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

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DOE Hydrogen Program Review

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Project ID #: **FC7**

Overview

Timeline

- Base Period:
  - 100% complete
  - Feb 17, 2006 to Feb. 16, 2008
- Option year 1 of 3:
  - 25% complete
  - Started Feb 16, 2008

Budget

- Total project funding
  - $325K (2 year base period)
  - $182k (opt. yr. 1)
  - Contractor share: $0
- Funding for FY 2007
  - $175k
- Funding for FY 2008
  - $182k

Barriers

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

DOE Cost Targets

Characteristic	Units	2007	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.

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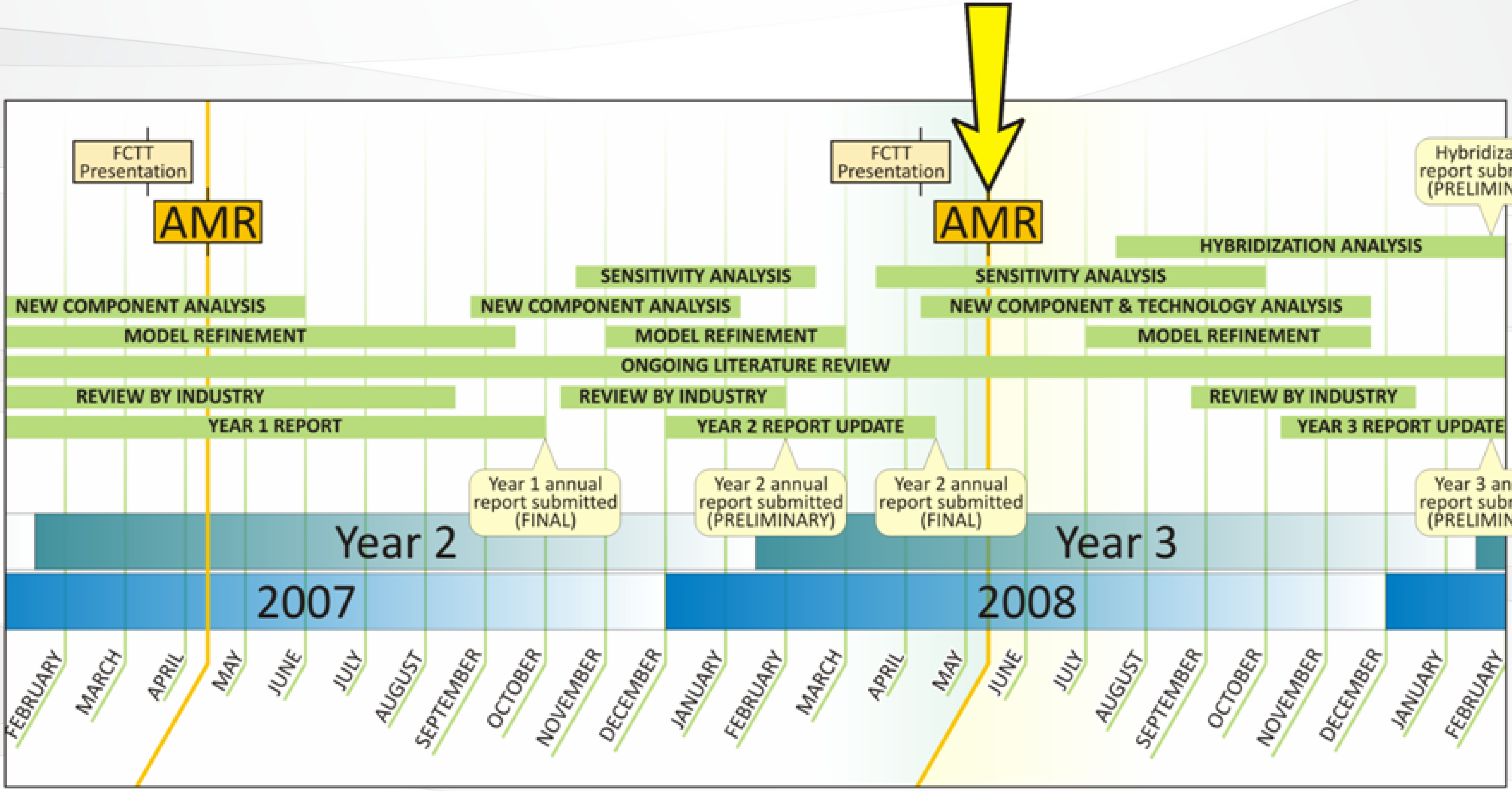
Project Timeline



- Focus since last year's AMR has been documenting, reporting and refining analysis
- Preliminary analysis conducted on nitrided bipolar plate coatings & alternative gasketing methods

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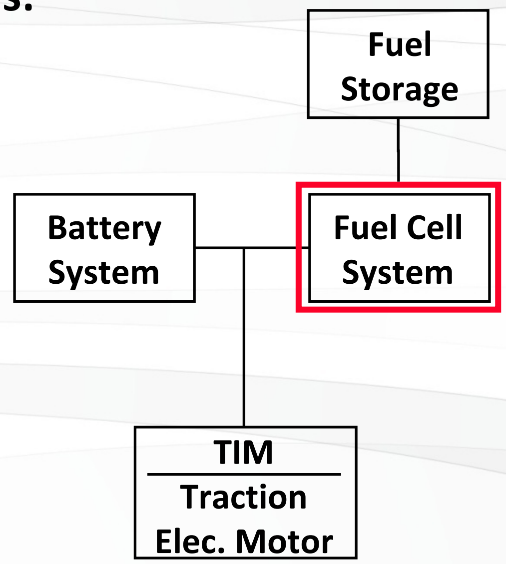
Objectives

