2018 Cost Projections of PEM Fuel Cell Systems for Automobiles and Medium-Duty Vehicles

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Fuel Cell Technologies Office Webinar

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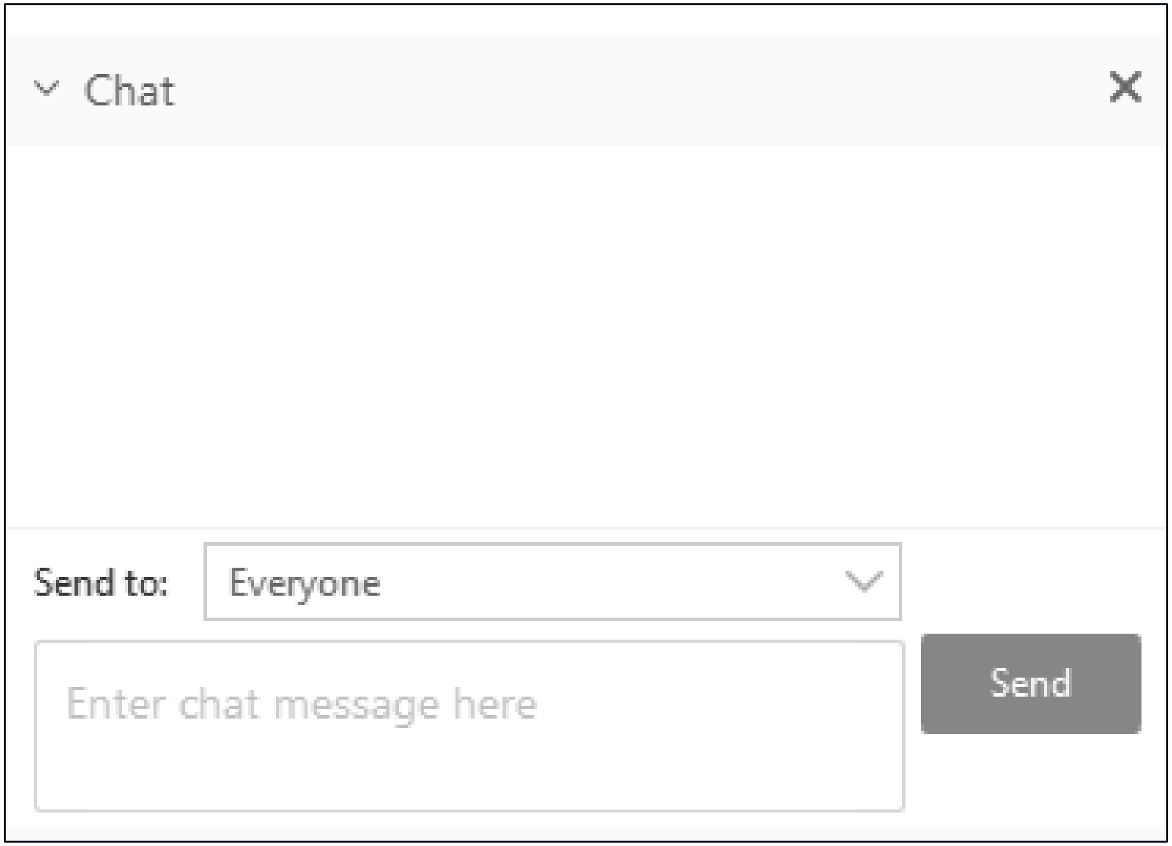
Question and Answer

- Please type your questions to the chat box. **Send to: (HOST)**



Motivation and Outline

- Identify fuel cell system cost drivers to inform Fuel Cell Technology Office early stage R&D plans
  - Project impact of technology improvements on system cost
  - Identify low cost pathways to achieve the DOE 2020 goal of $40/kWnet (automotive) at 500,000 systems per year
  - Benchmark against production vehicle power systems
- Updates to polymer electrolyte membrane (PEM) fuel cell system cost projections for
  - 80 kW automobiles (light duty vehicle)
  - 160 kW trucks (medium duty vehicle)
- Three levels of component technology, system configuration, and performance
  - current (2018),
  - near-term future (2020),
  - and future (2025).

Approach: DFMA methodology used to track annual cost impact of technology advances

What is DFMA?

