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

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DOE Hydrogen Program Review
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DOE Hydrogen Program

Project ID #
FC28

Overview

Timeline

- Start – 2/17/06
- Finish – 2/16/08
- 63% complete

Budget

- Total project funding
  - $325K
  - Contractor share: $0
- Funding for FY06
  - $150K
- Funding for FY07
  - $100K (+$75k pending)

Barriers

- Manufacturing Costs
- Materials Costs (particularly precious metal catalysts)
- Efficiency-Power Density Ratio

DOE Cost Targets

Characteristic	Units	2006	2010	2015
Stack Cost	$/kW$_e$	$70	$25	$15
System Cost	$/kW$_e$	$110	$45	$30

Collaborations

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

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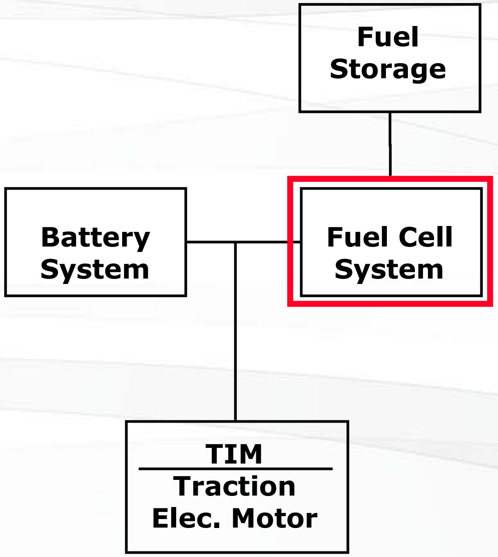
Objectives

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:**
   - Current status (2006)
   - 2010 projected technology
   - 2015 projected technology

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

Project Approach

Principles:

- Base on detailed, rigorous and consistent system design
- Consider current, 2010, and 2015 technologies
- Emphasize realistic and complete cost assessment

Approach:

1. **Research** (literature review, conducting interviews, etc.)
2. **Begin with System modeling** (HYSYS environment)
3. **Design each component** (materials, dimensions, thickness, etc.)
4. **Use DFMA® redesign and costing techniques**
    - **DFMA®= Design for Manufacturing & Assembly***
    - **Adjust for manufacturing rates** (material cost, lot size, setup costs, manufacturing methods, markup rates, etc.)

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DTI DFMA®-Style Costing Methodology

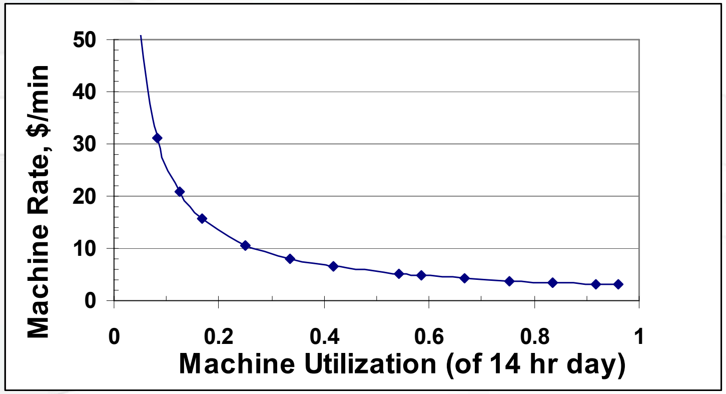
- **DFMA® (Design for Manufacturing and Assembly) is a registered trademark of Boothroyd-Dewhurst Inc.**
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Co. design/costing method for past 20+ years
- **DTI practices are a blend of:**
  - "Textbook" DFMA®, industry standards & practices,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

Markup Not Included

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
- Discount Rate
- Corp. Tax Rate

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

$$\frac{\text{Annual Capital Repayment} + \text{Annual Operating Payments}}{\text{Annual Minutes of Equipment Operation}} = \text{Machine Rate, \$/min}$$

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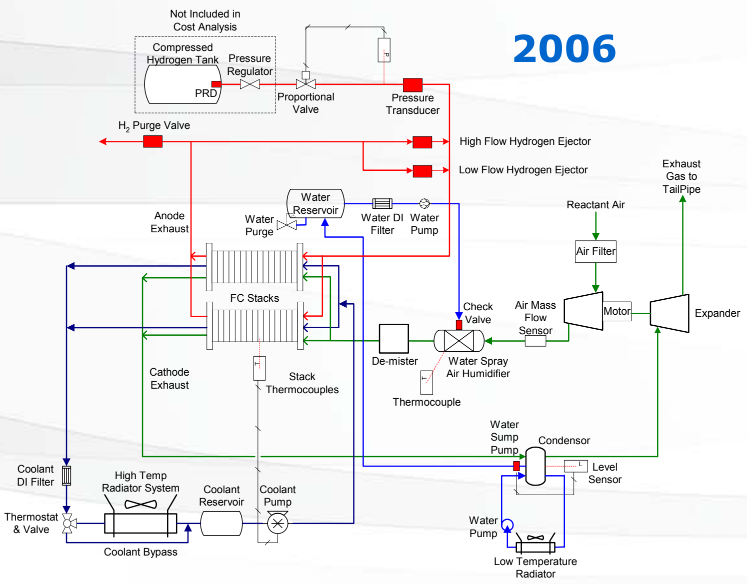
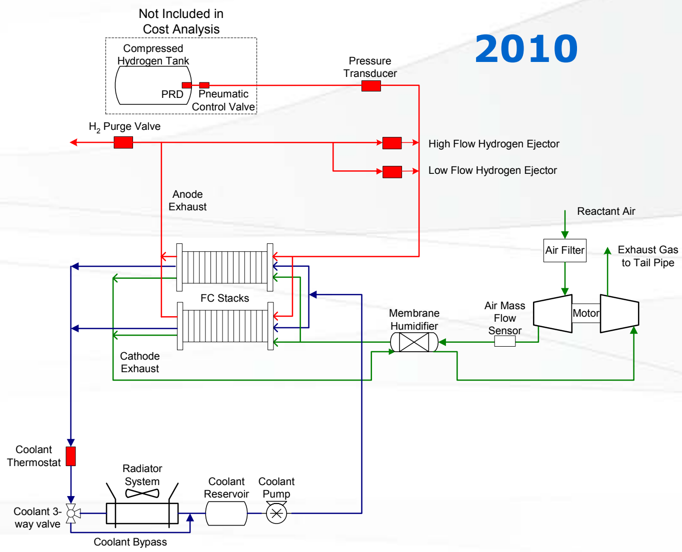
Key Tech. Targets Define System

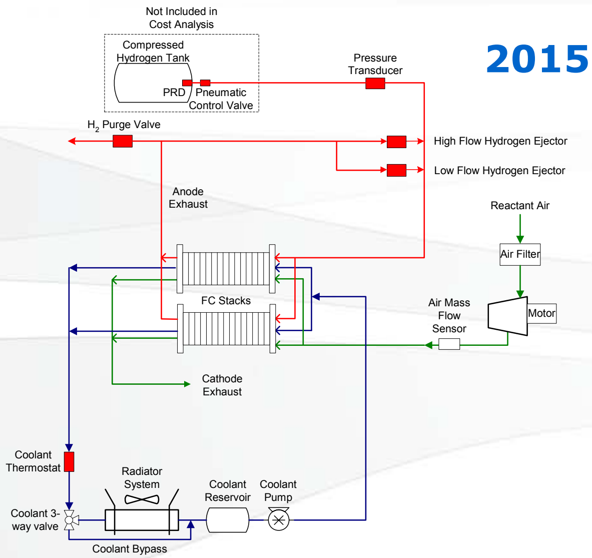
	units	2006	2010	2015
DOE Tech Targets that drive analysis:				
Stack Efficiency @ Rated Power	%	55%	55%	55%
MEA Areal Power Density @ Peak Power	mW/cm^2	700	1000	1000
Total Catalyst Loading	g/kW_{gross}	0.65	0.29	0.19
Key Derived Performance Parameters:				
System Gross Electric Power (Output)	g/kW_{gross}	90.6	87.6	87.1
Active Area	cm^2	348	235	234
Cell Voltage @ Peak Power	V/cell	0.68	0.68	0.68
Operating Pressure (Peak)	atm	2.3	2.0	1.5

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

Different Technology Schematics







Changes from 2006 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

System Comparison

	Current Technology System	2010 Technology System	2015 Technology System
Power Density (mW/cm^2)	700	1000	1000
Total Pt loading (mg/cm^2)	0.65	0.29	0.19
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	Stamped Stainless Steel (uncoated) or Injection Molded Carbon/Polymer	Stamped Stainless Steel (uncoated) or Injection 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	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
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	Silicon Injection molding of gasket around MEA	Silicon Injection molding of gasket around MEA	Silicon Injection molding of gasket around MEA
Freeze Protection	Drain water at shutdown	Drain water at shutdown	Drain water at shutdown
Hydrogen Sensors	2 H2 Sensors (for FC sys), 1 H2 Sensor (for passenger cabin: not in cost estimate), 1 H2 Sensor (for fuel sys: not in cost estimate	1 H2 Sensors (for FC sys), 1 H2 Sensor (for passenger cabin: not in cost estimate), 1 H2 Sensor (for fuel sys: not in cost estimate	No H2 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

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Bipolar Plates

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/stack)	$22.51	$22.51	$22.51	$22.51	$22.51
	Manufacturing ($/stack)	$104.38	$89.27	$90.31	$90.55	$89.44
	Tooling ($/stack)	$10.74	$7.73	$7.82	$7.85	$7.74
	Total Cost ($/stack)	$137.63	$119.50	$120.64	$120.90	$119.69
	Total Cost ($/kW$_{gross}$)	$6.08	$5.28	$5.33	$5.34	$5.29
2010	Material ($/stack)	$15.60	$15.60	$15.60	$15.60	$15.60
	Manufacturing ($/stack)	$77.60	$64.79	$61.04	$61.90	$61.04
	Tooling ($/stack)	$10.74	$6.98	$7.09	$7.20	$7.09
	Total Cost ($/stack)	$103.94	$87.37	$83.72	$84.70	$83.72
	Total Cost ($/kW$_{gross}$)	$4.75	$3.99	$3.82	$3.87	$3.82
2015	Material ($/stack)	$15.51	$15.51	$15.51	$15.51	$15.51
	Manufacturing ($/stack)	$77.28	$64.46	$60.72	$61.59	$60.72
	Tooling ($/stack)	$10.74	$6.98	$7.09	$7.20	$7.09
	Total Cost ($/stack)	$103.54	$86.95	$83.32	$84.30	$83.32
	Total Cost ($/kW$_{gross}$)	$4.76	$3.99	$3.83	$3.87	$3.83

Injection Molding

- 50/50 Polypropylene/Carbon
- Plate can be flipped 180 degrees, used for both Cathode & Anode
- Lowers manufacturing cost by doubling plate production & eliminating 2nd production line
- 50/50 mix of polypropylene and carbon powder
- ~30 second cycle time

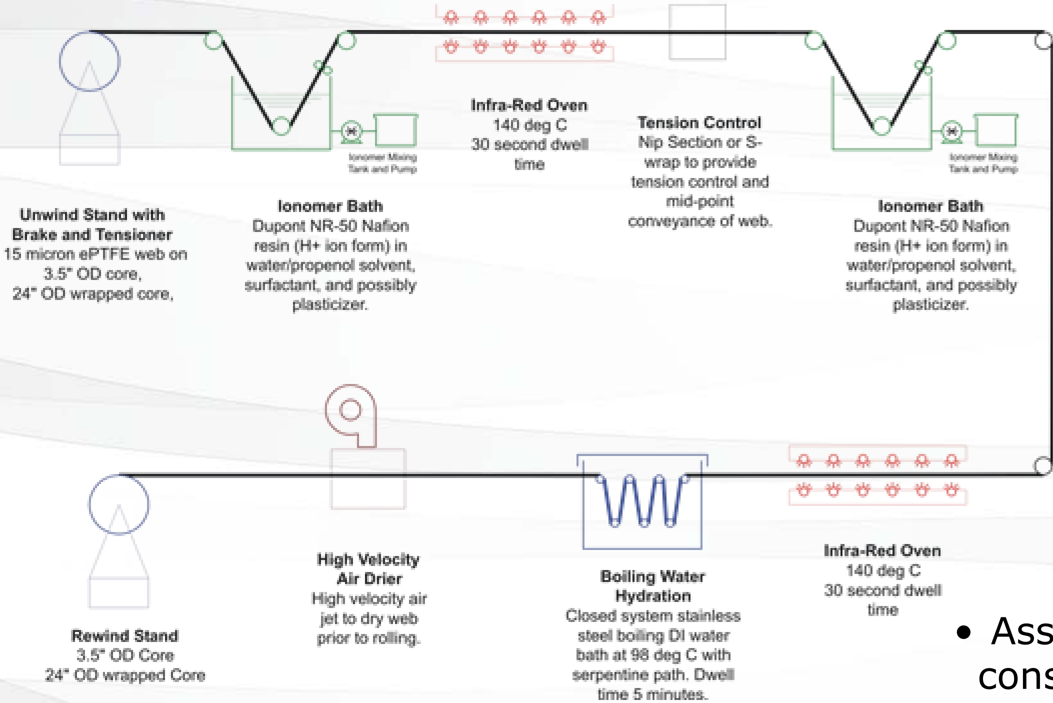
	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/stack)	$56.86	$56.86	$56.86	$56.86	$56.86
	Manufacturing ($/stack)	$14.83	$3.45	$3.34	$3.42	$3.33
	Tooling ($/stack)	$25.74	$26.07	$25.99	$26.11	$26.13
	Total Cost ($/stack)	$97.42	$86.39	$86.20	$86.39	$86.32
	Total Cost ($/kW$_{gross}$)	$4.30	$3.82	$3.81	$3.82	$3.81
2010	Material ($/stack)	$38.49	$38.49	$38.49	$38.49	$38.49
	Manufacturing ($/stack)	$14.01	$3.27	$3.17	$3.15	$3.08
	Tooling ($/stack)	$22.21	$22.56	$22.49	$22.59	$22.50
	Total Cost ($/stack)	$74.72	$64.33	$64.15	$64.22	$64.07
	Total Cost ($/kW$_{gross}$)	$3.41	$2.94	$2.93	$2.93	$2.93
2015	Material ($/stack)	$38.27	$38.27	$38.27	$38.27	$38.27
	Manufacturing ($/stack)	$14.00	$3.27	$3.17	$3.14	$3.08
	Tooling ($/stack)	$22.17	$22.52	$22.45	$22.54	$22.45
	Total Cost ($/stack)	$74.44	$64.06	$63.89	$63.96	$63.81
	Total Cost ($/kW$_{gross}$)	$3.42	$2.94	$2.93	$2.94	$2.93

