Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: 2007 Update

February 29, 2008
Final Version

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Contract No. GS-10F-0099J
to the U.S. Department of Energy
Energy Efficiency and Renewable Energy Office
Hydrogen, Fuel Cells & Infrastructure Technologies Program

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. Whereas internal combustion vehicles have historically been tethered to petroleum fuels, fuel cell vehicles operate on hydrogen, a renewable resource that can be produced domestically. A diverse portfolio of energy sources can be used to produce it, including nuclear, coal, natural gas, geothermal, wind, hydroelectric, solar, and biomass. Thus fuel cell vehicles offer an environmentally clean and energy-secure transportation pathway.

Fuel cell systems will have to be cost-competitive with conventional and advanced vehicle technologies within the passenger vehicle market. Since the light duty vehicle sector consumes the most oil, primarily due to the vast number of vehicles it represents, DOE has established detailed cost targets for automotive fuel cell systems and components. To help achieve these cost targets, 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 provide tracking information and pose the hypothetical question: How much would a typical automotive fuel cell system cost if produced in large quantities (i.e. 500,000 vehicles per year)?

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

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

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

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1. Overview

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

In this multi-year project conducted for the US Department of Energy, we estimate the material and manufacturing cost of complete 80 kW_{net} direct hydrogen Proton Exchange Membrane (PEM) fuel cell systems suitable for powering light duty automobiles. We estimate the system costs for three different technology levels; a "baseline" system that reflects 2007 technology, a predicted 2010 technology system, and a predicted 2015 technology system. To assess the cost benefits of mass manufacturing, five annual system production rates are examined: 1,000, 30,000, 80,000, 130,000, and 500,000.

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

In general, our 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/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, more manual operations are typically employed. For some repeat parts within the fuel cell stack, such as the membrane electrode assemblies (MEAs) and the bipolar flow plates, so many pieces are needed for each system that even at low systems production rates (1,000/year), hundreds of thousands of individual parts are needed annually. Thus for these parts, mass manufacturing cost reductions are achieved even at low system production rates. However, other fuel cell stack components, such as end plates and current collectors, and all balance of plant equipment, such as blowers/hoses/valves/etc., don't benefit from this manufacturing multiplier effect.

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

[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. Basic Approach

The three systems examined (2007 technology, 2010 technology, and 2015 technology) do not reflect the design of any one manufacturer but are composites of the best elements from a number of designs. All three systems are normalized to 80 kW_{net} system output power although their gross powers are different. Additionally, all three systems operate at 0.677 Volts/cell, with 1.8 oxidant stoichiometry. Stack pressure levels are projected to decrease with time, and are set at 2.3, 2.0, and 1.5 atm[2] for the 2007, 2010, and 2015 systems respectively.

The main fuel cell subsystems included in this analysis are:

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

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

- Main vehicle battery or ultracapacitor[3]
- Electric traction motor (that drives the vehicle wheels)
- Traction inverter module (TIM) (for control of the traction motor)
- Vehicle frame, body, interior, or comfort related features (e.g., driver's instruments, seats, and windows).

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

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

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

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

The cost for any component analyzed via DFMA techniques includes direct material cost, manufacturing cost, assembly costs, and markup. Direct material costs are determined from the exact type and mass of material employed in the component. This cost is usually based upon either historical volume prices for the material or vendor price quotations. In the case of materials not widely used at present, the manufacturing process must be analyzed to determine the probable high-volume price for the material. The manufacturing cost is based upon the required features of the part and the time required 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 and also varies with type of business and whether the manufacturer or assembler is adding value or just passing the product through his shop. (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.

3. Summary of Results

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

3.1. Changes from the 2006 Report

This report represents the first annual update of the 2006 baseline DTI fuel cell cost estimate report[4] under contract to the DOE. The 2006 baseline report (dated October 2007), documented cost estimates for fuel cell systems utilizing projected 2006, 2010, and 2015 technologies. This annual report updates the previous work to incorporate advances made over the course of 2007. The 2007 update report reflects advances made in technology, improvements/corrections made in the cost analysis, and alterations of how we anticipate the 2010 and 2015 systems will develop.

While numerous small changes and adjustments were made for this update report, the key changes with noteworthy cost impact are relatively few. These key changes are:

[4] "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.

- **Power Density and Catalyst Loading Change:** Catalyst loading affects stack polarization performance which in turn affects power density and stack cost. Consequently, multiple catalyst loading levels should be examined to determine which leads to lowest system cost. For the 2007 technology status, we have selected a different catalyst loading/power density design point for the cost analysis. Catalyst loading is decreased from 0.65 $mgPt/cm^2$ to 0.35 $mgPt/cm^2$ and power density is decreased from 700 mW/cm^2 to 583 mW/cm^2. The combined effect of these changes was to decrease system cost ~$7/kW for the 2007 system at 500,000 systems/year production rate. Catalyst loading and power density for the 2010 and 2015 were unchanged.

- **Two Stacks per System:** Based on input from Ballard, we have increased the permissible number of cells per stack. As a result, only two stacks are needed per system rather than the previous four. The number of total active cells remains the same, the stacks are just longer. This saves money in endplates, current collectors and assembly and was implemented for all three technology projections. Cost savings are approximately $1.2/kW for the 2007 system at 500,000 systems/year production rate.

- **Air Stoichiometry changed to 1.8x:** Based on input from fuel cell manufacturers, we have decreased the design point air stoichiometry from 2.0 to 1.8. This decreased the power rating of the air compressor and results in an overall system gross power reduction. Cost savings is ~$0.7/kW for the 2007 system at 500,000 systems/year production rate.

- **Twin-Lobe Air Compressor Efficiency decreased to 65%:** Based on further input from industry, the adiabatic compressor efficiency for a twin lobe compressor was reduced from 70% to 65%, and motor/controller efficiency was raised from 80% to 85%. This had the net affect of raising cost ~$0.3/kW for the 2007 system at 500,000 systems/year production rate.

- **Stamping Machinery Capital Cost Increase:** Based on industry input, capital cost of the entire progressive stamping line for the metallic bipolar plates was increased to ~$500,000 from the previous estimate of ~$100,000. All three technology projections were similarly affected. Cost increase is ~$0.2/kW for the 2007 system at 500,000 systems/year production rate.

- **Insertion Molding of Coolant Gaskets:** Previously, we postulated stand-alone injection molded silicon gaskets to seal between the faces of the bipolar plates that form a cooling cell (i.e. cooling gaskets). Upon further reflection and consultation with fuel cell manufacturers, we judge insertion molded gaskets to be more practical. Thus for all three technology projections, we now postulate that the cooling gaskets will be molded directly onto the appropriate face of the bipolar plates via insertion molding. Cost savings are negligible because the added cost of insertion molding is off-set by the decrease in assembly time.

Power Density (mW/cm²)	583	1,000	1,000
Total Pt loading (mg/cm²)	0.35	0.3	0.2
Operating Pressure (atm)	2.3	2	1.5
Peak Stack Temp. (°C)	70-90	99	120
Membrane Material	Nafion on ePTFE	Advanced High-Temperature Membrane	Advanced High-Temperature Membrane
Radiator/Cooling System	Aluminum Radiator, Water/Glycol coolant, DI filter	Smaller Aluminum Radiator, Water/Glycol coolant, DI filter	Smaller Aluminum Radiator, Water/Glycol coolant, DI filter
Bipolar Plates	Stamped Stainless Steel (uncoated) or Injection Molded Carbon/Polymer Future options: Embossed Flexible Graphite Flake (~GrafCell), Compression Molded Carbon/Polymer	Stamped Stainless Steel (uncoated) or Injection Molded Carbon/Polymer Future options: Embossed Flexible Graphite Flake (~GrafCell), Compression Molded Carbon/Polymer	Stamped Stainless Steel (uncoated) or Injection Molded Carbon/Polymer Future options: Embossed Flexible Graphite Flake (~GrafCell), Compression Molded Carbon/Polymer
Air Compression	Twin Lobe Compressor, Twin Lobe Expander	Centifugal Compressor, Radial Inflow Expander	Centifugal Compressor, No Expander
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous layer applied on top	Carbon Paper Macroporous Layer with Microporous layer applied on top Future options: Flexible Graphite Flake (Grafcell), Co-fab w/ Membrane/Bipolar Plate	Carbon Paper Macroporous Layer with Microporous layer applied on top Future options: Flexible Graphite Flake (Grafcell), Co-fab w/ Membrane/Bipolar Plate
Catalyst Application	Double-sided vertical die-slot coating of membrane	Double-sided vertical die-slot coating of membrane	Double-sided vertical die-slot coating of membrane
Hot Pressing	Hot pressing of MEA	Hot pressing of MEA	Hot pressing of MEA
Air Humidification	Water spray injection	Polyamide Membrane	None
Hydrogen Humidification	None	None	None
Exhaust Water Recovery	SS Condenser (Liquid/Gas HX)	SS Condenser (Liquid/Gas HX)	None
MEA Containment	MEA Frame with Hot Pressing	MEA Frame with Hot Pressing	MEA Frame with Hot Pressing
Gaskets	Silicone injection molding of gasket around MEA	Silicone injection molding of gasket around MEA Future option: "Mold-in-Place"	Silicone injection molding of gasket around MEA Future option: "Mold-in-Place"
Freeze Protection	Drain water at shutdown	Drain water at shutdown	Drain water at shutdown
Hydrogen Sensors	2 H_2 sensors (for FC sys), 1 H_2 sensor (for passenger cabin; not in cost estimate), 1 H_2 sensor (for fuel sys; not in cost estimate)	1 H_2 sensor (for FC sys), 1 H_2 sensor (for passenger cabin; not in cost estimate), 1 H_2 sensor (for fuel sys; not in cost estimate)	No H_2 sensors
End Plates/Compression System	Composite molded endplates with compression bands	Composite molded endplates with compression bands	Composite molded endplates with compression bands
Stack/System Conditioning	5 hours of power conditioning - from UTC's US Patent #7,078,118	4 hours of power conditioning - from UTC's US Patent #7,078,118	3 hours of power conditioning - from UTC's US Patent #7,078,118

Figure 1. Summary chart of the 3 different systems analyzed

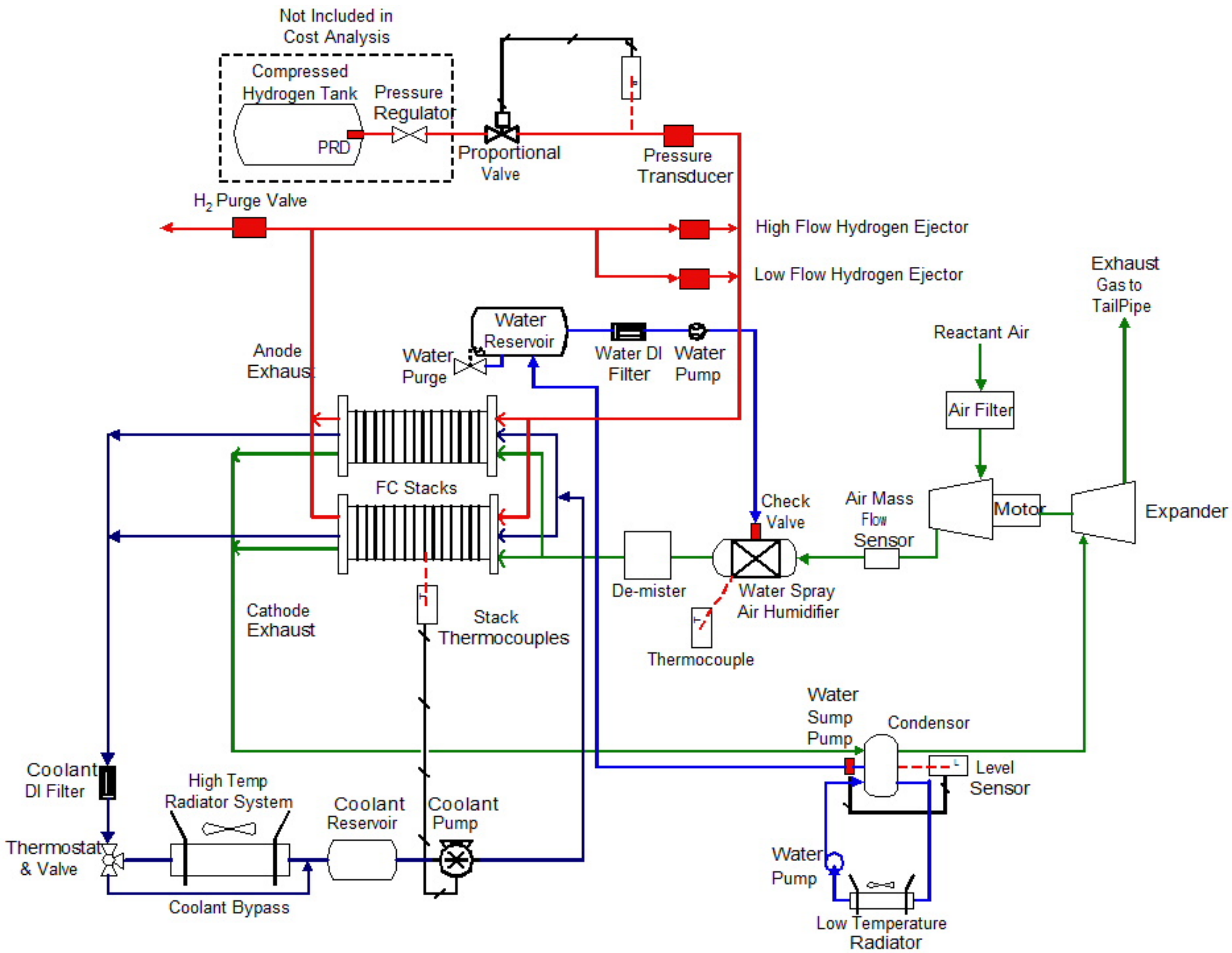

Figure 2. Flow schematic of the 2007 80 kW_{net} direct H_2 fuel cell system

The 2007 technology year system is a fairly standard direct hydrogen, pressurized air fuel cell system configuration. Main features include:

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

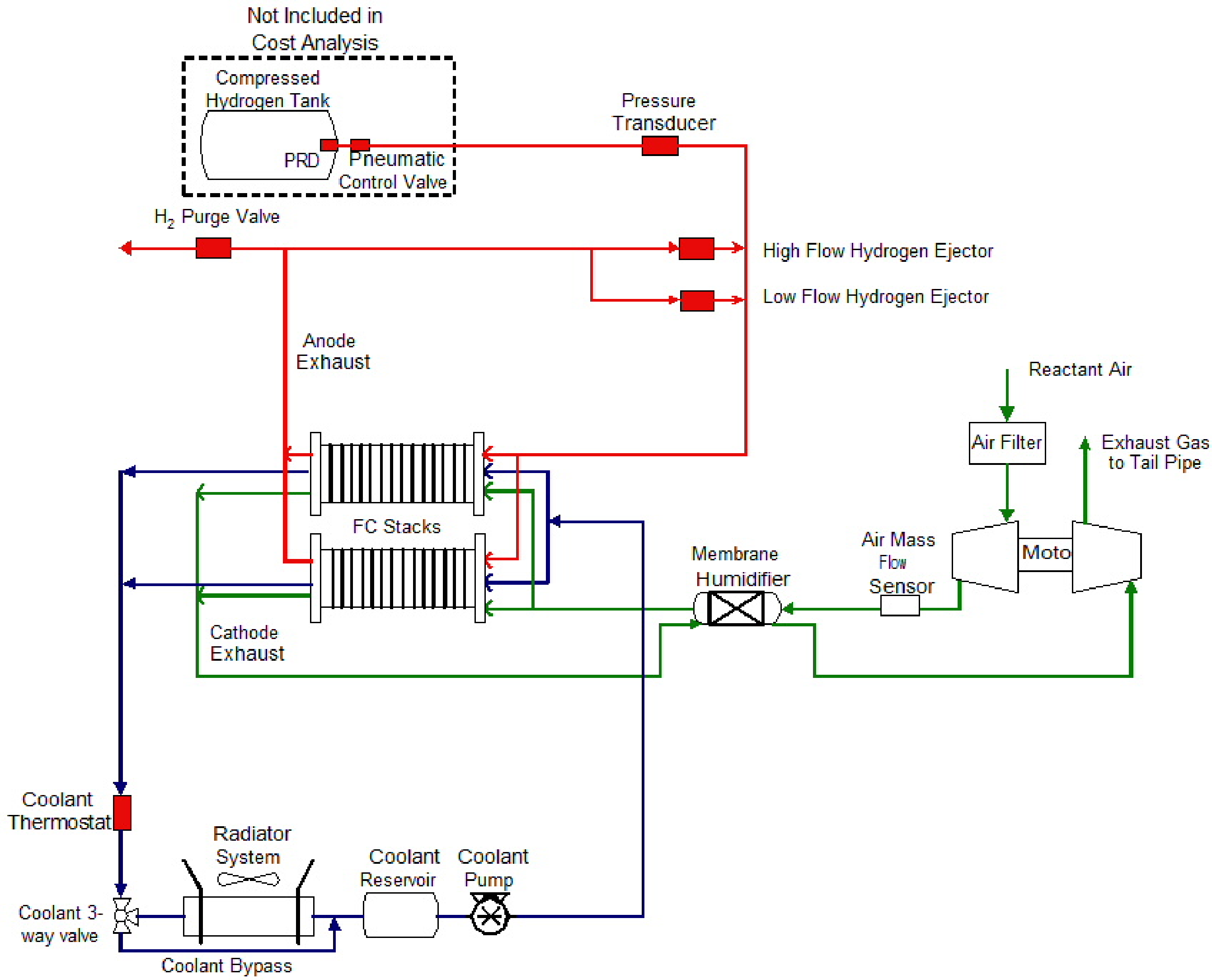

Figure 3. Flow schematic of the 2010 80 kW_{net} direct H_2 fuel cell system

The 2010 technology year system is based on the 2007 configuration but with the following key differences:

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

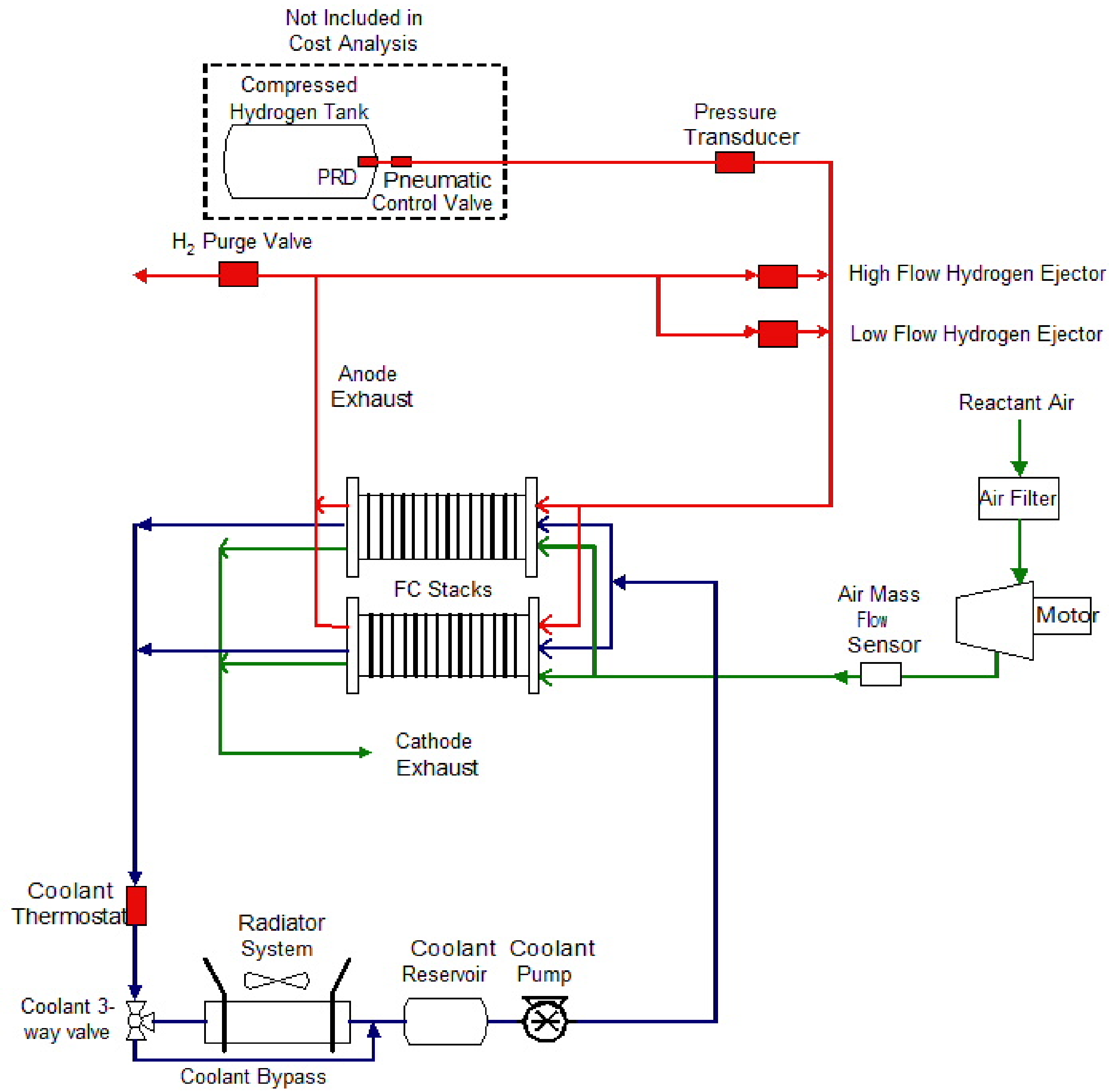

Figure 4. Flow schematic of the 2015 80 kW_{net} direct H_2 fuel cell system

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

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

3.2. Cost Summary of the 2007 Technology System

Results of the cost analysis of the 2007 technology system at each of the five annual production rates are shown below. Figure 5 details the cost of the stacks and Figure 6 details the remaining balance of plant components.

	2007				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	90.34	90.34	90.34	90.34	90.34
Bipolar Plates (Stamping)	$304.79	$209.88	$208.07	$208.08	$206.98
MEAs					
Membranes	$3,094.17	$527.23	$331.53	$261.53	$141.27
Catalyst Ink	$1,229.26	$1,140.39	$1,132.82	$1,131.03	$1,116.07
Catalyst Application	$172.03	$6.58	$7.29	$6.14	$6.01
GDLs	$1,421.32	$833.27	$524.40	$411.23	$197.59
M & E Hot Pressing	$38.29	$17.10	$17.10	$16.86	$16.85
M & E Cutting & Slitting	$27.44	$3.36	$2.84	$2.72	$2.73
MEA Frame/Gaskets	$199.53	$159.09	$155.20	$154.04	$154.48
Coolant & End Gaskets	$155.06	$90.23	$88.02	$88.19	$87.93
Endplates	$67.95	$33.49	$29.60	$27.74	$20.86
Current Collectors	$13.95	$8.42	$7.34	$6.86	$6.38
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Assembly	$51.59	$19.73	$17.10	$17.46	$17.03
Stack Conditioning & Testing	$31.32	$11.25	$10.78	$10.82	$10.76
10% Cost Contingency	$0.00	$0.00	$0.00	$0.00	$0.00
Total Stack Cost	$6,816.71	$3,068.03	$2,538.08	$2,348.20	$1,989.95
Total Cost for All Stacks	$13,633.42	$6,136.06	$5,076.16	$4,696.40	$3,979.91
Total Stack Cost ($/kW$_{net}$)	$170.42	$76.70	$63.45	$58.71	$49.75
Total Stack Cost ($/kW$_{gross}$)	$150.92	$67.92	$56.19	$51.99	$44.06

Figure 5. Detailed stack cost for the 2007 technology system

	2007				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	90.34	90.34	90.34	90.34	90.34
Fuel Cell Stacks	$13,633.42	$6,136.06	$5,076.16	$4,696.40	$3,979.91
Mounting Frames	$100.00	$43.00	$33.00	$30.00	$30.00
Air Loop	$2,614.77	$1,362.41	$1,062.19	$952.36	$788.88
Humidifier & Water Recovery Loop	$481.50	$408.60	$341.00	$326.08	$299.89
Coolant Loop (High & Low Temp)	$781.25	$668.00	$578.75	$547.10	$503.80
Fuel Loop	$927.50	$747.00	$566.50	$528.40	$457.20
System Controller/Sensors	$2,600.00	$988.38	$942.34	$898.30	$700.00
Miscellaneous/BOP	$1,161.32	$936.37	$714.84	$670.14	$579.28
System Assembly & Testing	$203.10	$149.58	$147.64	$147.79	$147.41
10% Cost Contingency	$0.00	$0.00	$0.00	$0.00	$0.00
Total System Cost	$22,502.86	$11,439.40	$9,462.41	$8,796.57	$7,486.37
Total System Cost ($/kW$_{net}$)	$281.29	$142.99	$118.28	$109.96	$93.58
Total System Cost ($/kW$_{gross}$)	$249.10	$126.63	$104.75	$97.37	$82.87

Figure 6. Detailed system cost for the 2007 technology system

3.3. Cost Summary of the 2010 Technology System

Results of the cost analysis of the 2010 technology system at each of the five annual production rates are shown below. Figure 7 details the cost of the stacks and Figure 8 details the remaining balance of plant components.

	2010				
Annual Production Rate	1,000	30,000	80,000	130,000	500,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	86.82	86.82	86.82	86.82	86.82
Bipolar Plates (Stamping)	$228.56	$138.66	$138.66	$137.76	$137.73
MEAs					
Membranes	$2,244.65	$397.05	$243.18	$188.99	$97.06
Catalyst Ink	$587.60	$541.97	$537.71	$536.64	$529.18
Catalyst Application	$171.59	$6.14	$4.72	$3.07	$3.17
GDLs	$893.14	$457.99	$287.50	$225.02	$107.34
M & E Hot Pressing	$34.00	$7.69	$7.81	$7.84	$7.71
M & E Cutting & Slitting	$27.32	$3.26	$2.74	$2.62	$2.53
MEA Frame/Gaskets	$160.34	$89.01	$85.18	$84.60	$81.76
Coolant & End Gaskets	$119.93	$66.76	$64.54	$64.72	$64.46
Endplates	$51.22	$23.44	$21.61	$19.66	$15.11
Current Collectors	$10.58	$5.29	$4.56	$4.27	$3.96
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Assembly	$51.59	$19.73	$17.10	$17.46	$17.03
Stack Conditioning & Testing	$29.82	$9.12	$8.81	$8.74	$8.62
10% Cost Contingency	$0.00	$0.00	$0.00	$0.00	$0.00
Total Stack Cost	$4,620.35	$1,774.10	$1,430.12	$1,306.89	$1,080.66
Total Cost for All Stacks	$9,240.69	$3,548.20	$2,860.25	$2,613.77	$2,161.32
Total Stack Cost ($/kW$_{net}$)	$115.51	$44.35	$35.75	$32.67	$27.02
Total Stack Cost ($/kW$_{gross}$)	$106.44	$40.87	$32.95	$30.11	$24.89

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)	86.82	86.82	86.82	86.82	86.82
Fuel Cell Stacks	$9,240.69	$3,548.20	$2,860.25	$2,613.77	$2,161.32
Mounting Frames	$100.00	$43.00	$33.00	$30.00	$30.00
Air Loop	$1,887.03	$1,327.82	$1,003.72	$891.74	$754.33
Humidifier & Water Recovery Loop	$900.00	$600.00	$425.00	$350.00	$250.00
Coolant Loop (High & Low Temp)	$498.24	$420.54	$358.32	$338.69	$310.92
Fuel Loop	$927.50	$747.00	$566.50	$528.40	$457.20
System Controller/Sensors	$2,600.00	$788.38	$755.34	$723.30	$550.00
Miscellaneous/BOP	$1,161.32	$936.37	$714.84	$670.14	$579.28
System Assembly & Testing	$202.89	$149.41	$147.48	$147.63	$147.25
10% Cost Contingency	$0.00	$0.00	$0.00	$0.00	$0.00
Total System Cost	$17,517.68	$8,560.72	$6,864.44	$6,293.66	$5,240.29
Total System Cost ($/kW$_{net}$)	$218.97	$107.01	$85.81	$78.67	$65.50
Total System Cost ($/kW$_{gross}$)	$201.78	$98.61	$79.07	$72.49	$60.36

Figure 8. Detailed system cost for the 2010 technology system

3.4. Cost Summary of the 2015 Technology System

Results of the cost analysis of the 2015 technology system at each of the five annual production rates are shown below. Figure 9 details the cost of the stacks and Figure 10 details the remaining balance of plant components.

