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

DOE Hydrogen Program

Brian James, Jeff Kalinoski & Kevin Baum

Status Presentation to Fuel Cell Tech Team

September 24, 2008

Directed Technologies, Inc.
3601 Wilson Blvd., Suite 650
Arlington, VA 22201
(703) 243-3383 [v]
(703) 243-2724 [f]

DIRECTED TECHNOLOGIES INC

Overview

Timeline

- Base Period:
  - 100% complete
  - Feb 17, 2006 to Feb. 16, 2008
- Option year 1 of 3:
  - 65% complete
  - Started Feb 16, 2008

Budget

- Total project funding
  - $325K (2 year base period)
  - $182k (opt. yr. 1)
  - Contractor share: $0
- Funding for FY 2008
  - $182k

Barriers

- Manufacturing costs
- Materials costs (particularly precious metal catalysts)

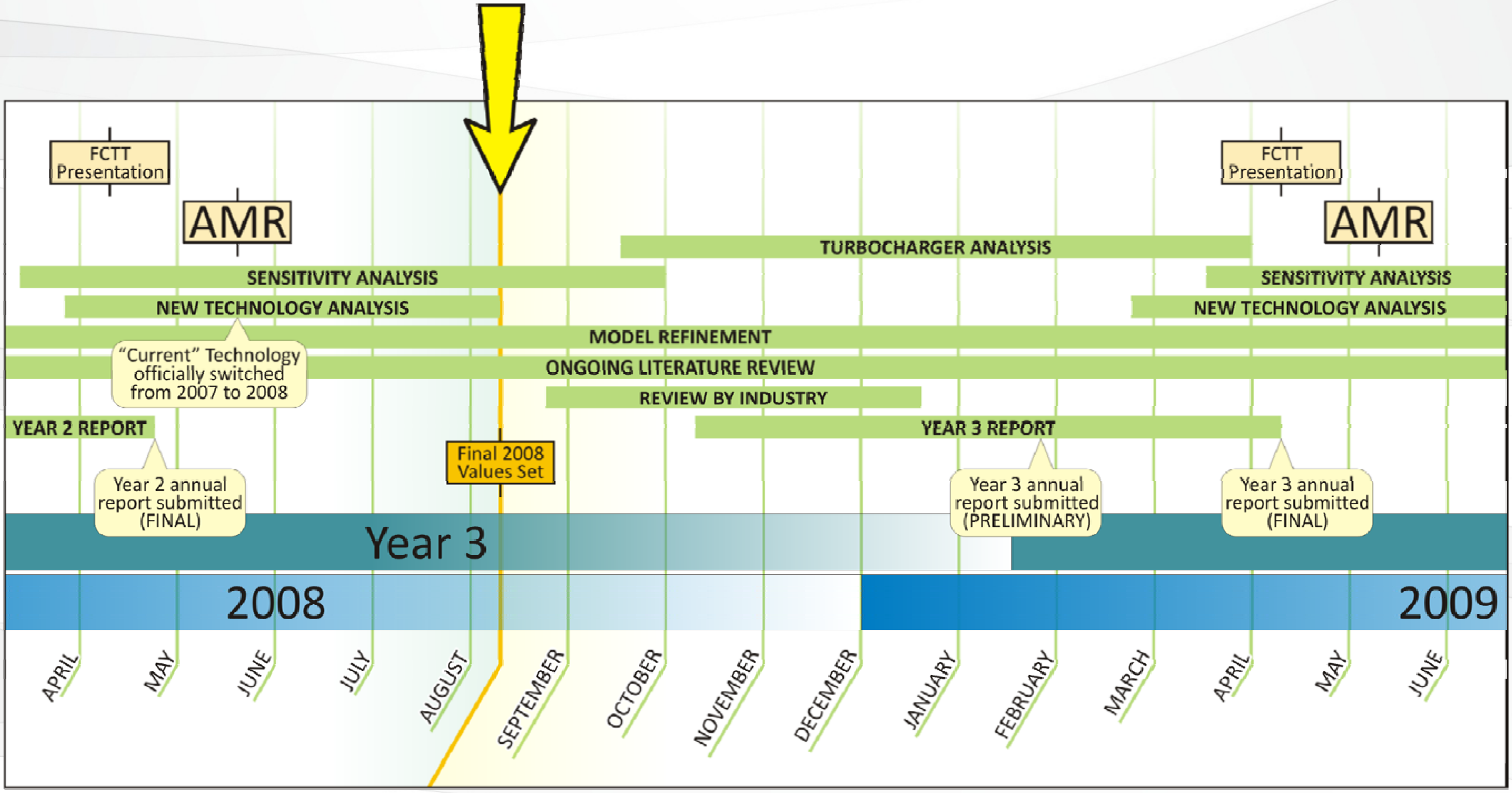
DOE Cost Targets

Characteristic	Units	2008	2010	2015
Stack Cost	$/kW$_{e\ (net)}$	-	$25	$15
System Cost	$/kW$_{e\ (net)}$	-	$45	$30

Collaborations

- Extensive interaction with industry/researchers to solicit design & manufacturing metrics as input to cost analysis.

Project Timeline



- Work since the AMR has been researching and applying changes to the determine 2008 system
- Primary focus was BOP components
- Bipolar plate coatings and alternative gasketing methods were also improved

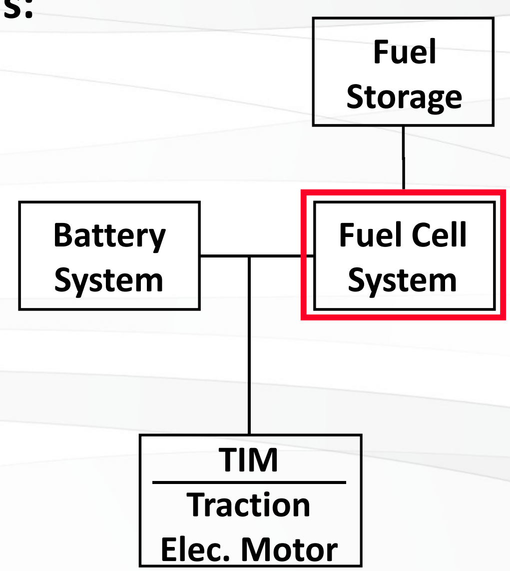
DIRECTED TECHNOLOGIES INC.

Objectives

1. **Identify the <u>lowest cost system design</u> and <u>manufacturing methods</u> for an 80 kW_e direct-H_2 automotive PEMFC system based on 3 technology levels:**
    - 2008 status technology
    - 2010 projected technology
    - 2015 projected technology

2. **Determine costs for these 3 tech level systems at 5 production rates:**
    - 1,000 vehicles/year
    - 30,000 vehicles/year
    - 80,000 vehicles/year
    - 130,000 vehicles/year
    - 500,000 vehicles/year

3. **Analyze, quantify & document impact of system performance on cost**
    - Use cost results to guide future component development



Project covers complete FC system (specifically excluding battery, traction motor/inverter, and storage)

General Rules

- 80kW$_{net}$ system (90 kW$_{gross}$ for 2008 system)
- 1k to 500k annual system production
- U.S. labor rates: $60/hr (fully loaded)
- $1,100/troy oz. Pt cost used for consistency (currently ~$1,370/troy oz.)

Some costs *NOT* included:

- 10% capital cost contingency
- Warranty
- Building costs (equipment cost included but not building in which equipment is housed)
- Sales Tax
- Non-Recurring Engineering Costs

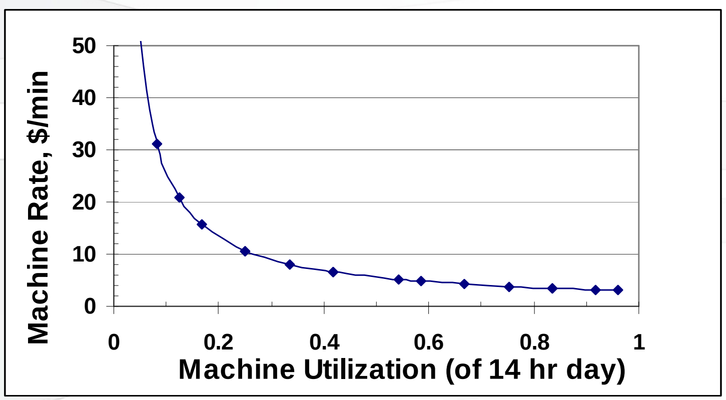
DTI's DFMA®-Style Costing Methodology

- **DFMA® (Design for Manufacturing and Assembly) is a registered trademark of Boothroyd-Dewhurst, Inc.**
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Co. design/costing method for past 20+ years
- **DTI practices are a blend of:**
  - "Textbook" DFMA®, industry standards & practices, DFMA® software, innovation and practicality

Estimated Cost = (Material Cost + Processing Cost + Assembly Cost) x Markup Factor

Manufacturing rate cost factors:

1. **Material Costs**
2. **Manufacturing Method**
3. **Machine Rate**
4. **Tooling Amortization**



Methodology Reflects Cost of Under-utilization:

Capital Cost, Installation → **Initial Expenses** → **Used to calculate annual Capital Recovery Factor based on:**
- Equipment Life
- Interest Rate
- Corporate Tax Rate

Maint./Spare Parts, Utilities, Miscellaneous → **Operating Expenses**

(Annual Capital Repayment + Annual Operating Payments) / Annual Minutes of Equipment Operation = Machine Rate ($/min)

DIRECTED TECHNOLOGIES INC.

Key Technical Targets Define System

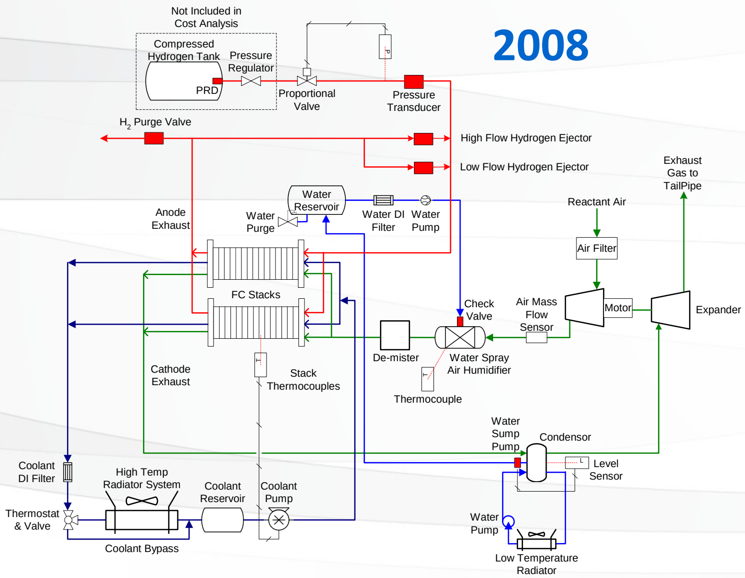
		Current (2007, 2008)		2010		2015	
		2007 Status	2008 Status	2007 Status	2008 Status	2007 Status	2008 Status
DOE Tech. Targets that drive analysis:							
Stack Efficiency @ Rated Power	%	55%	55%	55%	55%	55%	55%
MEA Areal Power Density @ Peak Power	mW/cm^2	583	525	1,000	1,000	1,000	1,000
Total Pt-Group Catalyst Loading	$mg PGM/cm^2$	0.35	0.21	0.30	0.30	0.20	0.20
Key Derived Performance Parameters:							
System Gross Electric Power (Output)	kW	90.3	90.3	86.8	86.8	87.1	87.1
Active Area	cm^2	417	463	233	233	234	234
Cell Voltage @ Peak Power	V/cell	0.677	0.677	0.677	0.677	0.677	0.677
Operating Pressure (Peak)	atm	2.3	2.3	2.0	2.0	1.5	1.5