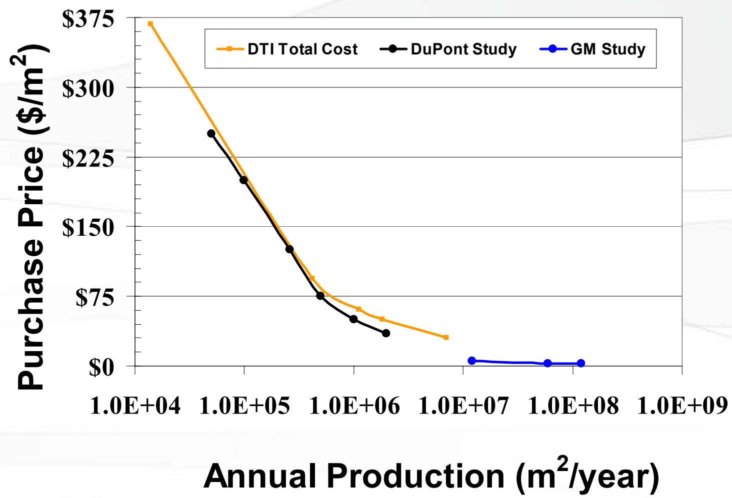
Stamping

- 0.75 mm thick uncoated 310 Stainless Steel
- 4-stage Progressive Die
- Greater tooling costs of progressive setup offset significantly by reduced labor & energy costs over individual die setup
- Rapid plate production (up to 80 plates/minute)

Proton Exchange Membrane

(Based on Gore-like approach)





	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/m^2)	$362.95	$89.39	$56.11	$45.05	$25.68
	Material ($/stack)	$1,265.98	$311.81	$195.70	$157.14	$89.57
	Total Cost ($/stack)	$1,265.98	$311.81	$195.70	$157.14	$89.57
	Total Cost ($/kW$_{gross}$)	$55.91	$13.77	$8.64	$6.94	$3.96
2010	Material ($/m^2)	$362.95	$101.99	$63.05	$50.22	$27.96
	Material ($/stack)	$860.09	$241.68	$149.41	$119.00	$66.26
	Total Cost ($/stack)	$860.09	$241.68	$149.41	$119.00	$66.26
	Total Cost ($/kW$_{gross}$)	$39.28	$11.04	$6.82	$5.43	$3.03
2015	Material ($/m^2)	$362.95	$102.20	$63.16	$50.30	$28.00
	Material ($/stack)	$855.18	$240.79	$148.82	$118.53	$65.97
	Total Cost ($/stack)	$855.18	$240.79	$148.82	$118.53	$65.97
	Total Cost ($/kW$_{gross}$)	$39.28	$11.06	$6.84	$5.44	$3.03

- 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

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Catalyst Ink & Catalyzation

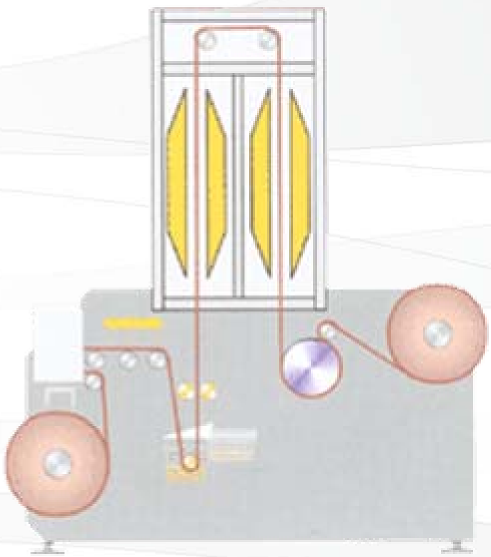
Catalyst Preparation

- 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 platinum cost ($1,175/troy oz.)

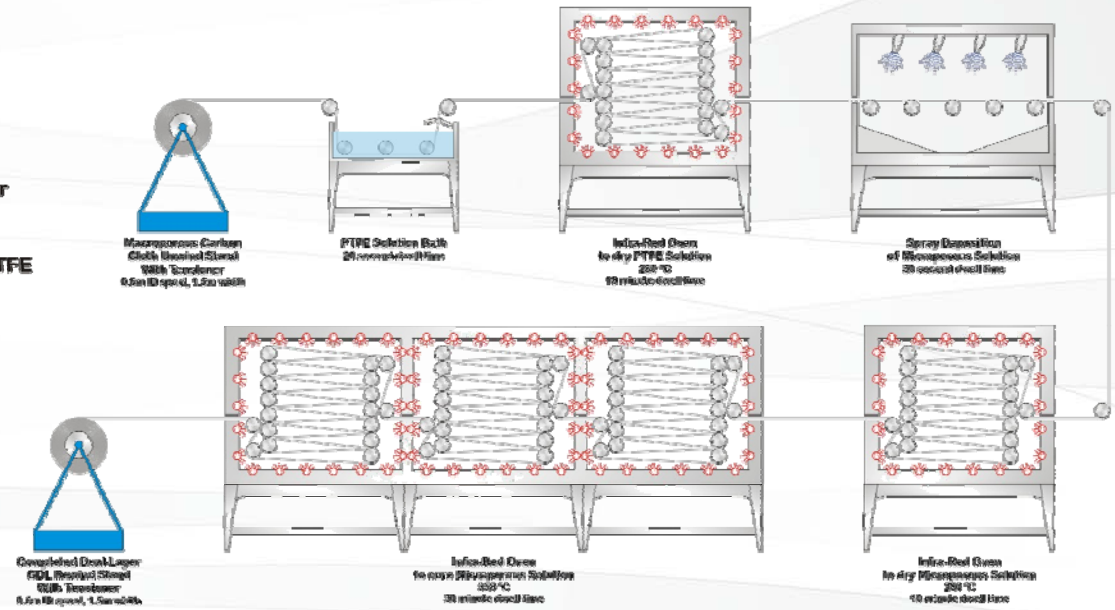
Coatema VertiCoater



	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/stack)	$1,479.46	$1,018.69	$966.56	$947.35	$909.88
	Manufacturing ($/stack)	$121.80	$4.38	$3.32	$3.08	$2.48
	Total Cost ($/stack)	$1,601.25	$1,023.08	$969.89	$950.43	$912.36
	Total Cost ($/$kW_{gross}$)	$70.72	$45.19	$42.84	$41.98	$40.30
2010	Material ($/stack)	$448.44	$308.78	$292.98	$287.15	$275.80
	Manufacturing ($/stack)	$121.70	$4.29	$3.23	$2.08	$2.13
	Total Cost ($/stack)	$570.14	$313.07	$296.21	$289.23	$277.93
	Total Cost ($/$kW_{gross}$)	$26.04	$14.30	$13.53	$13.21	$12.69
2015	Material ($/stack)	$292.13	$201.15	$190.86	$187.06	$179.66
	Manufacturing ($/stack)	$121.69	$4.28	$3.22	$2.07	$2.12
	Total Cost ($/stack)	$413.82	$205.43	$194.08	$189.13	$181.79
	Total Cost ($/$kW_{gross}$)	$19.01	$9.44	$8.91	$8.69	$8.35

- Dual-sided Vertical coating process
  - modeled as Coatema VertiCoater
  - die-slot catalyst applicator
- Apply platinum catalyst slurry simultaneously 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)

Dual-Layer GDL Process Line



- Microporous ink mixed in ultrasonic bath ($24,231 cap. cost)
  - 12% PTFE
  - 50% Solvent
  - 38% Vulcan XC-72

- Macroporous GDL Carbon Paper based on price quote of SGL Carbon's GDL 34 BA, $114-$12/m^2

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/stack)	$797.62	$498.15	$282.90	$208.03	$86.37
	Manufacturing ($/stack)	$175.43	$20.22	$15.91	$16.24	$15.39
	Total Cost ($/stack)	$973.05	$518.36	$298.81	$224.27	$101.76
	Total Cost ($/kW$_{gross}$)	$42.98	$22.89	$13.20	$9.91	$4.49
2010	Material ($/stack)	$541.63	$338.27	$192.10	$141.26	$58.64
	Manufacturing ($/stack)	$174.88	$13.93	$13.22	$13.05	$12.78
	Total Cost ($/stack)	$716.51	$352.20	$205.31	$154.31	$71.43
	Total Cost ($/kW$_{gross}$)	$32.72	$16.08	$9.38	$7.05	$3.26
2015	Material ($/stack)	$538.76	$336.47	$191.07	$140.50	$58.32
	Manufacturing ($/stack)	$174.88	$13.93	$13.21	$13.04	$12.78
	Total Cost ($/stack)	$713.64	$350.40	$204.28	$153.55	$71.10
	Total Cost ($/kW$_{gross}$)	$32.78	$16.09	$9.38	$7.05	$3.27

Process

1) Dip macroporous GDL in PTFE solution bath
2) Dry in oven 1
3) Spray apply microporous ink to macroporous substrate
4) Dry in oven 2
5) Cure in oven 3

- Based on the work of Branko N. Popov, et al., University of South Carolina

Other Stack Components

Total Cost ($/kW)

	2006		2010		2015		
System Production Rate	1k/yr	500k/yr	1k/yr	500k/yr	1k/yr	500k/yr	**Fabrication Method:**
Hot Pressing the MEA	$1.26	$0.28	$1.28	$0.24	$1.29	$0.24	Hot-Pressing
Cutting & Slitting the MEA	$1.58	$0.06	$1.64	$0.06	$1.65	$0.06	Roll-fed Cutting & Slitting
MEA Frame-Gasket	$3.03	$1.95	$3.29	$1.70	$3.30	$1.70	Insertion Molding
Coolant Gasket	$2.50	$1.54	$2.77	$1.27	$2.78	$1.28	Injection Molding
Endplates & Current Collectors	$2.41	$1.15	$1.84	$0.84	$1.85	$0.85	Compression Molding, Blanking

- **These components are a small fraction of the total cost**
- **None of these fabrication methods change with production rate**
  - Many repeat parts
  - High machine utilization even at low production

