10	0.10	0.10	0.10
	Line Utilization	17.36%	86.81%	99.21%	98.13%	99.78%
	Effective Total Machine Rate ($/hr)	$55.01	$21.87	$20.83	$20.91	$20.79
	Test Duration (hrs)	5	5	5	5	5
2010	Capital Cost ($/Line)	$110,600	$110,600	$110,600	$110,600	$110,600
	Simultaneous Lines	1	5	12	19	70
	Laborers per Line	0.10	0.10	0.10	0.10	0.10
	Line Utilization	13.89%	83.33%	92.59%	95.03%	99.21%
	Effective Total Machine Rate ($/hr)	$65.37	$22.21	$21.35	$21.15	$20.83
	Test Duration (hrs)	4	4	4	4	4
2015	Capital Cost ($/Line)	$110,600	$110,600	$110,600	$110,600	$110,600
	Simultaneous Lines	1	4	9	14	53
	Laborers per Line	0.10	0.10	0.10	0.10	0.10
	Line Utilization	10.42%	78.13%	92.59%	96.73%	98.27%
	Effective Total Machine Rate ($/hr)	$82.63	$22.79	$21.35	$21.02	$20.90
	Test Duration (hrs)	3	3	3	3	3

Figure 110. Stack conditioning process parameters

Note that while these stack conditioning costs are reasonable, the number of load banks at the 500,000 systems per year manufacturing rate is very high: as many as 87 load banks are required. This may be logistically unrealistic and an alternate method of testing may be required.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	10	10	10	10	10
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.205	0.205	0.205	0.205	0.205
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	7%	7%	7%	7%	7%
	Power Consumption (kW)	9	9	9	9	9

Figure 111. Machine rate parameters for stack conditioning process

maintain 5 separate loads simultaneously. Additionally, there are gas flows to be controlled that are not applicable to the ABC-150.

[66] A power conditioning savings of approximately \$1.80/stack was estimated based on the sale of electricity back to the grid at \$0.04/kWh (assuming no additional infrastructure capital costs were incurred).

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Conditioning/Testing ($/stack)	$27.50	$10.93	$10.42	$10.45	$10.39
	Total Cost ($/stack)	$27.50	$10.93	$10.42	$10.45	$10.39
	Total Cost ($/$kW_{gross}$)	$0.61	$0.24	$0.23	$0.23	$0.23
2010	Conditioning/Testing ($/stack)	$26.15	$8.88	$8.54	$8.46	$8.33
	Total Cost ($/stack)	$26.15	$8.88	$8.54	$8.46	$8.33
	Total Cost ($/$kW_{gross}$)	$0.60	$0.20	$0.20	$0.20	$0.19
2015	Conditioning/Testing ($/stack)	$24.79	$6.84	$6.40	$6.30	$6.27
	Total Cost ($/stack)	$24.79	$6.84	$6.40	$6.30	$6.27
	Total Cost ($/$kW_{gross}$)	$0.57	$0.16	$0.15	$0.14	$0.14

Figure 112. Cost breakdown for stack conditioning

4.5. Balance of Plant and System Assembly

While the stack is the heart of the fuel cell system, many other components are necessary to create a functioning system. In general, our cost analysis utilizes a DFMA-style analysis methodology for the stack but a less rigorous methodology for the balance of plant (BOP) components. Each of the BOP components is discussed below along with its corresponding cost basis.

4.5.1. Mounting Frames

It was assumed that the fuel cell power system would be built as a subsystem, then hoisted as an assembly into the automotive engine compartment. Consequently, the power system attaches to a mounting frame substructure to allow easy transport. These mounting frames were assumed to be contoured steel beams with various attachment points for power system components, facilitating attachment to the vehicle chassis. The cost is roughly estimated at $96 at 500,000/year to $160 at 1,000/year.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Mounting Frames ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/$kW_{net}$)	$1.25	$0.54	$0.41	$0.38	$0.38
2010	Mounting Frames ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/$kW_{net}$)	$1.25	$0.54	$0.41	$0.38	$0.38
2015	Mounting Frames ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/$kW_{net}$)	$1.25	$0.54	$0.41	$0.38	$0.38

Figure 113. Cost breakdown for mounting frames

4.5.2. Air Loop

The power system air loop consists of five elements:

Air Filter and Housing: Some fuel cell manufacturers filter inlet air both for particles and for volatile organic compounds[67]. However, while particle filters are needed, it is not clear that VOC filters are necessary. Consequently, a standard automotive air particle filter and polymer filter housing were assumed.

Air Compressor, Expander and Motor Unit (CMEU): The air compression system is envisioned as an integrated air compressor, exhaust gas expander, and permanent magnet motor. For 2008, the CMEU was based on a twin-

[67] Press Release from the Dana Company Inc.: "Smart Fuel Cell uses Donaldson filters in its new EFOY line of direct methanol fuel cells", 25 May 2006.

lobe compressor and twin-lobe expander whereas for 2010 and 2015 a centrifugal compressor and radial inflow expander was assumed. All estimates were based on a simplified DFMA analysis where the system is broken into seven cost elements: wheels/lobes, motor, controller, case, bearings, variable geometry, and assembly/test. A price quote was obtained from Opcon Autorotor of Sweden for a CMEU unit specifically designed and optimized for fuel cell systems of roughly 80 kilowatts. These Opcon estimates for low production (~$40,000 for quantity = 1) and high production (~$665 for 500,000/year) were used to validate the DTI costing estimates. Note that CMEU costs vary both due to production rate effects and that the CMEU design changes that occur from year to year due to switch from twin-lobe to centrifugal compression, lowering of air pressurization, and elimination of the expander in 2015.

Stack Inlet Manifold for the Air Stream: A polymer housing to guide cathode air into the stack.

Stack Outlet Manifold for the Air Stream: A polymer housing to guide cathode air out of the stack.

Air Mass Flow Sensor: A high performance (~2% signal error) automotive hot-wire mass flow sensor for measuring the air flow rate into the fuel cell system. Since these devices are already produced in very high quantities, little change in cost is expected between high and low production rates. The OEM cost of a mass flow sensor in high quantities was estimated to be about $65. This cost was increased to $100 for quantities of 1,000/year.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Filter & Housing ($/system)	$49.61	$45.10	$45.10	$45.10	$45.10
	Compressor, Expander & Motor ($/system)	$2,442.08	$1,214.06	$930.84	$827.01	$681.18
	Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Mass Flow Sensor ($/system)	$100.00	$85.00	$73.00	$68.00	$65.00
	Total Cost ($/system)	$2,616.69	$1,364.16	$1,063.94	$954.11	$803.28
	Total Cost ($/$kW_{net}$)	$32.71	$17.05	$13.30	$11.93	$10.04
2010	Filter & Housing ($/system)	$51.70	$47.00	$47.00	$47.00	$47.00
	Compressor, Expander & Motor ($/system)	$1,710.33	$1,175.82	$868.72	$762.74	$630.33
	Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Mass Flow Sensor ($/system)	$100.00	$85.00	$73.00	$68.00	$65.00
	Total Cost ($/system)	$1,887.03	$1,327.82	$1,003.72	$891.74	$754.33
	Total Cost ($/$kW_{net}$)	$23.59	$16.60	$12.55	$11.15	$9.43
2015	Filter & Housing ($/system)	$51.70	$47.00	$47.00	$47.00	$47.00
	Compressor, Expander & Motor ($/system)	$1,201.78	$817.57	$593.45	$522.05	$429.20
	Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Mass Flow Sensor ($/system)	$100.00	$85.00	$73.00	$68.00	$65.00
	Total Cost ($/system)	$1,378.48	$969.57	$728.45	$651.05	$553.20
	Total Cost ($/$kW_{net}$)	$17.23	$12.12	$9.11	$8.14	$6.91

Figure 114. Cost breakdown for air loop

4.5.3. Humidifier and Water Recovery Loop

The humidifier and water recovery loop consists of the ten elements described below (though no system actually has all ten):

Water Pump and Motor: The cost was estimated by applying a 30% discount to the list price of an electric brushless motor water pump currently produced at high volume (2.7 gpm Series 893 from March Pumps).

Air Humidifier Assembly: A 2008 estimate based on a 6-element DFMA-style cost computation of a water spray injection humidifier.

Air Humidifier Thermocouple: The cost was based on use of a conventional thermocouple.

Air Demister: The cost was based on a simple can filled with a porous media to remove liquid water droplets from the air stream prior to exit.

Exhaust Air Condenser: The cost was based on a conventional automotive heat exchanger.

Exhaust Air Condenser Water Level Sensor: The cost was based on the expected price of a float-type level sensor at purchases of 30,000/year and adjusted for actual purchase quantity.

Exhaust Air Condenser Sump Pump: The cost was based on a standard small electric water pump rated for de-ionized water duty.

Water Reservoir: The cost was based on a molded plastic water tank.

Humidifier Loop Deionizer: The cost was based on a resin deionizer bed in a plastic housing.