	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)	87.11	87.11	87.11	87.11	87.11
Bipolar Plates (Stamping)	$228.90	$138.96	$138.96	$138.05	$138.02
MEAs					
Membranes	$2,249.97	$398.84	$244.28	$189.85	$97.51
Catalyst Ink	$394.87	$362.58	$359.68	$358.96	$353.96
Catalyst Application	$171.59	$6.14	$4.72	$3.07	$3.18
GDLs	$895.41	$459.51	$288.43	$225.74	$107.64
M & E Hot Pressing	$34.00	$7.68	$7.81	$7.84	$7.71
M & E Cutting & Slitting	$27.32	$3.26	$2.74	$2.62	$2.53
MEA Frame/Gaskets	$160.70	$89.30	$82.23	$82.83	$82.05
Coolant & End Gaskets	$120.03	$66.86	$64.64	$64.81	$64.56
Endplates	$51.25	$23.44	$21.61	$19.67	$15.11
Current Collectors	$10.60	$5.30	$4.58	$4.28	$3.97
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Assembly	$51.59	$19.73	$17.10	$17.46	$17.03
Stack Conditioning & Testing	$28.32	$7.00	$6.61	$6.52	$6.49
10% Cost Contingency	$0.00	$0.00	$0.00	$0.00	$0.00
Total Stack Cost	$4,434.55	$1,596.60	$1,249.39	$1,127.20	$904.74
Total Cost for All Stacks	$8,869.11	$3,193.21	$2,498.78	$2,254.40	$1,809.48
Total Stack Cost ($/kW$_{net}$)	$110.86	$39.92	$31.23	$28.18	$22.62
Total Stack Cost ($/kW$_{gross}$)	$101.82	$36.66	$28.69	$25.88	$20.77

Figure 9. 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)	87.11	87.11	87.11	87.11	87.11
Fuel Cell Stacks	$8,869.11	$3,193.21	$2,498.78	$2,254.40	$1,809.48
Mounting Frames	$100.00	$43.00	$33.00	$30.00	$30.00
Air Loop	$1,374.58	$967.35	$726.79	$649.64	$552.07
Humidifier & Water Recovery Loop	$0.00	$0.00	$0.00	$0.00	$0.00
Coolant Loop (High & Low Temp)	$453.75	$380.50	$320.50	$303.10	$277.55
Fuel Loop	$927.50	$747.00	$566.50	$528.40	$457.20
System Controller/Sensors	$600.00	$588.38	$568.34	$548.30	$400.00
Miscellaneous/BOP	$1,161.32	$936.37	$714.84	$670.14	$579.28
System Assembly & Testing	$202.89	$149.41	$147.48	$147.63	$147.25
10% Cost Contingency	$0.00	$0.00	$0.00	$0.00	$0.00
Total System Cost	$13,689.15	$7,005.22	$5,576.22	$5,131.59	$4,252.83
Total System Cost ($/kW$_{net}$)	$171.11	$87.57	$69.70	$64.14	$53.16
Total System Cost ($/kW$_{gross}$)	$157.15	$80.42	$64.02	$58.91	$48.82

Figure 10. Detailed system cost for the 2015 technology system

3.5. Cost Comparison of All Three Systems

Stack and system costs for all three technology levels are compared in Figure 11 and Figure 12. Stack cost is seen to range from \$151/kW_{gross} (1,000 systems/year in 2007) to \$21/kW_{gross} (500,000 systems/year in 2015). System cost is seen to range from \$281/kW_{net} (1,000 systems/year in 2007) to \$53/kW_{net} (500,000 systems/year in 2015). All three technology levels experience an initial steep drop in price with the "knee of the curve") at around 50,000 systems per year. While each technology level represents a combination of configuration and performance improvements, the system cost reductions are primarily due to balance of plant configuration changes, and the stack cost reductions are primarily due to power density and catalyst loading improvements. Consequently the cost curves have very similar shapes but vary in amplitude according to cell performance and loading. Very little stack cost change is observed between 2010 and 2015 because stack performance/catalyst loadings are not expected to change.

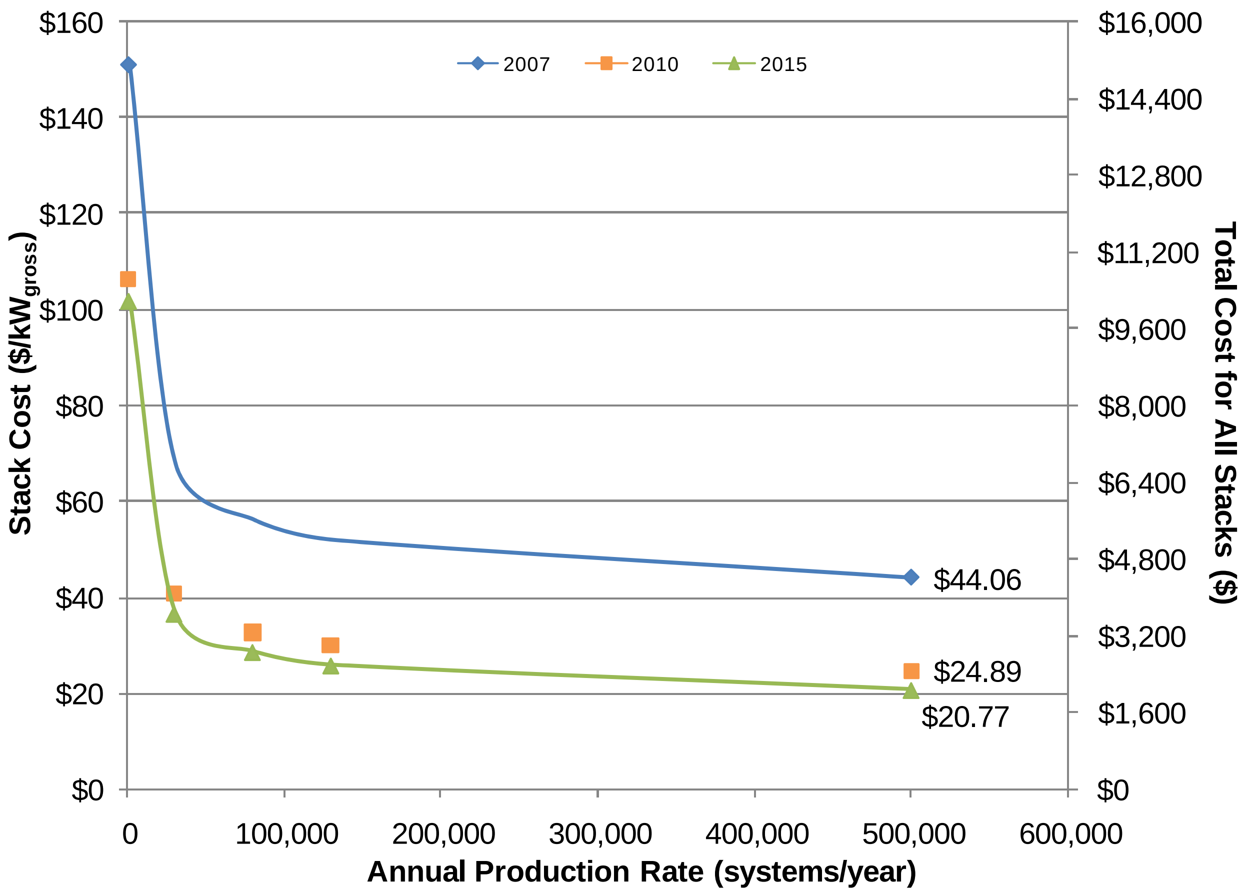

Figure 11. Stack cost vs. annual production rate

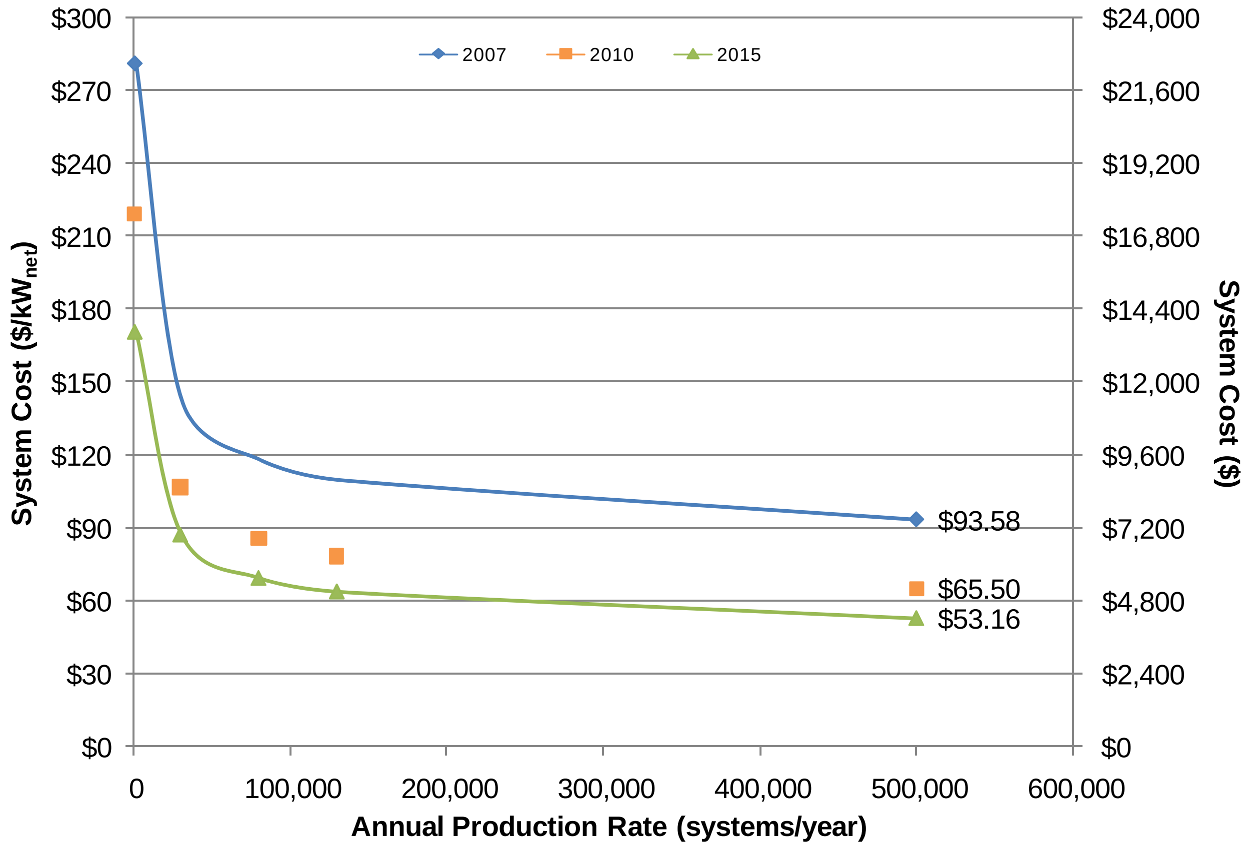

Figure 12. System cost vs. annual production rate

4. Detailed Assumptions

4.1. System Performance and Operation

The fuel cell stacks contained within each of the three technology level systems are identical in most design and operational parameters, differing only in active area per cell and stack gross power. However, even this variation in resulting gross power is not very large- 90.34 kW, 86.82 kW and 87.11 kW for 2007, 2010, and 2015 respectively. The differences are primarily the result of differences in the air compression load, which in turn results from different air compression approaches and levels of pressurization. Figure 13 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 system peak power must be evaluated at the most adverse temperature (40°C ambient). Figure 14 summarizes total system parasitic loads.

Compressor		2007	2010	2015
Gross Power	kW	91.54	87.59	87.08
Air Mass Flow	kg/h	308	292	290
Compression Ratio	atm	2.3	2	1.5
Compressor Efficiency		0.6	0.75	0.75
Ambient Temp	°C	40	40	40
Motor/Controller Efficiency		0.85	0.85	0.85
Expander				
Mass Flow	kg/h	313	297	**No expander in 2015 System**
Compression Ratio	atm	2	1.7	
Compressor Efficiency		0.75	0.8	
Starting Temp	°C	80	80	
Expander Shaft Power Out	kW	4.50	3.56	
Compression Alone				
Compressor Shaft Power Req	kW	12.11	7.49	4.17
Compressor Input Power Req	kW	14.25	8.81	4.91
Compressor-Expander Unit				
CMEU Input Power	kW	8.95	4.62	4.91

Figure 13. Basis of air compressor and expander power

(All values in kW)	2007	2010	2015
Fuel Cell Gross Electric Power (Output)	90.34	86.82	87.11
System Net Electrical Power (Output)	80	80	80
Air Compressor Motor	7.75	4.62	4.91
Coolant Pump	1.1	1.1	1.1
Coolant Radiator Fan	0.90	0.90	0.90
Exhaust Radiator Fan	0.38	0.00	0.00
Other (Controller, Instruments, etc.)	0.2	0.2	0.2
Total Parasitic Loads	10.34	6.82	7.11

Figure 14. Power production & loads at maximum power, under peak ambient temperature operating conditions

Stack design parameters and operating conditions are summarized in Figure 15 and Figure 16. All systems operate with low single-pass hydrogen utilization but high total utilization due to a hydrogen recirculation loop.

	2007	2010	2015
Number of Stacks per System	2		
Number of Active Cells per Stack*	186		
Number of Cooling Cells per Stack*	188		
Cell Coltage at Max. Power	0.677		
Membrane Power Density at Max. Power (mW/cm^2)	583	1,000	1,000

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

Figure 15. Stack design parameters

	2007	2010	2015
Peak Operating Pressure (atm)	2.3	2.0	1.5
Cell Temperature (°C)	70-90	99	120
Oxygen Stoichiometry	1.8x		
Anode Gas Stream			
Hydrogen Purity	99.999% (molar basis)		
Inlet Temperature (°C)	Ambient + ~10°C		
Relative Humidity	0%		
Max (single pass) H_2 flowrate	~5.5kg/hr(~1100slpm)		
Cathode Gas Stream			
Oxygen Purity	21% (molar basis)		
Inlet Temperature (°C)	75°C		
Relative Humidity	50%		
Max (single pass) Air flowrate	~300 kg/hr (~4200slpm)		

Figure 16. Stack operation parameters

The power density (listed in Figure 15) 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 17) describes everything between the endplates. The table in Figure 18 lists the numerical values of these dimensions.

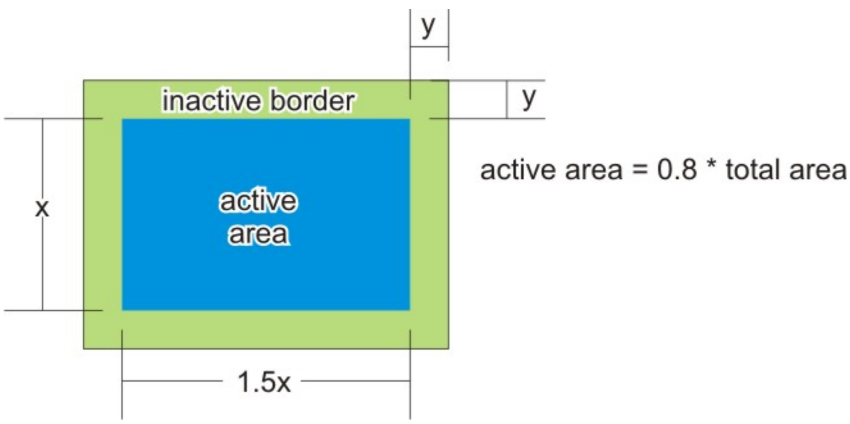

Figure 17. Cell geometry

	2007	2010	2015
Active Area (cm^2)	416.54	233.38	234.16
Active Width (cm)	25.00	18.71	18.74
Active Height (cm)	16.66	12.47	12.49
Total Area (cm^2)	520.67	291.73	292.70
Total Width (cm)	27.36	20.48	20.51
Total Height (cm)	19.03	14.24	14.27
Ratio of Width to Height	1.5	1.5	1.5
Ratio of Active Area to Total Area	0.8	0.8	0.8
Inactive Border (cm)	1.18	0.89	0.89

Figure 18. 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[5] but pay them only for use of the processing machinery.

Machine cost is determined by multiplying machine rate ($/min 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 (e.g. 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 be $3.3/min). However, these historical machine rates assume high machine utilization, typically 14 hours per day, 240 days per year. Consequently, they are of limited value to this study as we specifically want to explore the cost implications of low annual production rates.

To estimate machine rates at less than full machine utilizations, we break machine rate down into five components:

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

Overall machine rate is obtained by added these four 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: Fraction of uninstalled capital costs paid annually for maintenance and spare parts (typically 5- 20%).

[5] 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.

Miscellaneous Expense: Fraction of uninstalled capital costs paid annually for all other expenses (typically 7%).

Utility Costs: Costs associated with machine electricity, natural gas, etc. Typically computed by kW of machine power times electricity cost (typically $0.07/kWh).

Machine Labor: Cost of machine operator labor. Following automotive practices, US labor rates are generally $0.50 to $1.00 per minute depending on the level of skill required. All cases in this analysis use a rate of $1.00 per minute. For some processes, non-integer numbers of laborers are used per line (for instance, 0.25 is used for the injection molding process) because workers don't need to devote 100% of their time to it and can perform other tasks over the course of their work day. 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's 1.5 lines worth of work, and there are 2 lines, each machine is assumed to run 75% of the time. Full utilization is typically defined as 14 useful hours per day, 240 work days per year.

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

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

4.2.1. Machine Rate Validation

To demonstrate the validity of the above described machine rate calculation approach, Figure 19 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[6]. 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. We note 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. We judge the PT survey data to be significant at low machine sizes because it represents a minimum machine rate industry receives. Consequently, to achieve conservative estimates throughout, we impose a $25/hr

[6] 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.

minimum machine rate 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 20 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[7]. This is a direct consequence of the annual capital cost repayment needing to be collected even if the machine is used infrequently.

For each component manufacturing or assembly task, the batch volume, machine setup time, and time to complete the task are 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.

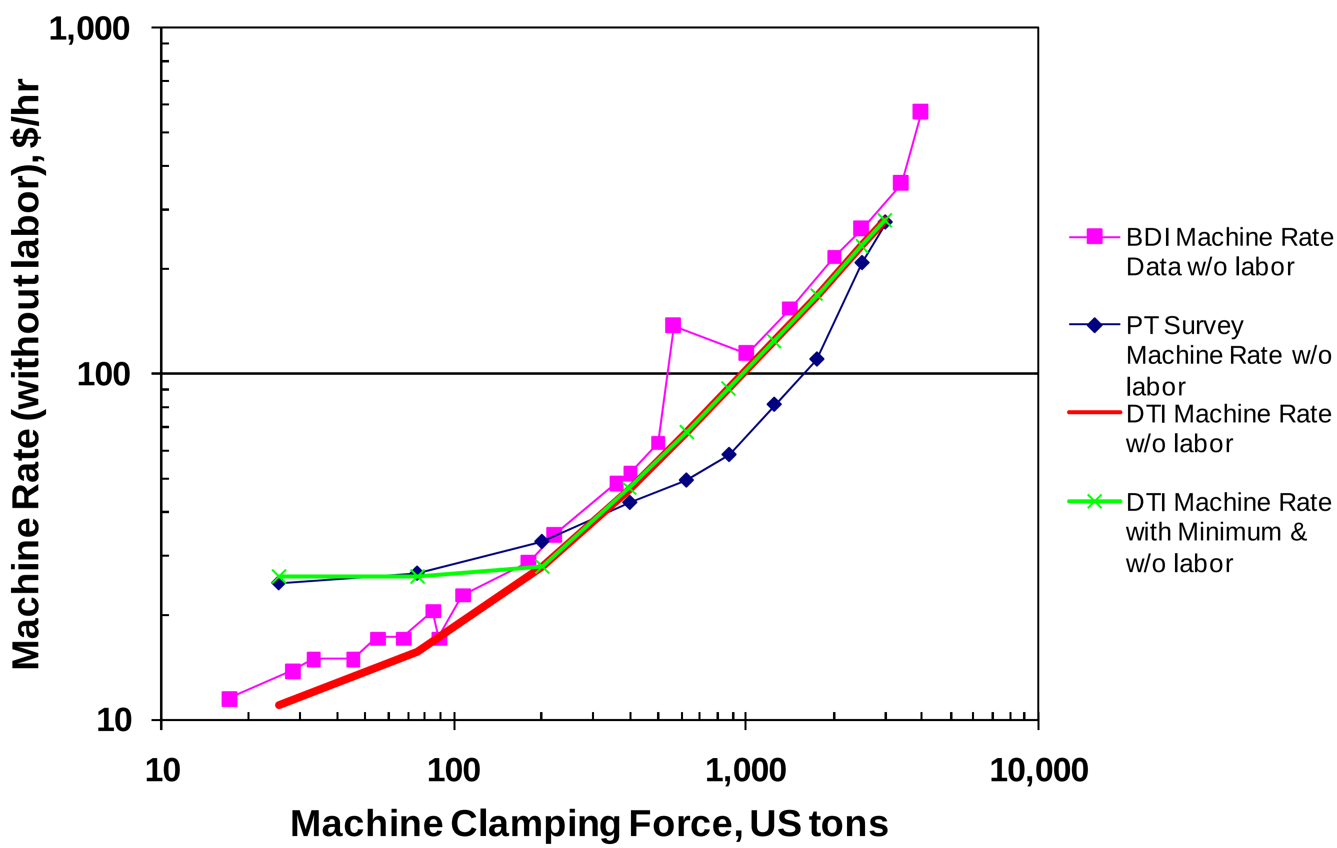

Figure 19. Injection molding machine rate vs. machine clamping force

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

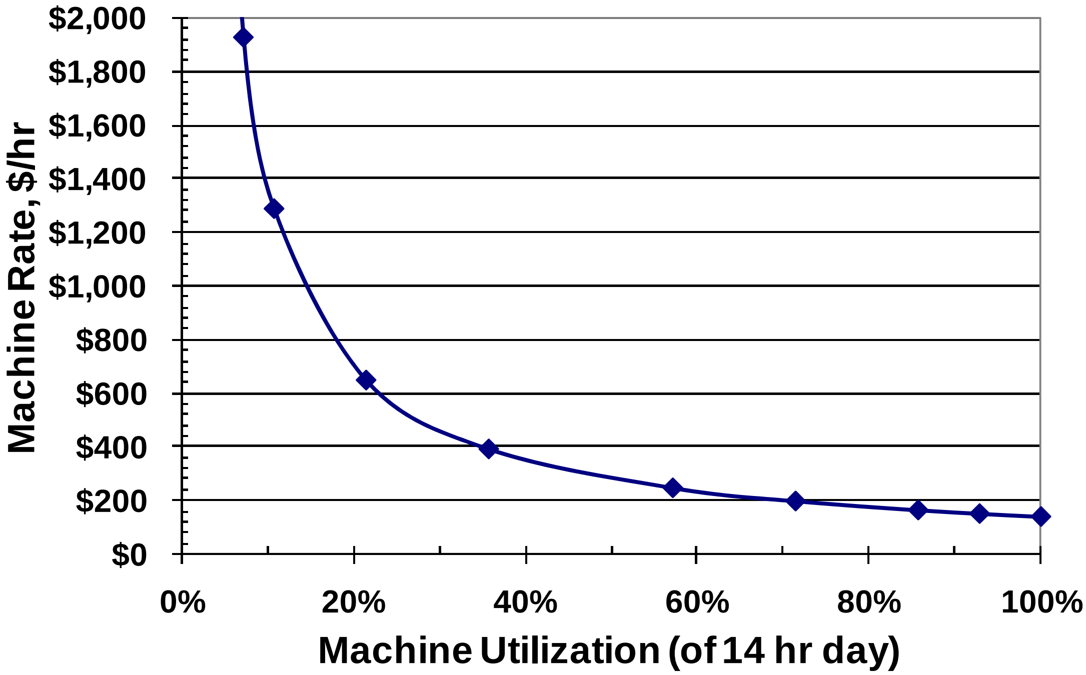

Figure 20. Machine rate vs. machine utilization

4.3. Markup Rates

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

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

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

	2007/ 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 Markup	30.00%	21.00%	20.00%	20.00%	19.00%
MEA Manufacturers Markup	70%	70%	60%	50%	35%
Auto Company Final Markup	37.00%	26.50%	23.50%	20%	15%

Figure 21 displays some representative markup rates for various situations. While the figure attempts to explain how and where markups were applied, there are many exceptions to the general rule. Different markup rates are used for different components because the type and quantity of work lend themselves to lower overhead costs. MEA manufacturing markups are expected to be 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[8] and not to the material cost.

	2007/ 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 Markup	30.00%	21.00%	20.00%	20.00%	19.00%
MEA Manufacturers Markup	70%	70%	60%	50%	35%
Auto Company Final Markup	37.00%	26.50%	23.50%	20%	15%

Figure 21. 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 22 displays an abridged view of the stack components, and Figure 23 shows a cross-sectional view of an assembled stack.

[8] 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.

