Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: *2010 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 gasses and pollutants than conventional internal combustion engine (ICE), advanced ICE, hybrid, or 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 to indicate how much a typical automotive fuel cell system would cost if produced in large quantities (up to 500,000 vehicles per year).

The capacity to produce fuel cell systems at high manufacturing rates does not yet exist, and significant investments will 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 analyses are conducted to explore the effects 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. The transparency of the assumptions and methodology serve to strengthen the validity of the analysis. 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 fourth 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 three different technology levels: a "current" system that reflected 2006 technology, a system based on projected 2010 technology, and another system based on projections for 2015. The 2007 Update report incorporated technology advances made in 2007 and re-appraised the projections for 2010 and 2015. Based on the earlier report, it consequently repeated the structure and much of the approach and explanatory text. The 2008 and 2009 Update reports followed suit, and this 2010 Update report[2] is another annual reappraisal of the state of technology and the corresponding costs. However, because the current year is now 2010, the "current" technology and the 2010 projected technology have merged, leaving only two technology levels to be examined: the current status (2010) and the 2015 projection. The reader is directed to section 3.1 for a high-level summary of the changes since the 2009 report.

In this multi-year project, DTI estimates the material and manufacturing costs of complete 80 kW_{net} direct-hydrogen Proton Exchange Membrane (PEM) fuel cell systems suitable for powering light-duty automobiles. To assess the cost benefits of mass manufacturing, five annual production rates are examined for each technology level: 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 not currently included in the cost estimates. In other DTI cost estimate projects, an additional 10% cost contingency has often been included, though it has not for 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 (e.g. the membrane electrode assemblies (MEAs) and bipolar plates), such a large number of 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 stack components (e.g. end plates and current collectors), and all balance of plant (BOP) equipment (e.g. compressors, hoses and valves), do not benefit from this manufacturing multiplier effect.

The 2010 system reflects the authors' best estimate of current technology and (with a few exceptions[3]) is not based on proprietary information. Public presentations by fuel cell companies and other researchers along with extensive review of the patent literature are 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 may be compared. Taken together, the analysis of these two systems (2010 and 2015) provides a good sense of the likely range of costs 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] For previous analyses, DTI was funded directly by the Department of Energy's Energy Efficiency and Renewable Energy Office. For the 2010 Annual Update report, DTI is funded by the National Renewable Energy Laboratory.

[3] The following components were modeled based on proprietary information that cannot be fully disclosed:

- Bipolar plate coatings - TreadStone Technologies, Inc.
- Turbocompressor - Honeywell

2. Project Approach

The two systems examined (2010 and 2015 technologies) do not reflect the design of any one manufacturer but are composites of the best elements from a number of designs. Both 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 BOP components, using an oxidant stoichiometry[4] of 2.0–2.5. 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 1.69 and 1.5 atm[5,6] for the 2010 and 2015 systems respectively.

The main fuel cell subsystems included in this analysis are:

- Fuel cell stacks
- Air loop
- Humidifier and water recovery loop
- High-temperature coolant loop
- Low-temperature coolant loop
- Fuel loop (but not fuel storage)
- Fuel cell system controller
- Sensors

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

- Main vehicle battery or ultra capacitor[7]
- 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

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[4] Air stoichiometry is 2.5 for 2010, and drops to 2.0 for 2015.

[5] The systems operate at these pressures (for both the air and hydrogen streams) at peak power. Because a centrifugal air compressor is used to achieve air pressurization, operating pressure is highest at full power and is at a lower level for part-power operation.

[6] In earlier years of the analysis (2006-2008), there was a wider spread of projected stack operating pressures for each of the technology levels, typically 1.5-2.3 atm. However, as will be discussed within the report, polarization curve improvements during the 2009 analysis caused stack pressure to be re-optimized, resulting in a lowering of stack pressure.

[7] 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.

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.

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 two baseline configurations (the 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 are configured to allow assembly of comprehensive system Bills of Materials. A system configuration summary for both technology levels is shown in Figure 2 below. System flow schematics for each of the systems are shown in Figure 3 through Figure 6. 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 (BOM) in Section 4.5 for a comprehensive listing of system elements.

3.1. Changes since the 2009 Update Report

This report represents the fourth annual update of the 2006 DTI fuel cell cost estimate report[8] 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 other three updates before it, this annual report updates the previous work to incorporate advances made over the course of 2010. These advances include new technologies, improvements and corrections made in the cost analysis, and alterations of how the systems are likely to develop. Since the year is now 2010, the "current" technology and the 2010 projected technology have now merged, leaving only two technology levels to examine: the current status (2010) and the 2015 projection.

As was the case with the 2009 Update, the majority of changes this year revolve around the BOP components. While most of these components are based on modifications of proven, existing technology, the stack designs are comparatively immature. The impact of this is twofold: the stack has the most room for technological improvement, and the component production methods are less refined. Therefore, most of the analysis from previous years of the project has been focused on the stack, since it provided the most potential for cost savings. Since the 2008 status update however, the focus has shifted towards the BOP, and changes to the stack analysis have primarily been adjustments of operating parameters rather than the additions of new components or changes in design.

Almost all of the BOP components were re-examined in greater detail, with extra emphasis on those with the largest contribution to cost. The system schematics (see Figure 3 through Figure 6) were refined and components were added and subtracted. Detailed analyses were conducted of the wiring and piping/tubing requirements, with consideration for flow rates, cooling and power requirements, and the physical distances between components.

A central theme of the past year's work has been the integration of performance-parameter-based scaling into the cost model. Although the previous cost model included performance parameters, we have enhanced the level of detail and interaction to better reflect actual performance. Integration between all of the components (in both the stack and the BOP) has been greatly increased, such that geometries and costs now scale dynamically based on a variety of parameters (e.g. operating pressure, air mass flow, and cooling and power requirements).

Noteworthy changes since the 2009 Update report are listed below:

- **Changed Temperature at Peak Power from 80°C to 90°C:** Improved durability allows a higher peak temperature, which allows for a smaller radiator.

[8] "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.

- **Lowered Channel Depth of Stamped Bipolar Plates from 0.92 to 0.5 mm**: The flow channel depth of the bipolar plates was reduced from 0.92 to 0.5 mm based on industry input. This results in a more-compact stack and the resulting reduction in gasket material lowered the cost by $1.03/kW$_{net}$.

- **Areal Power Density Tied Directly to Actual 3M NSTF Performance Curves:** Previously, the stack power density on which the stack was sized was determined by the Fuel Cell Tech Team and represented general stack status and improvements from a range of stack manufacturers. For 2010, stack power density is tied to a specific system (3M NSTF catalyst and membranes) and a specific set of operating conditions. This enables the entire cost model to more-realistically reflect changes in operating assumptions.

- **Low-Temperature Coolant Loop Added:** A separate, lower-temperature coolant loop is added to support the newly added air precooler. However, only 39% of the low temperature loop (LTL) cost is included in the fuel cell system cost estimate, due to the assumption that part of its thermal duty serves components not included in this cost analysis (e.g. the traction inverter module.)

- **Reconfigured Fuel Loop:** Based on industry input, the proportional valve and pressure transducer have been removed, and an over-pressure cut-off valve and check valves were added, as well as an inline filter for gas purity excursions. It is further assumed that the hydrogen storage system (which is not included in the cost analysis) can handle some of the pressure regulation requirements.

- **Improved System Controller DFMA Analysis:** A more-detailed cost analysis was conducted on the system controller (i.e. the electronic system controller analogous to the Electronic Engine Controller (EEC) in an internal combustion engine vehicle). The new cost projection extends the analysis down to the controller subcomponent level.

- **CEM costs scaled to better reflect operating parameters:** Based on additional data from Honeywell, the compressor-expander-motor (CEM) cost analysis was improved to scale dynamically with operating parameters such as power, mass flow, and pressure ratio.

- **Enlarged Membrane Humidifier:** The membrane air humidifier was modified to scale based on the actual mass flow rates and to correct a previous membrane area sizing error.

- **Air Precooler and Demister Added:** Based on interaction with Argonne National Laboratory, an air precooler and a demister have been added to the analysis. The air precooler lowers the temperature of the compressed air stream to an optimal temperature of 55°C prior to entry into the membrane humidifier. The demister removes liquid water droplets from the exhaust gas stream prior to entry into the expander to prevent expander blade erosion.

- **Stack Housing Added:** A vacuum-thermoformed polypropylene stack housing has been added as a new component. The housing primarily provides physical protection of the stack from liquids, road debris, and possible electrical shorting contacts, but also provides a small amount of thermal insulation.

- **Material and Part Yields Applied Across All Components:** Material and part yields were applied across every component in the cost model, with a newly uniform methodology, replacing the previous inconsistent treatment.

- **Improved Wiring Analysis:** The wiring analysis was examined in greater detail; cable lengths were updated by means of examining a more-detailed system configuration layout, and the power and amperage requirements were reassessed for each component. Furthermore, each cable's inclusion in the model is now tied dynamically to the inclusion of the corresponding components.

- **Assorted BOP Changes:** Improved cost analysis of many components (hydrogen piping, air tubing, mass air flow sensor, etc.)

- **Miscellaneous:** Numerous other small changes were made to the fuel cell system cost model, the result of which yields a small cumulative net savings. Although their net effect is comparatively small, the improvements enhance the analysis appreciably and lead to greater confidence in the cost estimates.

Figure 1 summarizes the major changes since the 2009 update and the corresponding effects on system cost. Figure 2 summarizes the main manufacturing aspects of the two systems analyzed.

		2010		2015	
Change	Reason	+/-	System Cost	+/-	System Cost
Final Values for 2009 Update			***$60.96***		***$50.56***
Reconfigured Ejector System	Industry input -> removed prop. valve & press. transducer, added OPCO & check valves, relies on H_2 storage system for some pressure regulation	($4.83)	**$56.13**	($4.63)	**$45.93**
Improved System Controller DFMA Analysis	Improved Cost Analysis by adding greater detail	($1.70)	**$54.43**	**($1.70)**	**$44.23**
Lowered channel depth of stamped plates from 0.92 to 0.5 mm	Industry input, allows gasket material reduction	($1.03)	**$53.39**	($0.84)	**$43.39**
Changed Temperature at Peak Power from 80°C to 90°C (for 2010) and from 120°C to 99° (for 2015)	Improved durability allows higher peak temperature	($0.50)	**$52.89**	$0.85	**$44.24**
Changed Membrane Humidifier to larger model	Previous model not large enough to handle mass flow	$0.40	**$53.29**	**N/A**	**$44.24**
Added Demister and Air Precooler	Added requirement after ANL review	$0.73	**$54.02**	N/A	**$44.24**
Added Part and Material Yields across all components	Added part yields at component level, homogenized methodology	$0.08	**$54.10**	$0.07	**$44.31**
Low-Temperature Coolant Loop reconfigured & reinserted	Needed for Air Precooler & CEM, but only 39% of LTL cost is included	$0.77	**$54.87**	N/A	**$44.31**
Improved Wiring Analysis	Improved and updated wire lengths and specifications	($0.84)	**$54.03**	($0.63)	**$43.68**
CEM costs scaled to better reflect operating parameters	New data from Honeywell, improved cost analysis	($0.65)	**$53.38**	($0.67)	**$43.01**
Assorted BOP Changes	Improved Cost Analysis (H_2 piping, air tubing, mass air flow sensor, etc.)	($2.09)	**$51.29**	**($3.30)**	**$39.71**
Miscellaneous Costs	Improved Cost Analysis (improved calculations, error fixes, etc.)	$0.07	**$51.37**	($0.25)	**$39.46**
Final Values for 2010 Update			***$51.37***		***$39.46***

Figure 1. Changes in system costs since 2009 update

	2010 Technology System	2015 Technology System
Power Density (mW/cm^2)	833	1,000
Total Pt loading ($mgPt/cm^2$)	0.15	0.15
Gross Power (kW_{gross})	87.91	87.27
Operating Pressure (atm)	1.69	1.5
Peak Stack Temp. (°C)	90	99
Active Cells	369	369
Membrane Material	Nafion on 25-micron ePTFE	Advanced High-Temperature Membrane
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Smaller Aluminum Radiator, Water/Glycol Coolant, DI Filter, No Air Precooler
Bipolar Plates	Stamped SS 316L with TreadStone Coating	Stamped SS 316L with TreadStone Coating
Air Compression	Centrifugal Compressor, Radial-Inflow Expander	Centrifugal Compressor, No Expander
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous Layer	Carbon Paper Macroporous Layer with Microporous Layer
Catalyst Application	Nanostructured Thin Film (NSTF)	Nanostructured Thin Film (NSTF)
Air Humidification	Tubular Membrane Humidifier	None
Hydrogen Humidification	None	None
Exhaust Water Recovery	None	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
Coolant & End Gaskets	Laser Welding/ Screen-Printed Adhesive Resin	Laser Welding/ Screen-Printed Adhesive Resin
Freeze Protection	Drain Water at Shutdown	Drain Water at Shutdown
Hydrogen Sensors	2 for FC System 1 for Passenger Cabin (not in cost estimate) 1 for Fuel System (not in cost estimate)	None
End Plates/ Compression System	Composite Molded End Plates with Compression Bands	Composite Molded End Plates with Compression Bands
Stack Conditioning (hrs)	5	3

Figure 2. Summary chart of the two different systems analyzed

3.2. System Schematics

As the analysis has evolved throughout the course of the annual updates, there has been a general trend toward system simplification. This reflects improvements in technology so as not to need as many parasitic supporting systems and facilitates reduced cost. Although there has been a small step back in this trend for the 2010 system, it is not indicative of a change in trend, and merely reflects adjustments in the analysis. The path to system simplification is likely to continue, and remains necessary for achieving or surpassing the cost parity with internal combustion engines.

3.2.1. 2008 System Schematic

The "current technology" system from two years ago (2008) is a fairly standard direct hydrogen, pressurized air fuel cell system configuration. It is shown here in order to illustrate the evolution of the system design. The 2006 and 2007 configurations are omitted from this report because their schematics are very similar to the 2008 system.

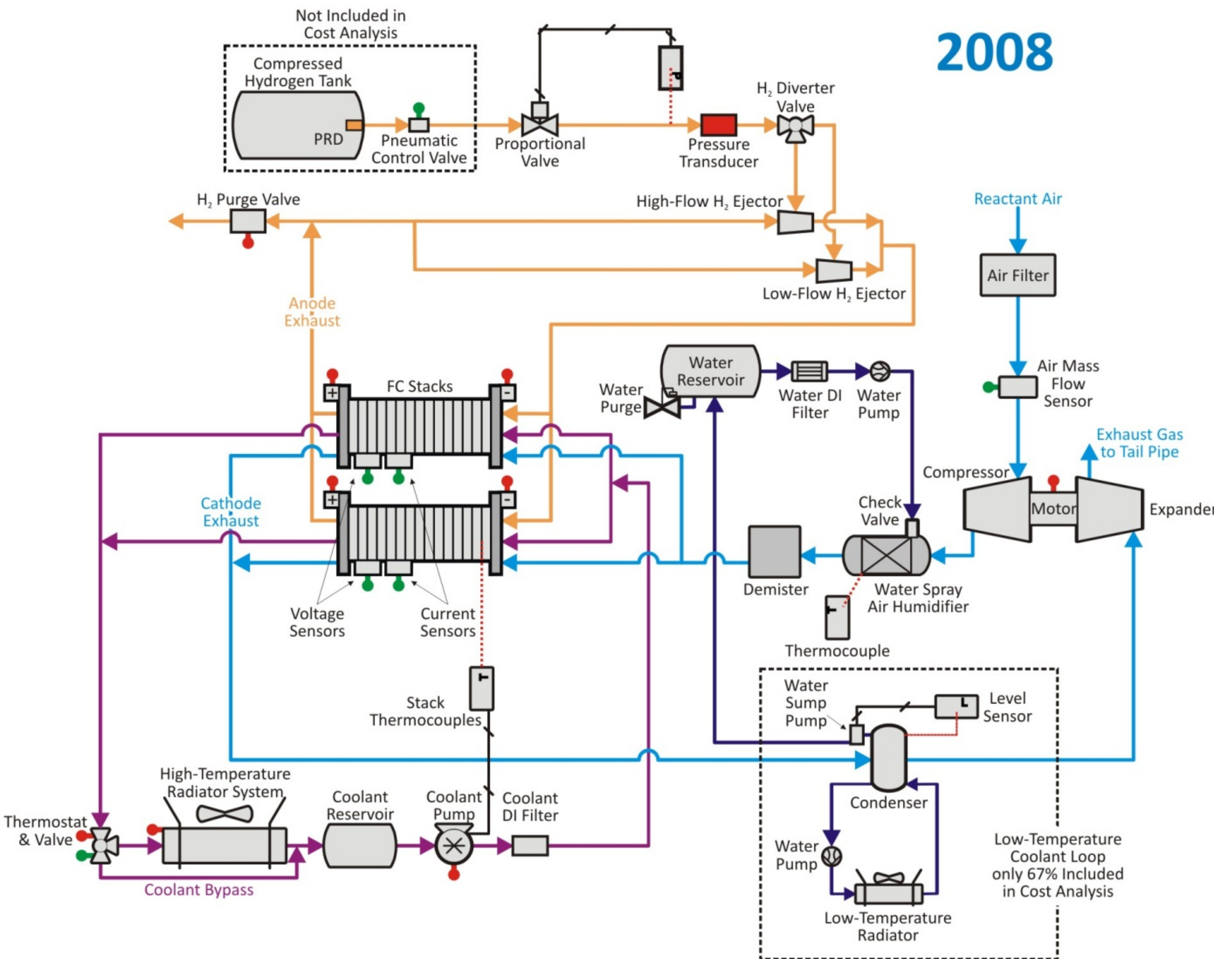

Figure 3. Flow schematic for the "current technology" fuel cell system from 2008

The main features of the 2008 system include:

- 2 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 the remainder of its duty is for components outside of the scope of this analysis
- Twin hydrogen ejectors(high-flow and low-flow) to utilize the high pressure (> 300 psi) in the hydrogen storage tanks to re-circulate anode hydrogen

3.2.2. 2009 System Schematic

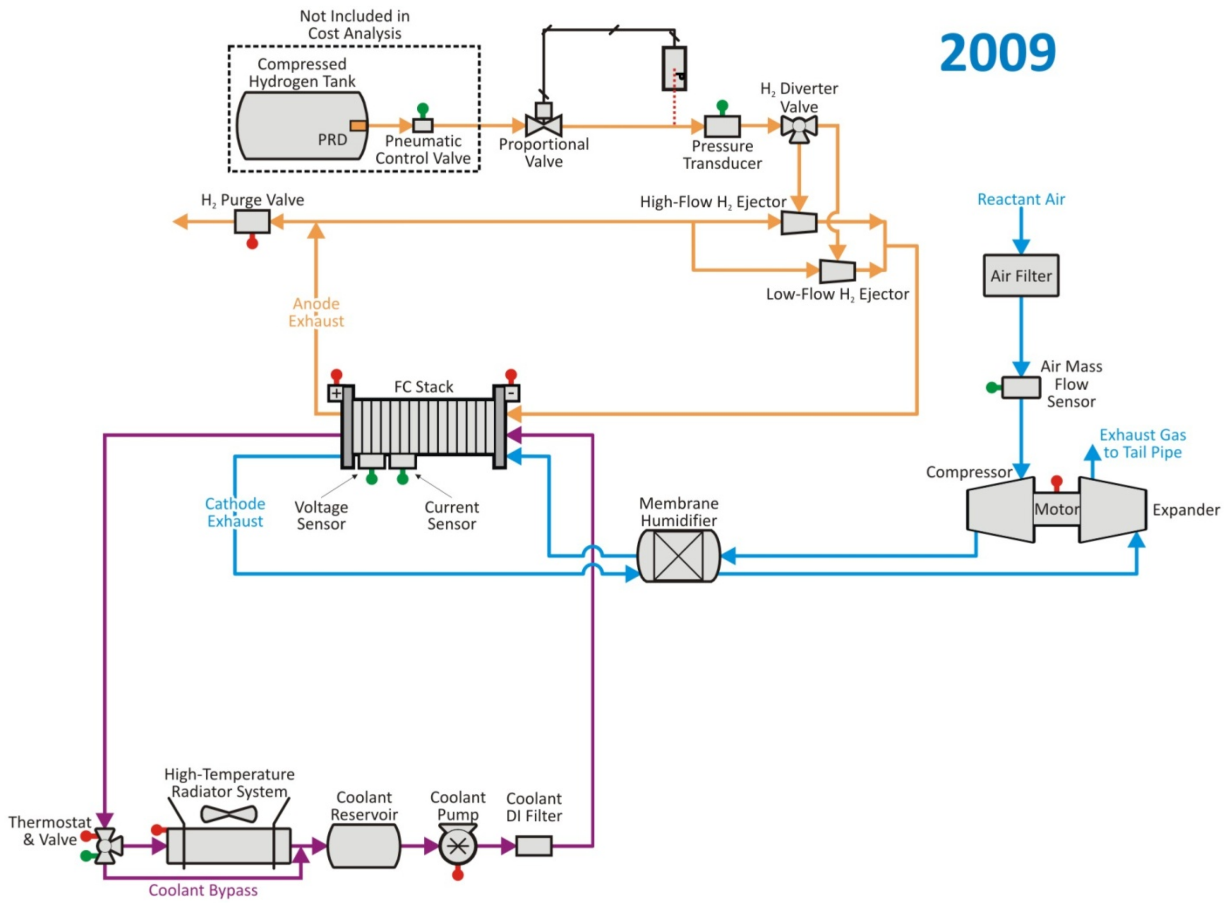

Figure 4. Flow schematic for the "current technology" fuel cell system from 2009

The 2009 system is much simpler than that of 2008, and differs in the following key ways:

- The number of stacks is reduced from 2 to 1
- 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)

3.2.3. 2010 System Schematic

For 2010, the current-technology system reflects both additions and subtractions to the BOP, though there is a net increase in complexity. This increase can be primarily attributed to feedback received from Rajesh Ahuwalia at Argonne National Laboratory suggesting the need for both a demister and an air precooler, the latter of which requires the re-addition of a low-temperature loop.

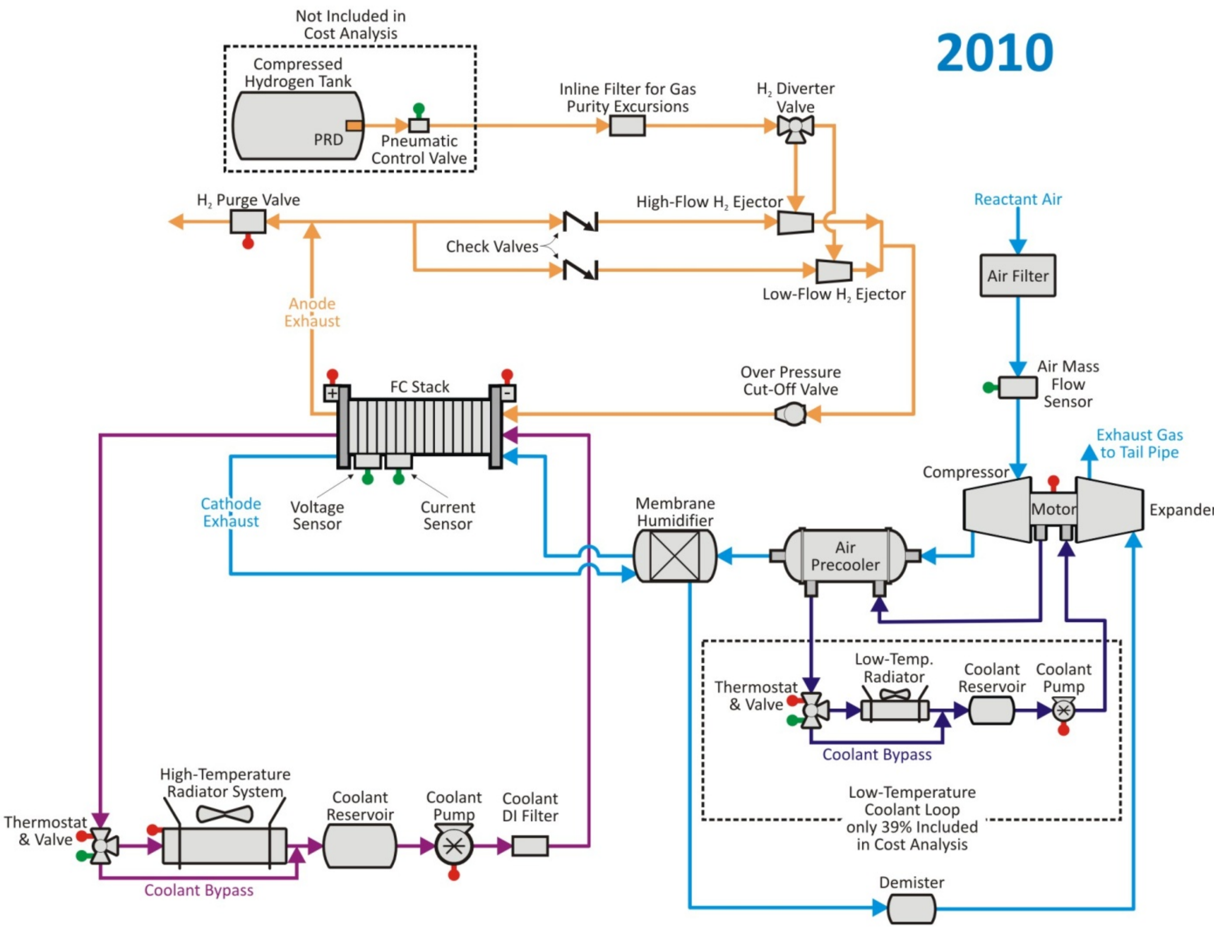

Figure 5. Flow schematic for the "current technology" (2010) fuel cell system

The 2010 system configuration differs from the 2009 version in the following key ways:

- The ejector system has been reconfigured with the assumption that the fuel storage system (not included in the cost analysis) handles some of the pressure regulation duties:
  - The proportional valve has been removed
  - The pressure transducer has been removed
  - An over-pressure cut-off (OPCO) valve has been added
  - Check valves have been added
  - An inline filter for gas purity excursions has been added
- A demister has been added in order to ensure that no ice may form in the expander

- A new low-temperature cooling loop (different from the one in the 2008 system) has been inserted into the system to cool the previously air-cooled CEM and the new air precooler. It also cools the traction inverter module (TIM), but as this is outside the boundary of this cost analysis, the fraction of the LTL cost proportionate to the TIM's cooling duty (61%) is excluded from the model.

- The high-temperature radiator is once again smaller than the previous year (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).

3.2.4. 2015 System Schematic

In keeping with the general trend of system simplification, the 2015 system is the simplest one of all.

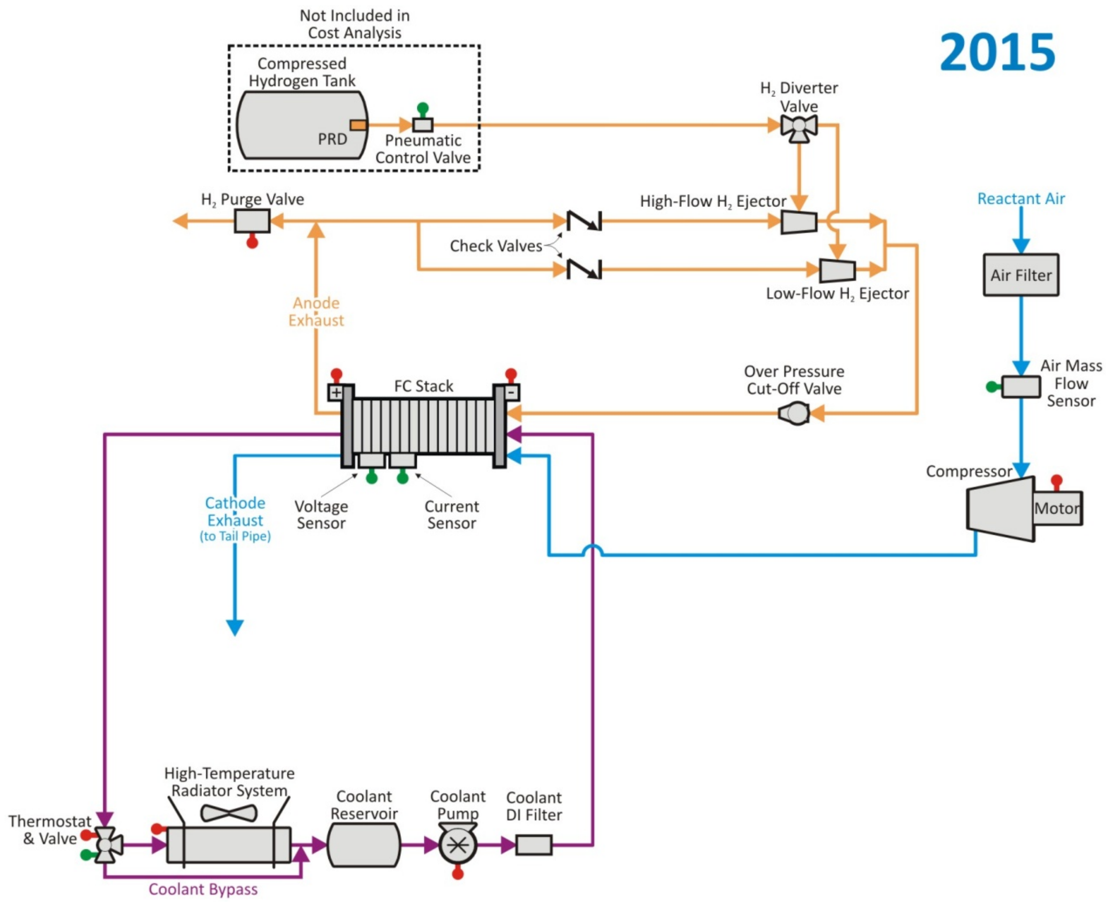

Figure 6. Flow schematic for the 2015 fuel cell system

It is marked by the following further key configuration changes:

- The centrifugal compressor shrinks (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 is even higher)

3.3. System Cost Summaries

3.3.1. 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 7 details the cost of the stacks, Figure 8 details the cost of the balance of plant components, and Figure 9 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)	87.91	87.91	87.91	87.91	87.91
Bipolar Plates (Stamped)	$1,684.28	$434.15	$439.95	$433.03	$429.07
MEAs					
Membranes	$5,184.51	$908.84	$562.23	$438.23	$230.78
Catalyst Ink & Application (NSTF)	$1,252.28	$700.37	$695.57	$698.62	$694.83
GDLs	$2,140.33	$1,111.35	$691.53	$537.04	$242.57
M & E Hot Pressing	$72.09	$9.98	$8.23	$8.36	$8.16
M & E Cutting & Slitting	$56.94	$4.42	$3.29	$3.02	$2.82
MEA Frame/Gaskets	$469.80	$319.59	$311.95	$308.29	$301.42
Coolant Gaskets (Laser Welding)	$185.48	$26.48	$29.43	$27.39	$25.54
End Gaskets (Screen Printing)	$149.48	$5.08	$1.97	$1.25	$0.54
End Plates	$87.43	$33.55	$28.91	$26.21	$19.86
Current Collectors	$16.79	$7.18	$5.99	$5.54	$5.07
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Housing	$61.44	$7.54	$6.44	$5.87	$5.16
Stack Assembly	$76.12	$40.69	$34.95	$33.62	$32.06
Stack Conditioning	$170.88	$53.87	$47.18	$41.38	$28.06
Total Stack Cost	$11,617.87	$3,671.08	$2,873.61	$2,573.36	$2,030.92
Total Stack Cost ($/kW$_{net}$)	$145.22	$45.89	$35.92	$32.17	$25.39
Total Stack Cost ($/kW$_{gross}$)	$132.16	$41.76	$32.69	$29.27	$23.10

Figure 7. 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)	87.91	87.91	87.91	87.91	87.91
Air Loop	$1,695.29	$990.72	$830.17	$802.46	$770.35
Humidifier and Water Recovery Loop	$1,656.02	$481.07	$300.35	$242.86	$153.26
High-Temperature Coolant Loop	$564.28	$478.15	$409.86	$387.20	$356.91
Low-Temperature Coolant Loop	$103.75	$90.66	$81.01	$76.36	$70.74
Fuel Loop	$251.94	$198.65	$170.49	$163.40	$152.96
System Controllers	$171.07	$136.85	$102.64	$95.80	$82.11
Sensors	$1,706.65	$893.00	$659.96	$543.45	$225.49
Miscellaneous	$331.71	$194.12	$171.44	$164.80	$156.69
Total BOP Cost	$6,480.71	$3,463.22	$2,725.93	$2,476.33	$1,968.52
Total BOP Cost ($/kW$_{net}$)	$81.01	$43.29	$34.07	$30.95	$24.61
Total BOP Cost ($/kW$_{gross}$)	$73.72	$39.40	$31.01	$28.17	$22.39

Figure 8. 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)	87.91	87.91	87.91	87.91	87.91
Fuel Cell Stacks	$11,617.87	$3,671.08	$2,873.61	$2,573.36	$2,030.92
Balance of Plant	$6,480.71	$3,463.22	$2,725.93	$2,476.33	$1,968.52
System Assembly & Testing	$157.17	$112.84	$110.91	$111.05	$110.67
Total System Cost ($)	$18,255.75	$7,247.14	$5,710.44	$5,160.75	$4,110.11
Total System Cost ($/$kW_{net}$)	$228.20	$90.59	$71.38	$64.51	$51.38
Total System Cost ($/$kW_{gross}$)	$207.67	$82.44	$64.96	$58.71	$46.75

Figure 9. Detailed system cost for the 2010 technology system

3.3.2. 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 10 details the cost of the stacks, Figure 11 details the remaining balance of plant components, and Figure 12 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)	87.27	87.27	87.27	87.27	87.27
Bipolar Plates (Stamped)	$1,634.29	$386.30	$392.11	$385.17	$380.72
MEAs					
Membranes	$4,657.35	$827.11	$507.81	$394.04	$204.21
Catalyst Ink & Application (NSTF)	$1,134.71	$578.48	$573.71	$572.51	$569.63
GDLs	$1,853.85	$916.89	$565.27	$440.78	$196.86
M & E Hot Pressing	$71.29	$6.83	$6.54	$5.94	$5.95
M & E Cutting & Slitting	$56.55	$3.90	$2.76	$2.50	$2.19
MEA Frame/Gaskets	$403.76	$263.06	$256.85	$253.61	$248.04
Coolant Gaskets (Laser Welding)	$184.80	$26.26	$24.78	$24.44	$23.90
End Gaskets (Screen Printing)	$149.48	$5.08	$1.97	$1.25	$0.53
End Plates	$77.96	$27.02	$23.58	$21.51	$16.46
Current Collectors	$15.08	$6.24	$5.16	$4.77	$4.36
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Housing	$61.03	$7.13	$6.03	$5.46	$4.75
Stack Assembly	$76.12	$40.69	$34.95	$33.62	$32.06
Stack Conditioning	$166.06	$35.11	$27.72	$24.98	$16.84
Total Stack Cost	$10,552.33	$3,138.09	$2,435.24	$2,176.09	$1,711.48
Total Stack Cost ($/$kW_{net}$)	$131.90	$39.23	$30.44	$27.20	$21.39
Total Stack Cost ($/$kW_{gross}$)	$120.91	$35.96	$27.90	$24.93	$19.61

Figure 10. 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)	87.27	87.27	87.27	87.27	87.27
Air Loop	$1,318.59	$786.05	$651.31	$628.59	$604.72
Humidifier and Water Recovery Loop	$0.00	$0.00	$0.00	$0.00	$0.00
High-Temperature Coolant Loop	$582.52	$493.84	$423.56	$400.06	$368.65
Low-Temperature Coolant Loop	$0.00	$0.00	$0.00	$0.00	$0.00
Fuel Loop	$233.74	$180.46	$152.29	$145.20	$134.76
System Controllers	$171.07	$136.85	$102.64	$95.80	$82.11
Sensors	$28.00	$28.00	$28.00	$28.00	$28.00
Miscellaneous	$300.42	$167.75	$147.31	$141.25	$134.52
Total BOP Cost	$2,634.34	$1,792.96	$1,505.11	$1,438.90	$1,352.76
Total BOP Cost ($/kW$_{net}$)	$32.93	$22.41	$18.81	$17.99	$16.91
Total BOP Cost ($/kW$_{gross}$)	$30.18	$20.54	$17.25	$16.49	$15.50

Figure 11. 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)	87.27	87.27	87.27	87.27	87.27
Fuel Cell Stacks	$10,552.33	$3,138.09	$2,435.24	$2,176.09	$1,711.48
Balance of Plant	$2,634.34	$1,792.96	$1,505.11	$1,438.90	$1,352.76
System Assembly & Testing	$130.55	$93.72	$92.12	$92.24	$91.92
Total System Cost ($)	$13,317.22	$5,024.77	$4,032.47	$3,707.23	$3,156.16
Total System Cost ($/kW$_{net}$)	$166.47	$62.81	$50.41	$46.34	$39.45
Total System Cost ($/kW$_{gross}$)	$152.59	$57.57	$46.20	$42.48	$36.16

Figure 12. Detailed system cost for the 2015 technology system

3.4. Cost Comparison of the Two Systems

The stack and system costs for both technology levels are compared in Figure 13 and Figure 14. 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.