Membrane Air Humidifier: A 2010 estimate based on a price quote from PermaPure for a 2,300 slpm fuel cell humidifier at 2.3 bar (FC300-1660-10HP): they cost $900 each at 1,000/year and $250 each at 500,000/year.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Water Pump & Motor ($/system)	$90.00	$80.00	$72.00	$69.00	$65.00
	Air Humidifier Assembly ($/system)	$174.63	$83.41	$81.24	$80.27	$78.93
	Air Humidifier Thermocouple ($/system)	$20.00	$16.00	$12.00	$11.20	$9.60
	Air Demister ($/system)	$37.50	$30.00	$22.50	$21.00	$18.00
	Exhaust Air Condensor ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Air Cond. Water Level Sensor ($/system)	$23.00	$18.40	$13.80	$12.88	$11.04
	Air Cond. Sump Pump ($/system)	$37.50	$30.00	$22.50	$21.00	$18.00
	Water Reservoir ($/system)	$50.00	$40.00	$30.00	$28.00	$24.00
	Humidifier Loop Deionizer ($/system)	$40.00	$32.00	$24.00	$22.40	$19.20
	Total Cost ($/system)	$535.13	$379.81	$315.54	$300.75	$273.77
	Total Cost ($/$kW_{net}$)	$6.69	$4.75	$3.94	$3.76	$3.42
2010	Membrane Air Humidifier ($/system)	$900.00	$600.00	$425.00	$350.00	$250.00
	Total Cost ($/system)	$900.00	$600.00	$425.00	$350.00	$250.00
	Total Cost ($/$kW_{net}$)	$11.25	$7.50	$5.31	$4.38	$3.13
2015	[Does Not Exist]					
	Total Cost ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/$kW_{net}$)	$0.00	$0.00	$0.00	$0.00	$0.00

Figure 115. Cost breakdown for humidifier & water recovery loop

4.5.4. Coolant Loops

The 2008 technology system has two coolant loops, a high-temperature loop to cool the fuel cell stacks and a low-temperature loop to condense the water vapor in the escaping exhaust. For the 2010 and 2015 technology systems, the exhaust loop is not included. Due to inefficiencies, the system loses about 75 kW of energy by heat that needs to be dissipated in the high temperature loop. With coolant liquid ΔT of 10°C, a fluid flow of 60 gallons per hour is required.

4.5.4.1. Coolant Loop (High Temperature)

Coolant Reservoir: The cost was based on a molded plastic water tank.

Coolant Pump: Small pumps to provide this flow are commercially available in large quantities at approximately $60 per pump at quantities of 1,000, dropping to $50 at high quantity.

Coolant DI Filter: The cost was based on a resin deionizer bed in a plastic housing.

Thermostat & Valve: The cost was based on standard automotive components.

Radiator: The heat dissipation requirements of the fuel cell system are similar to those of today's standard passenger cars. Consequently, costs for the high and low temperature loop radiators are aligned with those of appropriately sized radiators used in contemporary automotive applications.

Radiator Fan: The cost was based on standard automotive components.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Coolant Reservoir ($/system)	$18.75	$15.00	$11.25	$10.50	$9.00
	Coolant Pump ($/system)	$90.00	$80.00	$72.00	$69.00	$63.00
	Coolant DI Filter ($/system)	$75.00	$60.00	$45.00	$42.00	$36.00
	Thermostat & Valve ($/system)	$60.00	$48.00	$36.00	$33.60	$28.80
	Radiator ($/system)	$200.00	$180.00	$170.00	$160.00	$150.00
	Radiator Fan ($/system)	$85.00	$65.00	$50.00	$48.00	$45.00
	Total Cost ($/system)	$528.75	$448.00	$384.25	$363.10	$331.80
	Total Cost ($/$kW_{net}$)	$6.61	$5.60	$4.80	$4.54	$4.15
2010	Coolant Reservoir ($/system)	$18.75	$15.00	$11.25	$10.50	$9.00
	Coolant Pump ($/system)	$90.00	$80.00	$72.00	$69.00	$63.00
	Coolant DI Filter ($/system)	$75.00	$60.00	$45.00	$42.00	$36.00
	Thermostat & Valve ($/system)	$60.00	$48.00	$36.00	$33.60	$28.80
	Radiator ($/system)	$169.49	$152.54	$144.07	$135.59	$127.12
	Radiator Fan ($/system)	$85.00	$65.00	$50.00	$48.00	$45.00
	Total Cost ($/system)	$498.24	$420.54	$358.32	$338.69	$308.92
	Total Cost ($/$kW_{net}$)	$6.23	$5.26	$4.48	$4.23	$3.86
2015	Coolant Reservoir ($/system)	$18.75	$15.00	$11.25	$10.50	$9.00
	Coolant Pump ($/system)	$90.00	$80.00	$72.00	$69.00	$63.00
	Coolant DI Filter ($/system)	$75.00	$60.00	$45.00	$42.00	$36.00
	Thermostat & Valve ($/system)	$60.00	$48.00	$36.00	$33.60	$28.80
	Radiator ($/system)	$125.00	$112.50	$106.25	$100.00	$93.75
	Radiator Fan ($/system)	$85.00	$65.00	$50.00	$48.00	$45.00
	Total Cost ($/system)	$453.75	$380.50	$320.50	$303.10	$275.55
	Total Cost ($/$kW_{net}$)	$5.67	$4.76	$4.01	$3.79	$3.44

Figure 116. Cost breakdown for coolant loop

4.5.4.2. Exhaust Loop

As of the 2008 Update report, it was determined that some of the duties that the exhaust loop performs in the vehicle are not covered by the scope of this analysis. Because of this, only 67% of the exhaust loop cost is now included in the analysis, the fraction proportionate to the loops usage by the fuel cell system. Because the exhaust loop is not necessary in the 2010 and 2015 technology systems, this change only affects the 2008 system.

Water Pump: The low and high temperature loops require similar flow rates, so the same type of pump can be used in each.

Radiator: As with the radiator for the high-temperature coolant loop, the exhaust loop uses a radiator similar to those used in conventional automotive applications. It does not need to be as large as the one for the coolant loop however, so it is scaled down in cost.

Radiator Fan: The cost was based on standard automotive components.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
	Fractional Inclusion Percentage	67%	67%	67%	67%	67%
2008	Water Pump ($/system)	$90.00	$80.00	$72.00	$69.00	$65.00
	Radiator ($/system)	$100.00	$90.00	$85.00	$80.00	$75.00
	Radiator Fan ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Total Cost ($/system)	$253.17	$220.67	$195.17	$184.67	$170.67
	Total Cost ($/kW$_{net}$)	$3.16	$2.76	$2.44	$2.31	$2.13
2010	[Does Not Exist]					
	Total Cost ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/kW$_{net}$)	$0.00	$0.00	$0.00	$0.00	$0.00
2015	[Does Not Exist]					
	Total Cost ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/kW$_{net}$)	$0.00	$0.00	$0.00	$0.00	$0.00

Figure 117. Cost breakdown for exhaust loop

4.5.5. Fuel Loop

Per DOE system analysis guidelines, the hydrogen tank, the hydrogen pressure-relief device & regulator, and the hydrogen fueling receptacle were not included in the fuel cell power system cost analysis.

Pressure Transducer: The cost was based on an appropriately sized transducer by TTI, Incorporated. Based on discussions with TTI, it was estimated that this currently mass-manufactured part would cost $80 at low volume, decreasing to $50 at high volumes.

Hydrogen Proportional Valve: A proportional valve is used to meter high pressure hydrogen into the fuel lines and simultaneously conduct a pressure regulation function. The cost was based on the expected price of a hydrogen-rated valve at purchases of 30,000/year and adjusted for actual purchase quantity.

Hydrogen Low Flow Ejector/High Flow Ejector: An ejector system, based on the Bernoulli Principle, was used to combine low-pressure recycled hydrogen with high pressure hydrogen straight from the fuel tank. Two ejectors of fixed orifice diameter were used: one for high flow, one for low flow. The cost was based on previous discussions with ejector manufacturers and rough DFMA-style computations.