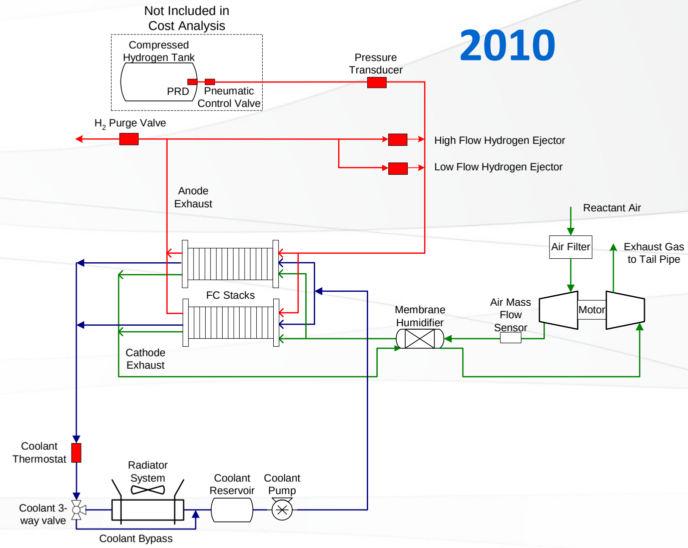
- **A few key DOE Technical Target values are used to anchor system definition**
- **All other system parameters flow from DTI calculations & judgment**

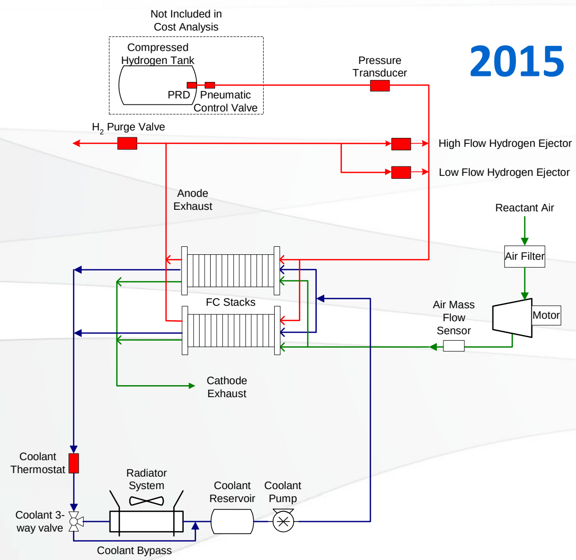
System Comparison

	2008 Technology	2010 Technology	2015 Technology
Power Density (mW/cm^2)	525 (was 583)	1,000	1,000
Total Pt loading (mg/cm^2)	0.21 (was 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 SS 316 (uncoated) **Future options: SS 304 with Coating**	Stamped SS 316 (uncoated) **Future options: SS 304 with Coating**	Stamped SS 316 (uncoated) **Future options: SS 304 with Coating**
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	Carbon Paper Macroporous Layer with Microporous layer applied on top
Catalyst Application	Double-sided vertical die-slot coating of membrane	Double-sided vertical die-slot coating of membrane	Double-sided vertical die-slot coating of membrane
Air Humidification	Water spray injection	Polyamide Membrane	None
H_2 Humidification	None	None	None
Exhaust Water Recovery	SS Condenser (Liquid/Gas HX)	SS Condenser (Liquid/Gas HX)	None
MEA Containment	Injection molded **Viton** MEA Frame around Hot-Pressed MEA	Injection molded **Viton** MEA Frame around Hot-Pressed MEA	Injection molded **Viton** MEA Frame around Hot-Pressed MEA
Coolant & End Gaskets	**Screen Printed Resin**	**Screen Printed Resin**	**Screen Printed Resin**
Freeze Protection	Drain water at shutdown	Drain water at shutdown	Drain water at shutdown
H_2 Sensors	2 for FC system 1 for passenger cabin (not in cost estimate) 1 for fuel system (not in cost estimate)	1 for FC system 1 for passenger cabin (not in cost estimate) 1 for fuel system (not in cost estimate)	None
End Plates/Compression System	Composite molded end plates with compression bands	Composite molded end plates with compression bands	Composite molded end plates with compression bands
Stack/System Conditioning	5 hours of power conditioning - from UTC's US Patent #7,078,118	4 hours of power conditioning - from UTC's US Patent #7,078,118	3 hours of power conditioning - from UTC's US Patent #7,078,118

Different Technology Schematics







Changes from 2008 to 2010:

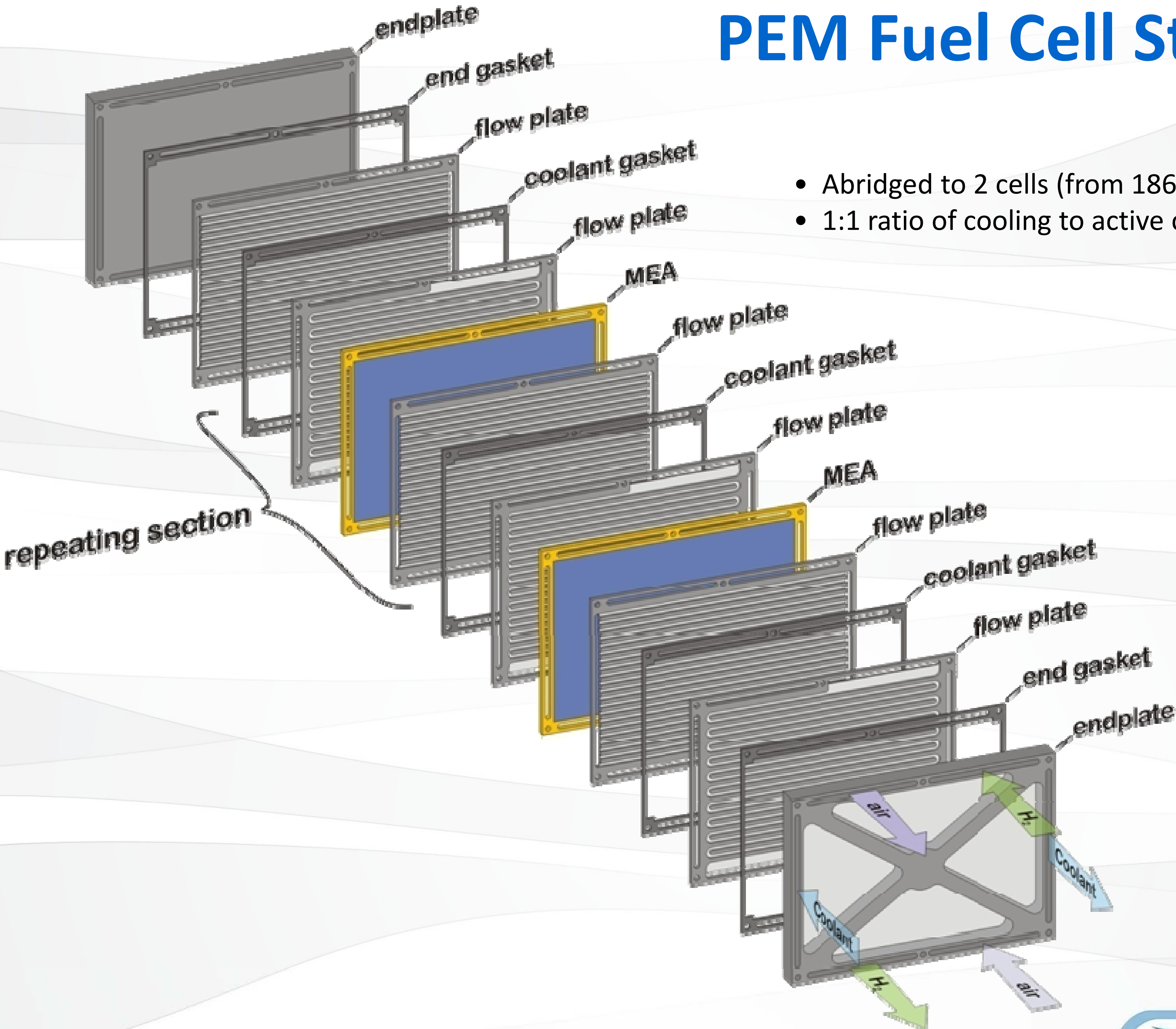
- Higher temperature, smaller radiator
- Use of membrane humidifier (instead of water spray)
- Lower pressure
- Centrifugal compressor/expander (instead of twin lobe compressor)

Changes from 2010 to 2015:

- Higher temperature, smaller radiator
- No humidification
- Lower pressure
- Smaller compressor
- No expander

DIRECTED TECHNOLOGIES INC.

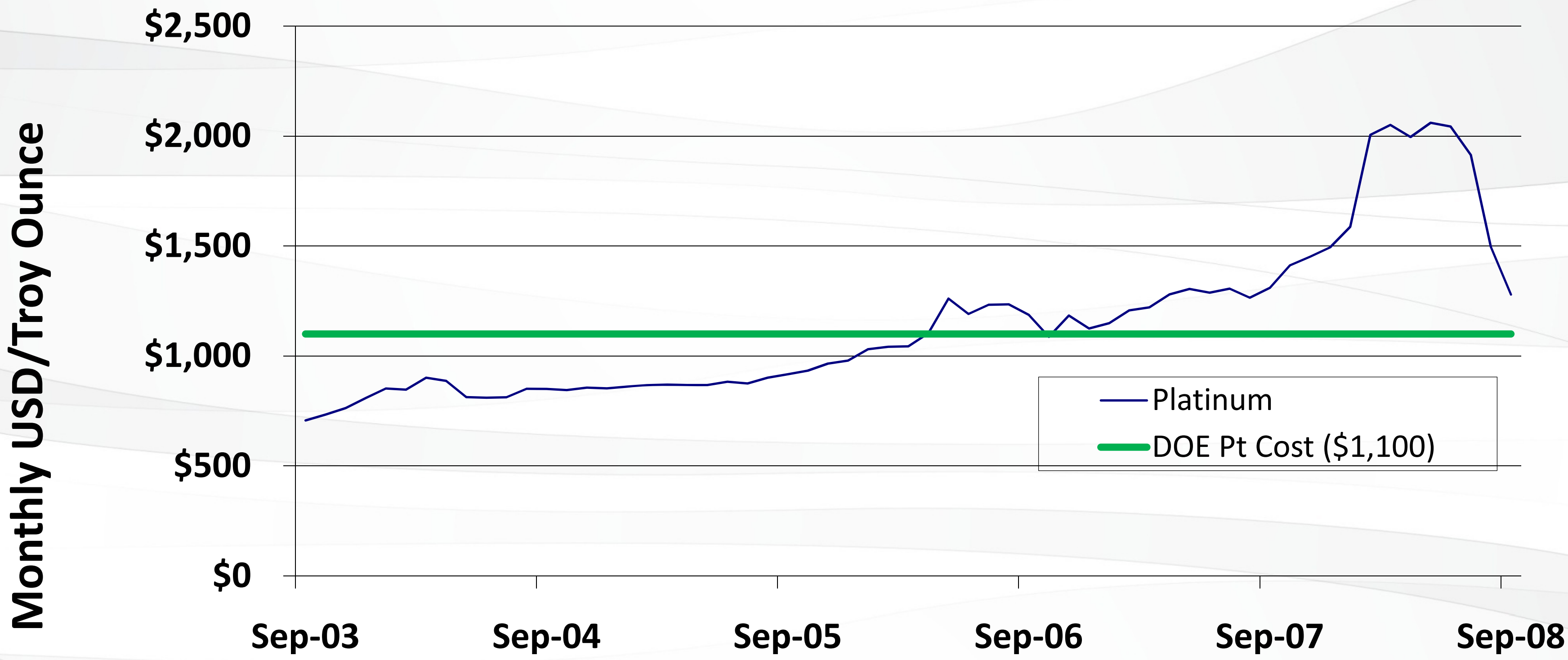
PEM Fuel Cell Stack



- Abridged to 2 cells (from 186) for clarity
- 1:1 ratio of cooling to active cells

DIRECTED TECHNOLOGIES INC.