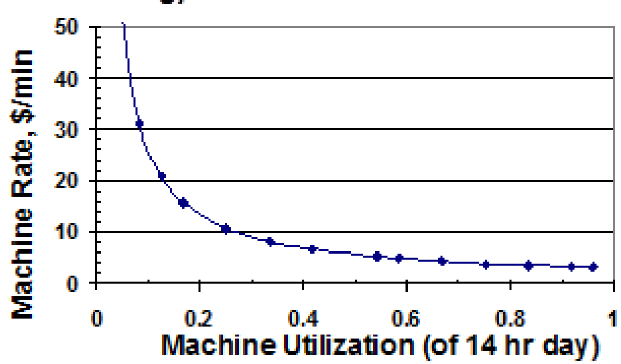
- DFMA = Design for Manufacture & Assembly = Process based cost estimation methodology
  - Registered trademark of Boothroyd-Dewhurst, Inc.
  - Used by hundreds of companies world-wide
  - Basis of Ford Motor Company (Ford) design/costing method for the past 20+ years
- SA practices are a blend of:
  - "Textbook" DFMA, industry standards and practices, DFMA software, innovation, and practicality

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

Manufacturing Cost Factors:

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

Methodology reflects cost of under-utilization:



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

Maintenance/Spare Parts Utilities
Miscellaneous
} Operating Expenses

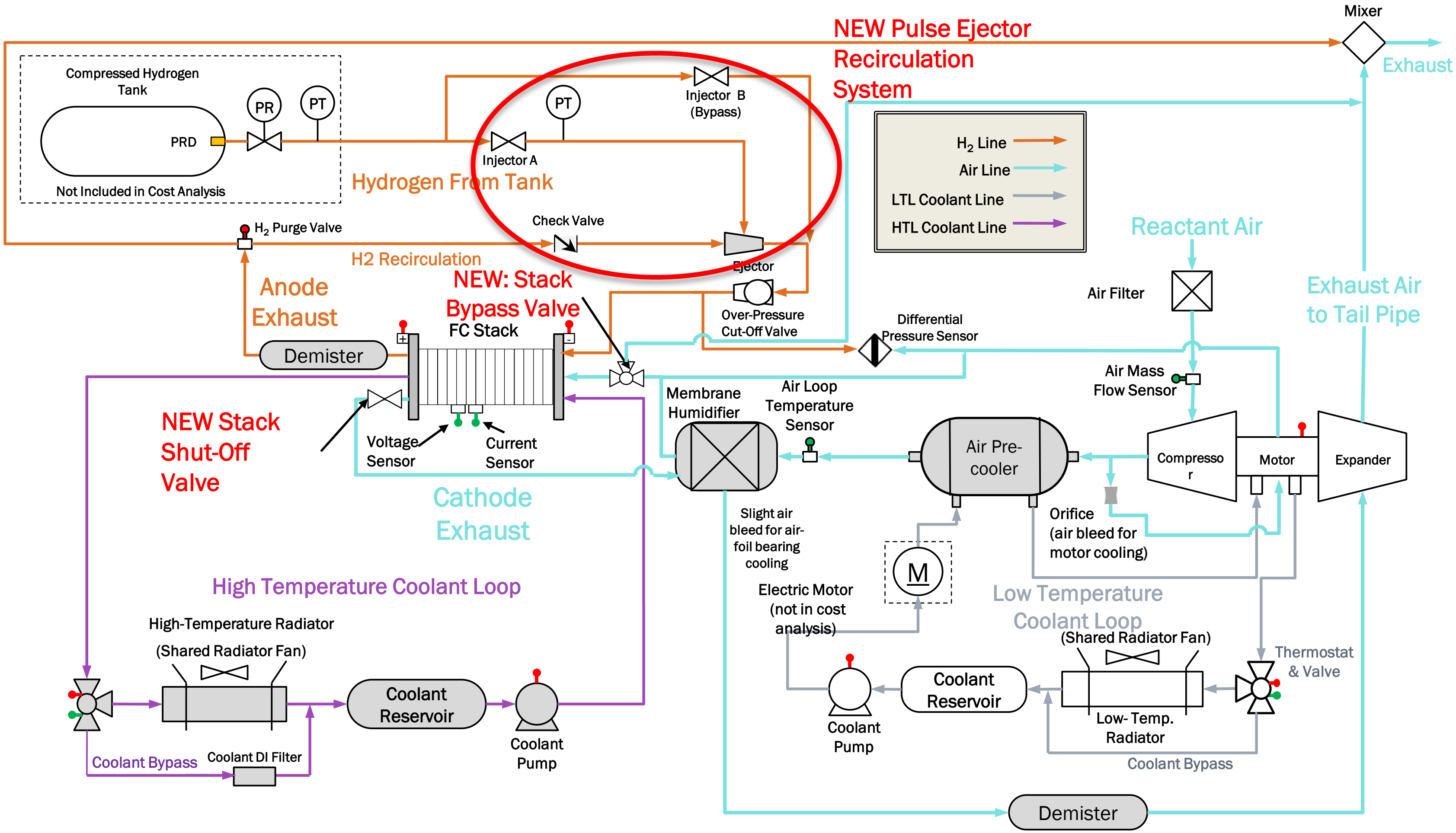
$$\frac{\text{Annual Capital Repayment} + \text{Annual Operating Payments}}{\text{Annual Minutes of Equipment Operation}} = \text{Machine Rate (\$/min)}$$