Hydrogen/Stack Inlet and Outlet Manifolds: The cost selected was a token amount to capture the fittings costs associated with the ejector system.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Pressure Transducer ($/system)	$100.00	$85.00	$70.00	$65.00	$60.00
	H_2 Proportional Valve ($/system)	$625.00	$500.00	$375.00	$350.00	$300.00
	H_2 Low Flow Ejector ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 High Flow Ejector ($/system)	$115.00	$92.00	$69.00	$64.40	$55.20
	H_2/Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	H_2/Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Total Cost ($/system)	$927.50	$747.00	$566.50	$528.40	$457.20
	Total Cost ($/kW$_{net}$)	$11.59	$9.34	$7.08	$6.61	$5.72
2010	Pressure Transducer ($/system)	$100.00	$85.00	$70.00	$65.00	$60.00
	H_2 Proportional Valve ($/system)	$625.00	$500.00	$375.00	$350.00	$300.00
	H_2 Low Flow Ejector ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 High Flow Ejector ($/system)	$115.00	$92.00	$69.00	$64.40	$55.20
	H_2/Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	H_2/Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Total Cost ($/system)	$927.50	$747.00	$566.50	$528.40	$457.20
	Total Cost ($/kW$_{net}$)	$11.59	$9.34	$7.08	$6.61	$5.72
2015	Pressure Transducer ($/system)	$100.00	$85.00	$70.00	$65.00	$60.00
	H_2 Proportional Valve ($/system)	$625.00	$500.00	$375.00	$350.00	$300.00
	H_2 Low Flow Ejector ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 High Flow Ejector ($/system)	$115.00	$92.00	$69.00	$64.40	$55.20
	H_2/Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	H_2/Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Total Cost ($/system)	$927.50	$747.00	$566.50	$528.40	$457.20
	Total Cost ($/kW$_{net}$)	$11.59	$9.34	$7.08	$6.61	$5.72

Figure 118. Cost breakdown for fuel loop

4.5.6. System Controllers

Conventional electronic engine controllers (EEC's) were assumed to control the fuel cell power system. These programmable circuit boards are currently mass produced for all conventional gasoline engines and are readily adaptable for fuel cell use. Prototype fuel cell vehicles may use four or more controllers out of convenience, so that each subsystem is able to have a separate controller. However, even at 1,000 vehicles per year, the system will be refined enough to minimize controller use out of cost and design simplicity rationale. A single EEC was judged necessary to supply adequate control and sensor leads to the power plant. Because EEC's are already manufactured in large quantities for gasoline vehicles, their cost is fairly constant and only varies from $300 to $200 each based on production rate. Figure 119 lists the estimated system controller costs.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	System Controllers per System	1	1	1	1	1
	System Controller ($)	$300.00	$245.00	$230.00	$222.00	$200.00
	Total Cost ($/system)	$300.00	$245.00	$230.00	$222.00	$200.00
	Total Cost ($/kW$_{net}$)	$3.75	$3.06	$2.88	$2.78	$2.50
2010	System Controllers per System	1	1	1	1	1
	System Controller ($)	$300.00	$245.00	$230.00	$222.00	$200.00
	Total Cost ($/system)	$300.00	$245.00	$230.00	$222.00	$200.00
	Total Cost ($/kW$_{net}$)	$3.75	$3.06	$2.88	$2.78	$2.50
2015	System Controllers per System	1	1	1	1	1
	System Controller ($)	$300.00	$245.00	$230.00	$222.00	$200.00
	Total Cost ($/system)	$300.00	$245.00	$230.00	$222.00	$200.00
	Total Cost ($/kW$_{net}$)	$3.75	$3.06	$2.88	$2.78	$2.50

Figure 119. Cost breakdown for system controller

4.5.7. Hydrogen Sensors

The vehicle will require a hydrogen sensing system to guard against hydrogen leakage accumulation and fire. It was postulated that a declining number of hydrogen sensors will be used within the fuel cell power system as a function of time and as real world safety data is accumulated. Consequently, it was estimated that two sensors would initially be used in the engine compartment, dropping to one in 2010, and zero in 2015. Additional sensors may be necessary for the passenger compartment and the fuel storage subsystem but these are not in the defined boundary of our fuel cell power system assessment.

The hydrogen sensor system specified is from Makel Engineering, based on the technology used in Ford's Model-U Hydrogen Powered Vehicle prototype. Each sensor unit (see Figure 120) is roughly the size of a quarter and contains two sensors: one for detecting large concentrations of hydrogen, and another for small concentrations. Each unit is accompanied by a control electronics box (also pictured in Figure 120).

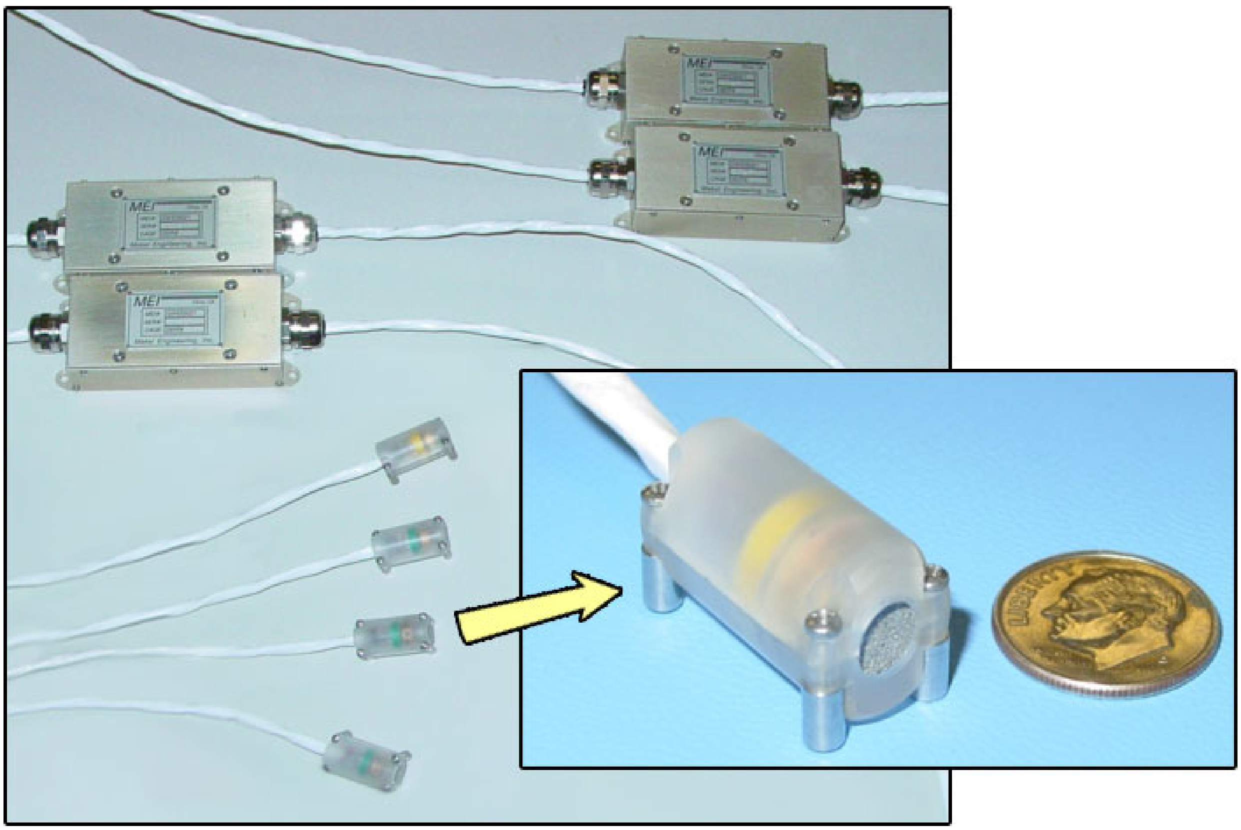

Figure 120. Hydrogen sensors & associated control electronics

Hydrogen sensors are currently quite expensive. The specified hydrogen sensors from Makel are currently hand built and cost approximately $850 each. Jeffrey Stroh from Makel estimates that such units would cost approximately $100 each if mass-produced at 500,000 per year. With further technology and manufacturing improvements, including a move to integrated circuitry, he estimates that the unit cost could drop to only $20 per sensor by the year 2015. However, since sensors were included in the 2015 system (which again does not include the passenger cabin or fuel storage), the cheapest sensor cost in the estimate is $50, in the 2010 system. Figure 121 lists the estimated hydrogen sensor costs.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Sensors per System	2	2	2	2	2
	Sensor ($)	$850.00	$438.00	$320.00	$261.00	$100.00
	Total Cost ($/system)	$1,700.00	$876.00	$640.00	$522.00	$200.00
	Total Cost ($/kW$_{net}$)	$21.25	$10.95	$8.00	$6.53	$2.50
2010	Sensors per System	1	1	1	1	1
	Sensor ($)	$750.00	$367.00	$256.00	$201.00	$50.00
	Total Cost ($/system)	$750.00	$367.00	$256.00	$201.00	$50.00
	Total Cost ($/kW$_{net}$)	$9.38	$4.59	$3.20	$2.51	$0.63
2015	Sensors per System	0	0	0	0	0
	Sensor ($)	$500.00	$238.00	$161.00	$124.00	$20.00
	Total Cost ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/kW$_{net}$)	$0.00	$0.00	$0.00	$0.00	$0.00

Figure 121. Cost breakdown for hydrogen sensors

4.5.8. Miscellaneous BOP

4.5.8.1. Belly Pan

This analysis is new to the 2008 Update. The belly pan is modeled as a 1 m by 1.5 m shallow rectangular pan, bolted to the underside of the fuel cell system to protect it from weather and other ambient conditions.