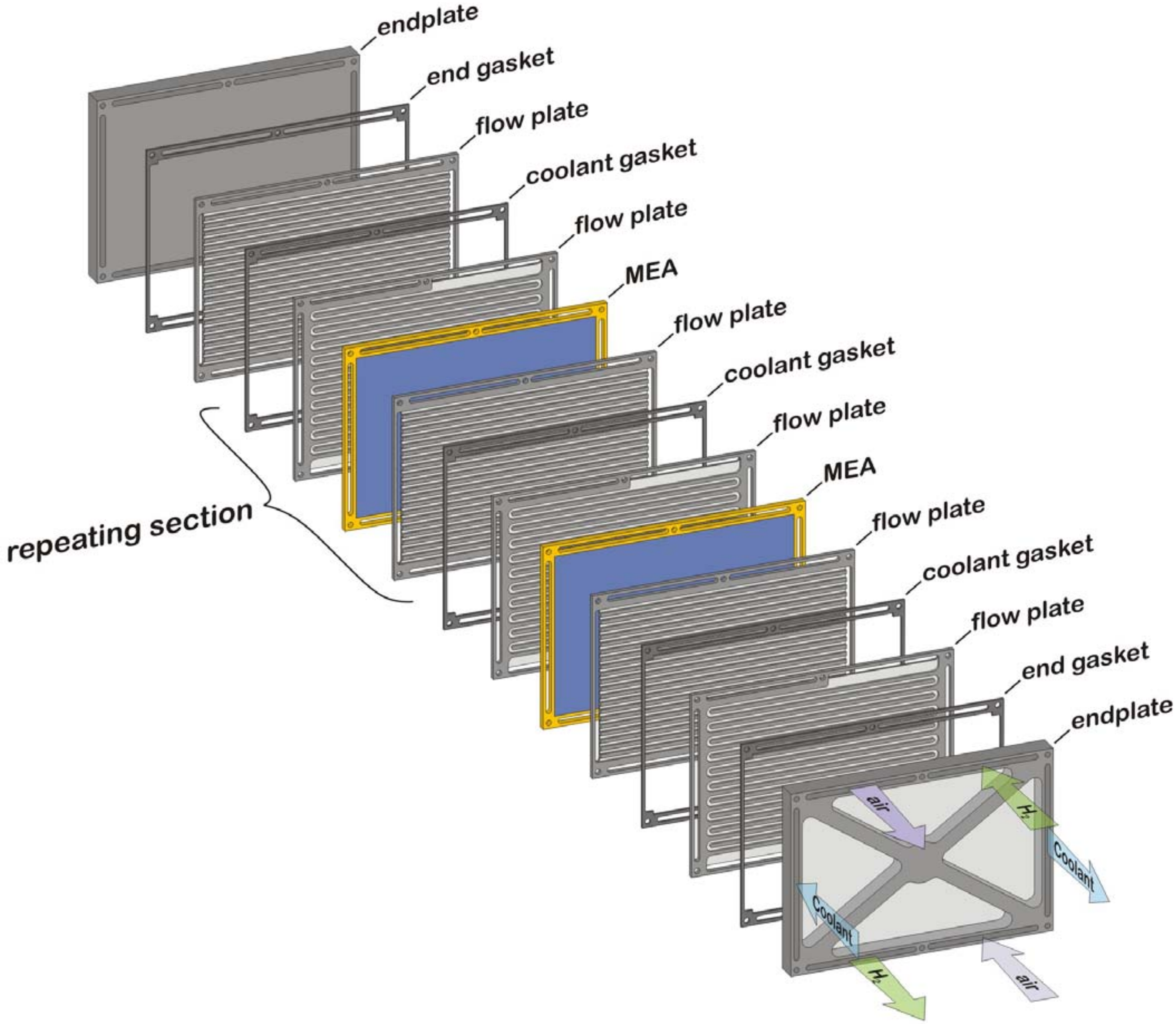

Figure 22. Exploded stack view (abridged to 2 cells for clarity)

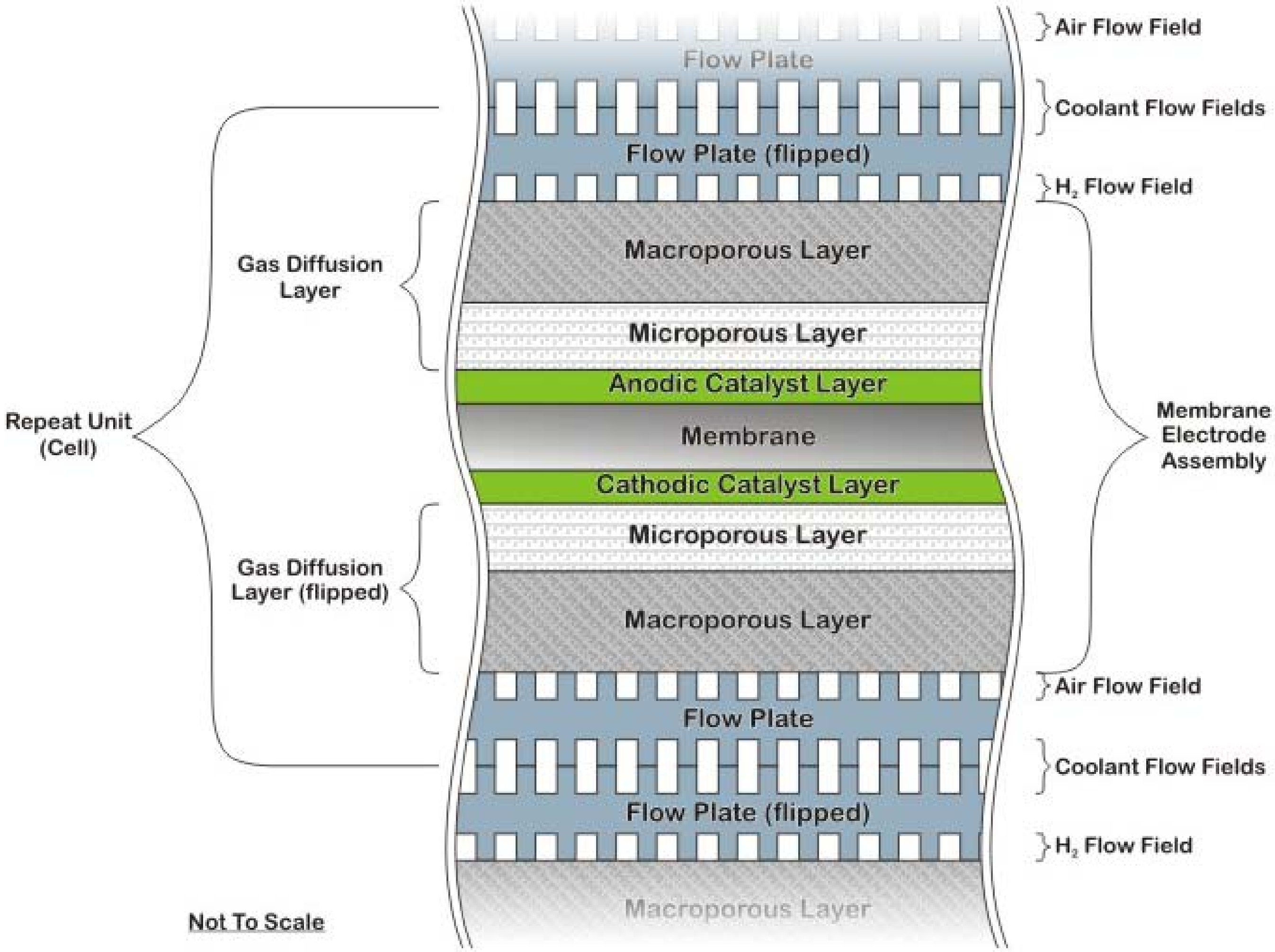

Figure 23. Stack cross-section

4.4.1. Bipolar Plates

Each stack in the system consists of 186 active cells, each of which contains 2 bipolar plates. We assume a 1:1 ratio of active cells to cooling cells 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, we envisioned the cathode and anode flow field sides of the bipolar plates to be identical flow patterns and symmetric. 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, we now assume unique designs for the anode and cathode plates. At each end of the stack, there is a plate that isn't part of the repeating cell unit, and 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. So the total number of plates in a stack is 374: 186 active cells * 2 plates per cell + 2 coolant-only plates. With 2 stacks per system, each system contains 748 bipolar plates, so even at the lowest production rate, there are hundreds of thousands of plates needed. This means that bipolar plate mass-manufacturing techniques remain appropriate across all production rates.

We have examined two different concepts for the bipolar plate: injection-molded carbon powder/polymer and stamped stainless steel. We assume equivalent polarization performance between the two designs. Consequently, the choice of bipolar plate material/construction is purely a cost decision with the stamped metal plates appearing to be the most promising, with costs ranging from $3.17/kW_{gross}$

(2015 technology, 500,000 systems/year) to $6.75/kW_{gross}$ (2007 technology, 1,000 systems/year), compared to $3.45/kW_{gross}$ and $6.32/kW_{gross}$ for the injection molded version.

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[9]. 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 24 and Figure 25.

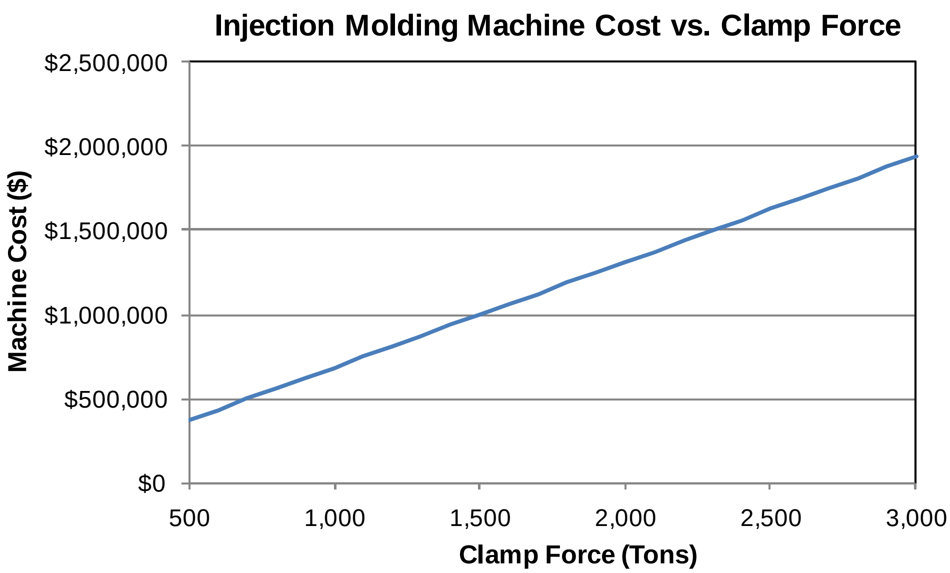

Figure 24. Injection molding machine cost vs. clamp force

[9] 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.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Capital Cost ($/Line)	$770,609	$2,187,483	$2,187,483	$2,187,483	$2,187,483
	Costs per Tooling Set ($)	$33,054	$71,320	$71,320	$71,320	$71,320
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	10	27	43	166
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	90.66%	99.22%	98.00%	99.99%	99.62%
	Cycle Time (s)	29.32	32.09	32.09	32.09	32.09
	Cavities/Platen	2	6	6	6	6
	Effective Total Machine Rate ($/hr)	$138.77	$329.13	$332.94	$326.79	$327.91
	Carbon Filler Cost ($/kg)	$6.35	$6.35	$6.35	$6.35	$6.35
2010	Capital Cost ($/Line)	$459,099	$1,649,881	$1,649,881	$1,649,881	$1,649,881
	Costs per Tooling Set ($)	$33,054	$87,230	$87,230	$87,230	$87,230
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	8	20	33	125
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	90.66%	93.02%	99.22%	97.72%	99.22%
	Cycle Time (s)	29.32	32.09	32.09	32.09	32.09
	Cavities/Platen	2	8	8	8	8
	Effective Total Machine Rate ($/hr)	$89.54	$267.71	$252.38	$255.92	$252.38
	Carbon Filler Cost ($/kg)	$6.35	$6.35	$6.35	$6.35	$6.35
2015	Capital Cost ($/Line)	$460,426	$1,655,189	$1,655,189	$1,655,189	$1,655,189
	Costs per Tooling Set ($)	$33,054	$87,230	$87,230	$87,230	$87,230
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	8	20	33	125
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	90.66%	93.02%	99.22%	97.72%	99.22%
	Cycle Time (s)	29.32	32.09	32.09	32.09	32.09
	Cavities/Platen	2	8	8	8	8
	Effective Total Machine Rate ($/hr)	$89.75	$268.51	$253.13	$256.68	$253.13
	Carbon Filler Cost ($/kg)	$6.35	$6.35	$6.35	$6.35	$6.35

Figure 25. Bipolar plate injection molding process parameters

As shown in Figure 27, costs are seen to vary between $3/kW and $6/kW and to be fairly level across manufacturing rate. Cost reduction for each of the advanced technology cases is due to higher power density leading to smaller plate area. Injection molding machine cost is the main contributor accounting for ~75% of bipolar plate cost. Materials and tooling contribute ~15% and ~10% respectively. Since polypropylene is very inexpensive, the electrically conductive carbon powder filler is the main contributor to material cost. We have assumed high purity carbon black as the conductive filler. Fuel cell manufacturers using polymer plates keep the exact proportions and material specifications as trade-secrets but may use a mix of multiple fillers, some possible very expensive. However, we have adopted a high fill fraction (40% by volume) and medium price ($6.35/kg, based on a quote for Vulcan XC-72) as a cost representative basis 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
2007/ 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%
	Fixed Charge Rate	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)	89	133	133	133	133

Figure 26. Machine rate parameters for bipolar plate injection molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Material ($/stack)	$53.10	$53.10	$53.10	$53.10	$53.10
	Manufacturing ($/stack)	$211.34	$182.88	$184.99	$181.57	$182.20
	Tooling ($/stack)	$20.93	$15.06	$15.24	$14.94	$15.00
	Total Cost ($/stack)	$285.37	$251.03	$253.34	$249.61	$250.29
	Total Cost ($/kW$_{gross}$)	$6.32	$5.56	$5.61	$5.53	$5.54
2010	Material ($/stack)	$30.77	$30.77	$30.77	$30.77	$30.77
	Manufacturing ($/stack)	$136.37	$111.56	$105.17	$106.65	$105.17
	Tooling ($/stack)	$20.93	$13.96	$13.81	$14.02	$13.81
	Total Cost ($/stack)	$188.08	$156.29	$149.76	$151.45	$149.76
	Total Cost ($/kW$_{gross}$)	$4.33	$3.60	$3.45	$3.49	$3.45
2015	Material ($/stack)	$30.87	$30.87	$30.87	$30.87	$30.87
	Manufacturing ($/stack)	$136.69	$111.89	$105.49	$106.96	$105.49
	Tooling ($/stack)	$20.93	$13.96	$13.81	$14.02	$13.81
	Total Cost ($/stack)	$188.50	$156.72	$150.17	$151.86	$150.17
	Total Cost ($/kW$_{gross}$)	$4.33	$3.60	$3.45	$3.49	$3.45

Figure 27. 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 that is suspected to be employed by General Motors for their fuel cell stacks[10]. Since approximately 800 plates are needed per system and multiple features are required on each plate (flow fields, manifolds, etc), progressive die stamping is the logical choice. In progressive die stamping, a coil of sheet metal is fed into a stamping press having a series of die stations, each one sequentially imparting one or more feature into the part as the coil advances. The parts move through the stationary die stations by indexing and a fully formed part emerges from the last station. Figure 28 displays a simplified drawing of progressive die operations.

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

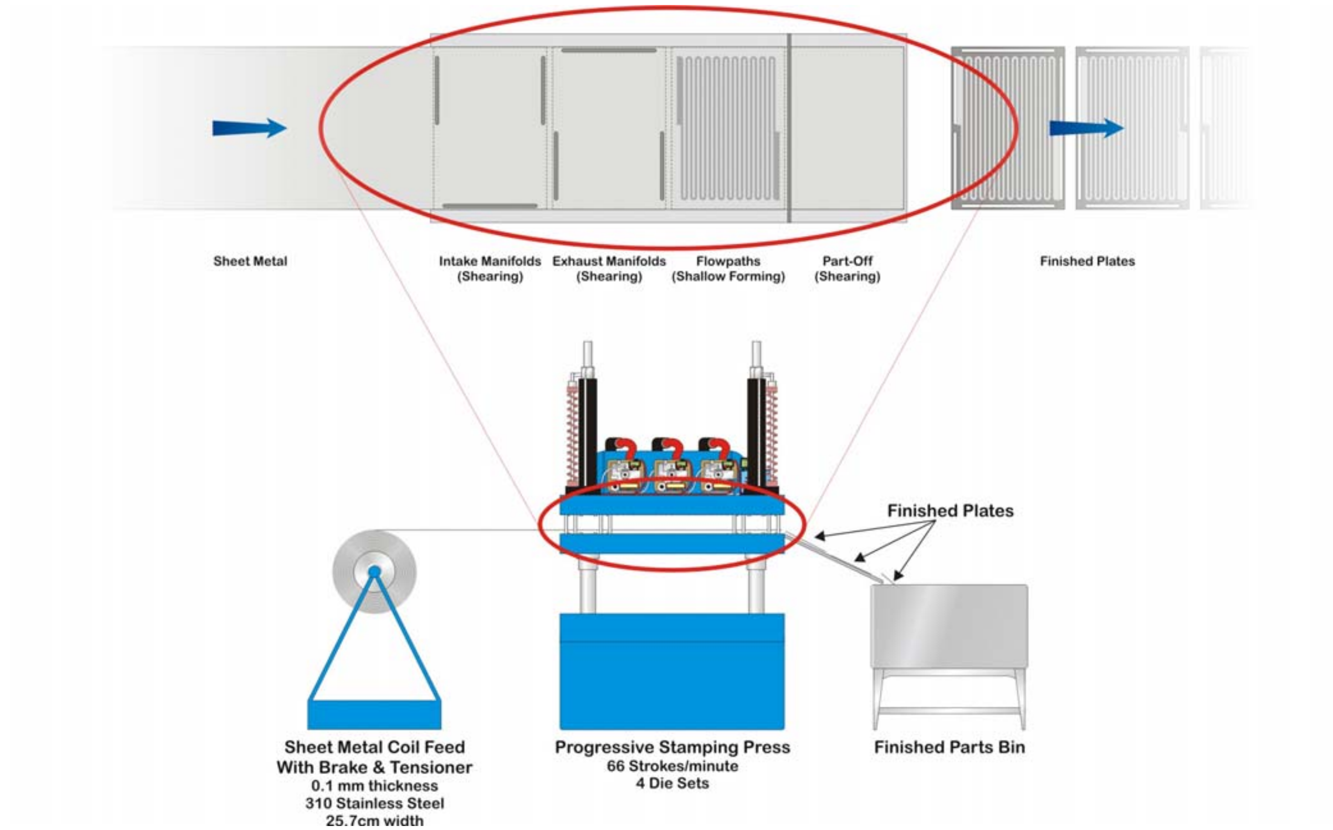

Figure 28. Bipolar plate stamping process diagram

Manufacturing Assumptions

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

Capital Cost and Press Tonnage: Clamping force is the primary sizing and pricing parameter of a metal forming press. For the 2006 cost report, we curve fit price quotes and performance data for AIRAM pneumatic presses ranging from 50 tons to 210 tons to yield approximate purchase cost as a function of press tonnage. We then added the cost of supporting equipment required for press operation to the base press cost. Some of the supporting equipment had a fixed cost regardless of press size, while other equipment scaled in cost. A sheet metal coil feeder was judged necessary and was costed largely independent of press size. To insure part accuracy, we added a sheet metal straightener[11], although it may prove to be ultimately unnecessary due to the thin material used (0.075mm). Typical capital costs used in the 2006 report are shown in Figure 29.

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

	2006 Report		2007 Update
Stamping Press	$56,979		
<u>Accesories</u>			
Air Compressor	$16,000		
ATC-10070 Control	$4,513		
Stand	$8,560		
Vibration Mounts	$1,210		
<u>Feeding Equipment</u>			
Reel	$6,110		
Loop Control	$2,030		
Servo Feed	$6,695		
Misc. Add-Ons	$1,000		
Total Capital Cost	**$103,098**	**× 5 =**	**$515,488**

Figure 29. Capital costs breakdown for a typical bipolar plate stamping production line

In the 2006 cost report we estimated that a 65 ton press[12] was necessary to produce the bipolar plates[13]. However, we noted disagreement in the bipolar plate stamping community regarding the necessary press tonnage to form the plates[14], 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, we have increased estimated capital cost five-fold (to $515,488 at 500,000 systems/year) 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, and future investigations will be made to more accurately assess required press tonnage and the corresponding capital costs.

Press Speed: The speed of the press (in strokes per minute) varies with press size (tons): a small press is capable of higher sustained operating speeds than a large press. Press speed was correlated to press size and is shown in Figure 30.

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

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

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

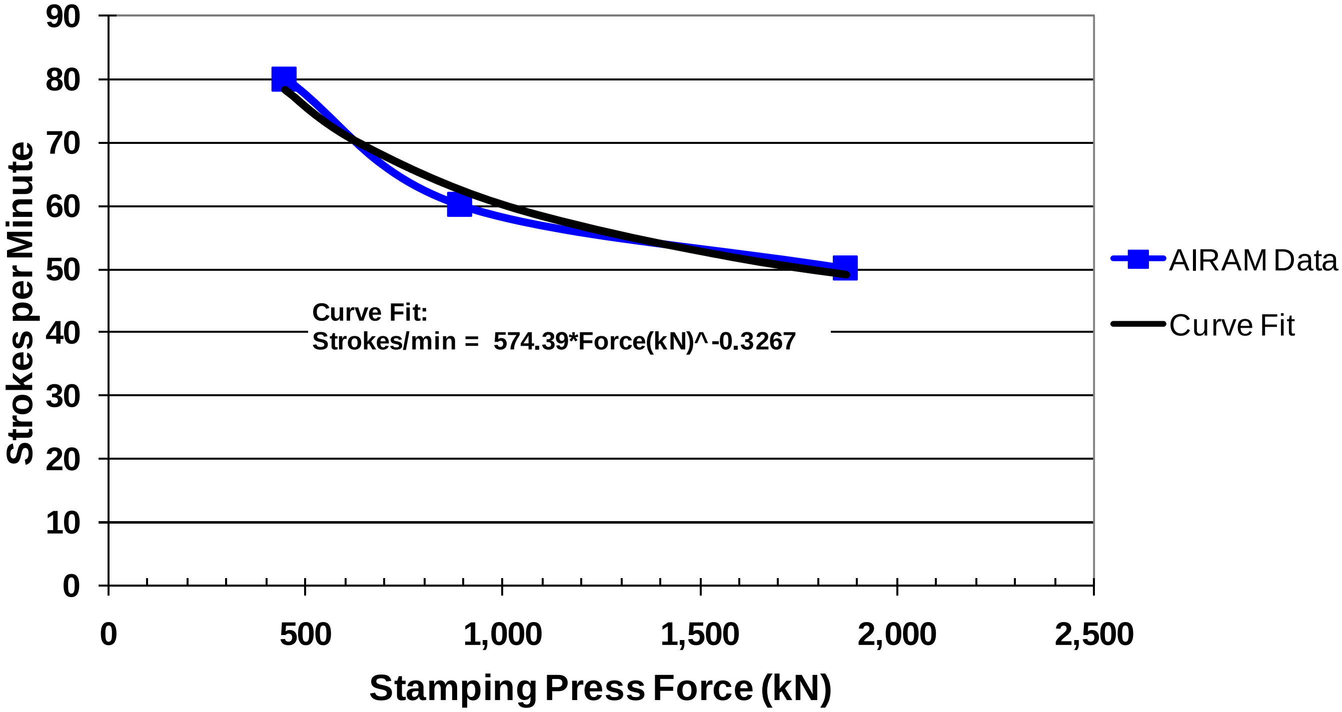

Figure 30. Press speed vs. press force

Maintenance: Given that a 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 is estimated at 10 million cycles[15] with a total replacement cost estimated at 20-25% of complete press initial capital cost[16] depending on machine size. Since the above cycle life is the minimum number of cycles but could be substantially more, we estimate maintenance cost of the press to be 15% of initial press capital cost every 10 million cycles. This deviates from our normal methodology which estimates maintenance costs as a percentage of initial capital per year rather than per cycle. Likewise, we estimate feeder equipment maintenance to be 5% of initial feeder capital cost every 10 million cycles[17].

Utilities: The principal power consumer in the progressive die process train is the air compressor for the pneumatic press and the coil feeder[18]. Compressor power is a function of the volumetric airflow (CFM) requirement of each press size and is estimated to vary between 19 kW at the low end (50 tons) to 30 kW at the high end (210 tons). Power consumption was curve fit to press size.

Machine Rate: Using the above information on total line capital cost, maintenance, and utilities, machine rates curves are able to be generated for various size presses at varying utilization. Basic input parameters are summarized in Figure 31 and Figure 32.

Die Cost: Die costing was estimated according to the equations outlined in the Boothroyd and Dewhurst section on sheet metal stamping. As expected, complex stamping operations require more intricate, and therefore more expensive, dies. The first two, and final, press steps are simple punching and sheering operations and therefore do not require expensive dies. The flow path forming step, with a

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

complex serpentine shape to be formed, requires a highly complex die that is significantly more expensive than the others in the process (this step also requires the majority of press force). The die cost figures can be seen below in Figure 33 (listed as "Tooling").

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, we estimate that dies for progressive bipolar plate stampings may last between 400,000 and 600,000 cycles before refurbishment, and may be refurbished 2 to 3 times before replacement. Thus we have specified a die lifetime of 1.8 million cycles (3 x 600,000) and a die cost of $277,274 ($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
2007/ 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%
	Fixed Charge Rate	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)	21	21	21	21	21

Figure 31. Machine rate parameters for bipolar plate stamping process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Capital Cost ($/Line)	$515,488	$515,488	$515,488	$515,488	$515,488
	Costs per Tooling Set ($)	$277,274	$277,274	$277,274	$277,274	$277,274
	Tooling Lifetime (cycles)	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
	Simultaneous Lines	1	4	9	14	53
	Laborers per Line	0.85	0.85	0.85	0.85	0.85
	Line Utilization	10.54%	79.05%	93.69%	97.87%	99.43%
	Cycle Time (s)	0.00	0.00	0.00	0.00	0.00
	Effective Total Machine Rate ($/hr)	$590.63	$93.02	$81.06	$78.29	$77.32
	Stainless Steel Cost ($/kg)	$8.00	$8.00	$8.00	$8.00	$8.00
2010	Capital Cost ($/Line)	$474,451	$474,451	$474,451	$474,451	$474,451
	Costs per Tooling Set ($)	$242,547	$242,547	$242,547	$242,547	$242,547
	Tooling Lifetime (cycles)	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
	Simultaneous Lines	1	3	8	12	45
	Laborers per Line	0.80	0.80	0.80	0.80	0.80
	Line Utilization	8.92%	89.23%	89.23%	96.66%	99.14%
	Cycle Time (s)	0.00	0.00	0.00	0.00	0.00
	Effective Total Machine Rate ($/hr)	$640.64	$78.82	$78.82	$74.01	$72.57
	Stainless Steel Cost ($/kg)	$8.00	$8.00	$8.00	$8.00	$8.00
2015	Capital Cost ($/Line)	$474,698	$474,698	$474,698	$474,698	$474,698
	Costs per Tooling Set ($)	$242,717	$242,717	$242,717	$242,717	$242,717
	Tooling Lifetime (cycles)	1,800,000	1,800,000	1,800,000	1,800,000	1,800,000
	Simultaneous Lines	1	3	8	12	45
	Laborers per Line	0.80	0.80	0.80	0.80	0.80
	Line Utilization	8.93%	89.33%	89.33%	96.78%	99.26%
	Cycle Time (s)	0.00	0.00	0.00	0.00	0.00
	Effective Total Machine Rate ($/hr)	$640.32	$78.78	$78.78	$73.98	$72.54
	Stainless Steel Cost ($/kg)	$8.00	$8.00	$8.00	$8.00	$8.00

Figure 32. Bipolar plate stamping process parameters

Alloy Selection and Corrosion Concerns

The baseline design specifies uncoated 0.075mm stainless steel 310 alloy metallic bipolar plates. There is much uncertainty in the fuel cell community as to which alloy and surface treatments are needed to provide adequate corrosion resistance. Literature and patent reviews and conversations with researchers indicate that coatings/surface treatments are not needed and an alloy 310 (or other commercial alloy of similar cost) is appropriate. We base this on two primary data sources.

Published in 2000, Davies[19] and fellow researchers at Loughborough University, UK, fabricated and tested bipolar plates of three uncoated stainless steel alloys[20] (904L, 310, and 316). Contact resistance testing and multi-thousand hour endurance tests in a functioning cell were conducted. They concluded that 904L performs better than 310, which performs better than 316, 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[21] 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[22] et al at the Netherlands Energy Research Foundation have also done comparative corrosion and performance testing of metallic bipolar plates. They examined seven alloys[23] (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[24] indicates that alloy B is a commercial available, high chromium alloy (containing some Molybdenum). Additionally, the recommended "adjusted pre-treatment" is a small modification of the standard pickling[25] process wherein the acid pickling solution is heated to a temperature above 50°C.

In spite of strong evidence supporting the conclusion that bipolar plate coatings are not necessary when using 310 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. In the absence of a definitive answer, we briefly examined the potential cost of applying protective coatings should they prove necessary. However, the cost of such coatings are not including in the baseline cost estimates.

There are a variety of surface treatments under investigation to provide bipolar plate corrosion resistance including:

[19] 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.

[20] 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.

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

[22] 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.

[23] A coated plated was also partially tested. However, only initial performance results, as opposed to performance after 3000 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.

[24] Private communication, Robert Makkus, April 2007.

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

1. **Nitriding:** surface diffusion of nitrogen into steel surface typically via nitrogen or ammonia at ~550°C to form AlN
2. **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
3. **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
4. **Pickling:** treatment of the bipolar plate surface with an acid mixture (typically hydrochloric and sulfuric) to order to remove impurities (rust, scale, etc.)

There are a large number of non-corrosive, highly conductive materials that are well suited to be used as coatings for stainless steel bipolar plates[26]. Gold is often considered to be one of the most effective; however its cost is prohibitive. Alternately, Fonk[27] from GM states that "most preferably, the [coating] particles will comprise carbon or graphite (i.e. hexagonally crystallized carbon)."

We made no quantitative judgment as to the fuel cell performance of one surface treatment method over another. However, from a general perspective, the most important aspects are application speed and ability to deliver a thin coating of reliable thickness with sufficient surface smoothness to uniformly cover the plate surface. Methods such as ion-beam assisted physical vapor deposition[28] are able to achieve excellent uniformity and low layer thickness (10 nanometer layer of gold with near perfect flatness) but are capital intensive and suffer from slow application speed if relatively thick layers proven necessary. Consequently, we have conducted a brief cost analysis of two surface treatment options (electroplating and magnetron sputtering (titanium nitriding)) to assess their potential cost impact should additional bipolar plate corrosion resistance be required.

Through conversations with industry, we estimate an electroplating cost of approximately $1.50/kW, (or 2.5 cents per 100 cm^2 of surface area), plus material costs. Electroplating provides a consistently reliable coating to a minimum thickness of 0.5 mils (0.00127 cm). Assuming this minimum coating thickness, only 1.1cm^3 of coating material is needed per plate. Consequently, material cost can rise to $30-54/kg before it adds $1/kW to stack cost. If carbon power is used as the coating material, total material and application cost is estimated at under $1.75/kW.

Alternately, we have conducted a preliminary analysis of aluminum plates with a titanium nitride surface treatment via magnetron sputtering. A 1997 patent to GM states that a preferred embodiment is an aluminum bipolar plate (6061-T6), coated with a 10 micron layer of stainless steel (Al-6XN), 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 20 minutes of sputtering time[29]. Since the patent is 10 years old, we have postulated a shorter deposition time consistent with thinner layers (or a single layer). Our preliminary analysis[30] indicates a total bipolar plate cost of $5-11/kW$_{gross}$ for production rates of 30,000 to 500,000 systems per year. (Analysis at the 1,000 systems per year rate was

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[26] "Gold, platinum, graphite, carbon, nickel, conductive metal borides, nitrides and carbides (e.g. titanium nitride, titanium carbide, 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)

[27] US Patent #6,372,376 titled "Corrosion resistant PEM fuel cell" issued to General Motors Corp.

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

[29] 20 minutes is only a rough estimate. A detailed analysis would have to be conducted to determine the exact duration and system configuration.

