STRATEGIC ANALYSIS INC

2015 DOE Hydrogen and Fuel Cells Program Review

Fuel Cell Vehicle and Bus Cost Analysis

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Project ID# FC018

Overview

Timeline

- Project Start Date: 9/30/11
- Project End Date: 9/30/16
- % complete: 40% (in year 4 or 5)

Barriers

- B: System cost
  - Realistic, process-based system costs
  - Need for realistic values for current and future cost targets
- Demonstrates impact of technical targets & barriers on system cost:
  - Balance of plant components
  - Materials of construction
  - System size and capacity (weight and volume)

Budget

- Total Project Budget: $739,997 (SA portion)
  - Total Recipient Share*: $499,446 (SA portion)
  - Total Federal Share: $0
- *As of 31 March 2015

Partners

- Project Lead: Strategic Analysis Inc.
- National Renewable Energy Laboratory (NREL)
- Argonne National Lab (ANL)

Relevance

Objectives:

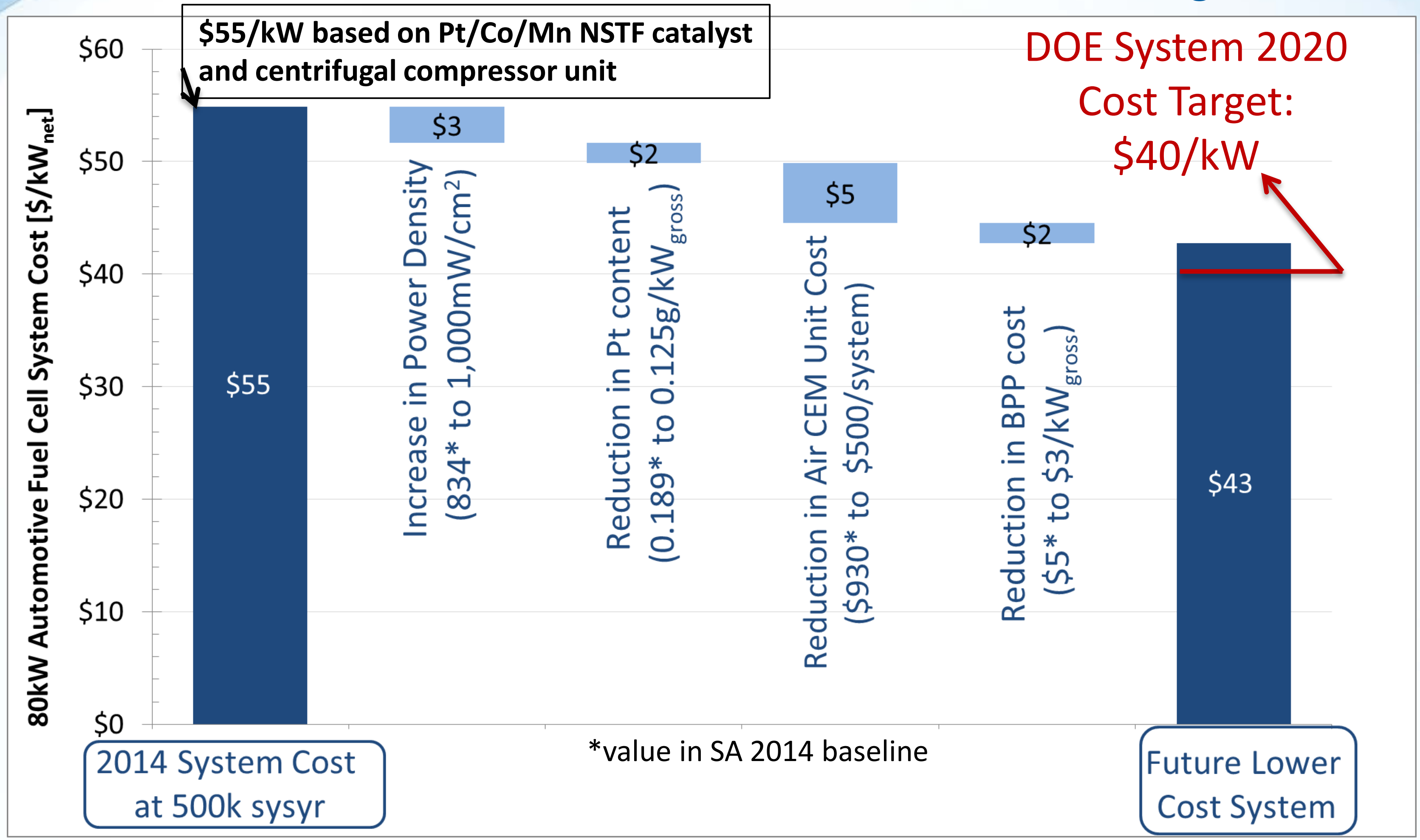
- Project a future cost of automotive and bus fuel cell systems at high manufacturing rates.
- Identify low cost pathways to achieve the DOE 2020 goal of \$40/kW_{net} (automotive) at 500,000 systems per year
- 2015 focus on low volume production (1k – 5k sys/yr) and near term applications
- Identify fuel cell system cost drivers to facilitate Fuel Cell Technology Office programmatic decisions.

Impact since 2014 AMR:

- No significant cost reduction to baseline cost models, however side analyses for future implementation show potential for lower system cost, particularly at low volumes (1k – 5k sys/yr).
- Reveals threshold power density of non-Pt catalyst (PANI) to equal cost of Pt-based systems.

Approach: Automotive System Cost Status

Potential Cost Reduction Based on US DRIVE Targets



- Example pathway to a $43/kW fuel cell system by applying US DRIVE Fuel Cell Technical Team Roadmap target values within SA's DFMA® cost model.
- Significant steps: increase in power density and reduction in CEM cost.

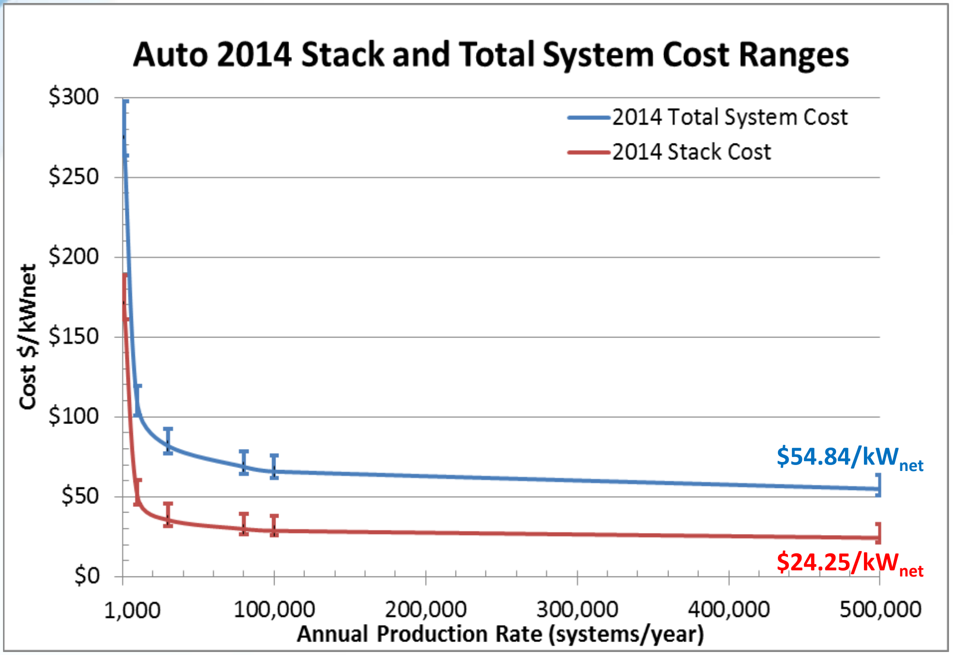
US DRIVE targets: http://energy.gov/sites/prod/files/2014/02/f8/fctt_roadmap_june2013.pdf
US DOE System target: http://hydrogen.energy.gov/pdfs/14012_fuel_cell_system_cost_2013.pdf