Light Duty Vehicle (LDV) Outline

- System schematic for three timeframes considered
- System definitions (catalyst loading, materials selection, etc.) for three timeframes
- Recent analyses of individual components
  - De-alloyed catalysts on high surface area carbon
  - Electrospun membrane supports, membranes, and catalyst layers
  - Vacuum deposited catalysts
  - Compressor-expander-motor units
  - Bipolar plate welding
- Projected LDV costs

2018, 2020, & 2025 System Configuration Summary
80kW$_{net}$ Light Duty Vehicle (Auto)

No change in system configuration between technology years



LDV System Definition- Part 1

(Configuration, Operating, and Manufacturing Parameters)

	2018 Auto System (2017 Yr Value if different)	2020 Auto System (2017 Yr Value)	2025 Auto System "High Innovation" (2017 Yr Value)
Stack Power Density @ Rated Power ($mW/cm^2_{active\ area}$)	1,165 (1,095) PtCo/HSC	1,250 (1,165) PtCo/HSC	1,500 Consistent with DOE 2020 target of 1,000 at $150kPa_{abs}$
Total Pt loading ($mgPt/cm^2_{total\ area}$)	0.125	0.125 DOE 2020 target	0.088 Reasonable improvement over 2020 target
Pt Group Metal (PGM) Total Content (g/kW_{gross})[1]	0.117 (0.114)	0.108 (0.107)	0.064 (0.065)
Net Power (kW_{net})	80	80	80
Gross Power (kW_{gross})	87.1 (87.9)	87.1 (87.9)	87.1 (87.9)
Cell Voltage (V)	0.663 (0.66)	0.663 (0.66)	0.663 (0.66)
Operating Pressure (atm)	2.5	2.5	2.5
Stack Temp. (Coolant Exit Temp) °C)	94	94	94
Air Stoichiometry	1.5	1.5	1.5
$Q/\Delta T$ ($kW_{th}/°C$)	1.45	1.45	1.45
Active Cells	377	377	377
Active-to-Total-Area Ratio	0.625	0.625	0.65
Membrane Material & Support	14 µm Nafion, 850EW, supported on ePTFE	10 µm Nafion, 850EW supported on Electrospun PPSU (ePTFE)	High performance membrane, cost based on 10 µm Nafion, 720EW on Electrospun PPSU **(Low-Cost Support [DSM, electrospun, other])**

[1] PGM Total Content here refers to only the active area. Approximately 7% would be added to the mass of Pt when accounting for the catalyst coated onto the non-active border.

Changes from 2017 analysis highlighted in green.

LDV System Definition- Part 2

(Configuration, Operating, and Manufacturing Parameters)

	2018 Auto System (2017 Yr Value)	2020 Auto System (2017 Yr Value)	2025 Auto System "High Innovation" (2017 Yr Value)
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.1 $mgPt/cm^2$ d-PtCo on HSC Anode: Dispersed 0.025$mgPt/cm^2$ Pt/C	Slot Die Coating of: Cath.: Dispersed 0.107 $mgPt/cm^2$ d-PtCo on HSC Anode: Dispersed 0.018$mgPt/cm^2$ Pt/C	Slot Die Coating of advanced performance catalyst. Cath.: Dispersed 0.07 $mgPt/cm^2$ d-PtCo on HSC Anode: Dispersed 0.018$mgPt/cm^2$ Pt/C (Assume catalyst cost still dominated by Pt price and no major improvements in application)
CCM Preparation	R2R dip-coated ePTFE/Ionomer memberane, Slot-Die coated electrodes, acid washing	Gore Direct-Coated Membrane with dual-side-slot-die coated electrodes, acid washing	Gore Direct-Coated Membrane with dual-side-slot-die coated electrodes, acid washing
Gas Diffusion Layers	150 microns Based on 105 μm GDL, 45 μm MPL, uncompressed	150 microns Based on 105 μm GDL, 45 μm MPL, uncompressed	150 microns Based on 105 μm GDL, 45 μm MPL, uncompressed
Catalyst Durability: ECSA loss after 30k cycles (per 2016 MYPP Table P.1 protocol)	50% Based on catalyst only, does not capture membrane degradation	40% Based on achievement of DOE 2020 target	<40% Exceeds DOE 2020 target
MEA Containment	R2R sub-gaskets, hot-pressed to CCM	R2R sub-gaskets, hot-pressed to CCM	R2R sub-gaskets, hot-pressed to CCM
Bipolar Plates and Coating	316SS with PVD Coating modeled as Treadstone Dots Gen2	304SS with PVD Coating, modeled as Treadstone TIOX	**304SS with PVD Coating, modeled as Treadstone TIOX (Alloy requiring no coating Modeled as SS 304L cost)**
BPP Forming/Joining	Progressive Stamping/ Laser Welding	**Hydroforming (Prog. Stamping)**/ Laser Welding	**Hydroforming (Prog. Stamping)**/ Laser Welding
BPP-to-MEA Gaskets	Screenprinted polyolefin elastomer seal on BPP	Screenprinted polyolefin elastomer seal on BPP	Screenprinted polyolefin elastomer seal on BPP

Changes from 2017 analysis highlighted in green.