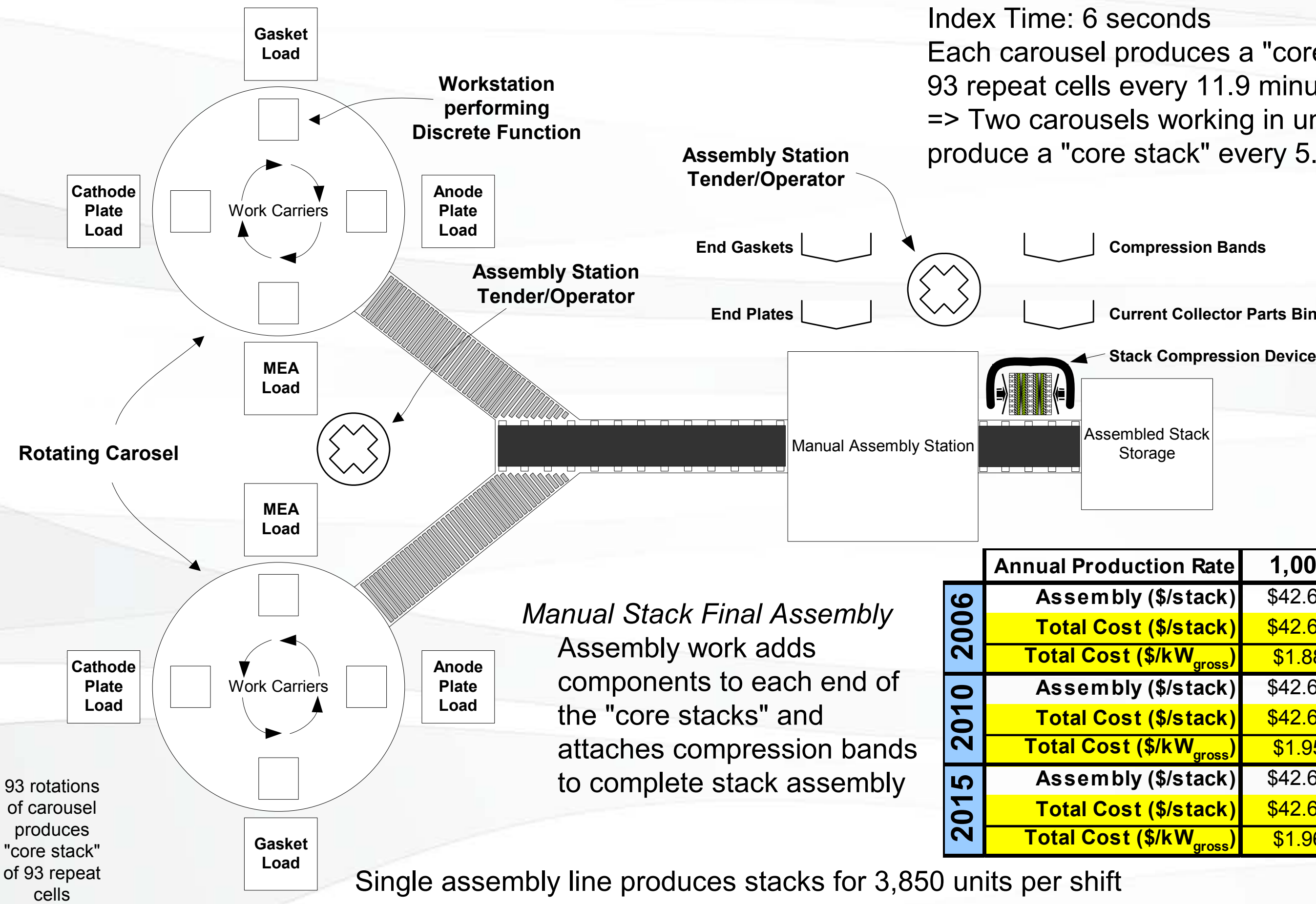
Stack Assembly

Assembly Station 1:
Assembly of Stack Repeat Cells

Assembly Station 2:
Final Stack Assembly

Robotic Assembly of Stack Repeat Parts

Index Time: 6 seconds
Each carousel produces a "core stack" of 93 repeat cells every 11.9 minutes
=> Two carousels working in unison produce a "core stack" every 5.95 minutes



Manual Stack Final Assembly

Assembly work adds components to each end of the "core stacks" and attaches compression bands to complete stack assembly

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Assembly ($/stack)	$42.68	$17.20	$14.50	$14.59	$14.55
	Total Cost ($/stack)	$42.68	$17.20	$14.50	$14.59	$14.55
	Total Cost ($/kW$_{gross}$)	$1.88	$0.76	$0.64	$0.64	$0.64
2010	Assembly ($/stack)	$42.68	$17.20	$14.50	$14.59	$14.55
	Total Cost ($/stack)	$42.68	$17.20	$14.50	$14.59	$14.55
	Total Cost ($/kW$_{gross}$)	$1.95	$0.79	$0.66	$0.67	$0.66
2015	Assembly ($/stack)	$42.68	$17.20	$14.50	$14.59	$14.55
	Total Cost ($/stack)	$42.68	$17.20	$14.50	$14.59	$14.55
	Total Cost ($/kW$_{gross}$)	$1.96	$0.79	$0.67	$0.67	$0.67

Single assembly line produces stacks for 3,850 units per shift

System Assembly & Conditioning

- Bill of Materials (BOM) components divided into 5 main categories and a notional installation time was attributed to each.
- Approx. system assembly time: 3 hrs
- Full Manual Assembly for 1k/yr manufacturing rate.
- 10 station assembly line used for all other rates

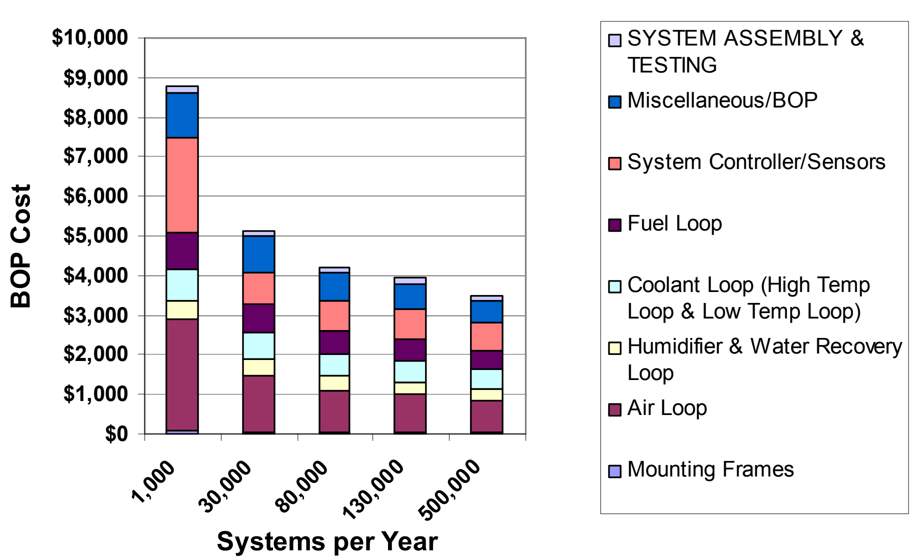
	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Assembly ($/system)	$187.09	$149.67	$149.67	$149.67	$149.67
	Total Cost ($/kW$_{net}$)	$2.34	$1.87	$1.87	$1.87	$1.87
2010	Assembly ($/system)	$187.09	$149.67	$149.67	$149.67	$149.67
	Total Cost ($/kW$_{net}$)	$2.34	$1.87	$1.87	$1.87	$1.87
2015	Assembly ($/system)	$187.09	$149.67	$149.67	$149.67	$149.67
	Total Cost ($/kW$_{net}$)	$2.34	$1.87	$1.87	$1.87	$1.87

- Stacks "conditioned" for enhanced performance
- Based on UTC Fuel Cells Patent 7,078,118
- Stacks condition per "Applied Voltage Embodiment"
- 10 stacks conditioned simultaneously
- Load bank ~$100k
- Conditioning of stacks staggered to limit peak testing load to ~50kW
- Stacks conditioned to achieve 95% of max performance (~5 hrs; max performance requires ~13 hrs)

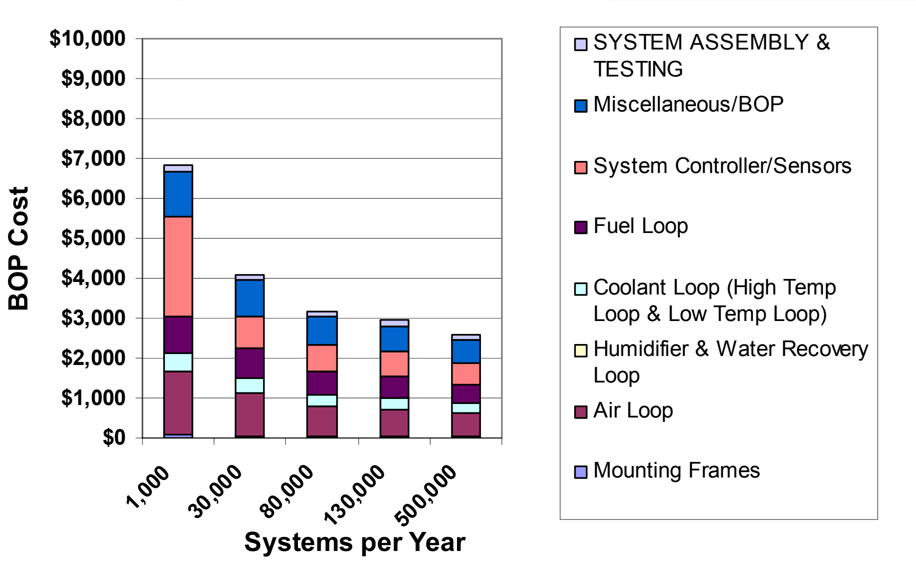
	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Conditioning/Testing ($/stack)	$18.84	$12.37	$12.20	$12.24	$12.18
	Total Cost ($/stack)	$18.84	$12.37	$12.20	$12.24	$12.18
	Total Cost ($/kW$_{gross}$)	$0.83	$0.55	$0.54	$0.54	$0.54
2010	Conditioning/Testing ($/stack)	$17.12	$9.97	$9.84	$9.81	$9.74
	Total Cost ($/stack)	$17.12	$9.97	$9.84	$9.81	$9.74
	Total Cost ($/kW$_{gross}$)	$0.78	$0.46	$0.45	$0.45	$0.44
2015	Conditioning/Testing ($/stack)	$15.39	$7.56	$7.35	$7.38	$7.32
	Total Cost ($/stack)	$15.39	$7.56	$7.35	$7.38	$7.32
	Total Cost ($/kW$_{gross}$)	$0.71	$0.35	$0.34	$0.34	$0.34

Balance of Plant

Current Technology System



2015 Technology System



- 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.

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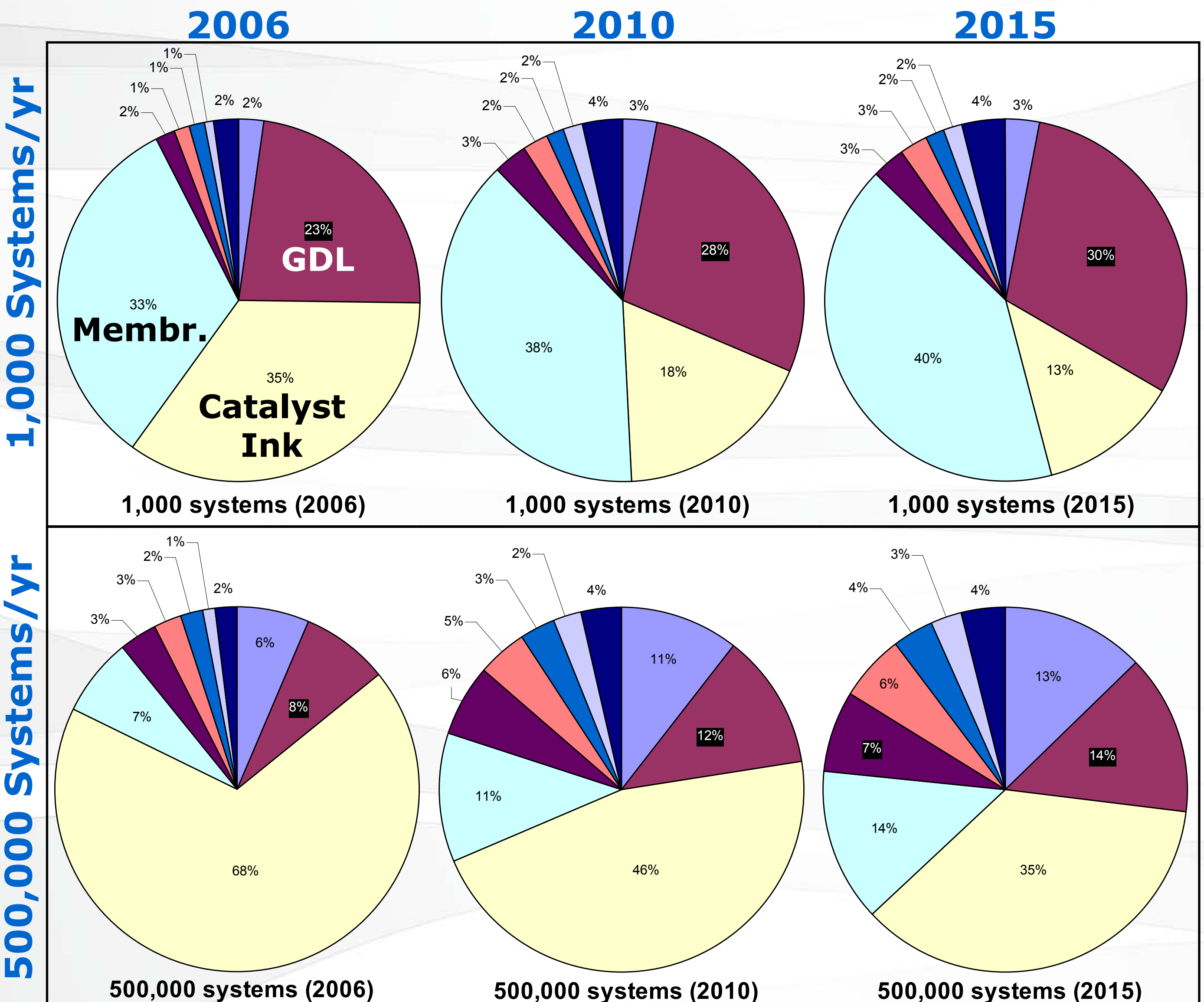
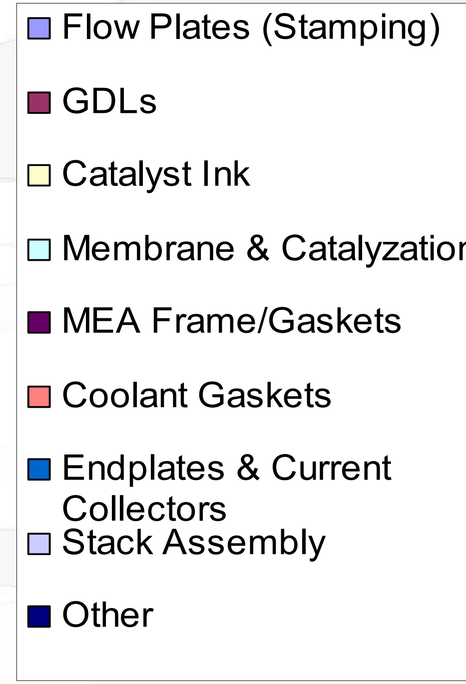
Stack Component Cost Distribution