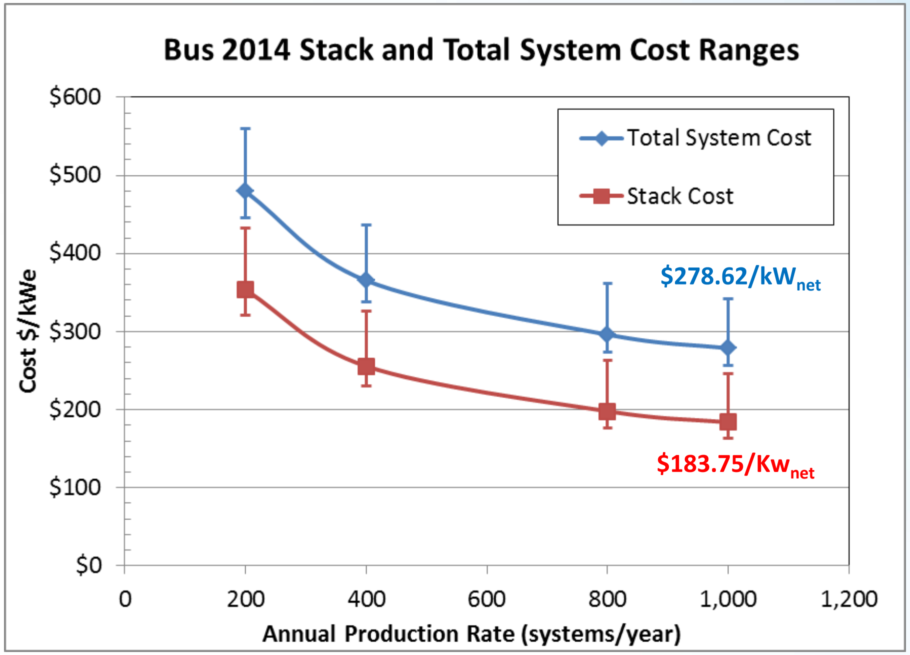
Approach: Topics Examined

Annually apply new technological advances and design of transportation systems into techno-economic models

Topics	Timeline	Topic Status	Estimated Cost Status
Automotive System	Ongoing	2014 Final system cost analysis completed and preliminary draft report written.	\$55/kW$_{net}$ (500k sys/yr)
JM-style Binary catalyst (PtNiC)	2014-2015	In 2014, completed analysis on catalyst synthesis and application. For 2015, combine results with performance under optimized conditions.	PtNiC: \$144.82/m$^2_{\text{active area}}$ Application.: \$2.44/m$^2_{\text{active area}}$
Eaton-style CEM (compressor/expander/motor)	2013-2015	2013 Completed initial cost assessment of CEM. 2014 made updates to dimensional and configurationally changes. 2015 Finalizing analysis with efficiency and operating conditions.	\$11/kWnet (500k sys/yr)
PANI-Fe-C Catalyst	2015	Alternative low cost catalyst cost assessment with preliminary results.	\$73.09/kg at 0.384kg per 80kWe stack (500k sys/yr)
Low Volume Focus	2015	New evaluation of alternative low volume manufacturing process methods.	
Bipolar Plates	2015	Reviewed forming and corrosion resistive coating at low prod vol. Preliminary results.	Ti plates (gold): \$3.50/plate SS plates (treadstone): \$2/plate (1k sys/yr)
Slot Die Coating Catalyst Application	2015	Alternative catalyst application (to NSTF) at low production volume. Preliminary results.	Slot Die Coating: \$30/m$^2_{\text{active area}}$ NSTF Process: \$106/m$^2_{\text{active area}}$ (1k sys/yr)
Giner Inert Thin Film Supported Membrane	2015	Background research initiated. No results to date.	--
Bus System	Ongoing	2014 final system cost analysis completed. 2015 incorporate life cycle cost analysis.	\$279/kW$_{net}$ (1k sys/yr)

Accomplishments and Progress:
2014 Cost Results for Automotive and Bus Fuel Cell Systems





<u>Significant Updates and Analyses (2014 AMR to end of 2014 calendar year)</u>

Update to Baseline DFMA® models:

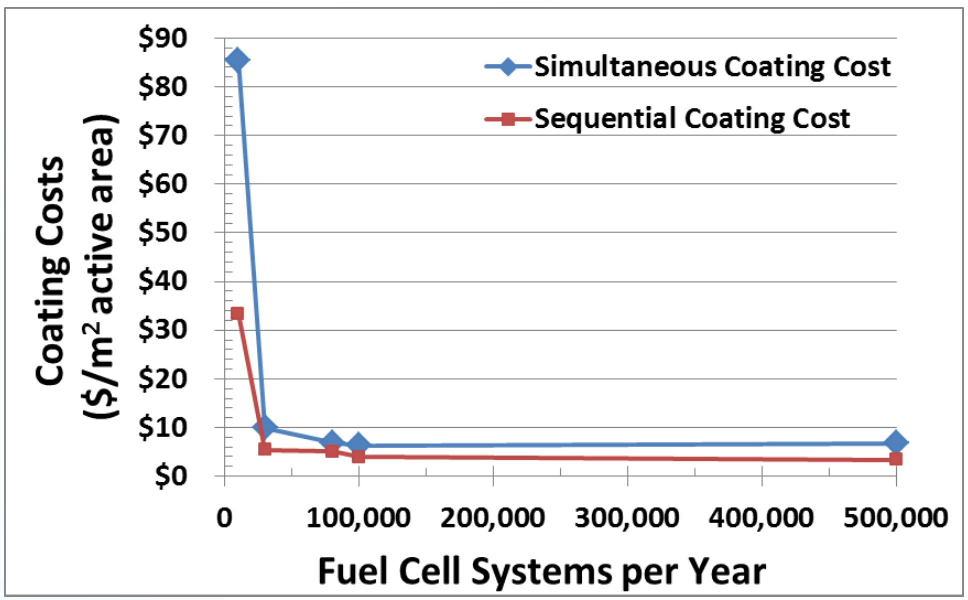
- Continued material price updates (all quotes from no earlier than 2012)

Additional Analyses:

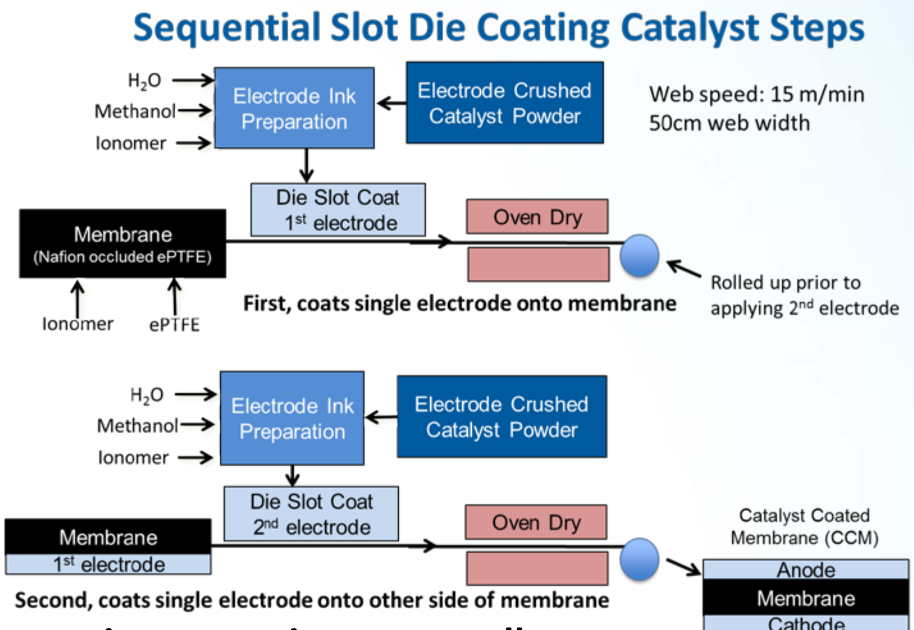
- Monte Carlo Sensitivity Analysis (stack & sys.) expanded to all manuf. rates (auto & bus)
- De-Alloyed PtNiC Catalyst Application Process (slot die coating DFMA®)
- Refinement of Eaton CEM (efficiency and dimensional changes) (for bus)

Accomplishments and Progress:
Johnson Matthey-Style PtNiC Catalyst Application

- Catalyst powder cost examined in 2014. In 2015 expanded to catalyst application.
- Slot die equipment parameters based on vendor information[1]
- Two types of slot die coating systems were analyzed:
  - *Double-Sided Simultaneous coating system (sized for large production volume)*
  - *Single-sided sequential coating system (multiple smaller sizes at low volume)*



Anode and cathode coated sequentially on single machine.



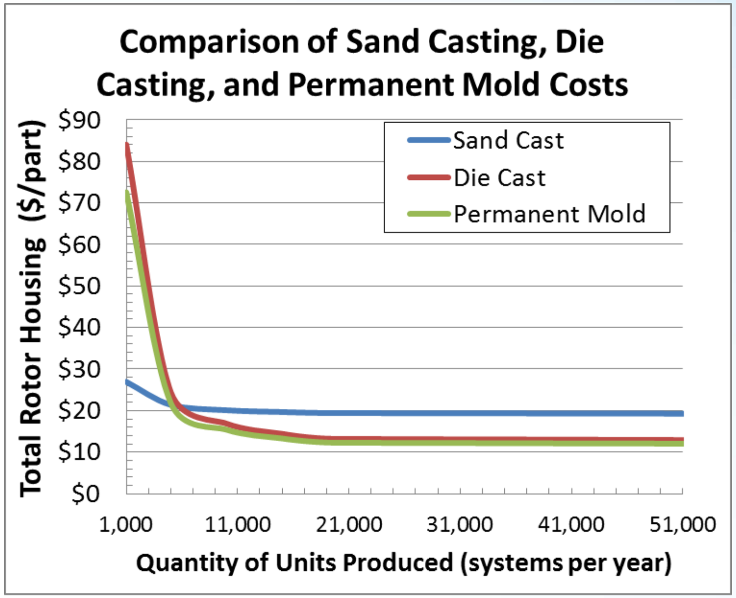
Sequential slot die coating method is currently less expensive per active area at all manufacturing rates (independent of performance).

[1]See coating machine information in backup slides

Accomplishments and Progress:

Alternate fabrication methods & Updated CEM Efficiency

- Based on industry input, SA re-examined potential processing method for casting the compressor rotor housing.
- Three types of casting were compared:
    1. Sand Casting –less expensive at low volumes
    2. Die Casting – expensive die costs
    3. Permanent Mold– less expensive at high vol.
- Interesting exercise, but identified little cost savings
- Eaton System still ~$11/kWnet at 500k sys/yr



(all efficiencies at rated power)	SA's 2013 and 2014 Baseline Values	Eaton's 2014 Status Values
Compressor Efficiency (adiabatic)	71%	58%
Expander Efficiency (adiabatic)	73%	59%
Combined Motor/Motor-Controller Efficiency	80%	95%

- Updated efficiency based on Eaton testing.
- Compressor & Expander Effic. lower but are (partially) offset by motor/control effic. increase.
- Net impact is ~$4/kW increase on system.
- Applied to bus baseline system only.

Accomplishments and Progress:

2015 Focus on Low Volume Production

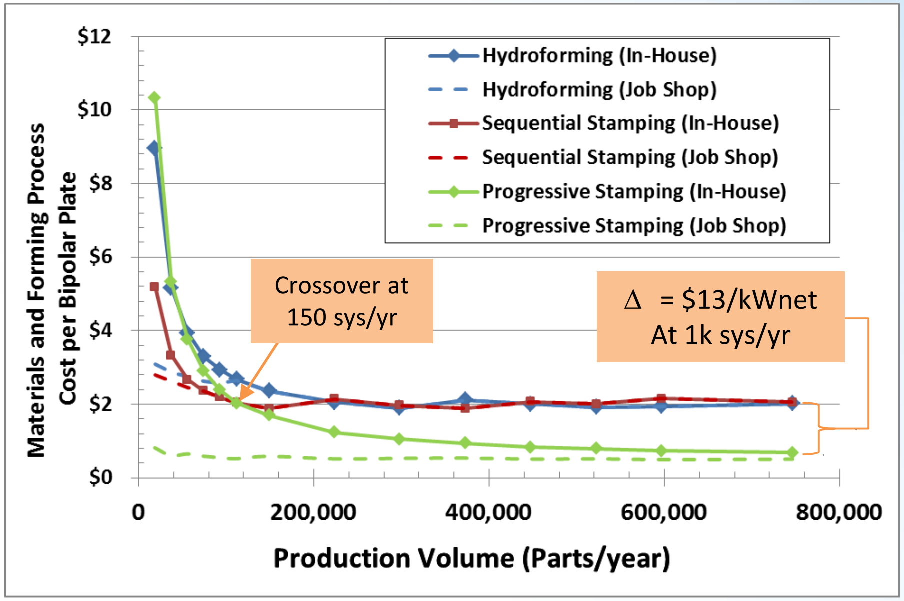
- Focus on low volume production (1k - 5k systems/year)
  - suggested by 2014 AMR Reviewers and by DOE FCTO
- Interested in prod. volume cross-over point between fab methods
- Identify lower cost methods, reduce near-term costs
- Currently Investigating:
  - Bipolar Plate Forming (hydroforming as alternative to stamping)
  - Bipolar Plate Coating (Titanium plates with Au coating as an alternative to Treadstone coating)
  - Catalyst Application (slot die coating as an alternative to NSTF)
  - Membrane (Giner Inert Thin Film Supported Membrane as an alternative to expanded PTFE) – Future Work

Accomplishments and Progress:

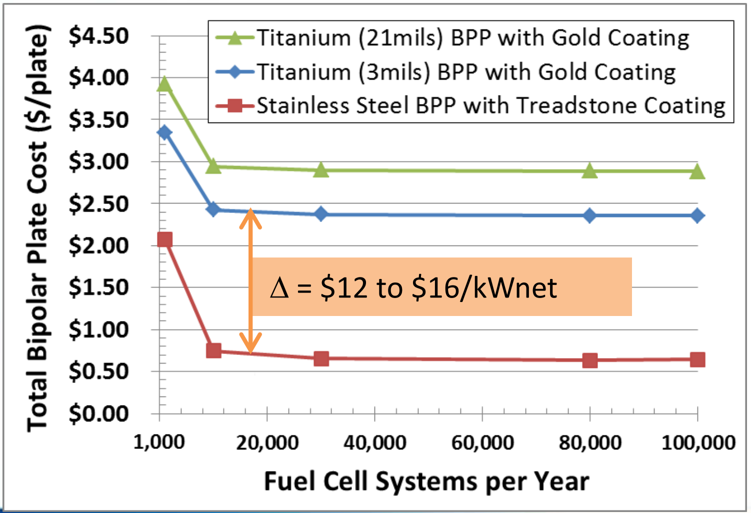
2015 Focus on Low Volume Production

Bipolar Plate Forming (Hydroforming Vs. Seq. and Progressive Stamping)