Platinum Cost



- Currently trading at **~$1,235/tr.oz.**
- Platinum cost is highly variable:
  - **3/04/08:** $2,280/tr.oz.
  - **9/16/08:** $1,105/tr.oz. *(almost back to our $1,100 value!)*
- Consistent use of $1,100 facilitates “apples-to-apples” system costs comparison
- Especially for the current technology system, Pt is a major system cost component, so estimates are highly susceptible to Pt cost fluctuations

DIRECTED TECHNOLOGIES INC.

Noteworthy Changes Since Last Year

Current Technology, 500,000 Systems/Year

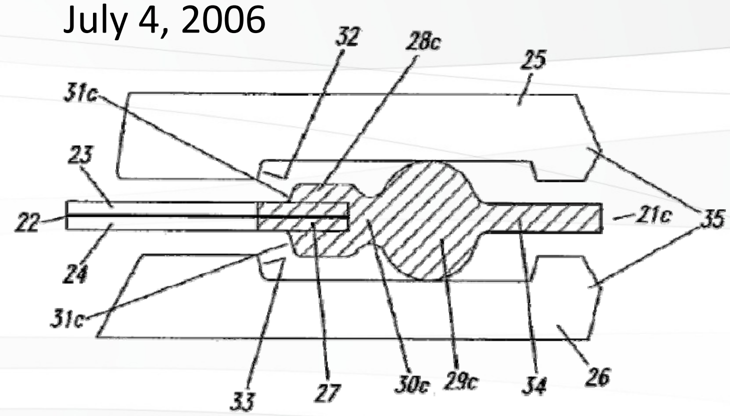
Item	Notes	Effect on System Cost ($/kW$_{net}$)
Technology Level	Changed baseline to "2008"	-
H_2 Sensors	Updated the Hydrogen sensor prices	($1.25)
System Controllers	Switched from 2 controllers to 1	($2.50)
Belly Pan	Added new DFMA analysis	($0.21)
Power Density	Changed MEA Areal Power Density to 525 mW/cm^2	$4.92
Catalyst Loading	Changed Total Platinum-Group Catalyst Loading to 0.21 mg/cm^2	($12.36)
Machine Lifetimes	Review and standardization of Machine Lifetimes	($0.05)
Wiring	Added new analysis	$0.03
MEA Frame	Updated Material costs, improved calculations	$1.80
Membrane	Changed membrane thickness	($0.08)
Humidifier	Improved Water Spray Humidifier cost estimate	($0.33)
Bipolar Plates	Updated 316L and 304 sheet metal prices from Allegheny Ludlum	$0.73
Coolant & End Gaskets	Switched to Screen Printed Coolant & End Gaskets	($4.06)
Startup Battery	Removed the Startup Battery from the analysis	($0.63)
Low Temp. Radiator Loop	Reduced to 67% of cost to account for duties not included in analysis	($0.70)
Miscellaneous	Numerous small changes	$1.80
Total System Cost ($/kW$_{net}$)		**($12.89)**

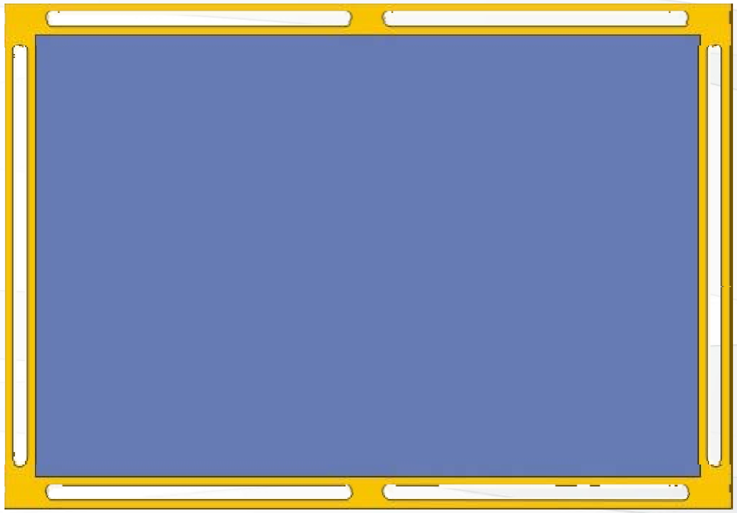
DIRECTED TECHNOLOGIES INC.

MEA Frame-Gasket Concept

MEA with Integrated Seal

Ballard Patent US 7,070,876
July 4, 2006





<u>Insertion molding of gasket around MEA</u>

DuPont Viton® GF-S w/filler & curing additives

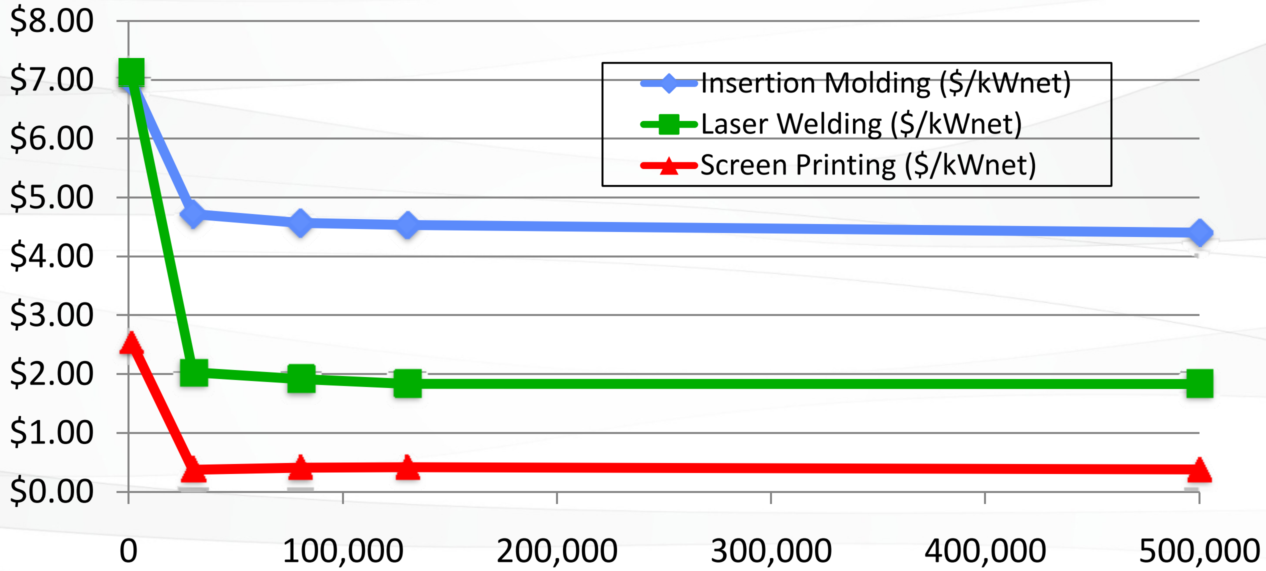
- $36.87/kg (for 500k systems/year)
- 1.92 g/cc density

		2007 Analysis	Silicone Updates	2008 Analysis
Material		Silicone	Henkel Loctite 5714	Viton GF-S
Cost	$/kg	$14.33	$56.70	$36.87
Density	g/cc	1.4	1.05	1.92
Cure Time	s	150	~180	120
Cure Temp		127 °C	-	187 °C

<u>Process:</u>

- Vacuum mixer to remove air bubbles
- Low pressure injection followed by 20 ksi compression
- 2 min cycle time at 187°C
- Add'l room temperature cure outside of mold

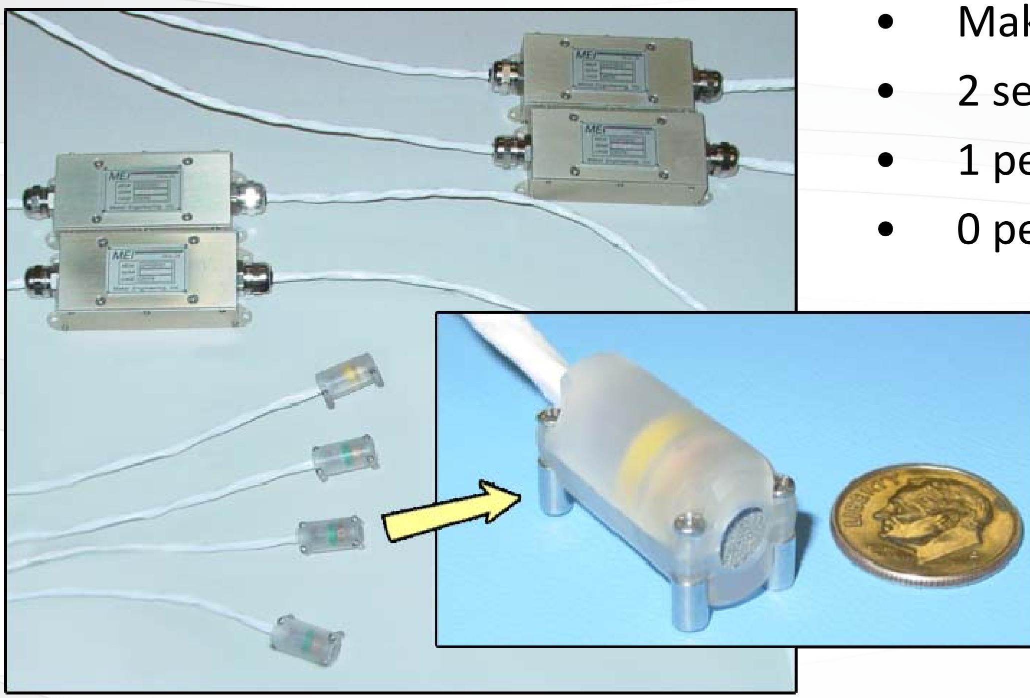
Coolant Gaskets



- 2007 Analysis used insertion molding for creation of coolant gaskets
- 2 new gasketing methods examined:
  - Laser Welding & Screen Printing
  - Both provide cost savings over Insertion Molding, especially with updated (higher) silicone/Viton costs
- **Screen-printing selected**
  - Formula-A Resin (from Dana Corp. Patent) printed onto the stainless steel bipolar plates
  - Indexed process, batch length ranges from **9.62 sec** to **4 sec**, depending on machine used
  - **$387k** process line used for 1,000 sys/year, faster **$1.4M** process line used for other 4 rates
  - UV Curing, robotic handling
  - **$0.38/kW$_{net}$** at 2008 technology, 500k sys/year
- Screen-printing process also applied to End Gaskets
  - **$0.04/kW$_{net}$ savings** compared to Insertion Molding

DIRECTED TECHNOLOGIES INC.

Hydrogen Sensors



- Makel Engineering sensors
- 2 sensors/system at 2008 tech.
- 1 per system for 2010 tech.
- 0 per system for 2015 tech.

- **$850/sensor** vs. $2000/sensor in '07 Analysis
  - 1k systems/year, 2008 tech.
- **$100/sensor** vs. $150/sensor in '07 Analysis
  - 500k systems/year 2008 tech.

		Current Technology					2010 Technology					2015 Technology				
	Annual Production Rate	1,000	30,000	80,000	130,000	500,000	1,000	30,000	80,000	130,000	500,000	1,000	30,000	80,000	130,000	500,000
2008	Sensors per System	2	2	2	2	2	1	1	1	1	1	0	0	0	0	0
2008	Hydrogen Sensor Cost ($)	$850.00	$438.00	$320.00	$261.00	$100.00	$750.00	$367.00	$256.00	$201.00	$50.00	$500.00	$238.00	$161.00	$124.00	$20.00
2008	Hydrogen Sensors Cost ($/system)	$1,700.00	$876.00	$640.00	$522.00	$200.00	$750.00	$367.00	$256.00	$201.00	$50.00	$0.00	$0.00	$0.00	$0.00	$0.00
2008	Hydrogen Sensors Cost ($/kW$_{net}$)	$21.25	$10.95	$8.00	$6.53	$2.50	$9.38	$4.59	$3.20	$2.51	$0.63	$0.00	$0.00	$0.00	$0.00	$0.00
2007	Sensors per System	1	2	2	2	2	1	1	1	1	1	0	0	0	0	0
2007	Hydrogen Sensor Cost ($)	$2,000.00	$200.00	$187.00	$175.00	$150.00	$2,000.00	$200.00	$187.00	$175.00	$150.00	$2,000.00	$200.00	$187.00	$175.00	$150.00
2007	Hydrogen Sensors Cost ($/system)	$2,000.00	$400.00	$374.00	$350.00	$300.00	$2,000.00	$200.00	$187.00	$175.00	$150.00	$0.00	$0.00	$0.00	$0.00	$0.00
2007	Hydrogen Sensors Cost ($/kW$_{net}$)	$25.00	$5.00	$4.68	$4.38	$3.75	$25.00	$2.50	$2.34	$2.19	$1.88	$0.00	$0.00	$0.00	$0.00	$0.00

DIRECTED TECHNOLOGIES INC.