The belly pan manufacturing process was modeled as a vacuum thermoforming process, in which thin polypropylene sheets are softened with heat and sucked down on top of a one-sided mold. The capital cost of the vacuum thermoforming machine is approximately $300,000, and utilizes an optional automatic loading system, which costs another $200,000. If manual loading is selected, the process requires one laborer per line, instead of the 1/4 laborer facilitated by the automatic loading system. It was found that the automatic system is only cost effective at the 500,000 systems per year production rate. Naturally, the loading option also changes the time per part; the vacuum time is 8 seconds per part, on top of which the insertion time adds another 11.2 seconds for the manual loading, or 2 seconds for the automatic method. The process parameters are shown in Figure 122, and the machine rate parameters are shown in Figure 123.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Machine Selection	Vacuum Thermo-former #1	Vacuum Thermo-former #1	Vacuum Thermo-former #2	Vacuum Thermo-former #2	Vacuum Thermo-former #2
	Assembly Type	Manual	Manual	Manual	Manual	Auto
	Capital Cost ($/Line)	$50,000	$50,000	$250,000	$250,000	$450,000
	Costs per Tooling Set ($)	$106,434	$106,434	$106,434	$106,434	$106,434
	Tooling Lifetime (years)	3	3	3	3	3
	Cavities per Platen	1	1	1	1	1
	Total Cycle Time (s)	71.20	71.20	15.20	15.20	7.00
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1	1	1	1	0.25
	Line Utilization	0.59%	17.66%	10.05%	16.34%	28.94%
	Effective Total Machine Rate ($/hr)	$1,136.18	$83.62	$310.12	$209.19	$178.45
	Material Cost ($/kg)	$1.31	$1.31	$1.31	$1.31	$1.31
2010	Machine Selection	Vacuum Thermo-former #1	Vacuum Thermo-former #1	Vacuum Thermo-former #2	Vacuum Thermo-former #2	Vacuum Thermo-former #2
	Assembly Type	Manual	Manual	Manual	Manual	Auto
	Capital Cost ($/Line)	$50,000	$50,000	$250,000	$250,000	$450,000
	Costs per Tooling Set ($)	$106,434	$106,434	$106,434	$106,434	$106,434
	Tooling Lifetime (years)	3	3	3	3	3
	Cavities per Platen	1	1	1	1	1
	Total Cycle Time (s)	71.20	71.20	15.20	15.20	7.00
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1	1	1	1	0.25
	Line Utilization	0.59%	17.66%	10.05%	16.34%	28.94%
	Effective Total Machine Rate ($/hr)	$1,136.18	$83.62	$310.12	$209.19	$178.45
	Material Cost ($/kg)	$1.31	$1.31	$1.31	$1.31	$1.31
2015	Machine Selection	Vacuum Thermo-former #1	Vacuum Thermo-former #1	Vacuum Thermo-former #2	Vacuum Thermo-former #2	Vacuum Thermo-former #2
	Assembly Type	Manual	Manual	Manual	Manual	Auto
	Capital Cost ($/Line)	$50,000	$50,000	$250,000	$250,000	$450,000
	Costs per Tooling Set ($)	$106,434	$106,434	$106,434	$106,434	$106,434
	Tooling Lifetime (years)	3	3	3	3	3
	Cavities per Platen	1	1	1	1	1
	Total Cycle Time (s)	71.20	71.20	15.20	15.20	7.00
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1	1	1	1	0.25
	Line Utilization	0.59%	17.66%	10.05%	16.34%	28.94%
	Effective Total Machine Rate ($/hr)	$1,136.18	$83.62	$310.12	$209.19	$178.45
	Material Cost ($/kg)	$1.31	$1.31	$1.31	$1.31	$1.31

Figure 122. Belly pan thermoforming process parameters

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008/ 2010/ 2015	Equipment Lifetime	8	8	15	15	15
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.229	0.229	0.175	0.175	0.175
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	5%	5%	5%	5%	5%
	Miscellaneous Expenses (% of CC)	6%	6%	6%	6%	6%
	Power Consumption (kW)	30	30	35	35	40

Figure 123. Machine rate parameters for belly pan thermoforming process

Because of the extremely soft nature of the hot polypropylene and the low impact of the process, each mold ($85,056) will easily last the entire lifetime of the machine. However, designs are likely to change well before the machine wears out, so the mold's lifetime was set at three years. This means that the tooling costs are sufficiently low to be ignored at all but the 1,000 systems per year level, where they account for almost 4% of the part cost. Figure 124 shows the cost breakdown.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Materials ($/system)	$3.88	$3.88	$3.88	$3.88	$3.88
	Manufacturing ($/system)	$22.47	$1.65	$1.31	$0.88	$0.35
	Tooling ($/system)	$39.91	$1.33	$0.44	$0.27	$0.07
	Total Cost ($/system)	$66.27	$6.87	$5.64	$5.04	$4.30
	Total Cost ($/kW$_{net}$)	$0.83	$0.09	$0.07	$0.06	$0.05
2010	Materials ($/system)	$3.88	$3.88	$3.88	$3.88	$3.88
	Manufacturing ($/system)	$22.47	$1.65	$1.31	$0.88	$0.35
	Tooling ($/system)	$39.91	$1.33	$0.44	$0.27	$0.07
	Total Cost ($/system)	$66.27	$6.87	$5.64	$5.04	$4.30
	Total Cost ($/kW$_{net}$)	$0.83	$0.09	$0.07	$0.06	$0.05
2015	Materials ($/system)	$3.88	$3.88	$3.88	$3.88	$3.88
	Manufacturing ($/system)	$22.47	$1.65	$1.31	$0.88	$0.35
	Tooling ($/system)	$39.91	$1.33	$0.44	$0.27	$0.07
	Total Cost ($/system)	$66.27	$6.87	$5.64	$5.04	$4.30
	Total Cost ($/kW$_{net}$)	$0.83	$0.09	$0.07	$0.06	$0.05

Figure 124. Cost breakdown for belly pan

4.5.8.2. Wiring

Prior to the 2008 analysis, the wiring costs were estimated via a rough approximation of the total wiring length required. Because the wiring costs were the largest contributor to the Miscellaneous BOP category, they were investigated more closely, and a detailed component specification and cost estimation were conducted. As in the previous analyses, these costs include only the materials, because the wiring installation costs are covered under the system assembly calculations.

The system schematics were examined and it was determined where cables were needed and whether they were for transmission of data, power, or both. Cable types were then selected based on the maximum current required by each electrical component. For each of the three technology levels, this worked out to be seven different types of cables in each system, though there was one type unique to the current technology, and another that was only used in the 2010 and 2015 systems. See Figure 125 for details.

	2008		2010		2015	
	Quantity	Length (m)	Quantity	Length (m)	Quantity	Length (m)
Cable Types						
Power Cable, OOOO Gauge	2	1.6	2	1.6	2	1.6
Power Cable, 1 Gauge	0	0	0	0	0	0
Power Cable, 3 Gauge	1	0.25	0	0	0	0
Power Cable, 4 Gauge	0	0	1	0.25	1	0.25
Power Cable, 6 Gauge	2	1.5	1	1	1	1
Power Cable, 7 Gauge	4	4	3	3	3	2.5
Power Cable, 9 Gauge	5	5	3	2.5	2	2
Power Cable, 12 Gauge	3	3	2	2	2	2
Data Cable, 16 Gauge	22	22	14	14	11	11
Totals	**39**	**37.35**	**26**	**24.35**	**22**	**20.35**

Figure 125. Wiring details

With the exception of the heavy-duty power cables attached to the current collectors, every cable was comprised of multiple wires. Each cable also required a unique type of connector, of which two were needed for each cable.

It was assumed that the wires and connectors would be purchased rather than manufactured in-house, and high-volume pricing estimates were obtained for the cable components from Waytek, Inc. Taking into account the required length of each cable, the number of wires per cable, and selecting the appropriate connectors, the component prices were applied to the wiring bill of materials and the total wiring cost was calculated for each system (see Figure 126).