- Compared both In-House fabrication and Job Shop
- The cost of Hydroforming versus sequential stamping is highly dependent on tooling cost and tooling lifetime
- Cross-over point where progressive stamping becomes less expensive than hydroforming or sequential stamping (100k parts/yr) is below our range of interest
- Progressive stamping is less expensive at all ranges of interest (>1k sys/yr)



Bipolar Plate Coating (Titanium plates with Au Coating Vs. Treadstone Coating)

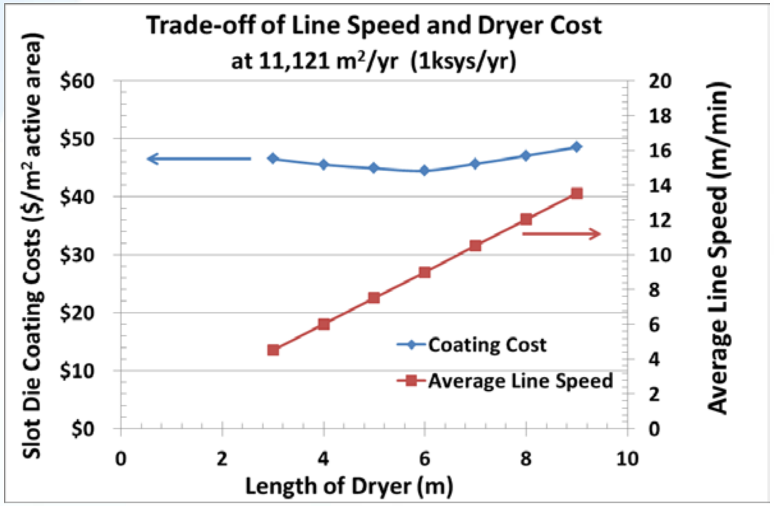


- Ti material cost for 0.003” thick CP Grade 2 with gold coating is much more expensive per plate than Treadstone coating.
- Ti at 0.021” ($27.27/kg) is less expensive per kg than Ti 0.003” ($152.78/kg), however creates a heavier and more expensive BPP.

Accomplishments and Progress:

2015 Focus on Low Volume Production

Catalyst Application (Slot Die Coating Vs. Nano Structured Thin Film)

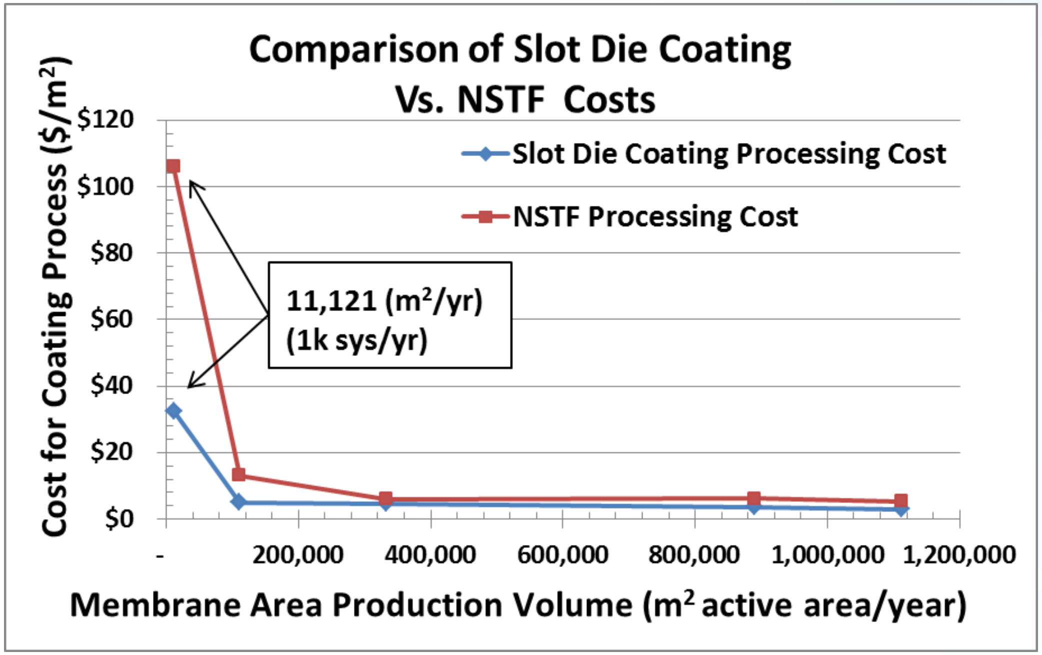


- Slot die coating line speed can minimize total cost (trade off extra capital cost of dryer for increased operating speed)
- Graph at left: based on 6m dryer length (30cm web width) in baseline capital cost and of $25,600/m of extra dryer space.
- At lower than 400,000m²/year, slot die coating seems to be the less expensive coating method (per area and not based on performance).

NSTF Equipment	Capital Cost
Evacuation Ch. #1	$81,143
Evacuation Ch. #2	$152,144
PR-149 Sublimation Unit	$104,167
PVD Catalyst Cylindrical Magnetron Sputtering Unit	$220,383
Annealing Oven	$446,426
Re-Press. Ch. #1	$131,858
Re-Press. Ch. #2	$81,143
Unwind/Rewind	$56,062
Catalyst Decal Appli. Sys.	$104,167
IR/DC QC System	$210,000
Total	**$1,587,496**