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:**
    - 2007 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 (91 kW gross for 2007 system)**
- **1k to 500k annual system production**
- **U.S. labor rates: $60/hr (fully loaded)**
- **10% capital cost contingency is NOT included**
- **$1100/troy oz. Pt cost used (currently ~$2,000/troy oz.)**

- **Some costs NOT included:**
  - **Warranty**
  - **Building costs** **(equipment cost included but not building in which equipment is housed)**
  - **Sales Tax**
  - **Non-Recurring Engineering Costs**

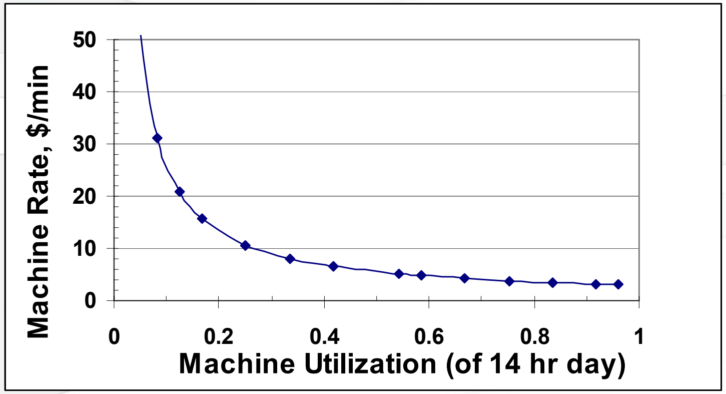
DTI's DFMA®-Style Costing Methodology

- **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**

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

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Key Technical Targets Define System

DOE Tech. Targets that drive analysis:		AMR 2007	AMR 2008	AMR 2007	AMR 2008	AMR 2007	AMR 2008
		Current (2006, 2007)		2010		2015	
Stack Efficiency @ Rated Power	%	55%	55%	55%	55%	55%	55%
MEA Areal Power Density @ Peak Power	mW/cm^2	700	583	1,000	1,000	1,000	1,000
Total Pt-Group Catalyst Loading	$mg\ PGM/cm^2$	0.65	0.35	0.29	0.30	0.19	0.20
Key Derived Performance Parameters:							
System Gross Electric Power (Output)	kW	90.6	90.3	87.6	86.8	87.1	87.1
Active Area	cm^2	348	417	235	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

	2007 Technology	2010 Technology	2015 Technology
Power Density	583 (was 700)	1,000	1,000
Total Pt loading	0.35 (was 0.65)	0.3 (was 0.29)	0.2 (was 0.19)
Operating Pressure	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
H_2 Humidification	None	None	None
Exhaust Water	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	Silicone injection molding of gasket around MEA
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	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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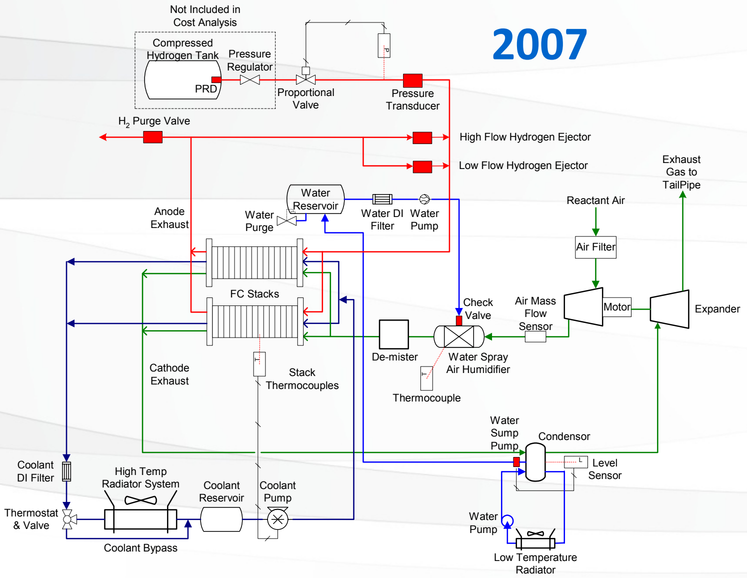
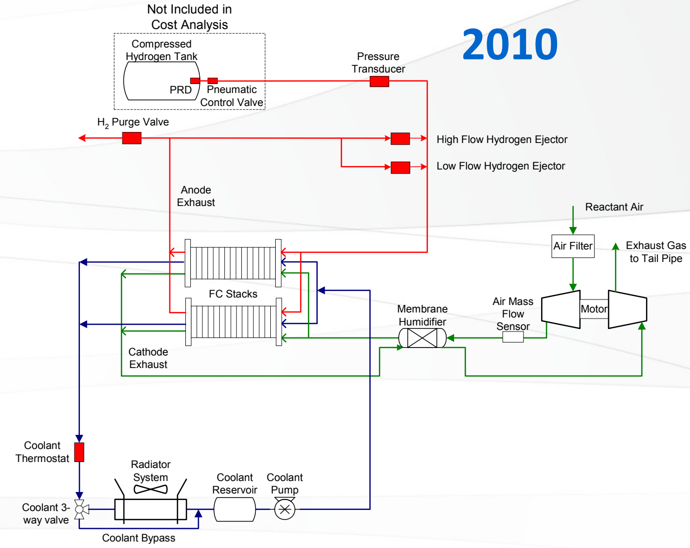
Different Technology Schematics