Belly Pan

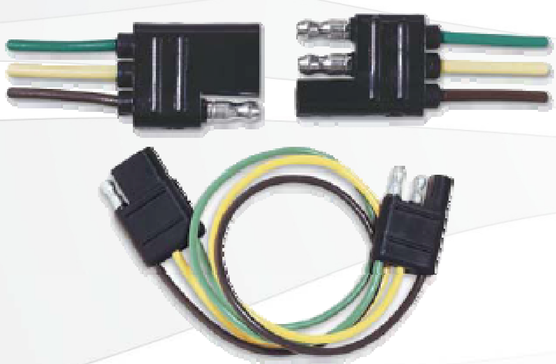
Analysis	Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2008 Analysis	2008	Material ($/system)	$3.41	$3.41	$3.41	$3.41	$3.41
		Manufacturing ($/system)	$139.70	$4.98	$2.08	$1.41	$0.51
		Tooling ($/system)	$5.67	$0.19	$0.07	$0.04	$0.01
		Total Cost ($/system)	$148.78	$8.58	$5.56	$4.86	$3.94
		Total Cost ($/kW_net)	$1.86	$0.11	$0.07	$0.06	$0.05
	2010	Material ($/system)	$3.41	$3.41	$3.41	$3.41	$3.41
		Manufacturing ($/system)	$139.70	$4.98	$2.08	$1.41	$0.51
		Tooling ($/system)	$5.67	$0.19	$0.07	$0.04	$0.01
		Total Cost ($/system)	$148.78	$8.58	$5.56	$4.86	$3.94
		Total Cost ($/kW_net)	$1.86	$0.11	$0.07	$0.06	$0.05
	2015	Material ($/system)	$3.41	$3.41	$3.41	$3.41	$3.41
		Manufacturing ($/system)	$139.70	$4.98	$2.08	$1.41	$0.51
		Tooling ($/system)	$5.67	$0.19	$0.07	$0.04	$0.01
		Total Cost ($/system)	$148.78	$8.58	$5.56	$4.86	$3.94
		Total Cost ($/kW_net)	$1.86	$0.11	$0.07	$0.06	$0.05
2007 Analysis	2007	**Total Cost ($/system)**	$400.12	$41.12	$17.58	$12.18	$5.75
		Total Cost ($/kW_net)	$5.00	$0.51	$0.22	$0.15	$0.07
	2010	**Total Cost ($/system)**	$219.04	$29.19	$13.09	$9.38	$5.02
		Total Cost ($/kW_net)	$2.74	$0.36	$0.16	$0.12	$0.06
	2015	**Total Cost ($/system)**	$219.66	$29.27	$13.12	$9.40	$5.02
		Total Cost ($/kW_net)	$2.75	$0.37	$0.16	$0.12	$0.06

- New bottom-up DFMA analysis
- Vacuum thermoforming process
- Polypropylene, **$1.15/kg**
- Manual Loading used at all mfg. rates except 500k/year
- **$0.05/kW_net** (500k/year)

Wiring

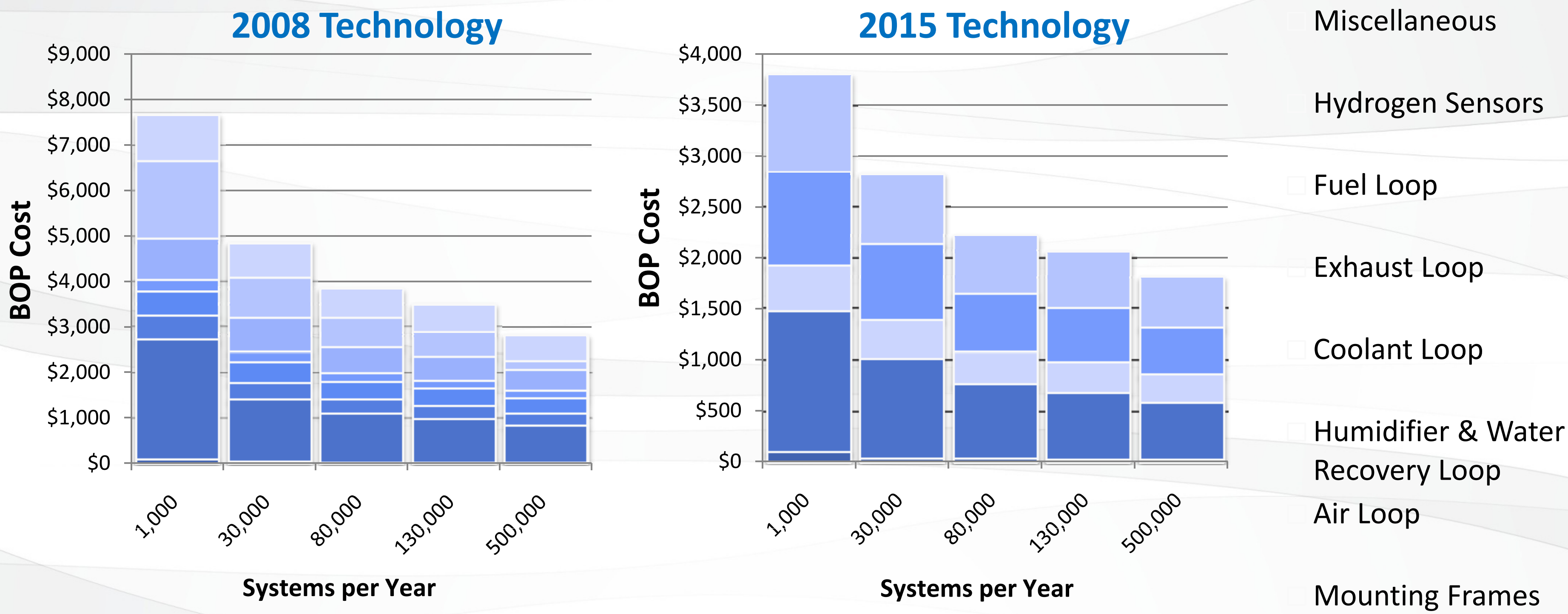
- New bottom-up analysis
  - Detailed wiring requirements & BOM
  - Vendor quotes on wires/connectors
- Analysis only covers materials costs
(installation covered in system assembly)

- 9 different cable types in each system:
  - 22 data cables
  - 17 power cables
  - 38 meters of total length
- **$2.65/kW$_{net}$**



DIRECTED TECHNOLOGIES INC.

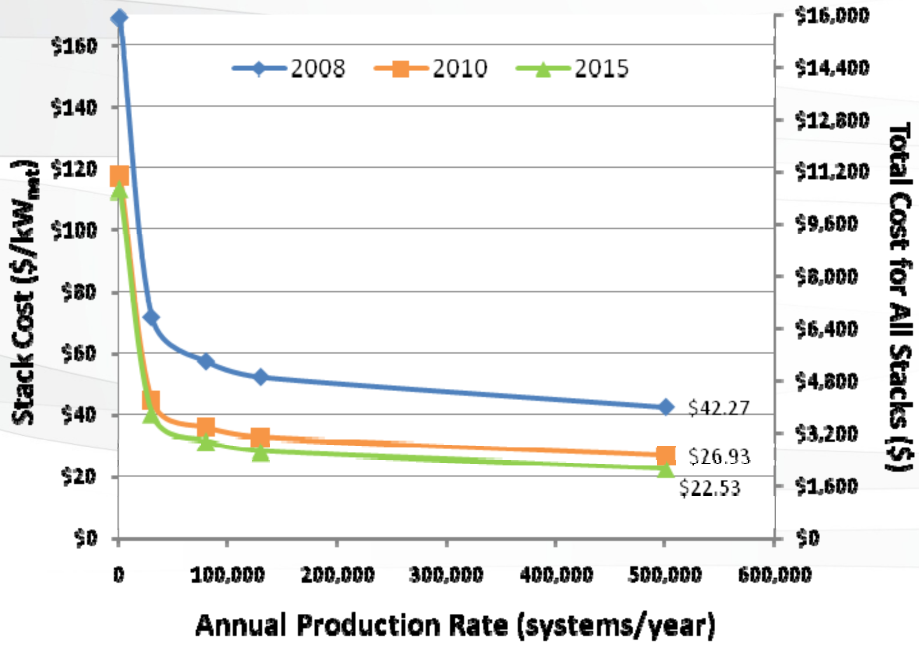
Balance of Plant

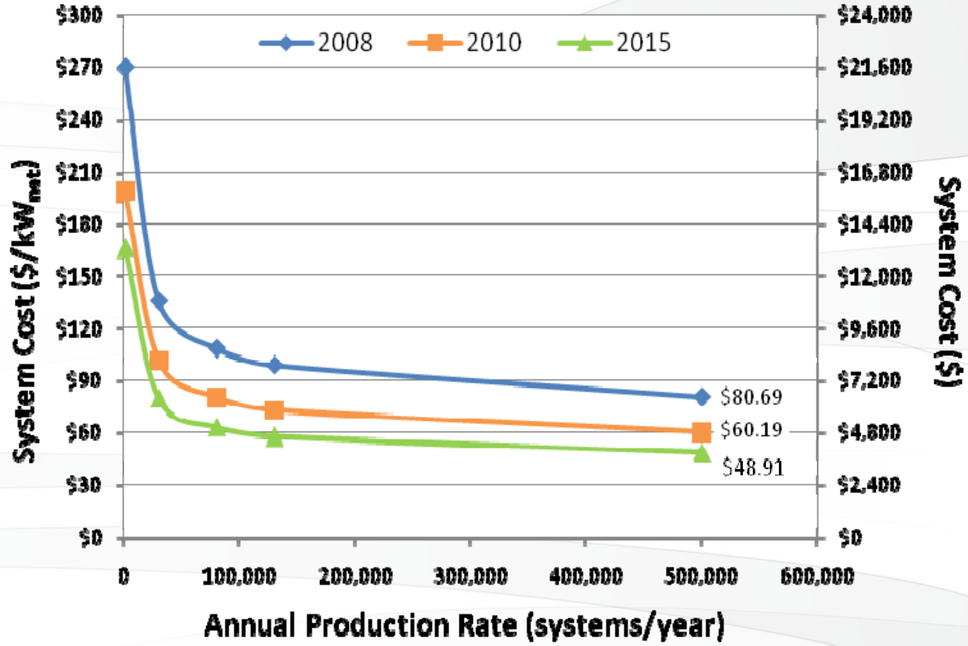


- Increases in manufacturing rate leads to largest savings.
- Air Compressors and Sensors are the two categories that have the largest $ decline, together yielding 70% of the BOP cost decline from low production to high production.
- Technology changes yields lesser BOP savings and comes in form of reduced/eliminated components.
- Simplifications of Air, Humidifier, & Coolant Loops yield majority of technology improvement savings.

DIRECTED TECHNOLOGIES INC.