Capital cost comparison at 1k sys/yr

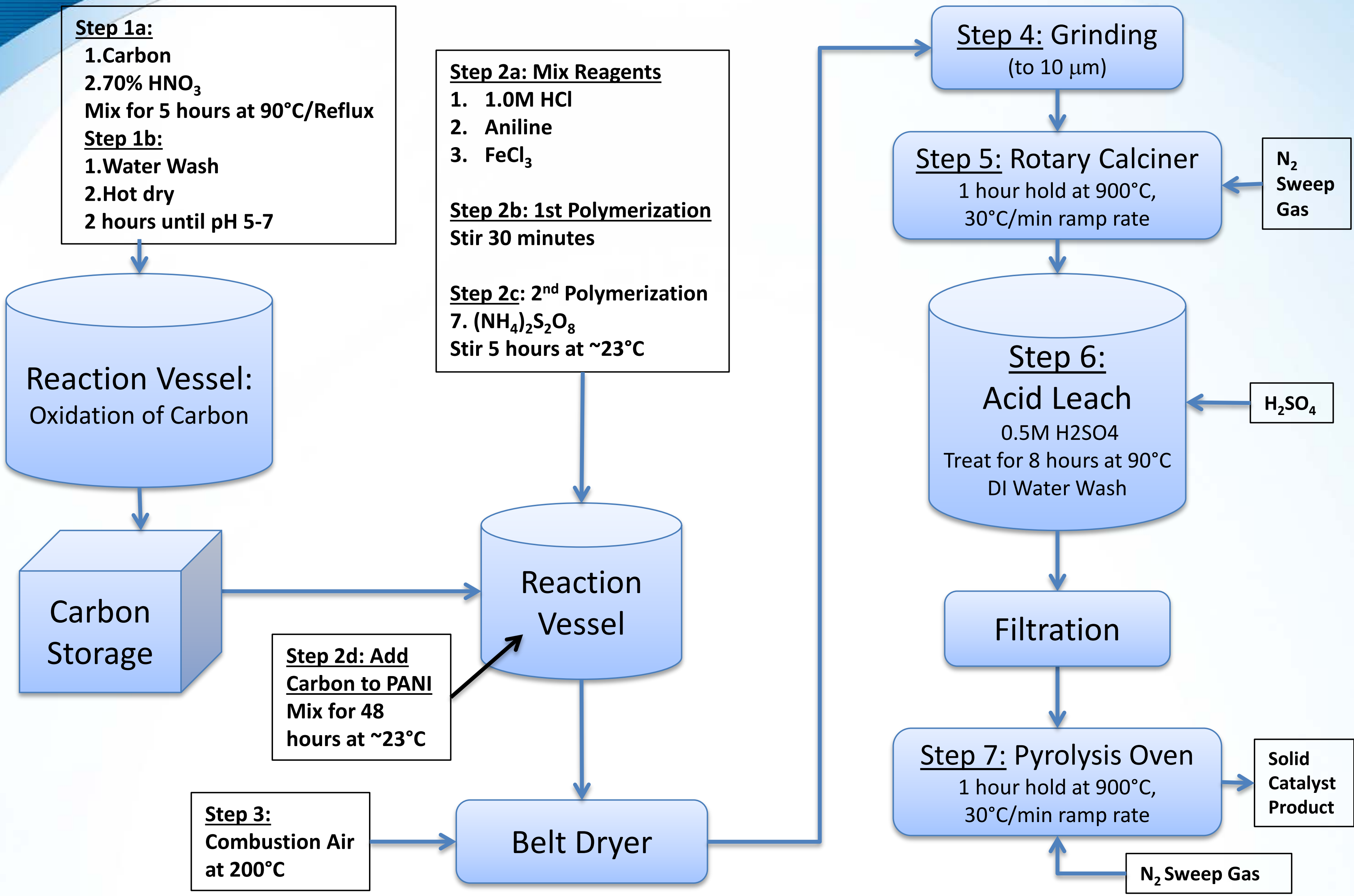
Slot Die Coating Equipment	Capital Cost
Ultrasonic Mixer	$27,169
Slot Die Coating Machine	$362,102
IR/DC QC System	$210,000
Total	**$572,102**



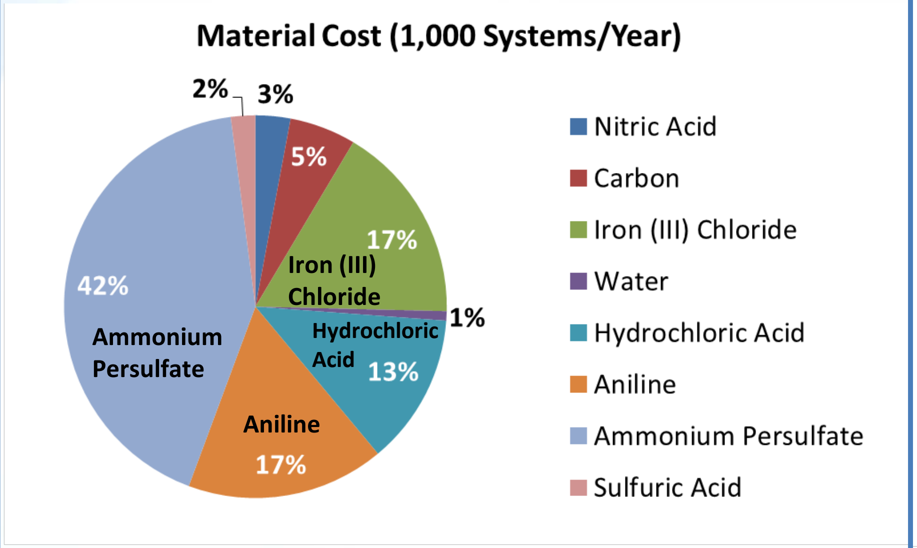
Accomplishments and Progress: LANL PANI-Fe-C Catalyst Production

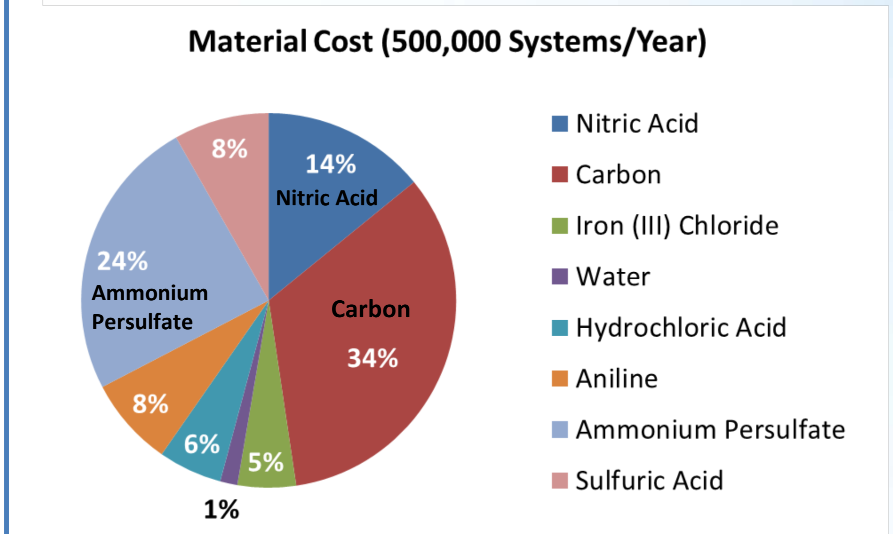
- **Conducted DFMA® cost analysis of non-Pt catalyst**
  - Replacement for baseline PtMnCo NSTF or De-alloyed PtNiCo
  - Examined Los Alamos National Lab (Zelanay) PANI-Fe-C catalyst
    - Polyaniline-Iron-Carbon Catalyst
    - 95 wt% Carbon, >2% Fe
    - Demonstrated power density: 330mW/cm^2
- **Analysis compares Pt-based catalyst coating to PANI catalyst coating**
  - Due to reduced power density, PANI stack must be larger than Pt-based stack
  - To achieve cost parity, PANI power density must surpass 475mW/cm^2 (despite the low cost of the PANI catalyst powder <$100/kg)