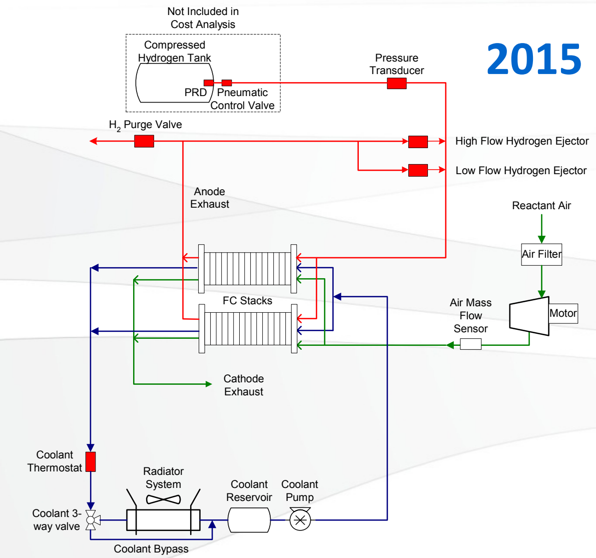
2007



2010



2015



Changes from 2007 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

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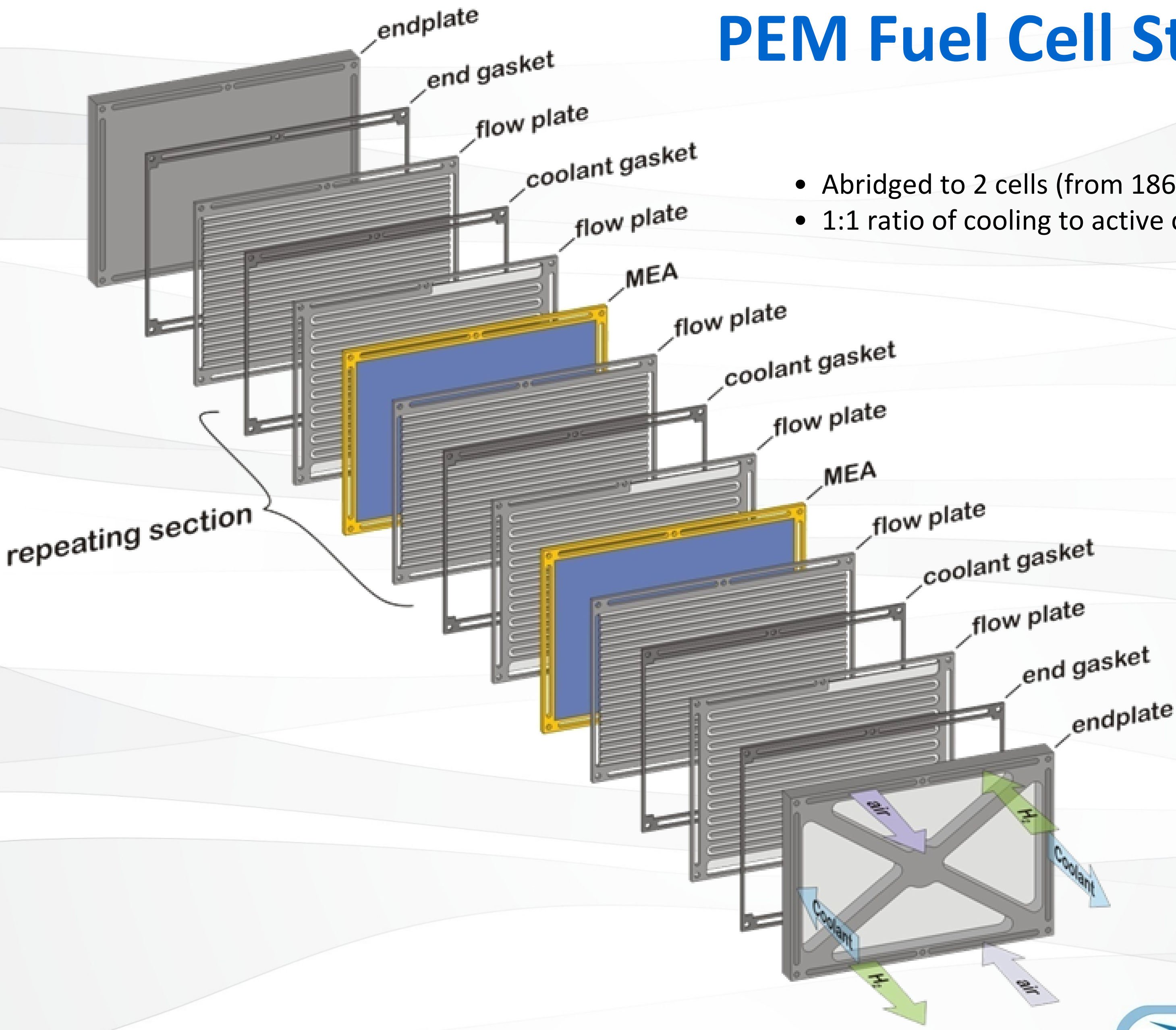
PEM Fuel Cell Stack