- **3 components make up the vast majority of cost (GDL/Membr./ Catalyst)**
- **Catalyst Ink dominates cost at high production.**

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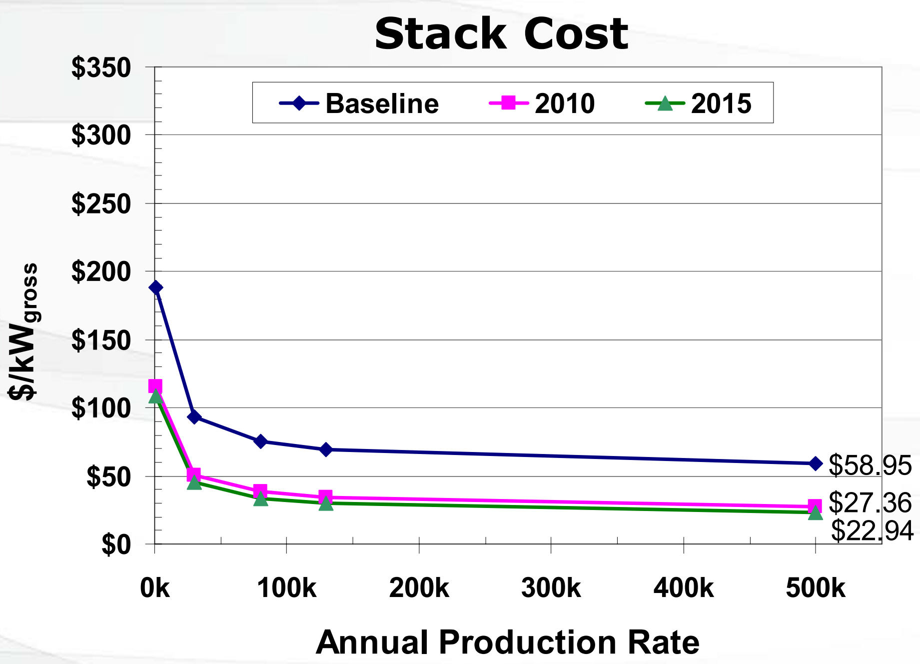
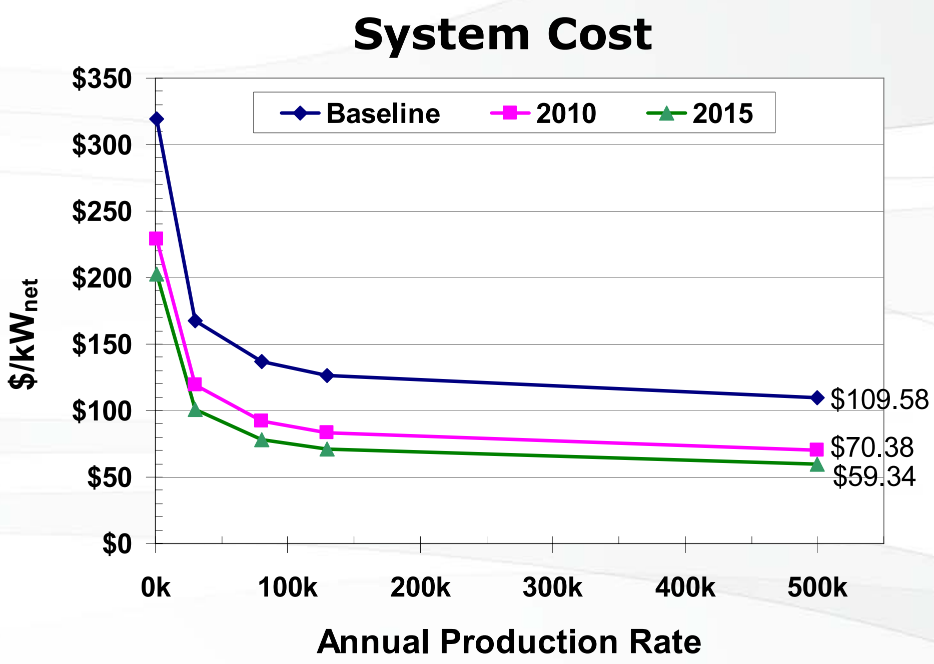
Stack & System Costs vs. Annual Production Rate





Source	Characteristic	Units	2006	2010	2015
DOE Target:	Stack Cost	$/kW$_e$	$70	$25	$15
DTI Estimate:	Stack Cost	$/kW$_e$	$67	$30	$25

DOE Target:	System Cost	$/kW$_e$	$110	$45	$30
DTI Estimate:	System Cost	$/kW$_e$	$110	$70	$59

Future Work

Complete Annual Report

- ~70 page report detailing all assumptions and results

Annual Updates

- **Year 2: Annual Update**
  - Due February 2008
  - Re-evaluation of costs to reflect 2007 progress
  - Exploration of alternate fabrication techniques
  - Refine BOP cost estimates

- **Year 3: Annual Update (Option)**
  - Due February 2009

- **Year 4: Annual Update (Option)**
  - Due February 2010

- **Year 5: Annual Update (Option)**
  - Due February 2011

Additional Slides

DOE Fuel Cell Technical Targets

DOE Tech. Targets (Integrated)

	units	2005 status	2010	2015
Energy efficiency @ 25% of rated power	%	59%	60%	60%
Energy efficiency @ rated power	%	50%	50%	50%
Power density	W/L	500	650	650
Specific power	W/kg	470	650	650
Cost	$\$/kW_e$	110	45	30
Transient response (time for 10% to 90% of rated power)	sec	1.5	1	1
Cold startup time to 50% of rated power		0	0	0
@ -20°C ambient temperature	sec	20	30	30
@ +20°C ambient temperature	sec	<10	5	5
Start up and shut down energy		0	0	0
from -20°C ambient temperature	MJ	7.5	5	5
from +20°C ambient temperature	MJ	n/a	1	1
Durability with cycling	hrs	~1000	5000	5000
Unassisted start from	°C	-20	-40	-40

DOE Tech. Targets (Stacks)

	units	2005 status	2010	2015
Stack power density	W/L	1,500	2,000	2,000
Stack specific power	W/kg	1,400	2,000	2,000
Stack efficiency @ 25% of rated power	%	65%	65%	65%
Stack efficiency @ rated power	%	55%	55%	55%
Cost	$\$/kW_e$	70	25	15
Durability with cycling	hours	200	5000	5000
Transient response (time for 10% to 90% of rated power)	sec	1	1	1
Cold start-up time to 50% of rated power		0	0	0
@ –20ºC ambient temperature	sec	20	30	30
@ +20ºC ambient temperature	sec	<10	5	5
Start up and shut down energy		0	0	0
from -20°C ambient temperature	MJ	7.5	5	5
from +20°C ambient temperature	MJ	n/a	1	1
Unassisted start from	ºC	-20	-40	-40

System Performance Assumptions

	units	2006	2010	2015
Annual Production Rate #1	systems/year	**1,000**	*1,000*	*1,000*
Annual Production Rate #2	systems/year	**30,000**	*30,000*	*30,000*
Annual Production Rate #3	systems/year	**80,000**	*80,000*	*80,000*
Annual Production Rate #4	systems/year	**130,000**	*130,000*	*130,000*
Annual Production Rate #5	systems/year	**500,000**	*500,000*	*500,000*
		0	0	0
System Net Electric Power (Output)	kW_{net}	**80**	**80**	**80**
System Gross Electric Power (Output)	kW_{gross}	90.6	87.6	87.1
		0	0	0
LHV of H_2	kJ/kg	**120,100**	*120,100*	*120,100*
% of O_2 in Air (by Volume)	%	**20.95%**	*20.95%*	*20.95%*
Power consumed	kW	181.1	175.2	174.2
H_2 consumed	kg/s	0.00151	0.00146	0.00145
Ratio of Oxygen to Hydrogen		**7.93**	*7.93*	*7.93*
Oxygen consumed	kg/s	0.01197	0.00018	0.00018
Air consumed	kg/s	0.05713	0.00088	0.00087
		0	0	0
Air compressor motor (net of expander)	kW	**8.29**	**5.31**	**4.81**
Coolant pump	kW	1.1	1.1	1.1
Coolant radiator fan	kW	0.59	0.59	0.59
Exhaust radiator fan	kW	0.38	0.38	0.38
Other (controller, instruments, etc.)	kW	0.2	0.2	0.2
Operating Pressure (Peak)	atm	**2.3**	**2.0**	**1.5**
Stack Operating Temperature	°C	**70-90**	**99**	**120**
MEA areal power density @ peak power	mW/cm^2	**700**	**1000**	**1000**
Current density @ peak power	mA/cm^2	1035	1478	1478
Active area	cm^2	348	235	234
Cell voltage @ peak power	V/cell	0.677	0.677	0.677
Cells/Stack		**93**	*93*	*93*
Stacks/System		**4**	*4*	*4*
System voltage @ peak power	V	251.7	251.7	251.7
System voltage @ open circuit (0.95V/cell)	V	353.4	353.4	353.4
		0	0	0
Anode (H_2) Catalyst loading	mg/cm^2	**0.3**	**0.09**	**0.04**
Cathode (air) Catalyst loading	mg/cm^2	0.35	0.2	0.15
Total Catalyst loading	mg/cm^2	**0.65**	**0.29**	**0.19**
Non-Active But Catalyzed Area (% of active area)	%	3.26%	2.73%	2.72%
Total Catalyst Loading	g/kW_{gross}	0.959	0.298	0.195