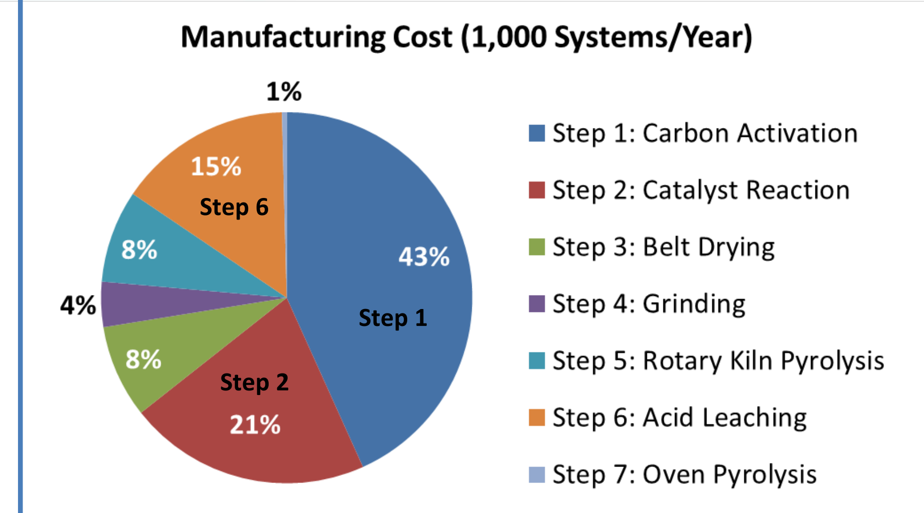
PANI-Fe-C Catalyst Process Model

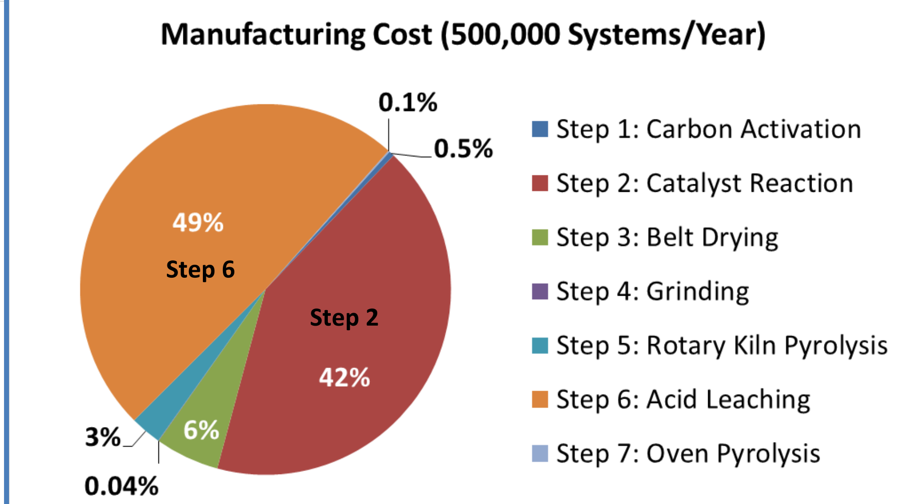


Material and Manufacturing Cost Breakdowns at 1k and 500k systems per year









Total PANI Cost = ~$129/kg

Total PANI Cost = ~$74/kg

PANI System Cost Comparison

	PANI		Ternary NSTF
	PANI-C-Fe		Pt/Mn/Co NSTF
$/kg catalyst	$74 - $129/kg		~$41,000/kg
Loading	4 mg/cm^2		0.153 mgPt/cm^2
Catalyst powder used	383 grams/system		22 grams/system
Catalyst powder cost (at baseline conditions and 500k sys/yr)	$28/system		~$900/system
Stack Cost (for 80kWnet system and 500k sys/yr)	(requires 2 stacks, 372 cells/stack at 377cm^2/cell)		(requires 1 stack, 372 cells/stack at 299cm^2/cell)
Power Density	At 330 mW/cm^2 (demonstrated perf. at 1.0 bar partial pressure of hydrogen and air at ~ 0.5 V)	At 475 mW/cm^2	At 834 mW/cm^2
$/kWnet (at 500k sys/yr)	$31.27 per kW_{net}	$24.25 per kW_{net}	$24.25 per kW_{net}

PANI performance improvement is needed to capitalize on avoidance of Pt.

Benchmarking Against Commercial FCEV

Operating Parameter	SA's 2015 Preliminary Conditions	SA's Estimate of Commercial Low Volume System*
Selection Basis	Best performing components tested in lab but not necessarily demonstrated in integrated system	Tested, integrated system, in low volume production, sold to public
Catalyst	Pt/Co/Mn NSTF	Pt/Co core-shell
Bipolar Plates (BPP)	stamped stainless steel	stamped Titanium (possibly with additional cathode flow field features)
BPP Coating	Treadstone Coating (inert material plus gold microdots)	carbon/gold coating for enhanced electrical conductivity
Seals/Frames	subgaskets, welded BPP	resin frames, adhesive sealants, rubber gasket
Cell Voltage	0.672 volts/cell	~ 0.6 volts/cell
Current Density	1,241 mA/cm^2	~ 1,373 mA/cm^2
Power Density	834 mW/cm^2	~ 824 mW/cm^2
Peak Stack Pressure	2.5 atm	1.8-2 atm
Total Pt Loading ($mgPt/cm^2$)	0.103 cathode, 0.05 anode	0.1-0.15 cathode, 0.05 anode
Peak Cell Temperature	100°C	~ 80°C+

RED = Expected to increase cost relative to SA baseline design

Orange = Expected to change cost (unknown direction) relative to SA baseline design

GREEN = Expected to decrease cost relative to SA baseline design

* estimated values/approach of parameters based on indirect evidence, patents, and deductive logic.

Benchmarking Against Commercial FCEV

Operating Parameter	SA's 2015 Preliminary Conditions	SA's Estimate of Low Volume System*
Stack kW_{gross}/L	3.1 kW/L (stack)	3.1 kW/L (stack)
Stack kW_{gross}/kg	2.2 kW/kg (stack)	2 kW/kg (stack)
Humidification	External unit	Internal humidification
H_2 Recirculation	H_2 Ejector	H_2 pump
Exhaust Gas Expander	Yes	No (since stack pressure is only ~1.8atm)
Q/ΔT Radiator Constraint	1.45	Est. 2.0 (higher Q, lower ΔT)

RED = Expected to increase cost relative to SA baseline design
Orange = Expected to change cost (unknown direction) relative to SA baseline design
GREEN = Expected to decrease cost relative to SA baseline design

* estimated values/approach of parameters based on indirect evidence, patents, and deductive logic.

Accomplishments and Progress:
Responses to Previous Year's Reviewers' Comments

Reviewer's Comments	Response to Reviewer's Comment
"The components design and fabrication process for bus application should select those that have low cost at low fabrication volume. Current analysis uses the same process for automobiles and buses; this is not suitable, because their production volumes are different."	The majority of SA's 2015 analysis is focused on low production volume manufacturing processes for both the automotive and bus systems.
"The validation of the approach needs to be continually reviewed by DOE to ensure the quality of the price projections."	For 2015, it is anticipated to perform a comparison with the ENE Farm Panasonic stationary fuel cell systems and to do some benchmarking against the Toyota Mirai.

Collaborations

Partner/Collaborator/Vendor	Project Role
National Renewable Energy Laboratory (NREL) (sub on contract)	• Provides knowledge and expertise on QC systems for MEA and bipolar plate manufacturing. • *Currently supporting SA on low production volume manufacturing systems for MEAs*
Argonne National Laboratory (ANL) (sub on contract)	• Supply detailed modeling results for CEM efficiency and mass flows for specific fuel cell operating conditions • Provided SA with model for membrane area requirements for temperature and desired water flux across the membrane.
DOE Sponsored Collaborators • Eaton • 3M • Johnson Matthey (JM) • GM • Los Alamos National Lab (LANL)	• Eaton continues to support SA on the automotive and Bus CEM DFMA® analyses, providing updated designs. • 3M and GM/JM continue to support the FCTO for MEA development • Worked with LANL to understand PANI catalyst synthesis process for DFMA® analysis
Other Collaborators and Vendors • ATI Metals • Continental Steel… • Vergason Technologies • Eurotech (supplier of Coatema Products) • Faustel • *ASI* • Frontier Industrial Technologies	• ATI and Continental Steel provided quotations for titanium • *Vergason Technologies quoted low volume PVD system* • Eurotech, Faustel, and Frontier supply slot die coating equipment for catalyst application • *ASI* was able to provide coating system dryer length given the substrate material, coating material moisture, web speed, and max temperature.