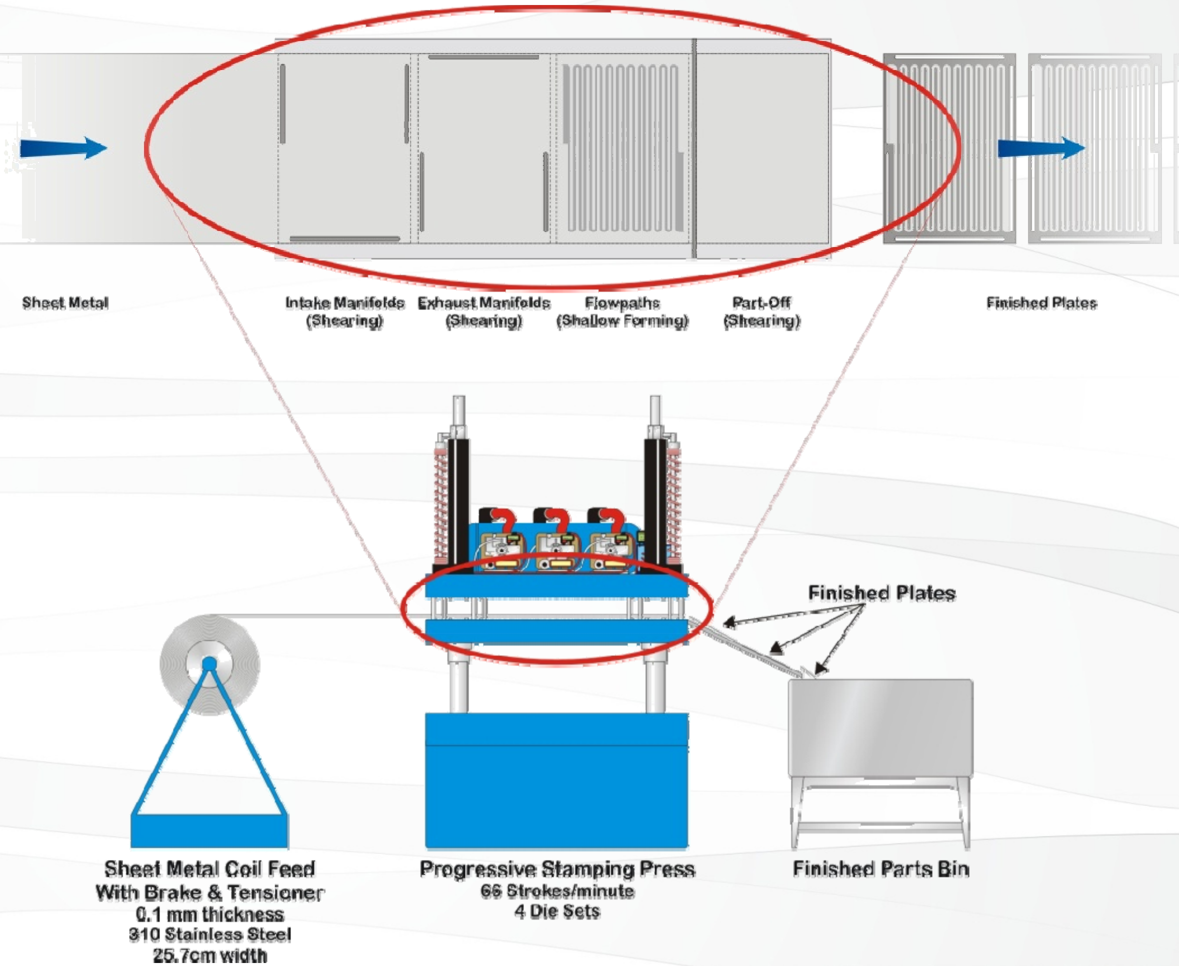
- Abridged to 2 cells (from 186) for clarity
- 1:1 ratio of cooling to active cells

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)



<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

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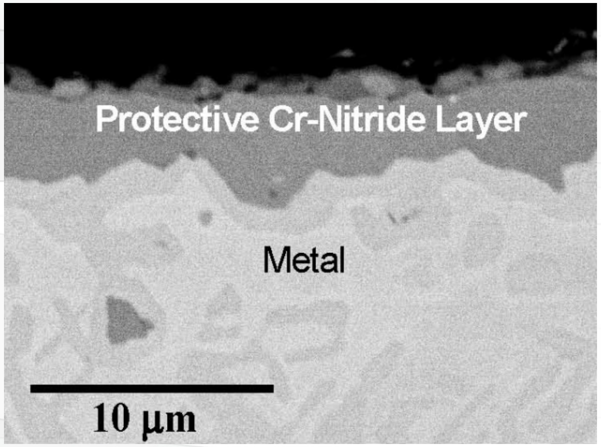
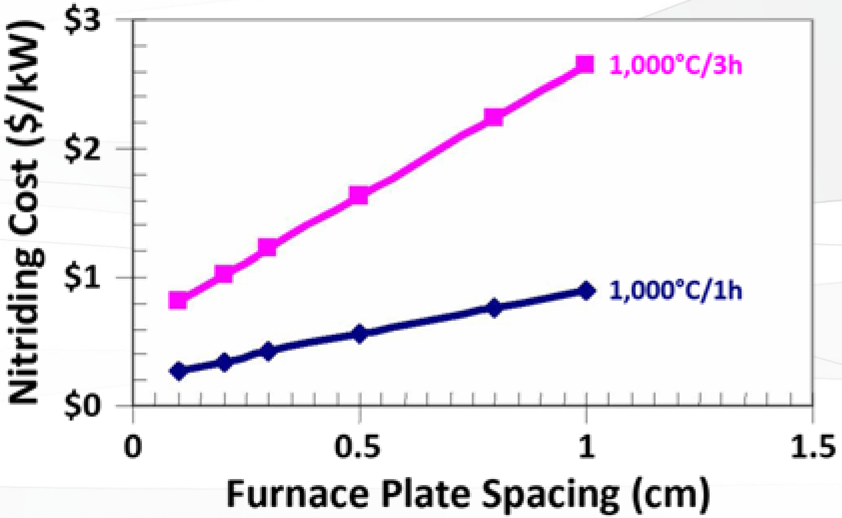
Nitrided Coatings for Stamped Bipolar Plates