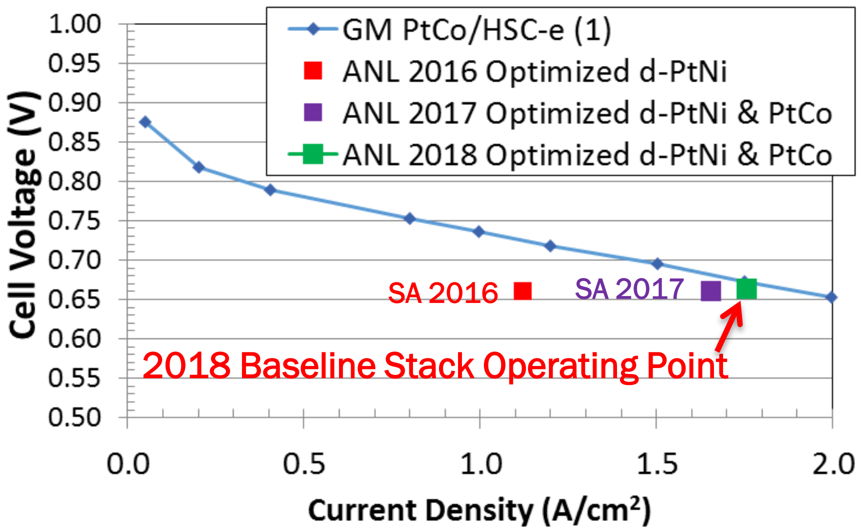
LDV System Definition- Part 3

(Configuration, Operating, and Manufacturing Parameters)

	2018 Auto System (2017 Yr Value)	2020 Auto System (2017 Yr Value)	2025 Auto System "High Innovation" (2017 Yr Value)
Air Compression/CEM Efficiencies	Centrifugal Compressor, Radial-Inflow Expander/ Comp: 71%, Expand: 73%, Motor/Control. 90% **(80%)**	Centrifugal Compressor, Radial-Inflow Expander/ Comp: 71%, Expand: 73%, Motor/Control. 90% **(80%)**	Centrifugal Compressor, Radial-Inflow Expander (with adv. mech. design)/ Comp: 71%, Expand: 73%, Motor/Control. 90% **(80%)**
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air-Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air-Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air-Precooler
Air Humidification	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)
Hydrogen Humidification	None	None	None
Anode Recirculation	**Pulse Ejector (2 fixed geometry ejectors)**	Pulse Ejector with bypass	Pulse Ejector with bypass
Exhaust Water Recovery	None	None	None
Coolant and End Gaskets	Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)
Cell Assembly	Robotic assembly of welded BPP assembly and sub-gasketed MEA	Robotic assembly of welded BPP assembly and sub-gasketed MEA	Robotic assembly of welded BPP assembly and sub-gasketed MEA
Freeze Protection	Drain water at shutdown	Drain water at shutdown	Drain water at shutdown
Hydrogen Sensors	None	None	None
End-Plate/Compression System	Composite molded end plates with compression bands	Composite molded end plates with compression bands	Composite molded end plates with compression bands
Stack Conditioning (hours)	2	2	1

Changes from 2017 analysis highlighted in green.

Power Density Increase due to Improved High Surface Carbon (HSC) Supports: ANL Optimized Performance Model with d-PtCo



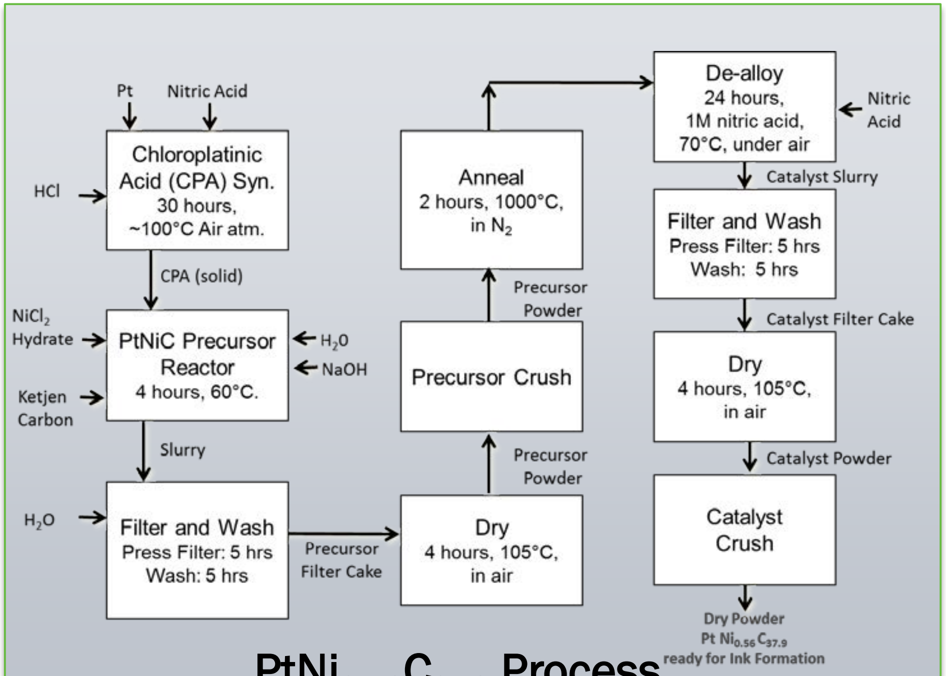
- **2017 Catalyst Assumptions (cathode)**
  - d-PtNi/C catalyst fabrication cost combined with derating of GM performance data for d-PtCo/HSC
- **2018 Baseline: d-PtCo/HSC (cathode)**
  - Data from GM for d-PtCo/HSC catalyst used in ANL optimized performance model
  - SA modeled d-PtCo/HSC fabrication cost