Remaining Barriers and Challenges

Automotive System

- PtNiC catalyst performance data is very limited (small single cells)
- PtNiC catalyst durability data not yet available
- Slot die coating versus NSTF catalyst performance (for the same catalyst) not yet known
- OEMs increasingly invested in fuel cell industry, are increasingly tight-lipped and/or require NDAs
- PANI (non-Pt catalyst) requires greater power density (>475mW/cm^2) to be cost competitive with Pt-based catalysts.

Bus System

- Modeling systems for bus are more limited than automotive fuel cell systems, may induce more uncertainty in cost results

Proposed Future Work

Automotive System

- Integrate ANL PtNiC polarization modeling results into side study cost analyses
  - JM/GM – ANL has already modeled stack performance
  - 3M – NSTF with binary catalyst (no performance models yet)
- Detailed BOP component cost investigation (promised last AMR)
  - Hydrogen sensors
  - Fuel ejectors
- Giner Inert Thin Film Supported Membranes
- Continued look at low volume manufacturing processes for stack components
- Baseline System Sensitivity (single and multi-variable analysis)

Bus System

- Incorporate logic for low volume manufacturing processes (from auto analysis)
- Life Cycle Cost Analysis

2015 Future Catalyst Cost Analysis Work

Catalyst	PtNi (on Carbon) Binary System	
Development Group	3M	Johnson-Matthey/General Motors
Synthesis Method	NSTF	Wet Syn., De-alloyed
Application Method	NSTF with de-alloying bath	Dispersion/Inking
Polarization Experimental Data	3M exp. data January and March 2015	JM/GM experimental data from ~2014
Polarization Modeling	ANL modeling to be completed	ANL modeling Completed
Cost Modeling	To be modeled in 2015	Synthesis Completed Application Completed Integration with Polarization to be completed

NSTF= 3M's nano-structured, thin film catalyst

Technology Transfer Activities

Not applicable for SA’s Cost Analysis

Summary

- Baseline auto cost results did not change between 2013 & 2014 (~$54.84)
- Achieving US DRIVE Fuel Cell Technical Team Roadmap target values may not result in DOE's 2020 target of $40/kW$_{net}$. Additional targets for cost reduction appears necessary.
- At low volumes, sand casting can be a less expensive alternative to die casting and permanent mold casting.
- Due to high number of repeat parts per system, progressive stamping of bipolar plates is always less expensive than hydroforming at >1k sys/yr.
- While Ti bipolar plates may be desirable for their corrosion resistance, their high material cost makes them uncompetitive even at low volumes
- Slot die coating can be a lower cost catalyst application method (than NSTF) (per active area coated) at lower than 400,000 m^2/year production
- Preliminary results for PANI catalyst synthesis shows very low catalyst cost (~$73/kg PANI vs. ~$41k/kg Pt-based) but must significantly increase its power density to achieve lower stack cost than Pt-catalyzed stacks.

Thank you!

Questions?

Technical Backup Slides

Recent Catalyst Systems (funded by DOE)

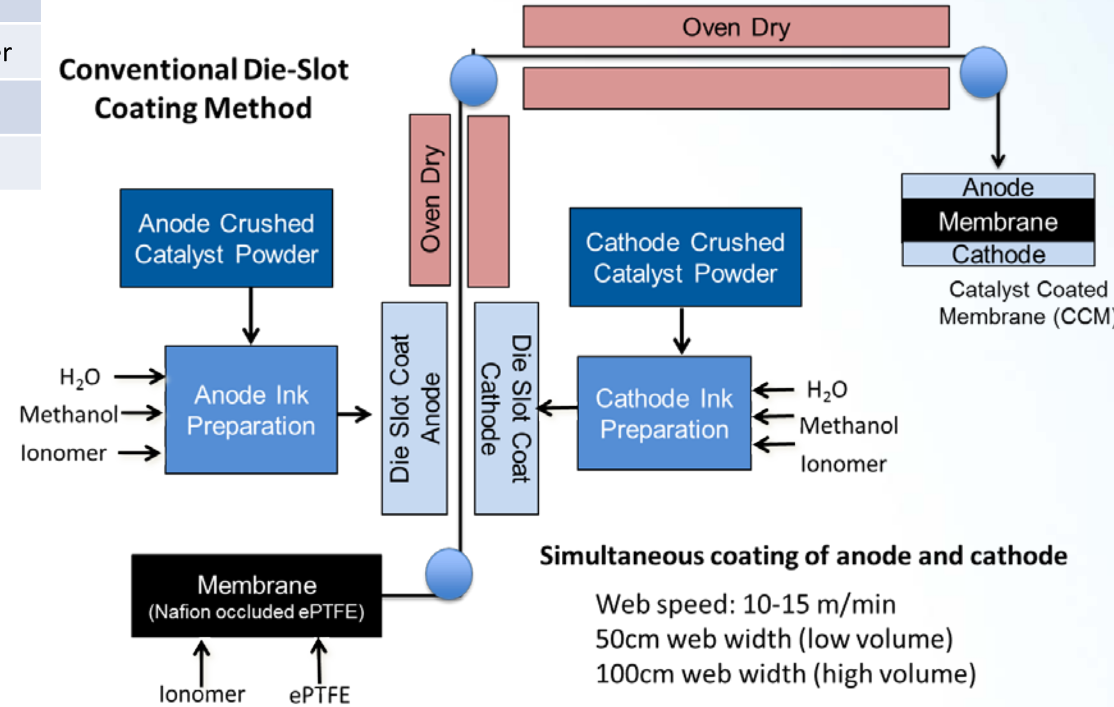
Catalyst	PtCoMn (Ternary)	PtNi (on Carbon) (Binary)		
Development Group	3M	3M	3M	Johnson-Matthey Fuel Cells
Synthesis Method	NSTF	NSTF, De-alloyed	Wet Syn., De-alloyed	Wet Syn., De-alloyed
Application Method	NSTF	NSTF	Inking	Inking
Polarization Experimental Data	Extensive 3M experimental data 2002-2012	Limited 3M exp. data since 2012	Limited 3M exp. data since 2012	Limited JMFC experimental data
Polarization Modeling	ANL (neural and non-neural net modeling)	ANL modeling in-process	NA	ANL modeling in-process
	2009-2014 Cost Analysis Baseline	3M main focus	Not 3M main focus	2014 Alternate Manufacturing Examination

NSTF= 3M's nano-structured, thin film catalyst

Simultaneous Slot Die Coating Machines for Catalyst Application

Coating Machine	Coatema Verticoater (VC500)	Coatema Verticoater (VS2)
Processing Rate (suggested)	8.5m/min	15.24m/min
Capital Cost	$1.5M	$7.5M
Coating Width (max)	500mm	1,000mm
Length of Dryer	Vertical Dryer	Vertical Dryer
Power Requirement	55kW	300kW
Number of Operators	1	3