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Cables ($/system)	$91.80	$78.95	$77.11	$76.19	$73.44
	Connectors ($/system)	$120.26	$103.43	$101.02	$99.82	$96.21
	Total Cost ($/system)	$212.06	$182.37	$178.13	$176.01	$169.65
	Total Cost ($/kW$_{net}$)	$2.65	$2.28	$2.23	$2.20	$2.12
2010	Cables ($/system)	$71.52	$61.51	$60.08	$59.36	$57.22
	Connectors ($/system)	$88.36	$75.99	$74.23	$73.34	$70.69
	Total Cost ($/system)	$159.89	$137.50	$134.30	$132.71	$127.91
	Total Cost ($/kW$_{net}$)	$2.00	$1.72	$1.68	$1.66	$1.60
2015	Cables ($/system)	$66.01	$56.77	$55.45	$54.79	$52.81
	Connectors ($/system)	$78.99	$67.93	$66.35	$65.56	$63.19
	Total Cost ($/system)	$145.00	$124.70	$121.80	$120.35	$116.00
	Total Cost ($/kW$_{net}$)	$1.81	$1.56	$1.52	$1.50	$1.45

Figure 126. Cost breakdown for wiring

4.5.8.3. Other Miscellaneous BOP Components

Air Ducting, Water Line Tubing, Coolant Liquid Piping, Hydrogen Piping/Ducting Materials, Cathode Gas Ducting, Anode Gas Ducting, and Fasteners for Wire/Hose/Pipe: A detailed DFMA analysis was not conducted for these components since the level of detailed required is well outside the bounds of this project. However, these components are necessary and, in aggregate, are of substantial cost. Consequently, they are enumerated individually to provide full transparency of our assumptions. Prior to the 2008 Update, a startup battery was included in this list. It was determined that although the battery is still a necessary component, it should not be book-kept as part of the fuel cell system, so it was removed from our cost analysis.

Figure 127 shows the cost breakdown for these components. Note that the wiring and belly pan are still included in the table, to show their costs relative to the other components, and because they are grouped under the "Miscellaneous" section of the bills of materials for the balance of plant (Figure 6, Figure 9, & Figure 12)

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Wiring ($/system)	$212.06	$182.37	$178.13	$176.01	$169.65
	Air Ducting ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Water Tubing ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Coolant Liquid Piping ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 Piping/Ducting Materials ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Cathode Ducting ($/system)	$87.50	$70.00	$52.50	$49.00	$42.00
	Anode Ducting ($/system)	$65.00	$52.00	$39.00	$36.40	$31.20
	Fasteners for Wire, Hose, Pipe ($/system)	$73.96	$60.44	$49.46	$47.14	$42.29
	Belly Pan for Fuel Cell System ($/system)	$66.27	$6.87	$5.64	$5.04	$4.30
	Total Cost ($/system)	$879.79	$671.68	$549.73	$523.59	$469.44
	Total Cost ($/kW$_{net}$)	$11.00	$8.40	$6.87	$6.54	$5.87
2010	Wiring ($/system)	$159.89	$137.50	$134.30	$132.71	$127.91
	Air Ducting ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Water Tubing ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Coolant Liquid Piping ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 Piping/Ducting Materials ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Cathode Ducting ($/system)	$87.50	$70.00	$52.50	$49.00	$42.00
	Anode Ducting ($/system)	$65.00	$52.00	$39.00	$36.40	$31.20
	Fasteners for Wire, Hose, Pipe ($/system)	$73.96	$60.44	$49.46	$47.14	$42.29
	Belly Pan for Fuel Cell System ($/system)	$66.27	$6.87	$5.64	$5.04	$4.30
	Total Cost ($/system)	$827.61	$626.81	$505.90	$480.29	$427.70
	Total Cost ($/kW$_{net}$)	$10.35	$7.84	$6.32	$6.00	$5.35
2015	Wiring ($/system)	$145.00	$124.70	$121.80	$120.35	$116.00
	Air Ducting ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Water Tubing ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Coolant Liquid Piping ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 Piping/Ducting Materials ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Cathode Ducting ($/system)	$87.50	$70.00	$52.50	$49.00	$42.00
	Anode Ducting ($/system)	$65.00	$52.00	$39.00	$36.40	$31.20
	Fasteners for Wire, Hose, Pipe ($/system)	$73.96	$60.44	$49.46	$47.14	$42.29
	Belly Pan for Fuel Cell System ($/system)	$66.27	$6.87	$5.64	$5.04	$4.30
	Total Cost ($/system)	$812.72	$614.00	$493.40	$467.93	$415.78
	Total Cost ($/kW$_{net}$)	$10.16	$7.68	$6.17	$5.85	$5.20

Figure 127. Cost breakdown for miscellaneous/BOP components

4.5.9. System Assembly

A detailed analysis of system assembly was not conducted since that would require detailed specification of all assembly steps including identification of all screws, clips, brackets, and a definition of specific component placement within the system. Such an analysis is clearly beyond the scope of this project. Instead, an estimate of system assembly time was obtained by breaking the system down into five categories of assembly components (major, minor, piping, hoses, wiring), estimating the number of components within each category, and then postulating a time to assemble each of those components. Specific assumptions and total estimated assembly time for manual assembly is shown in Figure 128.

	Number of Components	Component Placement Time (seconds)	Component Fixation Time (seconds)	Component Totals (minutes)
Major Components (Stack, motors, pumps, vessels, etc.)	**19**	**45**	**60**	**33.3**
Minor Components (instruments, devices, etc.)	**22**	**30**	**45**	**27.5**
Piping				
# of pipe segments		**5**		
bends per segment		**2**		
time per bend		**0**		
pipe placement time		**30**		
# welds per pipe		**2**		
weld time		**90**		
# threaded ends per pipe		**0**		
threading time		**0**		
				17.5
Hoses	**21**	**30**	105	**47.3**
Wiring (manual)	**23**	**41.8**	66.7	**41.6**
System Basic Functionality Test				**10.0**
Total System Assembly Time				**177.1**

Figure 128. Single-station system assembly assumptions

Two types of system assembly methods were examined: single-station and assembly line. In single-station assembly approach, a single workstation is used to conduct assembly of the entire fuel cell power plant. Very little custom machinery is needed to assemble the system and, and the components and subsystems are arrayed around the workstation for easy access. For 1,000 systems per year, only one such workstation is required.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	Assembly Method	Single Station	Assembly Line	Assembly Line	Assembly Line	Assembly Line
	Index Time (min)	177.1	14.2	14.2	14.2	14.2
	Capital Cost ($/Line)	$50,000	$150,000	$150,000	$150,000	$150,000
	Simultaneous Lines	1	3	6	10	36
	Laborers per Line	1.00	10.00	10.00	10.00	10.00
	Line Utilization	87.84%	70.27%	93.70%	91.36%	97.60%
	Effective Total Machine Rate ($/hr)	$53.82	$483.55	$475.36	$475.99	$474.37
	Cost per Stack ($)	$158.84	$114.18	$112.24	$112.39	$112.01
2010	Assembly Method	Single Station	Assembly Line	Assembly Line	Assembly Line	Assembly Line
	Index Time (min)	177.1	14.2	14.2	14.2	14.2
	Capital Cost ($/Line)	$50,000	$150,000	$150,000	$150,000	$150,000
	Simultaneous Lines	1	3	6	10	36
	Laborers per Line	1.00	10.00	10.00	10.00	10.00
	Line Utilization	87.84%	70.27%	93.70%	91.36%	97.60%
	Effective Total Machine Rate ($/hr)	$53.74	$482.78	$474.58	$475.21	$473.60
	Cost per Stack ($)	$158.62	$113.99	$112.06	$112.21	$111.83
2015	Assembly Method	Single Station	Assembly Line	Assembly Line	Assembly Line	Assembly Line
	Index Time (min)	177.1	14.2	14.2	14.2	14.2
	Capital Cost ($/Line)	$50,000	$150,000	$150,000	$150,000	$150,000
	Simultaneous Lines	1	3	6	10	36
	Laborers per Line	1.00	10.00	10.00	10.00	10.00
	Line Utilization	87.84%	70.27%	93.70%	91.36%	97.60%
	Effective Total Machine Rate ($/hr)	$53.74	$482.78	$474.58	$475.21	$473.60
	Cost per Stack ($)	$158.62	$113.99	$112.06	$112.21	$111.83

Figure 129. System assembly process parameters

The assembly for all other annual production rates uses a ten-workstation assembly line configuration. Each fuel cell system flows through the assembly line sequentially. The line reduces the total cumulative time required for system assembly because workers at each workstation on the line have their tools and components closer at hand than they do under the single workstation approach, and because tool changes are minimized due to the higher repetitive nature of an assembly line. This method is approximately 20% faster than the single-workstation approach, with an assembly line index time[68] of only 14.2 minutes. The system assembly cost is detailed in Figure 130.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008	System Assembly & Testing ($/system)	$158.84	$114.18	$112.24	$112.39	$112.01
	Total Cost ($/system)	$158.84	$114.18	$112.24	$112.39	$112.01
	Total Cost ($/kW$_{net}$)	$1.99	$1.43	$1.40	$1.40	$1.40
2010	System Assembly & Testing ($/system)	$158.62	$113.99	$112.06	$112.21	$111.83
	Total Cost ($/system)	$158.62	$113.99	$112.06	$112.21	$111.83
	Total Cost ($/kW$_{net}$)	$1.98	$1.42	$1.40	$1.40	$1.40
2015	System Assembly & Testing ($/system)	$158.62	$113.99	$112.06	$112.21	$111.83
	Total Cost ($/system)	$158.62	$113.99	$112.06	$112.21	$111.83
	Total Cost ($/kW$_{net}$)	$1.98	$1.42	$1.40	$1.40	$1.40

Figure 130. Cost breakdown for system assembly & testing

4.5.10. System Testing

A ten-minute system functionality and performance test is included in the system assembly process. The stack has separately undergone multiple hours of testing as part of stack conditioning and thus there is high confidence

[68] Assembly line index time is defined as the time interval each system spends at a given workstation.

in the stack performance. System testing is only needed to ensure that the peripheral systems are functioning properly and adequately supporting the stack. Typically, the only testing of gasoline engines contained within automobiles is a simple engine start-up as the vehicle is driven off the assembly line. Corresponding, the fuel cell "engine" is only minimally tested for functionality. Cost for this system testing is reported under system assembly.