PARASITIC LOADS

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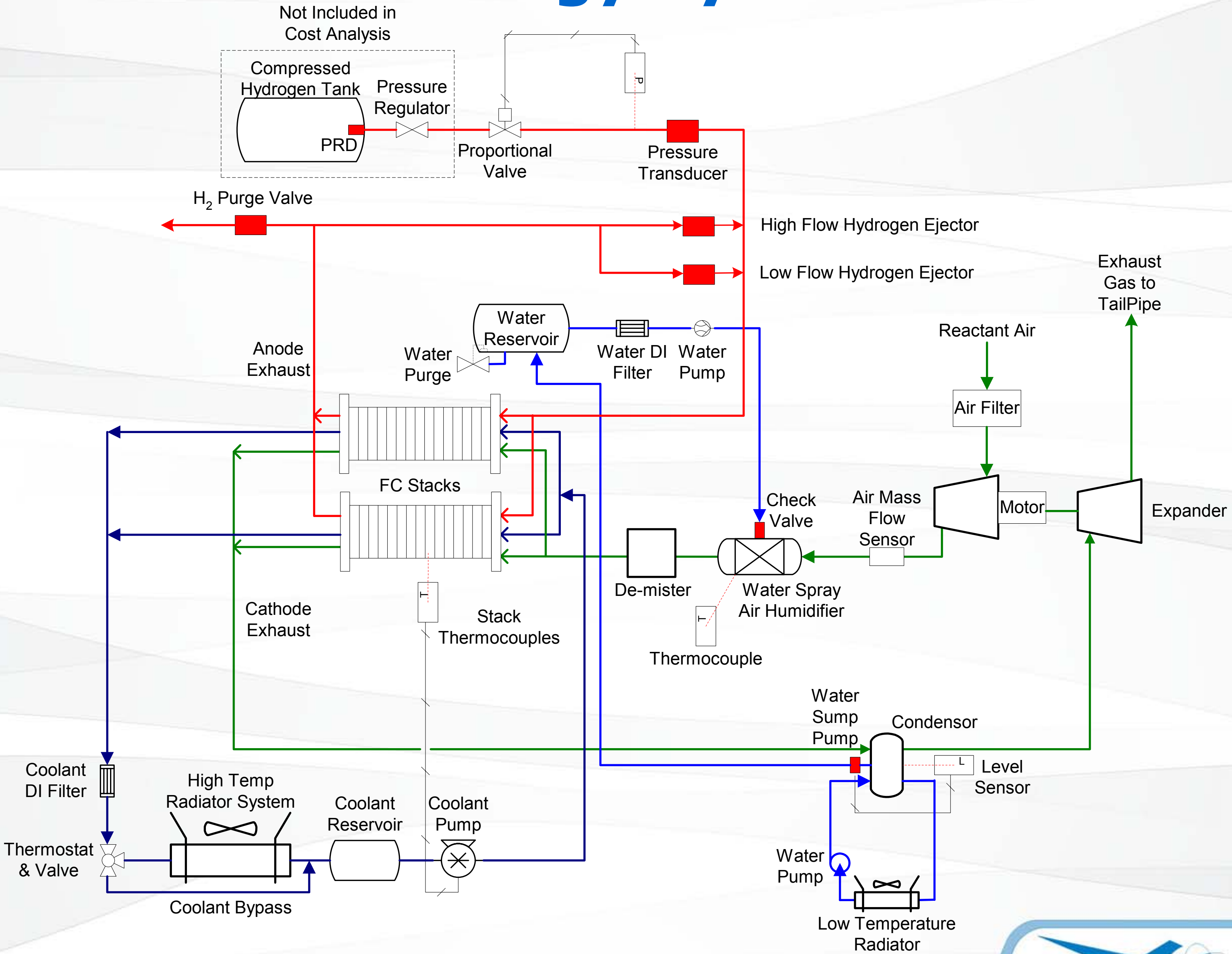
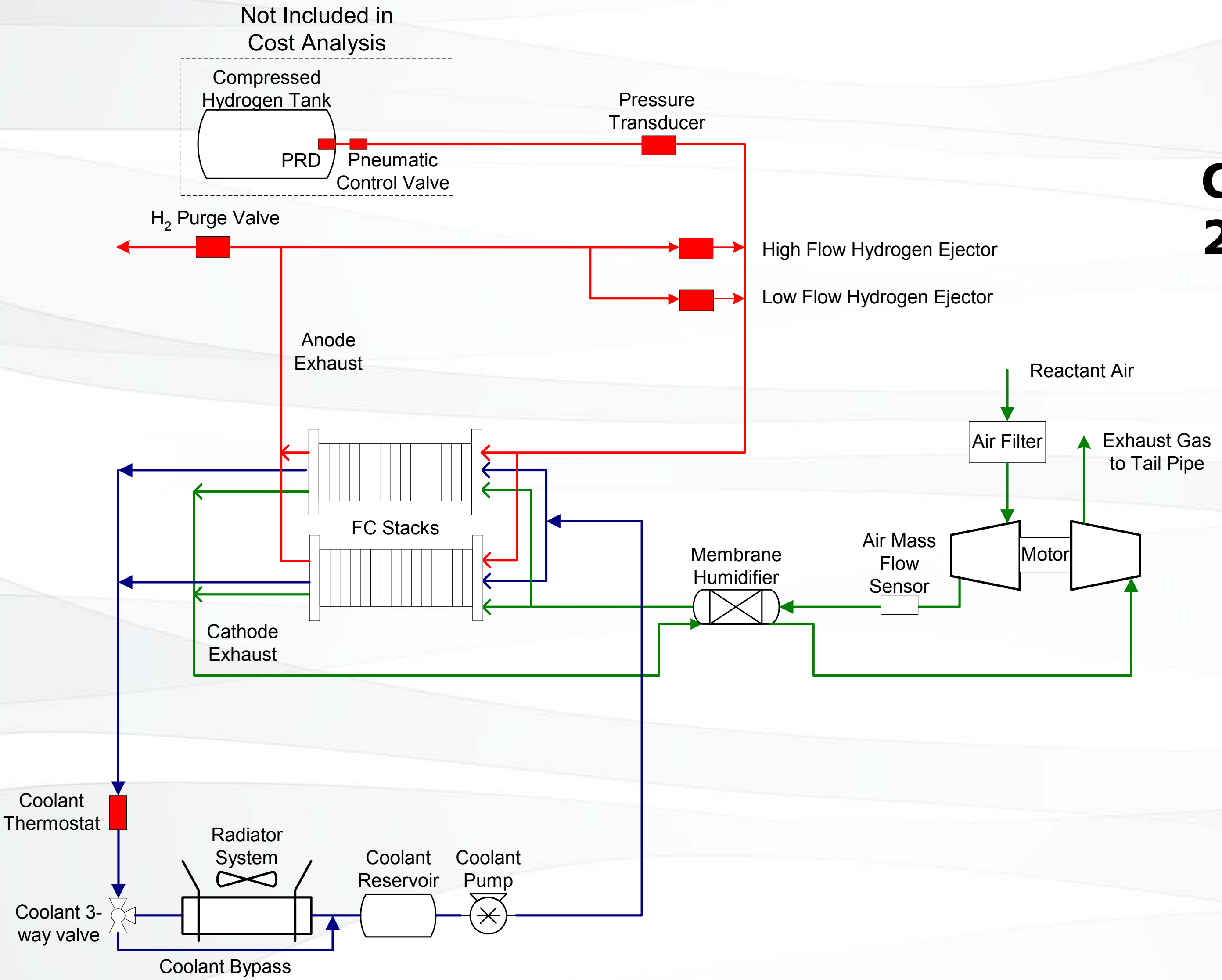
Current Technology System Schematic



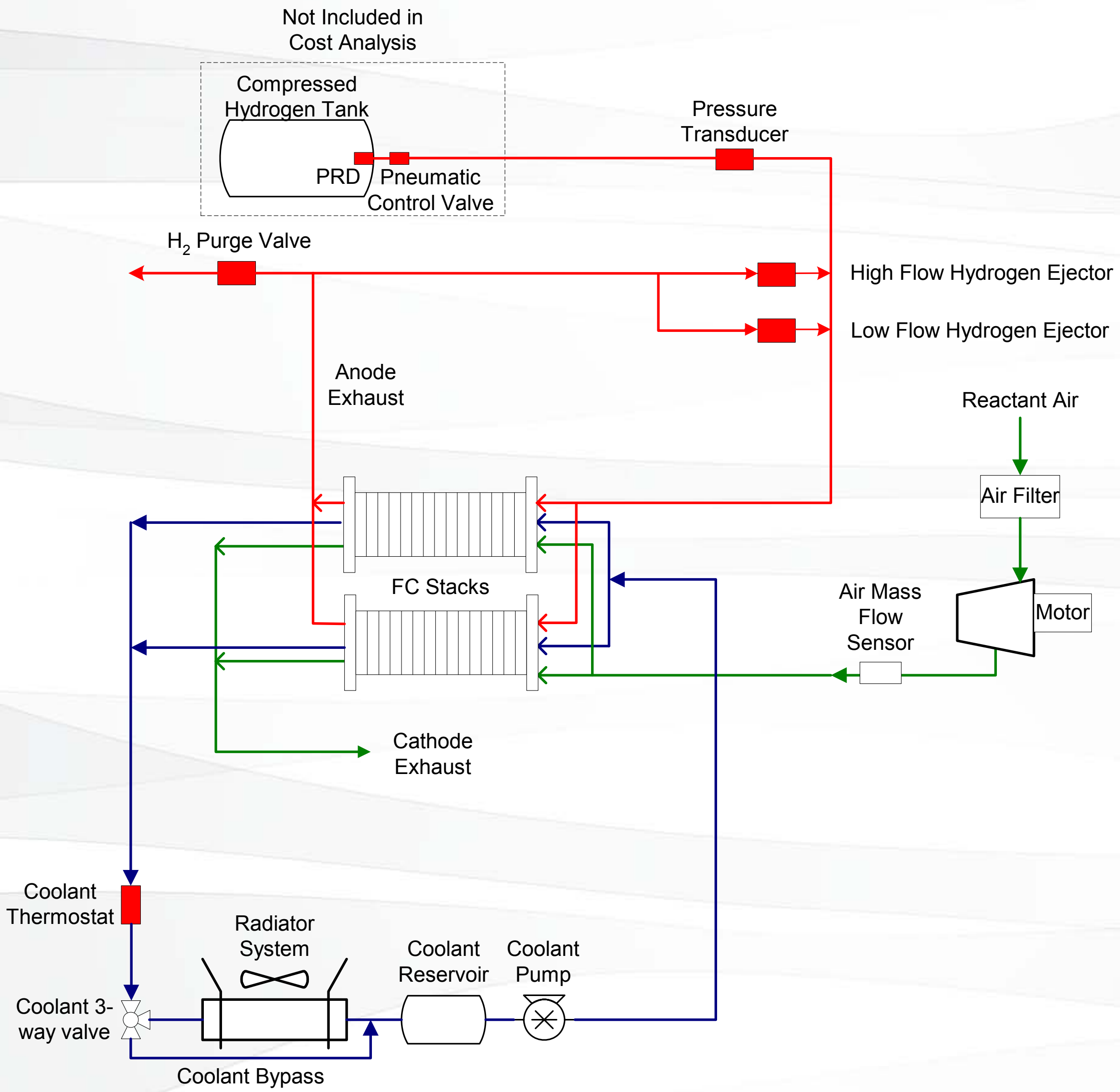
2010 Technology System Schematic



Changes from 2006 System:

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

2015 Technology System Schematic

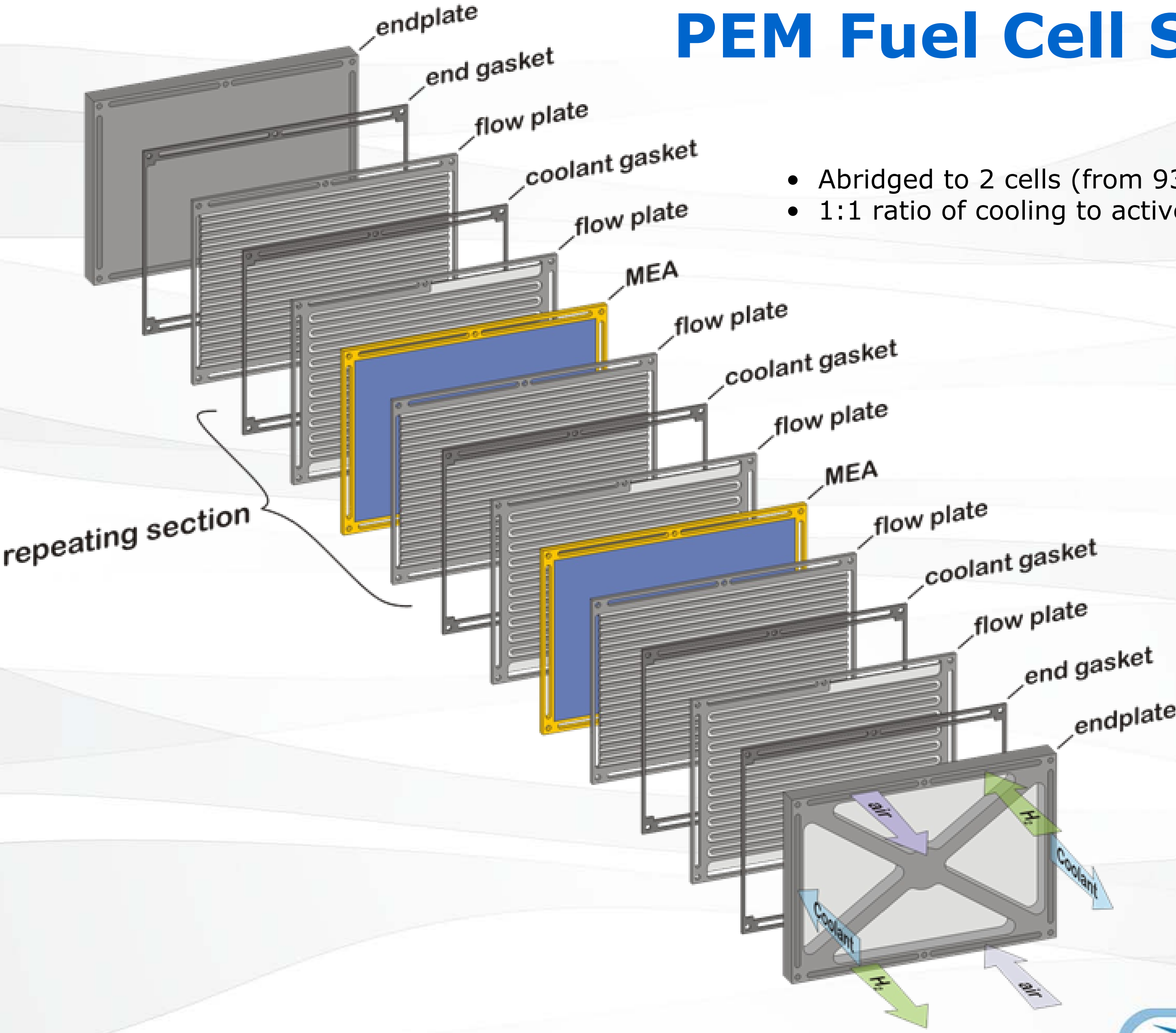


Changes from 2010 System:

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

PEM Fuel Cell Stack

- Abridged to 2 cells (from 93) for clarity
- 1:1 ratio of cooling to active cells