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

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 2 minutes to 10 minutes). Overall, titanium nitrided aluminum stamped plates represents a potential $2/kW to $8/kW cost adder compared to uncoated stainless steel stamped plates.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Material ($/stack)	$135.49	$135.49	$135.49	$135.49	$135.49
	Manufacturing ($/stack)	$104.61	$16.47	$14.35	$13.86	$13.69
	Tooling ($/stack)	$64.70	$57.92	$58.23	$58.73	$57.80
	Total Cost ($/stack)	$304.79	$209.88	$208.07	$208.08	$206.98
	Total Cost ($/kW$_{gross}$)	$6.75	$4.65	$4.61	$4.61	$4.58
2010	Material ($/stack)	$75.91	$75.91	$75.91	$75.91	$75.91
	Manufacturing ($/stack)	$96.05	$11.81	$11.81	$11.09	$10.88
	Tooling ($/stack)	$56.59	$50.93	$50.93	$50.75	$50.93
	Total Cost ($/stack)	$228.56	$138.66	$138.66	$137.76	$137.73
	Total Cost ($/kW$_{gross}$)	$5.27	$3.19	$3.19	$3.17	$3.17
2015	Material ($/stack)	$76.17	$76.17	$76.17	$76.17	$76.17
	Manufacturing ($/stack)	$96.10	$11.82	$11.82	$11.10	$10.89
	Tooling ($/stack)	$56.63	$50.97	$50.97	$50.78	$50.97
	Total Cost ($/stack)	$228.90	$138.96	$138.96	$138.05	$138.02
	Total Cost ($/kW$_{gross}$)	$5.26	$3.19	$3.19	$3.17	$3.17

Figure 33. Cost breakdown for stamped bipolar plates

4.4.2. Membrane Materials

4.4.2.1. Selection of 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[31], including partially fluorinated (PVDF) and non-fluorinated (BAM3G, S-PPBP, MBS-PBI, MBS-PPTA, S-PEK). Additionally, membranes may be homogenous, composites[32], or placed on a substrate for mechanical reinforcement.

For purposes of this study, we have selected Nafion® on a porous expanded polytetrafluoroethylene[33] (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, we have selected the Gore-like approach since it theoretically should supply substantially better mechanical properties and thus is 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 in our judgment roll-to-roll processing offers 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 34.

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

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

[33] 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	0.10 g/cc
Membrane Thickness	25.4 microns
Nafion Density	1.98 g/cc

Figure 34. 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 impacts overall membrane cost even though the membrane is very thin[34]. Based on vendor quotes of Nafion®, quotes for products similar to Nafion®, and on discussion with industry experts, we projected that Nafion® ionomer costs would drop by roughly 95% from low to high production (~$2000/kg to $92/kg). Figure 35 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[35] associated with the roll-to-roll manufacturing process which directly affect the membrane material costs. We apply the same yield rates to the materials as are applied to the manufacturing process (50-80% depending on production rate) but further assume that a portion of ionomer in the scrap membrane is able to be recycled. Consequently, for costing purposes we assume the ionomer material wastage rate is half that of the overall membrane areal scrap rate.

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

[35] 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.

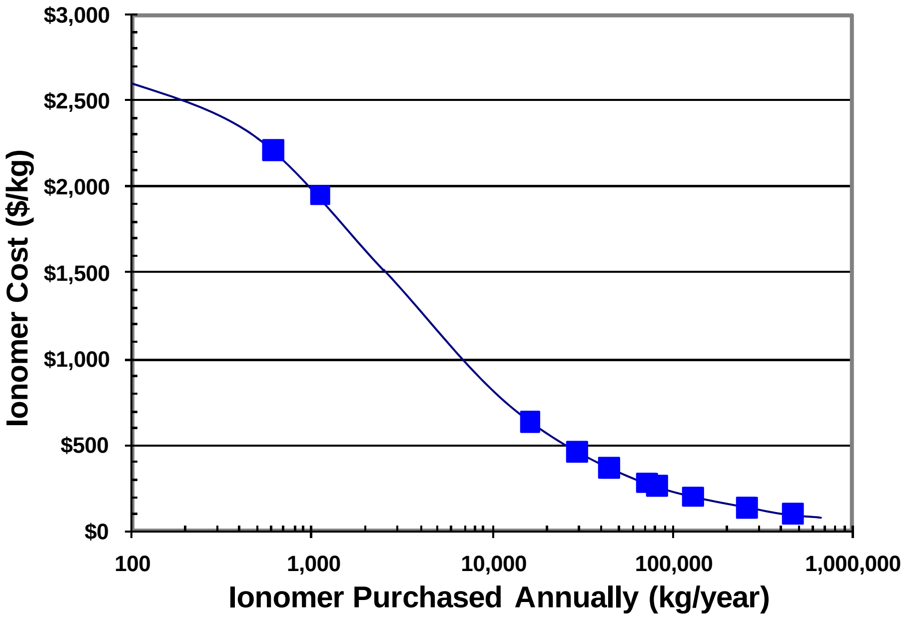

Figure 35. Ionomer material cost

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[36] the cost of a Gore-like[37] PEM membrane of 90%-by-volume Nafion® ionomer in an expanded-polytetrafluoroethylene (ePTFE) matrix. Multiple generation 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[38]. Processing parameter were modified and capital costs of the web processing equipment was estimated by vendor quotes from USWebcon. Multiple variants on the process train were considered including alteration of the starting ionomer form to eliminate the boiling water hydration step, multiple passes on the occlusion/dipping step to ensure pin-hole free coverage, and multiple rewind stations to reduce the continuous length of the process train.

[36] 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.

[37] 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.

[38] 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.

In 2005, DTI again refined the membrane fabrication process[39] 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[40] from 10 years to 5 years.
- Plan for significant plant underutilization[41] (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 2007 cost analysis is based strongly on the 2005 assessment. As schematically detailed in Figure 36, the membrane fabrication process consists of 8 main steps:

1. **Unwinding:** An unwind stand with tensioners to feed the previously procured ePTFE substrate into the process line. Web width is selected as the optimal width to match an integer number of cells and thereby minimize waste. A web width of ~ 1m is deemed feasible for both the membrane fabrication line and the subsequent catalyzation and MEA hot-pressing lines.
2. **First Ionomer Bath:** The ePTFE substrate is dipped into an ionomer/solvent bath to partially occlude the pores.
3. **First Infra-red Oven Drying:** The web is drying via infra-red ovens. A drying time of 30 seconds is 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, pin-hole free membrane.
5. **Second Infra-red Oven Drying:** The web is drying after the second ionomer bath.
6. **Boiling Water Hydration:** The web is held in boiling water for 5 minutes to fully hydrate the ionomer. Optimal selection of the ionomer may reduce or eliminate this boiling step.
7. **Air Dryer:** High velocity air is used to dry the web after the hydration step.
8. **Rewind:** The finished membrane is wound onto a spool for transport to the catalyzation process line.

[39] 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.

[40] 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.

[41] 67% capacity is based on 5-year average utilization of a plant with 25% annual production increases. 81% capacity is based on a 10-year average utilization of a plant with 5% annual production increases.

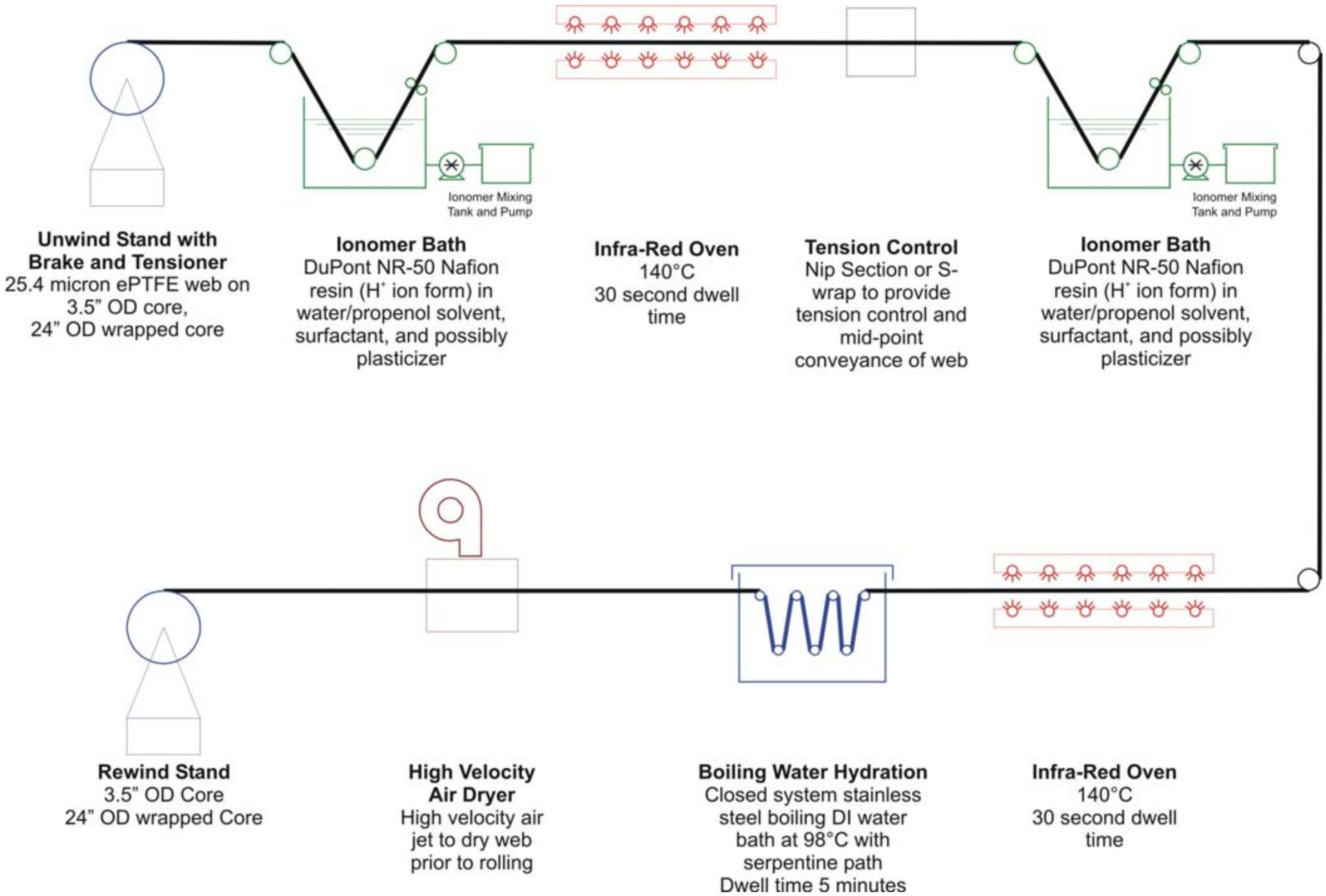

Figure 36. Membrane fabrication process diagram

Details of the membrane fabrication cost analysis are shown in Figure 37. 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[42]. This is a nod toward cost conservativeness and a reflection that the upper bound of membrane web speed is not known at this time.

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

Production for Simultaneous Product Lines: In virtually all other components of the fuel cell stack system, we have assumed vertical integration and dedicated component production for a single vehicle product. However for the membrane, it is likely that a separate company will fabricate the membrane for

[42] Several factors influence web speed selection: the inherent mechanical strength of the web as it endures high speed processing, the complexity/number-of-turns in a particular element to allow adequate dwell time when moving at high speed (if the web requires 30 seconds to dry, then the drying section must be 300 m long if moving at 100 m/min (0.5 min x 100 m/min)), and the web material losses if something should break or not perform adequately (many meters of web product are lost during a shut-down because of the inertial of the rollers).

multiple car companies or, at least, that the membrane plant will produce membrane for more than one line of vehicles. Consequently, we have included a multiplier on the yearly membrane demand 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: Conversations with a membrane supplier led us to limit the utilization of the plant as a means of reflecting rapid demand growth. Utilization (at most manufacturing rates) is limited to 67% to reflect the 5 year average utilization assuming 25%/year demand growth. For the 500,000 vehicles/year case, plant utilization is allowed to increase to 80% to reflect a more stable production scenario.

Production/Cutting Yield: Conversations with a membrane supplier led us to postulate a substantial loss rate in membrane production. Per supplier input, we assume a 50% yield up to 25% plant utilization, an 80% yield above 80% utilization, and a linear variance in between.

Work Days and Hours: We assume the maximum plant operating hours are 20 hours per day, 240 days per year. Actual hours vary based on actual plant utilization.

Cost Markup: The standard methodology throughout the analysis has 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 we deviate from the norm and include a markup in our membrane cost estimate. Furthermore, because the membrane is a critical component of the stack, we allocate significantly higher margins 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 into the analysis. Rather it is an output. However, it is worth noting that even at high membrane production rates, company revenues are still only ~$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.

		2007/ 2010/ 2015				
Annual Veh Prod. (1 product line)	**veh/year**	**1,000**	**30,000**	**80,000**	**130,000**	**500,000**
Capital Amortization						
Capital Cost (Membrane Fabrication)	**$**	**$15,000,000**	**$15,000,000**	**$25,000,000**	**$25,000,000**	**$30,000,000**
Machine Lifetime	**years**	**10**	**10**	**10**	**10**	**10**
Discount Rate	**%**	**20%**	**20%**	**20%**	**20%**	**20%**
Corporate Income Tax Rate	**%**	**40%**	**40%**	**40%**	**40%**	**40%**
Capital Recovery Factor (CRF)		0.331	0.331	0.331	0.331	0.331
Labor Costs						
Min. Mfg. Labor Staff (Simul. on 1 Shift)	**FTE**	**5**	**25**	**50**	**50**	**50**
Labor Rate	**$/min**	**1**	**1**	**1**	**1**	**1**
Machine Costs						
Maint./Spare Parts (% of inst. C.C./year)	**%**	**5%**	**5%**	**5%**	**5%**	**5%**
Miscellaneous Expenses	**%**	**5%**	**5%**	**5%**	**5%**	**5%**
Total Power Consumption	**kW**	**200**	**250**	**350**	**350**	**350**
Electrical Utility Cost	**$/kWh**	**0.07**	**0.07**	**0.07**	**0.07**	**0.07**
Membrane Production Parameters						
Simul. Prod. Lines to Which Mem. is Supplied		**4.5**	**1.5**	**3**	**2.15**	**1**
Vehicle Annual Production	**veh/year**	4,500	45,000	240,000	279,500	500,000
m^2 per Vehicle	**m^2/vehicle**	**13.95**	**13.95**	**13.95**	**13.95**	**13.95**
Peak Equipment Utilization Due to Growth	**%**	**67%**	**67%**	**67%**	**67%**	**80%**
Production/Cutting Yield	**%**	**50%**	**70%**	**64%**	**67%**	**80%**
Prod/Cutting Yield (to avoid circular logic)	**%**	50%	70%	65%	68%	80%
Gross Production @ 100% Utilization (plant)	**m^2/year**	187,388	1,338,486	7,807,836	8,685,732	10,898,438
Gross Production (plant)	**m^2/year**	125,550	896,786	5,231,250	5,819,440	8,718,750
Net Production (plant)	**m^2/year**	62,775	627,750	3,348,000	3,899,025	6,975,000
Net Production of 1 Line	**m^2/year**	13,950	418,500	1,116,000	1,813,500	6,975,000
Design Web Speed	**m/min**	**5**	**5**	**35**	**35**	**35**
Web Width	**m**	**1**	**1**	**1**	**1**	**1**
Work Days per Year	**days/year**	**240**	**240**	**240**	**240**	**240**
Plant Utilization (of 20 hr days)	**%**	8.7%	62.3%	51.9%	57.7%	86.5%
Hours per Year of Production	**hrs/year**	419	2,989	2,491	2,771	4,152
Hours per Day of Production	**hrs/day**	1.74	12.46	10.38	11.55	17.30
Annual Cost Summation						
Capital Recovery Cost	**$/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

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

Figure 37. Simplified membrane manufacturing cost analysis assumptions

Membrane manufacturing cost is plotted against membrane annual volume in Figure 38 below. Membrane material cost is not included. Note that annual membrane volume has two potential definitions depending on whether a single product line or multiple product lines are assumed. When all membrane production goes toward a single product line, membrane volume is total production volume. When multiple product lines are assumed, membrane volume represents annual sales volume (to a single customer). Thus in essence, the cost curve is shifted to the left due to economies of scale made possible by pooling multiple demands. The cost curve is seen to be uneven due to this effect. To aid in numerical calculation, we have fit a power curve fit to each relationship and utilize the less expensive, multiple product line curve in subsequent power system cost computations.

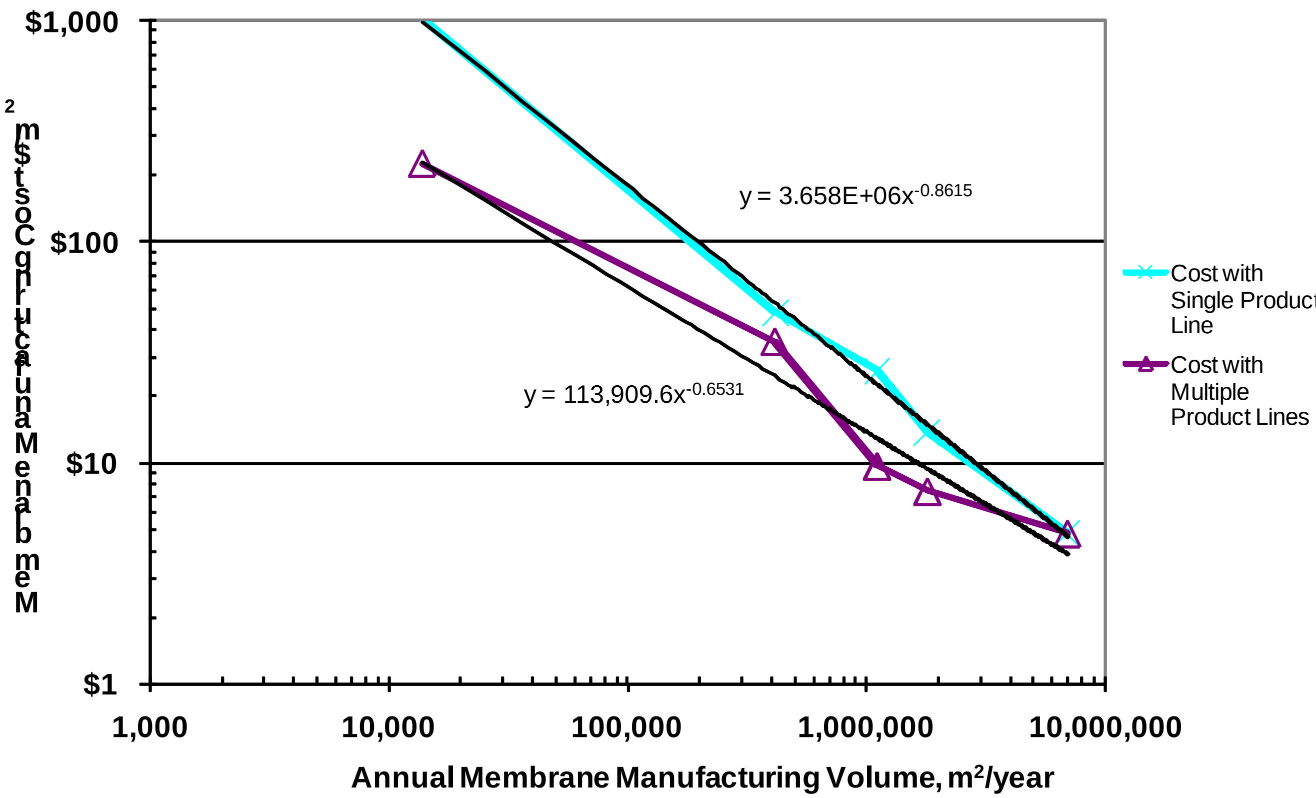

Figure 38. Membrane manufacturing cost vs. annual membrane manufacturing volume

4.4.2.4. Total Membrane Cost and Comparison to Other Estimates

Total membrane cost used in this study is shown in Figure 39 below along with 2005 membrane estimates[43] from DuPont and GM. The DuPont and GM estimates are for 25 micron thick, homogeneous PFSA membranes whereas the DTI estimates are 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 representing two distinctly different fabrication methods using the same ionic material. Figure 40 details the material and manufacturing costs of the uncatalyzed membrane. Note that unlike most elements in the cost analysis, membrane manufacturer markup has been added to the membrane cost as the membrane is likely to be produced by an outside vendor rather than made in-house by the fuel cell fabricator.

[43] "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.

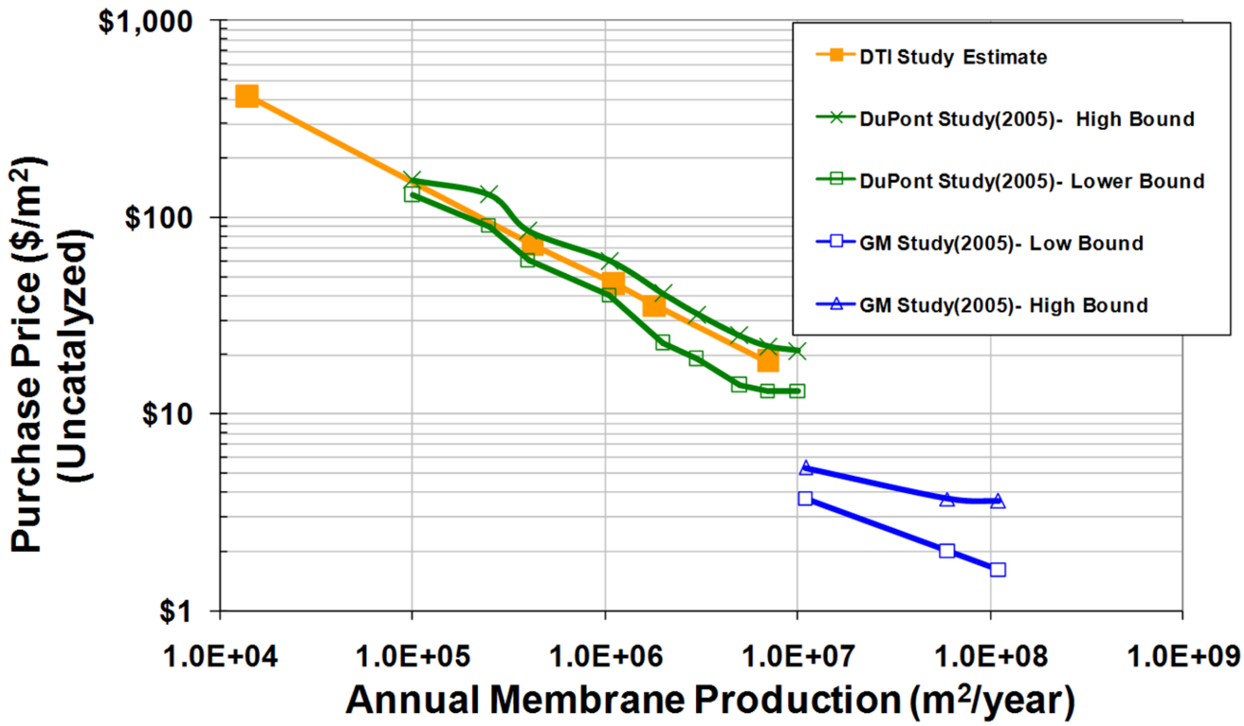

Figure 39. Membrane (material + manufacturing) cost, compared to previous analysis and vendor quotes

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Material ($/m²)	$167.43	$40.71	$27.77	$22.59	$13.23
	Manufacturing ($/m²)	$196.65	$21.33	$11.24	$8.19	$3.40
	Total Cost ($/m²)	$364.08	$62.04	$39.01	$30.77	$16.62
	Total Cost ($/stack)	$3,094.17	$527.23	$331.53	$261.53	$141.27
	Total Cost ($/kW$_{gross}$)	$68.50	$11.67	$7.34	$5.79	$3.13
2010	Material ($/m²)	$188.15	$53.10	$35.21	$28.17	$15.66
	Manufacturing ($/m²)	$289.61	$31.41	$16.55	$12.06	$5.00
	Total Cost ($/m²)	$477.76	$84.51	$51.76	$40.23	$20.66
	Total Cost ($/stack)	$2,244.65	$397.05	$243.18	$188.99	$97.06
	Total Cost ($/kW$_{gross}$)	$51.71	$9.15	$5.60	$4.35	$2.24
2015	Material ($/m²)	$188.33	$53.27	$35.30	$28.25	$15.69
	Manufacturing ($/m²)	$288.99	$31.35	$16.52	$12.03	$4.99
	Total Cost ($/m²)	$477.32	$84.61	$51.82	$40.28	$20.69
	Total Cost ($/stack)	$2,249.97	$398.84	$244.28	$189.85	$97.51
	Total Cost ($/kW$_{gross}$)	$51.66	$9.16	$5.61	$4.36	$2.24

Figure 40. Cost breakdown for un-catalyzed membrane

4.4.1. Catalyst Ink

The catalyst layer is formed by applying a catalyst ink to the membrane as described in the next section. The catalyst ink is based on a slurry of platinum, Vulcan XC-72 carbon powder, and 5% wt ionomer solution, with an aqueous methanol solution for a solvent. The platinum is dispersed on the carbon powder via a chloroplatinic acid (CPA) precipitation method[44]. The overall catalyst ink preparation process is described in Figure 41.

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

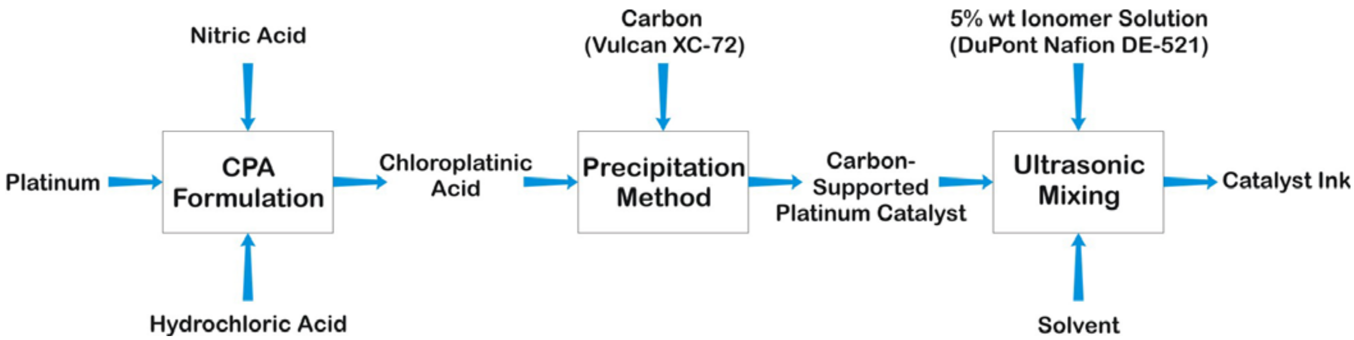

Figure 41. Catalyst ink preparation

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

$$\mathbf{Pt + 4\,HNO_3 + 6\,HCl \rightarrow H_2PtCl_6 + 4\,NO_2 + 4\,H_2O}$$

The CPA (H_2PtCl_6) is brownish-red, and is isolated by evaporating the solution to a syrup. It is then precipitated onto the carbon powder such that the mass ratio[45] is 60% carbon, 40% Pt.

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

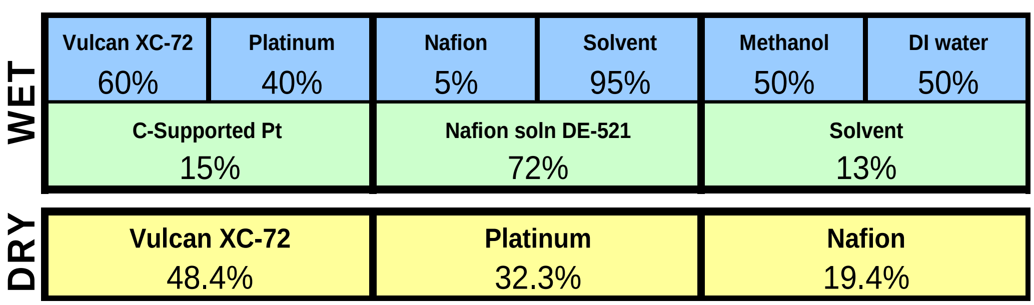

Figure 42. Catalyst ink composition

Figure 42 details the composition of the catalyst ink as specified in US Patent 7,141,270 to Umicore. After combining the ingredients, the slurry is mixed with an ultrasonic processor, which homogenizes the ink so it coats smoothly and evenly across the membrane. When the catalyst ink is dry, the solvent is assumed to have dissolved completely, leaving a coating that's 19.4% Nafion®, 32.3% Platinum, and 48.4% Vulcan XC-72.