4.5.11. Cost Contingency

It is common practice in the automotive industry[69] to include a 10% cost contingency to cover the cost of procedures or materials not already explicitly covered in the analysis, which serves as a guard against an underestimation of cost. However, no such contingency has been included in this cost analysis. It was omitted upon the request of the DOE, in order to present purer baseline cost estimates.

[69] Based on personal communication with Bob Mooradian, Ford Motor Company.

5. Sensitivity Analysis

In order to evaluate which factors have the greatest impact on the total system cost, a sensitivity analysis was conducted on key parameters. These parameters, along with their upper and lower bounds, are shown in Figure 131, Figure 133 and Figure 135. As is immediately seen in the tornado charts in Figure 132, Figure 134, and Figure 136, power density, platinum loading, and platinum cost are by far the most dominant parameters in the stack. Narrowing the uncertainty span in these parameters will greatly improve confidence in the cost estimates. These bounds will be examined in greater detail in future work.

System Cost ($/kW$_{net}$): 2008 Technology, 500,000 systems/year				Input		
Variable	Downside	Upside	Range	Downside	Upside	Base Case
Power Density (mW/cm^2)	$86.48	$58.05	$28.43	546	1,411	715
Platinum Loading (mg/cm^2)	$70.12	$98.33	$28.21	0.17	0.61	0.25
Platinum Cost ($/tr.oz.)	$72.60	$99.39	$26.79	$920	$2,879	$1,100
Membrane Cost ($/m^2)	$73.08	$80.91	$7.83	$7.78	$53.82	$19.46
Macroporous GDL Cost ($/m^2)	$73.25	$80.86	$7.61	$4.31	$26.67	$9.63
Bipolar Plate Coatings ($/kW$_{net}$)	$73.84	$77.67	$3.83	$0.26	$4.09	$1.48
Labor Rate ($/hr)	$74.15	$77.01	$2.86	$28	$80	$45
MEA Frame/Gasket Injection Cycle Time (sec)	$74.39	$75.72	$1.33	51	189	120
Stack Conditioning (hrs)	$74.84	$75.33	$0.49	1	10	5
Bipolar Plate Stamping Capital Cost ($)	$74.91	$75.27	$0.36	$159,082	$932,108	$487,857
Ionomer Cost ($/kg)	$75.05	$75.11	$0.07	$46	$309	$112
Base System Cost ($/kW$_{net}$)	**$75.07**					

Figure 131. Sensitivity analysis parameters - 2008 technology, 500,000 systems/year

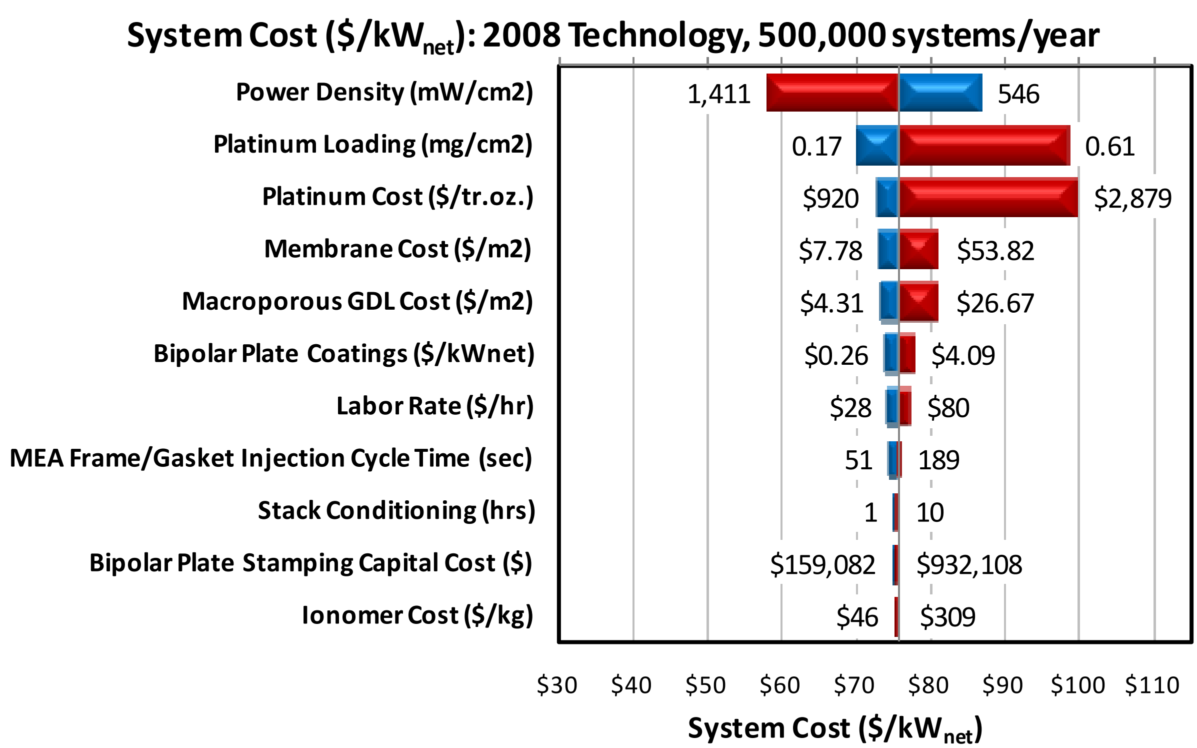

Figure 132. Sensitivity analysis tornado chart - 2008 technology, 500,000 systems/year

System Cost ($/kW$_{net}$): 2010 Technology, 500,000 systems/year				Input		
Variable	Downside	Upside	Range	Downside	Upside	Base Case
Power Density (mW/cm^2)	$82.16	$53.54	$28.61	571	1,429	1,000
Platinum Loading (mg/cm^2)	$53.28	$75.62	$22.34	0.11	0.61	0.30
Platinum Cost ($/tr.oz.)	$59.75	$81.92	$22.16	$920	$2,879	$1,100
Membrane Cost ($/m^2)	$60.15	$66.39	$6.24	$8.26	$61.45	$22.23
Macroporous GDL Cost ($/m^2)	$60.54	$65.79	$5.25	$4.31	$26.67	$9.63
Bipolar Plate Coatings ($/kW$_{net}$)	$60.73	$64.04	$3.31	$0.22	$3.53	$1.28
Labor Rate ($/hr)	$60.93	$63.62	$2.70	$28	$80	$45
MEA Frame/Gasket Injection Cycle Time (sec)	$61.31	$62.22	$0.91	51	189	120
Stack Conditioning (hrs)	$61.62	$62.11	$0.49	1	10	4
Bipolar Plate Stamping Capital Cost ($)	$61.66	$61.98	$0.32	$158,114	$931,277	$475,244
Ionomer Cost ($/kg)	$61.77	$61.84	$0.07	$50	$383	$139
Base System Cost ($/kW$_{net}$)	**$61.79**					

Figure 133. Sensitivity analysis parameters - 2010 technology, 500,000 systems/year