6% power density increase from 2017 to 2018

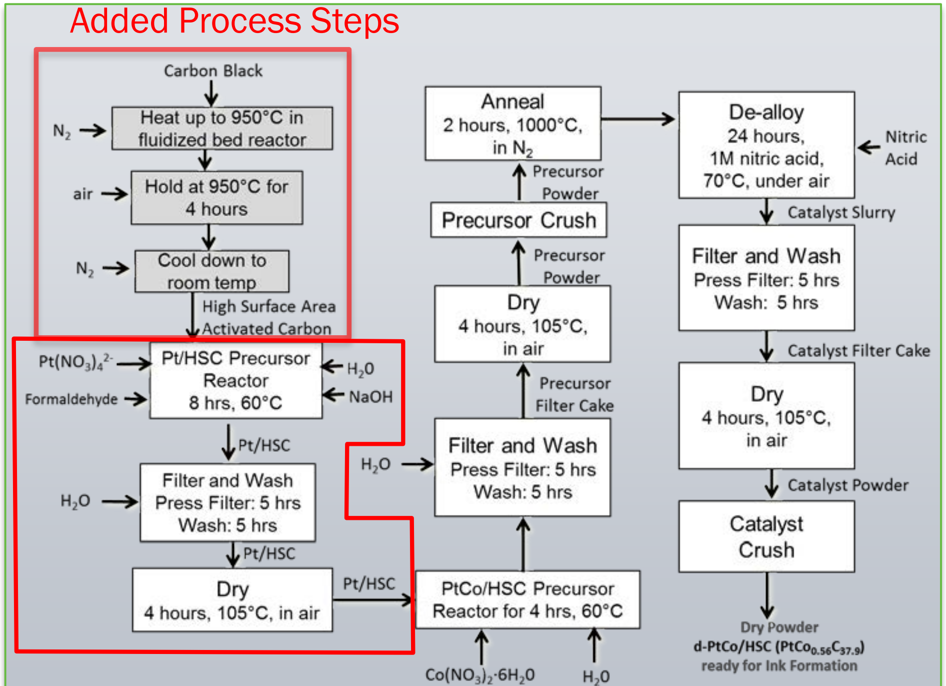
Parameter/Conditions	d-PtNi /C (2016)	d-PtCo/HSC (2017)	d-PtCo/HSC (ANL Update for 2018)
Power Density (mW/cm^2)	739	1,095	1,165
Cell Voltage	0.66	0.66	0.663
Stack Pressure (atm)	2.5 (inlet)	2.5 (inlet)	2.5 (inlet)
Temperature (coolant exit)	94°C	94°C	94°C
Total Pt Loading (mg/cm^2)*	0.134	0.125	0.125
Air Stoichiometry	1.4	1.5	1.5
System Cost ($/kWnet)	$52.89	$44.80	$46.16

(1) Kongkanand, A., Mathias, M., “The Priority and Challenge of High-Power Performance of Low-Platinum Proton-Exchange Membrane Fuel Cells”, Journal of Physical Chemistry Letters, 2016, 7, 1127-1137. *Anode catalyst is 0.025mgPt/cm^2 Pt/C for all systems.