The raw material cost of platinum is the major cost element of the catalyst ink. At the direction of the DOE, we used a platinum cost of $1,100 per troy ounce for consistency with other DOE projects. However, this number is somewhat outdated, and in recent months (the last 6 weeks particular), the

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

platinum cost has skyrocketed dramatically. Recently, platinum has been trading at roughly double that amount, hitting a peak of $2,280/tr.oz. in March of 2008.[46] While this may represent an anomalous spike in the market, careful consideration should be paid to this, as it will dramatically affect the system cost[47]. Assumptions and catalyst ink costs are summarized in Figure 43 and Figure 44.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 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%
	Fixed Charge Rate	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)	2	2	2	2	2

Figure 43. Machine rate parameters for ultrasonic mixing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Platinum ($/stack)	$1,051.95	$1,051.95	$1,051.95	$1,051.95	$1,051.95
	Other Material ($/stack)	$35.02	$8.37	$4.82	$3.74	$1.93
	Manufacturing ($/stack)	$142.30	$80.08	$76.06	$75.34	$62.19
	Total Cost ($/stack)	$1,229.26	$1,140.39	$1,132.82	$1,131.03	$1,116.07
	Total Cost ($/$kW_{gross}$)	$27.21	$25.25	$25.08	$25.04	$24.71
2010	Platinum ($/stack)	$498.47	$498.47	$498.47	$498.47	$498.47
	Other Material ($/stack)	$18.79	$5.46	$3.16	$2.45	$1.24
	Manufacturing ($/stack)	$70.34	$38.04	$36.08	$35.72	$29.47
	Total Cost ($/stack)	$587.60	$541.97	$537.71	$536.64	$529.18
	Total Cost ($/$kW_{gross}$)	$13.54	$12.49	$12.39	$12.36	$12.19
2015	Platinum ($/stack)	$333.41	$333.41	$333.41	$333.41	$333.41
	Other Material ($/stack)	$12.58	$3.66	$2.12	$1.64	$0.83
	Manufacturing ($/stack)	$48.88	$25.51	$24.15	$23.91	$19.72
	Total Cost ($/stack)	$394.87	$362.58	$359.68	$358.96	$353.96
	Total Cost ($/$kW_{gross}$)	$9.07	$8.32	$8.26	$8.24	$8.13

Figure 44. Catalyst ink cost summary

4.4.2. Catalyst Application

Approximately 60% of the fuel cell community applies catalyst ink to the GDL rather than directly to the membrane[48]. However, both are valid approaches and we chose to coat the membrane as this allows simultaneous application of both the anode and cathode layers, simplifying the overall process and reducing cost.

The anode and cathode each have different catalyst loadings for each technology level (0.1, 0.09, and 0.04 mg/cm^2 for the anode, and 0.25, 0.21, and 0.16 mg/cm^2 for the cathode). The ink formula (see section 4.4.1) is identical for both sides, which simplifies the ink preparation process, but a thicker catalyst layer is applied on the cathode side to achieve a higher platinum loading[49].

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

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

[48] Personal communication with Thomas Kolbusch of Coatema Coating Machinery GmbH, September 2006.

[49] Alternately, separate anode and cathode catalyst ink formulations could be prepared differing in C/Pt ratio so that catalyst layer thickness could be independently controlled. Such an approach would not add substantially to cost.

In order to simultaneously apply catalyst to both sides, we selected a vertical coating process. The machine (modeled here as the Coatema VertiCoater, see Figure 45) employs dual die slot coaters[50] on either side of the vertically moving membrane. The unit contains an integrated drying zone, as well as spool management for tension control. The feedstocks are rolls of uncatalyzed membrane, and platinum catalyst ink.

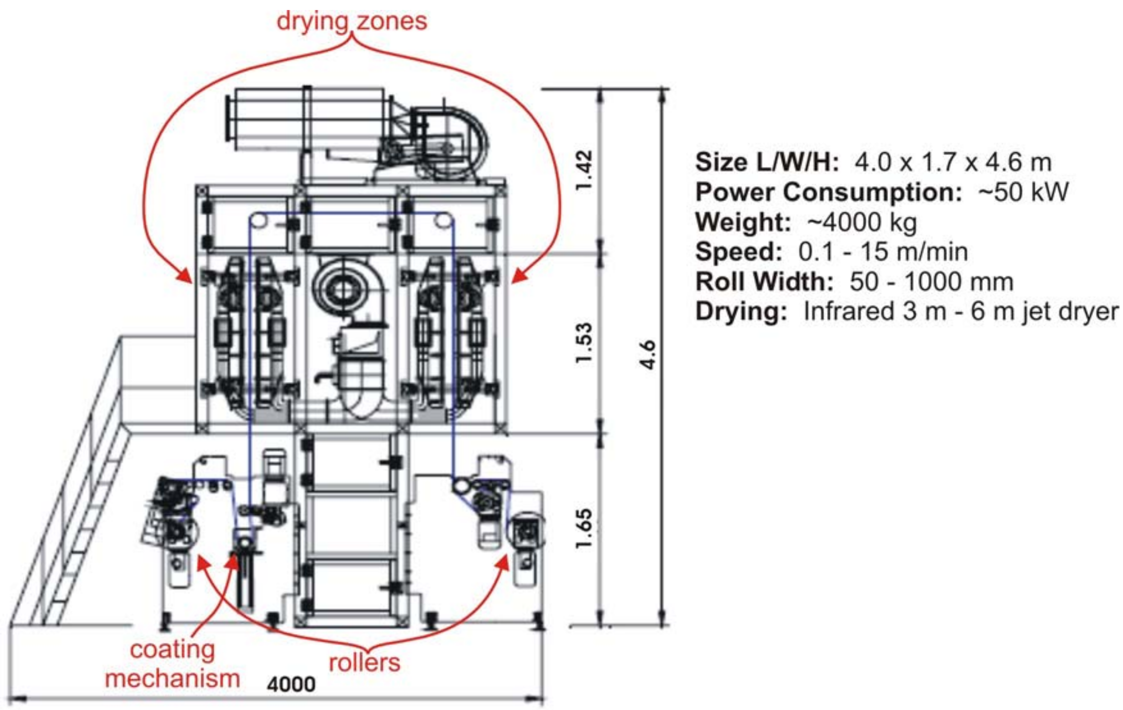

Figure 45. Coatema VertiCoater

The VertiCoater runs at a maximum rate of 15 meters per minute, but after consultation with Bob Sandbank of Eurotec, USA, a distributor of Coatema machinery, we opted to dial back the speed to 10 meters per minute, because of the delicate nature of the membrane[51]. While the VertiCoater can handle web widths of up to 1 m, we limit the width to 50 cm to match the maximum width of other components in the fabrication process[52].

[50] A variety of slurry application devices are compatible with the Coatema VertiCoater, such as the knife, commabar, engraved roller, and multi-roller systems.

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

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

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 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%
	Fixed Charge Rate	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)	50	50	50	50	50

Figure 46. Machine rate parameters for catalyst application process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Capital Cost ($/Line)	$750,000	$750,000	$750,000	$750,000	$750,000
	Simultaneous Lines	1	1	3	4	15
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	2.82%	84.23%	74.86%	91.24%	93.57%
	Effective Total Machine Rate ($/hr)	$3,636.92	$139.46	$154.59	$130.16	$127.37
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
2010	Capital Cost ($/Line)	$750,000	$750,000	$750,000	$750,000	$750,000
	Simultaneous Lines	1	1	2	2	8
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	1.41%	42.13%	56.17%	91.27%	87.75%
	Effective Total Machine Rate ($/hr)	$7,253.32	$260.34	$199.87	$130.12	$134.59
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
2015	Capital Cost ($/Line)	$750,000	$750,000	$750,000	$750,000	$750,000
	Simultaneous Lines	1	1	2	2	8
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	1.41%	42.20%	56.26%	91.42%	87.90%
	Effective Total Machine Rate ($/hr)	$7,243.15	$259.92	$199.57	$129.94	$134.40
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17

Figure 47. Catalyst application process parameters

Machine rate and process assumptions are displayed in Figure 46 and Figure 47. Capital costs for a single line are estimated at $750,000 for all manufacturing rates, but the majority of the costs for the catalyzed membrane come from the materials. This is largely due to the skyrocketing cost of platinum, and the cost of Nafion®.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Manufacturing ($/stack)	$172.03	$6.58	$7.29	$6.14	$6.01
	Total Cost ($/stack)	$172.03	$6.58	$7.29	$6.14	$6.01
	Total Cost ($\$/kW_{gross}$)	$3.81	$0.15	$0.16	$0.14	$0.13
2010	Manufacturing ($/stack)	$171.59	$6.14	$4.72	$3.07	$3.17
	Total Cost ($/stack)	$171.59	$6.14	$4.72	$3.07	$3.17
	Total Cost ($\$/kW_{gross}$)	$3.95	$0.14	$0.11	$0.07	$0.07
2015	Manufacturing ($/stack)	$171.59	$6.14	$4.72	$3.07	$3.18
	Total Cost ($/stack)	$171.59	$6.14	$4.72	$3.07	$3.18
	Total Cost ($\$/kW_{gross}$)	$3.94	$0.14	$0.11	$0.07	$0.07

Figure 48. Cost breakdown for catalyst application

Advanced catalyst deposition techniques have been proposed by Ballard, 3M and others to simultaneously enhance performance and lower precious metal loadings. In 2005 Ballard[53] anticipated

[53] www.iphe.net/IPHErestrictedarea/5th%20IPHE%20SC%20mtg/Final%20Presentations/Host%20Country%20Presentations/7.6_Ballard.pdf . Presentation to the Fifth International Partnership for the Hydrogen Economy (IPHE) Conference in

the future use (after 2010) of chemical vapor deposition (CVD) nanoparticle dispersions of catalyst to achieve < 0.3 $mgPt/cm^2$ loadings on non-carbon, corrosion free supports. This type of catalyst application, as opposed to the die slot techniques postulated for the cost analysis, may prove necessary to achieve uniform deposition at very low loadings. However, what is clear from the cost analysis is that roller application is so inexpensive (~$0.10/kW) that future advanced deposition techniques will not be able to offer any cost reduction- indeed, future techniques (if necessary) may actually increase catalyst application costs.

4.4.3. Gas Diffusion Layer

Figure 49 displays a cross-sectional diagram of the modeled gas diffusion layer (GDL). The GDL is assumed to be a dual-layer sheet, with macroporous & microporous layers, and is consistent with recent research[54]. The 0.28 mm thick macroporous layer is 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[55]. Rather, a price quote was obtained for the base macroporous layer and the costs of the microporous layer material and application were added to it.

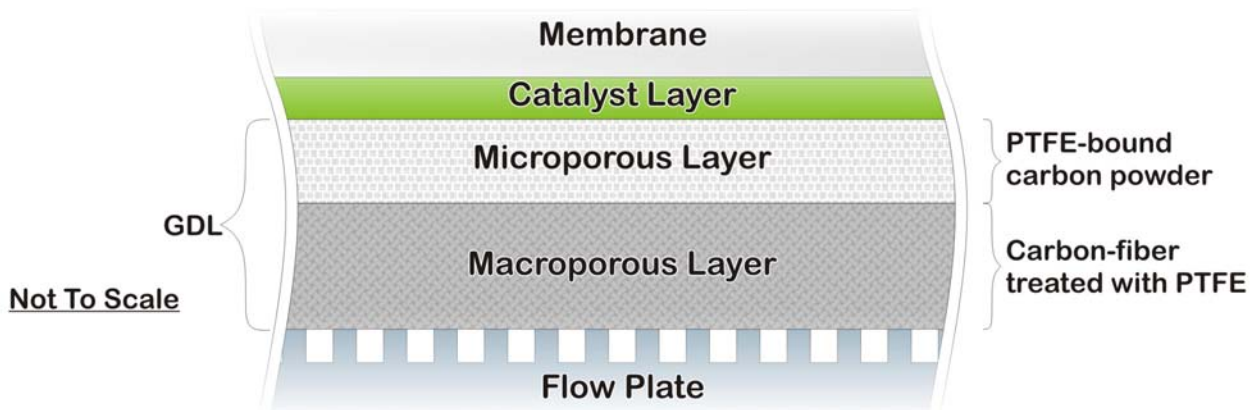

Figure 49. Cross-section of gas diffusion layer in stack

Figure 50 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

[54] *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)
[55] A ground-up analysis of the macroporous GDL layer is planned for a later stage of this project.

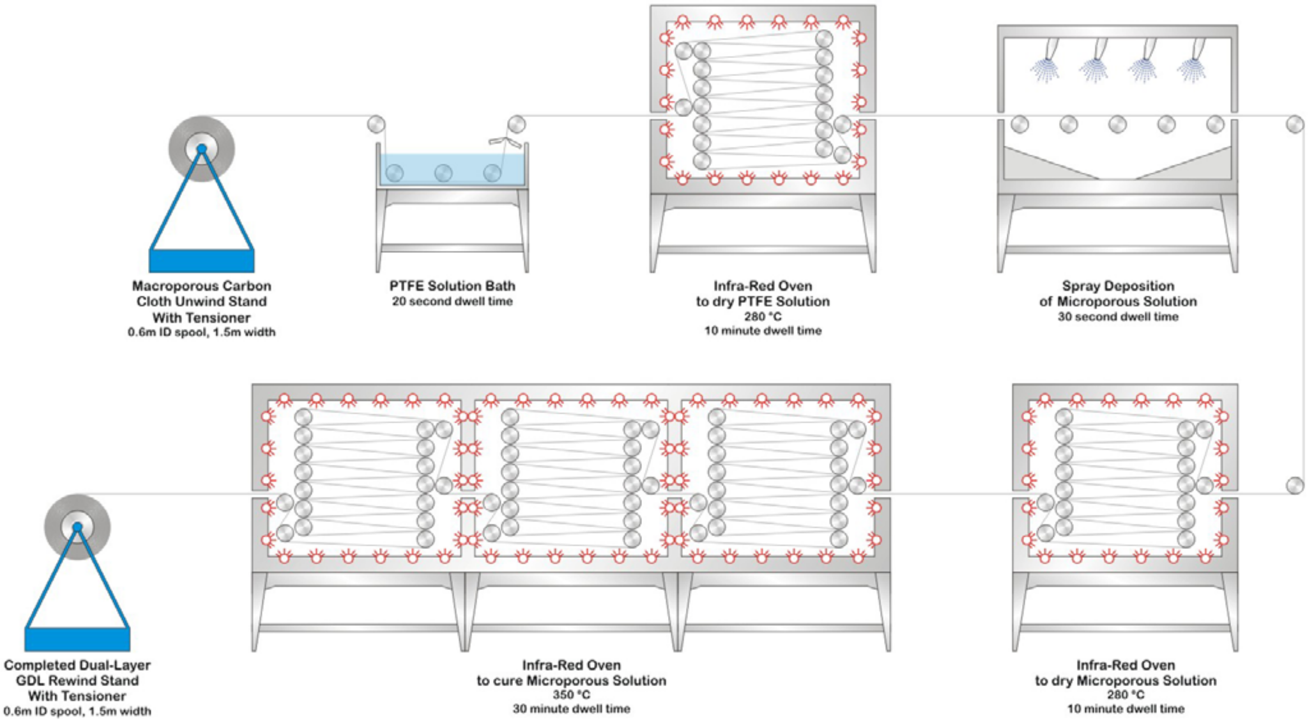

Figure 50. Dual-layer GDL process diagram

Unwind Stand w/ Tensioner	$25,000
Dipper	$75,000
Oven 1 (Macroporous Layer)	$100,000
VCF1500HV Ultrasonic Mixer	$24,231
Sprayer for Microporous Solution	$300,000
Oven 2 (Microporous Layer Stage 1)	$100,000
Oven 3 (Microporous Layer Stage 2)	$450,000
Rewind Stand w/Tensioner	$25,000
Total Capital Cost	$1,099,231

Figure 51. Capital cost breakdown for a typical microporous layer application line

Figure 52 and Figure 53 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 54 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 $2-31/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/year.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Capital Cost ($/Line)	$1,099,231	$1,099,231	$1,099,231	$1,099,231	$1,099,231
	Simultaneous Lines	1	4	10	16	59
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	11.72%	87.81%	93.67%	95.13%	99.22%
	Effective Total Machine Rate ($/hr)	$1,282.48	$213.96	$203.68	$201.30	$195.04
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
	Macroporous Layer Cost ($/m²)	$68.39	$46.19	$28.16	$21.53	$9.05
2010	Capital Cost ($/Line)	$1,099,231	$1,099,231	$1,099,231	$1,099,231	$1,099,231
	Simultaneous Lines	1	2	5	8	30
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.85%	87.76%	93.61%	95.07%	97.51%
	Effective Total Machine Rate ($/hr)	$2,519.06	$214.06	$203.77	$201.40	$197.60
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
	Macroporous Layer Cost ($/m²)	$68.39	$46.19	$28.16	$21.53	$9.05
2015	Capital Cost ($/Line)	$1,099,231	$1,099,231	$1,099,231	$1,099,231	$1,099,231
	Simultaneous Lines	1	2	5	8	30
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.87%	87.93%	93.79%	95.25%	97.69%
	Effective Total Machine Rate ($/hr)	$2,510.93	$213.74	$203.48	$201.11	$197.32
	Line Speed (m/s)	0.17	0.17	0.17	0.17	0.17
	Macroporous Layer Cost ($/m²)	$68.39	$46.19	$28.16	$21.53	$9.05

Figure 52. GDL manufacturing process parameters (microporous layer addition only)

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 2010/ 2015	Equipment Lifetime	11	11	11	11	11
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Fixed Charge Rate	0.194	0.194	0.194	0.194	0.194
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	7%	7%	7%	7%	7%
	Power Consumption (kW)	493	491	491	491	491

Figure 53. Machine rate parameters for GDL manufacturing process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Purchased Macroporous Layer ($/kW$_{gross}$)	$25.76	$17.40	$10.61	$8.11	$3.41
	Other Material ($/kW$_{gross}$)	$0.12	$0.12	$0.12	$0.12	$0.12
	Manufacturing ($/kW$_{gross}$)	$5.59	$0.93	$0.89	$0.88	$0.85
	Total Cost ($/kW$_{gross}$)	$31.47	$18.45	$11.61	$9.10	$4.37
2010	Purchased Macroporous Layer ($/kW$_{gross}$)	$14.80	$10.00	$6.10	$4.66	$1.96
	Other Material ($/kW$_{gross}$)	$0.07	$0.07	$0.07	$0.07	$0.07
	Manufacturing ($/kW$_{gross}$)	$5.71	$0.48	$0.46	$0.46	$0.45
	Total Cost ($/kW$_{gross}$)	$20.58	$10.55	$6.62	$5.18	$2.47
2015	Purchased Macroporous Layer ($/kW$_{gross}$)	$14.81	$10.00	$6.10	$4.66	$1.96
	Other Material ($/kW$_{gross}$)	$0.07	$0.07	$0.07	$0.07	$0.07
	Manufacturing ($/kW$_{gross}$)	$5.69	$0.48	$0.46	$0.45	$0.45
	Total Cost ($/kW$_{gross}$)	$20.56	$10.55	$6.62	$5.18	$2.47

Figure 54. Cost breakdown for gas diffusion layers

4.4.4. MEA Gaskets and MEA Assembly

The MEA gasket is 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.

4.4.4.1.   Hot-Pressing the Membrane and GDLs

The hot-pressing process (see Figure 55) starts with three rolls- two of GDL and one of catalyzed membrane. Because we chose to catalyze the membrane, 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.

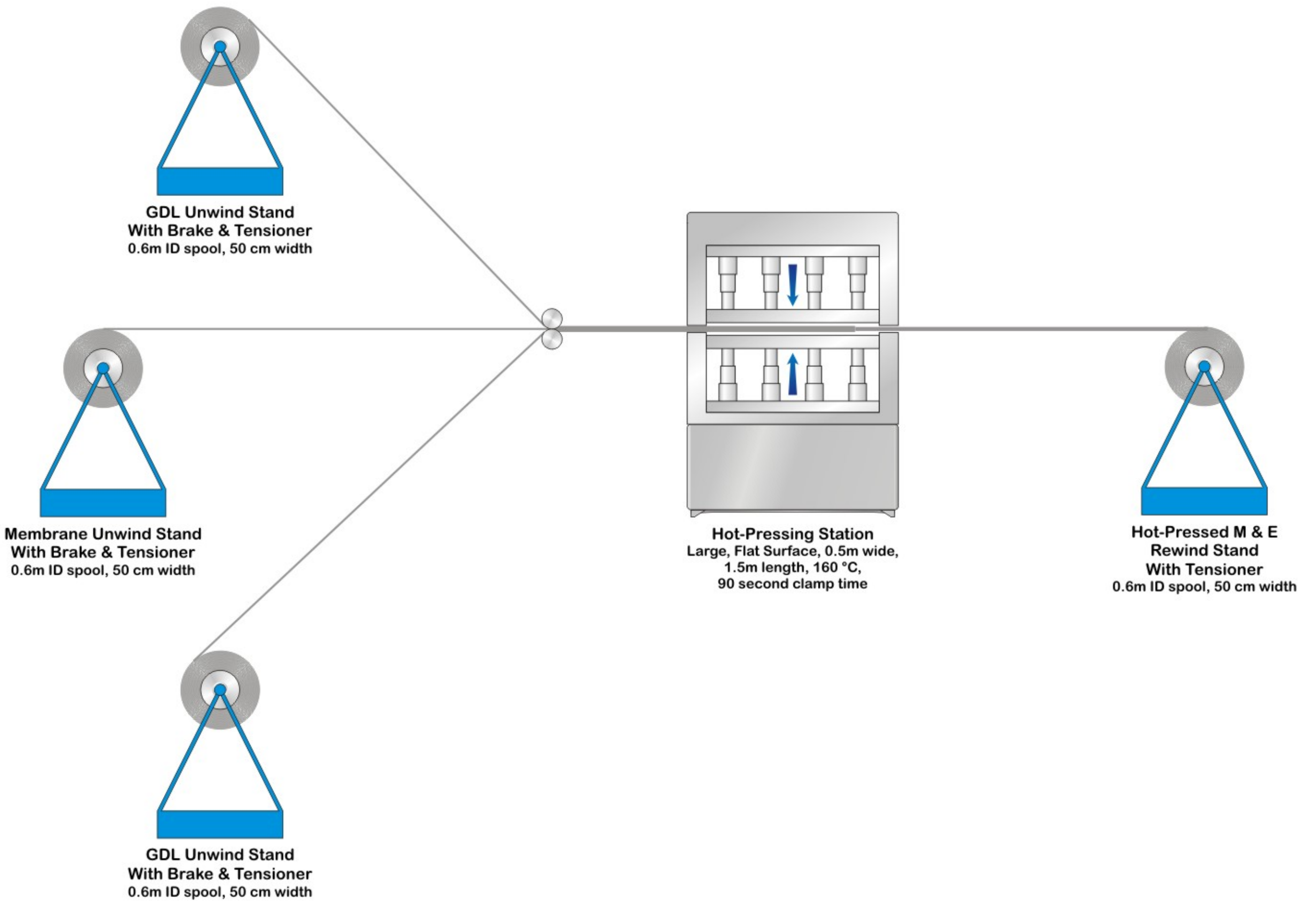

Figure 55. Hot-pressing process diagram

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 56.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Capital Cost ($/Line)	$165,000	$165,000	$165,000	$165,000	$165,000
	Costs per Tooling Set ($)	$10,000	$10,000	$10,000	$10,000	$10,000
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	9	24	38	146
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	29.07%	96.87%	96.87%	99.42%	99.53%
	Effective Total Machine Rate ($/hr)	$77.72	$34.61	$34.61	$34.14	$34.12
	Index Time (s)	93.00	93.00	93.00	93.00	93.00
2010	Capital Cost ($/Line)	$165,000	$165,000	$165,000	$165,000	$165,000
	Costs per Tooling Set ($)	$10,000	$10,000	$10,000	$10,000	$10,000
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	4	11	18	67
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	13.23%	99.23%	96.22%	95.56%	98.74%
	Effective Total Machine Rate ($/hr)	$151.40	$34.17	$34.74	$34.87	$34.27
	Index Time (s)	93.00	93.00	93.00	93.00	93.00
2015	Capital Cost ($/Line)	$165,000	$165,000	$165,000	$165,000	$165,000
	Costs per Tooling Set ($)	$10,000	$10,000	$10,000	$10,000	$10,000
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	4	11	18	67
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	13.23%	99.22%	96.21%	95.54%	98.72%
	Effective Total Machine Rate ($/hr)	$151.42	$34.18	$34.74	$34.87	$34.27
	Index Time (s)	93.00	93.00	93.00	93.00	93.00

Figure 56. Hot-pressing process parameters

Hot pressing cost is summarized in Figure 58. Because of the simplicity of the process, the cost is quite low, especially at high manufacturing rates. Since it's a flat press, tool wear is minimal. Material costs are zero since the cost of membrane and GDL were accounted for elsewhere.

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 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%
	Fixed Charge Rate	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 57. Machine rate parameters for hot-pressing process

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Manufacturing ($/stack)	$37.95	$16.90	$16.90	$16.67	$16.66
	Tooling ($/stack)	$0.33	$0.20	$0.20	$0.19	$0.19
	Total Cost ($/stack)	$38.29	$17.10	$17.10	$16.86	$16.85
	Total Cost ($/$kW_{gross}$)	$0.85	$0.38	$0.38	$0.37	$0.37
2010	Manufacturing ($/stack)	$33.66	$7.60	$7.72	$7.75	$7.62
	Tooling ($/stack)	$0.33	$0.09	$0.09	$0.09	$0.09
	Total Cost ($/stack)	$34.00	$7.69	$7.81	$7.84	$7.71
	Total Cost ($/$kW_{gross}$)	$0.78	$0.18	$0.18	$0.18	$0.18
2015	Manufacturing ($/stack)	$33.66	$7.60	$7.72	$7.75	$7.62
	Tooling ($/stack)	$0.33	$0.09	$0.09	$0.09	$0.09
	Total Cost ($/stack)	$34.00	$7.68	$7.81	$7.84	$7.71
	Total Cost ($/$kW_{gross}$)	$0.78	$0.18	$0.18	$0.18	$0.18

Figure 58. Cost breakdown for hot-pressing process

4.4.4.2. Cutting & Slitting

As shown in Figure 59, the rolls of hot-pressed membrane and GDL are next fed through cutters and slitters to achieve the desired dimensions for insertion into the MEA frame. The 50 cm wide input roll is slit into ribbon streams of the appropriate width (again, depending on cell geometry). The streams continue through to the cutters, which turn the continuous material into individual rectangles. These rectangles are then sorted into magazine racks.

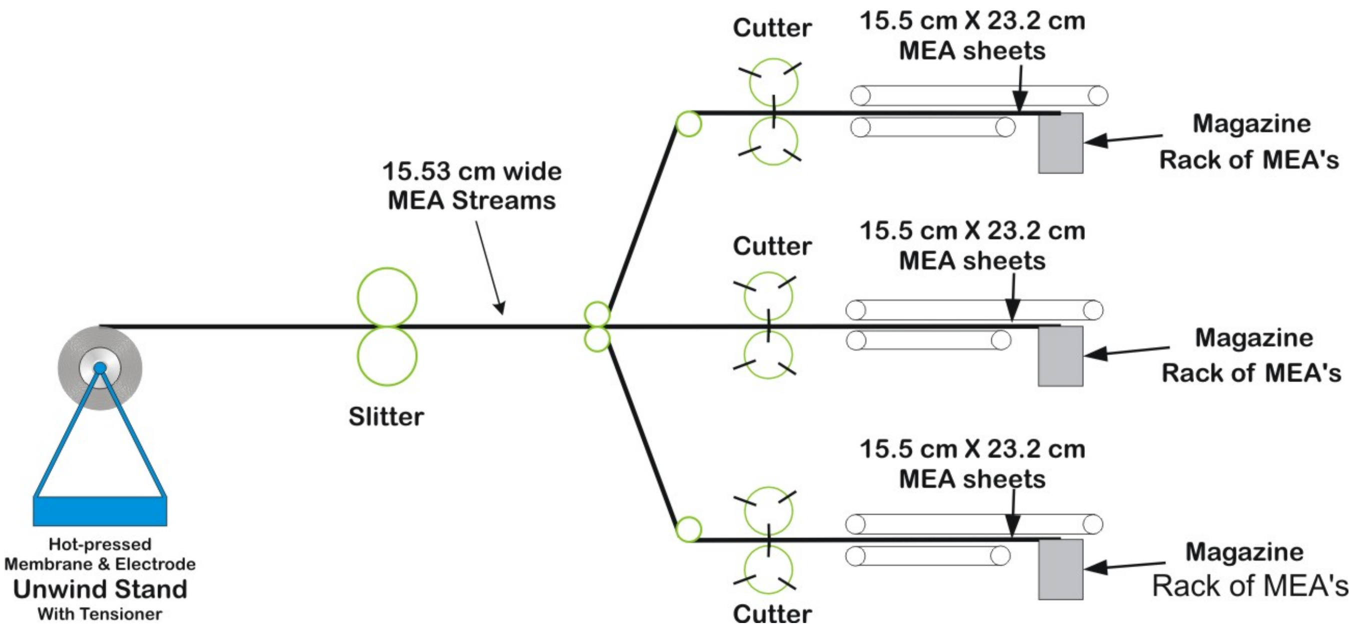

Figure 59. Cutting & slitting process diagram

Figure 61 further details the process parameters. Machine utilization at 1,000 systems per year is extremely poor (as low as 0.43%). However, costs associated with manual cutting are comparable to the automated system running at poor utilization. Consequently, for simplicity we present that process as being automated at all production rates. Figure 63 summarizes the overall cost of the cutting and slitting operation.