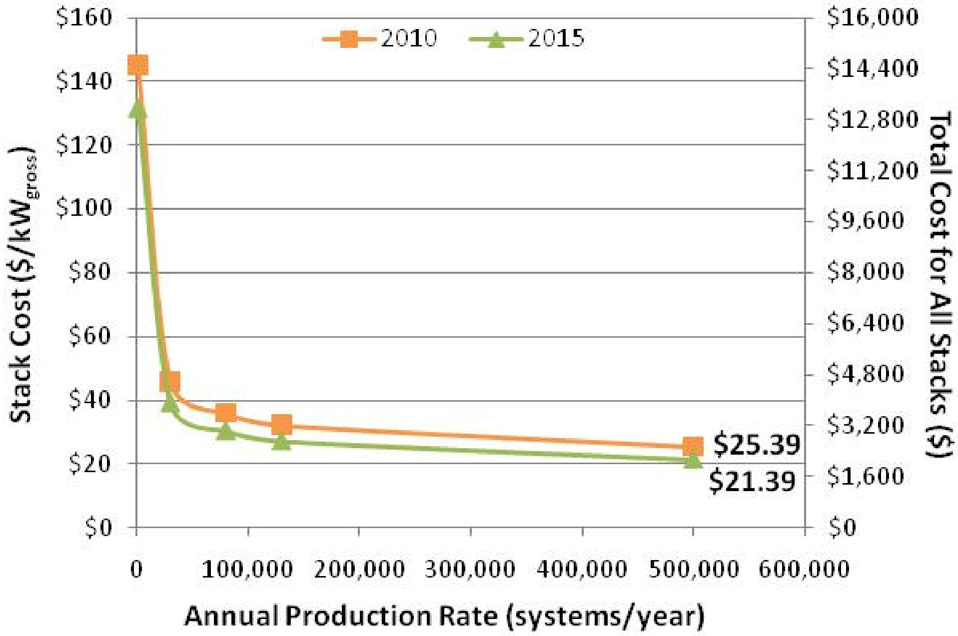

Figure 13. Gross stack cost vs. annual production rate

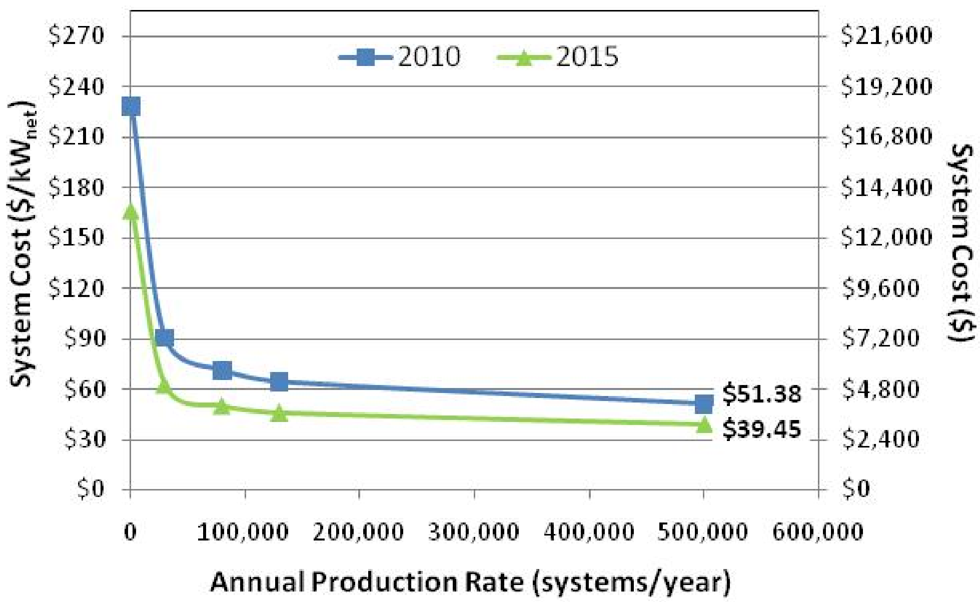

Figure 14. Net system cost vs. annual production rate

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, the stack gross power is nearly constant: 87.91 kW and 87.27 kW for 2010 and 2015 respectively. The slight 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 15 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 16 summarizes total system parasitic loads.

		2010	2015
Compressor			
Gross Power	kW	87.91	87.27
Air Mass Flow	kg/h	411	327
Peak Stack Operating Pressure	atm	1.69	1.50
Compression Ratio	atm	1.78	1.50
Compression Efficiency	%	75%	80%
Ambient Temperature	°C	40	40
Compressor Shaft Power Req	kW	8.61	4.40
Expander			
Mass Flow	kg/h	417	No expander in 2015 System
Compression Ratio	atm	1.48	
Compression Efficiency	%	80%	
Starting Temperature	°C	80	
Expander Shaft Power Out	kW	3.77	
Compressor-Expander Unit			
Motor/Controller Efficiency	%	85%	85%
CEM Input Power	kW	5.69	5.17

Figure 15. Basis of air compressor and expander power

(All values in kW)	2010	2015
Fuel Cell Gross Electric Power (Output)	87.91	87.27
System Net Electrical Power (Output)	80	80
Air Compressor Motor	5.69	5.17
Coolant Pump	1.1	1.1
Coolant Radiator Fan	0.90	0.90
Exhaust Radiator Fan	0.00	0.00
Other (Controller, Instruments, etc.)	0.1	0.1
Total Parasitic Loads	7.91	7.27

Figure 16. Power production & loads at max. power, under peak ambient temp. operating conditions

Stack design parameters and operating conditions are summarized in Figure 17 and Figure 18. All systems operate with low single-pass hydrogen utilization but high total utilization due to a hydrogen recirculation loop.

	2010	2015
Number of Stacks per System	1	
Number of Active Cells per Stack*	369	
Number of Cooling Cells per Stack*	371	
Cell Voltage at Max. Power	0.676	
Membrane Power Density at Max. Power (mW/cm^2)	833	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 17. Stack design parameters

	2010	2015
Peak Operating Pressure (atm)	1.7	1.5
Cell Temperature (°C)	90	99
Oxygen Stoichiometry	2.5	2.0
Anode Gas Stream		
Hydrogen Purity	99.999% (molar basis)	
Inlet Temperature (°C)	Ambient + ~10°C	
Relative Humidity	0%	
Max (single pass) H_2 flowrate (kg/hr)	7.90	8.78
Cathode Gas Stream		
Oxygen Purity	21% (molar basis)	
Inlet Temperature (°C)	75°C	
Relative Humidity	67%	3%
Max (single pass) Air flowrate (kg/hr)	498.70	443.37

Figure 18. Stack operation parameters

The power density (listed in Figure 17) 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 19) describes everything between the end plates. The table in Figure 20 lists the numerical values of these dimensions.

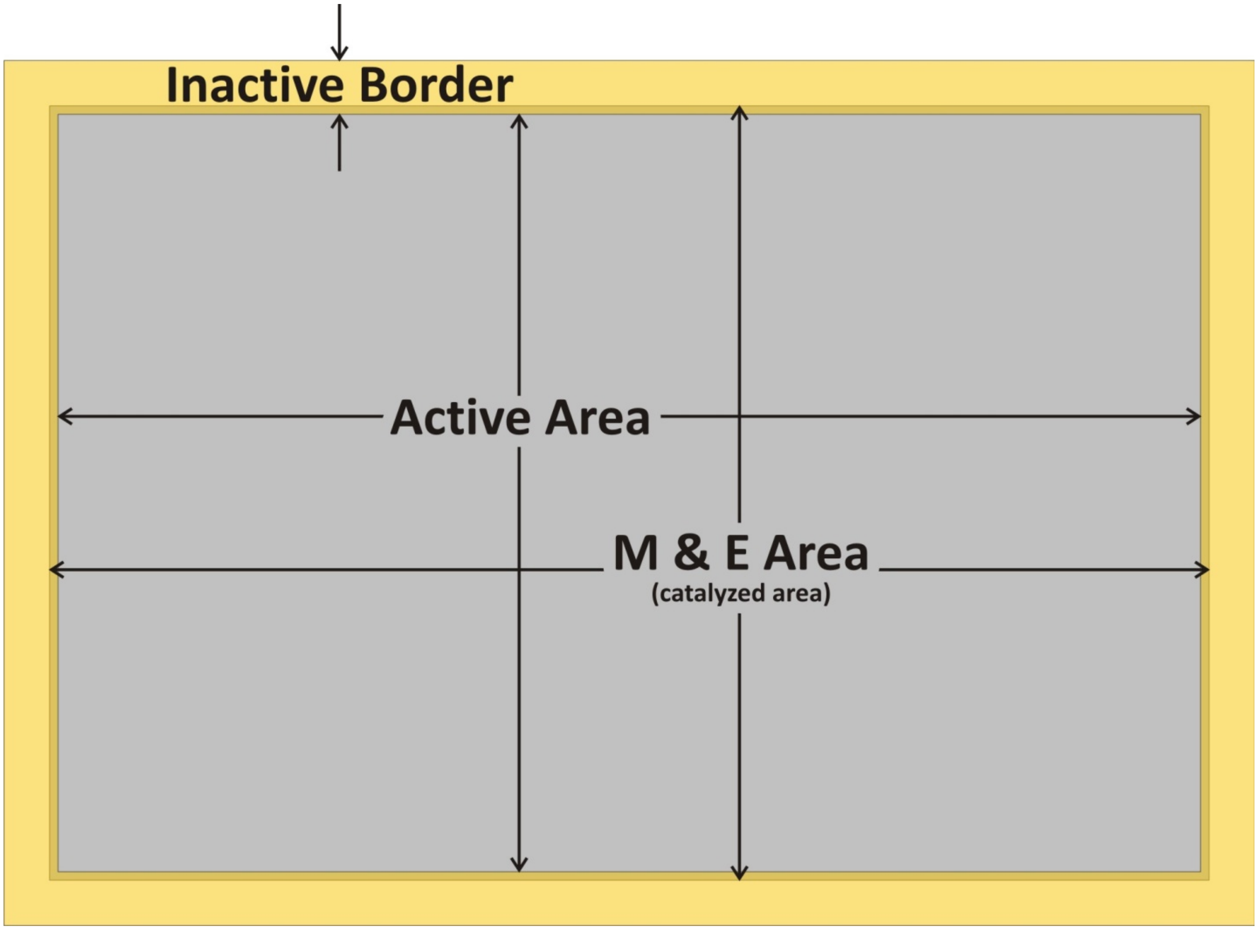

Figure 19. Cell geometry

	2010	2015
Active Area (cm^2)	285.84	236.52
Active Width (cm)	20.71	18.84
Active Height (cm)	13.80	12.56
M & E (Catalyzed) Area (cm^2)	8.86	6.66
M & E (Catalyzed) Width (cm)	0.55	0.42
M & E (Catalyzed) Height (cm)	294.70	243.17
Total Area (cm^2)	357.30	295.65
Total Width (cm)	22.67	20.62
Total Height (cm)	15.76	14.34
Ratio of Width to Height	1.5	1.5
Ratio of Active Area to Total Area	0.8	0.8
Inactive Border (cm)	0.98	0.89

Figure 20. 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[9] 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).

[9] 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.

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 the 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 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 is 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 calculated 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 21 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[10]. 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 22 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[11]. This is a direct consequence of the annual capital cost repayment needing to be collected even if the machine is used infrequently.

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[10] 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.

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

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

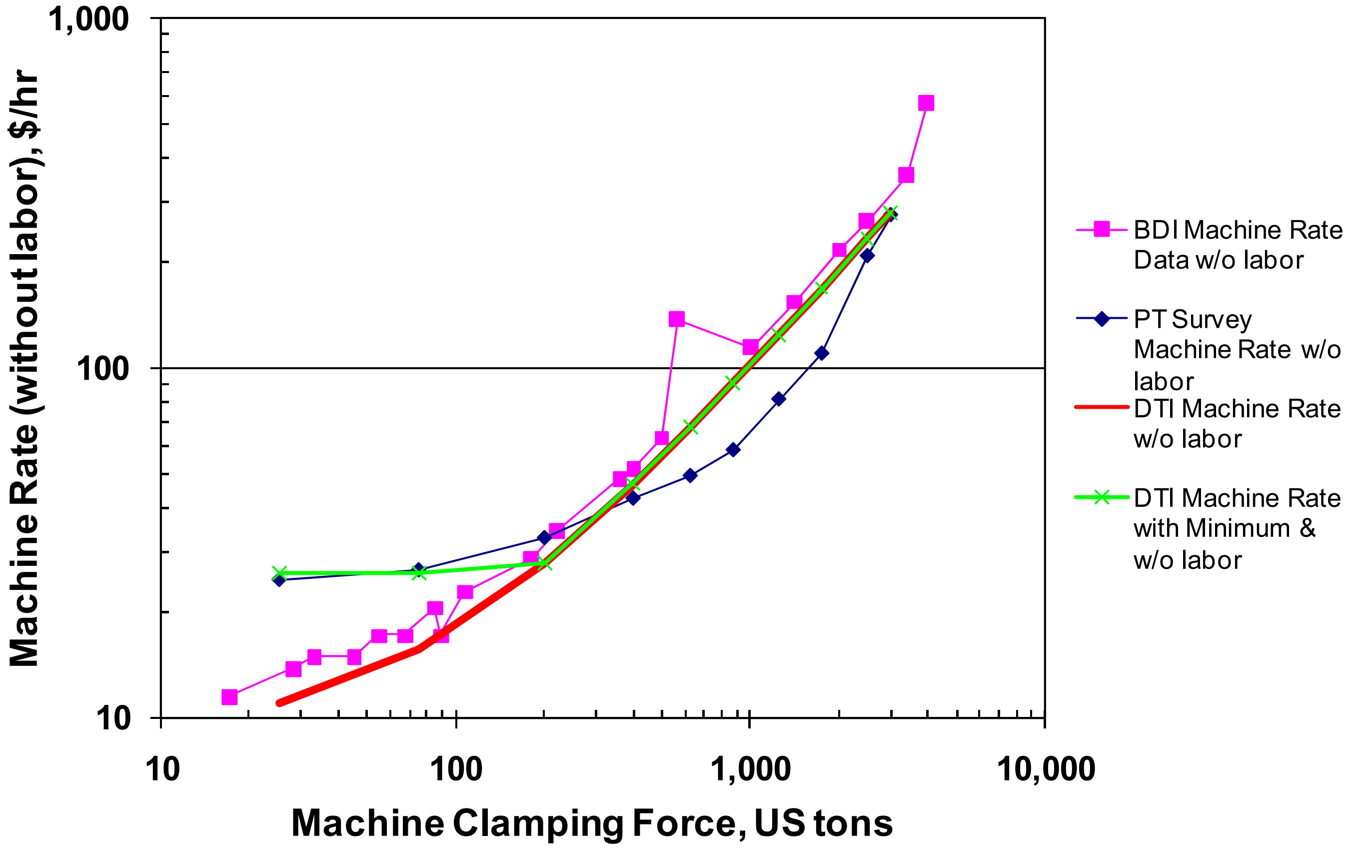

Figure 21. Injection-molding machine rate vs. machine clamping force

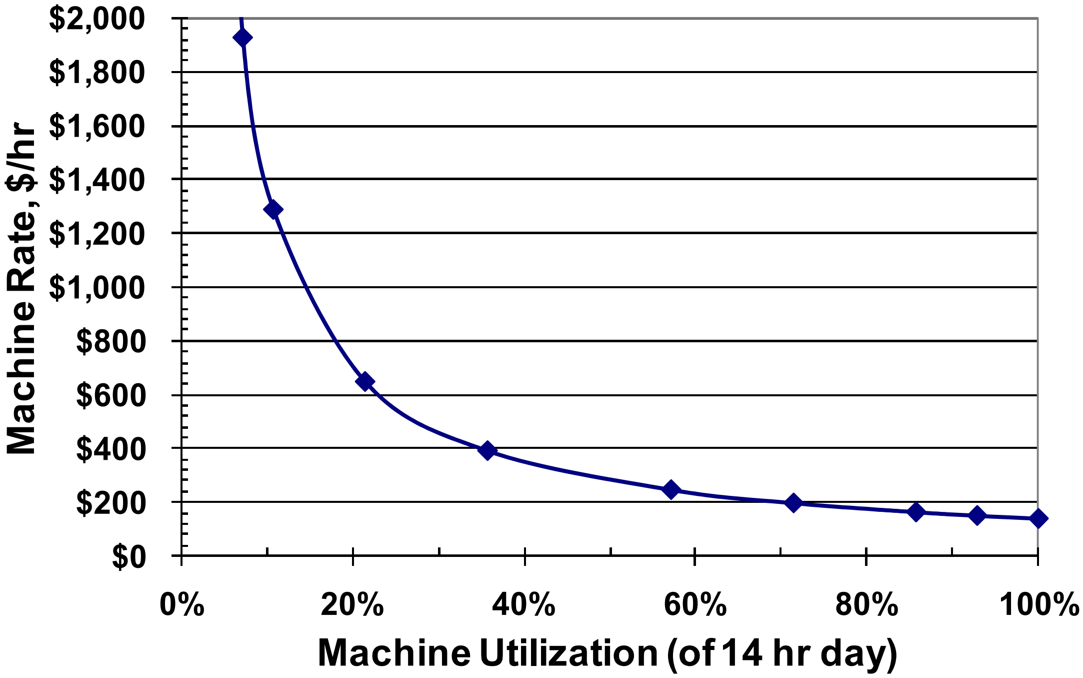

Figure 22. Machine rate vs. machine utilization

4.2.2. Material and Part Yields

For the 2010 analysis, material and part yield percentages (or inversely, scrap percentages[12]) were added to all components/processes. The material yield accounts for the scrap material lost in manufacturing for each part, and the part yield estimates the number of whole parts lost to defects in the manufacturing process. Material yields are typically much lower than part yields, which approach unity for well-refined high-volume production lines.

The yield percentages applied in this analysis are DTI estimates based on experience with industrial yields in previous work. Figure 23 shows the yields for each process. As the number of vehicles per year increases, part yields increase due to the improved manufacturing success associated with numerous repeat parts.

[12] The yield represents what is left after the scrap has been subtracted, so a yield rate of 95% corresponds to a scrap rate of 5%.

Material Yields					
Process/Material	1,000	30,000	80,000	130,000	500,000
BPP Stamping					
Stainless Steel Sheeting	95%	95%	95%	95%	95%
BPP Coating 1	95%	95%	95%	95%	95%
BPP Coating 2	95%	95%	95%	95%	95%
Membrane Production					
ePTFE Yield	50%	70%	64%	67%	80%
Ionomer Yield	75%	85%	82%	83.5%	90%
NSTF Catalyst Deposition					
Platinum	99%	99%	99%	99%	99%
GDL Production					
Solvent	80%	80%	80%	80%	80%
PTFE	80%	80%	80%	80%	80%
MEA Frame Gaskets					
Henkel Loctite Sealant	63.9%	63.9%	63.9%	63.9%	63.9%
End Gaskets					
Type A Resin	35%	35%	35%	35%	35%
End Plates					
Lytex 9063	92.9%	92.9%	92.9%	92.9%	92.9%
Current Collectors					
Copper	85%	95%	95%	95%	95%

Part Yields					
Process	1,000	30,000	80,000	130,000	500,000
BPP Stamping	99.9%	99.99%	99.999%	99.999%	99.999%
BPP Coating 1	99.5%	99.99%	99.999%	99.999%	99.999%
BPP Coating 2	99.5%	99.99%	99.999%	99.999%	99.999%
BPP Coating Heating	99.999%	99.999%	99.999%	99.999%	99.999%
Membrane Production	95%	98%	99%	99.9%	99.99%
NSTF Catalyst Deposition	95%	98%	99%	99.9%	99.99%
GDL Production	99.5%	99.99%	99.999%	99.999%	99.999%
M&E Hot Pressing	99.5%	99.99%	99.999%	99.999%	99.999%
MEA Cutting and Slitting	99.5%	99.99%	99.999%	99.999%	99.999%
MEA Frame Gaskets	99.5%	99.99%	99.999%	99.999%	99.999%
Coolant Gaskets	99.999%	99.999%	99.999%	99.999%	99.999%
End Gaskets	99.5%	99.99%	99.999%	99.999%	99.999%
End Plates	99%	99.99%	99.99%	99.99%	99.99%
Current Collectors	99.5%	99.99%	99.999%	99.999%	99.999%
Stack Assembly	99.5%	99.999%	99.999%	99.999%	99.999%
Stack Conditioning	99.99%	99.99%	99.999%	99.999%	99.999%

Figure 23. Material and part yield percentages applied

Prior to 2010, the analyses for many of the most important components (e.g. the catalyst ink) accounted for one or both type of yield, though there were some that did not. Fortunately for the validity of the previous years' analyses, the change resulted in a mere \$0.08/kW_{net} cost increase across the entire system. Despite the small cost impact, this improvement succeeded in improving the realism and fidelity of the model.

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 the 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, every step in the production process (from the acquisition of base materials to the 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. Completely vertical or horizontal integration is quite rare, but most companies 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 that add value (such as actual manufacturing or assembly steps) and 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 are applied, there are many exceptions to the general rule. Different markup rates are used for different components because the type and quantity of work lend themselves to lower overhead costs. MEA manufacturing markups are 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[13] and not to the material cost.

	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)

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

[13] 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.

25 displays an abridged view of the stack components, and Figure 26 shows a cross-sectional view of an assembled stack.

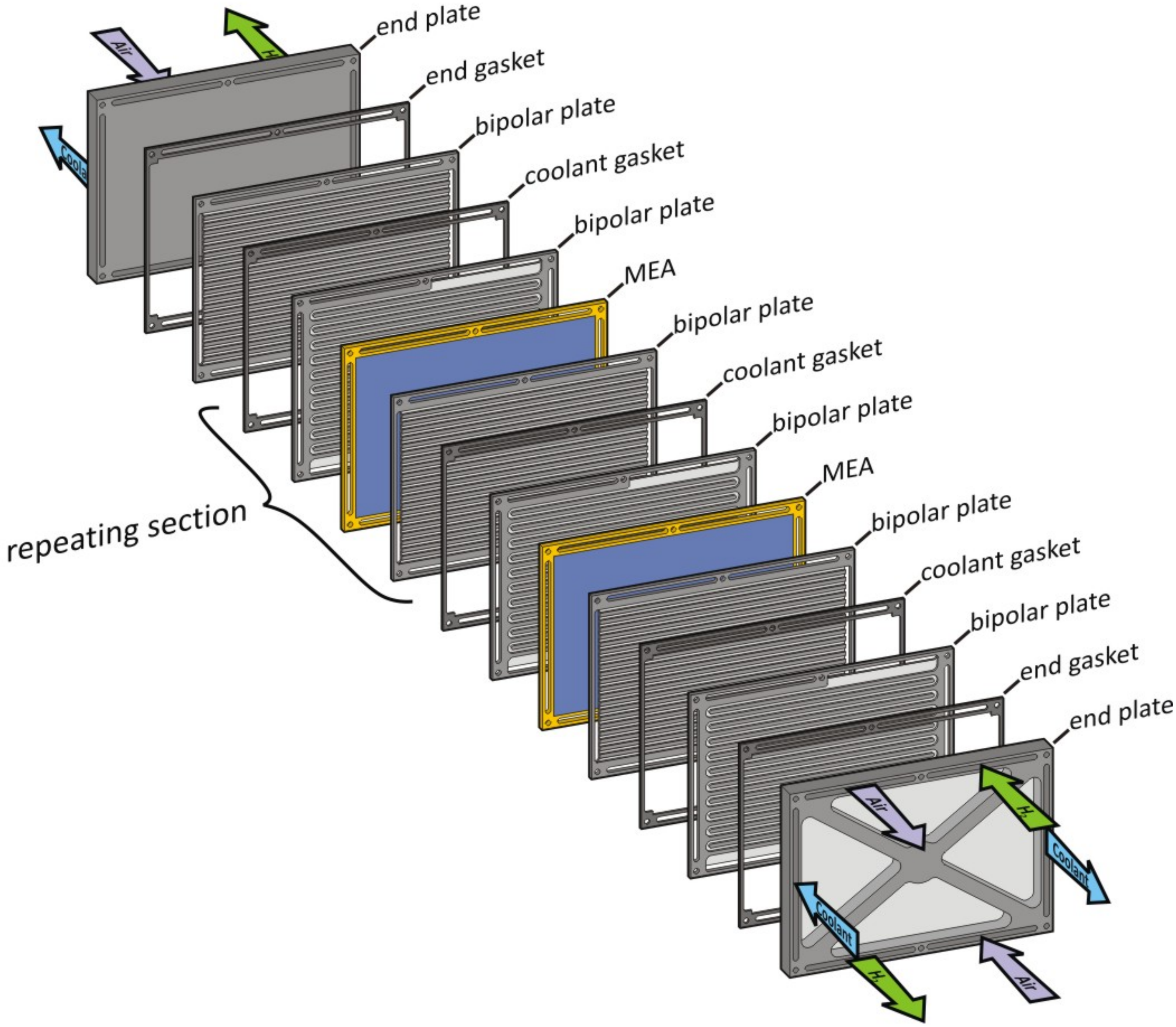

Figure 25. Exploded stack view (abridged to 2 cells for clarity)

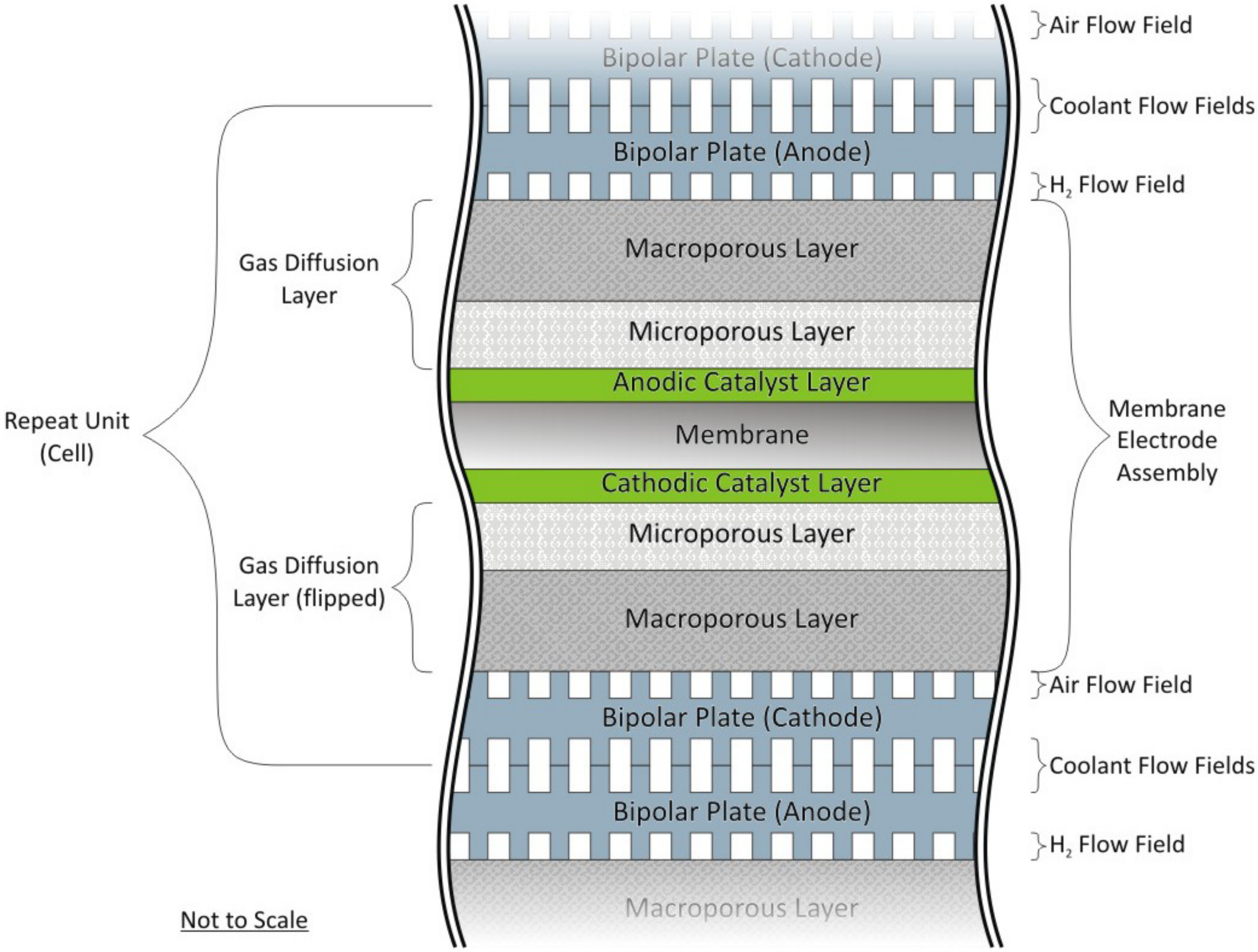

Figure 26. Stack cross-section

4.4.1. Bipolar Plates

Each stack in the system consists of 369 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 740: 369 active cells * 2 plates per cell + 2 coolant-only plates * 1 stack[14]. Because each system contains 740 bipolar plates, there are hundreds of thousands of plates needed, even at the lowest production rate. This means that bipolar plate mass-manufacturing techniques remain appropriate across all production rates.

[14] In previous years, there were multiple (smaller) stacks per system.

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 may provide an advantage in conductivity over carbon plates, but for now, equivalent polarization performance is 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 are 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[15]. 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.

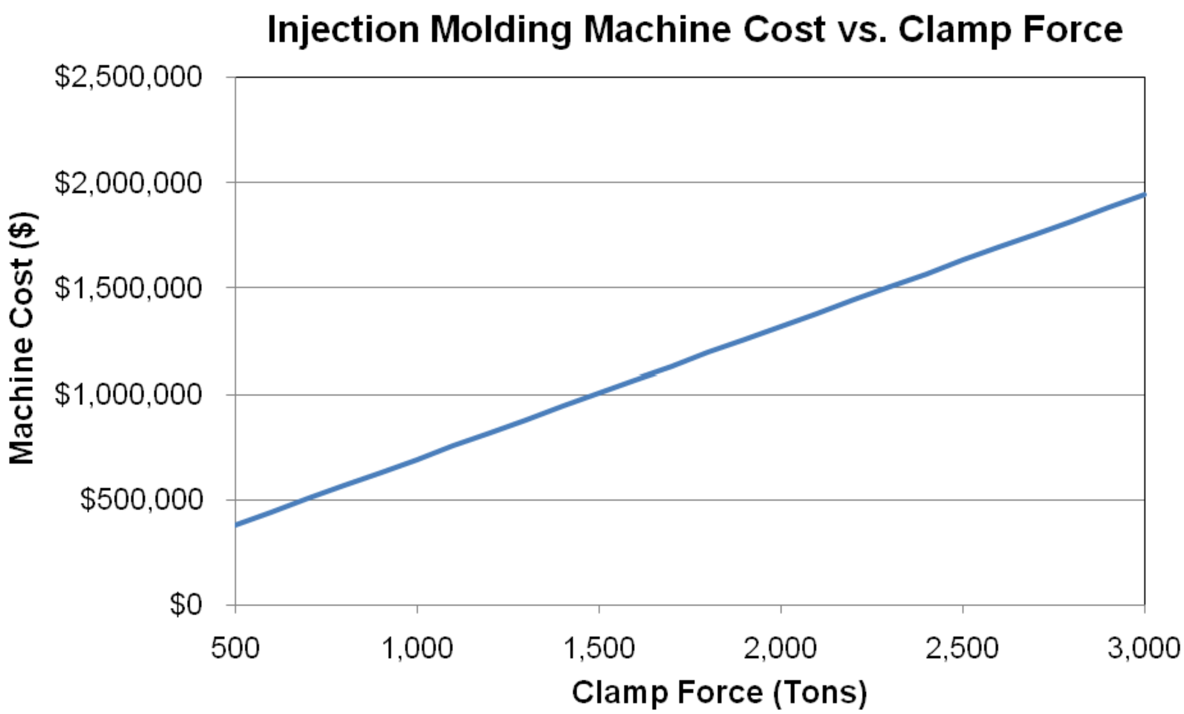

Figure 27. Injection-molding machine cost vs. clamp force

[15] 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
2010	Capital Cost ($/Line)	$174,621	$463,497	$463,497	$463,497	$463,497
	Costs per Tooling Set ($)	$42,704	$112,697	$112,697	$112,697	$112,697
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	4	10	16	59
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	9.34%	$0.88	$0.94	$0.95	$0.99
	Cycle Time (s)	24.3	30.7	30.7	30.7	30.7
	Cavities/Platen	4	16	16	16	16
	Effective Total Machine Rate ($/hr)	$918.91	$751.24	$746.91	$745.89	$743.22
	Carbon Filler Cost ($/kg)	$6.67	$6.67	$6.67	$6.67	$6.67
2015	Capital Cost ($/Line)	$158,005	$397,035	$397,035	$397,035	$397,035
	Costs per Tooling Set ($)	$42,704	$112,697	$112,697	$112,697	$112,697
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	3	8	13	47
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	9.34%	93.03%	92.94%	92.94%	98.87%
	Cycle Time (s)	24.3	24.3	24.3	24.3	24.3
	Cavities/Platen	4	16	16	16	16
	Effective Total Machine Rate ($/hr)	$895.49	$737.96	$738.02	$738.02	$734.60
	Carbon Filler Cost ($/kg)	$6.67	$6.67	$6.67	$6.67	$6.67

Figure 28. Bipolar plate injection-molding process parameters

As shown in Figure 30, costs are seen to vary between roughly $3/kW$_{net}$ and $5/kW$_{net}$. 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. The conductive filler is assumed to be high-purity carbon black. 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
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	0.159	0.163	0.163	0.163	0.163
	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)	83.0	189.6	189.6	189.6	189.6

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

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$78.18	$78.18	$78.18	$78.18	$78.18
	Manufacturing ($/stack)	$288.37	$296.42	$294.44	$294.04	$292.99
	Tooling ($/stack)	$0.58	$0.20	$0.20	$0.20	$0.20
	Total Cost ($/stack)	$367.13	$374.80	$372.82	$372.42	$371.36
	Total Cost ($/kW$_{nrt}$)	$4.59	$4.68	$4.66	$4.66	$4.64
2015	Materials ($/stack)	$65.45	$65.45	$65.45	$65.45	$65.45
	Manufacturing ($/stack)	$281.03	$230.66	$230.47	$230.47	$229.40
	Tooling ($/stack)	$0.58	$0.20	$0.20	$0.20	$0.20
	Total Cost ($/stack)	$347.06	$296.32	$296.13	$296.13	$295.05
	Total Cost ($/kW$_{nrt}$)	$4.34	$3.70	$3.70	$3.70	$3.69

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[16]. Since 740 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, coils of sheet metal are fed into stamping presses having a series of die stations, each one sequentially imparting one or more features 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.

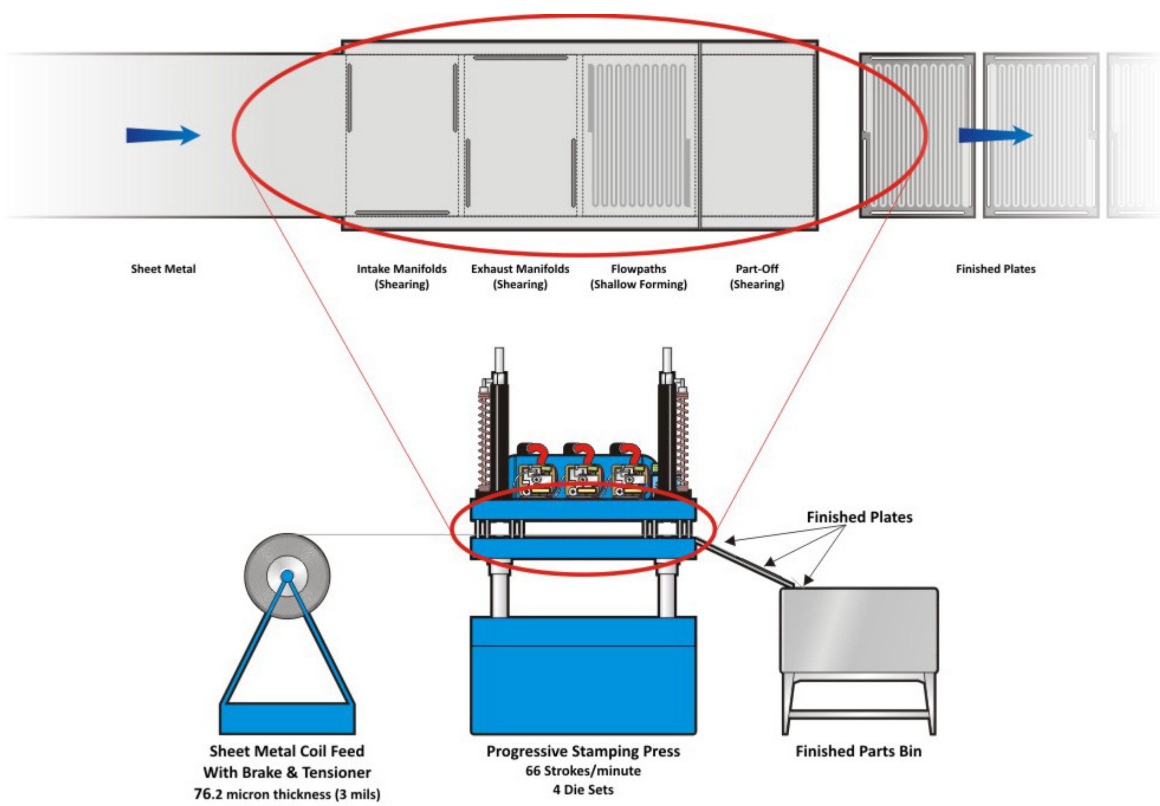

Figure 31. Bipolar plate stamping process diagram

16 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.