D-PtCo/HSC (High Surface Area Carbon) Similar Catalyst Synthesis to d-PtNi/C Process Leads to Low Cost Impact



$PtNi_{0.56}C_{37.9}$ Process Diagram



$PtCo_{0.56}C_{37.9}$ Process Diagram

- Added HSC process[1]: increased carbon cost from \$9/kg to ~\$116/kg at high volume
- Added Pt/HSC synthesis process[1]: use of $Pt(NO_3)_4$ rather than chloroplatinic acid
- PtCo/HSC synthesis[2] uses $Co(NO_3)_2 \cdot 6(H_2O)$ (between \$11 and \$72/kg)
- Cost results: ~\$0.13/kW_{net} cost decrease in switch from d-PtNi/C to d-PtCo/HSC

[1] JM Patent Application US2014/0295316 A1 (referenced in [2])
[2] GM/JM Patent Application US 2016/0104898 A1 (patent from DOE funded project: "High-Activity Dealloyed Catalysts", Final Technical Report, General Motors LLC, DE-EE0000458, 30 Sept 2014)

D-PtCo/HSC Catalyst Preliminary Results

d-PtCo/HSC 2018 Cost Estimate:

Added synthesis steps

PtCo/C Cathode Catalyst Powder Synthesis		Annual System Prodution Rate					
Component Costs per 80kWnet Fuel Cell System		1,000	10,000	20,000	50,000	100,000	500,000
Step 1: Pt/HSC Precursor	**$/system**	*$722.75*	*$647.74*	*$581.12*	*$507.92*	*$487.54*	*$466.64*
Step 2: Pt/HSC Filtration	**$/system**	*$15.70*	*$6.29*	*$3.00*	*$1.38*	*$0.78*	*$0.31*
Step 3: Pt/HSC Wash	**$/system**	*$6.03*	*$2.76*	*$1.35*	*$0.65*	*$0.47*	*$0.32*
Step 4: Catalyst PtCo/HSC Precursor	**$/system**	*$14.99*	*$8.58*	*$5.34*	*$3.49*	*$2.45*	*$1.20*
Step 5: Precursor Filtration	**$/system**	*$18.35*	*$9.18*	*$5.04*	*$2.08*	*$1.06*	*$0.21*
Step 6: Precusor Wash	**$/system**	*$6.87*	*$2.51*	*$1.13*	*$0.49*	*$0.27*	*$0.08*
Step 7: Precursor Drying	**$/system**	*$47.39*	*$17.02*	*$7.69*	*$3.24*	*$1.71*	*$0.42*
Step 8: Precursor Crushing	**$/system**	*$24.83*	*$8.88*	*$4.55*	*$1.90*	*$0.98*	*$0.21*
Step 9: Precursor Annealing	**$/system**	*$131.08*	*$47.50*	*$21.67*	*$9.38*	*$5.18*	*$3.73*
Step 10: Catalyst Dealloying	**$/system**	*$62.82*	*$34.99*	*$19.29*	*$8.63*	*$4.94*	*$1.74*
Step 11: Catalyst Filtration	**$/system**	*$17.90*	*$8.76*	*$4.76*	*$1.97*	*$1.00*	*$0.20*
Step 12: Catalyst Wash	**$/system**	*$6.87*	*$2.51*	*$1.14*	*$0.49*	*$0.27*	*$0.08*
Step 13: Catalyst Dry	**$/system**	*$47.99*	*$17.91*	*$8.19*	*$3.71*	*$2.19*	*$1.32*
Step 14: Catalyst Crushing	**$/system**	*$25.04*	*$9.42*	*$4.87*	*$2.23*	*$1.30*	*$0.28*
Step 15: Catalyst Quality Control Testing	**$/system**	*$6.67*	*$9.49*	*$5.83*	*$5.42*	*$5.32*	*$4.59*
Step 16: Cathode Catalyst Packaging	**$/system**	*$11.22*	*$4.14*	*$2.25*	*$1.00*	*$0.59*	*$0.23*
Total Catalyst Synthesis Cost	**$/system**	$1,166.52	$837.68	$677.22	$553.98	$516.05	$481.55

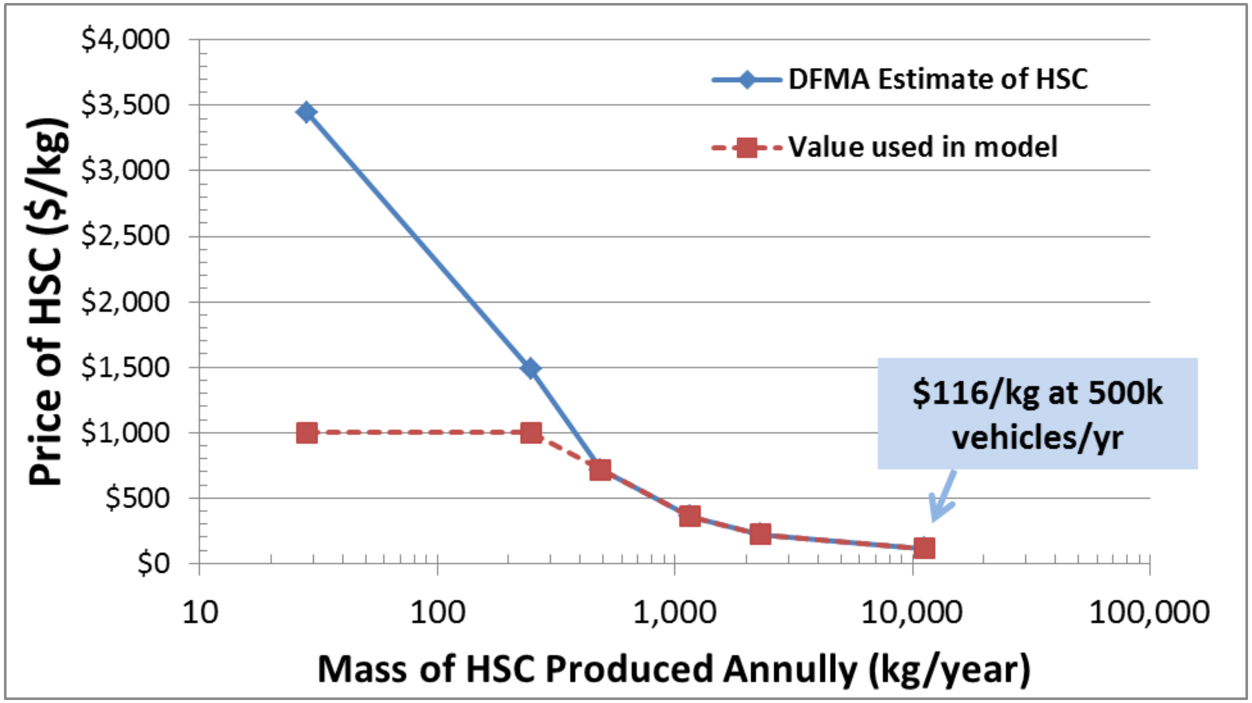
d-PtNi/C 2017 Cost Estimate:

Total Catalyst Synthesis Cost	**$/system**	$1,108.91	$756.55	$628.37	$540.10	$518.02	$492.28

Compared to 2017 Estimates for d-PtNi/C, cost is about the same, due to higher power density offsetting the added cost for Pt/HSC synthesis and assumption changes for 65% conversion of PtNitrate to Pt/HSC.

DFMA Estimate of HSC

HSC cathode catalyst support was introduced in the 2017 analysis but its cost was only approximated. For 2018, a DFMA cost analysis was conducted.



- Capped HSC price at $1,000/kg based on industry source
- Used curve fit to DFMA estimated value to project anode HSC price
- $116/kg is close to the $91/kg suggested for ultra-high surface-area anode carbon (although at an unknown volume)

HSC = high surface area carbon

Electrospun Materials for Fuel Cell Components

Three Materials Investigated:

1. Membrane Support Material (direct substitute for ePTFE)
2. Complete Membrane Dual-Fiber (co-spun) Support & Ionomer Material
3. Electrode Application to Membrane (Anode and Cathode)

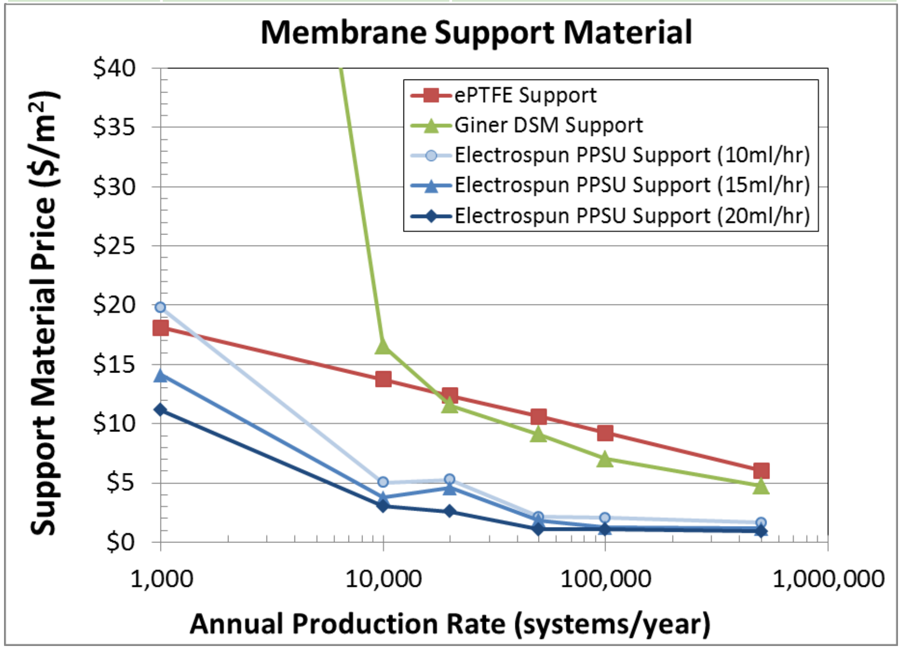
Electrospun Materials for Fuel Cell Components

Membrane Support Material (direct substitute for ePTFE)

Membrane Support Material

- Modeled as a substitute for ePTFE in $/m^2
- 22 vol% of 10µm thick membrane
- Inovenso Nanospinner 416
- Assumed output capacity:
  - 2.7 g/hr per nozzle x 154 nozzles = 416 g/hr
  - 10ml/hr (could be higher for tested material)
  - 3.6 g/m^2
- Line Rate: 1.8m/min
- Web width: 1m
- Price: <$2/m^2 compared to $6/m^2 for ePTFE
- ~$0.60/kW$_{net}$ reduction (at same performance)
- Used for 2020 and 2025 system analysis

	Polymer	Solvent
Support Slurry	PVDF or PPSU (25wt% of slurry)	N-methyl-2pyrrolidone (80wt%) Acetone (20wt%)



Material composition based on US Patent 9,350,036 B2, 2016 “Composite Membranes, Methods of Making Same, and Applications of Same”, P. Pintauro, A. Park, J. Ballengee.