Unwind Stand w/ Tensioner	$25,000
Cutter/Slitter	$85,000
Stacker	$10,000
Total Capital Cost	$120,000

Figure 60: Capital cost breakdown for the cutting and slitting process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Capital Cost ($/Line)	$120,000	$120,000	$120,000	$120,000	$120,000
	Costs per Tooling Set ($)	$5,000	$5,000	$5,000	$5,000	$5,000
	Tooling Lifetime (cycles)	200,000	200,000	200,000	200,000	200,000
	Simultaneous Lines	1	1	1	1	4
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.87%	22.82%	60.83%	98.85%	95.04%
	Effective Total Machine Rate ($/hr)	$1,725.69	$81.09	$40.55	$31.19	$31.79
	Line Speed (m/s)	1.00	1.33	1.33	1.33	1.33
2010	Capital Cost ($/Line)	$120,000	$120,000	$120,000	$120,000	$120,000
	Costs per Tooling Set ($)	$5,000	$5,000	$5,000	$5,000	$5,000
	Tooling Lifetime (cycles)	200,000	200,000	200,000	200,000	200,000
	Simultaneous Lines	1	1	1	1	2
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.43%	11.41%	30.44%	49.44%	95.07%
	Effective Total Machine Rate ($/hr)	$3,434.65	$145.95	$64.86	$46.15	$31.78
	Line Speed (m/s)	1.00	1.33	1.33	1.33	1.33
2015	Capital Cost ($/Line)	$120,000	$120,000	$120,000	$120,000	$120,000
	Costs per Tooling Set ($)	$5,000	$5,000	$5,000	$5,000	$5,000
	Tooling Lifetime (cycles)	200,000	200,000	200,000	200,000	200,000
	Simultaneous Lines	1	1	1	1	2
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	0.43%	11.43%	30.49%	49.52%	95.23%
	Effective Total Machine Rate ($/hr)	$3,432.05	$145.70	$64.78	$46.11	$31.76
	Line Speed (m/s)	1.00	1.33	1.33	1.33	1.33

Figure 61. Cutting & slitting process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 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%
	Fixed Charge Rate	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 62. Machine rate parameters for cutting & slitting process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Manufacturing ($/stack)	$25.11	$1.04	$0.52	$0.40	$0.41
	Tooling ($/stack)	$2.33	$2.33	$2.33	$2.33	$2.33
	Total Cost ($/stack)	$27.44	$3.36	$2.84	$2.72	$2.73
	Total Cost ($/kW$_{gross}$)	$0.61	$0.07	$0.06	$0.06	$0.06
2010	Manufacturing ($/stack)	$24.99	$0.93	$0.41	$0.29	$0.20
	Tooling ($/stack)	$2.33	$2.33	$2.33	$2.33	$2.33
	Total Cost ($/stack)	$27.32	$3.26	$2.74	$2.62	$2.53
	Total Cost ($/kW$_{gross}$)	$0.63	$0.08	$0.06	$0.06	$0.06
2015	Manufacturing ($/stack)	$24.99	$0.93	$0.41	$0.30	$0.20
	Tooling ($/stack)	$2.33	$2.33	$2.33	$2.33	$2.33
	Total Cost ($/stack)	$27.32	$3.26	$2.74	$2.62	$2.53
	Total Cost ($/kW$_{gross}$)	$0.63	$0.07	$0.06	$0.06	$0.06

Figure 63. Cost breakdown for cutting & slitting process

4.4.4.3. 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 64), the rectangular hot-pressed membrane/GDL is inserted into an injection molding machine, and silicone is molded into place around it.

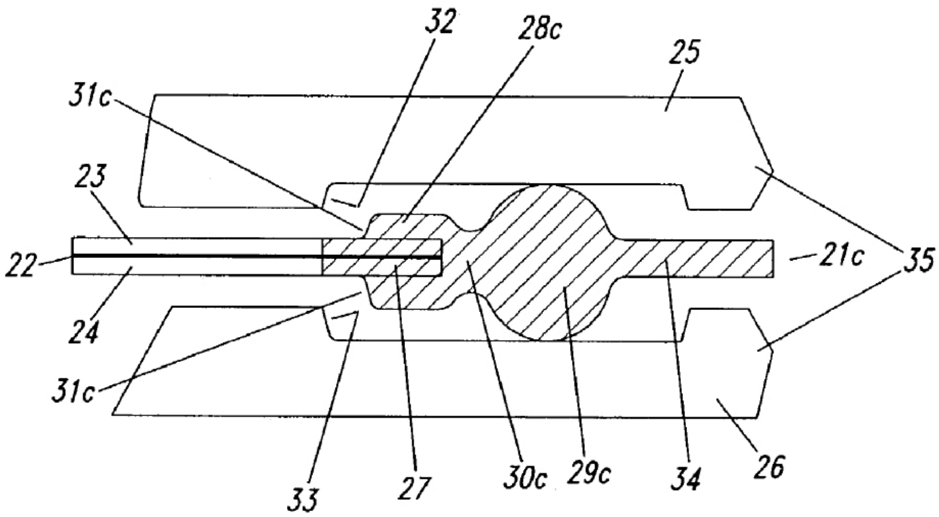

Figure 64. Insertion molded frame/gasket concept, US patent #7,070,876

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 2007 design for example, the part mass is 14.8 grams, and the shot mass is 21.7.

As shown in Figure 65, the optimal number of cavities per platen ranges from 6 to 15, as determined by lowest overall cost. The necessary clamping force ranges from 640 to 1300 tons, and the injection pressure is a constant 1,379 bar (20,000 psi) for each case.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Capital Cost ($/Line)	$455,454	$717,642	$848,736	$848,736	$848,736
	Costs per Tooling Set ($)	$59,190	$84,633	$96,154	$96,154	$96,154
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	17	38	61	232
	Laborers per Line	1.00	0.33	0.33	0.33	0.33
	Line Utilization	84.70%	95.19%	97.38%	98.57%	99.69%
	Cycle Time (s)	165	175	180	180	180
	Cavities/Platen	6	10	12	12	12
	Effective Total Machine Rate ($/hr)	$138.84	$130.26	$147.00	$145.54	$144.21
	Silicone Cost ($/kg)	$14.33	$14.33	$14.33	$14.33	$14.33
2010	Capital Cost ($/Line)	$302,831	$362,995	$423,160	$423,160	$513,407
	Costs per Tooling Set ($)	$72,394	$84,633	$96,154	$96,154	$112,410
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	17	38	61	193
	Laborers per Line	1.00	0.33	0.33	0.33	0.33
	Line Utilization	65.48%	95.19%	97.38%	98.57%	99.91%
	Cycle Time (s)	170	175	180	180	188
	Cavities/Platen	8	10	12	12	15
	Effective Total Machine Rate ($/hr)	$127.08	$76.44	$84.32	$83.59	$95.96
	Silicone Cost ($/kg)	$14.33	$14.33	$14.33	$14.33	$14.33
2015	Capital Cost ($/Line)	$303,988	$364,442	$515,577	$515,577	$515,577
	Costs per Tooling Set ($)	$72,394	$84,633	$112,410	$112,410	$112,410
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	17	31	51	193
	Laborers per Line	1.00	0.33	0.33	0.33	0.33
	Line Utilization	65.48%	95.19%	99.52%	98.30%	99.91%
	Cycle Time (s)	170	175	188	188	188
	Cavities/Platen	8	10	15	15	15
	Effective Total Machine Rate ($/hr)	$127.34	$76.66	$96.55	$97.44	$96.28
	Silicone Cost ($/kg)	$14.33	$14.33	$14.33	$14.33	$14.33

Figure 65. MEA frame/gasket insertion molding process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 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%
	Fixed Charge Rate	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)	64	86	93	93	93

Figure 66. Machine rate parameters for MEA frame/gasket insertion molding process

The cost summary for the MEA frame/gasket molding process is shown in Figure 67.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Material ($/stack)	$39.44	$39.44	$39.44	$39.44	$39.44
	Manufacturing ($/stack)	$197.56	$118.05	$114.23	$113.09	$112.06
	Tooling ($/stack)	$1.97	$1.60	$1.52	$1.50	$2.97
	Total Cost ($/stack)	$199.53	$159.09	$155.20	$154.04	$154.48
	Total Cost ($/$kW_{gross}$)	$4.42	$3.52	$3.44	$3.41	$3.42
2010	Material ($/stack)	$18.14	$18.14	$18.14	$18.14	$18.14
	Manufacturing ($/stack)	$139.79	$69.27	$65.52	$64.96	$62.17
	Tooling ($/stack)	$2.41	$1.60	$1.52	$1.50	$1.45
	Total Cost ($/stack)	$160.34	$89.01	$85.18	$84.60	$81.76
	Total Cost ($/$kW_{gross}$)	$3.69	$2.05	$1.96	$1.95	$1.88
2015	Material ($/stack)	$18.22	$18.22	$18.22	$18.22	$18.22
	Manufacturing ($/stack)	$140.07	$69.47	$62.56	$63.13	$62.38
	Tooling ($/stack)	$2.41	$1.60	$1.45	$1.47	$1.45
	Total Cost ($/stack)	$160.70	$89.30	$82.23	$82.83	$82.05
	Total Cost ($/$kW_{gross}$)	$3.69	$2.05	$1.89	$1.90	$1.88

Figure 67. Cost breakdown for MEA frame/gasket insertion molding

4.4.5. Endplates

In a typical PEM fuel cell stack, the purposes of an endplate 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 isolate the stack from the rest of the vehicle. However our endplate design, based on a UTC patent (see Figure 68), eliminates the need for separate insulators. Thus, our endplates also serve a fourth function: electrically insulate the ends of the stack.

Made from a compression-molded composite (LYTEX 9063), the endplate 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 endplate with lower cost and lower thermal capacity than the typical metal endplates, with the additional benefit of having no susceptibility to corrosion. The benefits of lower cost and corrosion resistance are obvious, and the low thermal capacity limits the thermal energy absorbed during a cold start, effectively accelerating the start-up period.

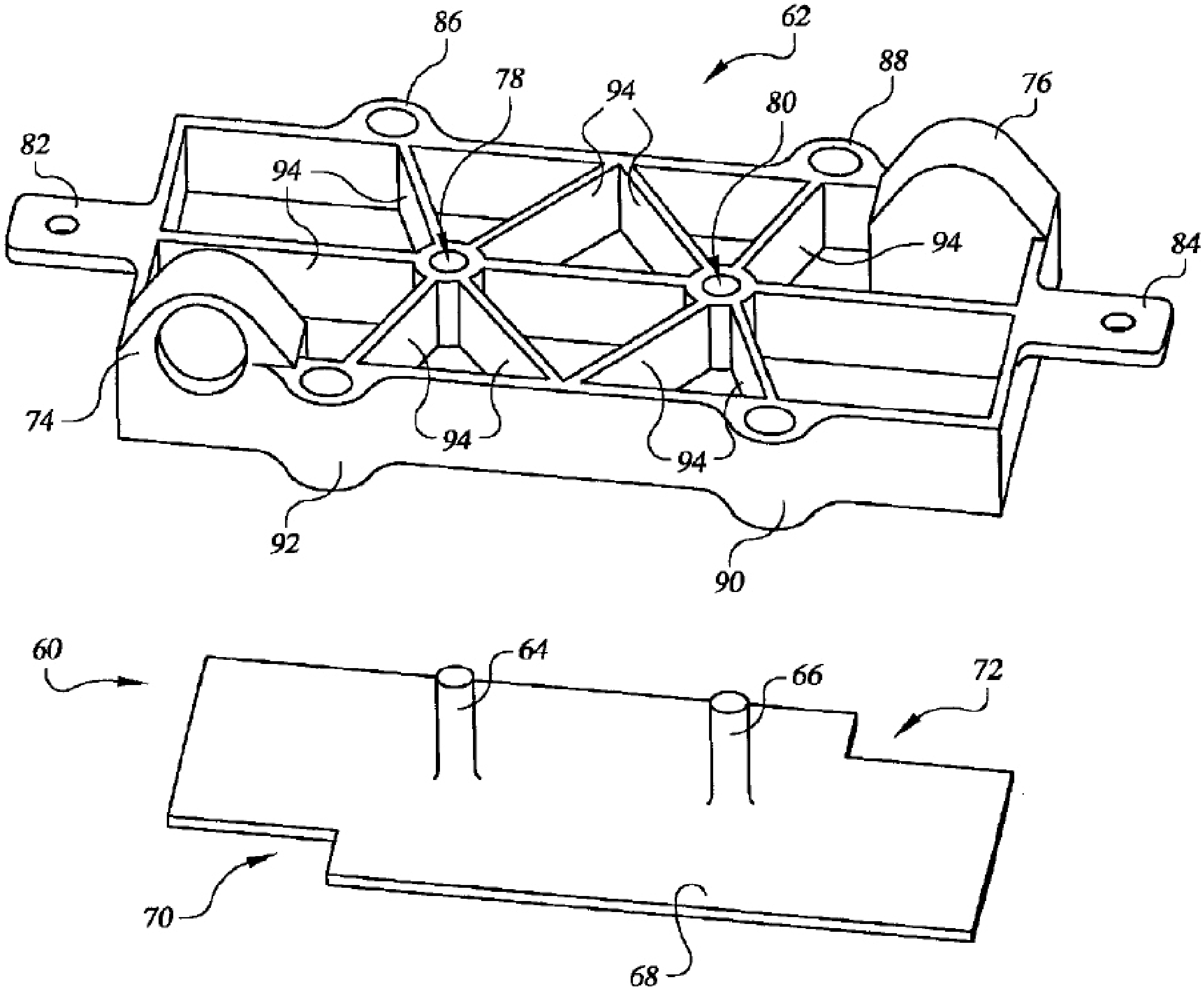

Figure 68. Endplate concept, US patent #6,764,786

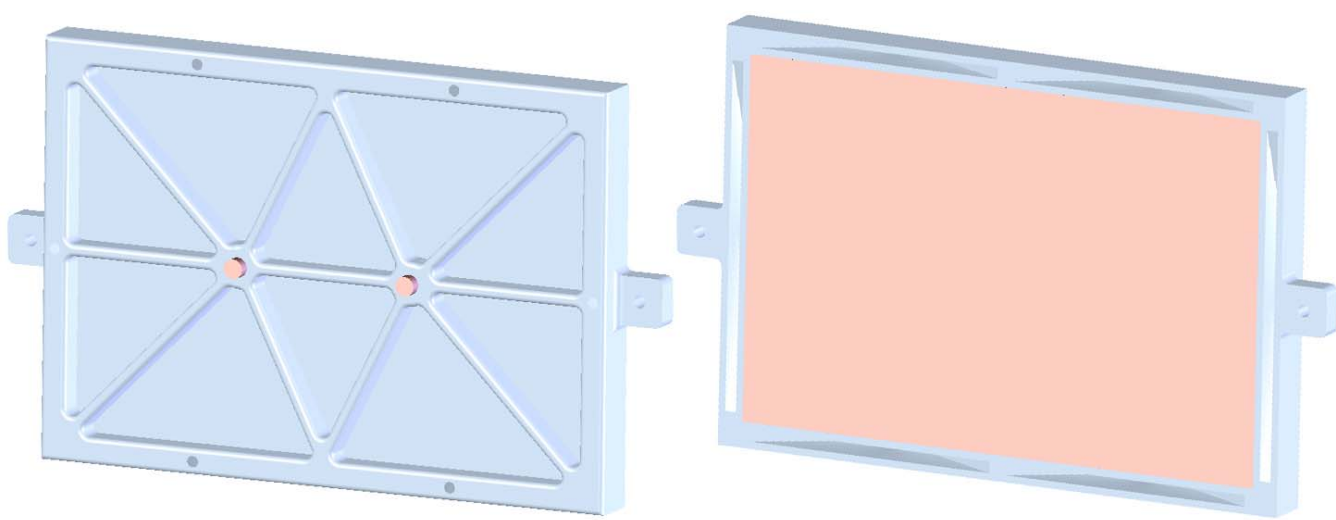

Figure 69. Endplate & current collector

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

The endplates are manufactured via compression molding. A summary of the procedure is as follows[56]:

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.

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

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Capital Cost ($/Line)	$129,561	$356,261	$388,647	$388,647	$453,418
	Costs per Tooling Set ($)	$29,979	$85,913	$92,489	$92,489	$105,079
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	1	1	2	5
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.13%	38.11%	92.80%	75.40%	99.47%
	Cycle Time (s)	310	346	351	351	361
	Cavities/Platen	2	9	10	10	12
	Effective Total Machine Rate ($/hr)	$378.31	$152.90	$79.31	$93.13	$84.96
	LYTEX Cost ($/kg)	$17.50	$15.43	$14.33	$13.23	$9.92
2010	Capital Cost ($/Line)	$101,081	$173,662	$173,662	$209,952	$209,952
	Costs per Tooling Set ($)	$29,979	$64,684	$64,684	$79,114	$79,114
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	1	2	2	8
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.13%	54.64%	72.86%	91.52%	88.00%
	Cycle Time (s)	310	330	330	341	341
	Cavities/Platen	2	6	6	8	8
	Effective Total Machine Rate ($/hr)	$298.51	$63.01	$51.65	$50.77	$52.08
	LYTEX Cost ($/kg)	$17.50	$15.43	$14.33	$13.23	$9.92
2015	Capital Cost ($/Line)	$101,202	$174,026	$174,026	$210,437	$210,437
	Costs per Tooling Set ($)	$29,979	$64,684	$64,684	$79,114	$79,114
	Tooling Lifetime (cycles)	300,000	300,000	300,000	300,000	300,000
	Simultaneous Lines	1	1	2	2	8
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	5.13%	54.64%	72.86%	91.52%	88.00%
	Cycle Time (s)	310	330	330	341	341
	Cavities/Platen	2	6	6	8	8
	Effective Total Machine Rate ($/hr)	$298.85	$63.11	$51.73	$50.85	$52.16
	LYTEX Cost ($/kg)	$17.50	$15.43	$14.33	$13.23	$9.92

Figure 70. Endplate compression molding process parameters

As seen in Figure 72, the material represents the majority of the endplate costs, ranging from 47% to 94%, depending on the production rate.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 2010/ 2015	Equipment Lifetime	13	13	13	13	13
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Fixed Charge Rate	0.186	0.186	0.186	0.186	0.186
	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)	29	60	63	63	68

Figure 71. Machine rate parameters for compression molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Material ($/stack)	$34.16	$30.12	$27.96	$25.81	$19.36
	Manufacturing ($/stack)	$32.59	$3.26	$1.55	$1.81	$1.42
	Tooling ($/stack)	$1.20	$0.11	$0.09	$0.11	$0.08
	Total Cost ($/stack)	$67.95	$33.49	$29.60	$27.74	$20.86
	Total Cost ($/kW$_{gross}$)	$1.50	$0.74	$0.66	$0.61	$0.46
2010	Material ($/stack)	$24.30	$21.43	$19.90	$18.37	$13.77
	Manufacturing ($/stack)	$25.72	$1.93	$1.58	$1.20	$1.23
	Tooling ($/stack)	$1.20	$0.09	$0.13	$0.10	$0.10
	Total Cost ($/stack)	$51.22	$23.44	$21.61	$19.66	$15.11
	Total Cost ($/kW$_{gross}$)	$1.18	$0.54	$0.50	$0.45	$0.35
2015	Material ($/stack)	$24.30	$21.43	$19.90	$18.37	$13.77
	Manufacturing ($/stack)	$25.75	$1.93	$1.58	$1.20	$1.23
	Tooling ($/stack)	$1.20	$0.09	$0.13	$0.10	$0.10
	Total Cost ($/stack)	$51.25	$23.44	$21.61	$19.67	$15.11
	Total Cost ($/kW$_{gross}$)	$1.18	$0.54	$0.50	$0.45	$0.35

Figure 72. Cost breakdown for endplates

4.4.6. 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 68) and shown in Figure 69, two copper current studs protrude through the endplates to connect to a copper sheet in contact with the last bipolar plate.

The current collectors are designed to fit snugly within the endplate. A shallow (0.3 mm) cavity in the endplate 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 endplate, and is sealed on the edges by the endplate gasket.

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 endplate. Two copper studs protrude through their corresponding holes in the endplate, and are brazed to the current collector sheet. On the outside of the endplate, 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
2007	Manufacturing Process	Manual	Auto	Auto	Auto	Auto
	Costs per Tooling Set ($)	$2,634	$2,634	$2,634	$2,634	$2,634
	Tooling Lifetime (cycles)	400,000	400,000	400,000	400,000	400,000
	Capital Cost ($/Line)	$20,962	$61,894	$61,894	$61,894	$61,894
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.00	0.00	0.00	0.00	0.00
	Line Utilization	0.11%	0.93%	2.48%	4.03%	15.49%
	Effective Total Machine Rate ($/hr)	$2,219	$798	$309	$197	$63
	Index Time (s)	0.00	0.00	0.00	0.00	0.00
	Copper Cost ($/kg)	$10.00	$10.00	$10.00	$10.00	$10.00
2010	Manufacturing Process	Manual	Auto	Auto	Auto	Auto
	Costs per Tooling Set ($)	$2,238	$2,238	$2,238	$2,238	$2,238
	Tooling Lifetime (cycles)	400,000	400,000	400,000	400,000	400,000
	Capital Cost ($/Line)	$23,047	$57,126	$57,126	$57,126	$57,126
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.00	0.00	0.00	0.00	0.00
	Line Utilization	0.11%	0.79%	2.10%	3.41%	13.09%
	Effective Total Machine Rate ($/hr)	$2,433	$866	$336	$213	$67
	Index Time (s)	0.00	0.00	0.00	0.00	0.00
	Copper Cost ($/kg)	$10.00	$10.00	$10.00	$10.00	$10.00
2015	Manufacturing Process	Manual	Auto	Auto	Auto	Auto
	Costs per Tooling Set ($)	$2,240	$2,240	$2,240	$2,240	$2,240
	Tooling Lifetime (cycles)	400,000	400,000	400,000	400,000	400,000
	Capital Cost ($/Line)	$23,067	$57,150	$57,150	$57,150	$57,150
	Simultaneous Lines	1	1	1	1	1
	Laborers per Line	0.00	0.00	0.00	0.00	0.00
	Line Utilization	0.11%	0.79%	2.10%	3.41%	13.10%
	Effective Total Machine Rate ($/hr)	$2,435	$866	$336	$213	$67
	Index Time (s)	0.00	0.00	0.00	0.00	0.00
	Copper Cost ($/kg)	$10.00	$10.00	$10.00	$10.00	$10.00

Figure 73. 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/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
2007/ 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%
	Fixed Charge Rate	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 74. Machine rate parameters for current collector manufacturing process

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Material ($/stack)	$9.09	$7.47	$6.64	$6.22	$5.81
	Manufacturing ($/stack)	$4.25	$0.42	$0.16	$0.10	$0.03
	Tooling ($/stack)	$0.09	$0.01	$0.01	$0.01	$0.01
	Total Cost ($/stack)	$13.95	$8.42	$7.34	$6.86	$6.38
	Total Cost ($/kW$_{gross}$)	$0.31	$0.19	$0.16	$0.15	$0.14
2010	Material ($/stack)	$5.31	$4.37	$3.88	$3.64	$3.40
	Manufacturing ($/stack)	$4.66	$0.38	$0.15	$0.09	$0.03
	Tooling ($/stack)	$0.07	$0.01	$0.01	$0.01	$0.01
	Total Cost ($/stack)	$10.58	$5.29	$4.56	$4.27	$3.96
	Total Cost ($/kW$_{gross}$)	$0.24	$0.12	$0.11	$0.10	$0.09
2015	Material ($/stack)	$5.33	$4.38	$3.89	$3.65	$3.41
	Manufacturing ($/stack)	$4.67	$0.38	$0.15	$0.09	$0.03
	Tooling ($/stack)	$0.07	$0.01	$0.01	$0.01	$0.01
	Total Cost ($/stack)	$10.60	$5.30	$4.58	$4.28	$3.97
	Total Cost ($/kW$_{gross}$)	$0.24	$0.12	$0.11	$0.10	$0.09

Figure 75. Cost breakdown for current collector manufacturing process

4.4.7. Coolant and End Gaskets

While the frame/gasket of the MEA seals between the facing gas flow sides of adjacent bipolar plates, there is no MEA between the facing coolant plates, so a separate coolant gasket must be provided. Similarly, there is no MEA between the endplates and the end bipolar plates, so an end gasket must be provided there as well.

The coolant and end gaskets have slightly different geometry from each other, and are very similar to the frame/gasket for the MEA. Because there is a coolant gasket in every repeat unit, plus an extra at the end of the stack (see Figure 22), there are 187 coolant gaskets needed per stack, vs. only 2 end gaskets.

The coolant gasket allows coolant from the manifolds to flow across the bipolar plates, while keeping the air and hydrogen manifolds sealed off. The endplate gasket must also have plugs incorporated into it to seal off the ends of the gas flow paths on the end bipolar plates. This prevents the reactant gases from coming in contact with the copper current collector, protecting it from corrosion.

Coolant and end gaskets are made via insertion molding and are formed directly on the bipolar plates. The process for making these gaskets is much the same process as the MEA frame/gasket, except that instead of the hot-pressed membrane and electrode, bipolar plates are inserted into the mold before each cycle. Figure 76 details the process parameters and Figure 78 summarizes the gasket costs.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Capital Cost ($/Line)	$364,651	$364,651	$364,651	$364,651	$364,651
	Costs per Tooling Set ($)	$59,190	$117,605	$117,605	$117,605	$117,605
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	12	30	49	187
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	86.06%	93.09%	99.29%	98.79%	99.56%
	Effective Total Machine Rate ($/hr)	$77.31	$75.71	$72.33	$72.59	$72.19
	Silicone Cost ($/kg)	$14.33	$14.33	$14.33	$14.33	$14.33
2010	Capital Cost ($/Line)	$364,651	$364,651	$364,651	$364,651	$364,651
	Costs per Tooling Set ($)	$117,605	$117,605	$117,605	$117,605	$117,605
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	12	30	49	187
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	37.23%	93.09%	99.29%	98.79%	99.56%
	Effective Total Machine Rate ($/hr)	$154.75	$73.51	$70.13	$70.39	$69.99
	Silicone Cost ($/kg)	$14.33	$14.33	$14.33	$14.33	$14.33
2015	Capital Cost ($/Line)	$364,651	$364,651	$364,651	$364,651	$364,651
	Costs per Tooling Set ($)	$117,605	$117,605	$117,605	$117,605	$117,605
	Tooling Lifetime (cycles)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	Simultaneous Lines	1	12	30	49	187
	Laborers per Line	0.25	0.25	0.25	0.25	0.25
	Line Utilization	37.23%	93.09%	99.29%	98.79%	99.56%
	Effective Total Machine Rate ($/hr)	$154.77	$73.53	$70.14	$70.40	$70.01
	Silicone Cost ($/kg)	$14.33	$14.33	$14.33	$14.33	$14.33

Figure 76. Gasket insertion molding process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 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%
	Fixed Charge Rate	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	94	94	94	94

Figure 77. Machine rate parameters for gasket insertion molding process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Material ($/stack)	$41.30	$41.30	$41.30	$41.30	$41.30
	Manufacturing ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Tooling ($/stack)	$1.97	$1.57	$1.47	$1.48	$1.47
	Total Cost ($/stack)	$155.06	$90.23	$88.02	$88.19	$87.93
	Total Cost ($/kW$_{gross}$)	$3.43	$2.00	$1.95	$1.95	$1.95
2010	Material ($/stack)	$19.21	$19.21	$19.21	$19.21	$19.21
	Manufacturing ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Tooling ($/stack)	$3.92	$1.57	$1.47	$1.48	$1.47
	Total Cost ($/stack)	$119.93	$66.76	$64.54	$64.72	$64.46
	Total Cost ($/kW$_{gross}$)	$2.76	$1.54	$1.49	$1.49	$1.48
2015	Material ($/stack)	$19.30	$19.30	$19.30	$19.30	$19.30
	Manufacturing ($/stack)	$0.00	$0.00	$0.00	$0.00	$0.00
	Tooling ($/stack)	$3.92	$1.57	$1.47	$1.48	$1.47
	Total Cost ($/stack)	$120.03	$66.86	$64.64	$64.81	$64.56
	Total Cost ($/kW$_{gross}$)	$2.76	$1.54	$1.48	$1.49	$1.48

Figure 78. Cost breakdown for gasket insertion molding

4.4.8. 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, we assume use of metallic compression bands as used by Ballard Power Systems and described in US Patent #5,993,987 (Figure 79). 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 endplates' low conductivity allows them to act as insulators, to prevent shorting of the stack. Custom recesses in the endplates 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 83.