- **Oak Ridge National Lab (Mike Brady) is investigating nitrided coatings for bipolar plate corrosion resistance with low surface contact resistance**
- **Conventional nitriding currently conducted in large automated facilities: anticipated process for bipolar plates is similar but simpler & faster**
- **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

Noteworthy Changes Since Last Year

Current Technology, 500,000 Systems/Year Item	Notes	AMR 2007	AMR 2008	Effect on System Cost ($/kW$_{net}$)
Stacks/System	Halved stacks/system, doubled cells/stack	4	2	($1.23)
Power Density	Updated value (from DOE)	700 mW/cm^2	583 mW/cm^2	$8.58
Total Catalyst Loading	Updated value (from DOE)	0.65 mgPt/cm^2	0.35 mgPt/cm^2	($19.56)
Platinum Cost	Switched from avg. of last 6-mo. of 2006 to DOE-provided number	$1,175/oz.	$1,100/oz.	($2.73)
Ionomer Cost	Updated industry projection	$195/kg	$92/kg	($1.10)
GDL Cost	Implied markup removed from Macroporous GDL cost	$12/m^2	$9/m^2	($1.05)
Bipolar Plates Stamping Machinery Capital Cost	Capital cost increased after industry consultation	$103,098	$515,488	$0.21
Bipolar Plate Design	Improved die designs, made anode plate different from cathode	Common plate design	Dual designs	$0.00
O_2 Stoichiometry	Lowered Oxygen Stoichiometry from 2.0 to 1.8	2.0	1.8	($0.59)
Compressor Efficiency	Corrected estimate, changed gross power	70%	65%	$0.70
Motor/Controller Efficiency	Revised based on industry input, changed gross power	80%	85%	($0.32)
System Assembly	Improved logic for object handling & process efficiency	Good	Better	($0.03)
Air Mass Flow Sensor	Left out of summation for last year's estimate	None	Included	$0.81
Belly Pan	Added a belly pan to the BOP under miscellaneous.	None	Included	$0.26
Other Misc. Changes	A variety of other changes were made, but net effect is small			$0.01
Total		**$109.62**	**$93.58**	**($16.04)**

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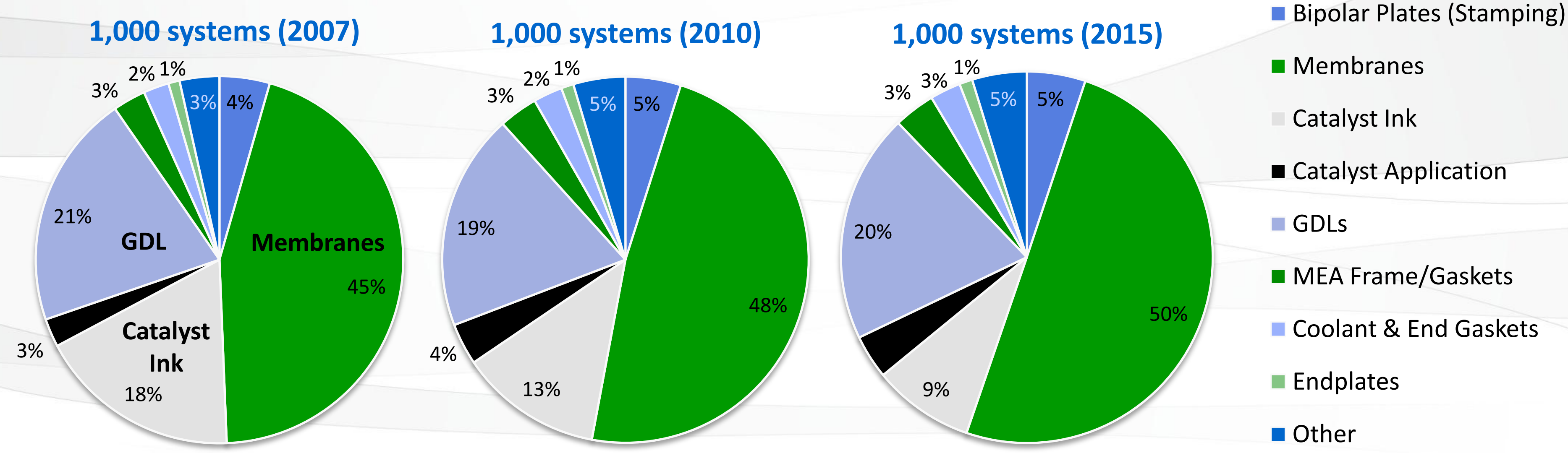
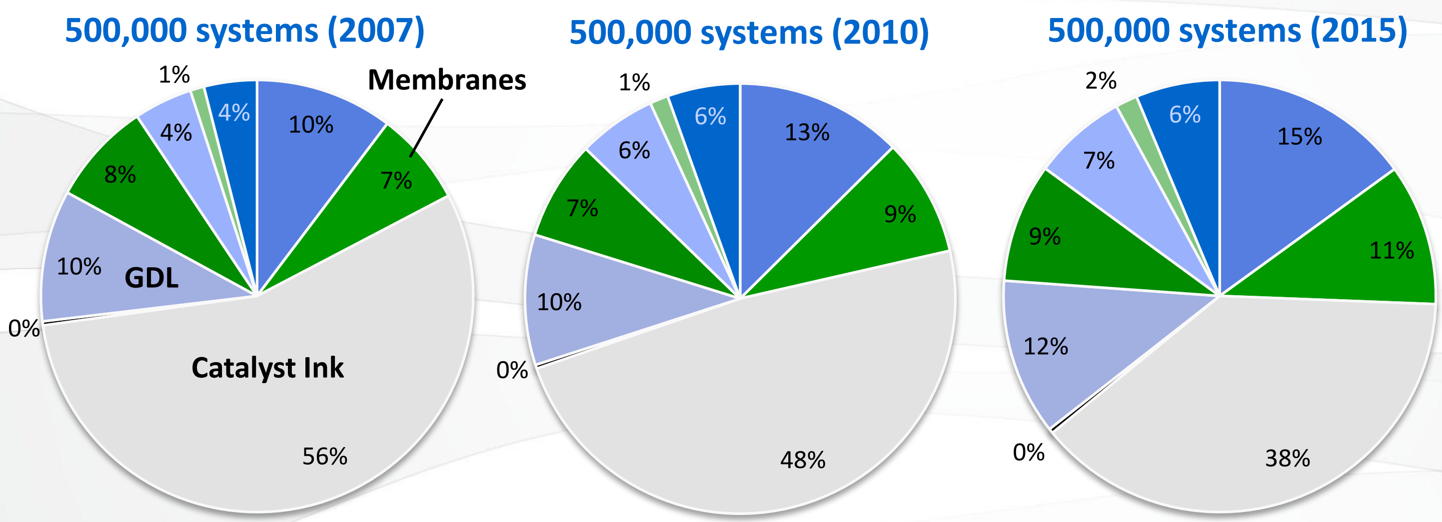
Stack Component Cost Distribution