Two-Sided Slot Die Coating Catalyst Steps



Sequential Slot Die Coating Machines for Catalyst Application

Coating Machine	Frontier (Dynacoat™)	Frontier (quote for FC pilot machine)	Faustel (Lab Master)	Faustel (MCL 600) (not used in analysis)
Processing Rate (suggested)	7.82m/min (thick layers) 10.53m/min (thin layer)	4.5m/min (thick layers) 9m/min (thin layers)	1.83m/min (with single dryer zone) 3.66m/min (with two dryer zones)	1.83m/min (with single dryer zone) 3.66m/min (with two dryer zones)
Capital Cost	$362,000	$1million (includes fluid deliver (no ultrasonic mixer), die-slot coating and larger than Dynacoat)	$297,500 (base) +$48,600 (Slot Die Pos. Mod) +$36,700 (Slot Die) +$68,700 (Extra dryer zone) **$451,500(total)**	$429,000 (base) +$99,850 (Slot Die Coat Mod) +$120,300 (Extra dryer zone) **$649,150 (total)**
Coating Width (max)	305mm	762mm	300 mm	610 mm
Length of Dryer	6m (8 independ. temp zones)	7.5m	6 m (2 zones) (pay extra to increase heater length)	6 m (2 zones) (pay extra to increase heater length)
Cost of extra dryer length	$25,600/m for electrical dryer	$25,600/m for electrical dryer	$22,900/m -electric heater type (w/out connection ductwork)	$40,100/m -natural gas burner type (w/ connection ductwork)
Dryer Temp Range	72-300F	72-300F	70-350 F	70-350 F
Power Requirement	80kW	96kW	80kW (Single Zone) 160kW (Two Zone)	480v., 3ph., 60hz.
Number of Operators	1	1	1	1

PANI Catalyst Material Cost Assumptions

		Manufacturing rate (systems/year)					
Material		**1,000**	**2,500**	**5,000**	**10,000**	**50,000**	**Quote Comments**
Water	$/kg	$ 0.00045	$ 0.00045	$ 0.00045	$ 0.00045	$ 0.00045	From Mof analysis
Nitric Acid	$/kg	0.5	0.497	0.492	0.482	0.4	alibaba.com
							Linear Price Curve
Ketjenblack	$/kg	50	50	50	50	50	alibaba.com
Ferric Chloride	$/kg	0.6	0.5911	0.5761	0.5461	0.3	alibaba.com
							Linear Price Curve
Hydrochloric Acid	$/kg	0.25	0.2489	0.2464	0.2414	0.18	alibaba.com
							Linear Price Curve
Aniline	$/kg	1.95	1.9367	1.9142	1.8692	1.5	alibaba.com
							Linear Price Curve
Ammonium Persulfate	$/kg	74	74	74	74	74	Santa Cruz Biotech
	$/kg	0.85	0.8396	0.8221	0.7871	0.5	alibaba.com
	$/kg	3.0856	3.05436888	3.01948	3.01649734	2.9754	
Sulfuric Acid	$/ton	300	275.927796	260	238.880783	200	
	$/kg	0.3	0.2759278	0.26	0.23888078	0.2	alibaba.com

Annual PANI Catalyst Demand Assumptions

System			PANI-Fe-C				
Production Volume	**Systems/Year**		**1,000**	**5,000**	**10,000**	**50,000**	**500,000**
Stack Power	**kW/System**		**80**	80	80	80	80
Laboratory Model Scale	g		1	1	1	1	1
PANI Catalyst Loading	mg/cm		**4**	4	4	4	4
Gross Power denstiy in stac	mW/cm2		**834**	834	834	834	834
Catalyst Power Density	kg catalyst/kW		**0.004796**	0.004796	0.004796	0.004796	0.004796
Catalyst Req	kg/stack		0.383693	0.383693	0.383693	0.383693	0.383693
Catalyst Req	kg/year		384	1,918	3,837	19,185	191,847
Days of Operation	days/year		**365**	365	365	365	365
hrs of Operation	hrs/day		**24**	24	24	24	24
Hours of Operation	hrs/year		*8760*	*8760*	*8760*	*8760*	*8760*

Stack Cost Comparison between PANI and NSTF Catalysts

			PANI Power Density (834 mW/cm²)		PANI Power Density (330 mW/cm²)	
Annual Production Rate	systems/year		1,000	500,000	1,000	500,000
System Net Electric Power (Output)	kWnet		80	80	80	80
System Gross Electric Power (Output)	kWgross		92.75	92.75	92.75	92.75
Stacks per System	stacks/system		1	1	2	2
Component Costs per Stack						
Bipolar Plates (Stamped)	$/stack	*Standard*	$1,544.41	$472.22	$1,079	$549
Bipolar Plate Coating Type Selected			*Treadstone*	*Treadstone*	*Treadstone*	*Treadstone*
MEAs			**$7,407.70**	**$477.57**	**$4,974**	**$498**
Membranes	$/stack		*$2,532.92*	*$181.66*	*$1,747*	*$217*
Catalyst and Application	$/stack		$391.62	$80.83	$230	$68
GDLs	$/stack	*Standard*	*$2,473.81*	*$95.01*	*$1,925*	*$74*
M & E Hot Pressing	$/stack	**Off**	*$0.00*	*$0.00*	*$0*	*$0*
M & E Cutting & Slitting	$/stack		*$541.26*	*$4.04*	*$276*	*$4*
MEA Frame/Gaskets	$/stack	**On**	*$1,468.09*	*$116.03*	*$796*	*$136*
Coolant Gaskets (Laser Welding)	$/stack		$218.66	$29.35	$115	$32
End Gaskets (Screen Printing)	$/stack		$153.28	$0.42	$77	$0.42
Stack Assembly	$/stack		*$78.77*	*$32.96*	*$76*	*$33*
Stack Conditioning	$/stack		*$175.58*	*$28.72*	*$176*	*$29*
Total Stack Cost	**$/stack**		$9,868.33	$1,095.37	$6,798.65	$1,250.66
Total Cost for all 1 Stacks	**$/1 stacks**		$9,868.33	$1,095.37	$13,597.30	$2,501.33
Total Stacks Cost (Net)	**$/kWnet**		$123.35	$13.69	$169.97	$31.27
Total Stacks Cost (Gross)	**$/kWgross**		$106.40	$11.81	$146.61	$26.97
Total Catalyst Cost	**$/kg**		$129.30	$73.85	$129.30	$73.85

PANI system would require 2 stacks for demonstrated power density

In the same range of cost per kWnet

- The PANI-Fe-C catalyst is much less expensive than Pt-based catalysts.
- The processing step costs are low and dominated by the acid leaching process or oven time, depending on the manufacturing rate.
- The material costs are low (as expected) and are dominated by cost of the carbon raw material.
- The $/kW is highly sensitive to mW/cm².

Bipolar Plate Forming

(Hydroforming , Sequential Stamping, and Progressive Stamping)

Parameter	Hydroforming	Sequential Stamping	Progressive Stamping
Base Machine Cost	$190k (total sys = $352k)	$75k (total sys = $175k)	$177k (total sys = $450k)
Die Cost ($/die)	$12k (hydroform) $26k (cutting) Total = $38k	$39k Complete tooling set (4 dies)	($39k x3)+($50k 2x) Complex Die Refurbishment = $217k
Lifetime (cycles)	~1,200k	600k	600k x3 =1,800k (two refurbishments)

Capital Cost Assumptions

- Triform 16-5BD ($190k) is able to hydroform to 0.002" thickness (BPP plates in current system are 0.003" thick)
- Sequential stamping machine has much lower capital cost investment ($75k), but need to change out die

- Hydroforming operation imprints the BPP flow field. But a stamping press is needed to trim and pierce the BPP.
- Total system cost includes forming, trimming, quality control, control, part feeding (progressive only).
- The cost of Hydoforming versus sequential stamping is highly dependent on tooling cost and lifetime.
- After 37,000 parts/yr, the BPP cost is less expensive when progressive stamping dies are refurbished twice.
- Hydroforming requires less expensive die with a longer lifetime.

Hydroforming Die Cost Assumptions: Matwick, S. E., "An Economic Evaluation of Sheet Hydroforming and Low Volume Stamping and the Effects of Manufacturing Systems Analysis", Masters Thesis for Master of Science in Material Science and Engineering at MIT, February, 2003. http://msl.mit.edu/theses/Matwick_S-thesis.pdf