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. 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 has a fixed cost regardless of press size, while other equipment scales 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[17] 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 are shown in Figure 32.

Component	Cost		
Stamping Press	$33,007		
Accesories			
Air Compressor	$17,461		
ATC-10070 Control	$3,498		
Stand	$6,044		
Vibration Mounts	$1,320		
Feeding Equipment			
Reel	$6,668		
Loop Control	$2,215		
Servo Feed	$7,306		
Misc. Add-Ons	$1,091		
Total Capital Cost	**$78,611**	**× 5 =**	**$393,057**

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[18] was necessary to produce the bipolar plates[19]. However, it was noted that there was disagreement in the bipolar plate stamping community regarding the necessary press tonnage to form the plates[20], 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.

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 is correlated to press size and is shown in Figure 33.

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

[18] Press force figure corroborated by Dan Connors of GenCell Corporation.

[19] This press tonnage reflects the total press force of all four die stations forming a ~400 cm^2 bipolar plate.

[20] Some flow fields require increased swaging of metal to form non-uniform thickness plates whereas others require only bending of a uniform thickness plate.

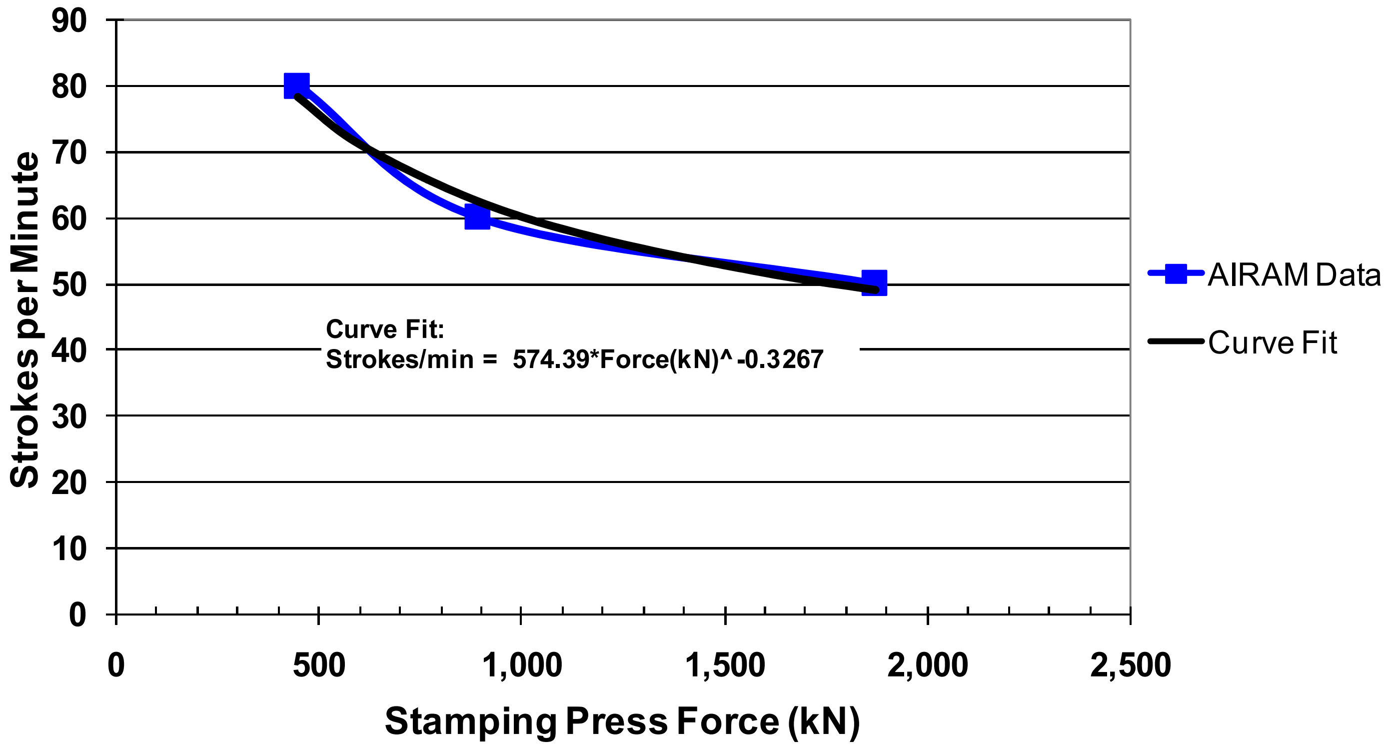

Figure 33. Press speed vs. press force

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[21] with a total replacement cost estimated at 20–25% of complete press initial capital cost[22] 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 is 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 is estimated to be 5% of initial feeder capital cost every 10 million cycles[23].

Utilities: The principal power consumer in the progressive die process train is the air compressor for the pneumatic press and the coil feeder[24]. 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 is 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 is 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 and therefore

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

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

[23] 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.

[24] The solenoid valves and controller unit each consume less than 50 watts, and are therefore negligible for costing purposes.

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 are listed below in Figure 34 (under "Tooling").

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$217.08	$217.08	$217.08	$217.08	$217.08
2010	Manufacturing ($/stack)	$158.47	$18.89	$16.95	$16.50	$16.10
2010	Tooling ($/stack)	$99.94	$88.52	$88.69	$89.39	$88.97
2010	Secondary Operations: Coating ($/stack)	$1,208.80	$109.66	$117.23	$110.05	$106.92
2010	Total Cost ($/stack)	$1,684.28	$434.15	$439.95	$433.03	$429.07
2010	Total Cost ($/$kW_{net}$)	$21.05	$5.43	$5.50	$5.41	$5.36
2015	Materials ($/stack)	$179.62	$179.62	$179.62	$179.62	$179.62
2015	Manufacturing ($/stack)	$157.18	$18.60	$16.68	$16.23	$15.21
2015	Tooling ($/stack)	$96.37	$85.35	$85.52	$86.20	$85.90
2015	Secondary Operations: Coating ($/stack)	$1,201.13	$102.72	$110.28	$103.11	$99.98
2015	Total Cost ($/stack)	$1,634.29	$386.30	$392.11	$385.17	$380.72
2015	Total Cost ($/$kW_{net}$)	$20.43	$4.83	$4.90	$4.81	$4.76

Figure 34. **Cost breakdown for stamped bipolar plates**

Die Life: 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 x 600,000) was specified, with a die cost of $214,149 ($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
2010 - 2015	Equipment Lifetime	15	15	15	15	15
2010 - 2015	Interest Rate	10%	10%	10%	10%	10%
2010 - 2015	Corporate Income Tax Rate	40%	40%	40%	40%	40%
2010 - 2015	Capital Recovery Factor	0.175	0.175	0.175	0.175	0.175
2010 - 2015	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
2010 - 2015	Maintenance/Spare Parts (% of CC)	13%	13%	13%	13%	13%
2010 - 2015	Miscellaneous Expenses (% of CC)	2%	2%	2%	2%	2%
2010 - 2015	Power Consumption (kW)	16.6	16.6	16.6	16.6	16.6

Figure 35. **Machine rate parameters for bipolar plate stamping process**

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/Line)	$393,057	$393,057	$393,057	$393,057	$393,057
	Costs per Tooling Set ($)	$214,149	$214,149	$214,149	$214,149	$214,149
	Tooling Lifetime (cycles)	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
	Simultaneous Lines	1	3	7	11	41
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	8.14%	81.27%	92.86%	96.03%	99.09%
	Cycle Time (s)	0.62	0.62	0.62	0.62	0.62
	Effective Total Machine Rate ($/hr)	$579.14	$69.17	$62.08	$60.44	$58.95
	Stainless Steel Cost ($/kg)	$12.83	$12.83	$12.83	$12.83	$12.83
2015	Capital Cost ($/Line)	$390,236	$390,236	$390,236	$390,236	$390,236
	Costs per Tooling Set ($)	$206,498	$206,498	$206,498	$206,498	$206,498
	Tooling Lifetime (cycles)	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
	Simultaneous Lines	1	3	7	11	39
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	7.73%	77.10%	88.09%	91.10%	98.82%
	Cycle Time (s)	0.61	0.61	0.61	0.61	0.61
	Effective Total Machine Rate ($/hr)	$605.32	$71.81	$64.39	$62.67	$58.74
	Stainless Steel Cost ($/kg)	$12.83	$12.83	$12.83	$12.83	$12.83

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 107). 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[25] and fellow researchers at Loughborough University, UK, fabricated and tested bipolar plates of three uncoated stainless steel alloys[26] (904L, 310, and 316L). Contact resistance testing and multi-thousand hour endurance tests in a functioning cell were conducted. They concluded that 904L performs

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[25] 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.

[26] 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.

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[27] 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[28] et al at the Netherlands Energy Research Foundation have also done comparative corrosion and performance testing of metallic bipolar plates. They examined seven alloys[29] (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[30] 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[31] 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.[32]

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:

- **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)

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

[28] 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.

[29] 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.

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

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

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

- **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[33]. Gold is often considered one of the most effective; however, its cost is usually prohibitive. Alternately, Fonk[34] 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[35] 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 $1.50/kW$_{net}$ (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 $1/kW$_{net}$ to stack cost. If carbon power is used as the coating material, the total material-and-application cost is estimated at under $1.75/kW$_{net}$.

Additionally, a preliminary analysis was conducted for aluminum plates with a titanium-nitride surface treatment via magnetron sputtering. A GM patent from 1997 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[36]. Since the patent is over ten years old, a shorter deposition time was postulated, which is consistent with using thinner layers (or a single layer). Preliminary analysis[37] indicates a total bipolar plate cost of $5–11/kW$_{net}$ for production rates of 30,000 to 500,000

[33] "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)

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

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

[36] 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.

[37] 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, and a 2-10 minute sputtering time.

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 $2/kW$_{net}$ to $8/kW$_{net}$ 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.

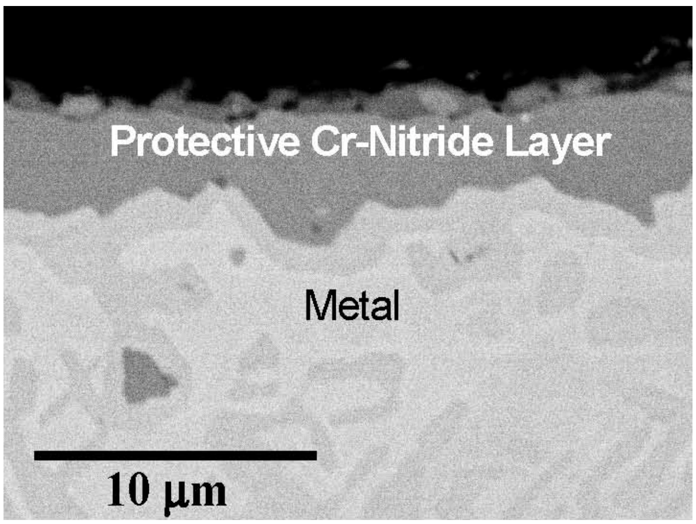

Figure 37. Magnified chromium nitride surface conversion

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.

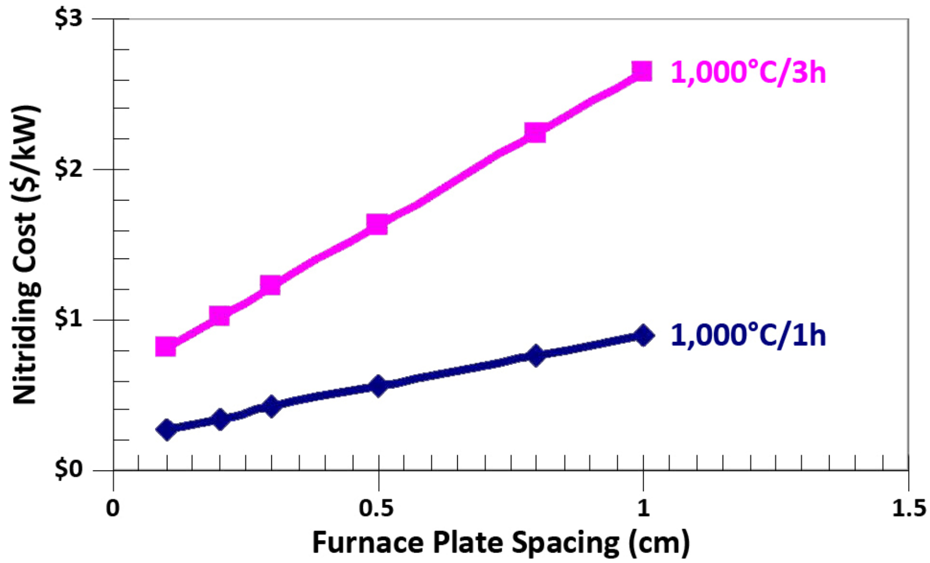

Figure 38. Impact of plate spacing on nitriding cost

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 (and the one integrated into the baseline model) is TreadStone's proprietary LiteCell 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)"[38] (see Figure 39). The resistant layer provides excellent corrosion protection, while the vias provide sufficient electrical conduction to improve overall conductivity through the plate.

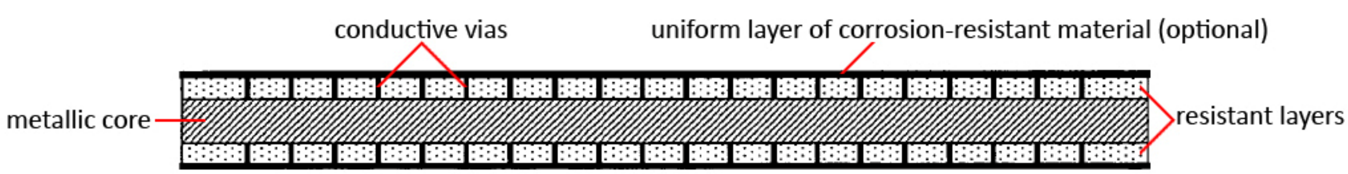

Figure 39. Conductive vias shown in US patent 7,309,540

The resistant layer is applied via a physical vapor deposition process. Details of the manufacturing process are considered proprietary, so only limited explanation is provided here.

The postulated coating application follows a three-step process. The major step is the deposition of a non-continuous layer of gold dots (~1% surface coverage) via a patented low-cost process designed to impart low contact resistance. The plate coating is applied after bipolar plate stamping. The gold layer is only applied to one side of the plates because only one side requires low contact resistance.

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

The cost breakdown for the TreadStone process is shown in Figure 40. The coating cost is observed to be primarily a function of annual production rate, with cost spiking at low quantities of only 1,000 systems per year. This is a reflection of low utilization of the coating system, and the application cost could perhaps be reduced with an alternate application technique.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$39.60	$39.60	$39.60	$39.60	$39.60
	Manufacturing ($/stack)	$1,169.20	$70.06	$77.63	$70.45	$67.32
	Total Cost ($/stack)	$1,208.80	$109.66	$117.23	$110.05	$106.92
	Total Cost ($/$kW_{net}$)	$15.11	$1.37	$1.47	$1.38	$1.34
2015	Materials ($/stack)	$32.76	$32.76	$32.76	$32.76	$32.76
	Manufacturing ($/stack)	$1,168.36	$69.96	$77.52	$70.35	$67.21
	Total Cost ($/stack)	$1,201.13	$102.72	$110.28	$103.11	$99.98
	Total Cost ($/$kW_{net}$)	$15.01	$1.28	$1.38	$1.29	$1.25

Figure 40. Cost breakdown for TreadStone LiteCell 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[39], including partially fluorinated (PVDF) and non-fluorinated (BAM3G, S-PPBP, MBS-PBI, MBS-PPTA, S-PEK). Additionally, membranes may be homogenous, composites[40], or placed on a substrate for mechanical reinforcement.

For purposes of this study, the approach selected was Nafion® on a porous expanded polytetrafluoroethylene[41] (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.

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

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

[41] 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.

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

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[42]. 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. 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[43] 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.

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

[43] 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.

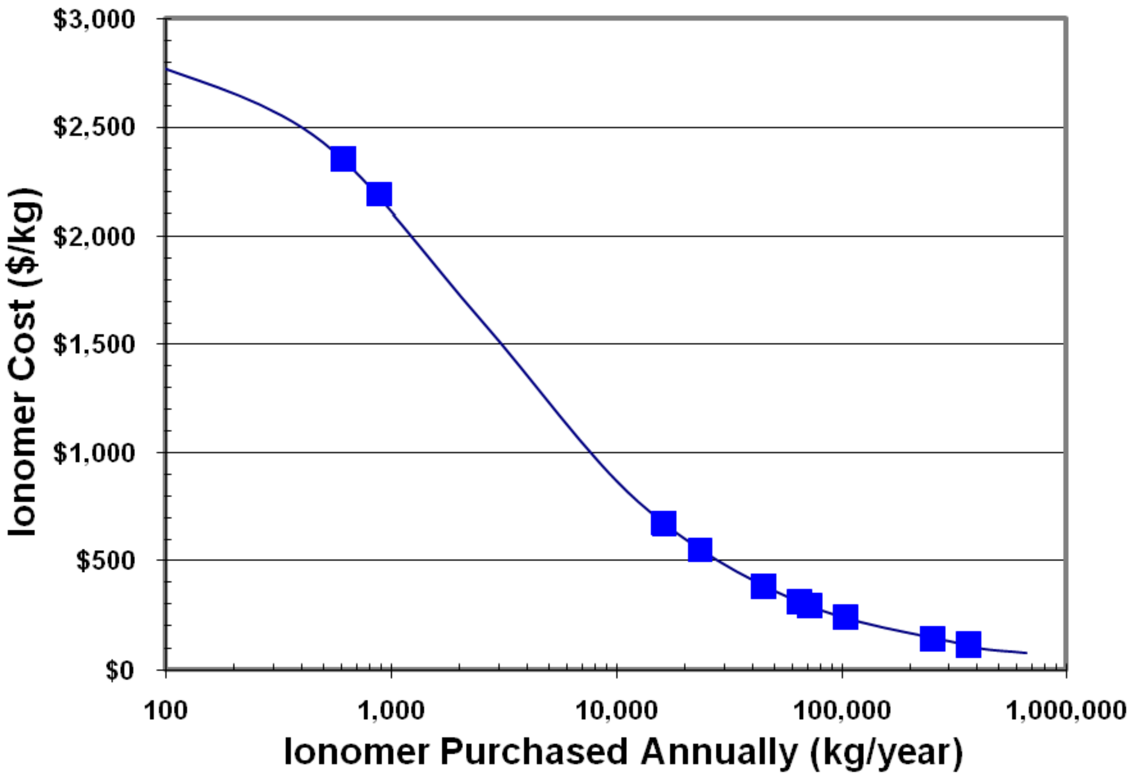

Figure 42. Ionomer material cost

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[44] the cost of a Gore-like[45] 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[46]. 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

[44] 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.

[45] 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.

[46] 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.

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[47] 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[48] from 10 years to 5 years.
- Plan for significant plant underutilization[49] (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:

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 Infrared Oven Drying:** The web dries via infrared 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 Infrared 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.

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[47] 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.

[48] 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.

[49] 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.

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

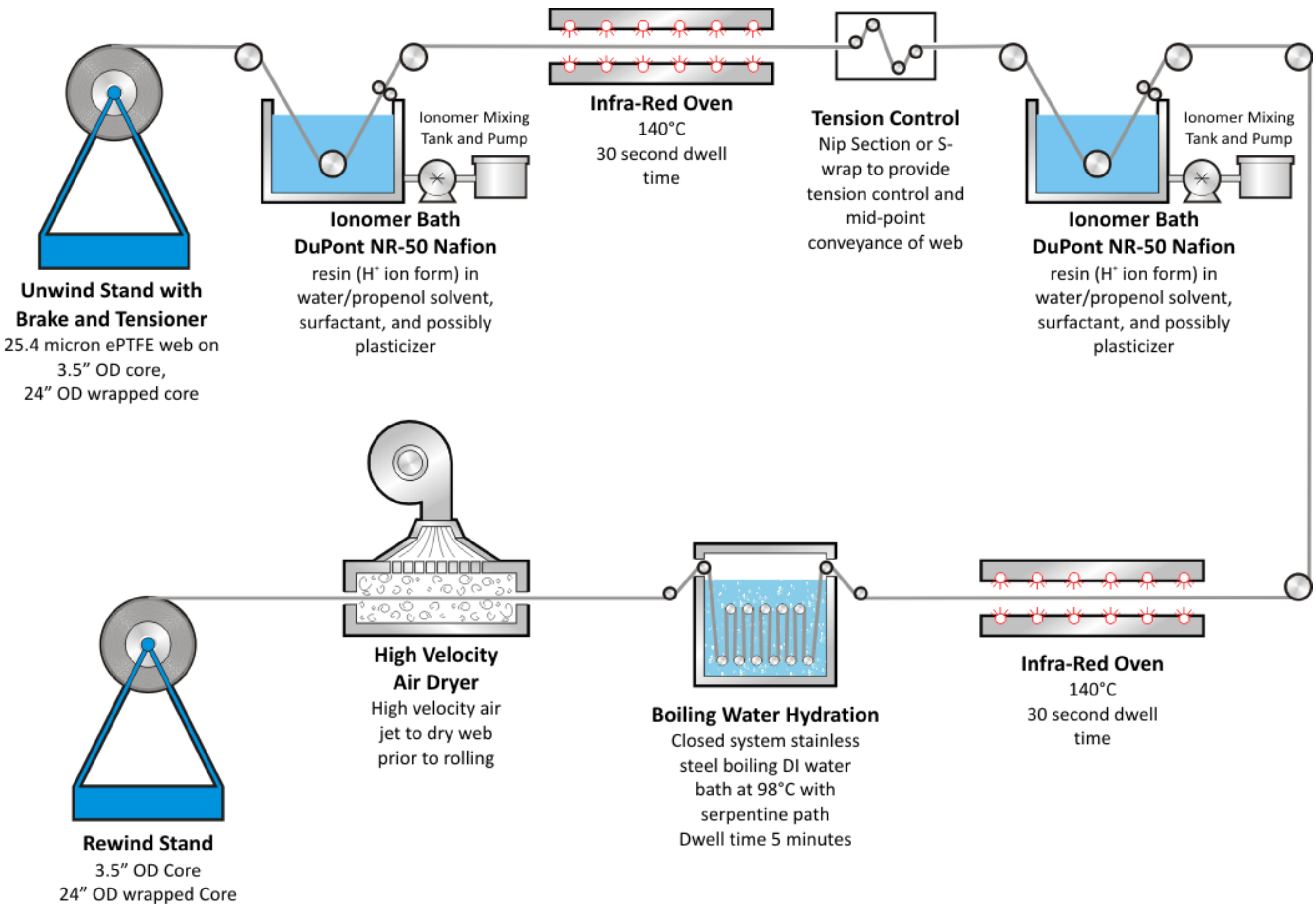

Figure 43. Membrane fabrication process diagram

Details of the membrane fabrication cost analysis are shown in Figure 44. Two roll-to-roll plants are 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 are 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[50]. 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.

[50] 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.

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 is 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 are allocated than are typical to the automotive industry where there is a large supplier base with virtually interchangeable products competing solely on price.

Revenue: Annual membrane fabricator revenue is not an input in the analysis. Rather it is 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.

		2010 - 2030				
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 Supplied		4.5	1.5	3	2.15	1
Vehicle Annual Production	veh/year	4,500	45,000	240,000	279,500	500,000
m^2 per Vehicle	m^2/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)	m^2/year	187,388	1,338,486	7,807,836	8,685,732	10,898,438
Gross Production (plant)	m^2/year	125,550	896,786	5,231,250	5,819,440	8,718,750
Net Production (plant)	m^2/year	62,775	627,750	3,348,000	3,899,025	6,975,000
Net Production of 1 Line	m^2/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 m^2 (Pre-Markup)	$/$m^2$	$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)*	$/$m^2$	$224.45	$35.04	$9.57	$7.37	$4.75 [51]

Figure 44. Simplified membrane manufacturing cost analysis assumptions

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

[51] 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).

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 is utilized in subsequent power system cost computations.

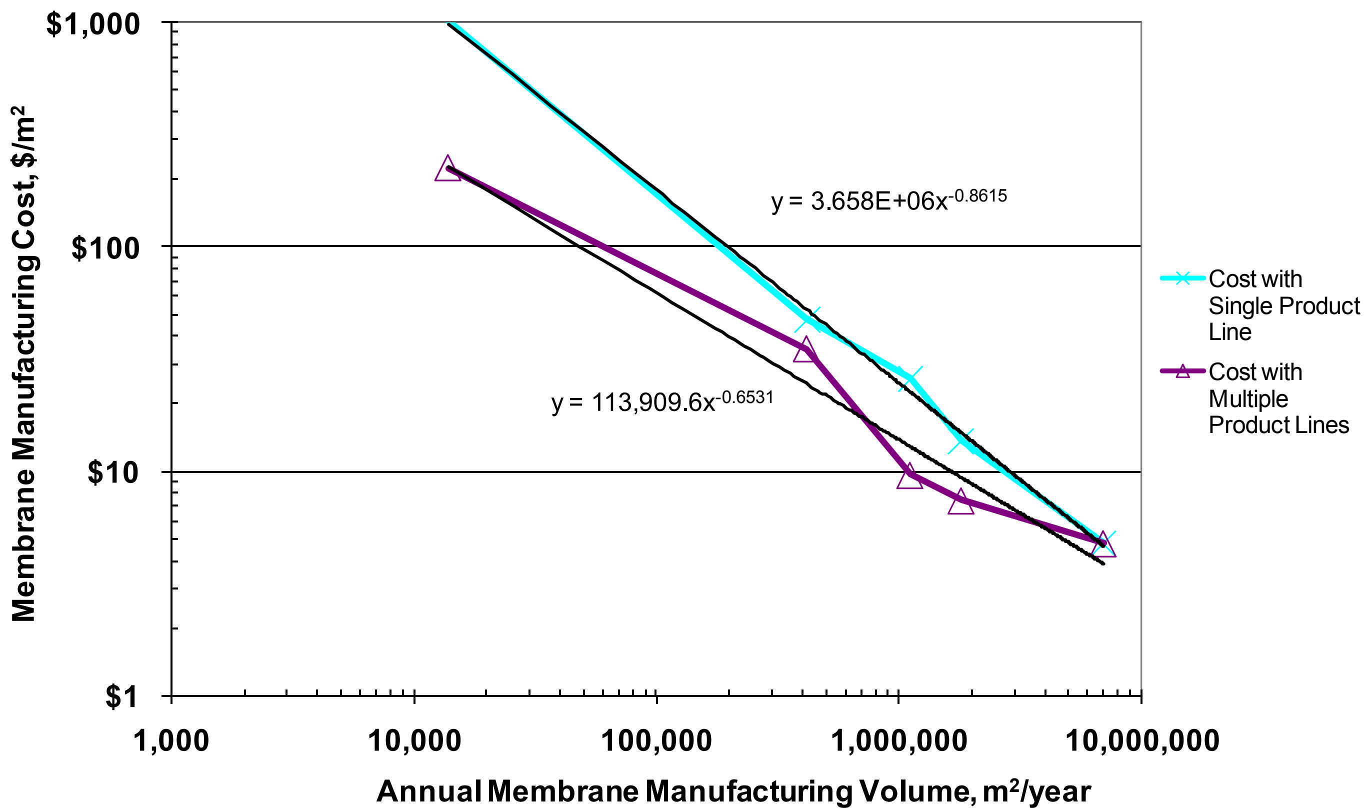

Figure 45. Membrane manufacturing cost vs. annual membrane manufacturing volume

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[52] 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 are 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 is 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.

[52] "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.

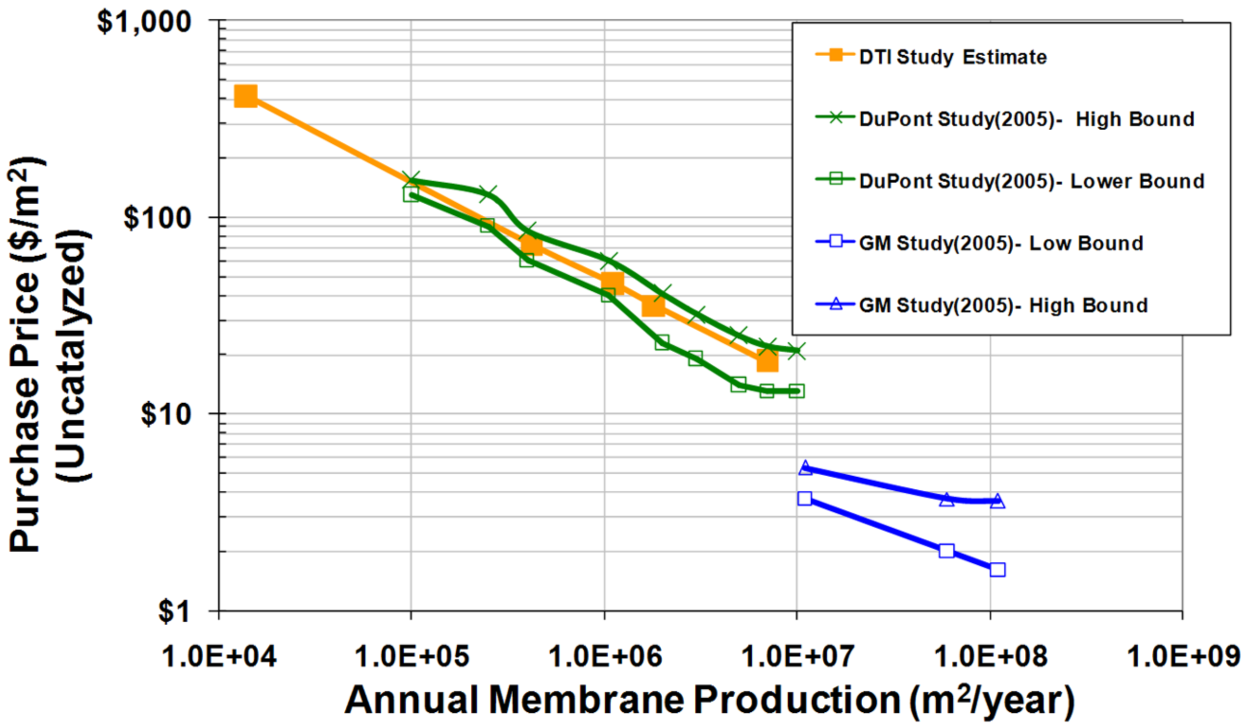

Figure 46. Membrane (material + manufacturing) cost, compared to previous analysis and vendor quotes

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/m^2)	$191.67	$52.25	$35.27	$28.54	$16.25
	Manufacturing ($/m^2)	$250.69	$27.75	$14.72	$10.78	$4.48
	Total Cost ($/m^2)	$442.36	$79.99	$49.99	$39.32	$20.73
	Total Cost ($/stack)	$5,184.51	$908.84	$562.23	$438.23	$230.78
	Total Cost ($/kW$_{net}$)	$64.81	$11.36	$7.03	$5.48	$2.88
2015	Materials ($/m^2)	$198.19	$56.95	$38.15	$30.72	$17.20
	Manufacturing ($/m^2)	$284.73	$31.52	$16.72	$12.25	$5.08
	Total Cost ($/m^2)	$482.92	$88.47	$54.87	$42.97	$22.29
	Total Cost ($/stack)	$4,657.35	$827.11	$507.81	$394.04	$204.21
	Total Cost ($/kW$_{net}$)	$58.22	$10.34	$6.35	$4.93	$2.55

Figure 47. Cost breakdown for un-catalyzed membrane

4.4.3. Nanostructured Thin Film (NSTF) Catalyst Application

Previous analysis by DTI has focused on roller-based application of carbon supported platinum catalysts deposited directly onto the PEM membrane. This technique has the advantage of being one of the least costly application techniques judged adequate for high production rates and reasonably high MEA performance. However, it is increasingly clear that further increases in power density with simultaneously lower Pt loading is probably not possible with this technique. Consequently, a new method of catalyst deposition was examined that has shown remarkable recent improvements in power density and durability at low Pt loadings. Developed at 3M, the Nanostructured Thin Film Catalyst (NSTF) deposition process begins with a layer of crystalline finger-like projections, or “whiskers”, that create a high surface area substrate on which the active catalysts may be deposited. Next, vapor deposition methods are utilized to deposit a very thin layer of a ternary catalyst allow onto the whiskers in a very precise and even manner. The resulting catalyst coated whiskers can then be hot-pressed into the fuel cell membrane to form a porous mat electrode intimately bonded to the membrane. 3M has recently demonstrated significant improvements in the durability and the power-density-to-catalyst-loading ratio that surpass the 2010 DOE performance targets.

4.4.3.1. Application Process

The NSTF application process involves four main steps as identified by a review of non-proprietary open source literature[53,54]. 3M representatives have reviewed and critiqued the analysis not for 100% accuracy as to how they would specifically carrying out the production, but rather to vet the general approach and major elements affecting cost. They judge the process and resulting cost estimate to be consistent with internal proprietary projections of resulting catalyst cost.

The main steps of the modeled NSTF catalyst application process are listed below and shown in Figure 48:

1. **Deposition:** Physical Vapor Deposition(PVD) of PR-149 (Perylene Red pigment 149) onto a DuPont Kapton® polyamide web (a temporary deposition substrate)

2. **Annealing:** Vacuum annealing of the PR-149, resulting in the formation of crystalline nanostructures through a screw dislocation growth process

3. **Catalyst Sputtering:** Ternary PtCoMn catalyst is magnetron-sputtered into the nanostructures

4. **Catalyst Transfer:** Roll-to roll transfer of the catalyst coated nanostructures from the Kapton® substrate to the PEM membrane

[53] US Patent #4,812,352 titled "Article having surface layer of uniformly oriented, crystalline, organic microstructures"

[54] "Advanced Cathodes and Supports for PEM Fuel Cell", presented by Mark Debe of 3M at the 2009 DOE Hydrogen Program Annual Review Meeting, Arlington, VA, 20 May 2009.

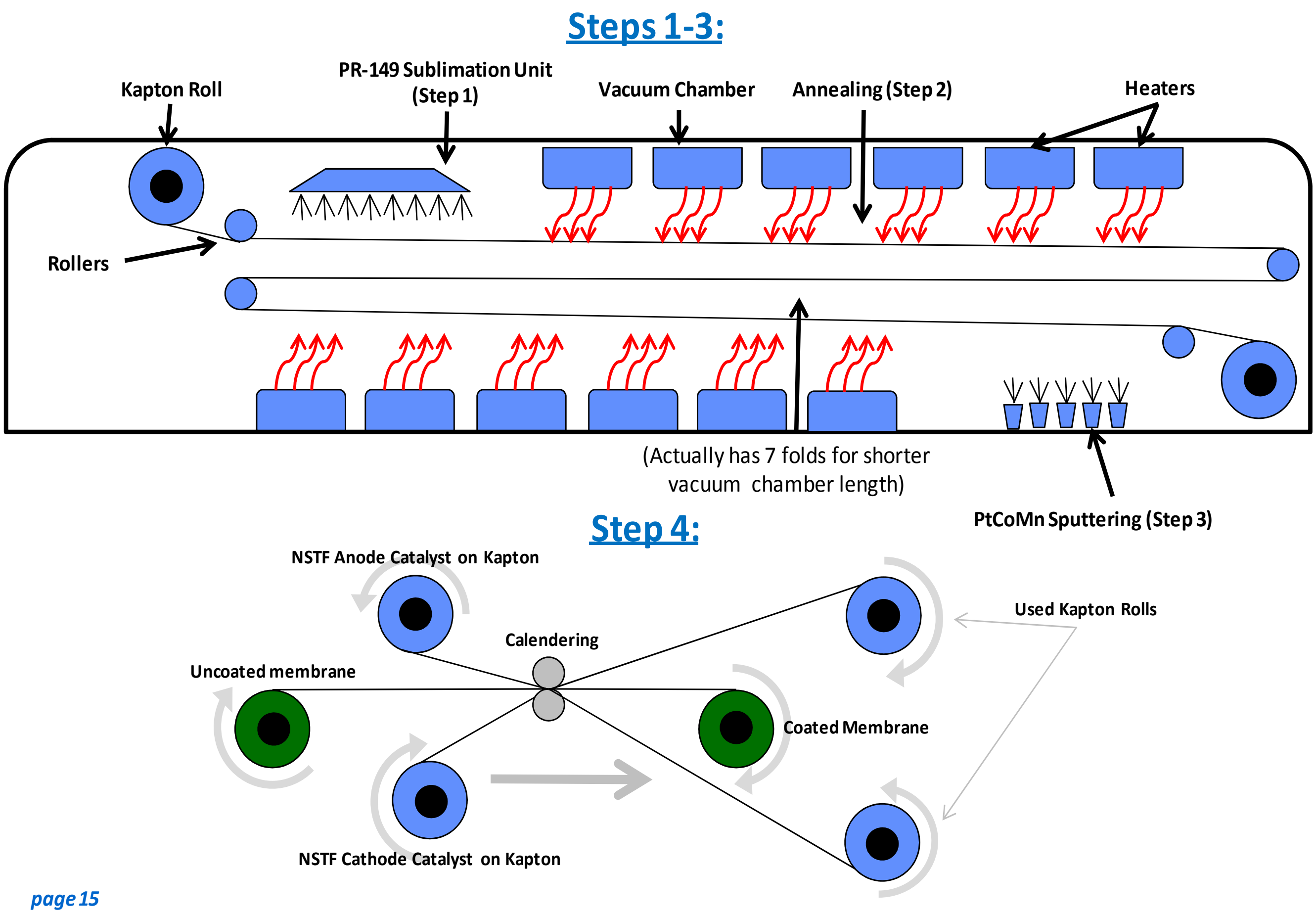

Figure 48. NSTF production process diagram

4.4.3.2. Cost and Performance Assumptions

Cost and performance assumptions concerning the NSTF catalyst creation system are listed below.