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

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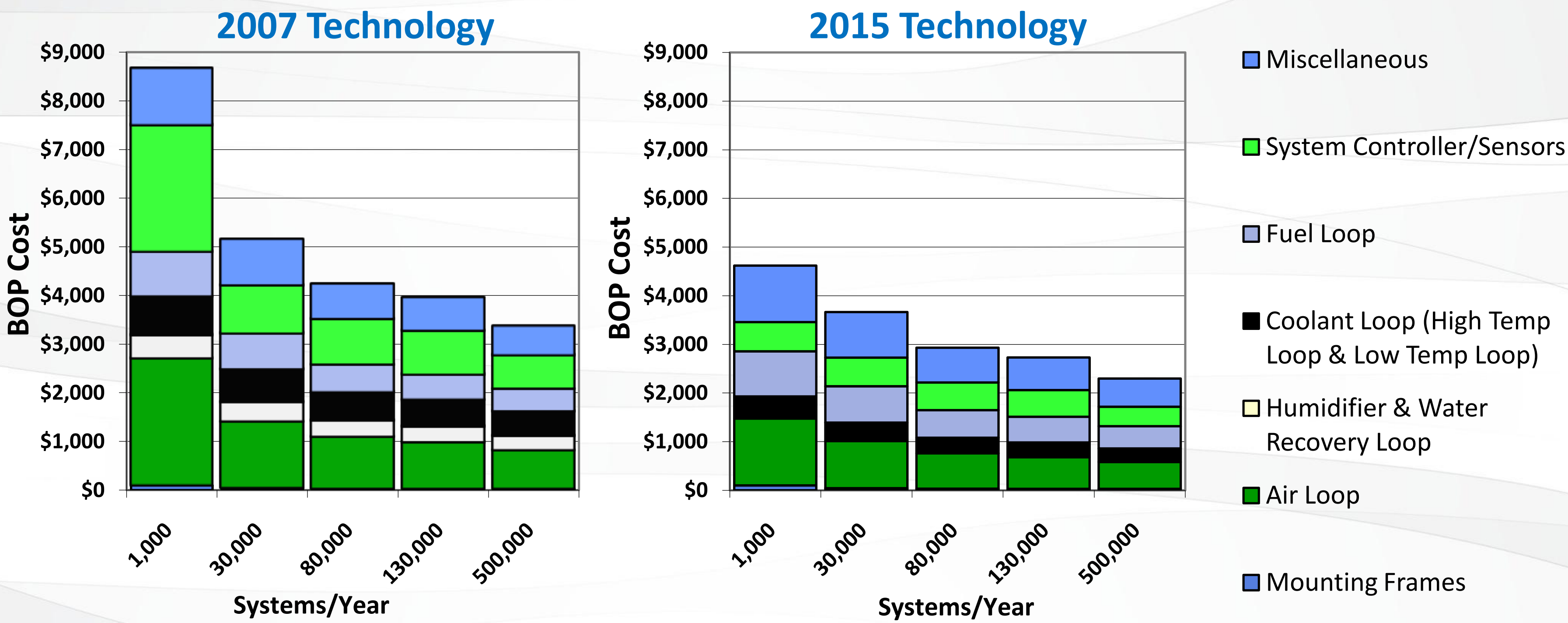
Balance of Plant



- 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.