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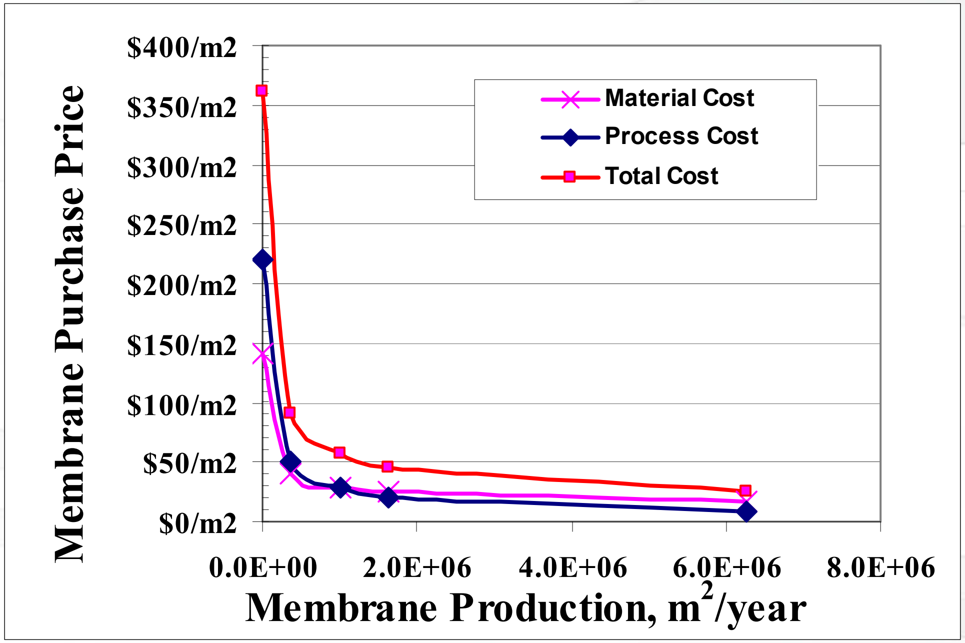
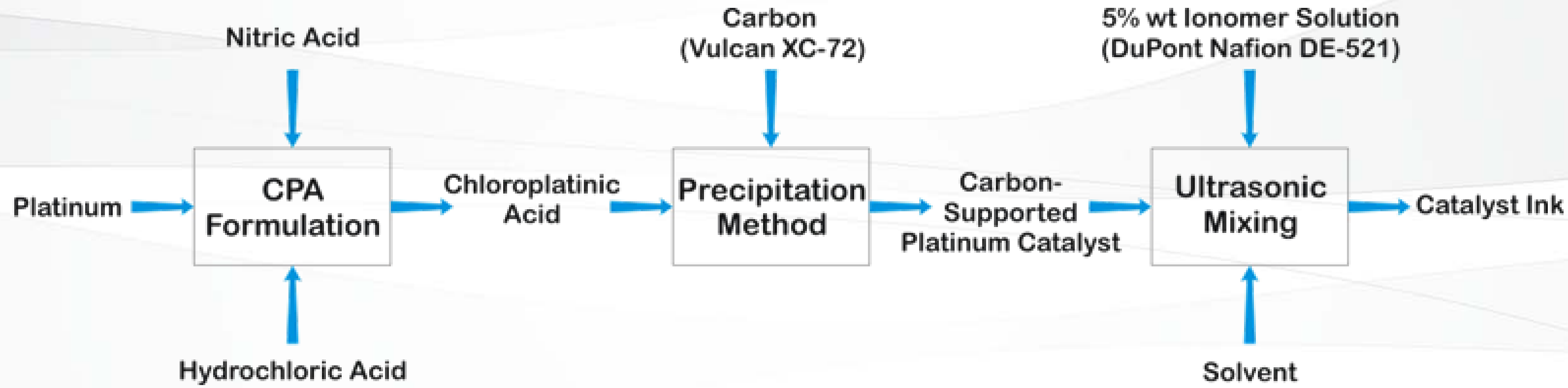
Membrane Assumptions

- Assumes 67% max equipment utilization consistent with 25%/year growth rate (over 5 years)
- Assumes 50%-80% membrane yields
- Membrane $/m² is reduced solely by increases in manufacturing rate, not by technological advancement with year
- However, fewer m² are required in future years because areal power density increases



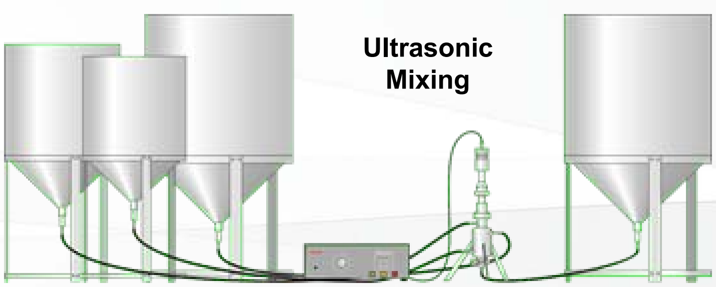
	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/m²)	$362.95	$89.39	$56.11	$45.05	$25.68
	Material ($/stack)	$1,265.98	$311.81	$195.70	$157.14	$89.57
	Total Cost ($/stack)	$1,265.98	$311.81	$195.70	$157.14	$89.57
	Total Cost ($/$kW_{gross}$)	$55.91	$13.77	$8.64	$6.94	$3.96
2010	Material ($/m²)	$362.95	$101.99	$63.05	$50.22	$27.96
	Material ($/stack)	$860.09	$241.68	$149.41	$119.00	$66.26
	Total Cost ($/stack)	$860.09	$241.68	$149.41	$119.00	$66.26
	Total Cost ($/$kW_{gross}$)	$39.28	$11.04	$6.82	$5.43	$3.03
2015	Material ($/m²)	$362.95	$102.20	$63.16	$50.30	$28.00
	Material ($/stack)	$855.18	$240.79	$148.82	$118.53	$65.97
	Total Cost ($/stack)	$855.18	$240.79	$148.82	$118.53	$65.97
	Total Cost ($/$kW_{gross}$)	$39.28	$11.06	$6.84	$5.44	$3.03

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 cost of platinum ($1,175/troy oz.)

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/stack)	$1,479.46	$1,018.69	$966.56	$947.35	$909.88
	Manufacturing ($/stack)	$3.87	$0.19	$0.11	$0.10	$0.09
	Total Cost ($/stack)	$1,483.33	$1,018.89	$966.68	$947.45	$909.97
	Total Cost ($/$kW_{gross}$)	$65.51	$45.00	$42.69	$41.85	$40.19
2010	Material ($/stack)	$448.44	$308.78	$292.98	$287.15	$275.80
	Manufacturing ($/stack)	$3.82	$0.15	$0.07	$0.05	$0.03
	Total Cost ($/stack)	$452.26	$308.93	$293.04	$287.20	$275.82
	Total Cost ($/$kW_{gross}$)	$20.65	$14.11	$13.38	$13.12	$12.60
2015	Material ($/stack)	$292.13	$201.15	$190.86	$187.06	$179.66
	Manufacturing ($/stack)	$3.81	$0.14	$0.06	$0.04	$0.02
	Total Cost ($/stack)	$295.94	$201.29	$190.92	$187.10	$179.68
	Total Cost ($/$kW_{gross}$)	$13.59	$9.25	$8.77	$8.59	$8.25



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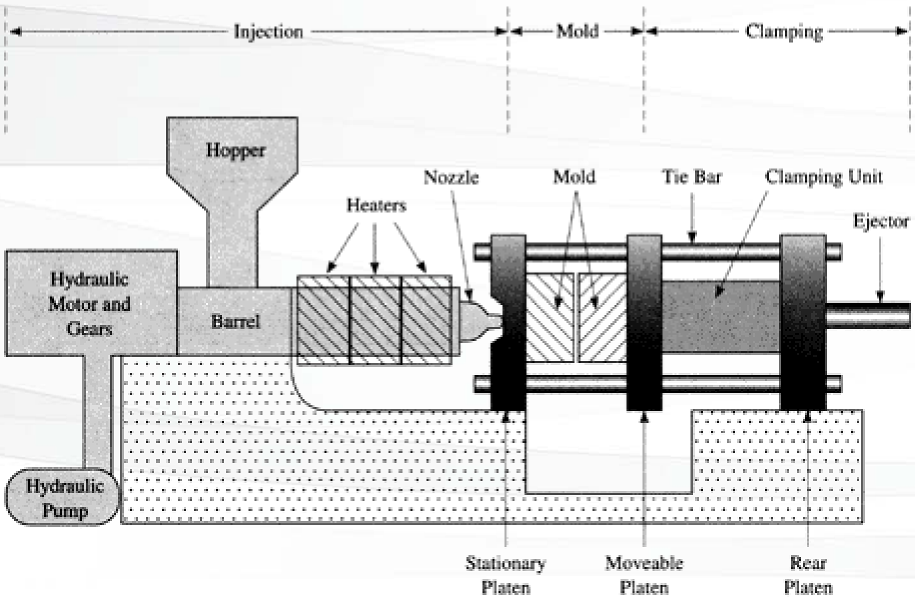
Injection Molded Flowplates



Coolant Flow Side

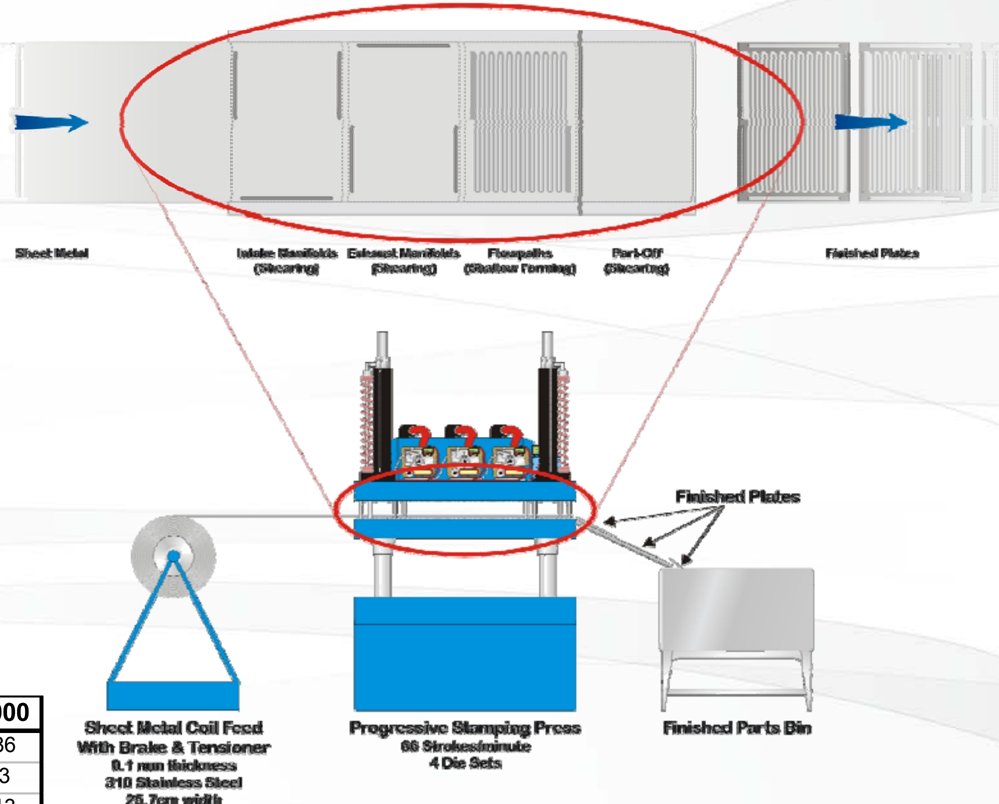
Gas Flow Side

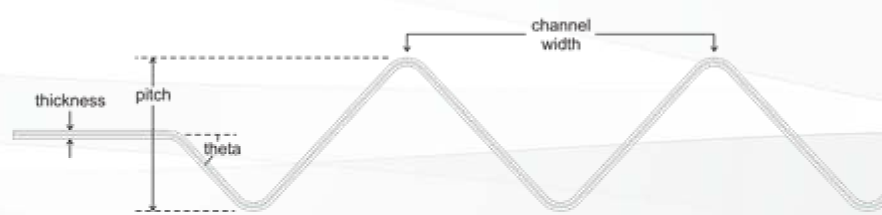
	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/stack)	$22.51	$22.51	$22.51	$22.51	$22.51
2006	Manufacturing ($/stack)	$104.38	$89.27	$90.31	$90.55	$89.44
2006	Tooling ($/stack)	$10.74	$7.73	$7.82	$7.85	$7.74
2006	Total Cost ($/stack)	$137.63	$119.50	$120.64	$120.90	$119.69
2006	Total Cost ($/$kW_{gross}$)	$6.08	$5.28	$5.33	$5.34	$5.29
2010	Material ($/stack)	$15.60	$15.60	$15.60	$15.60	$15.60
2010	Manufacturing ($/stack)	$77.60	$64.79	$61.04	$61.90	$61.04
2010	Tooling ($/stack)	$10.74	$6.98	$7.09	$7.20	$7.09
2010	Total Cost ($/stack)	$103.94	$87.37	$83.72	$84.70	$83.72
2010	Total Cost ($/$kW_{gross}$)	$4.75	$3.99	$3.82	$3.87	$3.82
2015	Material ($/stack)	$15.51	$15.51	$15.51	$15.51	$15.51
2015	Manufacturing ($/stack)	$77.28	$64.46	$60.72	$61.59	$60.72
2015	Tooling ($/stack)	$10.74	$6.98	$7.09	$7.20	$7.09
2015	Total Cost ($/stack)	$103.54	$86.95	$83.32	$84.30	$83.32
2015	Total Cost ($/$kW_{gross}$)	$4.76	$3.99	$3.83	$3.87	$3.83

- Plate can be flipped 180 degrees, used for both Cathode & Anode
- Lowers manufacturing cost by doubling plate production & eliminating 2nd production line
- 50/50 mix of polypropylene and carbon powder
- ~30 second cycle time

Stamped Flow Plates

- Stamped using a 4-stage Progressive Die setup
- Greater tooling costs offset significantly by reduced labor & energy costs over individual die setup
- Lower tooling cost than Injection Molding
- Rapid plate production (up to 80 plates/minute)