Stack & System Costs vs. Annual Production Rate



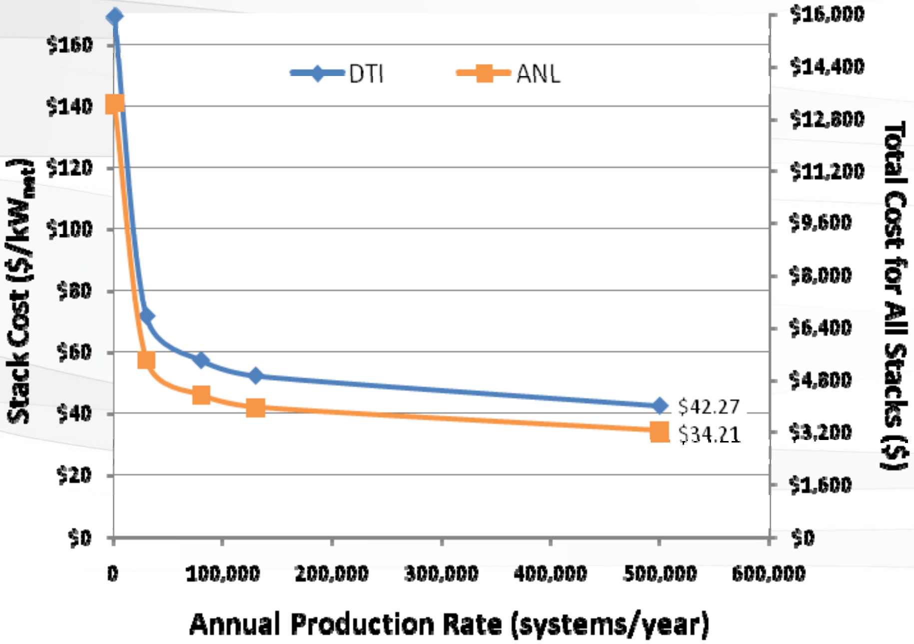


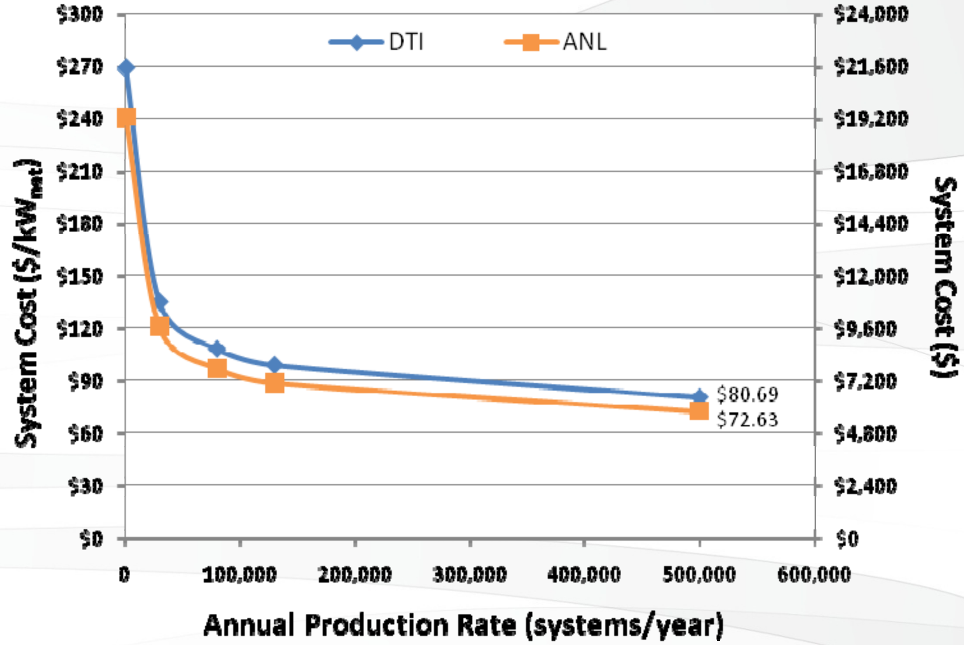
- Power Density = **525 mW/cm²**
- Catalyst Loading = **0.21 mg/cm²**

			2007 Status	2008 Status	2007 Status	2008 Status	2007 Status	2008 Status
			Current (2007, 2008)		**2010**		**2015**	
DOE Target:	Stack Cost	$/kW$_{e\ (net)}$	-	-	$25	$25	$15	$15
Study Estimate:	Stack Cost	$/kW$_{e\ (net)}$	$50	$42	$27	$27	$23	$23
DOE Target:	System Cost	$/kW$_{e\ (net)}$	-	-	$45	$45	$30	$30
Study Estimate:	System Cost	$/kW$_{e\ (net)}$	$94	$81	$66	$60	$53	$49

DIRECTED TECHNOLOGIES INC.

Stack & System Costs vs. Annual Production Rate (ANL vs. DTI)





DTI:

- Power Density = **525 mW/cm²**
- Catalyst Loading = **0.21 mg/cm²**

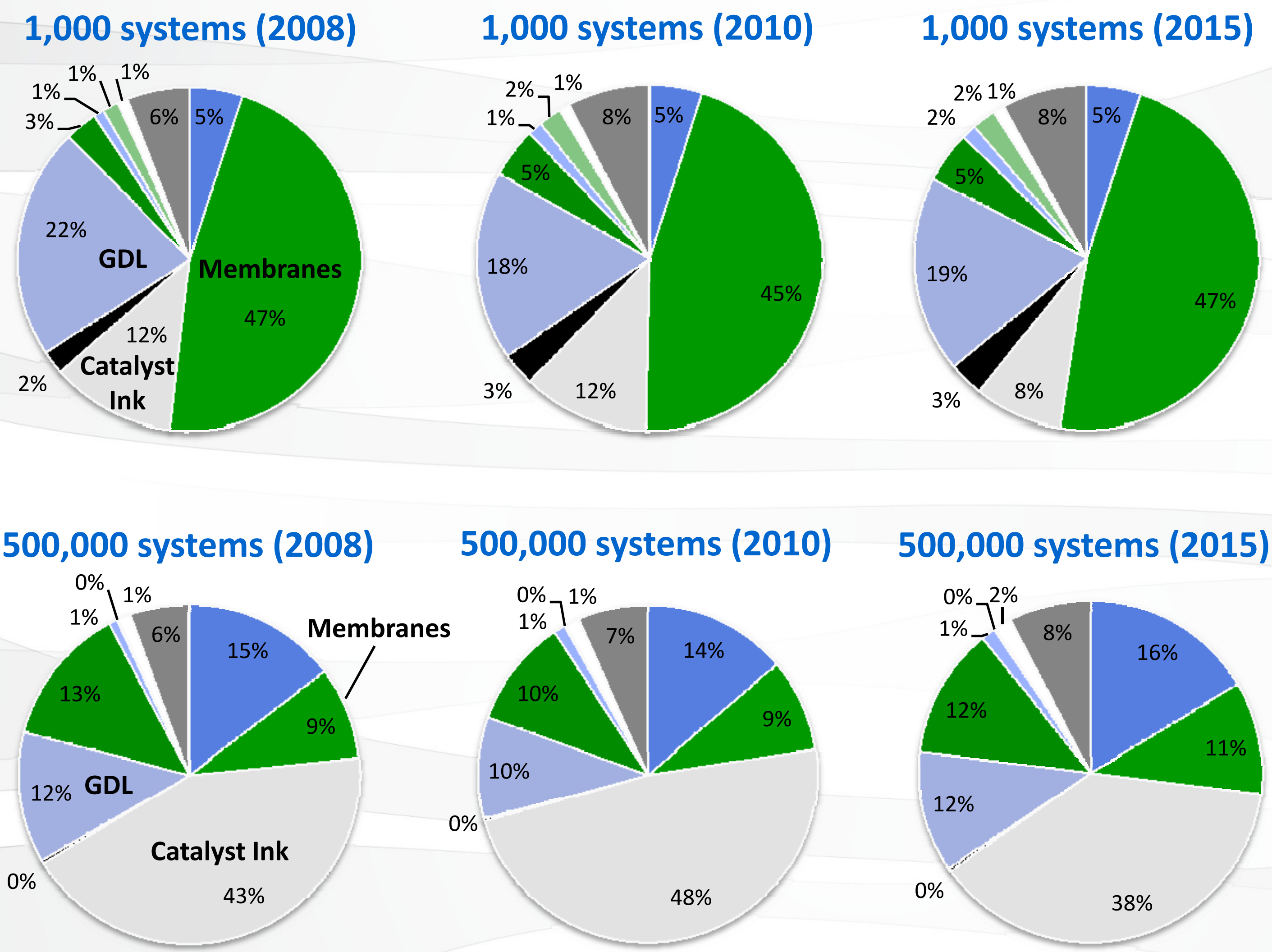
"ANL":

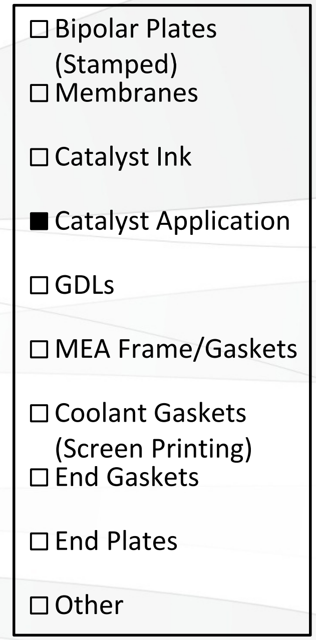
- Power Density = **715 mW/cm²**
- Catalyst Loading = **0.25 mg/cm²**

		DTI	ANL
		2008	
Stack Cost	$/kW$_{e\ (net)}$	$42	$34
System Cost	$/kW$_{e\ (net)}$	$81	$73

DIRECTED TECHNOLOGIES INC.

Stack Component Cost Distribution





- **Membrane dominates cost at low production**
- **Catalyst Ink dominates cost at high production**
- **Top 3 costs:**
  - **Membrane**
  - **Catalyst Ink**
  - **GDL**

DIRECTED TECHNOLOGIES INC.

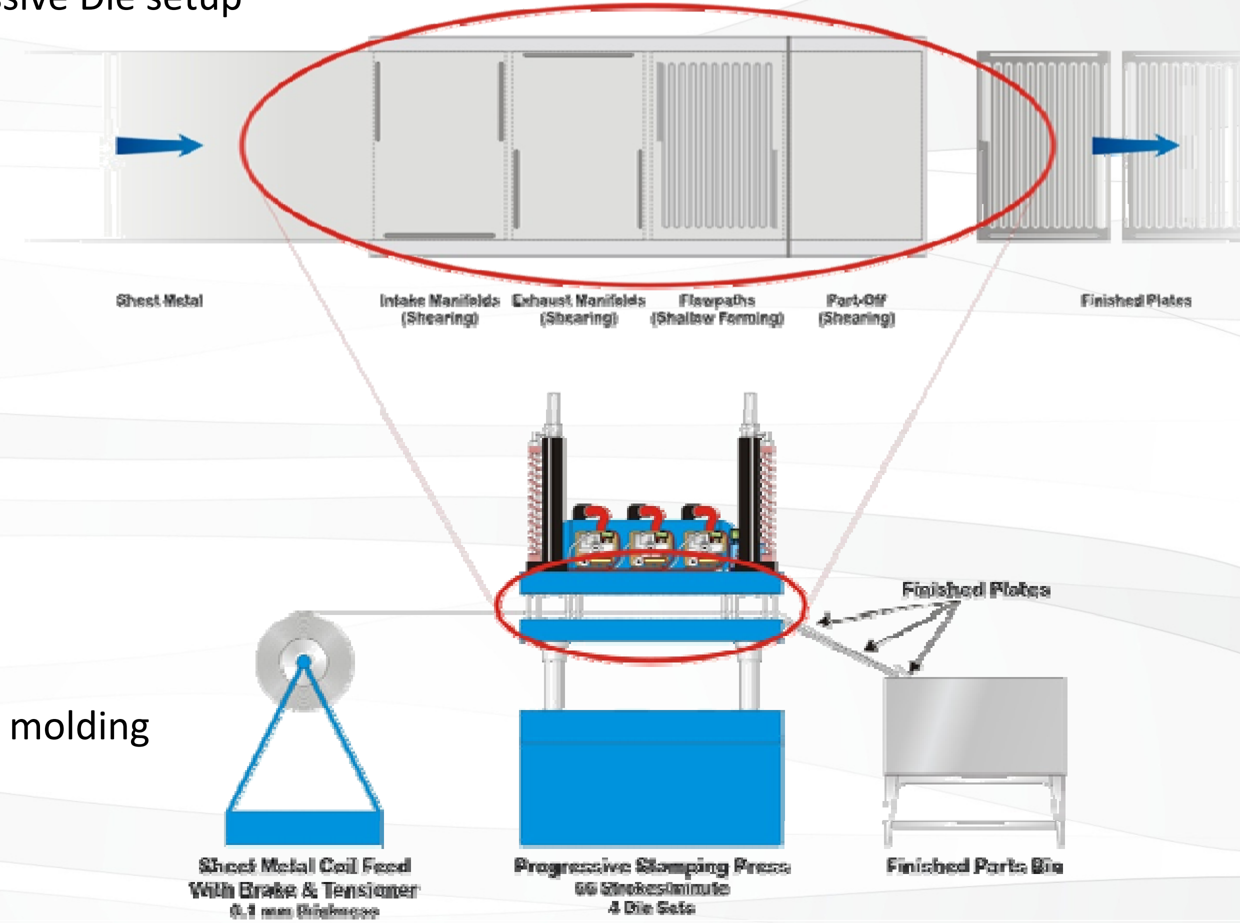
Additional Analyses Not Included in 2008 Update Cost