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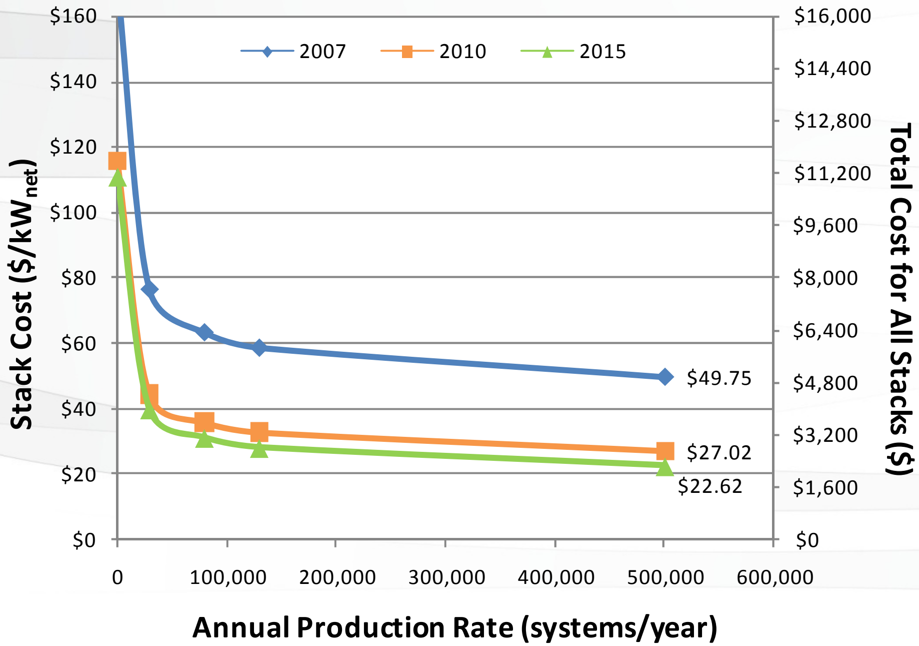
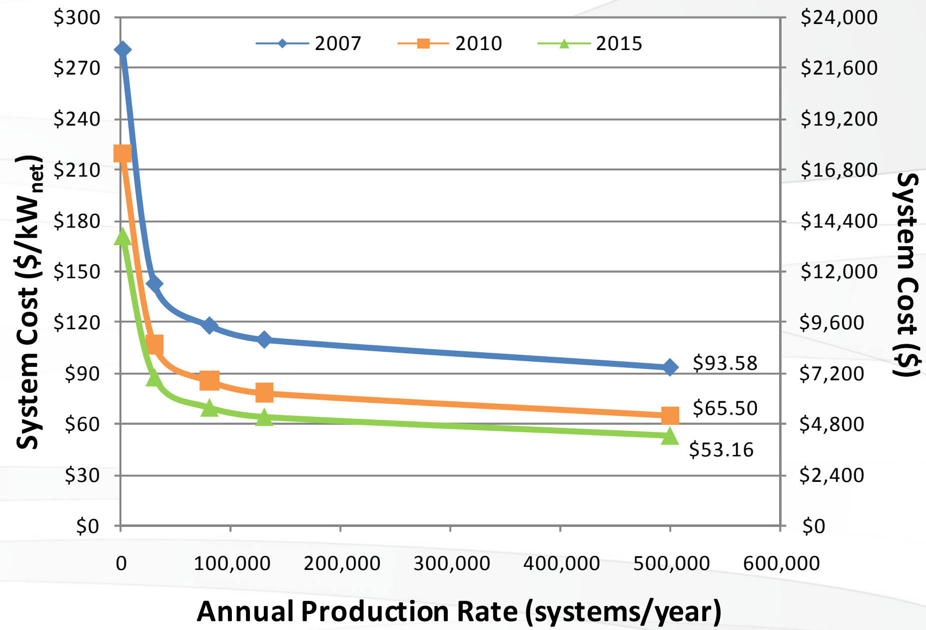
Stack & System Costs vs. Annual Production Rate