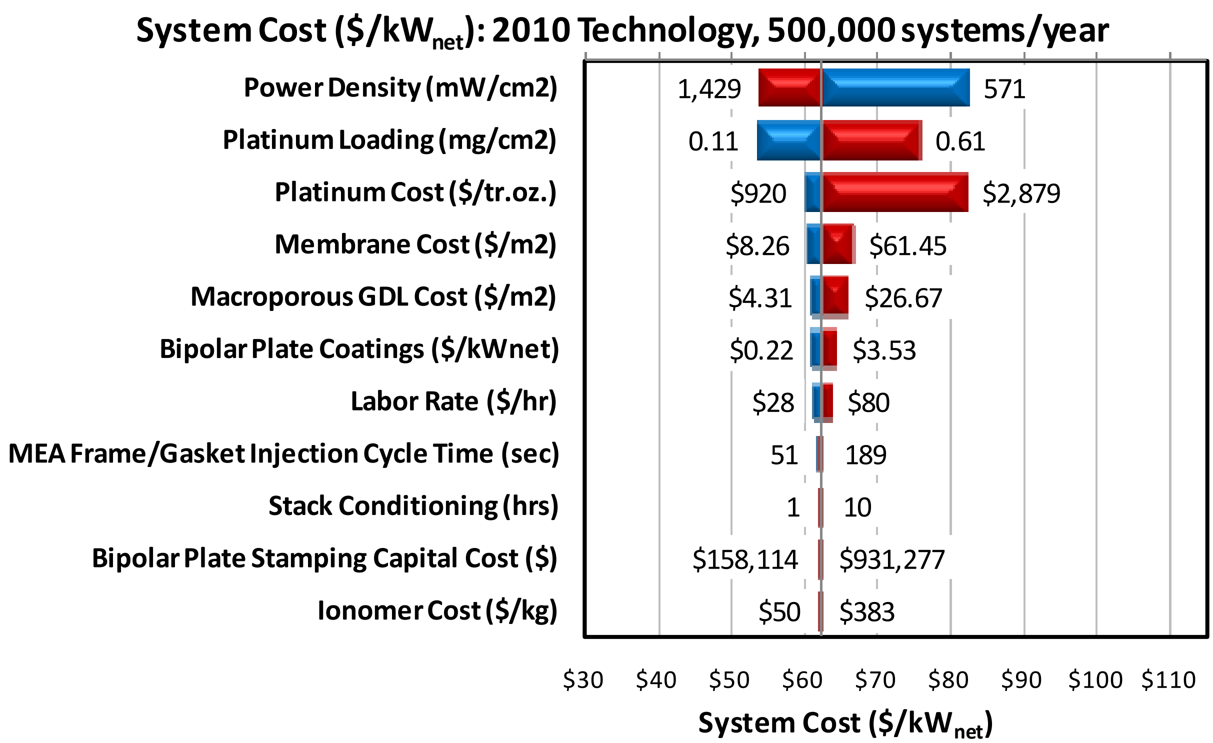

Figure 134. Sensitivity analysis tornado chart - 2010 technology, 500,000 systems/year

System Cost ($/kW$_{net}$): 2015 Technology, 500,000 systems/year				Input		
Variable	Downside	Upside	Range	Downside	Upside	Base Case
Power Density (mW/cm^2)	$67.61	$43.69	$23.92	571	1,429	1,000
Platinum Loading (mg/cm^2)	$44.91	$68.57	$23.66	0.07	0.61	0.20
Platinum Cost ($/tr.oz.)	$49.23	$64.06	$14.83	$920	$2,879	$1,100
Membrane Cost ($/m^2)	$48.94	$55.21	$6.27	$8.26	$61.52	$22.25
Macroporous GDL Cost ($/m^2)	$49.34	$54.60	$5.27	$4.31	$26.67	$9.63
Bipolar Plate Coatings ($/kW$_{net}$)	$49.53	$52.84	$3.31	$0.22	$3.54	$1.28
Labor Rate ($/hr)	$49.73	$52.41	$2.68	$28	$80	$45
MEA Frame/Gasket Injection Cycle Time (sec)	$50.11	$51.02	$0.92	51	189	120
Stack Conditioning (hrs)	$50.46	$50.96	$0.49	1	10	3
Bipolar Plate Stamping Capital Cost ($)	$50.46	$50.78	$0.32	$158,125	$931,287	$475,386
Ionomer Cost ($/kg)	$50.58	$50.63	$0.05	$51	$385	$139
Base System Cost ($/kW$_{net}$)	**$50.59**					

Figure 135. Sensitivity analysis parameters - 2015 technology, 500,000 systems/year

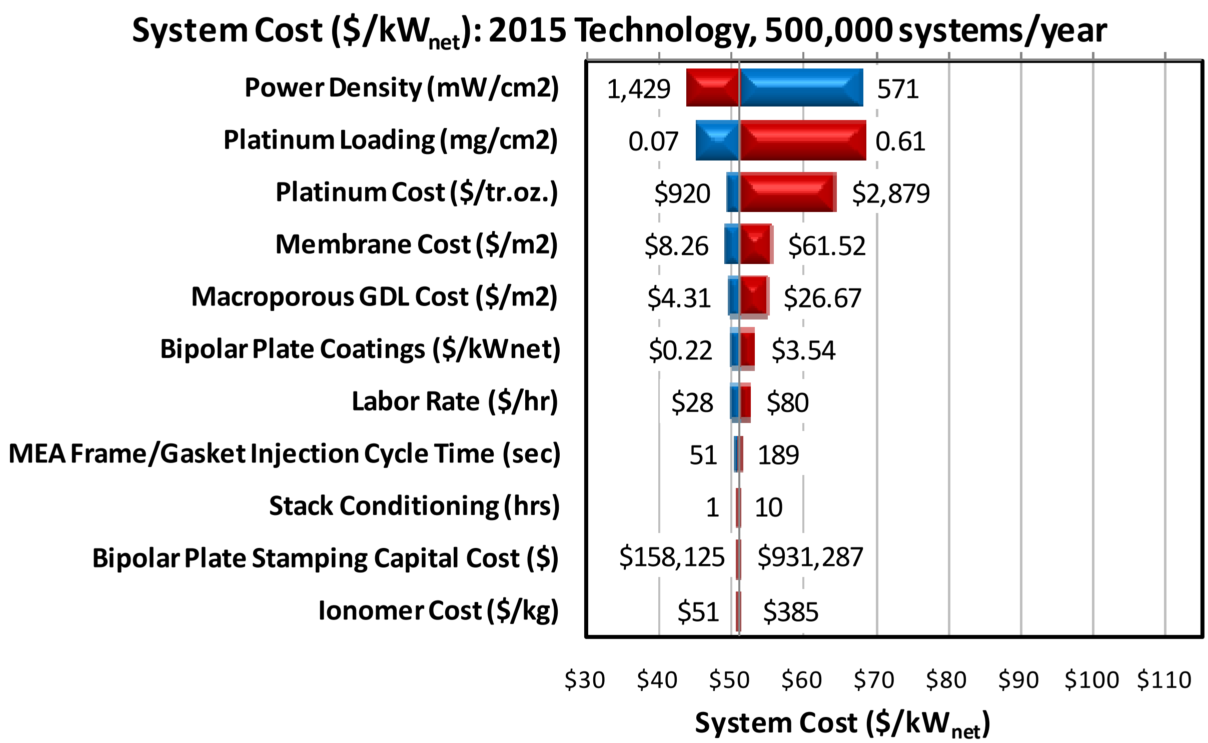

Figure 136. Sensitivity analysis tornado chart - 2015 technology, 500,000 systems/year

6. Conclusions

Figure 137 and Figure 138 (repeats of Figure 14 and Figure 15) graphically summarize the cost trends for the $80kW_{net}$ PEM fuel cell stacks and systems.