- Bipolar Plate Coatings
  - Oak Ridge National Labs – Nitriding
  - TreadStone – proprietary process

- NSTF catalyst deposition (3M)

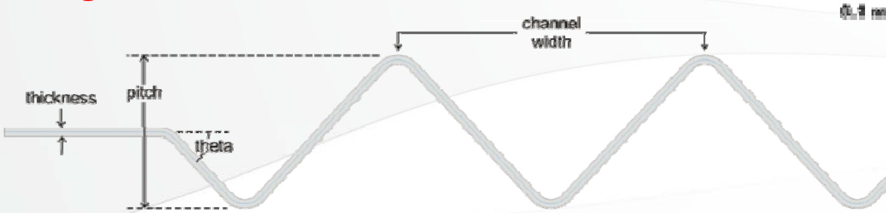
Stamped Stainless Steel Bipolar Plates

- Stamped using a 4-stage Progressive Die setup
- Greater tooling costs offset significantly by reduced labor & energy costs over individual die setup
- Rapid plate production (up to 80 plates/minute)
- SS 304 or SS 316



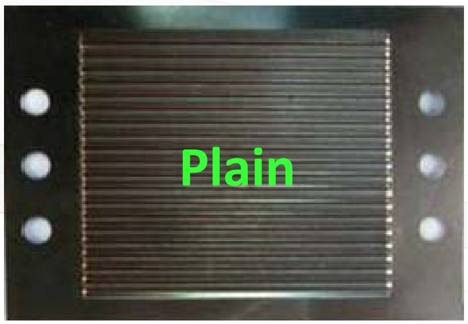
<u>Stamped vs. other methods:</u>

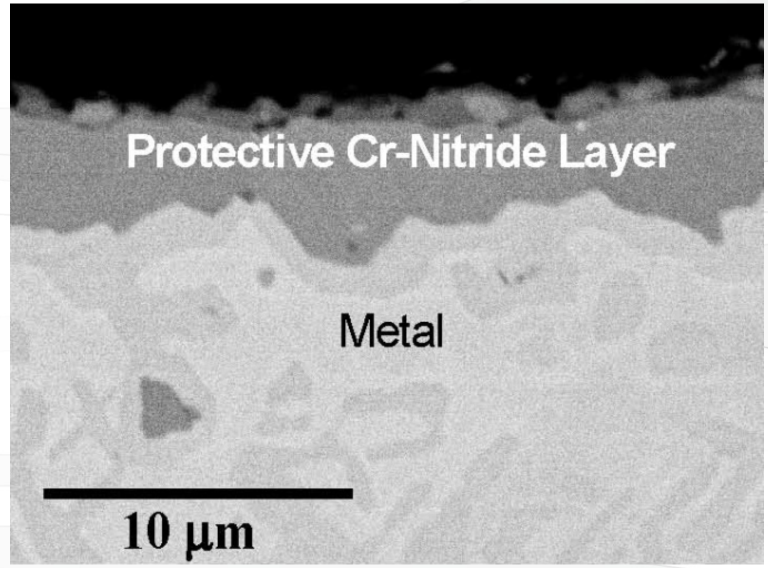
- Less brittle than composites
- Lower tooling cost than injection molding
- Lower gas permeation
- Borderline corrosion resistance
- High contact resistance



Nitrided Coatings for Stamped Bipolar Plates

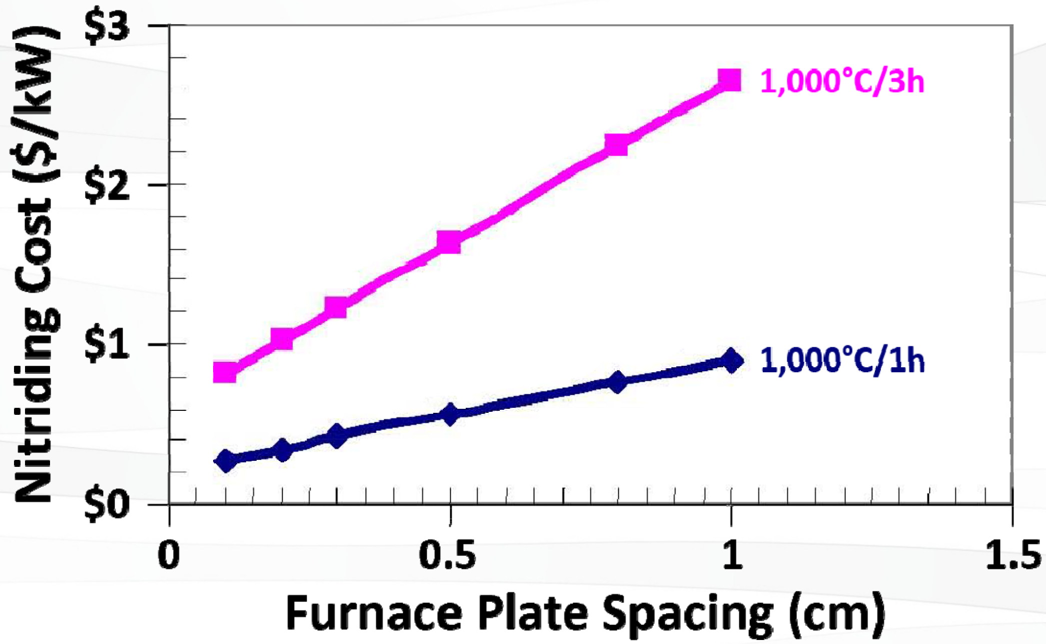
<u>Thermally Grown Cr-Nitride</u>





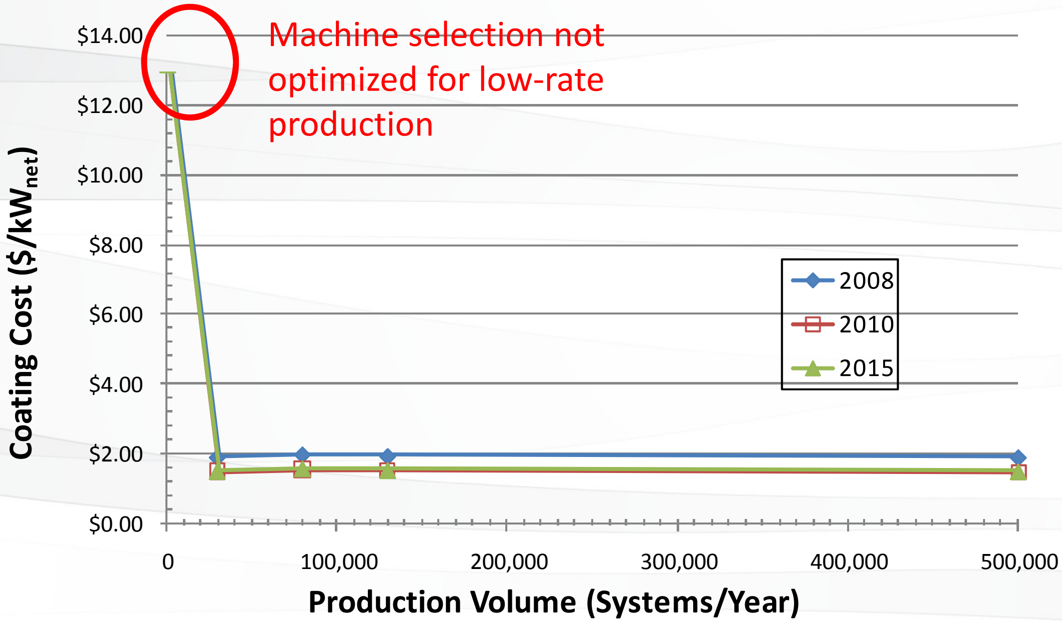
- **Oak Ridge National Lab (Mike Brady) is investigating nitrided coatings for bipolar plate corrosion resistance with low surface contact resistance**
- **Surface conversion, not a deposited coating: High temperature favors reaction of all exposed metal surfaces**
  - No pin-hole defects (other issues to overcome)
  - Amenable to complex geometries (flow field grooves)
- **Conventional nitriding currently conducted in large automated facilities: anticipated process for bipolar plates is similar but simpler & faster**

Nitrided Coatings for Bipolar Plates (continued)



- **Batch processing and automated "lights out" facilities analyzed**
- **Automated, step-continuous conventional nitriding system at 500,000 systems/year**
  - Markup not included
  - Keys are short nitriding cycle and high furnace plate stacking density
- **$0.75/kW potentially feasible**
- **Nitriding by pulsed plasma arc lamp in range of $0.16 - 0.44/kW**
  - Feasibility to nitride Ti in "seconds" previously demonstrated

TreadStone Coatings for Stamped Bipolar Plates



	2008	2015
316 Plate	$6.34/kW	$3.82/kW
Coating	$1.92/kW	$1.51/kW
Coated Plate	$8.26/kW	$5.33/kW

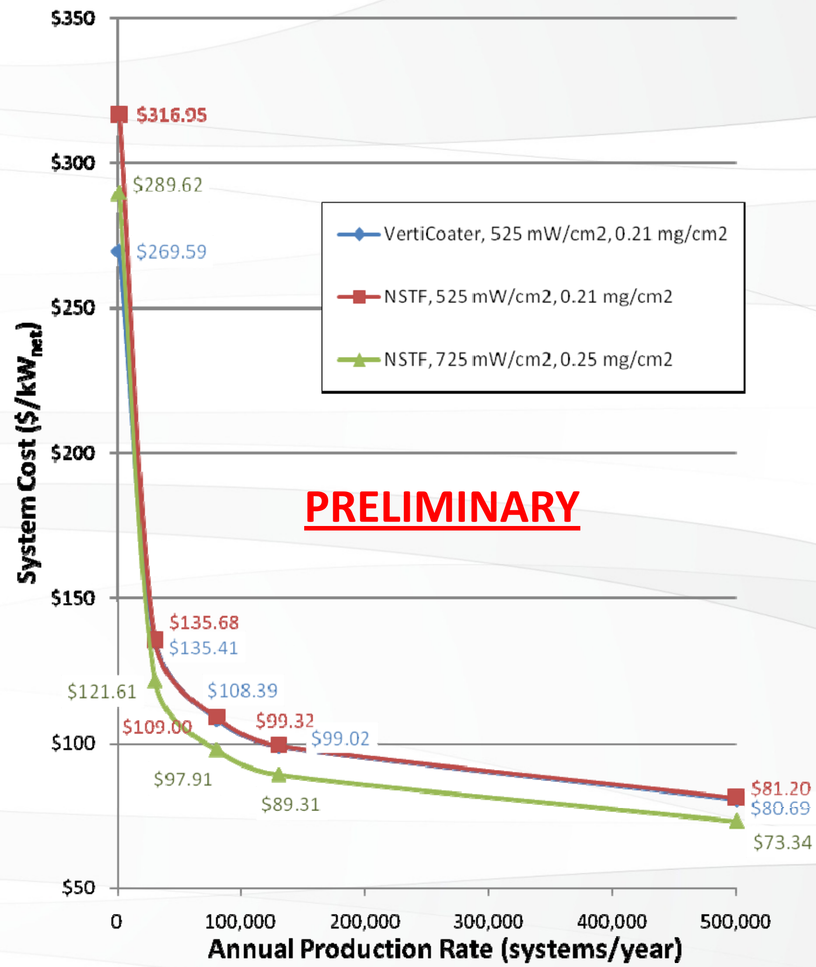
- **NDA signed with TreadStone, collaborated closely to model their multi-step process**
- **Based on US patent # 7,309,540 B2, and proprietary parameters**
- **Conducted preliminary evaluation based on information from TreadStone**
- **Conducted more in-depth version based on detailed equipment manufacturer specifications**
  - **Improved machinery schematics, capital costs, machine rates, etc.**
- **Analyzed the impact of switching from SS 316 to the cheaper SS 304 for coated plates**
  - **Cost savings of SS 304 is small**
  - **Further savings might be achieved with cheaper plate materials such as Aluminum**

DIRECTED TECHNOLOGIES INC.