Capital Cost: The capital costs of the manufacturing machinery were primarily based on conversations with industry representatives or derived from previous DTI work involving similar components. A complete list of capital cost is shown in Figure 49.

Component	Cost
Evacuation Chamber 1	$78,732
Evacuation Chamber 2	$147,623
Sublimation Unit	$100,000
Cylindrical Magnetron Sputtering Unit	$210,321
64 m (effective length) Vacuum Annealing Oven	$428,571
Re-Pressurization Chamber 1	$127,940
Re-Pressurization Chamber 2	$78,732
Hot Calender Decal Application (Step 4)	$100,000
Total Capital Cost per Line	**$1,271,921**

Figure 49. Capital costs of NSTF manufacturing line

Line Speed: The line speed calculation is based on a balance between the vacuum chamber length and the time needed for the sublimation, annealing, and sputtering operations and is set at 5.84 m/min. It is not cost effective to draw and release a vacuum for separate operations: thus all three are postulated to occur within the same vacuum chamber. The bulk of the chamber will be devoted to annealing, which, at the given line speed, requires 58.38m of length. Creating a vacuum chamber this long would be prohibitively expensive, and thus the web will travel in a serpentine pattern folding back on itself 7 times, so the annealing chamber itself will be ~8.5 m in total length. An additional ~3.5 m of sublimation and ~1.5m of sputtering chamber will be on either end of the annealing chamber. A minimum of ten minutes of annealing time is required for nanostructure formation. In addition to the annealing time, ~17 seconds is needed for catalyst deposition and 40 seconds is needed for PR-149 sublimation onto the substrate. These times are based on the thickness of the coatings (100nm for the PR-149 and 44nm for the catalyst coating) as indicated by 3M and an approximate deposition rate of 2.5 nm/sec. as indicated by representatives of Vergason Technology, Inc .

Catalyst Loading: 3M has demonstrated that high performance can be achieved at catalyst loadings of 0.15 mgPt/cm^2 in this configuration[55]. The assumed mole fraction for the ternary catalyst was assumed to be 73% Platinum, 24% Cobalt, and 2% Manganese.

Web Roll Assumptions: We have assumed a roll length of 1500 m, with a loading time of ~16 minutes per roll[56].

4.4.3.3. Results

When compared to the previous method of catalyst application considered (Die-slot application based on the Coatema VertiCoater), the total NSTF catalyst system and application is actually slightly more expensive for a given power density and catalyst loading. This is somewhat misleading however, since the NSTF method facilitates a lower catalyst loading and improved power density that cannot be otherwise achieved. Consequently, taking power density and catalyst loading into consideration, a net savings of \$10.28/kW$_{net}$ is obtained. A cost comparison of the two methods (assuming similar catalyst loading and power density) is shown in Figure 50.

[55] "Advanced Cathodes and Supports for PEM Fuel Cell", presented by Mark Debe of 3M at the 2009 DOE Hydrogen Program Annual Review Meeting, Arlington, VA, 20 May 2009.

[56] The 16 minute total time includes times for loading and unloading the Kapton rolls as well as pressurizing and drawing a vacuum.

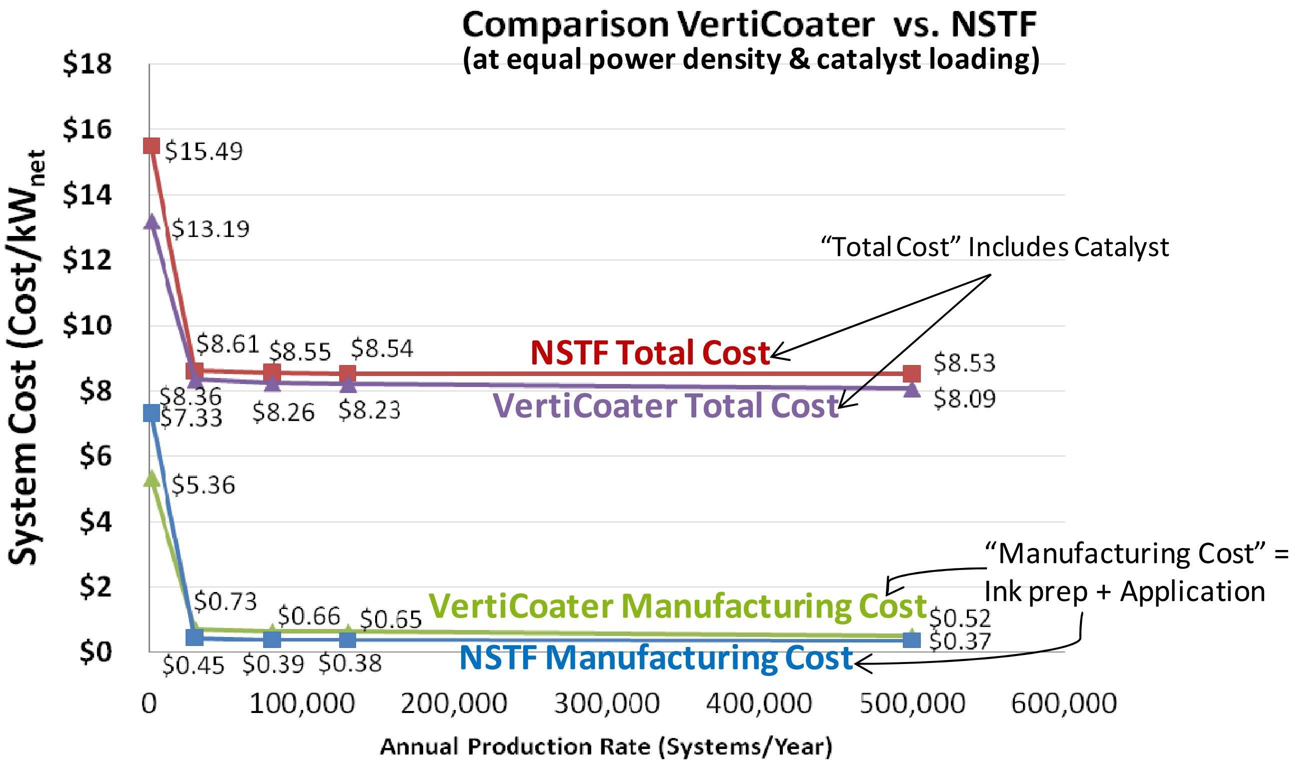

Figure 50. Cost comparison between NSTF and VertiCoater methods

Machine rate and process parameters are show in Figure 51 and Figure 52. The overall cost breakdown at various system values and technology levels is shown in Figure 53.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/Line)	$1,284,255	$1,284,255	$1,284,255	$1,284,255	$1,284,255
	Simultaneous Lines	1	1	2	4	12
	Laborers per Line	2	2	2	2	2
	Line Utilization	2.47%	71.78%	94.73%	76.27%	97.70%
	Effective Total Machine Rate ($/hr)	$6,775.71	$373.73	$318.36	$360.26	$313.10
	Line Speed (m/s)	0.0973	0.0973	0.0973	0.0973	0.0973
2015	Capital Cost ($/Line)	$1,282,957	$1,284,255	$1,284,255	$1,284,255	$1,284,255
	Simultaneous Lines	1	1	2	3	9
	Laborers per Line	2	2	2	2	2
	Line Utilization	1.81%	52.15%	68.82%	73.89%	94.64%
	Effective Total Machine Rate ($/hr)	$9,222.89	$459.73	$383.54	$367.21	$318.53
	Line Speed (m/s)	0.0973	0.0973	0.0973	0.0973	0.0973

Figure 51. NSTF application process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010 - 2015	Equipment Lifetime	12.67	12.67	12.67	12.67	12.67
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Capital Recovery Factor	0.185	0.185	0.185	0.185	0.185
	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)	737	737	737	737	737

Figure 52. Machine rate parameters for NSTF application process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Material ($/stack)	$662.34	$662.34	$662.34	$662.34	$662.34
	Manufacturing ($/stack)	$563.21	$30.04	$25.33	$28.41	$24.67
	Tooling ($/stack)	$26.73	$7.98	$7.89	$7.87	$7.82
	Total Cost ($/stack)	$1,252.28	$700.37	$695.57	$698.62	$694.83
	Total Cost ($/$kW_{net}$)	$15.65	$8.75	$8.69	$8.73	$8.69
2015	Material ($/stack)	$545.02	$545.02	$545.02	$545.02	$545.02
	Manufacturing ($/stack)	$559.42	$26.85	$22.17	$21.04	$18.23
	Tooling ($/stack)	$30.28	$6.60	$6.51	$6.45	$6.37
	Total Cost ($/stack)	$1,134.71	$578.48	$573.71	$572.51	$569.63
	Total Cost ($/$kW_{net}$)	$14.18	$7.23	$7.17	$7.16	$7.12

Figure 53. Cost breakdown for NSTF application process

4.4.4. Catalyst Cost

As described in the previous section, a PtCoMn catalyst is used for the NSTF catalyst system and is applied via a physical vapor deposition method (modeled as magnetron sputtering). Consistent with PVD, the metal is supplied in the form of a pure sputtering target for each metal. The cost of each target is estimated to be:

Platinum: $1,100/troy ounce
Cobalt: $2.87/troy ounce
Manganese: $ 0.15/troy ounce

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 is 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. In 2008 for example, the price of platinum varied greatly (as shown in Figure 54), with the daily trading values reaching an annual (and all-time) peak of $2,280/tr.oz. on March 4, and a low of $782/tr.oz on October 27.[57]

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

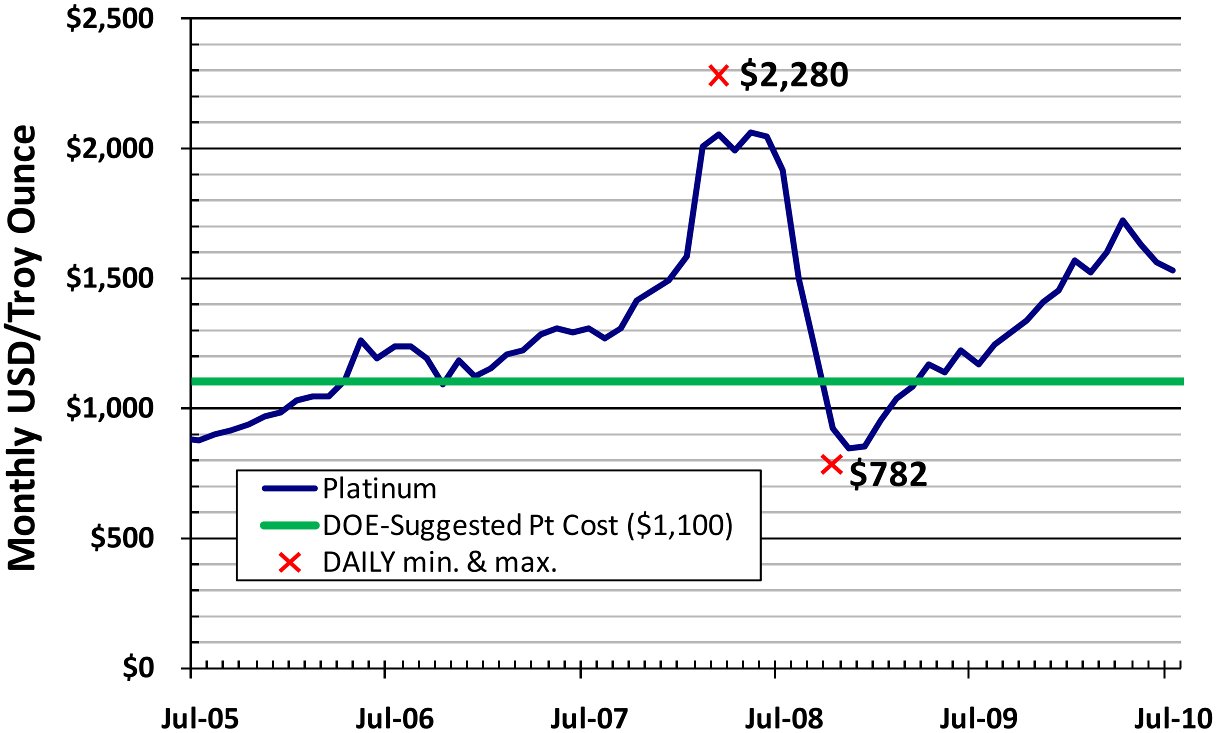

Figure 54. Five-year graph of monthly platinum prices

While 2008 may have been an anomalously turbulent year in the market, the five-year average cost is $1,312/tr.oz., which is relatively close to the $1,100 value provided by the DOE[58]. Careful consideration should be paid to this, as changes in platinum cost will dramatically affect the system cost[59].

4.4.5. Gas Diffusion Layer

Figure 55 displays a cross-sectional diagram of the modeled gas diffusion layer (GDL). Consistent with recent research,[60] 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[61]. 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.

[58] Prior to 2010, the 5-year average price was much closer to $1,100/tr.oz. If the price does not decrease sufficiently in upcoming months, it may be worthwhile to reexamine the price used in the model.

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

[60] *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)

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

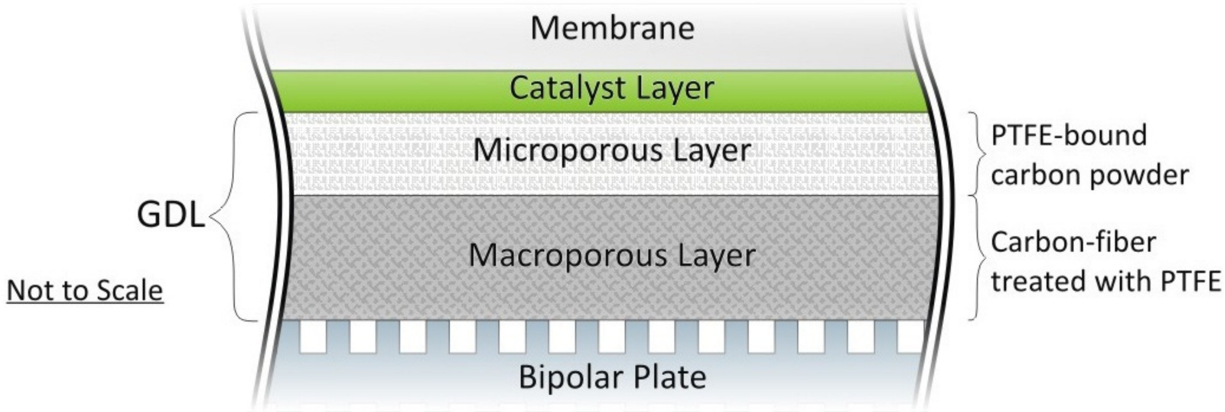

Figure 55. Cross-section of gas diffusion layer in stack

Figure 56 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

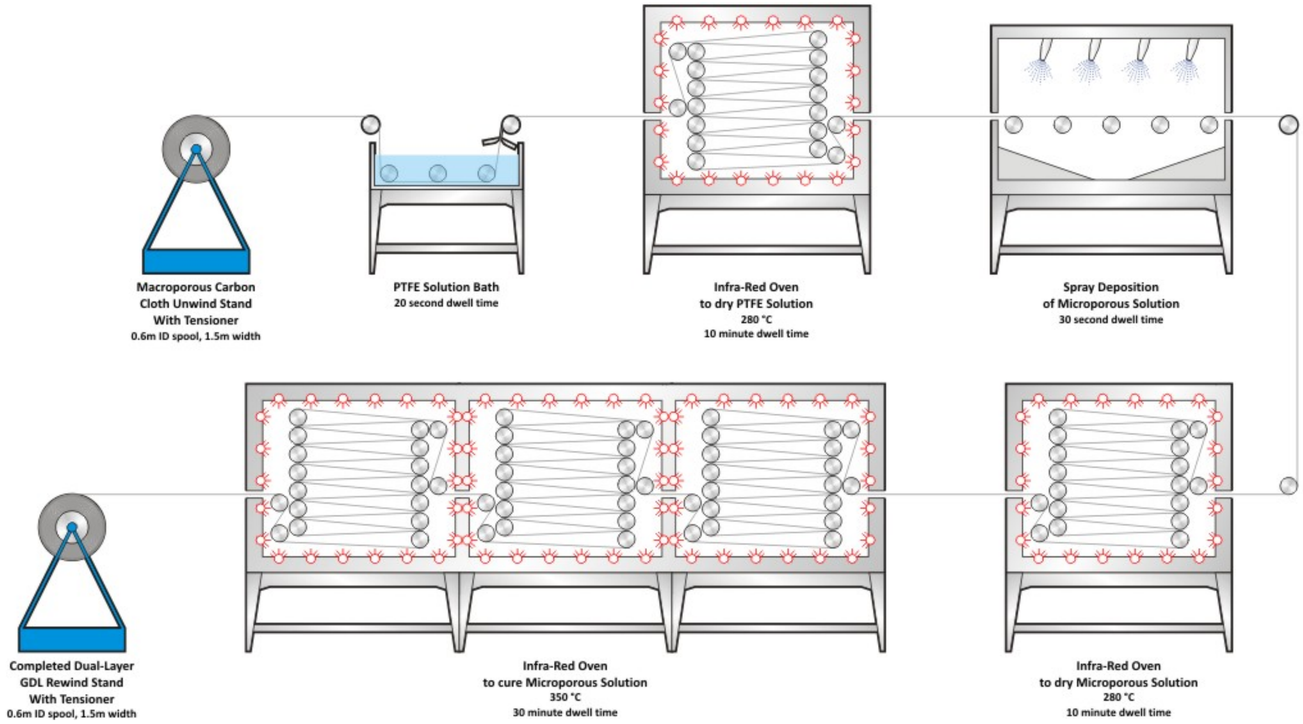

Figure 56. Dual-layer GDL process diagram

Component	Cost
Unwind Stand w/ Tensioner	$27,283
Dipper	$81,849
Oven 1 (Macroporous Layer)	$156,317
VCF1500HV Ultrasonic Mixer	$26,444
Sprayer for Microporous Solution	$327,396
Oven 2 (Microporous Layer Stage 1)	$156,317
Oven 3 (Microporous Layer Stage 2)	$468,951
Rewind Stand w/Tensioner	$27,283
Total Capital Cost	**$1,271,840**

Figure 57. Capital cost breakdown for a typical microporous layer application line

Figure 58 and Figure 59 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 60 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 $2–27/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.

2010	Capital Cost ($/Line)	$1,271,840	$1,271,840	$1,271,840	$1,271,840	$1,271,840
	Simultaneous Lines	1	1	3	5	17
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	3.24%	96.56%	85.81%	83.67%	94.65%
	Effective Total Machine Rate ($/hr)	$4,895.06	$211.29	$231.64	$236.32	$214.57
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
	Macroporous Layer Cost ($/m^2)	$71.83	$48.52	$29.58	$22.62	$9.51
2015	Capital Cost ($/Line)	$1,271,840	$1,271,840	$1,271,840	$1,271,840	$1,271,840
	Simultaneous Lines	1	1	2	4	12
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	2.36%	70.14%	93.51%	75.97%	97.40%
	Effective Total Machine Rate ($/hr)	$6,696.28	$272.49	$216.58	$255.32	$209.88
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
	Macroporous Layer Cost ($/m^2)	$71.83	$48.52	$29.58	$22.62	$9.51

Figure 58. GDL manufacturing process parameters (microporous layer addition only)

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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	493	493	493	493

Figure 59. Machine rate parameters for GDL manufacturing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Purchased Macroporous Layer ($/$kW_{net}$)	$20.00	$13.51	$8.24	$6.30	$2.65
	Other Materials ($/$kW_{net}$)	$0.09	$0.09	$0.09	$0.09	$0.09
	Manufacturing ($/$kW_{net}$)	$6.66	$0.29	$0.31	$0.32	$0.29
	Total Cost ($/$kW_{net}$)	$26.75	$13.89	$8.64	$6.71	$3.03
2015	Purchased Macroporous Layer ($/$kW_{net}$)	$16.46	$11.12	$6.78	$5.18	$2.18
	Other Materials ($/$kW_{net}$)	$0.08	$0.08	$0.08	$0.08	$0.08
	Manufacturing ($/$kW_{net}$)	$6.64	$0.27	$0.21	$0.25	$0.21
	Total Cost ($/$kW_{net}$)	$23.17	$11.46	$7.07	$5.51	$2.46

Figure 60. 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 61) 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.

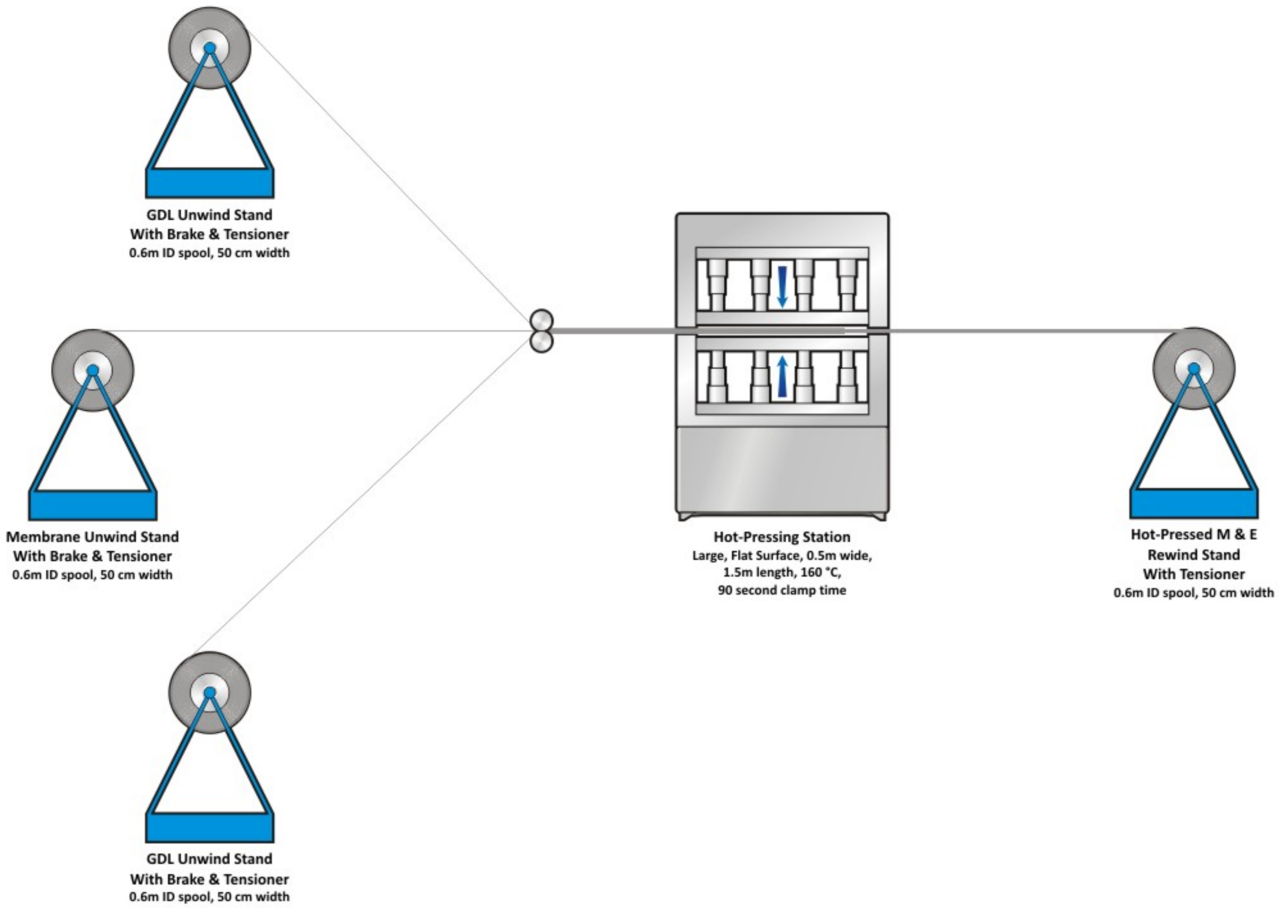

Figure 61. Hot-pressing process diagram

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 62.

2010	Capital Cost ($/Line)	$187,542	$187,542	$187,542	$187,542	$187,542
	Costs per Tooling Set ($)	$10,913	$10,913	$10,913	$10,913	$10,913
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	3	6	10	37
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	7.22%	72.16%	96.20%	93.80%	97.51%
	Effective Total Machine Rate ($/hr)	$294.15	$40.55	$33.50	$34.04	$33.21
	Index Time (s)	93.00	93.00	93.00	93.00	93.00
2015	Capital Cost ($/Line)	$187,542	$187,542	$187,542	$187,542	$187,542
	Costs per Tooling Set ($)	$10,913	$10,913	$10,913	$10,913	$10,913
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	2	5	7	27
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.29%	78.79%	84.03%	97.53%	97.25%
	Effective Total Machine Rate ($/hr)	$397.09	$38.17	$36.56	$33.21	$33.27
	Index Time (s)	93.00	93.00	93.00	93.00	93.00

Figure 62. Hot-pressing process parameters

Hot pressing cost is summarized in Figure 64. 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
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 63. Machine rate parameters for hot-pressing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Manufacturing ($/stack)	$71.36	$9.83	$8.12	$8.25	$8.05
	Tooling ($/stack)	$0.73	$0.15	$0.11	$0.11	$0.11
	Total Cost ($/stack)	$72.09	$9.98	$8.23	$8.36	$8.16
	Total Cost ($/kW$_{net}$)	$0.90	$0.12	$0.10	$0.10	$0.10
2015	Manufacturing ($/stack)	$70.56	$6.74	$6.45	$5.86	$5.87
	Tooling ($/stack)	$0.73	$0.10	$0.09	$0.08	$0.08
	Total Cost ($/stack)	$71.29	$6.83	$6.54	$5.94	$5.95
	Total Cost ($/kW$_{net}$)	$0.89	$0.09	$0.08	$0.07	$0.07

Figure 64. Cost breakdown for hot-pressing process

4.4.6.2. Cutting & Slitting

As shown in Figure 65, the rolls of hot-pressed membrane and GDL are fed through cutters and slitters to trim to 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.

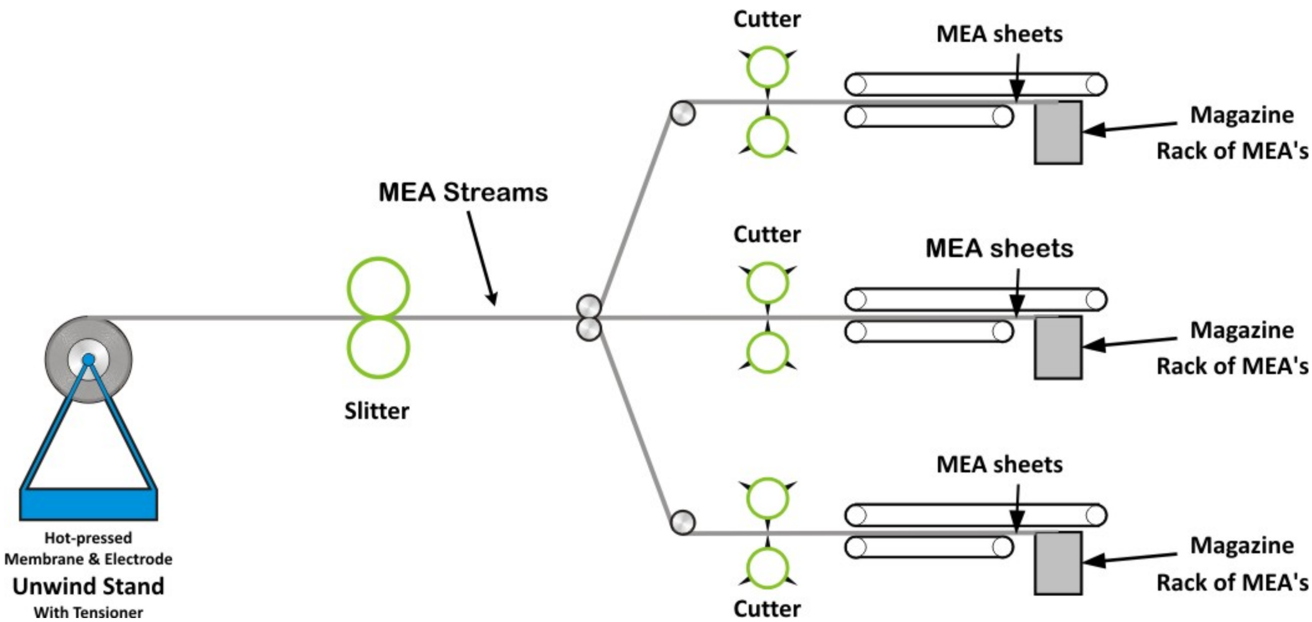

Figure 65. Cutting & slitting process diagram

Figure 67 further details the process parameters. Machine utilization at 1,000 systems per year is extremely poor (as low as 0.18%). However, costs associated with manual cutting are comparable to the automated system running at poor utilization. Consequently, for simplicity this process is presented as being automated at all production rates. Figure 69 summarizes the overall cost of the cutting and slitting operation.

Component	Cost
Unwind Stand w/ Tensioner	$27,283
Cutter/Slitter	$92,762
Stacker	$10,913
Total Capital Cost	$130,958

Figure 66. Capital cost breakdown for the cutting and slitting process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/Line)	$130,958	$130,958	$130,958	$130,958	$130,958
	Costs per Tooling Set ($)	$5,457	$5,457	$5,457	$5,457	$5,457
	Tooling Lifetime (cycles)	200,000	200,000	200,000	200,000	200,000
	Simultaneous Lines	1	1	1	1	2
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.24%	6.28%	16.73%	27.20%	52.28%
	Effective Total Machine Rate ($/hr)	$6,679.00	$269.62	$109.00	$71.84	$43.34
	Line Speed (m/s)	1.00	1.33	1.33	1.33	1.33
2015	Capital Cost ($/Line)	$130,958	$130,958	$130,958	$130,958	$130,958
	Costs per Tooling Set ($)	$5,457	$5,457	$5,457	$5,457	$5,457
	Tooling Lifetime (cycles)	200,000	200,000	200,000	200,000	200,000
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.18%	4.57%	12.16%	19.75%	75.95%
	Effective Total Machine Rate ($/hr)	$8,842.45	$366.31	$145.31	$94.23	$33.70
	Line Speed (m/s)	1.00	1.33	1.33	1.33	1.33

Figure 67. Cutting & slitting process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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 68. Machine rate parameters for cutting & slitting process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Manufacturing ($/stack)	$54.39	$1.90	$0.77	$0.50	$0.30
	Tooling ($/stack)	$2.55	$2.52	$2.52	$2.52	$2.52
	Total Cost ($/stack)	$56.94	$4.42	$3.29	$3.02	$2.82
	Total Cost ($/$kW_{net}$)	$0.71	$0.06	$0.04	$0.04	$0.04
2015	Manufacturing ($/stack)	$54.37	$1.87	$0.74	$0.48	$0.17
	Tooling ($/stack)	$2.18	$2.03	$2.01	$2.01	$2.01
	Total Cost ($/stack)	$56.55	$3.90	$2.76	$2.50	$2.19
	Total Cost ($/$kW_{net}$)	$0.71	$0.05	$0.03	$0.03	$0.03

Figure 69. 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 70), the rectangular hot-pressed membrane/GDL is inserted into an injection-molding machine, and the gasket is molded into place around it.

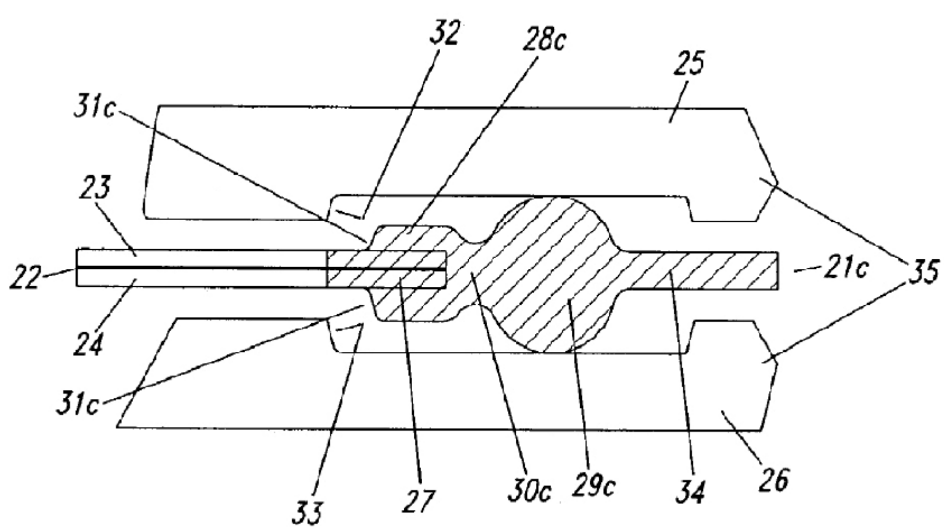

Figure 70. Insertion-molded frame/gasket concept, US patent 7,070,876

This process is similar to the insertion molding of the coolant & end gaskets (pages 66 & 73, 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. These materials are listed in Figure 71, with the best-in-group properties highlighted in red font. Although the new material costs more than the old (erroneous) silicone cost, it's 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 71. MEA frame/gasket materials comparison[62]

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 7.5 grams, and the shot mass is 11.7.

As shown in Figure 72, 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.

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

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/Line)	$278,367	$567,794	$567,794	$598,772	$598,772
	Costs per Tooling Set ($)	$62,634	$118,950	$118,950	$124,447	$124,447
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	10	26	40	154
	Laborers per Line	1.00	0.33	0.33	0.33	0.33
	Line Utilization	69.11%	96.47%	98.93%	99.54%	99.44%
	Cycle Time (s)	135	158	158	161	161
	Cavities/Platen	6	15	15	16	16
	Effective Total Machine Rate ($/hr)	$104.76	$103.15	$101.12	$105.15	$105.23
	Material Cost ($/kg)	$51.42	$46.91	$45.69	$45.09	$43.48
2015	Capital Cost ($/Line)	$257,779	$456,420	$480,444	$480,444	$480,444
	Costs per Tooling Set ($)	$69,770	$118,950	$124,447	$124,447	$124,447
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	10	25	40	154
	Laborers per Line	1.00	0.33	0.33	0.33	0.33
	Line Utilization	60.35%	96.47%	98.01%	99.54%	99.44%
	Cycle Time (s)	138	158	161	161	161
	Cavities/Platen	7	15	16	16	16
	Effective Total Machine Rate ($/hr)	$107.94	$86.39	$88.93	$87.89	$87.96
	Material Cost ($/kg)	$51.73	$47.19	$45.95	$45.36	$43.74

Figure 72. MEA frame/gasket insertion-molding process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010 - 2015	Equipment Lifetime	1	0	0	0	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)	61	91	91	94	94

Figure 73. Machine rate parameters for MEA frame/gasket insertion-molding process

The cost summary for the MEA frame/gasket molding process is shown in Figure 74.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$222.36	$202.85	$197.55	$194.98	$188.01
	Manufacturing ($/stack)	$243.26	$111.45	$109.25	$108.21	$108.29
	Tooling ($/stack)	$4.18	$5.29	$5.15	$5.11	$5.11
	Total Cost ($/stack)	$469.80	$319.59	$311.95	$308.29	$301.42
	Total Cost ($/$kW_{net}$)	$5.87	$3.99	$3.90	$3.85	$3.77
2015	Materials ($/stack)	$180.26	$164.44	$160.14	$158.06	$152.41
	Manufacturing ($/stack)	$218.86	$93.34	$91.52	$90.45	$90.52
	Tooling ($/stack)	$4.65	$5.29	$5.19	$5.11	$5.11
	Total Cost ($/stack)	$403.76	$263.06	$256.85	$253.61	$248.04
	Total Cost ($/$kW_{net}$)	$5.05	$3.29	$3.21	$3.17	$3.10

Figure 74. 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 75), 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 startup period.