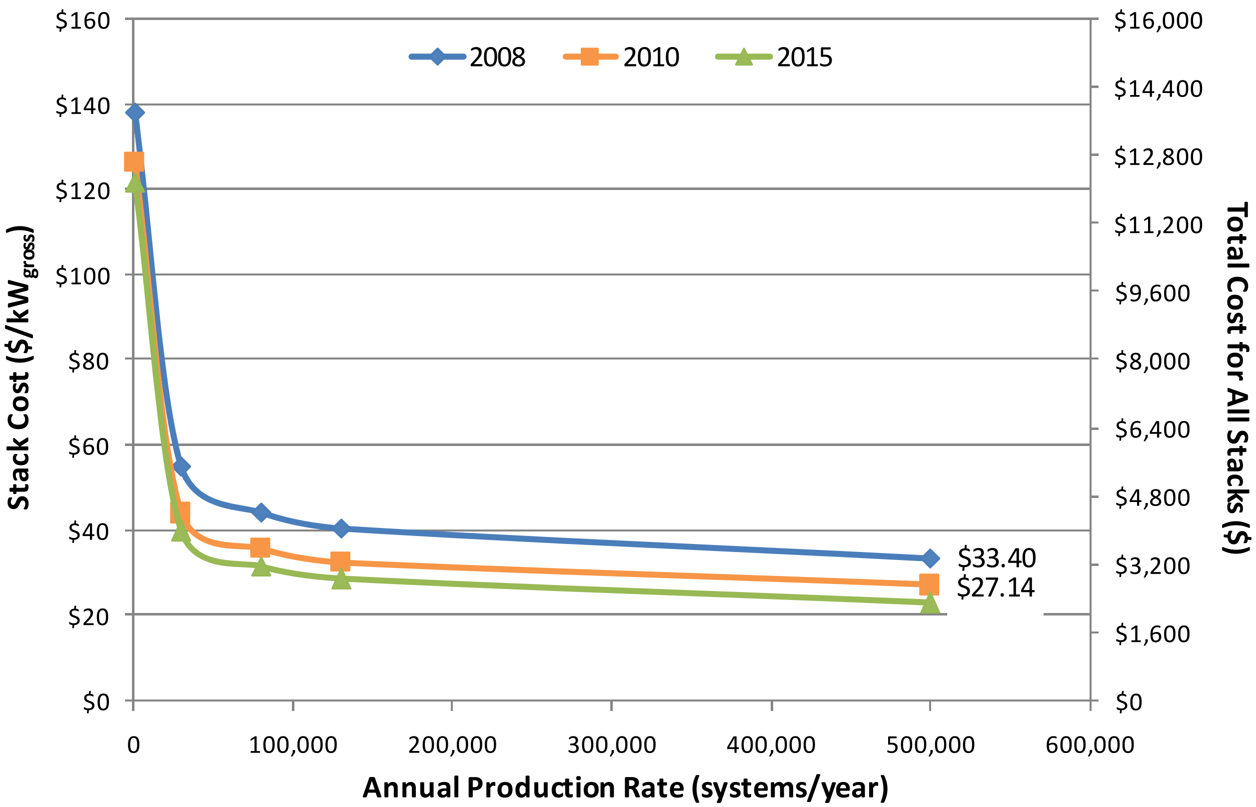

Figure 137. Gross stack cost vs. annual production rate

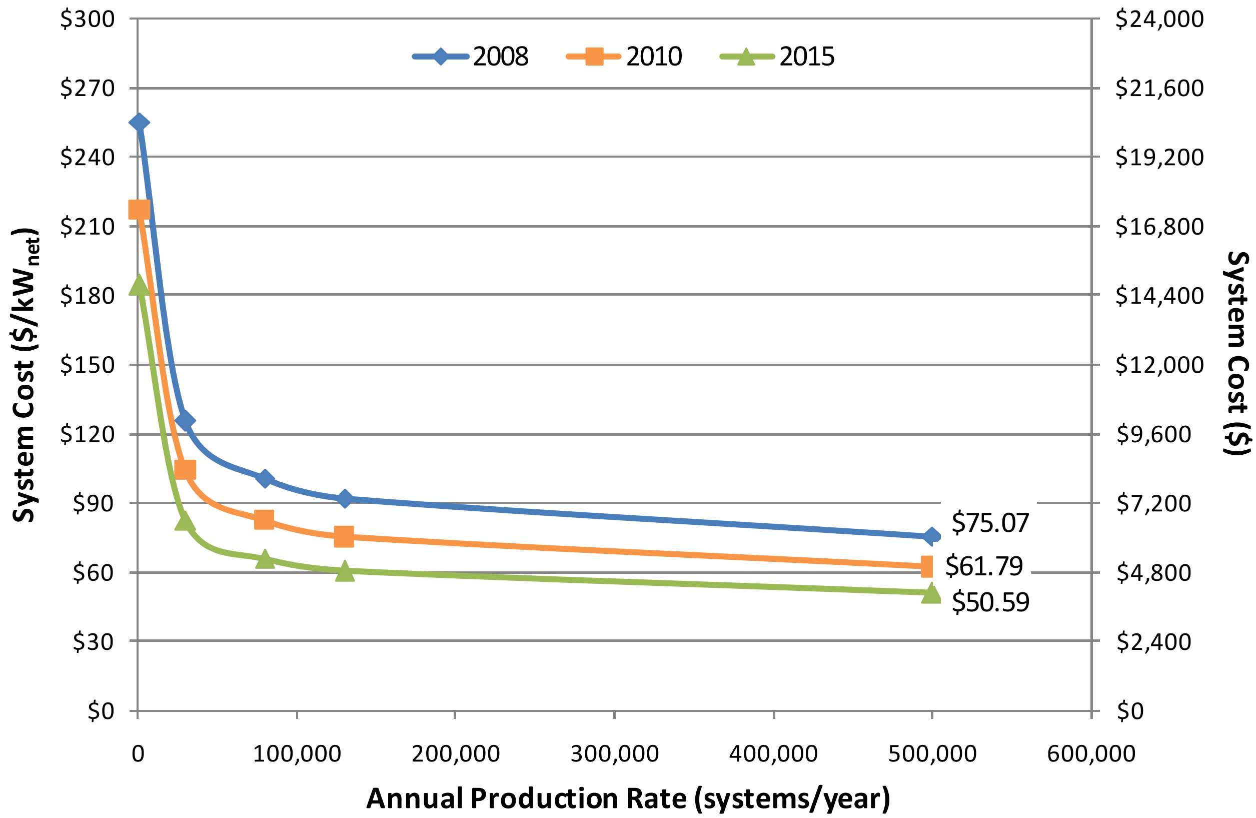

Figure 138. Net system cost vs. annual production rate

Source	Characteristic	Units	2008	2010	2015
DOE Target:	Stack Cost	$/kW$_{e\ (net)}$	**-**	**$25**	**$15**
Study Estimate:	Stack Cost	$/kW$_{e\ (net)}$	**$38**	**$29**	**$25**
DOE Target:	System Cost	$/kW$_{e\ (net)}$	**-**	**$45**	**$30**
Study Estimate:	System Cost	$/kW$_{e\ (net)}$	**$75**	**$62**	**$51**

Figure 139. DOE targets vs. DTI estimates for the stack & system

Key conclusions from the analysis include:

- Projections for the 2010 and 2015 technology systems are estimated at approximately $4-10/kW$_{net}$ higher than DOE targets for the stack and $17-21/kW$_{net}$ higher than DOE targets for the system.

- Substantial cost reductions (factors of 3-5) were achieved by increasing manufacturing volume from 1,000 to 500,000 systems per year production rate.

- 72% of the cost reduction between high (500,000 systems per year) and low production (1,000 systems per year) is achieved at the 30,000 systems per year production rate. 91% of the cost reduction is achieved at the 130,000 systems per year production rate.

- Balance of plant (BOP) elements (i.e. everything other than the fuel cell stacks) represents a large portion of total system cost (50-52%). Consequently, R&D to reduce, simplify, or eliminate BOP components is needed to achieve a significant overall system cost reduction.

- Four subsystems account for 79% of BOP costs: air compression, sensors/controllers, fuel loop (i.e. hydrogen pressure control), and wiring/piping/manifolding.

- BOP costs drop significantly as technology level advances due to simplification of the air compressor, humidification, and H_2 sensor subsystems. R&D is needed to ensure that these projected advances are achieved.

- While only a preliminary system assembly analysis was conducted, a maximum cost of $1.99/$kW_{net}$ is indicated, and only half of that at 500,000 systems per year. A more detailed analysis is required to improve confidence in this estimate.

- Metallic stamped bipolar plates and injected molded polymer bipolar plates are both economically viable pathways and have a projected cost of $4-20/$kW_{gross}$ across all production rates examined.
  - Performance and longevity issues may be a larger factor than cost in selecting between metallic plates and molded plates.
  - Appropriate alloy selection for metallic bipolar plates may obviate costly anti-corrosion coatings.

- A large advance in stack power density (from 715 mW/cm^2 to 1,000 mW/cm^2) is expected to occur between 2008 and 2010 as a result of improvements in basic membrane and MEA performance. This power density improvement results in a stack cost reduction of approximately 38%. Should this power density improvement not incur, stack costs will be much increased.

- Membrane cost is expected to drop a factor of 10 due primarily to mass production methods. Material cost of the Nafion ionomer (or some other ion conductive ionomer) likewise is expected to drop 10 fold in cost.

- Consistent with this analysis's goal of estimating the future fuel cell system cost based on expected advances in fuel cell technology, advanced membranes were postulated that simultaneously achieve improved performance (1,000 mW/cm^2) at elevated peak temperatures (120°C). Such performance is currently unachievable and the pathway to achievement is not clear. Consequently, this analysis estimates membrane cost as if a standard Nafion membrane is used in the future even though a substantially different chemistry membrane will almost undoubtedly be used.

- Even though platinum catalyst loadings are expected to drop (from 0.25 $mgPt/cm^2$ to 0.20 $mgPt/cm^2$) between 2008 and 2015, the catalyst still remains a significant cost element in the stack ($9-22/$kW_{net}$).

- High-speed catalyst application via roll-to-roll processing equipment holds promise in slashing application costs to ~$0.1/$kW_{net}$. However, such techniques must achieve excellent MEA performance - a point not yet proven.

- The gas diffusion layer (GDL) ranges from $3/$kW_{net}$ to $27/$kW_{net}$ and is identified as a significant cost element within the stack. While currently envisioned as a macroporous carbon electrode with a secondary microporous layer, alternate materials and fabrication methods should be explored to reduce cost.

- Hot pressing of the MEA and cutting it to cell size were observed to be minor cost elements.

- A polymer gasket insertion-molded around the MEA is seen to be a cost viable design and manufacturing concept consistent with system operation and the economically processing of the subcomponents. Costs are estimated at \$3-6/kW_{net}.

- Stack assembly using either manual or robotic assembly is relatively inexpensive: \$0.45/kW_{net} to \$0.99/kW_{net}.

- Stack conditioning to improve MEA performance is estimated at <\$1/kW_{net} based on an extrapolation of current procedures.

- The sensitivity analysis reveals that uncertainties in power density, platinum loading, and platinum cost lead to significant changes in the total system cost. Uncertainties in all other parameters have much smaller potential impact.