NanoStructured Thin Film Catalysts (NSTF) - 3M Method

(Preliminary Analysis)

- A **preliminary** DFMA analysis based on the work of 3M (Mark Debe)
- 4-step process:
  1) Physical vapor deposition of PR-149 (Perylene Red pigment 149) onto DuPont Kapton® polyamide web
     - **PR-149: 25°C, 0.1µm thickness**
  2) Vacuum annealing
     - **245°C**, **20 min** dwell time
     - Creates crystalline whiskers by a screw dislocation growth process
  3) Platinum and a bimetallic alloy are magnetron-sputtered onto the crystalline nanostructures
     - **30 second** dwell time
  4) Roll-to-roll transfer of catalyst from Kapton® to membrane
- Compared to existing VertiCoater method:
  - Appears to be **slightly more expensive**
    - **$0.51/kW_{net}$ increase** (2008 technology, 500k sys/yr)
  - May facilitate a higher Areal Power Density
    - **715 mW/cm², 0.25 mg/cm²** (from 3M), up from 525, 0.21
    - Net cost savings of **$7.35/kW_{net}$ (2008, 500k sys/yr)**



DIRECTED TECHNOLOGIES INC.

Future Work

- **Year 3 (Option Year 1):** Due February 2009
  - **Annual Update**
    - Expanded sensitivity analysis
      - Use results to drive the rest of the analysis
    - Documentation & Reporting
      - Write the 2008 Report Update
      - Refine the spreadsheet model for submission
    - Investigate platinum alloys & alternate catalyst deposition techniques, including NanoStructured Thin Film Catalysts
  - **Optional Task 3.3:**
    - Optimization analysis
      - Analyze trade-offs between power density & catalyst loading for minimized cost
    - CMEU cost study
      - Partner with Honeywell to determine a detailed CMEU cost
      - Seeking to find more detailed CMEU cost breakdown & new cost-saving pathways
      - Base analysis on existing Honeywell design
      - Honeywell will provide a detailed cost breakdown based largely on vendor quotes
      - DTI will develop a DFMA model around it

End of Presentation

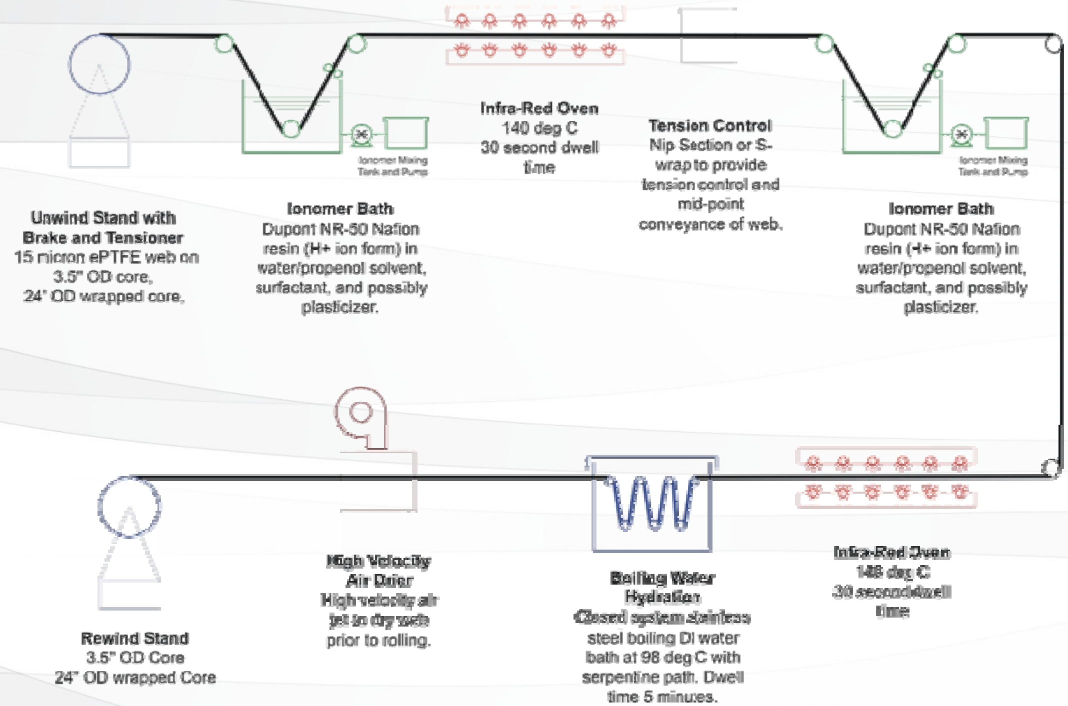
Thank you.

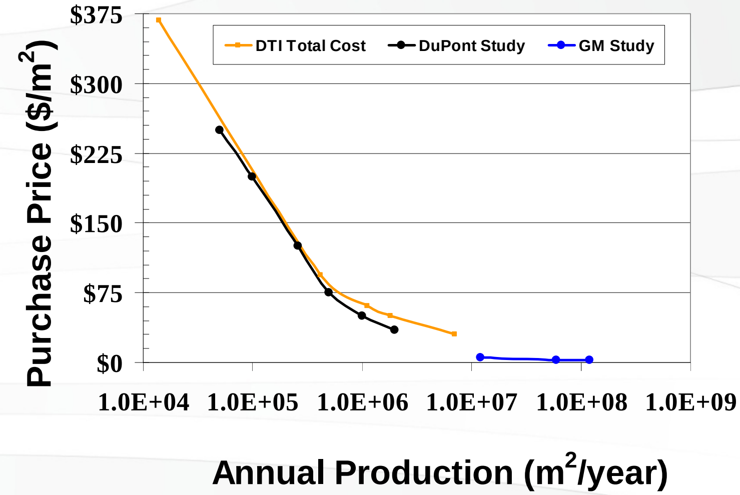
Additional Slides

The following slides are provided for further clarification

Proton Exchange Membrane

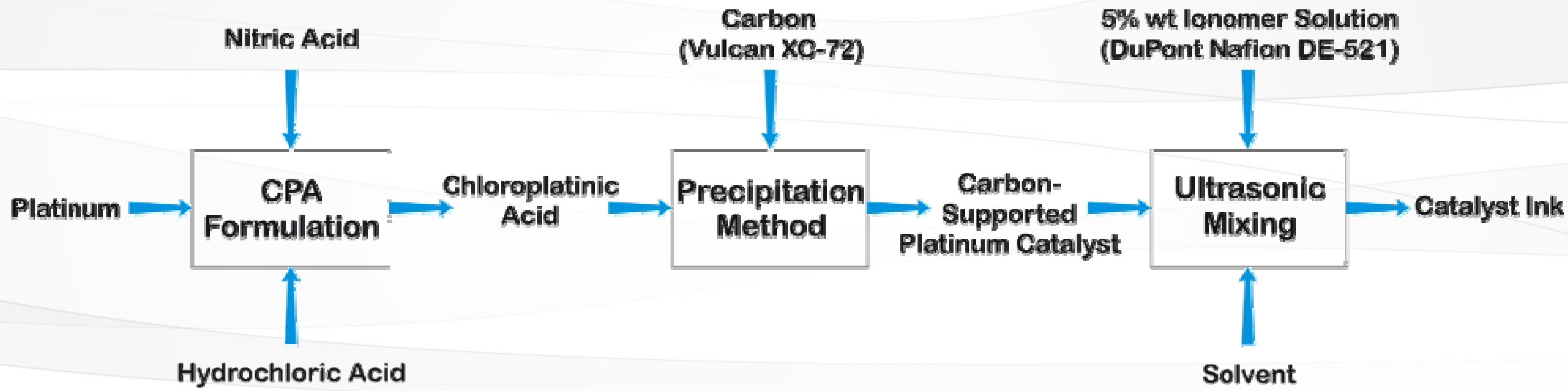
(Based on Gore-like approach)





- Assumes 67% max equipment utilization consistent with 25%/year growth rate (over 5 years)
- Assumes 50%-80% membrane yields
- Membrane $\$/m^2$ is reduced solely by increases in manufacturing rate, not by technological advancement with year
- However, fewer m^2 are required in future years because areal power density increases

Catalyst Ink



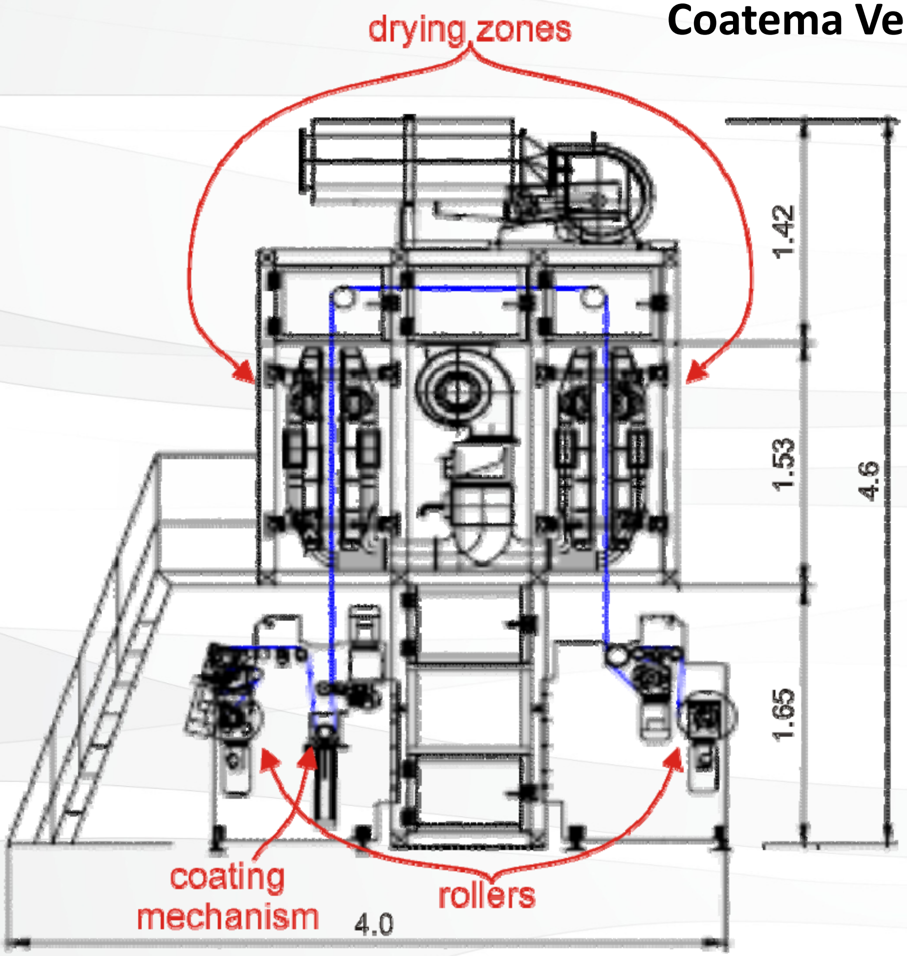
Catalyst Preparation

- Batch Pt-precipitation onto Vulcan XC-72 carbon support via a hexachloroplatinic acid (CPA) precursor (notional E-TEK-like precipitation method)

Catalyst Ink composition

- 7% (wt) Nafion Ionomer
- 15% (wt) Carbon supported Pt (40% (wt) Pt on Vulcan XC-72)
- 78% (wt) Solvent (50/50 mixture of methanol and DI water)
- Mixed Ultrasonically
- Material costs are dominated by the platinum ($1,100/tr. oz.)