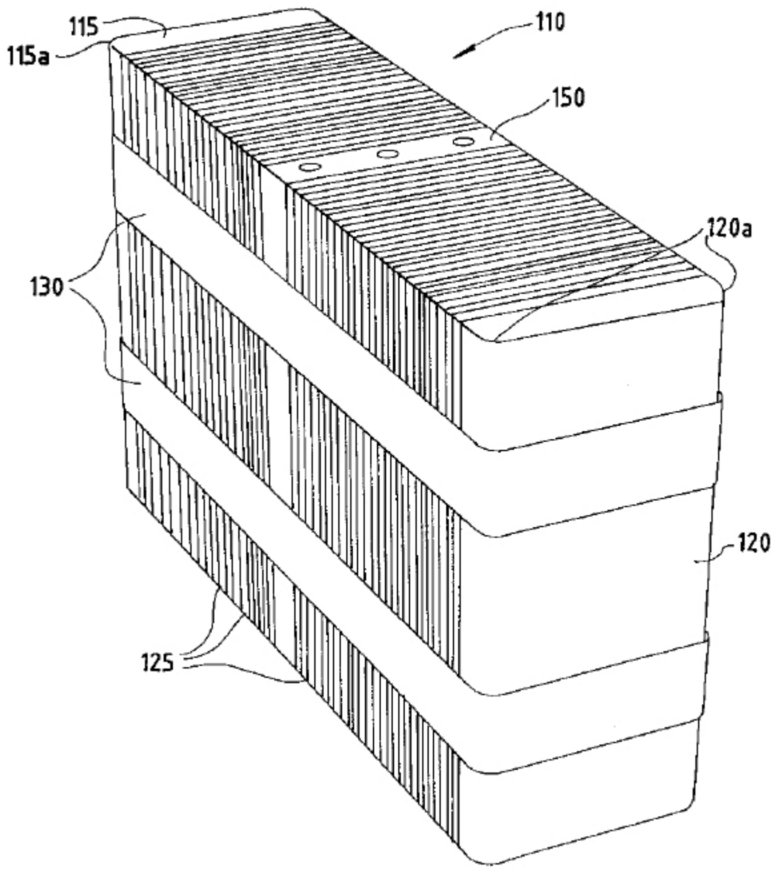

Figure 79. Stack compression bands concept, US patent #5,993,987

4.4.9. Stack Assembly

Stack assembly costs are based on amortized workstation costs and 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/year (2,000 stacks/year), manual assembly is 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. We term this semi-automatic because the end components (endplates, current conductors, and initial cells) are assembled manually but the 186 active cell repeat units are assembled via automated fixture. Figure 80 details the layout of the assembly workstations and Figure 81 lists additional processing parameters.

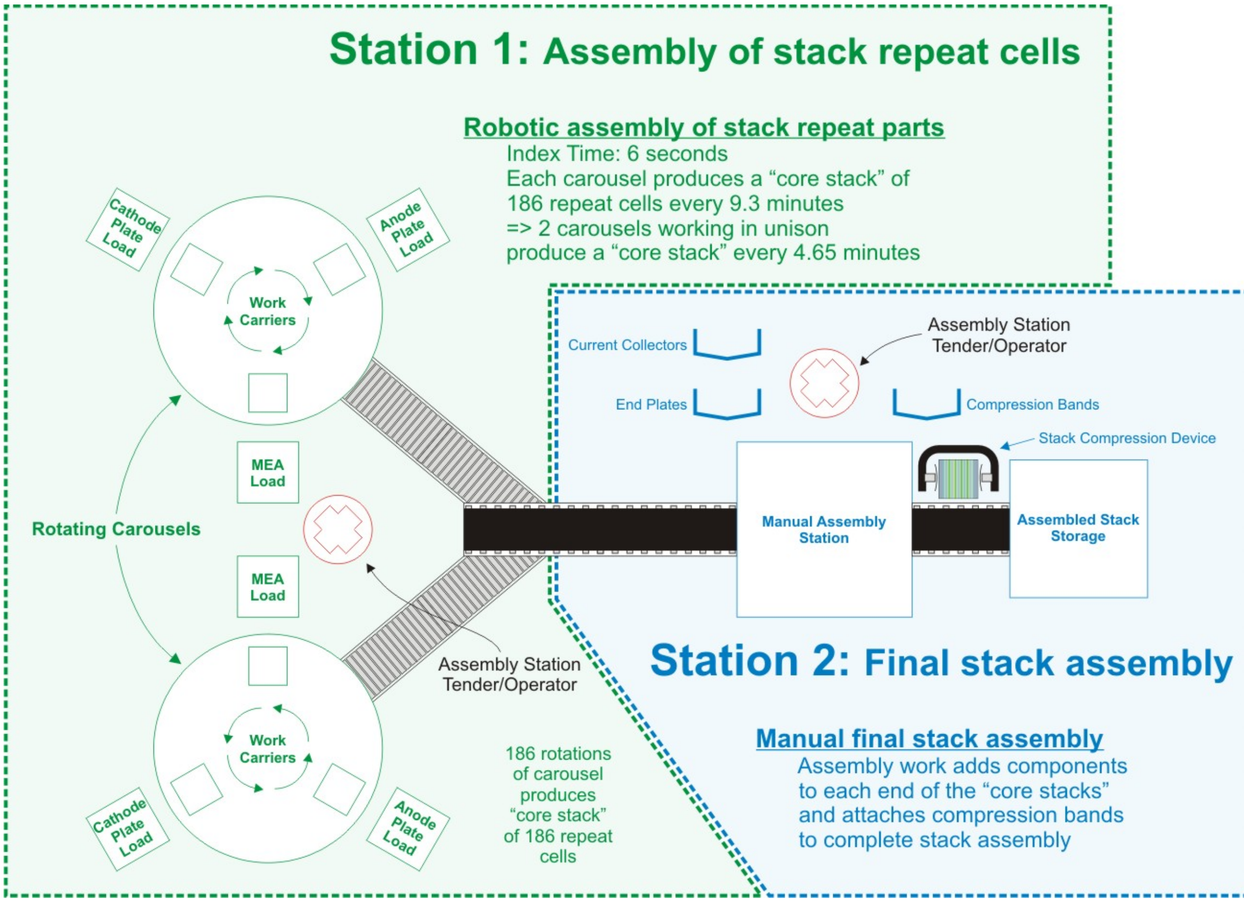

Figure 80. Semi-automated stack assembly work flow diagram

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 83, stack assembly is quite inexpensive, ranging from \$1.42 /kW_{gross} at the most (2010, 1,000 systems/year) to only \$0.49/kW_{gross} (2007, 500,000 systems/year). The only material costs are those of the compressive metal bands.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Assembly Method	Manual	Semi-Auto	Semi-Auto	Semi-Auto	Semi-Auto
	Capital Cost ($/Line)	$10,000	$732,524	$732,524	$732,524	$732,524
	Simultaneous Lines	1	4	9	15	56
	Laborers/Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	48.76%	83.41%	98.86%	96.39%	99.30%
	Effective Total Machine Rate ($/hr)	$62.98	$105.58	$91.50	$93.45	$91.16
	Index Time (min)	49.2	11.2	11.2	11.2	11.2
2010	Assembly Method	Manual	Semi-Auto	Semi-Auto	Semi-Auto	Semi-Auto
	Capital Cost ($/Line)	$10,000	$732,524	$732,524	$732,524	$732,524
	Simultaneous Lines	1	4	9	15	56
	Laborers/Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	48.76%	83.41%	98.86%	96.39%	99.30%
	Effective Total Machine Rate ($/hr)	$62.98	$105.58	$91.50	$93.45	$91.16
	Index Time (min)	49.2	11.2	11.2	11.2	11.2
2015	Assembly Method	Manual	Semi-Auto	Semi-Auto	Semi-Auto	Semi-Auto
	Capital Cost ($/Line)	$10,000	$732,524	$732,524	$732,524	$732,524
	Simultaneous Lines	1	4	9	15	56
	Laborers/Line	1.00	0.25	0.25	0.25	0.25
	Line Utilization	48.76%	83.41%	98.86%	96.39%	99.30%
	Effective Total Machine Rate ($/hr)	$62.98	$105.58	$91.50	$93.45	$91.16
	Index Time (min)	49.2	11.2	11.2	11.2	11.2

Figure 81. Stack assembly process parameters

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 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%
	Fixed Charge Rate	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 82. Machine rate parameters for stack assembly process

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Compression Bands ($/stack)	$10.00	$8.00	$6.00	$5.50	$5.00
	Assembly ($/stack)	$51.59	$19.73	$17.10	$17.46	$17.03
	Total Cost ($/stack)	$61.59	$27.73	$23.10	$22.96	$22.03
	Total Cost ($/kW$_{gross}$)	$1.36	$0.61	$0.51	$0.51	$0.49
2010	Compression Bands ($/stack)	$10.00	$8.00	$6.00	$5.50	$5.00
	Assembly ($/stack)	$51.59	$19.73	$17.10	$17.46	$17.03
	Total Cost ($/stack)	$61.59	$27.73	$23.10	$22.96	$22.03
	Total Cost ($/kW$_{gross}$)	$1.42	$0.64	$0.53	$0.53	$0.51
2015	Compression Bands ($/stack)	$10.00	$8.00	$6.00	$5.50	$5.00
	Assembly ($/stack)	$51.59	$19.73	$17.10	$17.46	$17.03
	Total Cost ($/stack)	$61.59	$27.73	$23.10	$22.96	$22.03
	Total Cost ($/kW$_{gross}$)	$1.41	$0.64	$0.53	$0.53	$0.51

Figure 83. Cost breakdown for stack assembly

4.4.10. Stack Conditioning and Testing

PEM fuel cell stacks have been observed to perform better in polarization tests if they first undergo "stack conditioning". Consequently, we have modeled a series of conditioning steps 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. We have selected the voltage variation method 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 84 details the stack conditioning steps. The UTC patent states that while prior art conditioning times were 70+ hours, the UTC accelerated break-in methodology is able to achieve 95% of the performance benefit in 5 hours and typically maximum performance in 13.3 hours[57]. We have selected a declining conditioning duration (5 hours for 2007 technology, 4 hours for 2010, and 3 hours for 2015) 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
	1	4% H_2-N_2	N_2	Open	Connected to Cathode	Cathode 0.04V to 1.04V	Low
Cathode Filling Cycles	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
	7	N_2	4% H_2-N_2	Open	Connected to Anode	Anode 0.04V to 1.04V	Low
Anode Filling Cycles	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 84. Stack conditioning process based on US patent #7,078,118 ("Applied Voltage Embodiment")

We have calculated conditioning cost 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 5 stacks simultaneously. Since the 5 stacks can be staggered in starting time, peak power can be considerably less than 10 times the individual stack rated power of 40 kW. We estimate that simultaneous peak power would be approximately 50 kW and cost approximately $100,000[58]. Hydrogen usage is estimated based on 50% fuel cell efficiency and $3/kg hydrogen. Use of

[57] 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.

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

our standard machine rate methodology results in machine rates of approximately $0.56/min for each load bank. Total costs for stack conditioning are shown in Figure 87. Note that considerable power is generated and rather than dumping the load to a resistor bank, it may be advantageous to sell the electricity back to the grid. This would require considerable electrical infrastructure and is expected to be only a relatively small benefit[59]; 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
2007	Capital Cost ($/Line)	$100,000	$100,000	$100,000	$100,000	$100,000
	Simultaneous Lines	1	6	14	23	87
	Laborers per Line	0.10	0.10	0.10	0.10	0.10
	Line Utilization	17.36%	86.81%	99.21%	98.13%	99.78%
	Effective Total Machine Rate ($/hr)	$62.64	$22.49	$21.56	$21.63	$21.52
	Test Duration (hrs)	5	5	5	5	5
2010	Capital Cost ($/Line)	$100,000	$100,000	$100,000	$100,000	$100,000
	Simultaneous Lines	1	5	12	19	70
	Laborers per Line	0.10	0.10	0.10	0.10	0.10
	Line Utilization	13.89%	83.33%	92.59%	95.03%	99.21%
	Effective Total Machine Rate ($/hr)	$74.54	$22.81	$22.03	$21.85	$21.56
	Test Duration (hrs)	4	4	4	4	4
2015	Capital Cost ($/Line)	$100,000	$100,000	$100,000	$100,000	$100,000
	Simultaneous Lines	1	4	9	14	53
	Laborers per Line	0.10	0.10	0.10	0.10	0.10
	Line Utilization	10.42%	78.13%	92.59%	96.73%	98.27%
	Effective Total Machine Rate ($/hr)	$94.39	$23.33	$22.03	$21.73	$21.62
	Test Duration (hrs)	3	3	3	3	3

Figure 85. Stack conditioning process parameters

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

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007/ 2010/ 2015	Equipment Lifetime	5	10	10	10	10
	Interest Rate	10%	10%	10%	10%	10%
	Corporate Income Tax Rate	40%	40%	40%	40%	40%
	Fixed Charge Rate	0.306	0.205	0.205	0.205	0.205
	Equipment Installation Factor	1.4	1.4	1.4	1.4	1.4
	Maintenance/Spare Parts (% of CC)	10%	10%	10%	10%	10%
	Miscellaneous Expenses (% of CC)	7%	7%	7%	7%	7%
	Power Consumption (kW)	9	9	9	9	9

Figure 86. Machine rate parameters for stack conditioning process

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

59 We estimate a power conditioning saving of approximately $1.80/stack based on sale of electricity back to the grid at $0.04/kWh (assuming no additional infrastructure capital costs were incurred).

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Conditioning/Testing ($/stack)	$31.32	$11.25	$10.78	$10.82	$10.76
	Total Cost ($/stack)	$31.32	$11.25	$10.78	$10.82	$10.76
	Total Cost ($/kW$_{gross}$)	$0.69	$0.25	$0.24	$0.24	$0.24
2010	Conditioning/Testing ($/stack)	$29.82	$9.12	$8.81	$8.74	$8.62
	Total Cost ($/stack)	$29.82	$9.12	$8.81	$8.74	$8.62
	Total Cost ($/kW$_{gross}$)	$0.69	$0.21	$0.20	$0.20	$0.20
2015	Conditioning/Testing ($/stack)	$28.32	$7.00	$6.61	$6.52	$6.49
	Total Cost ($/stack)	$28.32	$7.00	$6.61	$6.52	$6.49
	Total Cost ($/kW$_{gross}$)	$0.65	$0.16	$0.15	$0.15	$0.15

Figure 87. Cost breakdown for stack conditioning

4.5. Balance of Plant and System Assembly

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

4.5.1. Mounting Frames

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

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Mounting Frames ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/kW$_{net}$)	$1.25	$0.54	$0.41	$0.38	$0.38
2010	Mounting Frames ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/kW$_{net}$)	$1.25	$0.54	$0.41	$0.38	$0.38
2015	Mounting Frames ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/system)	$100.00	$43.00	$33.00	$30.00	$30.00
	Total Cost ($/kW$_{net}$)	$1.25	$0.54	$0.41	$0.38	$0.38

Figure 88. Cost breakdown for mounting frames

4.5.2. Air Loop

The power system air loop consists of five elements:

Air Filter and Housing: Some fuel cell manufacturers filter inlet air both for particles and for volatile organic compounds[60]. However, while particle filters are needed, it is not clear that VOC filters are necessary. Consequently, we assume a standard automotive air particle filter and polymer filter housing.

Air Compressor, Expander and Motor Unit (CMEU): The air compression system is envisioned as an integrated air compressor, exhaust gas expander, and permanent magnet motor. For 2007, the CMEU is based on a twin-lobe compressor and twin-lobe expander whereas for 2010 and 2015 a centrifugal compressor and radial inflow expander is assumed. All estimates are based on a simplified DFMA analysis where the system is broken into 7 cost elements: wheels/lobes, motor, controller, case, bearings,

[60] 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.

variable geometry, and assembly/test. A price quote was obtained from Opcon Autorotor of Sweden for a CMEU unit specifically designed and optimized for fuel cell systems of roughly 80 kilowatts. These Opcon estimates for low production (~$40,000 for quantity = 1) and high production (~$665 for 500,000/year) were used to validate the DTI costing estimates. Note that CMEU costs vary both due to production rate effects and that the CMEU design changes that occur from year to year due to switch from twin-lobe to centrifugal compression, lowering of air pressurization, and elimination of the expander in 2015.

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

Stack Outlet Manifold for the Air Stream: A polymer housing to guide cathode air out of the stack.
Air Mass Flow Sensor: A high performance (~2% signal error) automotive hot-wire mass flow sensor for measuring the air flow rate into the fuel cell system. Since these devices are already produced in very high quantities, little change in cost is expected between high and low production rates. We estimate the OEM cost of a mass flow sensor in high quantities to be about $65. We increase this cost by 50% for quantities of 1,000/year. ($100)

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Filter & Housing ($/system)	$47.69	$43.35	$43.35	$43.35	$43.35
	Compressor, Expander & Motor ($/system)	$2,442.08	$1,214.06	$930.84	$827.01	$668.53
	Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Mass Flow Sensor ($/system)	$100.00	$85.00	$73.00	$68.00	$65.00
	Total Cost ($/system)	$2,614.77	$1,362.41	$1,062.19	$952.36	$788.88
	Total Cost ($/kW$_{net}$)	$32.68	$17.03	$13.28	$11.90	$9.86
2010	Filter & Housing ($/system)	$51.70	$47.00	$47.00	$47.00	$47.00
	Compressor, Expander & Motor ($/system)	$1,710.33	$1,175.82	$868.72	$762.74	$630.33
	Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Mass Flow Sensor ($/system)	$100.00	$85.00	$73.00	$68.00	$65.00
	Total Cost ($/system)	$1,887.03	$1,327.82	$1,003.72	$891.74	$754.33
	Total Cost ($/kW$_{net}$)	$23.59	$16.60	$12.55	$11.15	$9.43
2015	Filter & Housing ($/system)	$51.70	$47.00	$47.00	$47.00	$47.00
	Compressor, Expander & Motor ($/system)	$1,197.88	$815.35	$591.79	$520.64	$428.07
	Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Mass Flow Sensor ($/system)	$100.00	$85.00	$73.00	$68.00	$65.00
	Total Cost ($/system)	$1,374.58	$967.35	$726.79	$649.64	$552.07
	Total Cost ($/kW$_{net}$)	$17.18	$12.09	$9.08	$8.12	$6.90

Figure 89. Cost breakdown for air loop

4.5.3. Humidifier and Water Recovery Loop

The humidifier and water recovery loop consists of the ten elements described below (though no system actually has all 10):

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

Air Humidifier Assembly: 2007 estimate based on a 6-element DFMA-style cost computation of a water spray injection humidifier.

Air Humidifier Thermocouple: Cost based on use of a conventional thermocouple.

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

Exhaust Air Condenser: Cost based on a conventional automotive heat exchanger.

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

Exhaust Air Condenser Sump Pump: Cost based on a standard small electric water pump rated for deionized water duty.

Water Reservoir: Cost based on a molded plastic water tank.

Humidifier Loop Deionizer: Cost based on a resin deionizer bed in a plastic housing.

Membrane Air Humidifier: 2010 estimate based on a price quote from PermaPure for a 2,300 slpm fuel cell humidifier at 2.3 bar (FC300-1660-10HP): $900 each at 1000/year and $250 each at 500,000/year.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Water Pump & Motor ($/system)	$90.00	$80.00	$72.00	$69.00	$65.00
	Air Humidifier Assembly ($/system)	$121.00	$112.20	$106.70	$105.60	$105.05
	Air Humidifier Thermocouple ($/system)	$20.00	$16.00	$12.00	$11.20	$9.60
	Air Demister ($/system)	$37.50	$30.00	$22.50	$21.00	$18.00
	Exhaust Air Condensor ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Air Cond. Water Level Sensor ($/system)	$23.00	$18.40	$13.80	$12.88	$11.04
	Air Cond. Sump Pump ($/system)	$37.50	$30.00	$22.50	$21.00	$18.00
	Water Reservoir ($/system)	$50.00	$40.00	$30.00	$28.00	$24.00
	Humidifier Loop Deionizer ($/system)	$40.00	$32.00	$24.00	$22.40	$19.20
	Total Cost ($/system)	$481.50	$408.60	$341.00	$326.08	$299.89
	Total Cost ($/$kW_{net}$)	$6.02	$5.11	$4.26	$4.08	$3.75
2010	Membrane Air Humidifier ($/system)	$900.00	$600.00	$425.00	$350.00	$250.00
	Total Cost ($/system)	$900.00	$600.00	$425.00	$350.00	$250.00
	Total Cost ($/$kW_{net}$)	$11.25	$7.50	$5.31	$4.38	$3.13
2015	[Does Not Exist]					
	Total Cost ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/$kW_{net}$)	$0.00	$0.00	$0.00	$0.00	$0.00

Figure 90. Cost breakdown for humidifier & water recovery loop

4.5.4. Coolant Loop

The system has two coolant loops, a high temperature loop (HTL) to cool the fuel cell stacks and a low temperature loop (LTL) to condense the water vapor in the escaping exhaust. 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.

High and Low Temperature Loop Coolant Pumps: The low and high temperature loops require similar flow rates, so the same type of pump can be used in each. 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.

Radiators: 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 were aligned with those of appropriately sized radiators used in contemporary automotive applications.

HTL: Coolant Reservoir: Cost based on a molded plastic water tank.

HTL: Coolant DI Filter: Cost based on a resin deionizer bed in a plastic housing.

HTL: Thermostat & Valve: Cost based on standard automotive components.

HTL: Radiator Fan: Cost based on standard automotive components.

LTL: Radiator Fan: Cost based on standard automotive components.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	HTL: Coolant Reservoir ($/system)	$18.75	$15.00	$11.25	$10.50	$9.00
	HTL: Coolant Pump ($/system)	$90.00	$80.00	$72.00	$69.00	$65.00
	HTL: Coolant DI Filter ($/system)	$75.00	$60.00	$45.00	$42.00	$36.00
	HTL: Thermostat & Valve ($/system)	$60.00	$48.00	$36.00	$33.60	$28.80
	HTL: Radiator Fan ($/system)	$85.00	$65.00	$50.00	$48.00	$45.00
	HTL: Radiator ($/system)	$200.00	$180.00	$170.00	$160.00	$150.00
	LTL: Coolant Pump ($/system)	$90.00	$80.00	$72.00	$69.00	$65.00
	LTL: Radiator ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	LTL: Radiator Fan ($/system)	$100.00	$90.00	$85.00	$80.00	$75.00
	Total Cost ($/system)	$781.25	$668.00	$578.75	$547.10	$503.80
	Total Cost ($/$kW_{net}$)	$9.77	$8.35	$7.23	$6.84	$6.30
2010	HTL: Coolant Reservoir ($/system)	$18.75	$15.00	$11.25	$10.50	$9.00
	HTL: Coolant Pump ($/system)	$90.00	$80.00	$72.00	$69.00	$65.00
	HTL: Coolant DI Filter ($/system)	$75.00	$60.00	$45.00	$42.00	$36.00
	HTL: Thermostat & Valve ($/system)	$60.00	$48.00	$36.00	$33.60	$28.80
	HTL: Radiator Fan ($/system)	$85.00	$65.00	$50.00	$48.00	$45.00
	HTL: Radiator ($/system)	$169.49	$152.54	$144.07	$135.59	$127.12
	Total Cost ($/system)	$498.24	$420.54	$358.32	$338.69	$310.92
	Total Cost ($/$kW_{net}$)	$6.23	$5.26	$4.48	$4.23	$3.89
2015	HTL: Coolant Reservoir ($/system)	$18.75	$15.00	$11.25	$10.50	$9.00
	HTL: Coolant Pump ($/system)	$90.00	$80.00	$72.00	$69.00	$65.00
	HTL: Coolant DI Filter ($/system)	$75.00	$60.00	$45.00	$42.00	$36.00
	HTL: Thermostat & Valve ($/system)	$60.00	$48.00	$36.00	$33.60	$28.80
	HTL: Radiator Fan ($/system)	$85.00	$65.00	$50.00	$48.00	$45.00
	HTL: Radiator ($/system)	$125.00	$112.50	$106.25	$100.00	$93.75
	Total Cost ($/system)	$453.75	$380.50	$320.50	$303.10	$277.55
	Total Cost ($/$kW_{net}$)	$5.67	$4.76	$4.01	$3.79	$3.47

Figure 91. Cost breakdown for coolant loop

4.5.5. Fuel Loop

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

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

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

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

Hydrogen/Stack Inlet and Outlet Manifolds: Cost is a token amount to capture the fittings costs associated with the ejector system.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Pressure Transducer ($/system)	$100.00	$85.00	$70.00	$65.00	$60.00
	H_2 Proportional Valve ($/system)	$625.00	$500.00	$375.00	$350.00	$300.00
	H_2 Low Flow Ejector ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 High Flow Ejector ($/system)	$115.00	$92.00	$69.00	$64.40	$55.20
	H_2/Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	H_2/Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Total Cost ($/system)	$927.50	$747.00	$566.50	$528.40	$457.20
	Total Cost ($/kW$_{net}$)	$11.59	$9.34	$7.08	$6.61	$5.72
2010	Pressure Transducer ($/system)	$100.00	$85.00	$70.00	$65.00	$60.00
	H_2 Proportional Valve ($/system)	$625.00	$500.00	$375.00	$350.00	$300.00
	H_2 Low Flow Ejector ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 High Flow Ejector ($/system)	$115.00	$92.00	$69.00	$64.40	$55.20
	H_2/Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	H_2/Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Total Cost ($/system)	$927.50	$747.00	$566.50	$528.40	$457.20
	Total Cost ($/kW$_{net}$)	$11.59	$9.34	$7.08	$6.61	$5.72
2015	Pressure Transducer ($/system)	$100.00	$85.00	$70.00	$65.00	$60.00
	H_2 Proportional Valve ($/system)	$625.00	$500.00	$375.00	$350.00	$300.00
	H_2 Low Flow Ejector ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 High Flow Ejector ($/system)	$115.00	$92.00	$69.00	$64.40	$55.20
	H_2/Stack Inlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	H_2/Stack Outlet Manifold ($/system)	$12.50	$10.00	$7.50	$7.00	$6.00
	Total Cost ($/system)	$927.50	$747.00	$566.50	$528.40	$457.20
	Total Cost ($/kW$_{net}$)	$11.59	$9.34	$7.08	$6.61	$5.72

Figure 92. Cost breakdown for fuel loop

4.5.6. System Controllers/Sensors

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 out of cost and design simplicity rationale. We judge that two EEC's are necessary to supply adequate control and sensor leads to the power plant. Because the EEC's are already manufactured in large quantities for gasoline vehicles, their cost is fairly constant and only varies from $300 to $200 each based on production rate.

The vehicle will require some type of hydrogen sensing system to guard against hydrogen leakage accumulation and fire. Hydrogen sensors are currently very expensive. Hydrogen sensors from RKI Instruments suitable for fuel cell vehicle use are currently hand built and cost approximately $2,000 each. We estimate that such units would cost approximately $150 each if mass-produced at 500,000 per year.

We postulate 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, we estimate that two sensors will initially be used, dropping to one in 2010, and zero in 2015. Additional sensors may be necessary for the passenger compartment and the fuel storage subsystem but these are not in the defined boundary of our fuel cell power system assessment. Additionally, given the high cost of current low production volume sensors, we rationalize using only one sensor at the 1,000 systems/year production rate. Figure 93 lists the estimated total hydrogen sensor costs.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Controller ($/system)	$600.00	$588.38	$568.34	$548.30	$400.00
	H_2 Sensor System ($/system)	$2,000.00	$400.00	$374.00	$350.00	$300.00
	Total Cost ($/system)	$2,600.00	$988.38	$942.34	$898.30	$700.00
	Total Cost ($/kW$_{net}$)	$32.50	$12.35	$11.78	$11.23	$8.75
2010	Controller ($/system)	$600.00	$588.38	$568.34	$548.30	$400.00
	H_2 Sensor System ($/system)	$2,000.00	$200.00	$187.00	$175.00	$150.00
	Total Cost ($/system)	$2,600.00	$788.38	$755.34	$723.30	$550.00
	Total Cost ($/kW$_{net}$)	$32.50	$9.85	$9.44	$9.04	$6.88
2015	Controller ($/system)	$600.00	$588.38	$568.34	$548.30	$400.00
	H_2 Sensor System ($/system)	$0.00	$0.00	$0.00	$0.00	$0.00
	Total Cost ($/system)	$600.00	$588.38	$568.34	$548.30	$400.00
	Total Cost ($/kW$_{net}$)	$7.50	$7.35	$7.10	$6.85	$5.00

Figure 93. Cost breakdown for system controller/sensors

4.5.7. Miscellaneous BOP

Startup Battery: Cost based on standard automotive starting-lighting-ignition (SLI) lead-acid battery.