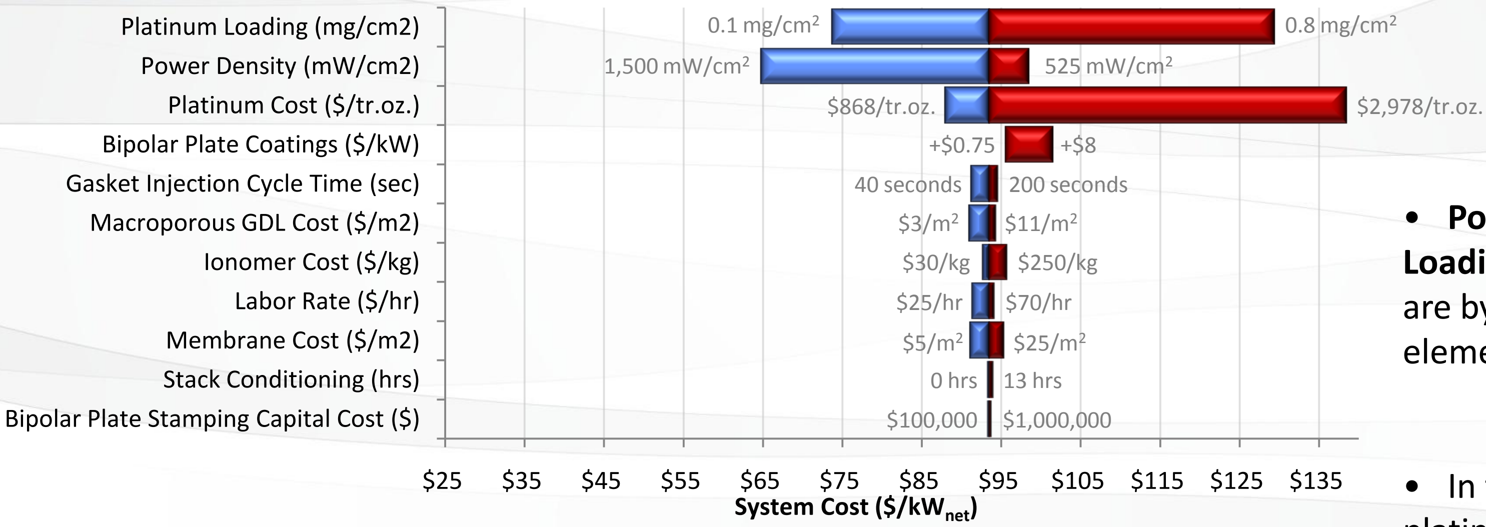




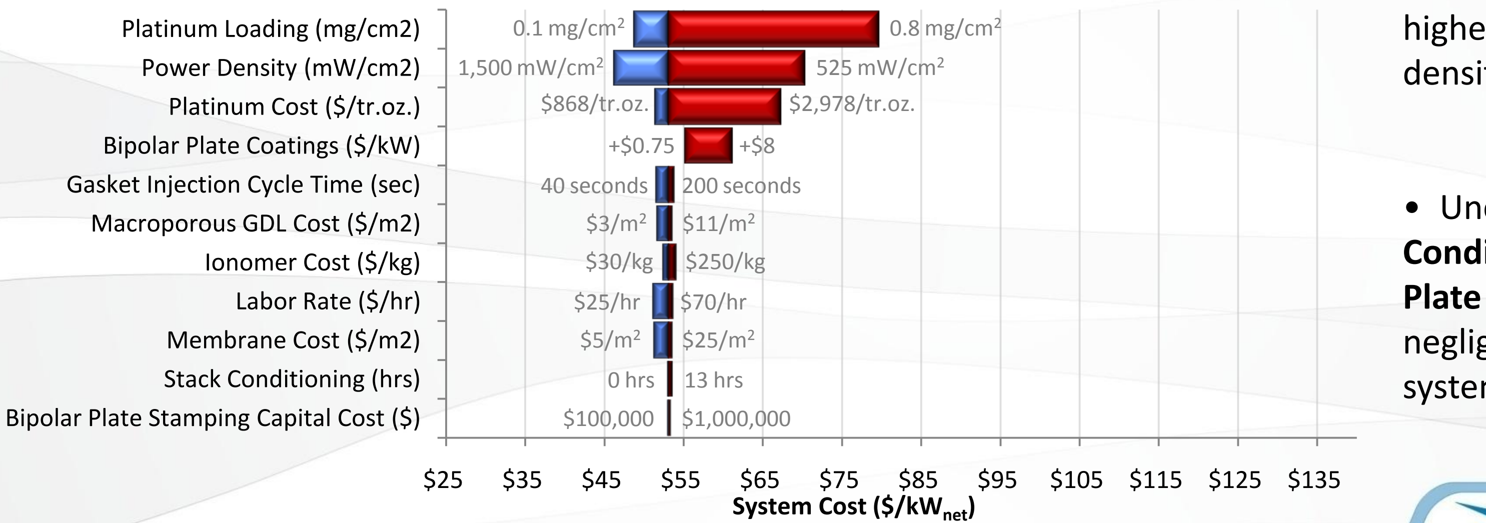
			Current (2006, 2007)		2010		2015	
			AMR 2007	AMR 2008	AMR 2007	AMR 2008	AMR 2007	AMR 2008
DOE Target:	Stack Cost	$/kW$_{e\,(net)}$	-	-	$25	$25	$15	$15
Study Estimate:	Stack Cost	$/kW$_{e\,(net)}$	$67	$50	$30	$27	$25	$23
DOE Target:	System Cost	$/kW$_{e\,(net)}$	-	-	$45	$45	$30	$30
Study Estimate:	System Cost	$/kW$_{e\,(net)}$	$110	$94	$70	$66	$59	$53

Sensitivity Analysis

2007 Technology, 500,000 systems/year



2015 Technology, 500,000 systems/year



- **Power Density**, **Platinum Loading**, and **Platinum Cost** are by far the three biggest elements of cost uncertainty
- In the 2015 system, the platinum doesn't have as much effect due to the higher assumed power density
- Uncertainties in **Stack Conditioning** and **Bipolar Plate Stamping Cost** have negligible effect on the total system cost

Cost Reduction Observations

- **Power density is single most important stack cost driver**
  - Affects entire stack
- **Pt loading is key cost driver at high production rates**
  - Non-Pt catalyst would be breakthrough
  - Lower Pt-loadings are needed **BUT**
    - Must not sacrifice power density
    - Must not sacrifice **DURABILITY**
- **Membrane is key cost driver at low production rates**
  - Mass manufacturing of Nafion®-like ionomer leads to low cost
  - Path to low membrane cost at **LOW** production volume is needed
- **BOP of plant costs are significant**
  - Mass manufacturing improves a factor of 2-3
  - BOP simplification is needed
    - Tradeoff between simplification & performance needs to be better understood
- **Need to be open to radically different approaches to stack/configuration**

Future Work

- **Year 3 (Option Year 1):** Due February 2009
  - **Annual Update**
    - Expanded sensitivity analysis
      - Use results to drive the rest of the analysis
    - Refine BOP cost estimates
      - BOP currently comprises 45-57% of stack cost
      - Analyze cost savings potential for components identified in sensitivity analysis
    - Re-evaluation of technology and cost to reflect 2008 progress
    - Investigate platinum alloys & alternate catalyst deposition techniques
    - Examine gasketing alternatives

  Focus for this year

  - **Optional Task 3.3:**
    - Optimization analysis
      - Analyze trade-offs between power density & catalyst loading for minimized cost

- **Year 4 (Option Year 2):** Due February 2010
  - **Annual Update**

- **Year 5 (Option Year 3):** Due February 2011
  - **Annual Update**

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