	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/stack)	$56.86	$56.86	$56.86	$56.86	$56.86
	Manufacturing ($/stack)	$14.83	$3.45	$3.34	$3.42	$3.33
	Tooling ($/stack)	$25.74	$26.07	$25.99	$26.11	$26.13
	Total Cost ($/stack)	$97.42	$86.39	$86.20	$86.39	$86.32
	Total Cost ($/$kW_{gross}$)	$4.30	$3.82	$3.81	$3.82	$3.81
2010	Material ($/stack)	$38.49	$38.49	$38.49	$38.49	$38.49
	Manufacturing ($/stack)	$14.01	$3.27	$3.17	$3.15	$3.08
	Tooling ($/stack)	$22.21	$22.56	$22.49	$22.59	$22.50
	Total Cost ($/stack)	$74.72	$64.33	$64.15	$64.22	$64.07
	Total Cost ($/$kW_{gross}$)	$3.41	$2.94	$2.93	$2.93	$2.93
2015	Material ($/stack)	$38.27	$38.27	$38.27	$38.27	$38.27
	Manufacturing ($/stack)	$14.00	$3.27	$3.17	$3.14	$3.08
	Tooling ($/stack)	$22.17	$22.52	$22.45	$22.54	$22.45
	Total Cost ($/stack)	$74.44	$64.06	$63.89	$63.96	$63.81
	Total Cost ($/$kW_{gross}$)	$3.42	$2.94	$2.93	$2.94	$2.93

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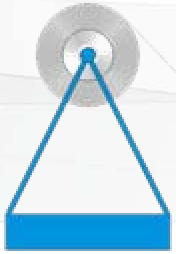
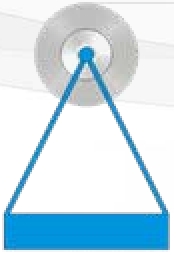
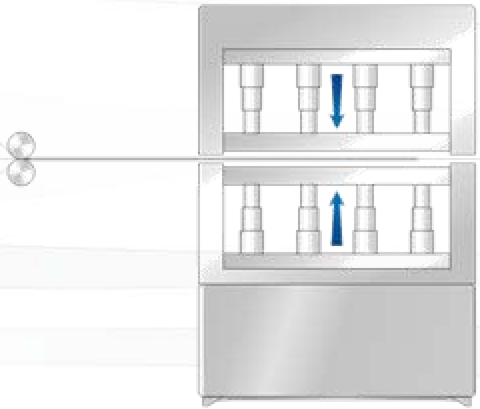
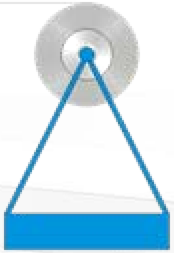
Indexed Hot-Pressing of MEA

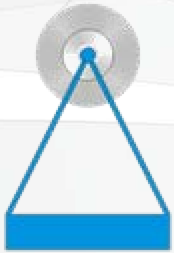
- Large heated press with 90 second index time
- Very low cost hot-pressing
- Process parameters (90 seconds at 160°C)
  based on US Pat. 5,187,025 to Analytic Power Corp.







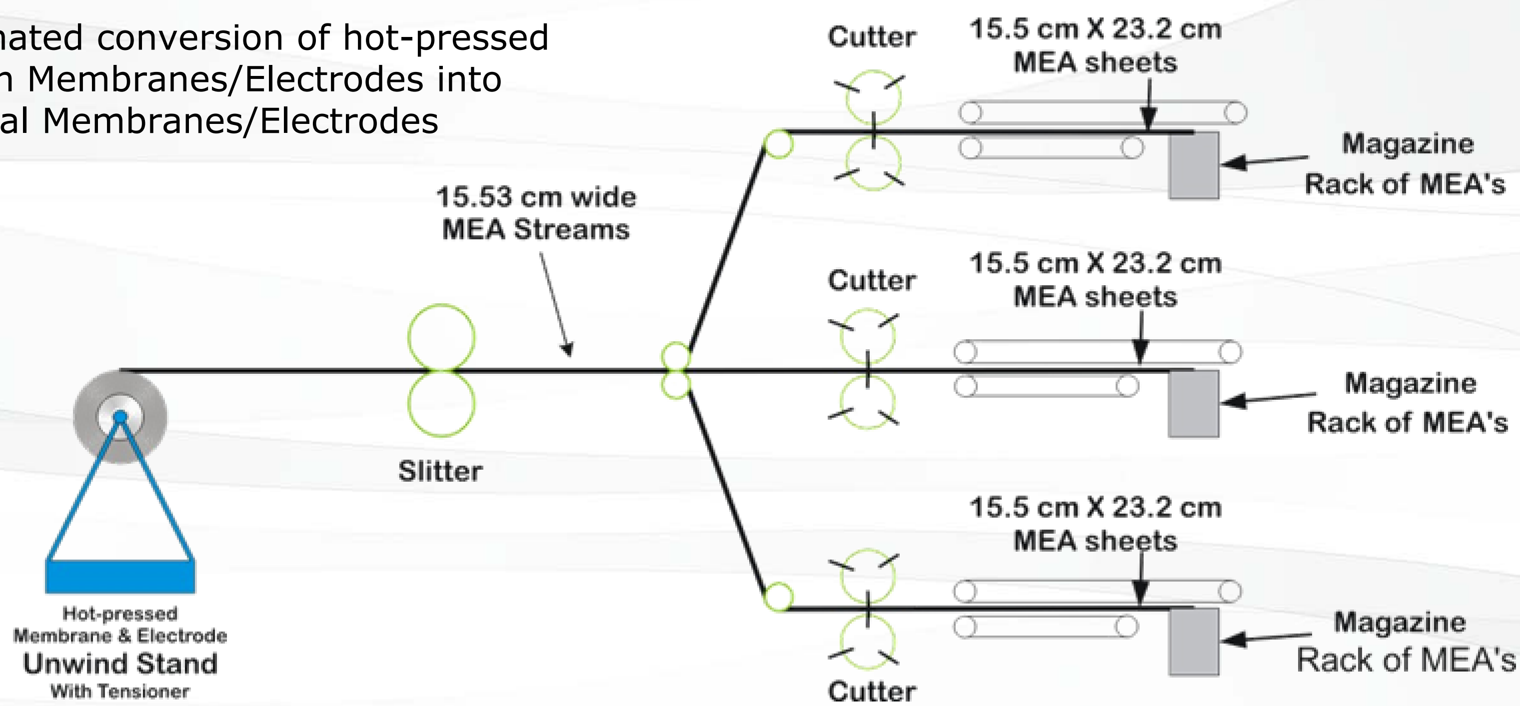




	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Manufacturing ($/stack)	$28.08	$6.51	$6.40	$6.57	$6.39
	Tooling ($/stack)	$0.36	$0.06	$0.06	$0.06	$0.06
	Total Cost ($/stack)	$28.44	$6.57	$6.46	$6.63	$6.44
	Total Cost ($/$kW_{gross}$)	$1.26	$0.29	$0.29	$0.29	$0.28
2010	Manufacturing ($/stack)	$27.68	$5.24	$5.35	$5.38	$5.26
	Tooling ($/stack)	$0.36	$0.05	$0.05	$0.05	$0.05
	Total Cost ($/stack)	$28.04	$5.29	$5.40	$5.43	$5.31
	Total Cost ($/$kW_{gross}$)	$1.28	$0.24	$0.25	$0.25	$0.24
2015	Manufacturing ($/stack)	$27.68	$5.24	$5.35	$5.38	$5.26
	Tooling ($/stack)	$0.36	$0.05	$0.05	$0.05	$0.05
	Total Cost ($/stack)	$28.03	$5.29	$5.40	$5.43	$5.31
	Total Cost ($/$kW_{gross}$)	$1.29	$0.24	$0.25	$0.25	$0.24

Cutting MEA to Size

- Automated conversion of hot-pressed roll-form Membranes/Electrodes into individual Membranes/Electrodes



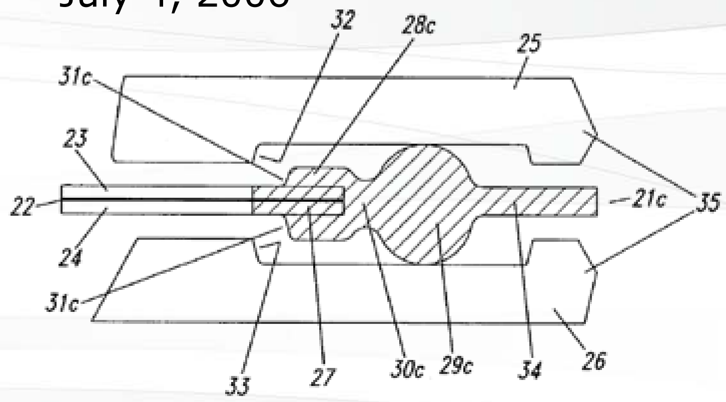
	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Manufacturing ($/stack)	$34.58	$1.21	$0.49	$0.33	$0.27
	Tooling ($/stack)	$1.25	$1.17	$1.16	$1.16	$1.16
	Total Cost ($/stack)	$35.83	$2.38	$1.66	$1.49	$1.43
	Total Cost ($/$kW_{gross}$)	$1.58	$0.11	$0.07	$0.07	$0.06
2010	Manufacturing ($/stack)	$34.57	$1.20	$0.48	$0.32	$0.19
	Tooling ($/stack)	$1.25	$1.17	$1.16	$1.16	$1.16
	Total Cost ($/stack)	$35.82	$2.37	$1.65	$1.48	$1.35
	Total Cost ($/$kW_{gross}$)	$1.64	$0.11	$0.08	$0.07	$0.06
2015	Manufacturing ($/stack)	$34.57	$1.20	$0.48	$0.32	$0.19
	Tooling ($/stack)	$1.25	$1.17	$1.16	$1.16	$1.16
	Total Cost ($/stack)	$35.82	$2.37	$1.65	$1.48	$1.35
	Total Cost ($/$kW_{gross}$)	$1.65	$0.11	$0.08	$0.07	$0.06

MEA Frame-Gasket Concept

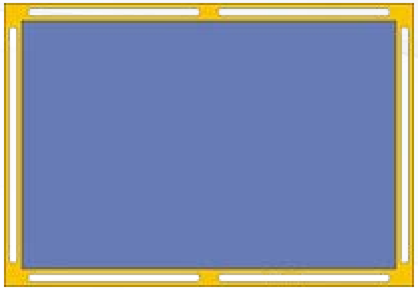
- Insertion molding of gasket around MEA
- Process:
  - two-part silicone mix
  - vacuum mixer to remove air bubbles
  - low pressure injection followed by 20 ksi compression
  - 2.5 min cycle time at 130°C
  - room temperature cure outside of mold
- Silicone may have compression set problems: EPDM is an alternative
- $14.3/kg (in barrel quantities)

MEA with Integrated Seal

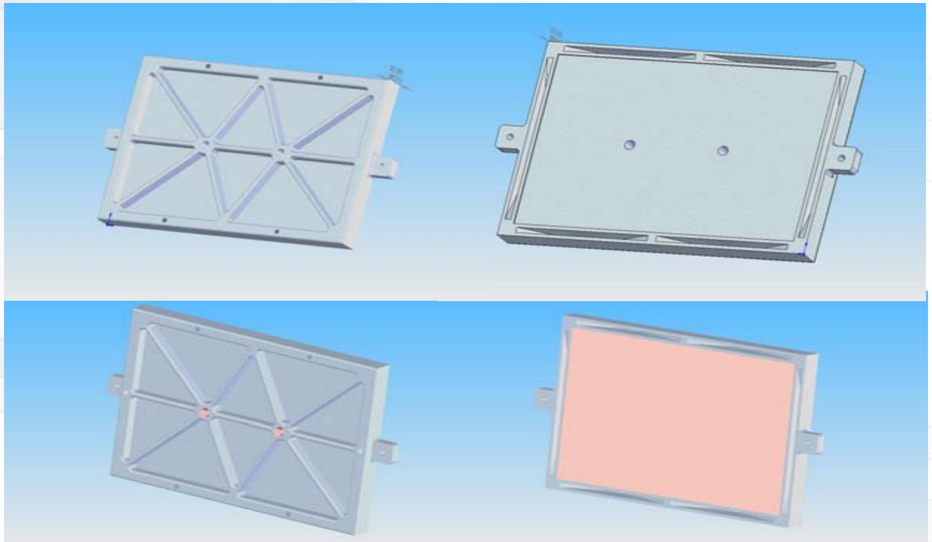
Ballard Patent US7070876
July 4, 2006



	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/stack)	$15.64	$15.64	$15.64	$15.64	$15.64
	Manufacturing ($/stack)	$67.03	$28.28	$27.61	$27.46	$27.32
	Tooling ($/stack)	$1.48	$1.18	$1.14	$1.13	$1.12
	Total Cost ($/stack)	$68.51	$45.09	$44.39	$44.22	$44.08
	Total Cost ($/kW$_{gross}$)	$3.03	$1.99	$1.96	$1.95	$1.95
2010	Material ($/stack)	$9.18	$9.18	$9.18	$9.18	$9.18
	Manufacturing ($/stack)	$59.86	$27.81	$27.14	$26.99	$26.85
	Tooling ($/stack)	$2.94	$1.18	$1.14	$1.13	$1.12
	Total Cost ($/stack)	$71.99	$38.17	$37.47	$37.30	$37.16
	Total Cost ($/kW$_{gross}$)	$3.29	$1.74	$1.71	$1.70	$1.70
2015	Material ($/stack)	$9.11	$9.11	$9.11	$9.11	$9.11
	Manufacturing ($/stack)	$59.85	$27.80	$27.13	$26.98	$26.84
	Tooling ($/stack)	$2.94	$1.18	$1.14	$1.13	$1.12
	Total Cost ($/stack)	$71.90	$38.09	$37.38	$37.22	$37.07
	Total Cost ($/kW$_{gross}$)	$3.30	$1.75	$1.72	$1.71	$1.70