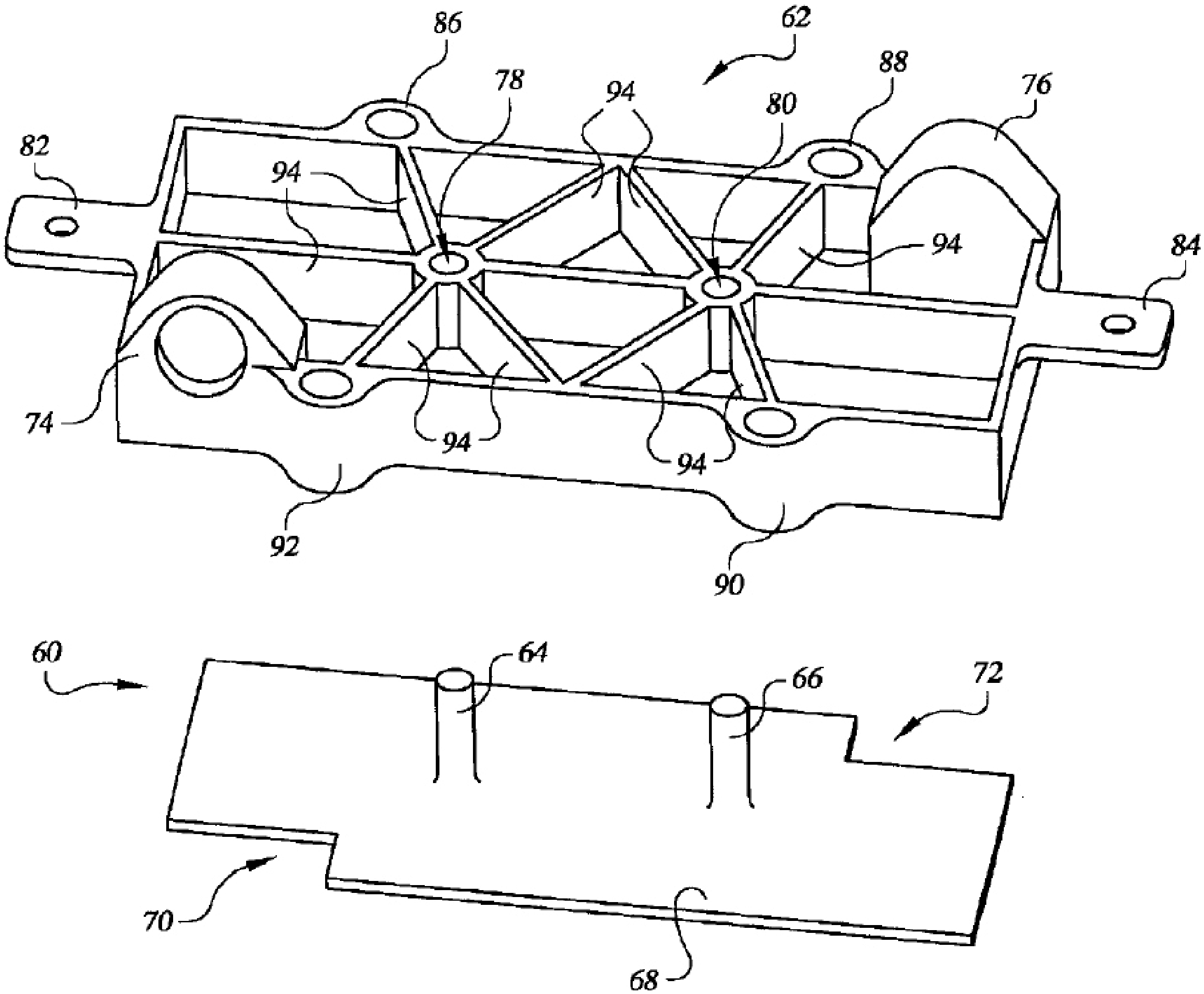

Figure 75. End plate concept, US patent 6,764,786

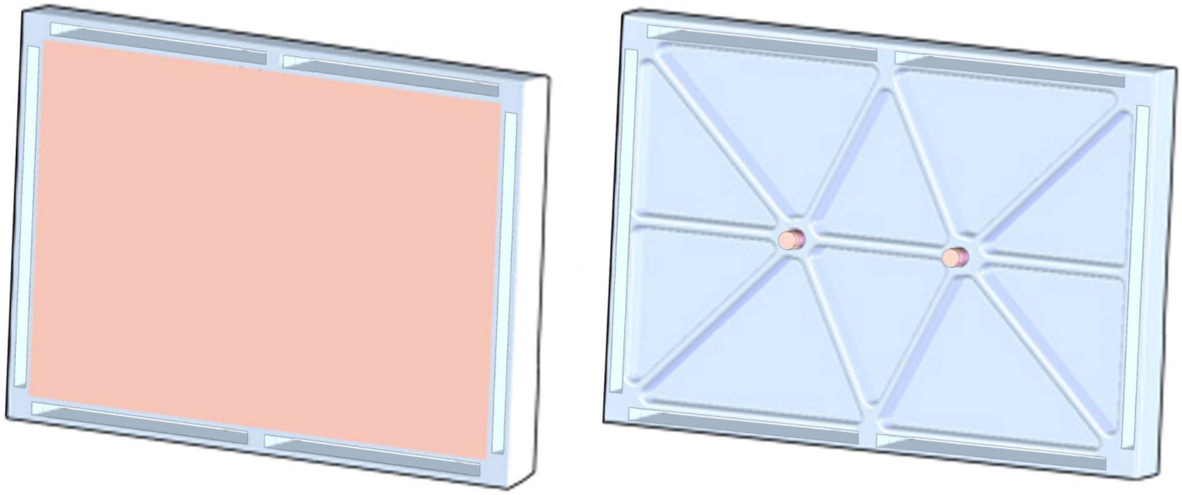

Figure 76. End plate & current collector[63]

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[64]:

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.

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[63] Some details of the port connections are not shown in the illustration.

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

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/Line)	$111,521	$267,088	$289,312	$289,312	$333,760
	Costs per Tooling Set ($)	$25,114	$71,971	$77,480	$77,480	$88,027
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	1	1	1	3
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	2.59%	19.06%	46.41%	75.41%	82.90%
	Cycle Time (s)	310	346	351	351	361
	Cavities/Platen	2	9	10	10	12
	Effective Total Machine Rate ($/hr)	$608.33	$208.71	$101.33	$68.18	$71.18
	LYTEX Cost ($/kg)	$19.10	$16.84	$15.64	$14.44	$10.83
2015	Capital Cost ($/Line)	$103,851	$177,407	$177,407	$214,186	$214,186
	Costs per Tooling Set ($)	$25,114	$54,187	$54,187	$66,275	$66,275
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	1	1	1	4
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	2.59%	27.32%	72.86%	91.53%	88.01%
	Cycle Time (s)	310	330	330	341	341
	Cavities/Platen	2	6	6	8	8
	Effective Total Machine Rate ($/hr)	$567.28	$103.69	$47.59	$46.72	$48.01
	LYTEX Cost ($/kg)	$19.10	$16.84	$15.64	$14.44	$10.83

Figure 77. End plate compression molding process parameters

As seen in Figure 79, the material represents the majority of the end plate costs, ranging from 35% to 95%, depending on the production rate.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010 - 2015	Equipment Lifetime	15.0	15.0	15.0	15.0	15.0
	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)	25	50	53	53	58

Figure 78. Machine rate parameters for compression molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$32.82	$28.93	$26.87	$24.80	$18.60
	Manufacturing ($/stack)	$52.94	$4.45	$1.97	$1.33	$1.19
	Tooling ($/stack)	$1.67	$0.16	$0.06	$0.08	$0.07
	Total Cost ($/stack)	$87.43	$33.55	$28.91	$26.21	$19.86
	Total Cost ($/$kW_{net}$)	$1.09	$0.42	$0.36	$0.33	$0.25
2015	Materials ($/stack)	$26.92	$23.73	$22.03	$20.34	$15.25
	Manufacturing ($/stack)	$49.37	$3.17	$1.46	$1.11	$1.14
	Tooling ($/stack)	$1.67	$0.12	$0.09	$0.07	$0.07
	Total Cost ($/stack)	$77.96	$27.02	$23.58	$21.51	$16.46
	Total Cost ($/$kW_{net}$)	$0.97	$0.34	$0.29	$0.27	$0.21

Figure 79. 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 75) and shown in Figure 76, 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.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Manufacturing Process	Manual	Auto	Auto	Auto	Auto
	Costs per Tooling Set ($)	$1,799	$1,799	$1,799	$1,799	$1,799
	Tooling Lifetime (cycles)	400,000	400,000	400,000	400,000	400,000
	Capital Cost ($/Line)	$22,959	$67,089	$67,089	$67,089	$67,089
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	0.06%	0.42%	1.11%	1.80%	6.94%
	Effective Total Machine Rate ($/hr)	$4,748	$1,896	$719	$449	$126
	Index Time (s)	3.00	0.53	0.53	0.53	0.53
	Copper Cost ($/kg)	$10.91	$10.91	$10.91	$10.91	$10.91
2015	Manufacturing Process	Manual	Auto	Auto	Auto	Auto
	Costs per Tooling Set ($)	$1,716	$1,716	$1,716	$1,716	$1,716
	Tooling Lifetime (cycles)	400,000	400,000	400,000	400,000	400,000
	Capital Cost ($/Line)	$21,440	$65,094	$65,094	$65,094	$65,094
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	0.06%	0.40%	1.06%	1.71%	6.57%
	Effective Total Machine Rate ($/hr)	$4,437	$1,946	$736	$459	$129
	Index Time (s)	3.00	0.51	0.51	0.51	0.51
	Copper Cost ($/kg)	$10.91	$10.91	$10.91	$10.91	$10.91

Figure 80. 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.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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)	16	16	16	16	16

Figure 81. Machine rate parameters for current collector manufacturing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$7.00	$5.75	$5.11	$4.79	$4.48
	Manufacturing ($/stack)	$9.15	$0.89	$0.34	$0.21	$0.06
	Tooling ($/stack)	$0.12	$0.01	$0.01	$0.01	$0.01
	Secondary Operations ($/stack)	$0.53	$0.53	$0.53	$0.53	$0.53
	Total Cost ($/stack)	$16.79	$7.18	$5.99	$5.54	$5.07
	Total Cost ($/$kW_{net}$)	$0.21	$0.09	$0.07	$0.07	$0.06
2015	Materials ($/stack)	$5.89	$4.84	$4.30	$4.04	$3.77
	Manufacturing ($/stack)	$8.55	$0.86	$0.33	$0.20	$0.06
	Tooling ($/stack)	$0.11	$0.01	$0.01	$0.01	$0.01
	Secondary Operations ($/stack)	$0.53	$0.53	$0.53	$0.53	$0.53
	Total Cost ($/stack)	$15.08	$6.24	$5.16	$4.77	$4.36
	Total Cost ($/$kW_{net}$)	$0.19	$0.08	$0.06	$0.06	$0.05

Figure 82. 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 370 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 was specified for the baseline systems prior to the 2008 Update. Two more methods have since been examined: laser welding and screen printing, the former of which was ultimately selected. Figure 83 shows a comparison between the costs of the three methods.

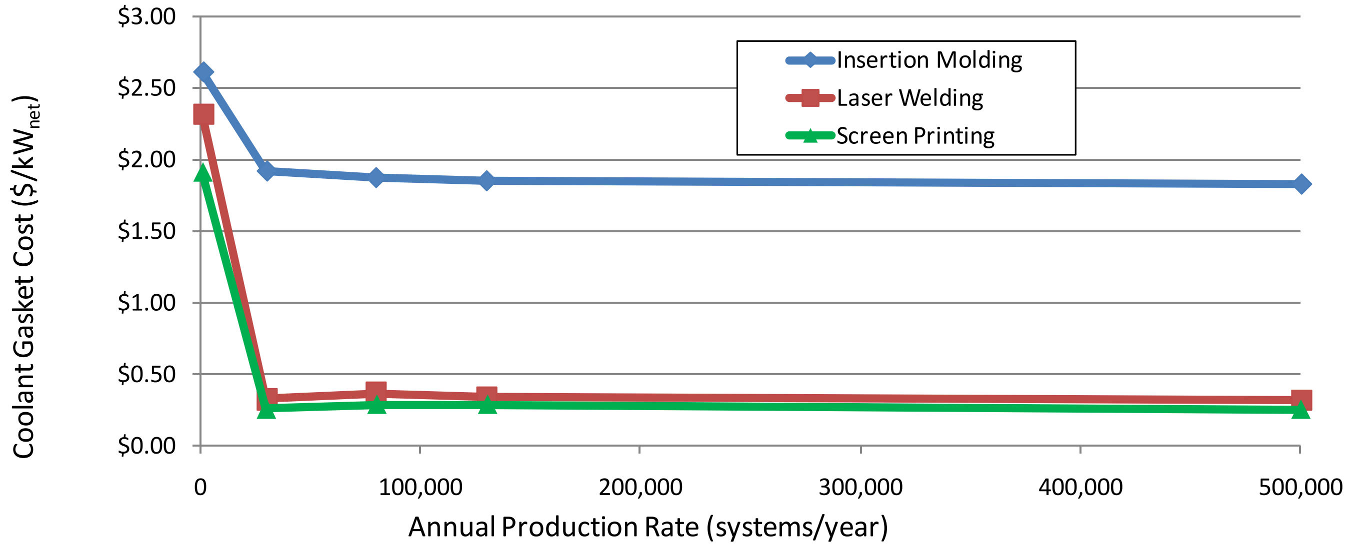

Figure 83. Coolant gasket manufacturing method cost comparison (for 2010 technology)

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 84 details the process parameters and Figure 86 summarizes the gasket costs.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/Line)	$221,621	$495,804	$521,983	$521,983	$521,983
	Costs per Tooling Set ($)	$55,129	$118,950	$124,447	$124,447	$124,447
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	5	15	16	16	16
	Total Cycle Time (s)	132.7	158.1	160.6	160.6	160.6
	Simultaneous Lines	1	10	25	40	154
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	81.59%	96.73%	98.28%	99.81%	99.71%
	Effective Total Machine Rate ($/hr)	$52.72	$88.38	$91.15	$90.02	$90.09
	Material Cost ($/kg)	$51.42	$46.91	$45.69	$45.09	$43.48
2015	Capital Cost ($/Line)	$190,040	$402,183	$422,592	$422,592	$422,592
	Costs per Tooling Set ($)	$55,129	$118,950	$124,447	$124,447	$124,447
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	5	15	16	16	16
	Total Cycle Time (s)	133	158	161	161	161
	Simultaneous Lines	1	10	25	40	154
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	81.59%	96.73%	98.28%	99.81%	99.71%
	Effective Total Machine Rate ($/hr)	$47.05	$74.28	$76.41	$75.50	$75.56
	Material Cost ($/kg)	$51.73	$47.19	$45.95	$45.36	$43.74

Figure 84. Gasket insertion-molding process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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)	53	84	86	86	86

Figure 85. Machine rate parameters for gasket insertion-molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$57.39	$52.35	$50.98	$50.32	$48.52
	Manufacturing ($/stack)	$144.53	$95.75	$94.05	$92.89	$92.96
	Tooling ($/stack)	$7.35	$5.29	$5.19	$5.11	$5.11
	Total Cost ($/stack)	$209.27	$153.39	$150.22	$148.31	$146.59
	Total Cost ($/$kW_{net}$)	$2.62	$1.92	$1.88	$1.85	$1.83
2015	Materials ($/stack)	$44.45	$40.55	$39.49	$38.98	$37.59
	Manufacturing ($/stack)	$128.98	$80.47	$78.85	$77.91	$77.97
	Tooling ($/stack)	$7.35	$5.29	$5.19	$5.11	$5.11
	Total Cost ($/stack)	$180.79	$126.31	$123.53	$121.99	$120.67
	Total Cost ($/$kW_{net}$)	$2.26	$1.58	$1.54	$1.52	$1.51

Figure 86. 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 87 shows the key process parameters.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/Line)	$394,977	$789,955	$789,955	$789,955	$789,955
	Gaskets Welded Simultaneously	1	3	3	3	3
	Runtime per Gasket (s)	6.22	2.1	2.1	2.1	2.1
	Simultaneous Lines	1	2	6	9	32
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	19.03%	95.16%	84.59%	91.64%	99.13%
	Effective Total Machine Rate ($/hr)	$290.05	$124.24	$138.06	$128.49	$119.82
	Material Cost ($/kg)	$0.00	$0.00	$0.00	$0.00	$0.00
2015	Capital Cost ($/Line)	$394,977	$789,955	$789,955	$789,955	$789,955
	Gaskets Welded Simultaneously	1	3	3	3	3
	Runtime per Gasket (s)	6	2	2	2	2
	Simultaneous Lines	1	2	5	8	30
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	17.55%	87.74%	93.59%	95.06%	97.49%
	Effective Total Machine Rate ($/hr)	$313.41	$133.59	$126.09	$124.36	$121.60
	Material Cost ($/kg)	$0.00	$0.00	$0.00	$0.00	$0.00

Figure 87. 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*,[65] 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 88 shows the machine rate parameters, and Figure 89 shows the cost breakdown.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010 - 2015	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 88. Machine rate parameters for gasket laser-welding process

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

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Manufacturing ($/stack)	$185.48	$26.48	$29.43	$27.39	$25.54
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$185.48	$26.48	$29.43	$27.39	$25.54
	Total Cost ($/kW$_{net}$)	$2.32	$0.33	$0.37	$0.34	$0.32
2015	Materials ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Manufacturing ($/stack)	$184.80	$26.26	$24.78	$24.44	$23.90
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$184.80	$26.26	$24.78	$24.44	$23.90
	Total Cost ($/kW$_{net}$)	$2.31	$0.33	$0.31	$0.31	$0.30

Figure 89. 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 90. 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 91 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 90. Screen printer comparison

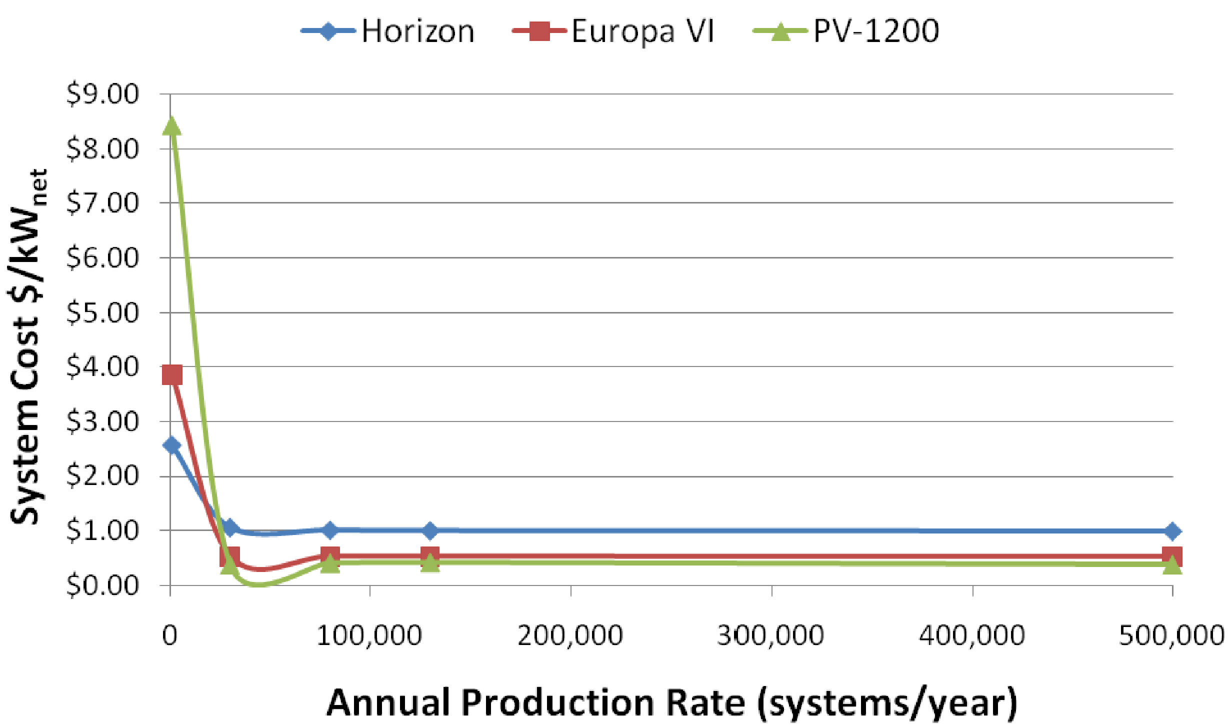

Figure 91. Screen printer cost vs. annual production rate

<u>Resin:</u> 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.

<u>UV Curing:</u> 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 92 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
2010	Capital Cost ($/Line)	$382,339	$1,420,142	$1,420,142	$1,420,142	$1,420,142
	Gaskets Printed Simultaneously	1	4	4	4	4
	Runtime per Gasket (s)	9.76	1.0	1.0	1.0	1.0
	Simultaneous Lines	1	1	3	5	16
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	29.86%	94.93%	84.38%	82.28%	98.89%
	Effective Total Machine Rate ($/hr)	$164.68	$189.21	$209.89	$214.66	$182.59
	Material Cost ($/kg)	$13.04	$13.04	$13.04	$13.04	$13.04
2015	Capital Cost ($/Line)	$382,339	$1,420,142	$1,420,142	$1,420,142	$1,420,142
	Gaskets Printed Simultaneously	1	4	4	4	4
	Runtime per Gasket (s)	10	1	1	1	1
	Simultaneous Lines	1	1	3	5	16
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	29.97%	94.66%	84.13%	82.03%	98.59%
	Effective Total Machine Rate ($/hr)	$164.12	$189.69	$210.45	$215.23	$183.07
	Material Cost ($/kg)	$13.04	$13.04	$13.04	$13.04	$13.04

Figure 92. 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 93 shows the assumed machine rate parameters.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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 93. 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. The total power usage, ranging from 61 to 166 kW, is primarily consumed by the lamps, but also by the exhaust blowers and the modular blowers for the lamps. Figure 94 shows the cost breakdown for the process.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$2.64	$2.64	$2.64	$2.64	$2.64
	Manufacturing ($/stack)	$165.24	$20.12	$22.32	$22.82	$19.41
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$167.88	$22.76	$24.96	$25.47	$22.06
	Total Cost ($/kW$_{net}$)	$1.91	$0.26	$0.28	$0.29	$0.25
2015	Materials ($/stack)	$2.04	$2.04	$2.04	$2.04	$2.04
	Manufacturing ($/stack)	$165.30	$20.11	$22.31	$22.82	$19.41
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$167.33	$22.15	$24.34	$24.85	$21.44
	Total Cost ($/kW$_{net}$)	$1.92	$0.25	$0.28	$0.28	$0.25

Figure 94. 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 gaskets and end gaskets is simply the quantity needed; with only two end gaskets per stack, there are far fewer of them than the coolant gaskets. Although the same methodology is applied to their manufacture, the processes are optimized from those used for the coolant gaskets, in order to account for the lower quantities. Figure 95 shows a comparison between the costs of the two different 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.

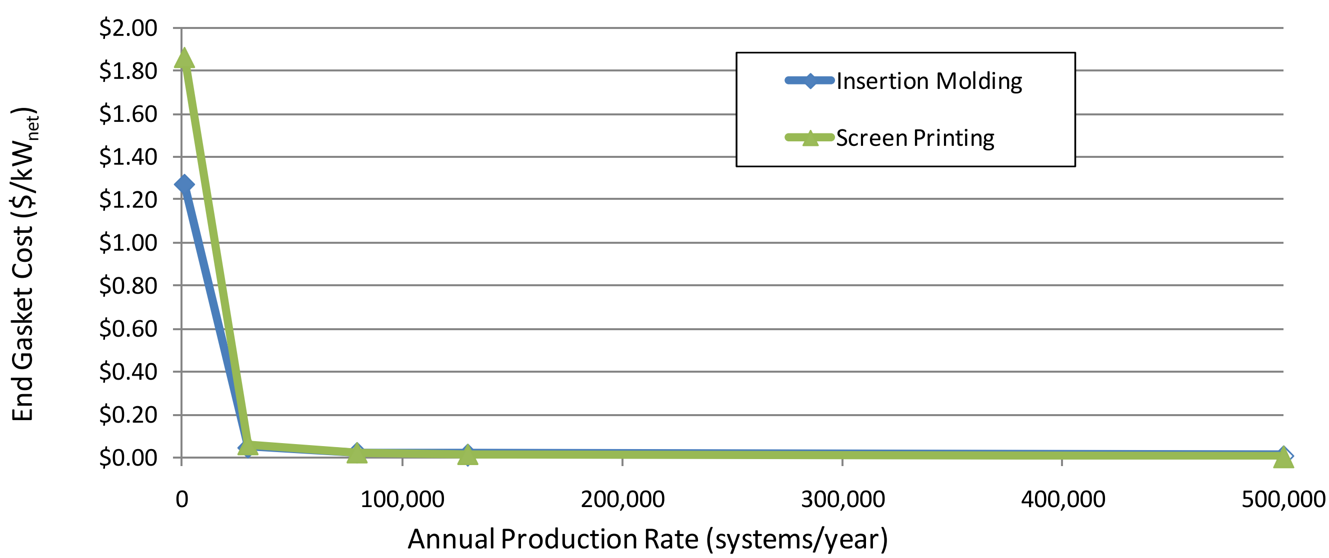

Figure 95. End gasket manufacturing method cost comparison (for 2008 technology)

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
2010	Capital Cost ($/Line)	$212,868	$209,325	$242,074	$307,573	$535,045
	Costs per Tooling Set ($)	$34,888	$34,888	$40,787	$51,619	$83,855
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	4	4	5	7	14
	Total Cycle Time (s)	132.7	158.1	160.6	160.6	160.6
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.55%	19.61%	42.50%	49.33%	94.86%
	Effective Total Machine Rate ($/hr)	$5,353.72	$162.71	$94.19	$102.26	$95.83
	Material Cost ($/kg)	$51.42	$46.91	$45.69	$45.09	$43.48
2015	Capital Cost ($/Line)	$182,483	$179,260	$204,896	$254,556	$430,784
	Costs per Tooling Set ($)	$34,888	$34,888	$40,787	$51,619	$83,855
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	4	4	5	7	14
	Total Cycle Time (s)	133	158	161	161	161
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.55%	19.61%	42.50%	49.33%	94.86%
	Effective Total Machine Rate ($/hr)	$4,591.37	$141.20	$81.71	$86.90	$79.86
	Material Cost ($/kg)	$51.73	$47.19	$45.95	$45.36	$43.74

Figure 96. End gasket insertion-molding process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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)	52	52	57	65	88

Figure 97. Machine rate parameters for end gasket insertion-molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$0.37	$0.34	$0.33	$0.33	$0.31
	Manufacturing ($/stack)	$99.17	$3.57	$1.68	$1.30	$0.61
	Tooling ($/stack)	$2.33	$0.08	$0.03	$0.03	$0.02
	Total Cost ($/stack)	$101.86	$3.99	$2.04	$1.66	$0.95
	Total Cost ($/kW$_{net}$)	$1.27	$0.05	$0.03	$0.02	$0.01
2015	Materials ($/stack)	$0.29	$0.26	$0.25	$0.25	$0.24
	Manufacturing ($/stack)	$85.05	$3.10	$1.46	$1.11	$0.51
	Tooling ($/stack)	$2.33	$0.08	$0.03	$0.03	$0.02
	Total Cost ($/stack)	$87.66	$3.44	$1.75	$1.39	$0.77
	Total Cost ($/kW$_{net}$)	$1.10	$0.04	$0.02	$0.02	$0.01

Figure 98. 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 are 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
2010	Capital Cost ($/Line)	$382,339	$382,339	$382,339	$382,339	$630,187
	Gaskets Printed Simultaneously	1	1	1	1	4
	Runtime per Gasket (s)	9.76	9.76	9.76	9.76	3.10
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.16%	4.84%	12.91%	20.98%	25.63%
	Effective Total Machine Rate ($/hr)	$27,420.33	$933.78	$360.08	$227.66	$301.89
	Material Cost ($/kg)	$13.04	$13.04	$13.04	$13.04	$13.04
2015	Capital Cost ($/Line)	$382,339	$382,339	$382,339	$382,339	$630,187
	Gaskets Printed Simultaneously	1	1	1	1	4
	Runtime per Gasket (s)	10	10	10	10	3
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.16%	4.84%	12.90%	20.96%	25.60%
	Effective Total Machine Rate ($/hr)	$27,455.39	$934.96	$360.52	$227.93	$302.17
	Material Cost ($/kg)	$13.04	$13.04	$13.04	$13.04	$13.04

Figure 99. End gasket screen printing process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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%	3%	3%	3%	2%
	Miscellaneous Expenses (% of CC)	12%	12%	12%	12%	12%
	Power Consumption (kW)	61	61	61	61	162

Figure 100. Machine rate parameters for end gasket screen printing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$0.02	$0.02	$0.02	$0.02	$0.02
	Manufacturing ($/stack)	$149.47	$5.07	$1.95	$1.23	$0.52
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$149.48	$5.08	$1.97	$1.25	$0.54
	Total Cost ($/$kW_{net}$)	$1.87	$0.06	$0.02	$0.02	$0.01
2015	Materials ($/stack)	$0.01	$0.01	$0.01	$0.01	$0.01
	Manufacturing ($/stack)	$149.47	$5.06	$1.95	$1.23	$0.52
	Tooling ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/stack)	$149.48	$5.08	$1.97	$1.25	$0.53
	Total Cost ($/$kW_{net}$)	$1.87	$0.06	$0.02	$0.02	$0.01

Figure 101. 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 102). 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 106.

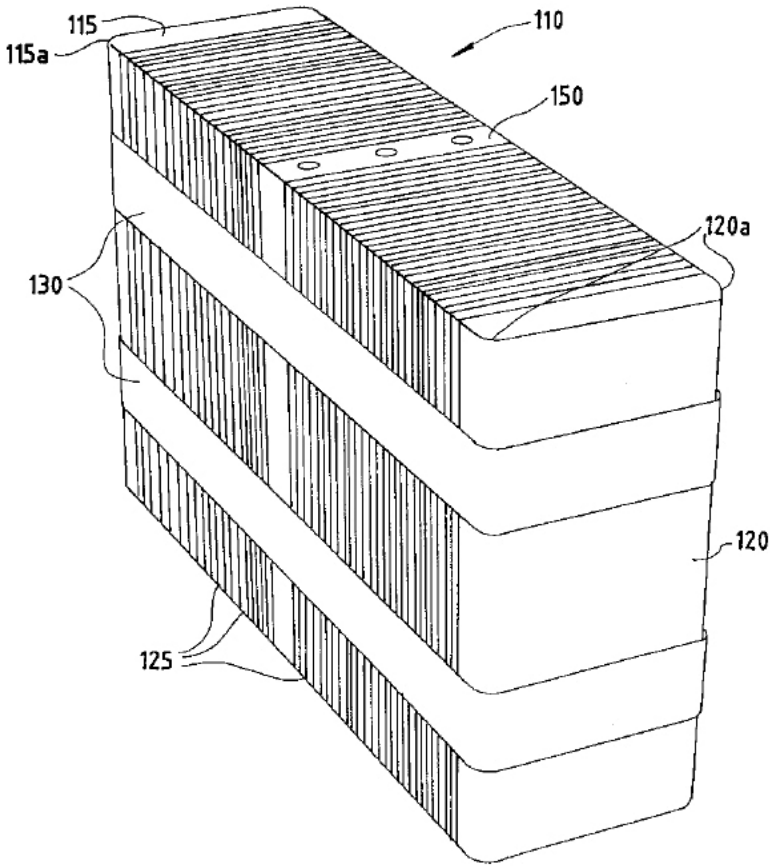

Figure 102. Stack compression bands concept, US patent 5,993,987

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, 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 369 active cell repeat units are assembled via automated fixture. Figure 103 details the layout of the assembly workstations and Figure 104 and Figure 105 lists additional processing parameters.

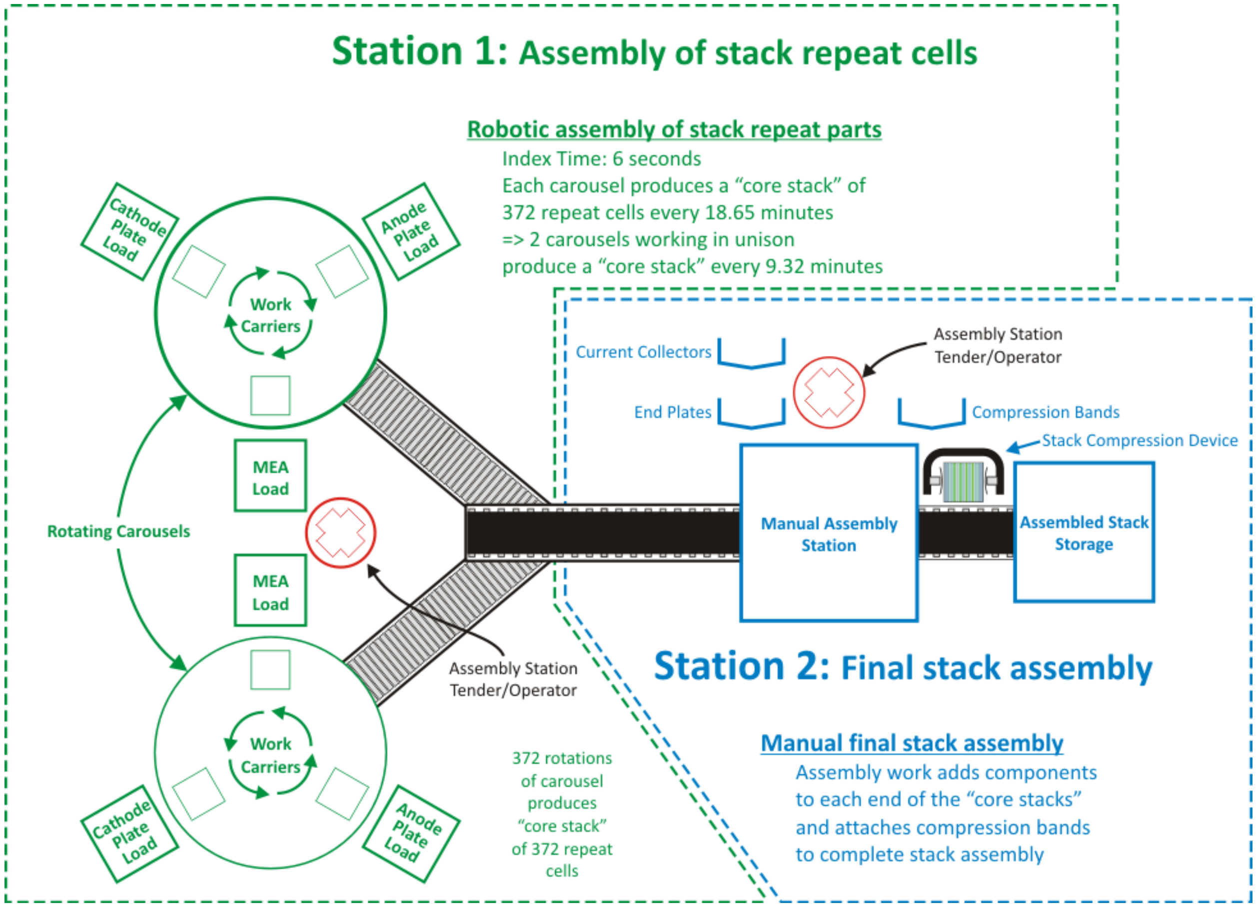

Figure 103. Semi-automated stack assembly work flow diagram

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 106, stack assembly is quite inexpensive, ranging from \$1.08/kW$_{net}$ at the most to only \$0.46/kW$_{net}$. The only material costs are those of the compressive metal bands.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Assembly Method	Manual	Semi-Auto	Semi-Auto	Semi-Auto	Semi-Auto
	Capital Cost ($/Line)	$10,913	$799,418	$799,418	$799,418	$799,418
	Simultaneous Lines	1	4	9	14	51
	Laborers/Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	47.68%	75.75%	89.77%	93.78%	99.02%
	Effective Total Machine Rate ($/hr)	$47.76	$119.91	$102.99	$99.09	$94.47
	Index Time (min)	95.6	20.4	20.4	20.4	20.4
2015	Assembly Method	Manual	Semi-Auto	Semi-Auto	Semi-Auto	Semi-Auto
	Capital Cost ($/Line)	$10,913	$799,418	$799,418	$799,418	$799,418
	Simultaneous Lines	1	4	9	14	51
	Laborers/Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	47.68%	75.75%	89.77%	93.78%	99.02%
	Effective Total Machine Rate ($/hr)	$47.76	$119.91	$102.99	$99.09	$94.47
	Index Time (min)	95.6	20.4	20.4	20.4	20.4

Figure 104. Stack assembly process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010 - 2015	Equipment Lifetime	5	15	15	15	15
	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 105. Machine rate parameters for stack assembly process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Compression Bands ($/stack)	$10.00	$8.00	$6.00	$5.50	$5.00
	Assembly ($/stack)	$76.12	$40.69	$34.95	$33.62	$32.06
	Total Cost ($/stack)	$86.12	$48.69	$40.95	$39.12	$37.06
	Total Cost ($/kW$_{net}$)	$1.08	$0.61	$0.51	$0.49	$0.46
2015	Compression Bands ($/stack)	$10.00	$8.00	$6.00	$5.50	$5.00
	Assembly ($/stack)	$76.12	$40.69	$34.95	$33.62	$32.06
	Total Cost ($/stack)	$86.12	$48.69	$40.95	$39.12	$37.06
	Total Cost ($/kW$_{net}$)	$1.08	$0.61	$0.51	$0.49	$0.46

Figure 106. Cost breakdown for stack assembly

4.4.13. Stack Housing

The stack insulation housing is a plastic housing that encases the stack. It is meant primarily for protection from physical damage caused by road debris and liquids, as well as for protection from electrical shorting contacts and a small amount of thermal insulation. It is modeled as vacuum-thermoformed polypropylene. It is 0.5 cm thick, and is separated from the stack by a 1 cm gap. At high production rate, the cycle time is seven seconds: three for insertion, and four for the vacuum thermoforming. A cost breakdown of the stack housing production is shown below in Figure 107 and additional processing parameters are shown in Figure 108 and Figure 109.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/stack)	$5.07	$5.07	$5.07	$5.07	$5.07
	Manufacturing ($/stack)	$22.46	$1.64	$1.31	$0.88	$0.34
	Tooling ($/stack)	$34.22	$1.14	$0.38	$0.23	$0.06
	Total Cost ($/stack)	$61.75	$7.85	$6.76	$6.18	$5.47
	Total Cost ($/kW$_{net}$)	$0.77	$0.10	$0.08	$0.08	$0.07
2015	Materials ($/stack)	$4.34	$4.34	$4.34	$4.34	$4.34
	Manufacturing ($/stack)	$22.46	$1.64	$1.31	$0.88	$0.34
	Tooling ($/stack)	$34.22	$1.14	$0.38	$0.23	$0.06
	Total Cost ($/stack)	$61.03	$7.13	$6.03	$5.46	$4.75
	Total Cost ($/kW$_{net}$)	$0.76	$0.09	$0.08	$0.07	$0.06

Figure 107. Cost breakdown for stack housing

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/Line)	$50,000	$50,000	$250,000	$250,000	$447,489
	Costs per Tooling Set ($)	$91,260	$91,260	$91,260	$91,260	$91,260
	Tooling Lifetime (years)	3	3	3	3	3
	Cavities per Platen	1	1	1	1	1
	Total Cycle Time (s)	71.2	71.2	15.2	15.2	7.0
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1.00	1.00	1.00	1.00	0.25
	Line Utilization	0.59%	17.66%	10.05%	16.34%	28.94%
	Effective Total Machine Rate ($/hr)	$1,135.58	$83.02	$309.52	$208.59	$177.35
	Material Cost ($/kg)	$1.29	$1.29	$1.29	$1.29	$1.29
2015	Capital Cost ($/Line)	$50,000	$50,000	$250,000	$250,000	$447,489
	Costs per Tooling Set ($)	$91,260	$91,260	$91,260	$91,260	$91,260
	Tooling Lifetime (years)	3	3	3	3	3
	Cavities per Platen	1	1	1	1	1
	Total Cycle Time (s)	71	71	15	15	7
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1.00	1.00	1.00	1.00	0.25
	Line Utilization	0.59%	17.66%	10.05%	16.34%	28.94%
	Effective Total Machine Rate ($/hr)	$1,135.58	$83.02	$309.52	$208.59	$177.35
	Material Cost ($/kg)	$1.29	$1.29	$1.29	$1.29	$1.29

Figure 108. Stack housing vacuum thermoforming process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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	0.229	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 109. Machine rate parameters for stack housing vacuum thermoforming process

4.4.14. 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 are 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 is 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 110 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 achieve maximum performance in 13.3 hours[66]. Declining conditioning durations (5 hours for

[66] 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.