Catalyst Application



Coatema VertiCoater

Size L/W/H: 4.0 x 1.7 x 4.6 m
Power Consumption: ~50 kW
Weight: ~4000 kg
Speed: 0.1 - 15 m/min
Roll Width: 50 - 1000 mm
Drying: Infrared 3 m - 6 m jet dryer

- Dual-sided Vertical coating process
  - Die-slot catalyst applicator
  - Modeled as Coatema VertiCoater
- Simultaneously applies catalyst slurry to both sides of the membrane
- Maximum roll width of **1 meter**
- Line speed of **10m/min**
- **$750,000 capital cost/line** (not counting 40% for installation)

Bill of Materials: Stack (2008 Technology)

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 (Stamped)	$352.33	$256.05	$254.22	$254.95	$253.67
MEAs					
Membranes	$3,276.06	$556.89	$352.06	$278.52	$151.80
Catalyst Ink & Application	$974.90	$764.47	$760.17	$757.96	$747.94
GDLs	$1,532.80	$917.04	$575.23	$451.70	$214.87
M & E Hot Pressing	$38.30	$17.11	$17.11	$16.87	$16.86
M & E Cutting & Slitting	$27.46	$3.38	$2.85	$2.93	$2.79
MEA Frame/Gaskets	$196.31	$240.25	$232.80	$232.26	$226.35
Coolant Gaskets (Screen Printing)	$102.52	$14.98	$16.37	$16.70	$15.21
End Gaskets (Screen Printing)	$90.08	$11.18	$4.22	$2.62	$0.71
End Plates	$68.43	$33.64	$29.66	$27.81	$20.92
Current Collectors	$15.07	$9.21	$8.03	$7.52	$6.99
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	$26.27	$11.28	$10.81	$10.85	$10.80
10% Cost Contingency	$0.00	$0.00	$0.00	$0.00	$0.00
Total Stack Cost	$6,762.11	$2,863.20	$2,286.62	$2,083.62	$1,690.94
Total Cost for All Stacks	$13,524.22	$5,726.40	$4,573.25	$4,167.25	$3,381.88
Total Stack Cost ($/kW$_{net}$)	$169.05	$71.58	$57.17	$52.09	$42.27
Total Stack Cost ($/kW$_{gross}$)	$149.71	$63.39	$50.62	$46.13	$37.44

- 3.5 to 1 cost reduction between low and high manufacturing rates

DIRECTED TECHNOLOGIES INC

Bill of Materials: Stack (2010 Technology)

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 (Stamped)	$243.36	$153.47	$153.47	$152.56	$152.53
MEAs					
Membranes	$2,244.65	$397.05	$243.18	$188.99	$97.06
Catalyst Ink & Application	$742.99	$547.57	$542.02	$539.47	$532.10
GDLs	$878.18	$456.99	$286.57	$224.10	$106.44
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	$201.34	$124.93	$119.70	$119.38	$115.25
Coolant Gaskets (Screen Printing)	$100.97	$13.47	$14.86	$15.18	$13.03
End Gaskets (Screen Printing)	$90.06	$11.16	$4.20	$2.60	$0.70
End Plates	$50.25	$23.38	$21.55	$19.63	$15.07
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	$24.76	$9.15	$8.84	$8.77	$8.65
10% Cost Contingency	$0.00	$0.00	$0.00	$0.00	$0.00
Total Stack Cost	$4,710.06	$1,781.13	$1,432.61	$1,308.37	$1,077.06
Total Cost for All Stacks	$9,420.13	$3,562.26	$2,865.22	$2,616.73	$2,154.13
Total Stack Cost ($/kW$_{net}$)	$117.75	$44.53	$35.82	$32.71	$26.93
Total Stack Cost ($/kW$_{gross}$)	$108.50	$41.03	$33.00	$30.14	$24.81

- 4.3 to 1 cost reduction between low and high manufacturing rates

Bill of Materials: Stack (2015 Technology)

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 (Stamped)	$243.76	$153.81	$153.81	$152.91	$152.88
MEAs					
Membranes	$2,249.97	$398.84	$244.28	$189.85	$97.51
Catalyst Ink & Application	$550.26	$368.18	$364.00	$361.79	$356.88
GDLs	$880.45	$458.52	$287.50	$224.81	$106.74
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	$201.87	$125.32	$118.58	$118.49	$115.64
Coolant Gaskets (Screen Printing)	$100.98	$13.48	$14.87	$15.19	$13.03
End Gaskets (Screen Printing)	$90.06	$11.16	$4.20	$2.60	$0.70
End Plates	$50.28	$23.39	$21.56	$19.63	$15.07
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	$23.25	$7.02	$6.63	$6.54	$6.51
10% Cost Contingency	$0.00	$0.00	$0.00	$0.00	$0.00
Total Stack Cost	$4,524.38	$1,603.69	$1,253.65	$1,129.50	$901.19
Total Cost for All Stacks	$9,048.76	$3,207.38	$2,507.31	$2,259.00	$1,802.38
Total Stack Cost ($/kW$_{net}$)	$113.11	$40.09	$31.34	$28.24	$22.53
Total Stack Cost ($/kW$_{gross}$)	$103.88	$36.82	$28.78	$25.93	$20.69

- 4.9 to 1 cost reduction between low and high manufacturing rates

Bill of Materials: Balance of Plant (2008 Technology)

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
Mounting Frames	$100.00	$43.00	$33.00	$30.00	$30.00
Air Loop	$2,616.69	$1,364.16	$1,063.94	$954.11	$803.28
Humidifier & Water Recovery Loop	$535.13	$379.81	$315.54	$300.75	$273.77
Coolant Loop (High Temperature)	$528.75	$448.00	$384.25	$363.10	$331.80
Exhaust Loop (Low Temperature)	$169.18	$147.40	$130.32	$123.28	$113.90
Fuel Loop	$927.50	$747.00	$566.50	$528.40	$457.20
System Controller/Sensors	$300.00	$245.00	$230.00	$222.00	$200.00
Hydrogen Sensors	$1,700.00	$876.00	$640.00	$522.00	$200.00
Miscellaneous	$962.30	$706.05	$586.98	$563.07	$515.73
Total BOP Cost	$7,839.55	$4,956.42	$3,950.52	$3,606.71	$2,925.68
Total BOP Cost ($/kW$_{net}$)	$97.99	$61.96	$49.38	$45.08	$36.57
Total BOP Cost ($/kW$_{gross}$)	$86.78	$54.87	$43.73	$39.92	$32.39

- 2.6 to 1 cost reduction between low and high manufacturing rates

Bill of Materials: Balance of Plant (2010 Technology)

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
Mounting Frames	$100.00	$43.00	$33.00	$30.00	$30.00
Air Loop	$1,887.03	$1,327.82	$1,003.72	$891.74	$754.33
Humidifier & Water Recovery Loop	$900.00	$600.00	$425.00	$350.00	$250.00
Coolant Loop (High Temperature)	$498.24	$420.54	$358.32	$338.69	$308.92
Exhaust Loop (Low Temperature)	$0.00	$0.00	$0.00	$0.00	$0.00
Fuel Loop	$927.50	$747.00	$566.50	$528.40	$457.20
System Controller/Sensors	$300.00	$245.00	$230.00	$222.00	$200.00
Hydrogen Sensors	$750.00	$367.00	$256.00	$201.00	$50.00
Miscellaneous	$910.12	$653.87	$534.80	$510.89	$463.55
Total BOP Cost	$6,272.89	$4,404.23	$3,407.34	$3,072.72	$2,514.00
Total BOP Cost ($/kW$_{net}$)	$78.41	$55.05	$42.59	$38.41	$31.42
Total BOP Cost ($/kW$_{gross}$)	$72.25	$50.73	$39.25	$35.39	$28.96

- 2.6 to 1 cost reduction between low and high manufacturing rates

Bill of Materials: Balance of Plant (2015 Technology)

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
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 Temperature)	$453.75	$380.50	$320.50	$303.10	$275.55
Exhaust Loop (Low Temperature)	$0.00	$0.00	$0.00	$0.00	$0.00
Fuel Loop	$927.50	$747.00	$566.50	$528.40	$457.20
System Controller/Sensors	$300.00	$245.00	$230.00	$222.00	$200.00
Hydrogen Sensors	$0.00	$0.00	$0.00	$0.00	$0.00
Miscellaneous	$895.23	$638.98	$519.91	$496.00	$448.66
Total BOP Cost	$4,051.06	$3,021.83	$2,396.70	$2,229.14	$1,963.48
Total BOP Cost ($/kW$_{net}$)	$50.64	$37.77	$29.96	$27.86	$24.54
Total BOP Cost ($/kW$_{gross}$)	$46.51	$34.69	$27.51	$25.59	$22.54

- 2 to 1 cost reduction between low and high manufacturing rates

DIRECTED TECHNOLOGIES INC.

Bill of Materials: System (2008 Technology)

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	$13,524.22	$5,726.40	$4,573.25	$4,167.25	$3,381.88
Balance of Plant	$7,839.55	$4,956.42	$3,950.52	$3,606.71	$2,925.68
System Assembly & Testing	$203.10	$149.58	$147.64	$147.79	$147.41
Total System Cost	$21,566.86	$10,832.40	$8,671.42	$7,921.75	$6,454.97
Total System Cost ($/kW$_{net}$)	$269.59	$135.41	$108.39	$99.02	$80.69
Total System Cost ($/kW$_{gross}$)	$238.74	$119.91	$95.99	$87.69	$71.45

- 3 to 1 cost reduction between low and high manufacturing rates

Bill of Materials: System (2010 Technology)

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	$9,420.13	$3,562.26	$2,865.22	$2,616.73	$2,154.13
Balance of Plant	$6,272.89	$4,404.23	$3,407.34	$3,072.72	$2,514.00
System Assembly & Testing	$202.89	$149.41	$147.48	$147.63	$147.25
Total System Cost	$15,895.91	$8,115.91	$6,420.04	$5,837.08	$4,815.37
Total System Cost ($/kW$_{net}$)	$198.70	$101.45	$80.25	$72.96	$60.19
Total System Cost ($/kW$_{gross}$)	$183.10	$93.48	$73.95	$67.23	$55.47

- 3.3 to 1 cost reduction between low and high manufacturing rates

Bill of Materials: System (2015 Technology)

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	$9,048.76	$3,207.38	$2,507.31	$2,259.00	$1,802.38
Balance of Plant	$4,051.06	$3,021.83	$2,396.70	$2,229.14	$1,963.48
System Assembly & Testing	$202.89	$149.41	$147.48	$147.63	$147.25
Total System Cost	$13,302.71	$6,378.62	$5,051.49	$4,635.76	$3,913.10
Total System Cost ($/kW$_{net}$)	$166.28	$79.73	$63.14	$57.95	$48.91
Total System Cost ($/kW$_{gross}$)	$152.72	$73.23	$57.99	$53.22	$44.92

- 3.2 to 1 cost reduction between low and high manufacturing rates

DIRECTED TECHNOLOGIES INC.