Wiring, Air Ducting, Water Line Tubing, Coolant Liquid Piping, Hydrogen Piping/Ducting Materials, Cathode Gas Ducting, Anode Gas Ducting, Fasteners for Wire/Hose/Pipe: A detailed DFMA analysis was not conducted for these components since the level of detailed required is well outside the bounds of this projects. However, these components are necessary and, in aggregate, are of substantial cost. Consequently, they are enumerated individually to provide full transparency of our assumptions.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	Startup Battery ($/system)	$437.50	$350.00	$262.50	$245.00	$210.00
	Wiring ($/system)	$56.07	$52.17	$51.69	$51.20	$48.76
	Air Ducting ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Water Tubing ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Coolant Liquid Piping ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 Piping/Ducting Materials ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Cathode Ducting ($/system)	$87.50	$70.00	$52.50	$49.00	$42.00
	Anode Ducting ($/system)	$65.00	$52.00	$39.00	$36.40	$31.20
	Belly Pan for Fuel Cell System ($/system)	$43.75	$35.00	$26.25	$24.50	$21.00
	Fasteners for Wire, Hose, Pipe ($/system)	$96.50	$77.20	$57.90	$54.04	$46.32
	Total Cost ($/system)	$1,161.32	$936.37	$714.84	$670.14	$579.28
	Total Cost ($/$kW_{net}$)	$14.52	$11.70	$8.94	$8.38	$7.24
2010	Startup Battery ($/system)	$437.50	$350.00	$262.50	$245.00	$210.00
	Wiring ($/system)	$56.07	$52.17	$51.69	$51.20	$48.76
	Air Ducting ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Water Tubing ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Coolant Liquid Piping ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 Piping/Ducting Materials ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Cathode Ducting ($/system)	$87.50	$70.00	$52.50	$49.00	$42.00
	Anode Ducting ($/system)	$65.00	$52.00	$39.00	$36.40	$31.20
	Belly Pan for Fuel Cell System ($/system)	$43.75	$35.00	$26.25	$24.50	$21.00
	Fasteners for Wire, Hose, Pipe ($/system)	$96.50	$77.20	$57.90	$54.04	$46.32
	Total Cost ($/system)	$1,161.32	$936.37	$714.84	$670.14	$579.28
	Total Cost ($/$kW_{net}$)	$14.52	$11.70	$8.94	$8.38	$7.24
2015	Startup Battery ($/system)	$437.50	$350.00	$262.50	$245.00	$210.00
	Wiring ($/system)	$56.07	$52.17	$51.69	$51.20	$48.76
	Air Ducting ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Water Tubing ($/system)	$125.00	$100.00	$75.00	$70.00	$60.00
	Coolant Liquid Piping ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	H_2 Piping/Ducting Materials ($/system)	$62.50	$50.00	$37.50	$35.00	$30.00
	Cathode Ducting ($/system)	$87.50	$70.00	$52.50	$49.00	$42.00
	Anode Ducting ($/system)	$65.00	$52.00	$39.00	$36.40	$31.20
	Belly Pan for Fuel Cell System ($/system)	$43.75	$35.00	$26.25	$24.50	$21.00
	Fasteners for Wire, Hose, Pipe ($/system)	$96.50	$77.20	$57.90	$54.04	$46.32
	Total Cost ($/system)	$1,161.32	$936.37	$714.84	$670.14	$579.28
	Total Cost ($/$kW_{net}$)	$14.52	$11.70	$8.94	$8.38	$7.24

Figure 94. Cost breakdown for miscellaneous/BOP components

4.5.8. System Assembly

A detailed analysis of system assembly was not conducted since that would require detailed specification of all assembly steps including identification of all screws, clips, brackets, and a definition of specific component placement within the system. Such an analysis is clearly beyond the scope of this project. Instead, an estimate of system assembly time was obtained by breaking the system down into five categories of assembly components (major, minor, piping, hoses, wiring), estimating the number of components within each category, and then postulating a time to assemble each of those components. Specific assumptions and total estimated assembly time for manual assembly is shown in Figure 95.

	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 95. Single station system assembly assumptions

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

	Annual Production Rate	**1,000**	**30,000**	**80,000**	**130,000**	**500,000**
2007	**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)	$68.81	$633.48	$625.28	$625.91	$624.30
	Cost per Stack ($)	$203.10	$149.58	$147.64	$147.79	$147.41
2010	**Assembly Method**	Single Station	Assembly Line	Assembly Line	Assembly Line	Assembly Line
	Index Time (min)	177.1	14.2	14.2	14.2	14.2
	Capital Cost ($/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)	$68.74	$632.78	$624.58	$625.21	$623.60
	Cost per Stack ($)	$202.89	$149.41	$147.48	$147.63	$147.25
2015	**Assembly Method**	Single Station	Assembly Line	Assembly Line	Assembly Line	Assembly Line
	Index Time (min)	177.1	14.2	14.2	14.2	14.2
	Capital Cost ($/Line)	$50,000	$150,000	$150,000	$150,000	$150,000
	Simultaneous Lines	1	3	6	10	36
	Laborers per Line	1.00	10.00	10.00	10.00	10.00
	Line Utilization	87.84%	70.27%	93.70%	91.36%	97.60%
	Effective Total Machine Rate ($/hr)	$68.74	$632.78	$624.58	$625.21	$623.60
	Cost per Stack ($)	$202.89	$149.41	$147.48	$147.63	$147.25

Figure 96. System assembly process parameters

An assembly line method is selected for all other annual production rates. For the assembly line method, we postulated a 10 workstation configuration. Each fuel cell system flows through the assembly system sequentially. Because workers at each workstation have components closer at hand than under the single workstation approach, and tool changes are minimized due to the higher repetitive nature of an assembly line, total cumulative time for system assembly is reduced. We estimate a 20% time savings over single workstation assembly and a corresponding assembly line index time[61] of 14.2 minutes. System assembly cost is detailed in Figure 97.

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2007	System Assembly & Testing ($/system)	$96.50	$77.20	$57.90	$54.04	$46.32
	Total Cost ($/system)	$96.50	$77.20	$57.90	$54.04	$46.32
	Total Cost ($/kW$_{net}$)	$1.21	$0.97	$0.72	$0.68	$0.58
2010	System Assembly & Testing ($/system)	$96.50	$77.20	$57.90	$54.04	$46.32
	Total Cost ($/system)	$96.50	$77.20	$57.90	$54.04	$46.32
	Total Cost ($/kW$_{net}$)	$1.21	$0.97	$0.72	$0.68	$0.58
2015	System Assembly & Testing ($/system)	$96.50	$77.20	$57.90	$54.04	$46.32
	Total Cost ($/system)	$96.50	$77.20	$57.90	$54.04	$46.32
	Total Cost ($/kW$_{net}$)	$1.21	$0.97	$0.72	$0.68	$0.58

Figure 97. Cost breakdown for system assembly & testing

4.5.9. System Testing

A 10 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 start-up as the vehicle is driven off the assembly line. Corresponding, the fuel cell "engine" is only minimally tested for functionality. Cost for this system testing is reported under system assembly.

4.5.10. Cost Contingency

While it is common automotive industry practice[62] to include a 10% cost contingency to cover the cost of procedures or materials not already explicitly covered in the analysis to guard against an underestimation of cost, we have not done so in this cost analysis. We omit this contingency upon the request of the DOE, so as to present a true "central" baseline cost estimate.

5. Sensitivity Analysis

In order to evaluate which factors have the greatest impact on the total system cost, we conducted a sensitivity analysis on key parameters. These parameters, along with their upper and lower bounds, are shown in Figure 98 and Figure 100. As is immediately seen in the tornado charts in Figure 99 and Figure 101, power density, platinum loading, and platinum cost are by far the most dominant parameters in the stack. Narrowing the uncertainty span in these parameters will greatly improve confidence in the cost estimates. We will examine these bounds in greater detail in future work.

[61] Assembly line index time is defined as the time interval each system spends at a given workstation.
[62] Personal communication with Bob Mooradian, Ford Motor Company.

Variable	Minimum	Current	Maximum	$/kW$_{net}$ min	$/kW$_{net}$ max
	2007, 500k/year				
Platinum Loading (mg/cm^2)	0.1	0.35	0.8	$73.67	$129.41
Power Density (mW/cm^2)	1,500	583	525	$64.81	$98.49
Platinum Cost ($/tr.oz.)	$868	$1,100	$2,978	$88.03	$138.46
Bipolar Plate Coatings ($/kW)	+$2	$0	+$8	$95.58	$101.58
Gasket Injection Cycle Time (sec)	40	150	200	$91.20	$94.62
Macroporous GDL Cost ($/m^2)	$3	$9.05	$11.00	$91.00	$94.40
Ionomer Cost ($/kg)	$30	$92	$250	$92.72	$95.77
Labor Rate ($/hr)	$25	$60	$70	$91.40	$94.20
Membrane Cost ($/m^2)	$5.00	$16.62	$25.00	$91.11	$95.36
Stack Conditioning (hrs)	0	5	13	$93.31	$94.01
Bipolar Plate Stamping Capital Cost ($)	$100,000	$515,488	$1,000,000	$93.36	$93.83
Base System Cost ($/kW$_{net}$)				**$93.58**	

Figure 98. Sensitivity analysis parameters - 2007 technology, 500,000 systems/year

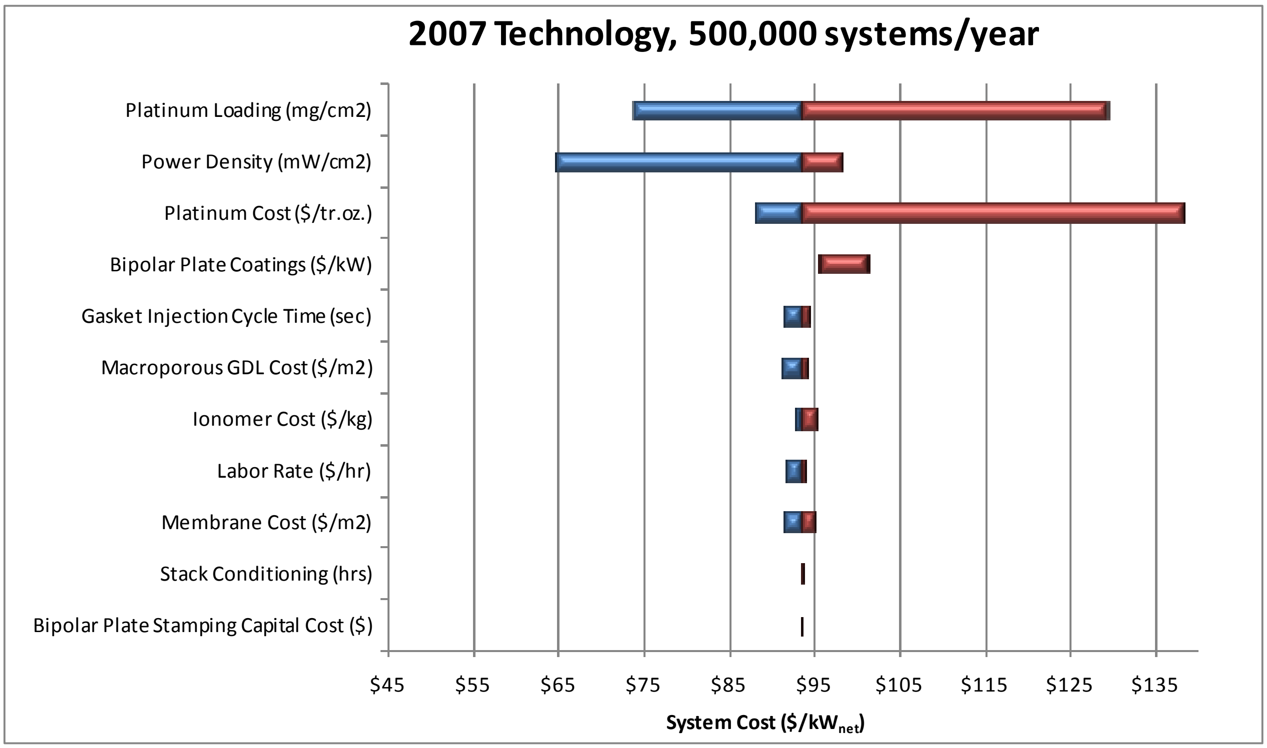

Figure 99. Sensitivity analysis tornado chart - 2007 technology, 500,000 systems/year

Variable	2015, 500k/year Minimum	Current	Maximum	$\$/kW_{net}$ min	$\$/kW_{net}$ max
Platinum Loading (mg/cm^2)	0.1	0.2	0.8	$48.74	$79.67
Power Density (mW/cm^2) 0.1 mg/cm^2	1,500	1,000	525	$46.21	$70.49 0.8 mg/cm
Platinum Cost ($/tr.oz.)	$868	$1,100	$2,978	$51.40	$67.38
Bipolar Plate Coatings ($/kW)	+$2	$0	+$8	$55.16	$61.16
Gasket Injection Cycle Time (sec)	40	150	200	$51.60	$53.88
Macroporous GDL Cost ($\$/m^2$)	$3	$9.05	$11.00	$51.73	$53.62
Ionomer Cost ($/kg)	$30	$131	$250	$52.39	$54.06
Labor Rate ($/hr)	$25	$60	$70	$51.21	$53.71
Membrane Cost ($\$/m^2$)	$5.00	$20.69	$25.00	$51.31	$53.67
Stack Conditioning (hrs)	0	3	13	$53.00	$53.69
Bipolar Plate Stamping Capital Cost ($)	$100,000	$474,698	$1,000,000	$52.99	$53.39
Base System Cost ($\$/kW_{net}$)				$53.16	

Figure 100. Sensitivity analysis parameters - 2015 technology, 500,000 systems/year

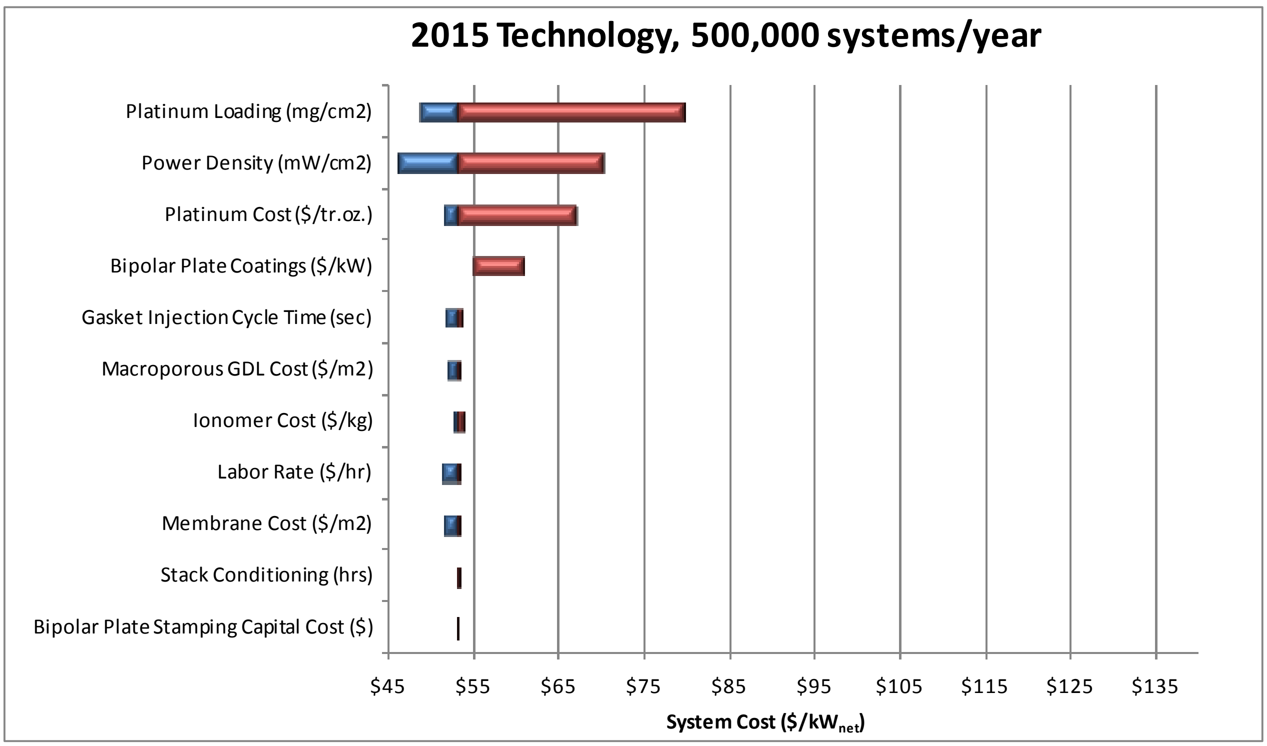

Figure 101. Sensitivity analysis tornado chart - 2015 technology, 500,000 systems/year

6. Conclusions

Figure 102 and Figure 103 (repeats of Figure 11 and Figure 12) graphically summarize the cost trends for the $80kW_{net}$ PEM fuel cell stacks and systems.

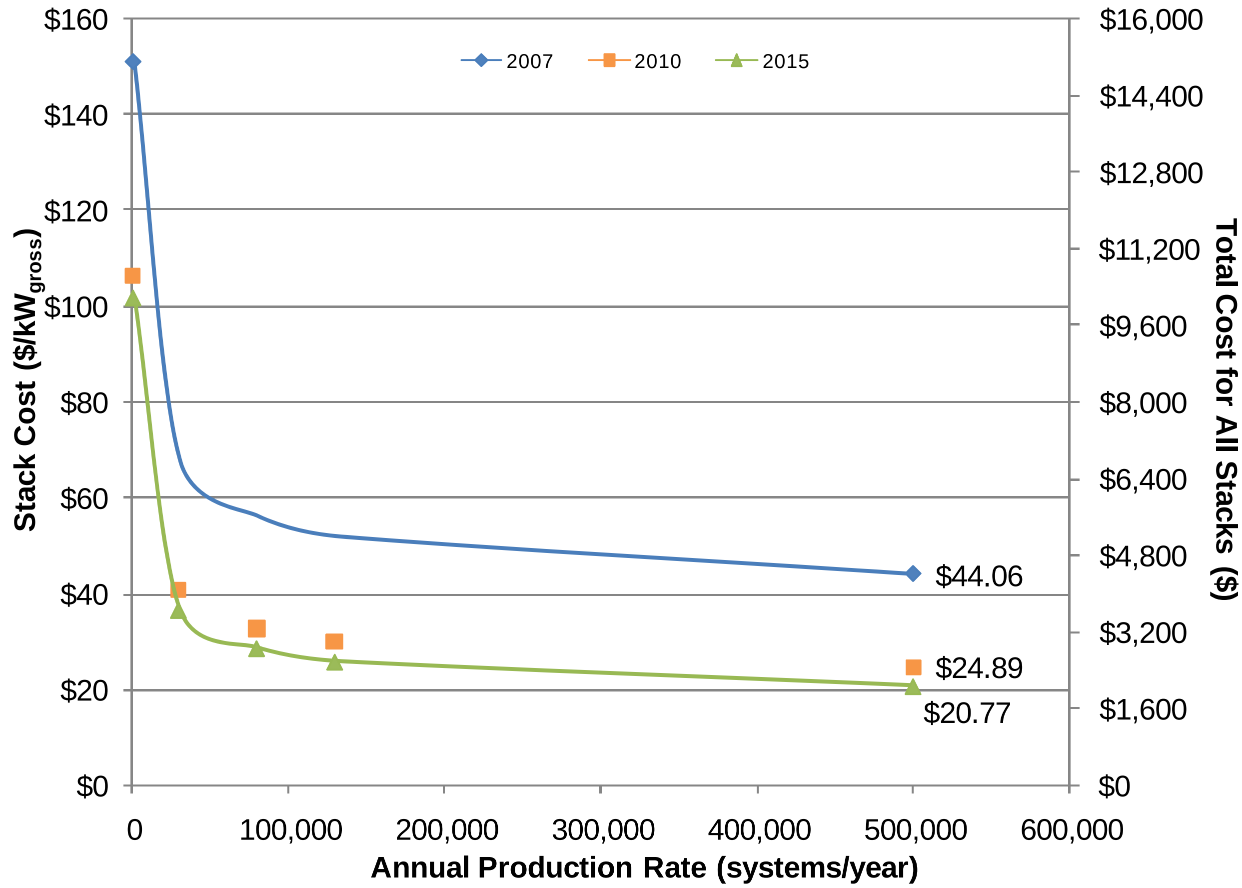

Figure 102. Stack cost vs. annual production rate

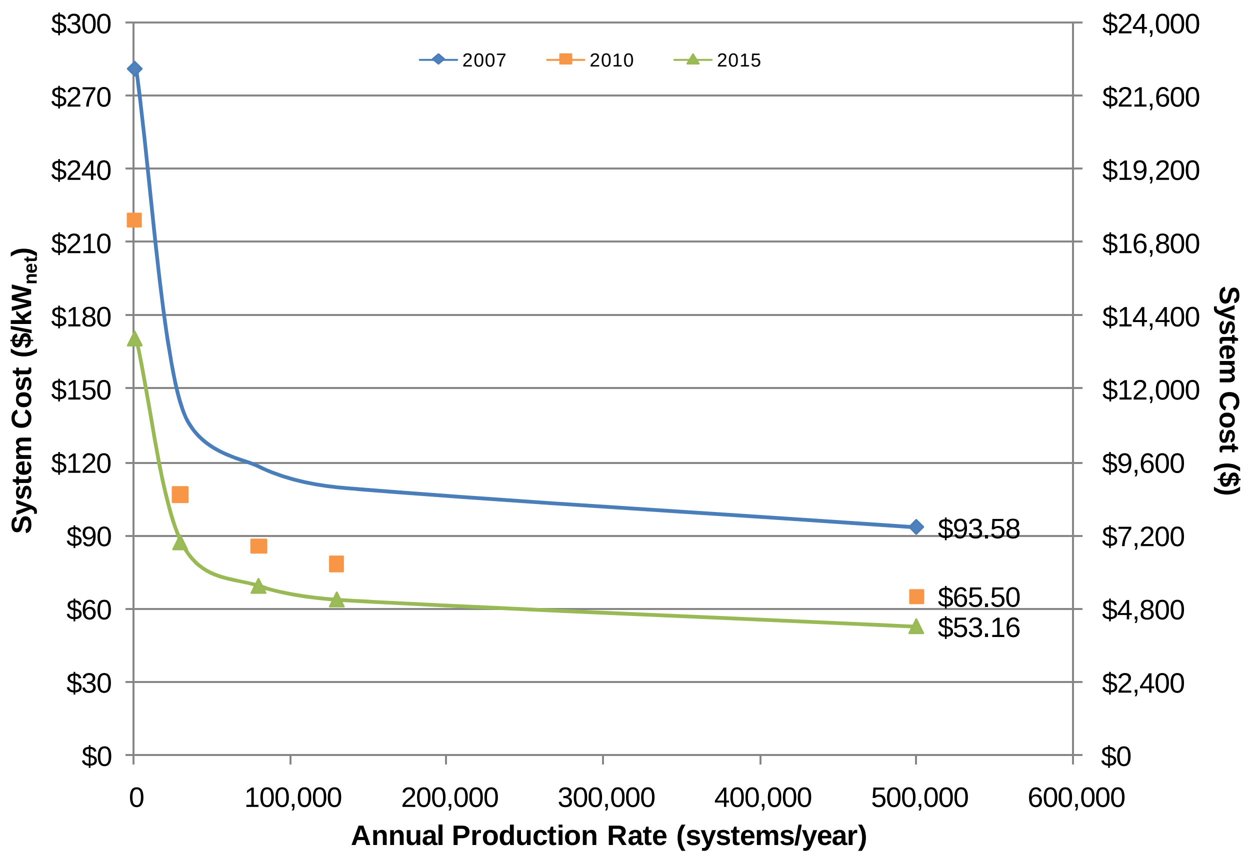

Figure 103. System cost vs. annual production rate

Source	Characteristic	Units	2007	2010	2015
DOE Target:	Stack Cost	$/kW$_{e\ (net)}$	**-**	**$25**	**$15**
Study Estimate:	Stack Cost	$/kW$_{e\ (net)}$	**$50**	**$27**	**$23**
DOE Target:	System Cost	$/kW$_{e\ (net)}$	**-**	**$45**	**$30**
Study Estimate:	System Cost	$/kW$_{e\ (net)}$	**$94**	**$66**	**$53**

Figure 104. DOE targets vs. DTI estimates for the stack & system

Key conclusions from the analysis include:

- Projections for the 2010 and 2015 technology systems are estimated at approximately $2-8/kW higher than DOE targets for the stack and $21-23/kW higher than DOE targets for the system.
- Substantial cost reductions (factors of 3-5) are achieved by increasing manufacturing volume from 1,000 to 500,000 systems per year production rate.
- 74% of the cost reduction between high (500,000 systems/year) and low production (1,000 systems/year) is achieved at the 30,000 systems/year production rate. 91% of the cost reduction is achieved at the 130,000 systems/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 (47-59%). Consequently, R&D to reduce, simplify, or eliminate BOP components is needed to achieve a significant overall system cost reduction.
- Four subsystems account for 85% of BOP costs: air compression, sensors/controllers, fuel loop (i.e. hydrogen pressure control), and wiring/piping/manifolding.
- BOP costs drop significantly as technology level advances due to simplification of the air compressor, humidification, and H_2 sensor subsystems. R&D is needed to ensure that these projected advances are achieved.
- While only a preliminary system assembly analysis was conducted, a maximum cost of ~$1.2/kW is indicated, and only half of that at 500,000 systems/year. More detailed analysis is required to improve confidence in this estimate.
- Metallic stamped bipolar plates and injected molded polymer bipolar plates are both economically viable pathways and have a projected cost of $3-7/kW across all production rates examined.
    - Performance and longevity issues may be a larger factor than cost in selecting between metallic plates and molded plates.
    - Appropriate alloy selection for metallic bipolar plates may obviate costly anti-corrosion coatings.
- A large advance in stack power density (from 583 mW/cm^2 to 1,000 mW/cm^2) is expected to occur between 2007 and 2010 as a result of improvements in basic membrane and MEA performance. This power density improvements results in an approximate 38% stack cost reduction. Should this power density improvement not incur, stack costs will be much increased.
- Membrane cost is expected to drop a factor of 10 due primarily to mass production methods. Material cost of the Nafion ionomer (or some other ion conductive ionomer) likewise is expected to drop 10 fold in cost.
- Consistent with this analysis's goal of estimating the future fuel cell system cost based on expected advances in fuel cell technology, we have postulated advanced membranes that simultaneously achieve improved performance (1,000 mW/cm^2) at elevated peak temperatures (120°C). Such performance is currently unachievable and the pathway to achievement is not clear. Consequently, this analysis estimates membrane cost as if a standard Nafion membrane is used in the future even though a substantially different chemistry membrane will almost undoubtedly be used.

- Even though platinum catalyst loadings are expected to drop (from 0.35 $mgPt/cm^2$ to 0.2 $mgPt/cm^2$) between 2007 and 2015, catalyst still remains a significant cost element in the stack ($8-65/kW).
- High speed catalyst application via roll-to-roll processing equipment holds promise in slashing application costs to ~$0.1/kW. However, such techniques must achieve excellent MEA performance - a point not yet proven.
- The gas diffusion layer (GDL) ranges from $3/kW to $43/kW and is identified as a significant cost element within the stack. While currently envisioned as a macroporous carbon electrode with a secondary microporous layer, alternate materials and fabrication methods should be explored to reduce cost.
- Hot pressing of the MEA and cutting it to cell size are observed to be minor cost elements.
- A polymer gasket insertion molded around the MEA is seen to be a cost viable design and manufacturing concept consistent with system operation and the economically processing of the subcomponents. Costs are estimated at $2-3/kW.
- Stack assembly using either manual or robotic assembly is relatively inexpensive: $0.7/kW to $2/kW.
- Stack conditioning to improve MEA performance is estimated at <$1/kW based on an extrapolation of current procedures.
- Basic 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.

Future work will concentrate on refining the analysis to ensure accuracy and on exploring ways that future cost reductions may be realized. In particular, balance of plant components will be further scrutinized to obtain more accurate cost estimates.