2008 technology, 4 hours for 2010, and 3 hours for 2015) are 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 110. Stack conditioning process based on US patent 7,078,118 ("Applied Voltage Embodiment")

Conditioning cost is 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 are assumed to condition three stacks simultaneously. Since the three stacks can be staggered in starting time, peak power can be considerably less than 3 times the individual stack rated power of 88 kW_{gross} (for the 2010 system). It is estimated that simultaneous peak power would be approximately 150 kW and cost approximately $145,000 at 500,000 fuel cell systems/year[67]. Hydrogen usage is estimated based on 50% fuel cell efficiency and $3/kg hydrogen. DTI's standard machine rate methodology yields machine rates as low as $0.28/min for each load bank. Total costs for stack conditioning are shown in Figure 113. 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.

[67] The costs of the programmable load banks are modeled on systems from FuelCon Systems Inc. for which a ROM price quote of $210,000 to $280,000 per bank was obtained for production quantities of 10-20.

This would require considerable electrical infrastructure and is expected to provide only a relatively small benefit[68]; 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
2010	Capital Cost ($/Line)	$424,062	$372,317	$312,775	$268,019	$147,516
	Simultaneous Lines	1	9	24	38	145
	Laborers per Line	0.10	0.10	0.10	0.10	0.10
	Line Utilization	28.94%	96.46%	96.45%	98.99%	99.78%
	Effective Total Machine Rate ($/hr)	$102.52	$32.32	$28.31	$24.83	$16.84
	Test Duration (hrs)	5	5	5	5	5
2015	Capital Cost ($/Line)	$424,062	$372,317	$312,775	$268,019	$147,516
	Simultaneous Lines	1	6	14	23	87
	Laborers per Line	0.10	0.10	0.10	0.10	0.10
	Line Utilization	17.36%	86.81%	99.21%	98.13%	99.78%
	Effective Total Machine Rate ($/hr)	$166.05	$35.11	$27.72	$24.98	$16.84
	Test Duration (hrs)	3	3	3	3	3

Figure 111. Stack conditioning process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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)	3	3	3	3	3

Figure 112. Machine rate parameters for stack conditioning process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Conditioning/Testing ($/stack)	$170.88	$53.87	$47.18	$41.38	$28.06
	Total Cost ($/stack)	$170.88	$53.87	$47.18	$41.38	$28.06
	Total Cost ($/kW$_{net}$)	$2.14	$0.67	$0.59	$0.52	$0.35
2015	Conditioning/Testing ($/stack)	$166.06	$35.11	$27.72	$24.98	$16.84
	Total Cost ($/stack)	$166.06	$35.11	$27.72	$24.98	$16.84
	Total Cost ($/kW$_{net}$)	$2.08	$0.44	$0.35	$0.31	$0.21

Figure 113. Cost breakdown for stack conditioning

4.5. Balance of Plant (BOP)

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. Air Loop

The power system air loop consists of five elements:

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

- **Air Compressor, Expander and Motor (CEM) Unit**
- **Air Mass Flow Sensor**
- **Air Filter and Housing**
- **Air Ducting**

These components are described in the subsections below. The cost breakdown is show below in Figure 114.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Filter & Housing ($/system)	$54.50	$49.55	$49.55	$49.55	$49.55
	Compressor, Expander & Motor ($/system)	$1,483.28	$815.16	$686.12	$664.71	$645.20
	Mass Flow Sensor ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Air Ducting ($/system)	$95.00	$76.00	$57.00	$53.20	$45.60
	Total Cost ($/system)	$1,695.29	$990.72	$830.17	$802.46	$770.35
	Total Cost ($/kW$_{net}$)	$21.19	$12.38	$10.38	$10.03	$9.63
2015	Filter & Housing ($/system)	$54.50	$49.55	$49.55	$49.55	$49.55
	Compressor, Expander & Motor ($/system)	$1,158.41	$651.95	$538.35	$519.86	$504.44
	Mass Flow Sensor ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Air Ducting ($/system)	$43.18	$34.55	$25.91	$24.18	$20.73
	Total Cost ($/system)	$1,318.59	$786.05	$651.31	$628.59	$604.72
	Total Cost ($/kW$_{net}$)	$16.48	$9.83	$8.14	$7.86	$7.56

Figure 114. Cost breakdown for air loop

4.5.1.1. Compressor-Expander-Motor Unit & Motor Controller

The air compression system is envisioned as an integrated air compressor, exhaust gas expander, and permanent magnet motor. An electronic CEM controller is also included in the system.

In previous years' analyses, the cost estimates for the compressor-expander-motor unit (CEM) were based on a simplified DFMA analysis in which the system was 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 twin-lobe compressor and expander 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.

For the 2009 analysis, an all-new, extremely detailed CEM cost estimate was conducted in collaboration with Honeywell[69]. It is a bottom-up cost analysis based directly on the blueprints from an existing Honeywell design[70], which pairs a centrifugal compressor and a radial-inflow expander, with a permanent-magnet motor running on air bearings at 100,000 rpm. After analyzing the base design, engineers from both DTI and Honeywell simplified and improved the design to increase its performance and lower cost, to better-reflect a mass-production design. Ultimately, six different configurations were examined; three main configurations, plus a version of each without an expander.

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[69] Details of the Honeywell design were provided under a non-disclosure agreement. Consequently, many of the details of the CEM analysis are omitted from this report.

[70] Honeywell Aerospace report to the US DOE: "Cost and Performance Enhancements for a PEM Fuel Cell Turbocompressor" (Contract DE-FC36-02AL67624)

The six different configurations examined are listed in Figure 115. "Design #1" is based on the existing Honeywell design, which runs at 100,000 rpm. Design #2 is an optimized version of Design #1 running at 165,000 rpm, in order to reduce its size. Design #3 is a further-optimized future system, based on Design #2 but with slightly more aggressive design assumptions. Designs #4, 5, and 6 are identical to Designs #1, 2, and 3 respectively, but with the expander removed.

	Current (100k rpm)	Near Future (165k rpm)	Future (165k rpm)
With Expander	Design 1	Design 2 (2010 tech)	Design 3
Without Expander	Design 4	Design 5	Design 6 (2015 tech)

Figure 115. Matrix of CEM design configurations

The estimate utilizes a combination of DFMA methodology and price quotes from established Honeywell vendors. Excluding repeat parts, the existing Honeywell turbocompressor design (Design #1) has 104 different components and assemblies. Each of these components is categorized into one of three different tiers. "Tier 1" consists of the 26 largest/most-significant components in need of the most careful cost analysis. "Tier 2" corresponds to the 42 mid-level components for which a vendor quote is sufficient. The "Tier 3" components are the minor components such as screws and adhesives that are insignificant enough that educated guesses are sufficient in lieu of vendor quotes. Honeywell engineers solicited price quotes from their existing supplier base for components in the top two tiers, as well as for some of the components in Tier 3, and supplied these values to DTI for review and analysis.

In some cases, the high-volume quotes were judged to be inappropriate, as they were merely based on repeated use of low-production-rate manufacturing methods rather than low-cost, high-manufacturing-rate production and assembly methods[71]. Consequently, these quotes were replaced with cost estimates based on a mix of DFMA techniques and our best judgment.

After having completed the initial cost summation for Design #1, the unit costs seemed prohibitively high. Consequently, Honeywell engineers reviewed their design and created a list of potential improvements. DTI augmented the list with some DFMA-based suggestions, the list was vetted by both parties, and the design changes incorporated into the cost model. Changes deemed reasonable to describe as "current technology" were applied to Design #2, and the more aggressive improvements were used to define Design #3. The most important of these improvements is the switch from 100,000 to 165,000 rpm, which facilitates a reduction in the size of the CEM by roughly 35%, thereby saving greatly on material (and to a lesser extent, manufacturing) costs, while also providing the intrinsic benefits of reduced size. These improvements are listed in Figure 116.

[71] The vendors approached were typically those used by Honeywell in the past. Unfortunately, several vendors were prototype and low/moderate volume manufacturing facilities and were not well suited for true high rate production.

		2010				2015
Design #	**1**	**2**	**3**	**4**	**5**	**6**
	With Expander			Without Expander		
	Current (100k rpm)	Future (165k rpm)	Future (165k rpm)	Current (100k rpm)	Future (165k rpm)	Future (165k rpm)
Removed Turbine (Expander)	[Baseline System Design]			x	x	x
Increased speed from 100,000 to 165,000 rpm		x	x		x	x
Improved turbine wheel design		x	x		x	x
Improved variable nozzle technology		x	x		x	x
Lower cost electrical connectors		x	x		x	x
Design change to integrate housing into single casting			x			x
Integrate/eliminate mounting bosses on main housing			x			x
Compressor housing design change to re-route cooling air over motor			x			x
Improved foil bearing design			x			x
Back-to-back compressor wheel			x			x
Removed washers/face bolts			x			x
Improved bearing installation/design			x			x
Improved labryinth seal			x			x
Changed fasteners to more common, inexpensive design			x			x
Changed threaded inserts to more common, inexpensive design			x			x
Reduced testing of machined/cast parts			x			x
Aluminum turbine wheel			x			

Figure 116. List of Improvements for the 6 Compressor Configurations

Each of the six CEM designs was analyzed across the range of five production rates (1,000 to 500,000 systems per year): this yields 30 different cost estimates for each of the 100+ components. Summed together, they provide 30 different estimates for the CEM cost. The five Design #2 estimates provide the 2010 compressor costs across the range of production rates, and the Design #6 estimates are used for 2015.

For the 2010 update, the CEM cost model was fully integrated into the fuel cell system cost model, and adjusted to scale dynamically based on the pressure and power requirements of the system. This was achieved via a complex system of multipliers that are applied differently for almost every different component, since there are a wide variety of combinations and permutations for costing methods across the range of components, and not everything scales at the same rate. For example, as the pressure ratio increases and the CEM increases in size, the diameter of the turbine wheel increases, and its volume increases at a rate proportional to the square of its diameter. The diameter of the compressor wheel scales at a different rate than that of the turbine (expander) wheel, and the shaft length and motor mass each scale at yet another rate. The geometric scaling factors were derived from data that Honeywell provided showing dimensions of key components across a range of performance parameters such as pressure ratio, mass flow rate, and shaft power.

The materials cost of each component increases proportionately with the volume of material needed, and the manufacturing costs scale separately, at rates dependent on the manufacturing processes involved and the specifics of each process.

For components whose cost estimates are derived partially or completely from price quotes rather than full DFMA analysis (such as those in Tier 2 and Tier 3), assumptions were made about the fractional split between the component's material and manufacturing costs, so that each fraction can be scaled independently.

With this new scaling and integration into the main fuel cell system cost model, the size and cost of the CEM now scale dynamically based on the performance requirements of the system. So if a new electrical component is added to the BOP that increases the parasitic load (and thus increases the gross power required), the CEM will scale to accommodate.

The DTI/Honeywell CEM analysis also examined the motor controller, for which the same design was deemed applicable to control all six compressor designs. Unlike with the custom parts involved in the compressor, the motor controller uses almost exclusively off-the-shelf parts that are already manufactured at high volume. As such, there is limited value in conducting a detailed DFMA analysis[72], so the cost analysis is primarily based on vendor quotation. The original Honeywell controller design was a standalone unit with its own air or water cooling. However, in order to cut costs, it is now assumed that the CEM controller is integrated into the water-cooled electronics housing for the overall fuel cell system controller.

The CEM and motor controller costs for the various configurations are shown below in Figure 117. Because the costs now scale with performance parameters, costs for the same design number are different between 2010 and 2015. Values used in the 2010 and 2015 fuel cell system cost estimates are shown in green.

[72] While a bottoms-up manufacturing analysis was not conducted for the controller components, assembly of the controller was assessed using DFMA techniques.

Design	Sys/year	CEM Cost 2010	CEM Cost 2015	CEM Assy	CEM Markup	Motor Controller Cost 2010	Motor Controller Cost 2015	Motor Controller Assy	Motor Controller Markup	Total Cost 2010	Total Cost 2015
Design 1	1,000	$1,215.81	$1,162.47			$408.92	$408.92			$1,882.88	$1,821.53
Existing Tech.	30,000	$513.51	$476.13			$340.11	$340.11			$999.54	$956.55
100,000 RPM	80,000	$388.81	$352.61	$23.00	15%	$328.94	$328.94	$7.67	10%	$843.85	$802.21
	130,000	$381.84	$345.86			$314.23	$314.23			$819.65	$778.28
	500,000	$371.18	$335.57			$303.39	$303.39			$795.47	$754.52
Design 2	1,000	$868.33	$838.81			$408.92	$408.92			$1,483.28	$1,449.33
"Near-Future"	30,000	$353.18	$330.02			$340.11	$340.11			$815.16	$788.53
165,000 RPM	80,000	$251.66	$229.20	$23.00	15%	$328.94	$328.94	$7.67	10%	$686.12	$660.29
	130,000	$247.10	$224.78			$314.23	$314.23			$664.71	$639.03
	500,000	$240.51	$218.39			$303.39	$303.39			$645.20	$619.76
Design 3	1,000	$737.42	$712.46			$408.92	$408.92			$1,332.73	$1,304.02
"Future"	30,000	$311.21	$292.59			$340.11	$340.11			$766.90	$745.48
165,000 RPM	80,000	$217.26	$199.17	$23.00	15%	$328.94	$328.94	$7.67	10%	$646.56	$625.76
	130,000	$213.28	$195.28			$314.23	$314.23			$625.81	$605.11
	500,000	$207.49	$189.66			$303.39	$303.39			$607.23	$586.72
Design 4	1,000	$893.95	$863.79			$408.92	$408.92			$1,512.73	$1,478.05
Existing Tech.	30,000	$337.94	$312.27			$340.11	$340.11			$797.64	$768.12
100,000 RPM	80,000	$223.88	$198.98	$23.00	15%	$328.94	$328.94	$7.67	10%	$654.18	$625.54
No Expander	130,000	$220.31	$195.55			$314.23	$314.23			$633.90	$605.42
	500,000	$215.41	$190.86			$303.39	$303.39			$616.34	$588.10
Design 5	1,000	$722.86	$703.74			$408.92	$408.92			$1,315.99	$1,294.00
"Near-Future"	30,000	$257.22	$241.26			$340.11	$340.11			$704.81	$686.45
165,000 RPM	80,000	$161.48	$145.97	$23.00	15%	$328.94	$328.94	$7.67	10%	$582.41	$564.58
No Expander	130,000	$158.89	$143.47			$314.23	$314.23			$563.27	$545.52
	500,000	$155.03	$139.73			$303.39	$303.39			$546.91	$529.31
Design 6	1,000	$602.40	$585.84			$408.92	$408.92			$1,177.46	$1,158.41
"Future"	30,000	$224.53	$211.26			$340.11	$340.11			$667.21	$651.95
165,000 RPM	80,000	$136.10	$123.16	$23.00	15%	$328.94	$328.94	$7.67	10%	$553.23	$538.35
No Expander	130,000	$134.02	$121.15			$314.23	$314.23			$534.67	$519.86
	500,000	$130.89	$118.10			$303.39	$303.39			$519.14	$504.44

Figure 117. CEM cost results

4.5.1.2. 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 for quantities of 1,000 per year is estimated to be roughly $100, and drops to about $65 for high quantities.

4.5.1.3. Air Ducting

The air ducting is modeled as conformal polymer tubes to guide the cathode air in and out of the stack.

4.5.1.4. Air Filter and Housing

Some fuel cell manufacturers filter inlet air both for particles and for volatile organic compounds[73]. 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 are assumed.

4.5.2. Humidifier & Water Recovery Loop

Based on interaction with Rajesh Ahuwalia at Argonne National Laboratory, an Air Precooler and a Demister were added to the balance of plant for the 2010 update. None of these components are included in the 2015 system.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Air Precooler ($/system)	$52.75	$52.75	$52.75	$52.75	$52.75
	Demister ($/system)	$116.20	$13.38	$8.83	$7.83	$6.26
	Membrane Air Humidifier ($/system)	$1,487.07	$414.94	$238.76	$182.28	$94.25
	Total Cost ($/system)	$1,656.02	$481.07	$300.35	$242.86	$153.26
	Total Cost ($/$kW_{net}$)	$20.70	$6.01	$3.75	$3.04	$1.92
2015	Air Precooler ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Demister ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Membrane Air Humidifier ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/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 118. Cost breakdown for humidifier & water recovery loop

4.5.2.1. Air Precooler

The air precooler sits between the air compressor and the membrane humidifier, where it cools the hot compressed air to the humidifier's optimal inlet temperature of 55°C. The design is based on the ANL-supplied key parameters for a compact liquid/air cross-flow intercooler, and the dimensions are scaled based on the specific heat transfer requirements. The unit is 100% aluminum and uses an array of 0.4-mm-thick tubes with 0.08-mm-thick fins spaced at 24 fins per inch, which cool the air with a very minimal pressure drop (0.05 psi). Because the cost impact of the precooler is small, a full DFMA analysis was not conducted. Instead, the mass and volume of the radiator core were determined by heat transfer calculations conducted at ANL, and the materials cost of the unit was estimated based on detailed geometry assumptions and the cost of aluminum ($7.70/kg). The materials cost was then simply doubled to account for the cost of manufacturing.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/system)	$26.38	$26.38	$26.38	$26.38	$26.38
	Manufacturing ($/system)	$26.38	$26.38	$26.38	$26.38	$26.38
	Total Cost ($/system)	$52.75	$52.75	$52.75	$52.75	$52.75
	Total Cost ($/$kW_{net}$)	$0.66	$0.66	$0.66	$0.66	$0.66
2015	Materials ($/system)	$17.22	$17.22	$17.22	$17.22	$17.22
	Manufacturing ($/system)	$17.22	$17.22	$17.22	$17.22	$17.22
	Total Cost ($/system)	$34.44	$34.44	$34.44	$34.44	$34.44
	Total Cost ($/$kW_{net}$)	$0.43	$0.43	$0.43	$0.43	$0.43

Figure 119. Cost breakdown for air precooler

[73] 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.

4.5.2.2. Demister

The demister removes liquid water droplets from the cathode exhaust stream and thereby prevent erosion of the turbine blades. Designed by DTI, the demister's housing consists of two threaded, hollow 2-mm-thick polypropylene frustums that unscrew from one another to allow access to the filter inside. The filter is a nylon mesh Millipore product designed for water removal and costed at $5.84 each at high volume (assuming 81 cm^2 per demister). The polypropylene adds only 10 cents of material cost per part, and at high volume, the injection molding process is only 15 cents per part. Because the housing is so inexpensive, the filter dominates the total demister cost ($6.12, or $0.08/$kW_{net}$).

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/system)	$12.27	$9.83	$7.40	$6.92	$5.94
	Manufacturing ($/system)	$99.73	$3.40	$1.33	$0.85	$0.26
	Tooling ($/system)	$4.20	$0.14	$0.11	$0.06	$0.05
	Total Cost ($/system)	$116.20	$13.38	$8.83	$7.83	$6.26
	Total Cost ($/$kW_{net}$)	$1.45	$0.17	$0.11	$0.10	$0.08
2015	Materials ($/system)	$12.27	$9.83	$7.40	$6.92	$5.94
	Manufacturing ($/system)	$99.73	$3.41	$1.33	$0.85	$0.26
	Tooling ($/system)	$4.20	$0.14	$0.11	$0.06	$0.05
	Total Cost ($/system)	$116.20	$13.38	$8.84	$7.83	$6.26
	Total Cost ($/$kW_{net}$)	$1.45	$0.17	$0.11	$0.10	$0.08

Figure 120. Cost breakdown for demister

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/Line)	$280,793	$280,793	$280,793	$280,793	$309,696
	Costs per Tooling Set ($)	$31,524	$31,524	$31,524	$31,524	$51,212
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	1	1	1	1	2
	Total Cycle Time (s)	6.40	6.40	6.40	6.40	6.81
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1	1	1	1	1
	Line Utilization	0.11%	1.65%	4.29%	6.94%	14.13%
	Effective Total Machine Rate ($/hr)	$26,398.30	$1,845.09	$736.27	$473.08	$278.02
	Material Cost ($/kg)	$1.29	$1.29	$1.29	$1.29	$1.29
2015	Capital Cost ($/Line)	$280,793	$280,793	$280,793	$280,793	$309,696
	Costs per Tooling Set ($)	$31,524	$31,524	$31,524	$31,524	$51,212
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Cavities per Platen	1	1	1	1	2
	Total Cycle Time (s)	6.81	6.81	6.81	6.81	6.81
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1	1	1	1	1
	Line Utilization	0.12%	1.75%	4.56%	7.38%	14.13%
	Effective Total Machine Rate ($/hr)	$25,628.33	$1,740.68	$695.35	$447.63	$278.02
	Material Cost ($/kg)	$1.29	$1.29	$1.29	$1.29	$1.29

Figure 121. Demister injection molding process parameters

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	0.17	0.17	0.17	0.17	0.17
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)	21	21	21	21	31

Figure 122. Machine rate parameters for demister injection molding process

4.5.2.3. Membrane Humidifier

The design and material parameters are based on the FC200-780-7PP membrane humidifier from Perma Pure LLC, but the sizing is adjusted for actual flow rates. A representative diagram of this humidifier is shown in Figure 123.

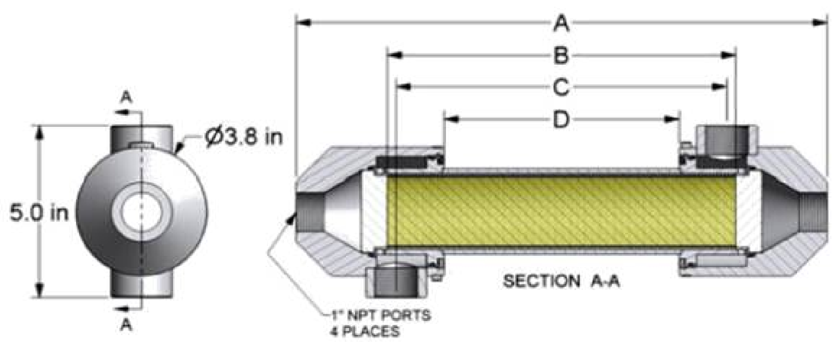

Figure 123. Perma Pure FC200-780-7PP humidifier[74]

The manufacturing process postulated for the cost analysis involves nine steps. The steps are listed below and are illustrated in Figure 124**:**

1. **Extrusion:** 960 parallel Nafion tubes (~1 mm OD) are simultaneously extruded and subsequently wrapped in nylon mesh to create a tube bundle for facilitated handling.

2. **De-ionized (DI) Water Bath:** Hydration of the Nafion tubing in a near boiling water bath.

3. **Tube Cutting:** Cut the tube bundles into their appropriate length.

4. **Quality Control:** Optical quality control measurements (includes length, concentricity check, etc.)

5. **Dipping:** End caps are dipped in polyurethane to secure the tube bundles in the appropriate shape and provide a barrier to gas flow between the tubes at the tube ends.

6. **End Cap Trimming:** Cut polyurethane end caps to expose the inner diameter ends and allow unimpeded flow through each tube.

[74] Image from http://www.permapure.com/.

7. **Injection Molding:** Each separately molded side of the Noryl housing has two ports for the intake and exhaust gas flows.

8. **Final Assembly:** Combine casing, tube bundle, O-rings, C-clips, and nylon mesh filters (but do not secure).

9. **Vibration Welding:** Vibrationally weld the two halves of the plastic case, thereby trapping all interior components in place.

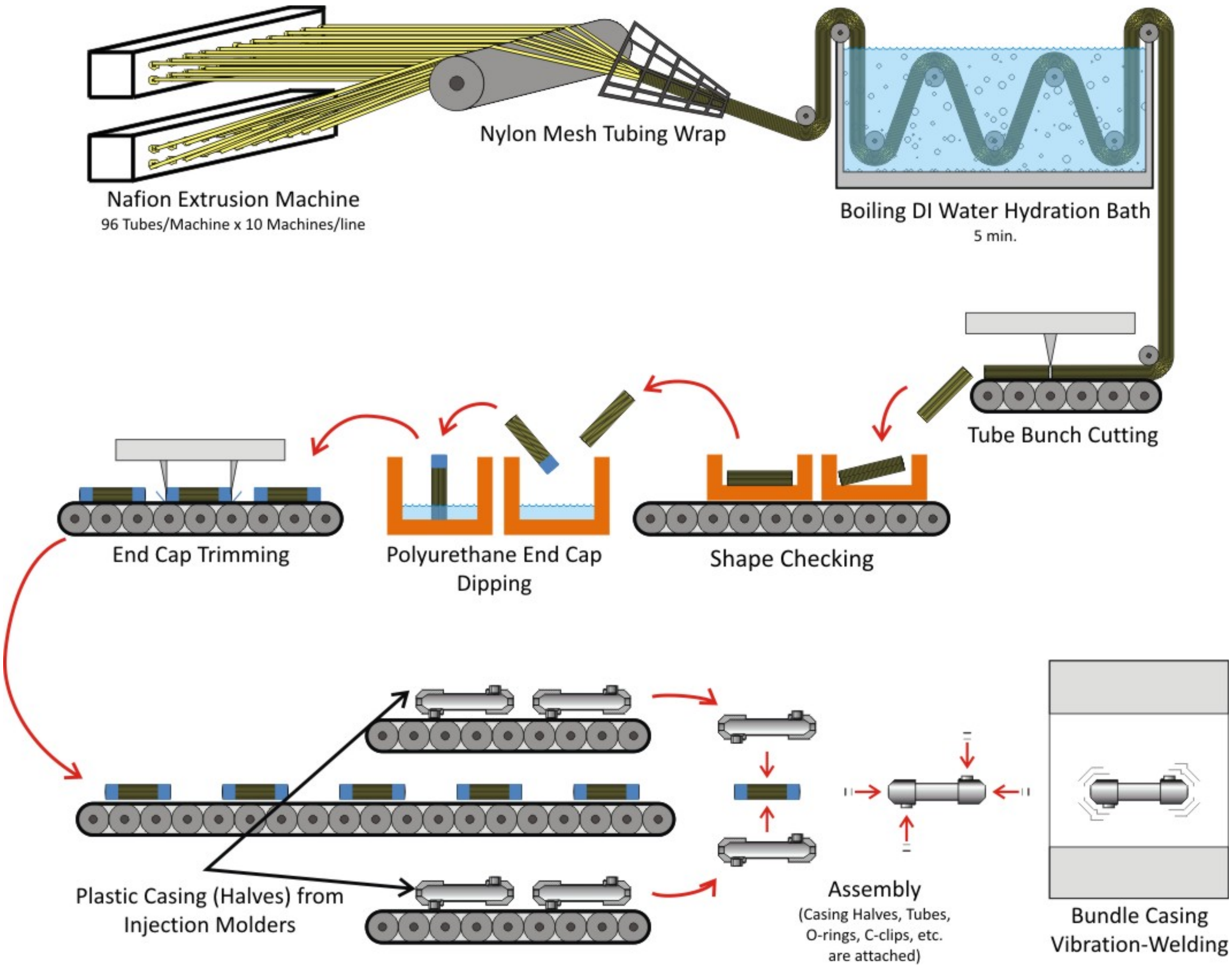

Figure 124. Membrane humidifier manufacturing process diagram

Key assumptions made concerning the humidifier manufacturing are listed below.

Manufacturing:

- Nafion extrusion rate is 45 cm/min
- 5 minute DI water bath dwell time
- 30 second polyurethane end cap set time
- 10 second total vibration welding cycle time

- Assumed 5 seconds to pick up and place each O-ring, C-clip, and mesh filter
- The effective line length of the DI bath is 2.25 meters with the tube bundle traveling along a serpentine path to increase line length

Capital Cost: Capital costs are primarily derived from previous DTI work involving similar components. The complete list of capital costs is shown in Figure 125.

Component	Cost
Nafion Extruder	$200,000
DI Water Bath	$50,000
Tube Bunch Cutting Machine	$100,000
Shape Checking Quality Control	$200,000
Polyurethane End Cap Dipper	$100,000
Tube Bunch Cutting Machine	$100,000
Final Assembly	$10,000
Housing Injection Molder	$600,000
Vibration Welder	$700,000
Total per Line	**$2,060,000**

Figure 125. Capital cost breakdown for a typical membrane humidifier manufacturing process

Production Speed: The production speed of the process train depicted in Figure 124 is limited by the slowest manufacturing step, which is the Nafion extrusion machine. For lower annual production quantities, a single extrusion machines[75] is shared between hydration beds in order to increase machine utilization and lower capital cost. The extrusion machine creates Nafion tubing which is then coiled on spools. The spools are then used to feed the hydration beds.

Labor: It is assumed that three laborers are needed per line to oversee the process and take care of the quality control checking

The machine rate and process parameters are shown in Figure 126 and Figure 127. Figure 128 shows the cost breakdown for the membrane air humidifier.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Capital Cost ($/line)	$844,654	$1,995,126	$2,501,614	$3,008,103	$4,021,081
	Simultaneous Lines	1	2	2	2	4
	Laborers per Line	3	3.00	3.00	3.00	3.00
	Line Utilization	7.09%	53.14%	70.86%	76.76%	88.57%
	Effective Total Machine Rate ($/hr)	$1,544.92	$588.28	$566.58	$616.76	$698.87
	Production Rate (humidifiers/min/line)	7.87	7.87	7.87	7.87	7.87
2015	Capital Cost ($/line)	$844,654	$1,995,126	$2,501,614	$3,008,103	$4,021,081
	Simultaneous Lines	1	2	2	2	4
	Laborers per Line	3	3.00	3.00	3.00	3.00
	Line Utilization	6.68%	50.07%	66.76%	72.33%	83.45%
	Effective Total Machine Rate ($/hr)	$1,629.18	$613.75	$589.64	$647.50	$735.00
	Production Rate (humidifiers/min/line)	7.87	7.87	7.87	7.87	7.87

Figure 126. Membrane humidifier production process parameters

[75] The extrusion machine creates Nafion tubing which is then coiled on spools. The spools are then used to feed the hydration beds.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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)	155	185	245	305	425

Figure 127. Machine rate parameters for membrane humidifier production process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Material ($/system)	$1,119.26	$344.91	$205.04	$157.81	$77.61
	Manufacturing ($/system)	$367.81	$70.03	$33.72	$24.47	$16.64
	Markup ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/system)	$1,487.07	$414.94	$238.76	$182.28	$94.25
	Total Cost ($/kW$_{net}$)	$18.59	$5.19	$2.98	$2.28	$1.18
2015	Material ($/system)	$694.12	$266.44	$162.71	$126.28	$63.26
	Manufacturing ($/system)	$365.47	$68.84	$33.07	$24.21	$16.49
	Markup ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/system)	$1,059.58	$335.28	$195.78	$150.49	$79.75
	Total Cost ($/kW$_{net}$)	$13.24	$4.19	$2.45	$1.88	$1.00

Figure 128. Cost breakdown for membrane air humidifier

The Fuel Cell Technical Team (FCTT) has recently suggested the exploration of non-Nafion® membrane materials as well as alternatives to the tube configuration, so this will be investigated as part of the 2011 analysis.

4.5.3. Coolant Loops

The 2010 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 2015 technology system, the low-temperature 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.

4.5.3.1. High-Temperature Coolant Loop

Coolant Reservoir: The cost is 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 is based on a resin deionizer bed in a plastic housing.

Thermostat & Valve: The cost is 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 a standard automotive radiator fan and sized based on the cooling load.

Coolant Piping: Assumed 2" diameter rubber pipe from McMaster Carr, at $6.93/ft.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Coolant Reservoir ($/system)	$13.13	$10.50	$7.88	$7.35	$6.30
2010	Coolant Pump ($/system)	$94.54	$84.03	$75.63	$72.48	$69.51
2010	Coolant DI Filter ($/system)	$78.78	$63.03	$47.27	$44.12	$37.82
2010	Thermostat & Valve ($/system)	$10.50	$8.40	$6.30	$5.88	$5.04
2010	Radiator ($/system)	$213.57	$192.21	$181.53	$170.86	$160.18
2010	Radiator Fan ($/system)	$86.10	$65.84	$50.65	$48.62	$45.58
2010	Coolant Piping ($/system)	$67.65	$54.12	$40.59	$37.89	$32.47
2010	Total Cost ($/system)	$564.28	$478.15	$409.86	$387.20	$356.91
2010	Total Cost ($/$kW_{net}$)	$7.05	$5.98	$5.12	$4.84	$4.46
2015	Coolant Reservoir ($/system)	$13.13	$10.50	$7.88	$7.35	$6.30
2015	Coolant Pump ($/system)	$94.54	$84.03	$75.63	$72.48	$69.51
2015	Coolant DI Filter ($/system)	$78.78	$63.03	$47.27	$44.12	$37.82
2015	Thermostat & Valve ($/system)	$10.50	$8.40	$6.30	$5.88	$5.04
2015	Radiator ($/system)	$224.61	$202.15	$190.92	$179.69	$168.46
2015	Radiator Fan ($/system)	$86.10	$65.84	$50.65	$48.62	$45.58
2015	Coolant Piping ($/system)	$74.85	$59.88	$44.91	$41.92	$35.93
2015	Total Cost ($/system)	$582.52	$493.84	$423.56	$400.06	$368.65
2015	Total Cost ($/$kW_{net}$)	$7.28	$6.17	$5.29	$5.00	$4.61

Figure 129. Cost breakdown for high-temperature coolant loop

4.5.3.2. Low-Temperature Coolant 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.

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

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

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

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: It is assumed that the radiators for the high and low-temperature loops are installed together such that the air flow exiting the low-temperature radiator immediately enters the high-temperature radiator, and as such, there is a single fan for both radiators, which is accounted for in the high-temperature coolant loop.