Endplates & Current Collectors



	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Material ($/stack)	$40.36	$35.70	$32.93	$30.47	$25.85
	Manufacturing ($/stack)	$13.55	$1.38	$0.63	$0.37	$0.12
	Tooling ($/stack)	$0.75	$0.07	$0.06	$0.07	$0.06
	Total Cost ($/stack)	$54.66	$37.15	$33.62	$30.91	$26.04
	Total Cost ($/$kW_{gross}$)	$2.41	$1.64	$1.48	$1.37	$1.15
2010	Material ($/stack)	$28.50	$25.21	$23.26	$21.52	$18.25
	Manufacturing ($/stack)	$11.05	$0.76	$0.31	$0.22	$0.14
	Tooling ($/stack)	$0.75	$0.11	$0.08	$0.07	$0.07
	Total Cost ($/stack)	$40.30	$26.07	$23.65	$21.81	$18.46
	Total Cost ($/$kW_{gross}$)	$1.84	$1.19	$1.08	$1.00	$0.84
2015	Material ($/stack)	$28.48	$25.19	$23.24	$21.50	$18.23
	Manufacturing ($/stack)	$11.02	$0.76	$0.31	$0.22	$0.14
	Tooling ($/stack)	$0.75	$0.11	$0.08	$0.07	$0.07
	Total Cost ($/stack)	$40.25	$26.05	$23.63	$21.79	$18.44
	Total Cost ($/$kW_{gross}$)	$1.85	$1.20	$1.09	$1.00	$0.85

- Concept based on UTC Fuel Cells US Patent 6,764,786
- Compression molded non-conductive composite (Lytex 9063 glass fiber reinforced epoxy resin)
- Eliminates need for electrical insulators
- Provides thermal insulation
- Copper Current Collector plates are press fit into endplates with copper studs protruding through endplates for current extraction
- 5 minute cycle/cure time
- $11-$18/kg Lytex material cost (depending on quantity purchased)

Stack Conditioning

Cycle	Step	Gas on Anode	Gas on Cathode	Primary Load Switch	DC Power Supply Positive Terminal	Electrode Potential	Current Density
	1	4% H2-N2	N2	Open	Connected to Cathode	Cathode 0.04V to 1.04V	Low
	2	4% H2-N2	N2	Open	Connected to Cathode	Cathode 0.04V to 1.04V	Low
Cathode Filling Cycles	3	Repeat Step #1					Low
Cathode Filling Cycles	4	Repeat Step #2					Low
Cathode Filling Cycles	5	Repeat Step #1					Low
Cathode Filling Cycles	6	Repeat Step #2					Low
Anode Filling Cycles	7	N2	4% H2-N2	Open	Connected to Anode	Anode 0.04V to 1.04V	Low
Anode Filling Cycles	8	N2	4% H2-N2	Open	Connected to Anode	Anode 0.04V to 1.04V	Low
Anode Filling Cycles	9	Repeat Step #7					Low
Anode Filling Cycles	10	Repeat Step #8					Low
Anode Filling Cycles	11	Repeat Step #7					Low
Anode Filling Cycles	12	Repeat Step #8					Low
Performance Calibrations	13	H2	Air	Closed	Not Connected	Depending on current density	0-1600mA/cm2
	14	Repeat step #13 up to 10 times					

- Stacks "conditioned" for enhanced performance
- Based on UTC Fuel Cells Patent 7,078,118
- Stacks condition per "Applied Voltage Embodiment"
- 10 stacks conditioned simultaneously
- Load bank ~$100k
- Conditioning of stacks staggered to limit peak testing load to ~50kW
- Stacks conditioned to achieve 95% of max performance (~5 hrs; max performance requires ~13 hrs)

Year	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Conditioning/Testing ($/stack)	$18.84	$12.37	$12.20	$12.24	$12.18
2006	Total Cost ($/stack)	$18.84	$12.37	$12.20	$12.24	$12.18
2006	Total Cost ($/$kW_{gross}$)	$0.83	$0.55	$0.54	$0.54	$0.54
2010	Conditioning/Testing ($/stack)	$17.12	$9.97	$9.84	$9.81	$9.74
2010	Total Cost ($/stack)	$17.12	$9.97	$9.84	$9.81	$9.74
2010	Total Cost ($/$kW_{gross}$)	$0.78	$0.46	$0.45	$0.45	$0.44
2015	Conditioning/Testing ($/stack)	$15.39	$7.56	$7.35	$7.38	$7.32
2015	Total Cost ($/stack)	$15.39	$7.56	$7.35	$7.38	$7.32
2015	Total Cost ($/$kW_{gross}$)	$0.71	$0.35	$0.34	$0.34	$0.34

System Assembly

	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				**17.5**
# 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**		
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**

- Detailed DFMA not conducted
- Bill of Materials (BOM) components divided into 5 main categories and a notional installation time was attributed to each.
- Full Manual Assembly for 1k/yr manufacturing rate.
- 10 station assembly line used for all other rates

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2006	Assembly ($/system)	$187.09	$149.67	$149.67	$149.67	$149.67
	Total Cost ($/kW$_{net}$)	$2.34	$1.87	$1.87	$1.87	$1.87
2010	Assembly ($/system)	$187.09	$149.67	$149.67	$149.67	$149.67
	Total Cost ($/kW$_{net}$)	$2.34	$1.87	$1.87	$1.87	$1.87
2015	Assembly ($/system)	$187.09	$149.67	$149.67	$149.67	$149.67
	Total Cost ($/kW$_{net}$)	$2.34	$1.87	$1.87	$1.87	$1.87

Noteworthy BOP Components

	Current/2006	2010	2015
Air Compression	Twin Lobe Compr./Exp./ Motor $2700-$750	Centrifugal Compr./Exp./ Motor $2000-$720	Centrifugal Compressor $1500-$520
Humidification	Water Spray Humid & Water Recov. System $934-$720	Membrane Humidifier $900-$250	None Required $0
H_2 Sensors	Two sensors needed $2000-$200	One sensor needed $1000-$150	No sensors needed $0

Components within the BOP Subsystems

Coolant Loop (High Temp Loop & Low Temp Loop)

- HTL: Coolant reservoir
- HTL: Coolant pump
- HTL: Coolant DI Filter
- HTL: Thermostat & Valve
- HTL: Radiator fan
- HTL: Radiator heat exchanger
- LTL: Coolant Pump
- LTL: Radiator
- LTL: Radiator Fan

System Controller/Sensors

- Controller
- Hydrogen Sensor System

Fuel Loop

- Hydrogen tank (not included in cost analysis)
- Hydrogen pressure relief device & regulator (not included in cost analysis)
- Hydrogen fueling receptacle (not included in cost analysis)
- Pressure Transducer
- Hydrogen proportional valve
- Hydrogen Low Flow Ejector
- Hydrogen High Flow Ejector
- Hydrogen/stack inlet manifold
- Hydrogen/stack outlet manifold

Air Loop

- Air filter & Housing
- Air compressor, expander & motor
- Air/stack inlet manifold
- Air/stack outlet manifold
- Air Mass Flow Sensor

Humidifier & Water Recovery Loop

- High Pressure Water pump & motor
- Air Humidifier Assembly
- Air Humidifier Thermocouple
- Exh. Air Condenser Water Level Sensor
- Exh. Air Condenser Sump Pump
- Water Reservoir
- Humidifier Loop Deionizer
- Membrane Air Humidifier
- Air Demister
- Exhaust Air Condenser

Miscellaneous/BOP

- Wiring
- Startup Battery
- Air ducting
- Water tubing
- Coolant liquid piping
- Hydrogen piping/ducting materials
- Fasteners for wire, hose, pipe
- Anode ducting
- Cathode ducting

Stack Bill of Materials (Current Technology)

2006	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
	Flow Plates (Stamping)	$97.42	$86.39	$86.20	$86.39	$86.32
	MEAs					
	GDLs	$973.05	$518.36	$298.81	$224.27	$101.76
	Catalyst Ink	$1,483.33	$1,018.89	$966.68	$947.45	$909.97
	Membrane & Catalyzation	$1,383.90	$315.99	$198.91	$160.12	$91.96
	M & E Hot Pressing	$28.44	$6.57	$6.46	$6.63	$6.44
	M & E Cutting & Slitting	$35.83	$2.38	$1.66	$1.49	$1.43
	MEA Frame/Gaskets	$68.51	$45.09	$44.39	$44.22	$44.08
	Coolant Gaskets	$56.56	$35.32	$35.32	$34.97	$34.95
	Endplates & Current Collectors	$54.66	$37.15	$33.62	$30.91	$26.04
	Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
	Stack Assembly	$42.68	$17.20	$14.50	$14.59	$14.55
	Stack Conditioning & Testing	$18.84	$12.37	$12.20	$12.24	$12.18
	Total Stack Cost	$4,253.22	$2,103.72	$1,704.74	$1,568.79	$1,334.69
	Total Cost for all 4 Stacks	$17,012.86	$8,414.87	$6,818.96	$6,275.14	$5,338.75
	Total Stack $/kW (Net)	$212.66	$105.19	$85.24	$78.44	$66.73
	Total Stack $/kW (Gross)	$187.85	$92.91	$75.29	$69.29	$58.95

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

Stack Bill of Materials (2010 Technology)

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2010	Flow Plates (Stamping)	$74.72	$64.33	$64.15	$64.22	$64.07
	MEAs					
	GDLs	$716.51	$352.20	$205.31	$154.31	$71.43
	Catalyst Ink	$452.26	$308.93	$293.04	$287.20	$275.82
	Membrane & Catalyzation	$977.97	$245.82	$152.57	$121.03	$68.36
	M & E Hot Pressing	$28.04	$5.29	$5.40	$5.43	$5.31
	M & E Cutting & Slitting	$35.82	$2.37	$1.65	$1.48	$1.35
	MEA Frame/Gaskets	$71.99	$38.17	$37.47	$37.30	$37.16
	Coolant Gaskets	$60.60	$28.27	$28.27	$27.92	$27.90
	Endplates & Current Collectors	$40.30	$26.07	$23.65	$21.81	$18.46
	Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
	Stack Assembly	$42.68	$17.20	$14.50	$14.59	$14.55
	Stack Conditioning & Testing	$17.12	$9.97	$9.84	$9.81	$9.74
	Total Stack Cost	$2,528.00	$1,106.62	$841.86	$750.61	$599.15
	Total Cost for all 4 Stacks	$10,111.99	$4,426.47	$3,367.43	$3,002.43	$2,396.62
	Total Stack $/kW (Net)	$126.40	$55.33	$42.09	$37.53	$29.96
	Total Stack $/kW (Gross)	$115.45	$50.54	$38.45	$34.28	$27.36

- ~50% stack cost reduction between 2006 and 2010 due primarily to:
  - 40% increase in power density (700mW/cm^2 to 1000mW/cm^2)
  - 55% reduction in catalyst loading (0.65 mg/cm^2 to 0.29 mg/cm^2)

Stack Bill of Materials (2015 Technology)

	Annual Production Rate	1,000	30,000	80,000	130,000	500,000
2015	Flow Plates (Stamping)	$74.44	$64.06	$63.89	$63.96	$63.81
	MEAs					
	GDLs	$713.64	$350.40	$204.28	$153.55	$71.10
	Catalyst Ink	$295.94	$201.29	$190.92	$187.10	$179.68
	Membrane & Catalyzation	$973.06	$244.93	$151.98	$120.56	$68.07
	M & E Hot Pressing	$28.03	$5.29	$5.40	$5.43	$5.31
	M & E Cutting & Slitting	$35.82	$2.37	$1.65	$1.48	$1.35
	MEA Frame/Gaskets	$71.90	$38.09	$37.38	$37.22	$37.07
	Coolant Gaskets	$60.52	$28.19	$28.19	$27.84	$27.82
	Endplates & Current Collectors	$40.25	$26.05	$23.63	$21.79	$18.44
	Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
	Stack Assembly	$42.68	$17.20	$14.50	$14.59	$14.55
	Stack Conditioning & Testing	$15.39	$7.56	$7.35	$7.38	$7.32
	Total Stack Cost	$2,361.68	$993.43	$735.17	$646.38	$499.53
	Total Cost for all 4 Stacks	$9,446.70	$3,973.70	$2,940.68	$2,585.53	$1,998.11
	Total Stack \$/kW (Net)	$118.08	$49.67	$36.76	$32.32	$24.98
	Total Stack \$/kW (Gross)	$108.48	$45.63	$33.77	$29.69	$22.94

- ~10% stack cost reduction between 2010 and 2015 due primarily to 35% reduction in catalyst loading (0.29 mg/cm^2 to 0.19 mg/cm^2)

DIRECTED TECHNOLOGIES INC.