Coolant Piping: Assumed 2" diameter rubber pipe from McMaster Carr, at $6.93/ft.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Coolant Reservoir ($/system)	$4.10	$3.28	$2.46	$2.30	$1.97
	Coolant Pump ($/system)	$43.54	$38.70	$34.83	$33.38	$32.01
	Thermostat & Valve ($/system)	$6.26	$5.01	$3.76	$3.51	$3.01
	Radiator ($/system)	$156.41	$140.77	$132.95	$125.13	$117.31
	Radiator Fan ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Coolant Piping ($/system)	$54.00	$43.20	$32.40	$30.24	$25.92
	Total Cost ($/system)	$103.75	$90.66	$81.01	$76.36	$70.74
	Total Cost ($/$kW_{net}$)	$1.30	$1.13	$1.01	$0.95	$0.88
2015	Coolant Reservoir ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Coolant Pump ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Thermostat & Valve ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Radiator ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Radiator Fan ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Coolant Piping ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/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 130. Cost breakdown for low-temperature coolant loop

4.5.4. Fuel Loop

Per DOE system analysis guidelines, the hydrogen tank, the hydrogen pressure-relief device & regulator, and the hydrogen fueling receptacle are not included in the fuel cell power system cost analysis. Based on industry input, the proportional valve and pressure transducer were removed for the 2010 Update. Check valves and an over-pressure cut-off valve were also added. These changes rely on the hydrogen storage system (not included in cost analysis) to handle some of the pressure regulation duties.

Inline Filter for Gas Purity Excursions: This filter ensures that any contaminants that may have gotten into the fuel lines do not damage the stack.

Flow Diverter Valve: The flow diverter valve routes hydrogen to either the low-flow or the high-flow ejector, depending on the pressure.

Over-Pressure Cut-Off (OPCO) Valve: The over-pressure cut-off valve was added as a safety precaution after the proportional valve was removed.

Low-Flow and High-Flow Ejectors: For the 2010 system, dual static ejectors are employed to re-circulate hydrogen from the anode exhaust to the anode inlet to achieve target flow rates and hence high stack performance. The ejectors operate on the Bernoulli Principle wherein high-pressure hydrogen gas from the fuel tank (>250 psi) flows through a converging-diverging nozzle to entrain lower-pressure anode exhaust gas. Two ejectors (high-flow and low-flow) are operated in parallel to achieve a wide turn-down range. The design of the ejectors is based on concepts from Graham Manufacturing and the patent literature (US Patent 5,441,821). The fabrication of each ejector consists of stainless steel investment casting of a two-part assembly, followed by machining, welding, and polishing. DTI is also investigating ejectors with variable geometry for future systems and, as indicated by ANL modeling, whether a hydrogen recirculation blower is needed during very low part-power system operation.

Check Valves: The check valves ensure that no hydrogen may flow backwards from the ejectors

Purge Valve: The purge valve allows for periodic purging of the hydrogen in the fuel loop.

Hydrogen Piping: The piping through which the hydrogen flows. It is modeled as ¾" SS304 schedule 10 pipe, $20.61/m from McMaster Carr.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Inline Filter for GPE ($/system)	$18.20	$18.20	$18.20	$18.20	$18.20
	Flow Diverter Valve ($/system)	$15.19	$15.19	$15.19	$15.19	$15.19
	Pressure Switch ($/system)	$25.00	$20.00	$15.00	$14.00	$12.00
	Low-Flow Ejector ($/system)	$50.89	$35.52	$32.70	$31.36	$30.64
	High-Flow Ejector ($/system)	$43.71	$28.59	$26.03	$24.85	$24.24
	Check Valves ($/system)	$10.00	$10.00	$10.00	$10.00	$10.00
	Purge Valve ($/system)	$25.00	$20.00	$15.00	$14.00	$12.00
	Hydrogen Piping ($/system)	$63.94	$51.15	$38.36	$35.80	$30.69
	Total Cost ($/system)	$251.94	$198.65	$170.49	$163.40	$152.96
	Total Cost ($/kW$_{net}$)	$3.15	$2.48	$2.13	$2.04	$1.91
2015	Inline Filter for GPE ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Flow Diverter Valve ($/system)	$15.19	$15.19	$15.19	$15.19	$15.19
	Pressure Switch ($/system)	$25.00	$20.00	$15.00	$14.00	$12.00
	Low-Flow Ejector ($/system)	$50.89	$35.52	$32.70	$31.36	$30.64
	High-Flow Ejector ($/system)	$43.71	$28.59	$26.03	$24.85	$24.24
	Check Valves ($/system)	$10.00	$10.00	$10.00	$10.00	$10.00
	Purge Valve ($/system)	$25.00	$20.00	$15.00	$14.00	$12.00
	Hydrogen Piping ($/system)	$63.94	$51.15	$38.36	$35.80	$30.69
	Total Cost ($/system)	$233.74	$180.46	$152.29	$145.20	$134.76
	Total Cost ($/kW$_{net}$)	$2.92	$2.26	$1.90	$1.82	$1.68

Figure 131. Cost breakdown for fuel loop

4.5.5. System Controller

Conventional electronic engine controllers (EEC's) are 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 on the rationale of simplicity of cost and design. A single EEC is judged necessary to supply adequate control and sensor leads to the power plant.

For the 2010 Update, a new bottom-up analysis of the system controller was conducted. The controller was broken down into 17 input and output circuits, as listed in Figure 132.

Name	Signal
Inputs	
Air Mass Flow Sensor	Analog
H_2 Pressure Sensor (upstream of ejector)	Analog
H_2 Pressure Sensor (stack inlet manifold)	Analog
Air Pressure Sensor (after compressor)	Analog
Stack Voltage (DC bus)	Analog
Throttle Request	Analog
Current Sensors (drawn from motor)	Analog
Current Sensors (output from stack)	Analog
Signal for Coolant Temperature	Analog
H_2 Leak Detector	Digital
Outputs	
Signal to TIM	Analog
Signal to CEM	Analog
Signal to Ejector 1	PWM
Signal to Ejector 2	PWM
High Voltage System Relay	Digital
Signal to Coolant Pump	PWM
Signal to H_2 Purge Valve	Digital
Total Analog	**11**
Total Digital	**3**
Total PWM	**3**
Total Inputs/Outputs	**17**

Figure 132. System controller input & output requirements

For each input or output circuit, it was estimated that approximately 50 cents in electronic components (referencing catalog prices) would be needed. The costs of input and output connectors, an embedded controller, and the housing were also estimated by catalog pricing. A quote was used for the assumed dual-layer 6.5" x 4.5"circuit board. Assembly of 50 parts was based on robotic pick-and-place methods. This new controller analysis is currently undergoing industry vetting to validate assumptions, during which time a 10% cost contingency is added to cover any unforeseen cost increases.

Figure 133 and Figure 134 list the estimated system controller costs.

Component	Description	Cost at 500k systems/year	Cost Basis
Main Circuit Board	2 layer punchboard	$8.01	$5.34 for single layer of 6.5"x4.5" punchboard, Q=500, Assume 25% discount for Q=500k
Input Connector	Wire connector for inputs	$0.18	$0.23 each in Q=10k, reduced ~20% for Q=500k
Output Connector	Wire connector for outputs	$0.20	$0.23 each in Q=10k, reduced ~20% for Q=500k
Embedded Controller	25 MHz, 25 channel microprocessor board	$32.50	Digi-Key Part No. 336-1489-ND, $50@Q=1, assumed 35% reduction for Q=500k
MOSFETs (17 total, 1 each per I/O)	P-channel, 2W, 49MOhm @5A, 10V	$3.74	Digi-Key Part No. 785-1047-2-ND, $0.2352@Q=3k,$0.2184@Q=12k
Misc. Board Elements	Capacitor, resistors, etc.	$4.25	Estimate based on $0.25 component for each input/output
Housing	Shielded plastic housing, watertight	$5.00	Estimate based on comparable shielded, electronic enclosures. Includes fasteners.
Assembly	Assembly of boards/housing	$5.83	Robotic assembly of approx. 50 parts at 3.5 sec each, $2/min assembly cost.
Contingency	10% of all components	$5.97	Standard DFMA additional cost to capture un-enumerated elements/activities.
Markup	25% of all Components	$16.42	Manufacturer's Markup
Total		**$82.11**	

Figure 133. System controller component costs

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Controller ($)	$171.07	$136.85	$102.64	$95.80	$82.11
2010	Total Cost ($/system)	$171.07	$136.85	$102.64	$95.80	$82.11
2010	Total Cost ($/$kW_{net}$)	$2.14	$1.71	$1.28	$1.20	$1.03
2015	Controller ($)	$171.07	$136.85	$102.64	$95.80	$82.11
2015	Total Cost ($/system)	$171.07	$136.85	$102.64	$95.80	$82.11
2015	Total Cost ($/$kW_{net}$)	$2.14	$1.71	$1.28	$1.20	$1.03

Figure 134. Cost breakdown for system controller

4.5.6. Sensors

Aside from the air mass flow sensor (which is book-kept as part of the air loop), there are three types of sensors in the fuel cell system: current sensors, voltage sensors, and hydrogen sensors. The basic sensor descriptions and their costs are listed in Figure 135 and Figure 136.

Component	Description	Cost at 500k systems/year	Cost Basis
Current Sensor (for stack current)	~400A, Hall Effect transducer	$10.00	Based on LEM Automotive Current Transducer HAH1BV S/06, 400 A.
Current Sensor (for motor current)	~400A, Hall Effect transducer	$10.00	Based on LEM Automotive Current Transducer HAH1BV S/06, 400 A.
Voltage Sensor	225-335V	$8.00	Rough estimate based on a small Hall Effect sensor in series with a resistor
H_2 Sensor	Dual-sensor unit for large and small H_2 concentrations	$98.74	Makel Engineering price quote
H_2 Sensor	Dual-sensor unit for large and small H_2 concentrations	$98.74	Makel Engineering price quote
Total		**$28.00**	

Figure 135. Sensor details

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Current Sensors ($/system)	$20.00	$20.00	$20.00	$20.00	$20.00
	Voltage Sensors ($/system)	$8.00	$8.00	$8.00	$8.00	$8.00
	Hydrogen Sensors ($/system)	$1,678.65	$865.00	$631.96	$515.45	$197.49
	Total Cost ($/system)	$1,706.65	$893.00	$659.96	$543.45	$225.49
	Total Cost ($/$kW_{net}$)	$21.33	$11.16	$8.25	$6.79	$2.82
2015	Current Sensors ($/system)	$20.00	$20.00	$20.00	$20.00	$20.00
	Voltage Sensors ($/system)	$8.00	$8.00	$8.00	$8.00	$8.00
	Hydrogen Sensors ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/system)	$28.00	$28.00	$28.00	$28.00	$28.00
	Total Cost ($/$kW_{net}$)	$0.35	$0.35	$0.35	$0.35	$0.35

Figure 136. Cost breakdown for sensors

4.5.6.1. Current Sensors

The current sensors are located on the stack, and allow the system controller to monitor the current being produced.

4.5.6.2. Voltage Sensors

The voltage sensors are located on the stack, and allow the system controller to monitor the voltage being produced.

4.5.6.3. 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 is estimated that two sensors would initially be used in the engine compartment, dropping to 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 137) 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 137).

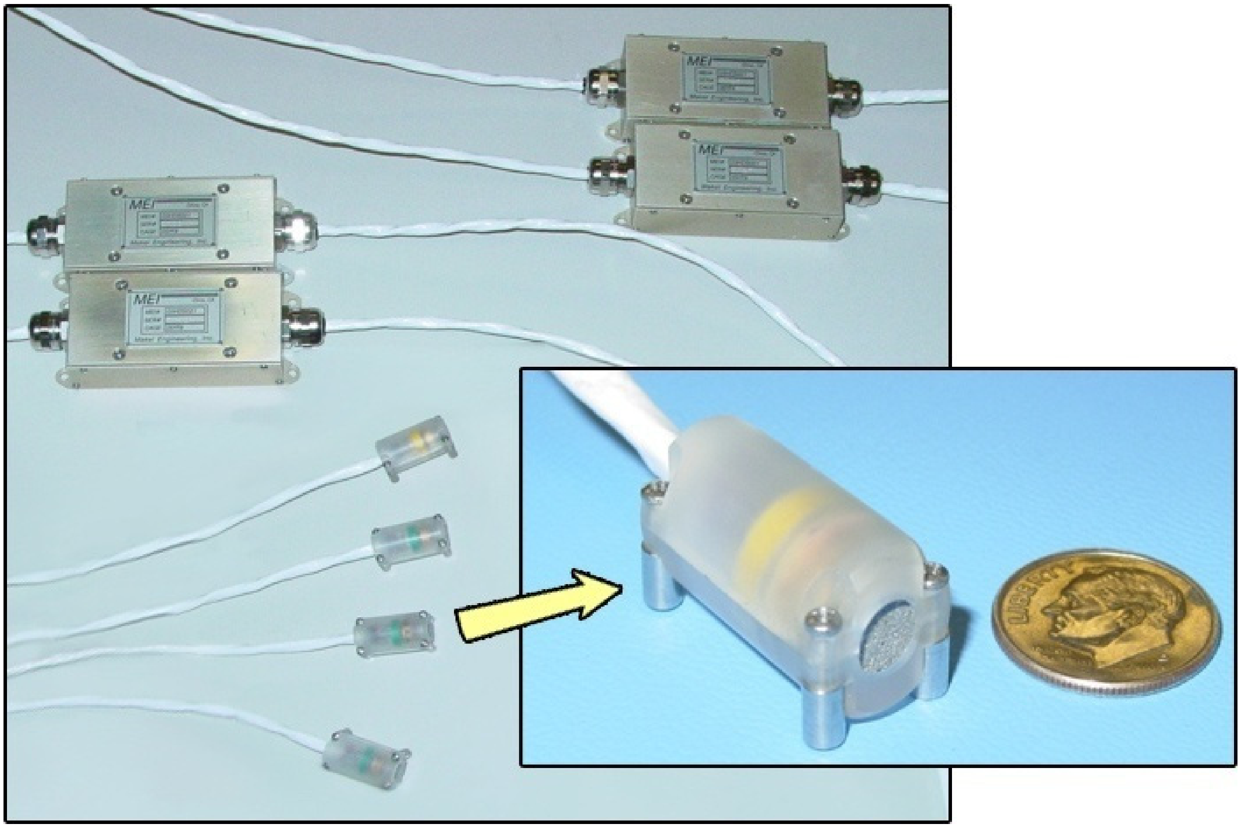

Figure 137. Hydrogen sensors & associated control electronics

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 hydrogen sensors were not included in the 2015 system (which again does not include the passenger cabin or fuel storage), the cheapest sensor cost in the estimate is in the 2010 system. Figure 138 lists the estimated hydrogen sensor costs.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Sensors per System	2	2	2	2	2
	Sensor ($)	$839.33	$432.50	$315.98	$257.72	$98.74
	Total Cost ($/system)	$1,678.65	$865.00	$631.96	$515.45	$197.49
	Total Cost ($/kW$_{net}$)	$20.98	$10.81	$7.90	$6.44	$2.47
2015	Sensors per System	2	2	2	2	2
	Sensor ($)	$493.72	$235.01	$158.98	$122.44	$19.75
	Total Cost ($/system)	$987.44	$470.02	$317.96	$244.89	$39.50
	Total Cost ($/kW$_{net}$)	$12.34	$5.88	$3.97	$3.06	$0.49

Figure 138. Cost breakdown for hydrogen sensors

4.5.7. Miscellaneous BOP

The BOP components which did not fit into any of the other categories are listed here in the miscellaneous section.

Figure 139 shows the cost breakdown for these components.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Belly Pan ($/system)	$60.51	$6.61	$5.52	$4.95	$4.24
	Mounting Frames ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Wiring ($/system)	$104.90	$90.21	$88.11	$87.06	$83.92
	Fasteners for Wiring & Piping ($/system)	$66.30	$54.30	$44.81	$42.79	$38.54
	Voltage Sensors ($/system)	$8.00	$8.00	$8.00	$8.00	$8.00
	Current Sensors ($/system)	$20.00	$20.00	$20.00	$20.00	$20.00
	Total Cost ($/system)	$331.71	$194.12	$171.44	$164.80	$156.69
	Total Cost ($/$kW_{net}$)	$4.15	$2.43	$2.14	$2.06	$1.96
2015	Belly Pan ($/system)	$60.51	$6.61	$5.52	$4.95	$4.24
	Mounting Frames ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Wiring ($/system)	$86.26	$74.19	$72.46	$71.60	$69.01
	Fasteners for Wiring & Piping ($/system)	$53.65	$43.95	$36.33	$34.70	$31.27
	Voltage Sensors ($/system)	$8.00	$8.00	$8.00	$8.00	$8.00
	Current Sensors ($/system)	$20.00	$20.00	$20.00	$20.00	$20.00
	Total Cost ($/system)	$300.42	$167.75	$147.31	$141.25	$134.52
	Total Cost ($/$kW_{net}$)	$3.76	$2.10	$1.84	$1.77	$1.68

Figure 139. Cost breakdown for miscellaneous BOP components

4.5.7.1. Belly Pan

The belly pan is modeled as a 1 x 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 is 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. The analysis shows 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 140, and the machine rate parameters are shown in Figure 141.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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	$447,489
	Costs per Tooling Set ($)	$91,260	$91,260	$91,260	$91,260	$91,260
	Tooling Lifetime (years)	3	3	3	3	3
	Cavities per Platen	1	1	1	1	1
	Total Cycle Time (s)	71.20	71.20	15.20	15.20	7.00
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1	1	1	1	0.25
	Line Utilization	0.59%	17.66%	10.05%	16.34%	28.94%
	Effective Total Machine Rate ($/hr)	$1,135.58	$83.02	$309.52	$208.59	$177.35
	Material Cost ($/kg)	$1.29	$1.29	$1.29	$1.29	$1.29
2015	Machine Selection	Vacuum Thermo-former #1	Vacuum Thermo-former #1	Vacuum Thermo-former #2	Vacuum Thermo-former #2	Vacuum Thermo-former #2
	Assembly Type	Manual	Manual	Manual	Manual	Auto
	Capital Cost ($/Line)	$50,000	$50,000	$250,000	$250,000	$447,489
	Costs per Tooling Set ($)	$91,260	$91,260	$91,260	$91,260	$91,260
	Tooling Lifetime (years)	3	3	3	3	3
	Cavities per Platen	1	1	1	1	1
	Total Cycle Time (s)	71.20	71.20	15.20	15.20	7.00
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	1	1	1	1	0.25
	Line Utilization	0.59%	17.66%	10.05%	16.34%	28.94%
	Effective Total Machine Rate ($/hr)	$1,135.58	$83.02	$309.52	$208.59	$177.35
	Material Cost ($/kg)	$1.29	$1.29	$1.29	$1.29	$1.29

Figure 140. Belly pan thermoforming process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
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 141. 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 ignore at all but the 1,000 systems per year level, where they account for almost 4% of the part cost. Figure 142 shows the cost breakdown.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Materials ($/system)	$3.83	$3.83	$3.83	$3.83	$3.83
	Manufacturing ($/system)	$22.46	$1.64	$1.31	$0.88	$0.34
	Tooling ($/system)	$34.22	$1.14	$0.38	$0.23	$0.06
	Total Cost ($/system)	$60.51	$6.61	$5.52	$4.95	$4.24
	Total Cost ($/kW$_{net}$)	$0.76	$0.08	$0.07	$0.06	$0.05
2015	Materials ($/system)	$3.83	$3.83	$3.83	$3.83	$3.83
	Manufacturing ($/system)	$22.46	$1.64	$1.31	$0.88	$0.34
	Tooling ($/system)	$34.22	$1.14	$0.38	$0.23	$0.06
	Total Cost ($/system)	$60.51	$6.61	$5.52	$4.95	$4.24
	Total Cost ($/kW$_{net}$)	$0.76	$0.08	$0.07	$0.06	$0.05

Figure 142. Cost breakdown for belly pan

4.5.7.2. 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 $30 at 500,000/year to $100 at 1,000/year.

4.5.7.3. 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 have since been 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.

A conceptual fuel cell system wiring schematic (Figure 143) was created to determine where cables were needed and whether they were for transmission of data, power, or both. Cable types were selected based on the maximum current required by each electrical component.

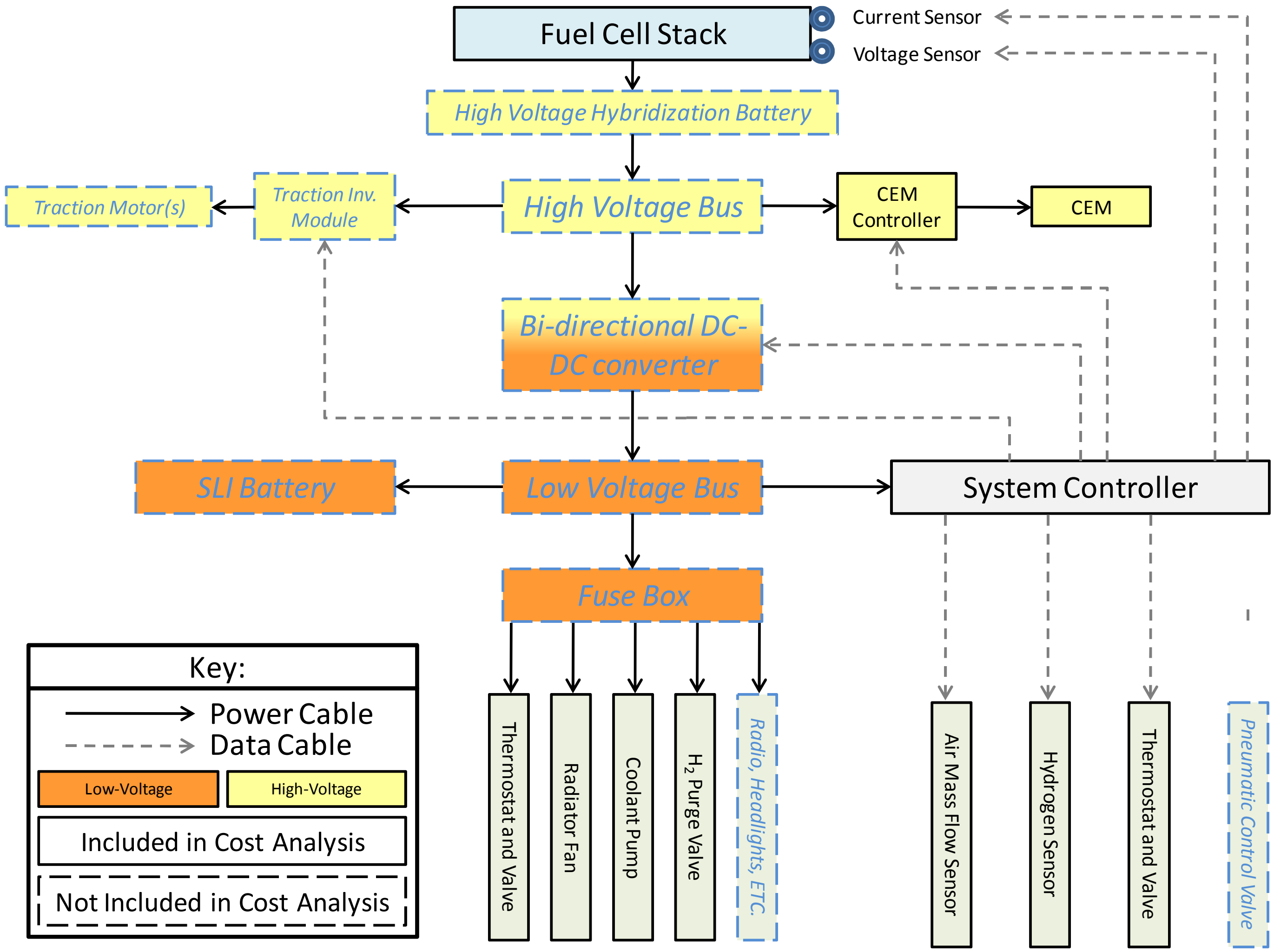

Figure 143. Fuel cell system wiring schematic

For both of the technology levels, this worked out to be five different types of cables in each system. See Figure 144 for details.

	2010		2015	
	Quantity	Length (m)	Quantity	Length (m)
Cable Types				
Power Cable, OOOO Gauge	2	0.5	2	0.5
Power Cable, 6 Gauge	1	0.25	1	0.25
Power Cable, 7 Gauge	4	3.5	3	2.5
Power Cable, 12 Gauge	3	3	2	2
Data Cable, 16 Gauge	10	9	7	6
Totals	**20**	**16.25**	**15**	**11.25**

Figure 144. 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 are needed for each cable.

It is 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 are applied to the wiring bill of materials and the total wiring cost is calculated for each system (see Figure 145).

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Cables ($/system)	$34.84	$29.96	$29.26	$28.91	$27.87
	Connectors ($/system)	$70.06	$60.25	$58.85	$58.15	$56.05
	Total Cost ($/system)	$104.90	$90.21	$88.11	$87.06	$83.92
	Total Cost ($/$kW_{net}$)	$1.31	$1.13	$1.10	$1.09	$1.05
2015	Cables ($/system)	$27.80	$23.91	$23.35	$23.08	$22.24
	Connectors ($/system)	$58.46	$50.28	$49.11	$48.52	$46.77
	Total Cost ($/system)	$86.26	$74.19	$72.46	$71.60	$69.01
	Total Cost ($/$kW_{net}$)	$1.08	$0.93	$0.91	$0.89	$0.86

Figure 145. Cost breakdown for wiring

4.5.7.4. Fasteners for Wiring & Piping

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, it was assumed that the cost and mass of the fasteners were equal to 20% of the wiring and piping. The volumes were book-kept as zero because the additional space they fill was deemed negligible.

4.6. 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 is 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 146.

	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 146. Single-station system assembly assumptions

Two types of system assembly methods are 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
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)	$53.25	$477.89	$469.70	$470.33	$468.71
	Cost per Stack ($)	$157.17	$112.84	$110.91	$111.05	$110.67
2015	**Assembly Method**	Single Station	Assembly Line	Assembly Line	Assembly Line	Assembly Line
	Index Time (min)	147.1	11.8	11.8	11.8	11.8
	Capital Cost ($/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)	$53.25	$477.89	$469.70	$470.33	$468.71
	Cost per Stack ($)	$130.55	$93.72	$92.12	$92.24	$91.92

Figure 147. 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[76] of only 14.2 minutes. The system assembly cost is detailed in Figure 148.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	System Assembly & Testing ($/system)	$157.17	$112.84	$110.91	$111.05	$110.67
	Total Cost ($/system)	$157.17	$112.84	$110.91	$111.05	$110.67
	Total Cost ($/kW$_{net}$)	$1.96	$1.41	$1.39	$1.39	$1.38
2015	System Assembly & Testing ($/system)	$130.55	$93.72	$92.12	$92.24	$91.92
	Total Cost ($/system)	$130.55	$93.72	$92.12	$92.24	$91.92
	Total Cost ($/kW$_{net}$)	$1.63	$1.17	$1.15	$1.15	$1.15

Figure 148. Cost breakdown for system assembly & testing

4.7. 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 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 startup as the vehicles are driven off the assembly line. Corresponding, the fuel cell "engines" are only minimally tested for functionality. Cost for this system testing is reported under system assembly.

4.8. Cost Contingency

It is common practice in the automotive industry[77] 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.

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

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

5. Sensitivity Analysis

In addition to the baseline cost calculations, a Monte Carlo analysis and a single-variable sensitivity analysis were conducted. Triangular probability distribution functions were applied to each of the parameters analyzed, with the likeliest values (the baseline assumptions) at the peaks of the triangles. Figure 149 and Figure 150 show the parameters used in the Monte Carlo analysis.

2010 Technology, 500,00 Systems/year				
Parameter	**Units**	**Minimum Cost**	**Likeliest Cost**	**Maximum Cost**
Power Density	**mW/cm^2**	700	**833**	1000
Pt Loading	**$mgPt/cm^2$**	0.1	**0.15**	0.2
Membrane Cost	**$\$/m^2$**	$2.50	**$20.73**	$24.88
GDL Cost	**$\$/m^2$**	$3.00	**$11.15**	$13.38
Bipolar Plate Cost Factor		0.75	**1.00**	1.25
Bipolar Plate Coating Cost Factor		0	**1**	2
Operating Pressure	**atm**	1.5	**1.69**	2
Operating Temperature	**°C**	80	**90**	95
Air Stoichiometry		1.5	**2.50**	2.75
Membrane Humidifier Cost	**$/system**	$75.00	**$94.25**	$125.00
Compressor Efficiency	**%**	50.0%	**63.8%**	69.0%
Air Compressor Cost	**$/system**	$516.16	**$645.20**	$774.24
Balance of Air Compressor Cost	**$/system**	$83.43	**$125.15**	$187.73
Hydrogen Recirculation System Cost	**$/system**	$101.97	**$152.96**	$229.44

Figure 149. Monte Carlo parameters for 2010 technology, 500k sys/yr

2015 Technology, 500,00 Systems/year				
Parameter	**Units**	**Minimum Cost**	**Likeliest Cost**	**Maximum Cost**
Power Density	**mW/cm^2**	833	**1000**	1200
Pt Loading	**$mgPt/cm^2$**	0.1	**0.15**	0.2
Membrane Cost	**$\$/m^2$**	$2.50	**$22.29**	$30.00
GDL Cost	**$\$/m^2$**	$3.00	**$10.97**	$30.00
Bipolar Plate Cost Factor		0.75	**1.00**	1.25
Bipolar Plate Coating Cost Factor		0.00	**1.00**	2.00
Operating Pressure	**atm**	1.5	**1.69**	2
Operating Temperature	**°C**	90	**99**	120
Air Stoichiometry		1.25	**2.00**	2
Membrane Humidifier Cost	**$/system**	$0.00	**$0.00**	$100.00
Compressor Efficiency	**%**	65.0%	**68.0%**	73.0%
Air Compressor Cost	**$/system**	$403.55	**$504.44**	$605.33
Balance of Air Compressor Cost	**$/system**	$66.85	**$100.28**	$150.42
Hydrogen Recirculation System Cost	**$/system**	$89.84	**$134.76**	$202.14

Figure 150. Monte Carlo parameters for 2015 technology, 500k sys/yr

5.1. Monte Carlo Parameters

The parameters chosen for the 2010 analysis are different than those used in the 2009 analysis, reflecting changes in the depth and complexity of the model. Each parameter is explained in detail below:

- **Power Density (mW/cm^2) –** The power density per cm^2 of active area
- **Platinum Loading (mg/cm^2) –**Total Pt-group metal loading per cm^2 of active area for both anode and cathode combined
- **Membrane Cost (\$/m^2) –** Cost of the membrane (m^2 on the roll, not the active area)
- **GDL Cost (\$/m^2) –** Cost of the macroporous GDL material (m^2 on the roll, not the active area)
- **Bipolar Plate Cost Factor –** A factor multiplied by the manufacturing costs (manufacturing and tooling costs, but not materials costs) of the bipolar plate production. Since the material costs are dependent on the area of the cell (which varies with power density, pressure, compressor size and power draw) it would be inappropriate to use plate cost as a Monte Carlo parameter, as it would not be reflective of the other parameters related to plate sizing.
- **Bipolar Plate Coating Cost Factor –** This multiplier applies to the total cost of coating the Bipolar Plate. Thus it applies to the total materials, manufacturing, and tooling associated with the plate coating (but not the bipolar plate itself).
- **Operating Pressure (atm) –** Pressure at which the fuel cell stack operates
- **Operating Temperature (°C) –** Average stack operating temperature
- **Air Stoichiometry –** The total amount of oxygen (in air) entering the fuel cell divided by the oxygen consumed by the fuel cell reaction
- **Membrane Humidifier Cost ($) –** Cost of the membrane humidifier
- **Compressor Efficiency (%) –**The isentropic efficiency of the air compressor, including the impact of the controller efficiency
- **Air Compressor Cost ($) –** Includes the cost of the air compressor, expander, and compressor motor controller
- **Balance of Air Compressor Cost ($) –** Includes air filter, air filter housing, and the air mass flow sensor
- **Hydrogen Recirculation System Cost ($) –** Includes all components of the fuel system such as ejectors, pressure switches, check valves, purge valves, inline filters, and all associated piping and ducting

5.2. Monte Carlo Results

The analysis was conducted using the Monte Carlo simulation package *@Risk*, a plug-in for *Microsoft Excel*. The simulation ran for 10,000 iterations and yielded cost outputs for each technology level (in \$/kW$_{net}$), for both the stack and the system. The stack results are shown in the next two figures (Figure 151 and Figure 152), and the system results are shown in the two figures after that (Figure 153 through Figure 154). The solid red area in each chart indicates the middle 90% probability range of cost estimates of the Monte Carlo runs, i.e. it is 5% likely that costs will be below this range and 5% likely that costs will be above it. This provides a high degree of confidence that the actual result will be within the indicated range and is a more meaningful means of conveying the system cost than a single-value cost estimate.

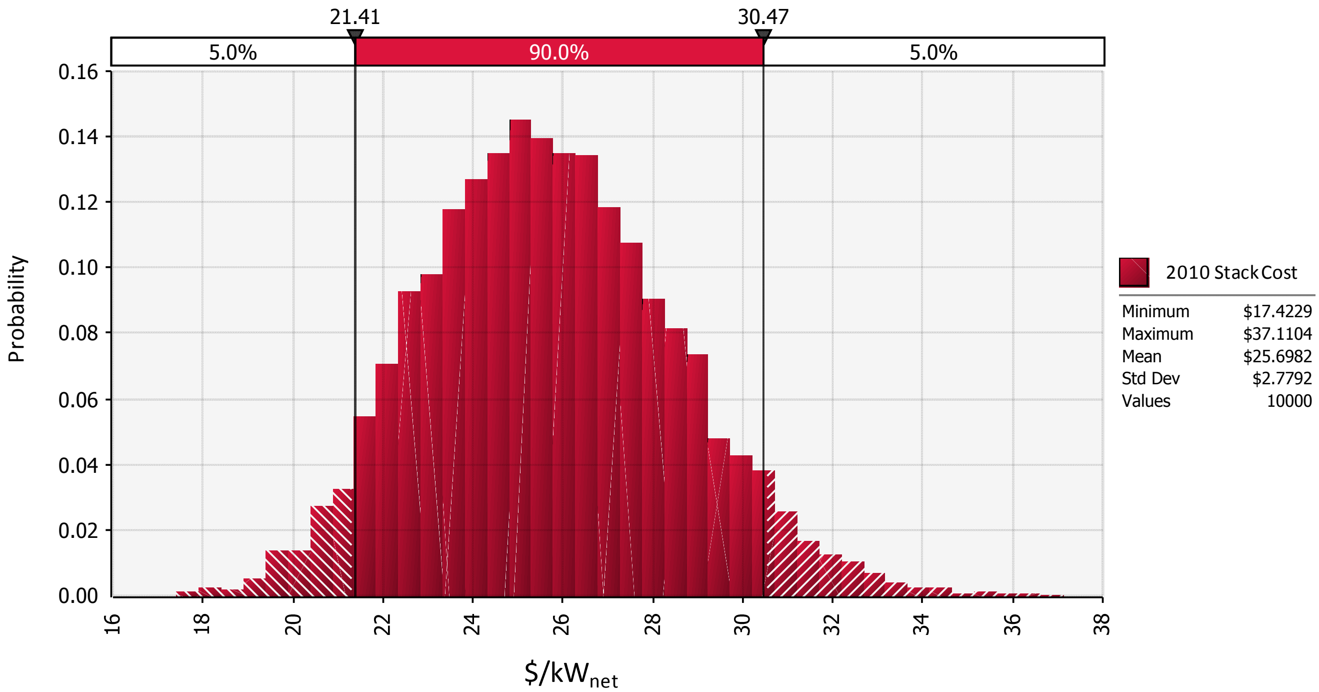

Figure 151. Monte Carlo results for fuel cell stack cost (2010 technology, 500k sys/yr)

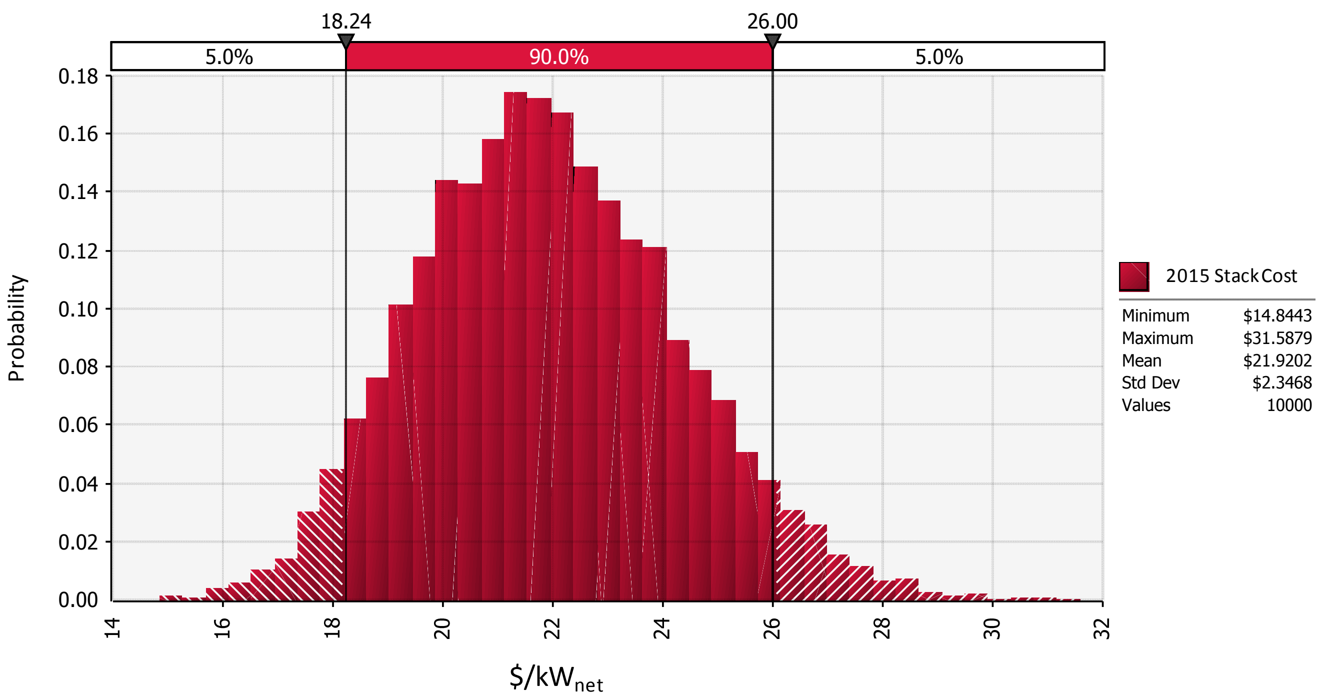

Figure 152. Monte Carlo results for fuel cell stack cost (2015 technology, 500k sys/yr)

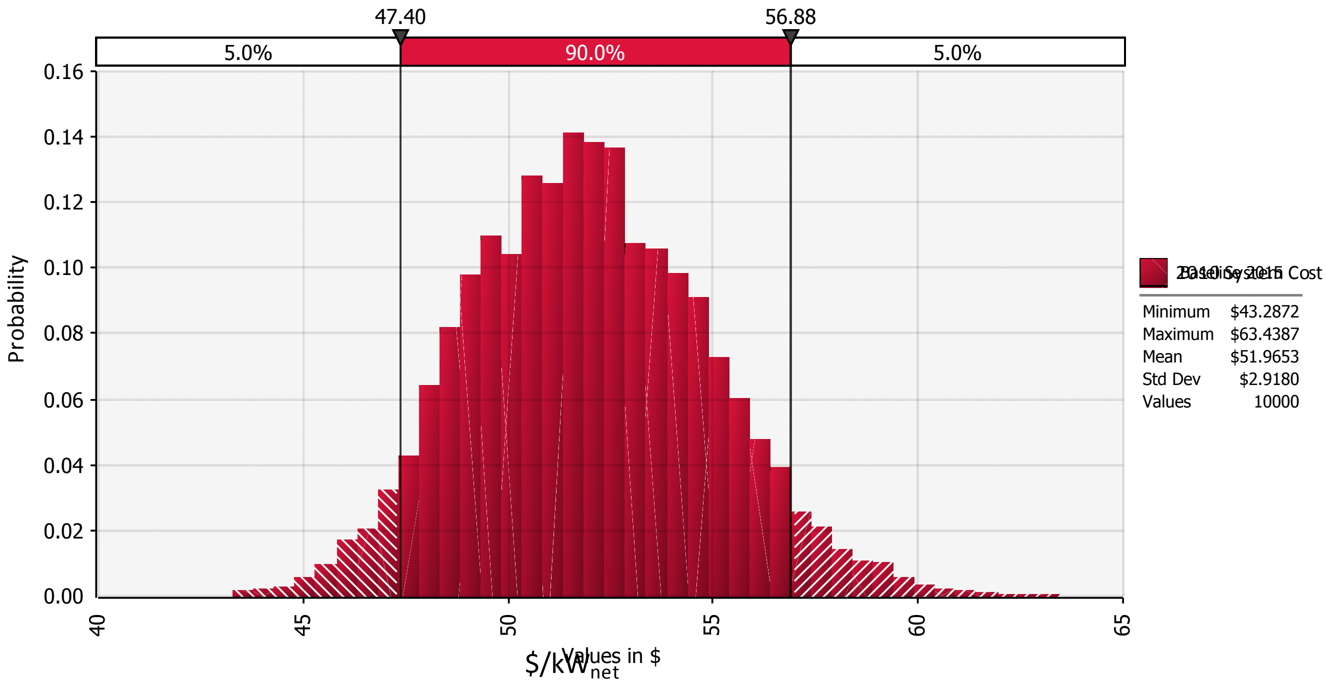

Figure 153. Monte Carlo results for fuel cell system cost (2010 technology, 500k sys/yr)

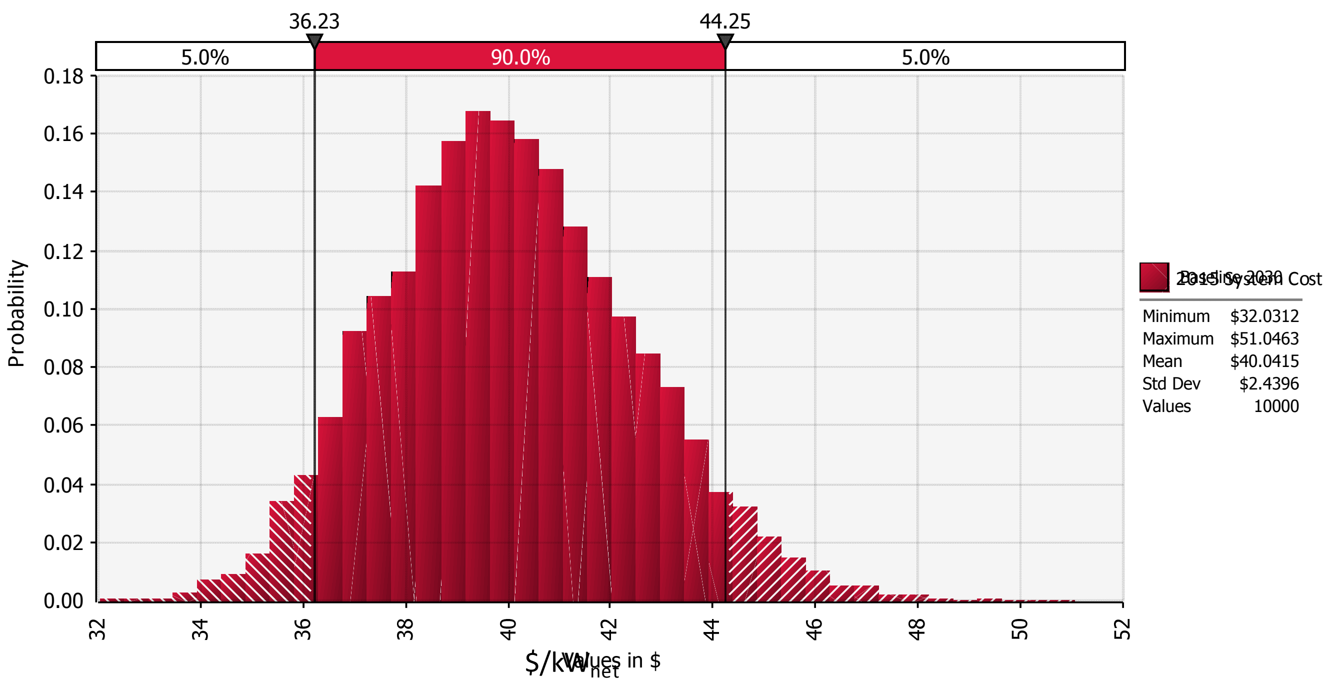

Figure 154. Monte Carlo results for fuel cell system cost (2015 technology, 500k sys/yr)

5.3. Single-Variable Sensitivity

The parameters for the single-variable sensitivity are similar to the parameters in the Monte Carlo analysis. Thirty different cases were run for each variable. These parameters are shown in Figure 155 and Figure 157. The analysis was conducted on the 500k systems/year case. Figure 156 and Figure 158 show the results of this analysis plotted on tornado charts.

System Cost ($/kW$_{net}$): 2010 Technology, 500,000 systems/year				Input		
Variable	***Downside***	***Upside***	***Range***	***Downside***	***Upside***	***Base Case***
Power Density (mW/cm^2)	$55.65	$47.52	$8.13	700	1,000	833
GDL Cost ($/m^2)	$49.16	$56.50	$7.34	$3.00	$30.00	$11.15
Pt Loading (mgPt/cm^2)	$48.60	$54.15	$5.56	0.10	0.20	0.15
Membrane Cost ($/m^2)	$48.84	$52.67	$3.83	$2.50	$30.00	$20.73
Air Compressor Cost ($/system)	$49.76	$52.99	$3.23	$516.16	$774.24	$645.20
Bipolar Plate Coating Cost Factor	$50.04	$52.71	$2.67	0.00	2.00	1.00
Bipolar Plate Cost Factor	$50.37	$52.38	$2.01	0.75	1.25	1.00
Hydrogen Recirculation System Cost ($/system)	$50.74	$52.33	$1.59	$101.97	$229.44	$152.96
Air Stoichiometry	$50.29	$51.63	$1.34	1.50	2.75	2.50
Balance of Air Compressor Cost ($/system)	$50.85	$52.16	$1.30	$83.43	$187.73	$125.15
Expert Compressor Efficiency (%)	$52.12	$51.20	$0.92	50%	69%	64%
Operating Temperature (°C)	$52.02	$51.14	$0.88	80	95	90
Operating Pressure (atm)	$51.12	$51.81	$0.69	1.50	2.00	1.69
Membrane Humidifier Cost ($/system)	$51.13	$51.76	$0.63	$75.00	$125.00	$94.25

Figure 155. Inputs & cost results for tornado chart (2010 technology, 500k sys/yr)

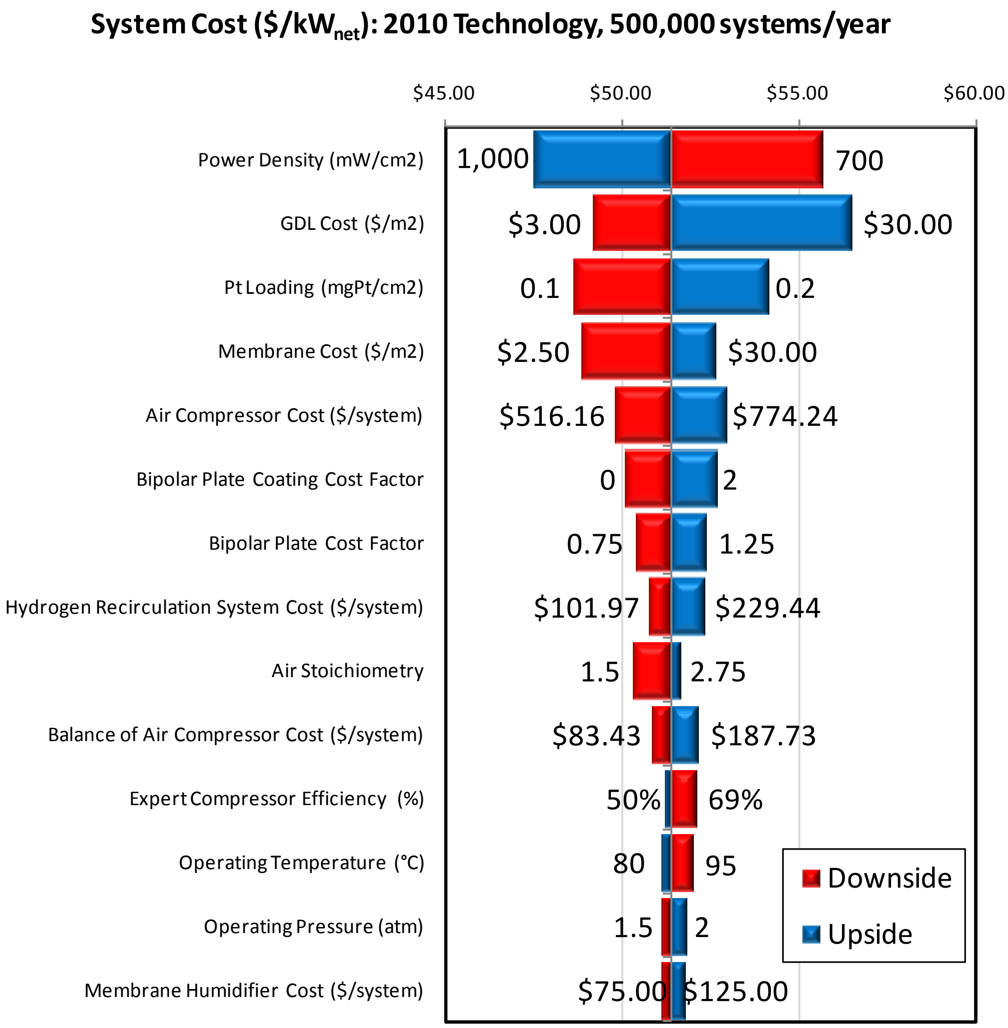

Figure 156. Tornado chart: cost results for single-variable sensitivity analysis (2010 technology, 500k sys/yr)

System Cost ($/kW$_{net}$), 2015 Technology, 500,000 systems/year				Input		
Variable	*Downside*	*Upside*	*Range*	*Downside*	*Upside*	*Best Case*
Power Density (mW/cm^2)	$43.50	$36.46	***$7.04***	833	1,200	1,000
GDL Cost ($/m^2)	$37.83	$43.90	***$6.07***	$3.00	$30.00	$10.97
Pt Loading (mgPt/cm^2)	$37.33	$41.91	***$4.58***	0.10	0.20	0.15
Membrane Cost ($/m^2)	$37.35	$40.51	***$3.15***	$2.50	$30.00	$22.29
Air Compressor Cost ($/system)	$38.36	$40.88	***$2.52***	$403.55	$605.33	$504.44
Bipolar Plate Coating Cost Factor	$38.37	$40.87	***$2.50***	0.00	2.00	1.00
Bipolar Plate Cost Factor	$38.74	$40.50	***$1.76***	0.75	1.25	1.00
Hydrogen Recirculation System Cost ($/system)	$39.06	$40.46	***$1.40***	$89.84	$202.14	$134.76
Membrane Humidifier Cost ($/system)	$39.62	$40.87	***$1.25***	$0.00	$100.00	$0.00
Balance of Air Compressor Cost ($/system)	$39.20	$40.25	***$1.04***	$66.85	$150.42	$100.28
Operating Temperature (°C)	$40.00	$39.07	***$0.93***	90	120	99.00
Air Stoichiometry	$39.14	$39.62	***$0.48***	1.25	2.00	2.00
Operating Pressure (atm)	$39.62	$40.69	***$1.07***	1.50	2.00	1.50
Expert Compressor Efficiency (%)	$39.68	$39.53	***$0.15***	65%	73%	68%

Figure 157. Inputs and cost results for tornado chart (2015 technology, 500k sys/yr)

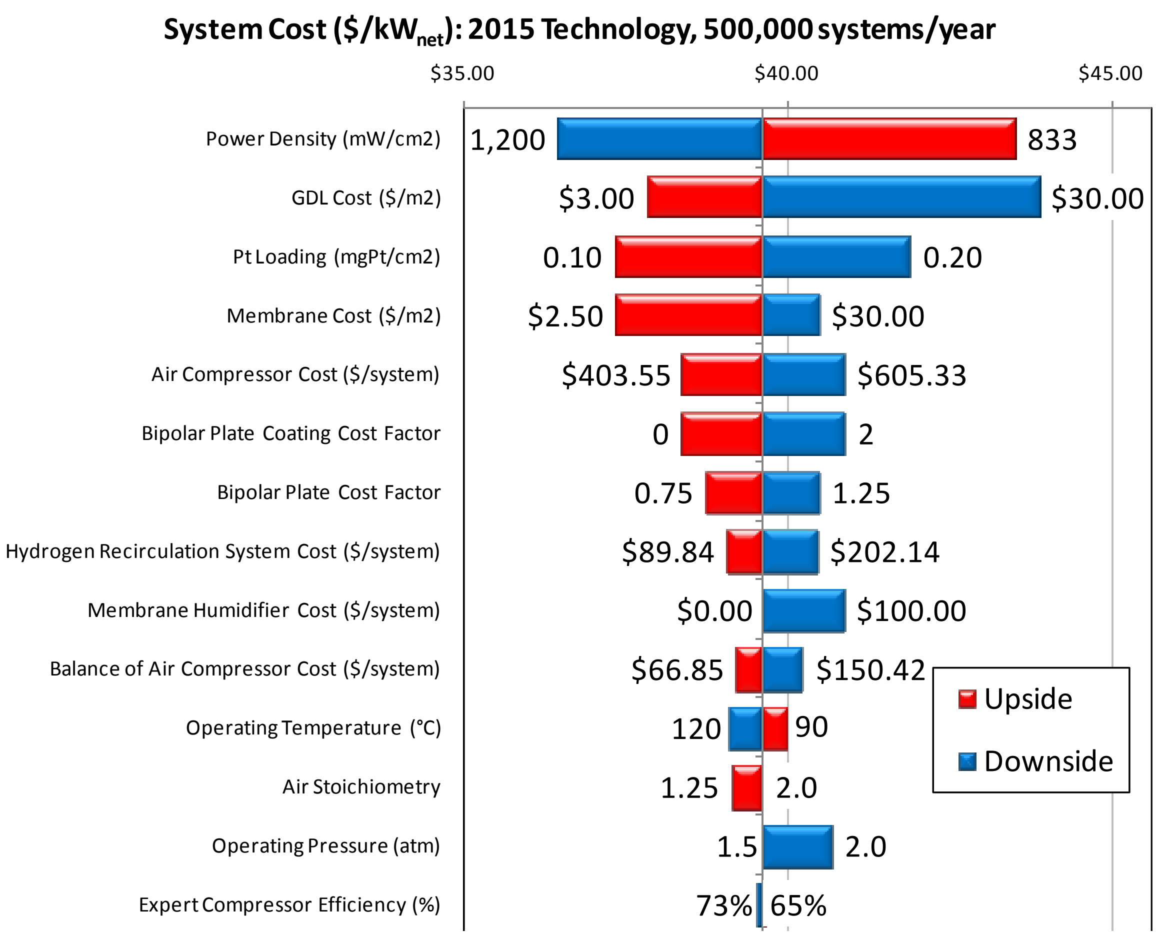

Figure 158. Tornado chart of cost results for single-variable sensitivity analysis (2015 technology, 500k sys/yr)

The single-variable sensitivity analysis highlights some important aspects not reflected in the Monte Carlo analysis:

1. The four most important factors affecting cost for both the 2010 and 2015 systems relate to the stack: power density, GDL cost, catalyst loading, and membrane cost. Despite the high cost of several balance of plant items (such as the CEM), the foreseeable benefit from improvements in BOP costs is minor compared to the huge benefit achievable from changes in stack parameters. Future research should focus on these issues.

2. Parameters related to the gaseous thermodynamic conditions (such as pressure, temperature, air stoichiometry and compressor efficiency) have a surprisingly minimal effect on system cost.

5.4. Peak Power Operating Point

Analysis suggests that operating at a lower peak-power cell voltage (0.6 V/cell instead of 0.676 V/cell) will yield a large cost savings due to substantially increased power density. However, while this shift results in a physically smaller (and thus less-expensive) fuel cell stack, it has the disadvantages of a large radiator, larger compressor, and decreased overall fuel economy. Consequently, to partially quantify these effects, the cost and performance model were run at 0.6 V/cell.

Based on recent 3M polarization curves, it is expected that power density increases 34% from this voltage shift (833 mW/cm^2 at 0.676 V/cell to 1,115 mW/cm^2 at 0.6V/cell). Such a change necessitates a 29% increase in radiator size due to increased waste heat dissipation and a 14% increase in CEM size due to increased air flow. Additionally, it leads to a reduction in peak-power system efficiency and a slight change (~1–2 mpgge) in fuel economy when averaged over the entire drive cycle. However, the increased power density from this decrease in voltage gives a substantial reduction in stack size and a \$4.33/kW$_{net}$ savings in overall system cost. Figure 159 outlines the changes between the current system, and the postulated lower-voltage system.

	2010 Status	Alternate
Stack Eff. @ Rated Power	55%	48.8%
System Eff. @ Rated Power	50.1%	44.1%
Current Density (mA/cm^2)	1,233	1,859
Cell Voltage (V)	0.676	0.600
Areal Power Density (mW/cm^2)	833	1,115
Stack Cost Impact (\$/kW$_{net}$)	--	(\$5.20)
Radiator Cost Impact (\$/kW$_{net}$)	--	\$0.57
CEM Cost Impact (\$/kW$_{net}$)	--	\$0.10
System Cost (\$/kW$_{net}$)	\$51.38	\$47.05
Cost Difference (\$/kW$_{net}$):	(\$4.33)	

Figure 159. Results of shifted power operating point

6. Conclusions

Figure 160 and Figure 161 (repeats of Figure 13 and Figure 14) graphically summarize the cost trends for the 80kW$_{net}$ PEM fuel cell stacks and systems.

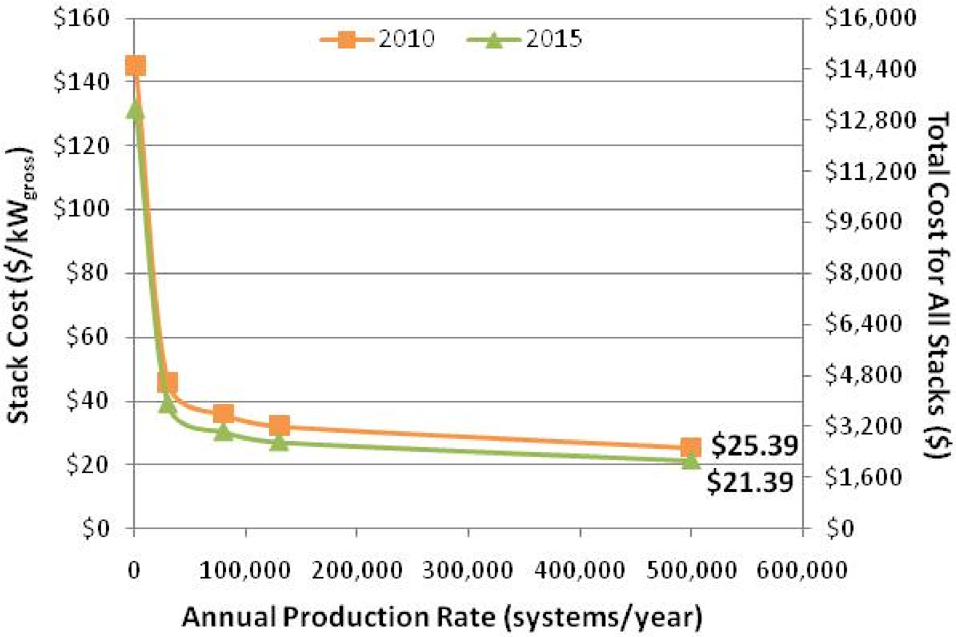

Figure 160. Gross stack cost vs. annual production rate

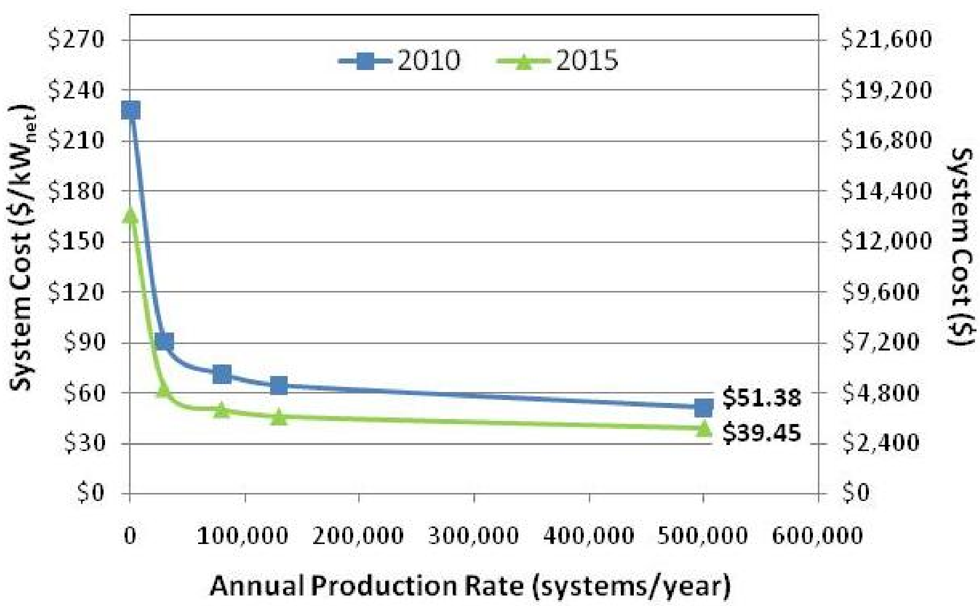

Figure 161. Net system cost vs. annual production rate

In addition to the downward trend in the current cost projections, there have been significant cost reductions compared to the previous four years of analysis, a consequence of technology improvement and analysis refinement. The current technology (2010) cost projection is 51% lower than the initial analysis (2006) at 500k systems/year production level. Figure 162 shows the downward trend in current technology cost since the beginning of the project. Figure 163 shows that the annual updates of projections for the 2010 and 2015 systems also display a downward trend.

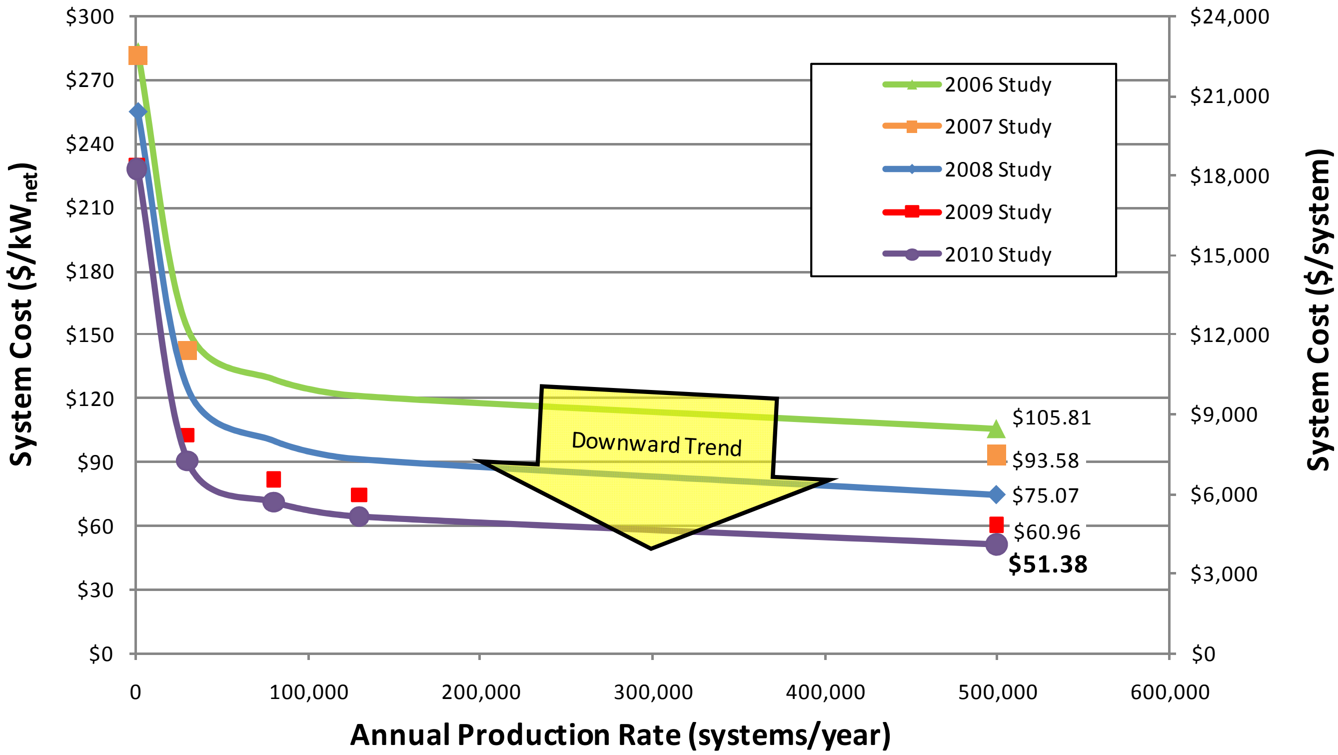

Figure 162. Current-technology cost evolution

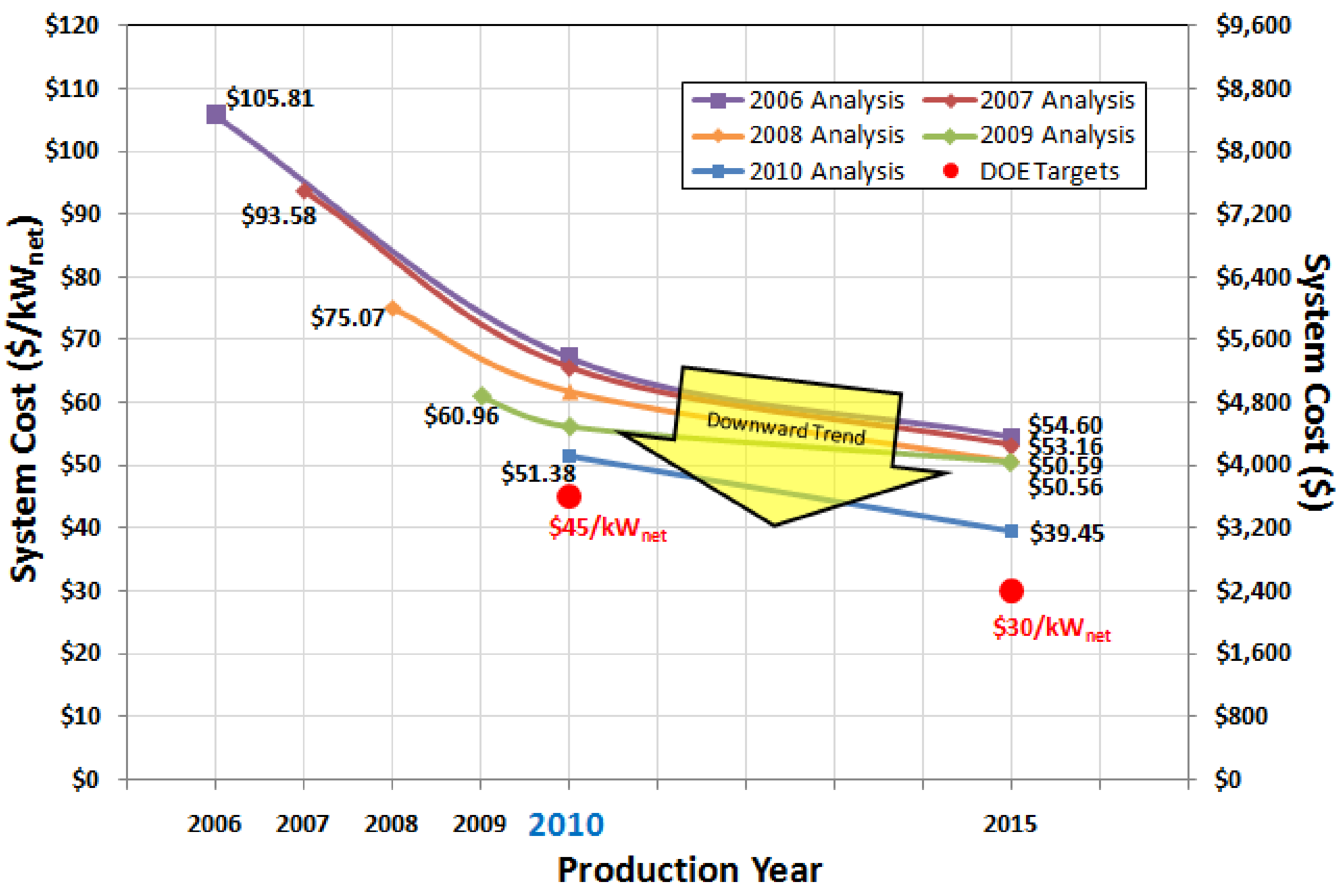

Figure 163. System cost future projections (500k sys/yr)

It should be noted that, as shown in Figure 164, current study estimates for future cost projections fall short of the DOE target costs. (DOE cost targets are indicated as red dots in Figure 163.) However, given the overall downward trend of cost projections further significant cost reductions can likely be achieved with technology advancements that have not yet been discovered.

Source	Characteristic	Units	2010	2015
DOE Target:	Stack Cost	$\$/kW_{e\ (net)}$	**$25**	**$15**
Study Estimate:	Stack Cost	$\$/kW_{e\ (net)}$	**$25**	**$21**
DOE Target:	System Cost	$\$/kW_{e\ (net)}$	**$45**	**$30**
Study Estimate:	System Cost	$\$/kW_{e\ (net)}$	**$51**	**$39**

Figure 164. DOE targets vs. DTI estimates for the stack & system

Key conclusions from the analysis include:

- System cost projections are 13% and 30% above the 2010 and 2015 DOE cost targets, respectively.
    - Stack Cost: The projections meet the 2010 DOE target but are $6/kW over for 2015.
    - System Cost: The projections are $6/kW over the 2010 DOE target and $9/kW over for 2015.
- Substantial cost reductions (factors of 3–5) are achievable by increasing manufacturing volume from 1,000 to 500,000 systems per year production rate.
- 78% 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. 93% 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 (20%–48%). Consequently, R&D to reduce, simplify, or eliminate BOP components is needed to achieve significant overall system cost reductions.
- Three subsystems account for 74% of BOP costs: air loop, high-temperature cooling loop, and sensors.
- 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 $\$1.96/kW_{net}$ 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.
- Stamped metallic bipolar plates increasingly appear to be the industry standard. However both stamped metallic and injected molded polymer bipolar plates are economically viable pathways and have a projected cost of $\$4–21/kW_{net}$ 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 bipolar plates may obviate costly anti-corrosion coatings.

- Confidence has increased in the last year that a cost-competitive metal plate coating system exists that provides adequate corrosion resistance.
- Metal plates allow welding to be used in lieu of gaskets for plate sealing.

- Development of NSTF (Nanostructured Thin Film) catalysts enabled significant improvements in power density and catalyst loading between 2008 and 2009 (715 mW/cm^2 at 0.25 mgPt/cm^2 vs. 833 mW/cm^2 at 0.15 mgPt/cm^2). These improvements yielded a system cost reduction of ~\$10/kW$_{net}$.
- Further modest power density improvements are expected in the future (1,000 mW/cm^2 in 2015) and are expected to result in further cost reductions.
- While additional platinum catalyst usage reduction would obviously be cost beneficial, we project future loadings to remain approximately constant at 0.15 mgPt/cm^2. This catalyst loading is sufficiently low that platinum cost is no longer a dominant element of the system as it once was. We anticipate performance advances to instead manifest themselves in power density and durability improvements.
- Membrane cost is expected to drop a factor of ten due primarily to mass production methods. Material cost of the Nafion ionomer (or some other ion conductive ionomer) likewise is expected to drop ten-fold in cost. Alternate membranes with reduced manufacturing complexity offer an additional route to material cost reduction.
- Application of the NSTF catalyst at high production rates can be quite low-cost: ~\$0.40/kW$_{net}$.
- The gas diffusion layer (GDL) ranges from \$2–27/kW$_{net}$ and is 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 are observed to be minor cost elements.
- A polymer frame/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: \$0.40–\$0.95/kW$_{net}$.
- Stack conditioning to improve MEA performance is estimated at <\$1/kW$_{net}$ based on an extrapolation of current procedures. However, ultimately the MEA and stack conditioning procedure must be optimized together. The current analysis postulates only a generic conditioning procedure.
- 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.
- There is a 90% likelihood that the system costs are between the following values:
  - 2010, 500,000 systems/year: \$47.44–\$56.93/kW$_{net}$ (-8% to +11% of \$51.38 projected value)
  - 2015, 500,000 systems/year: \$36.23–\$44.25/kW$_{net}$ (-8% to +12% of \$39.45 projected value)
  - Overall, the range of cost variation (generally ±10%) while still maintaining 90% confidence is quite narrow.