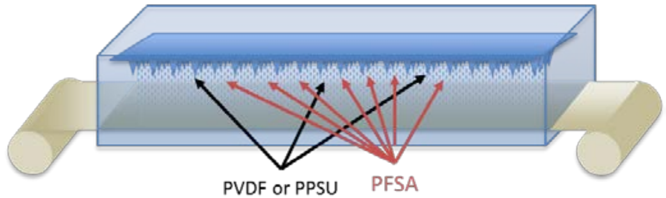
Electrospun support cost projected to be significantly less than ePTFE.

Electrospun Materials for Fuel Cell Components

Dual-Fiber (co-spun) Membrane Support and Ionomer Material

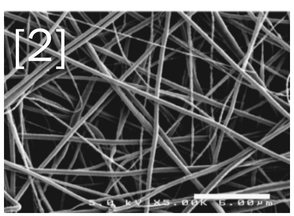
Electrospinning Machine: Inovenso (14 rows of 11 nozzles)

-3 rows of PVDF or PPSU nozzles (10ml/hr nozzles)
-11 rows of PFSA nozzles (10ml/hr nozzles)
-PVDF or PPSU and Nafion nozzles interspersed

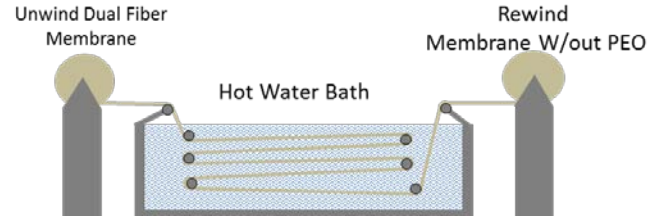


Component	Polymer(s) [1]	Solvent [1]
Support Slurry	PVDF or PPSU	N-methyl-2pyrrolidone (80wt%) Acetone (20wt%)
Ionomer Slurry	Nafion (99wt%) PEO (1wt%)	N-propanol (66.6wt%) Water (33.3wt%)

Nafion/PPSU Dual-Fiber Mat before compaction

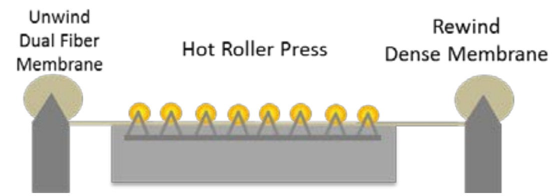


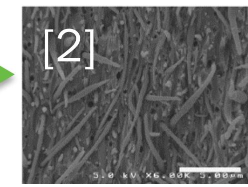
Removal of PEO in Hot Water Bath

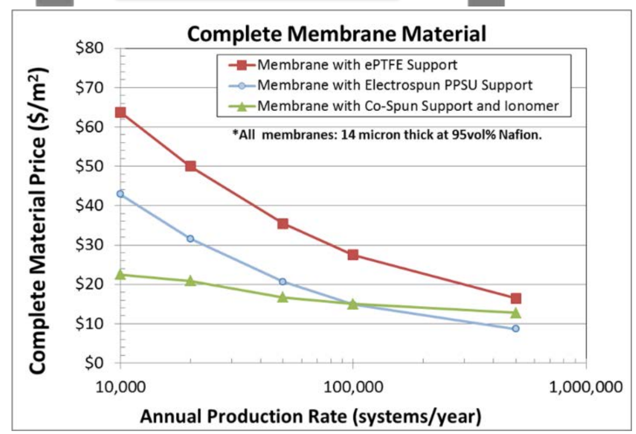


Hot Roller Compression/Compaction

- Final Material: Dense Nafion layer reinforced with PPSU nanofibers (Nafion melted around PPSU fiber)







[1] US Patent 9,350,036 B2, 2016 "Composite Membranes, Methods of Making Same, and Applications of Same", P. Pintauro, A. Park, J. Ballengee.
[2] J.B. Ballengee, P.N. Pintauro, "Preparation of nanofiber composite proton exchange membranes from dual fiber electrospun mats", Journal of Membrane Science 442 (2013) 187-195. (Fig. 8)

Electrospun membrane projected to be less than ePTFE-supported membrane.

Electrospun Materials for Fuel Cell Components

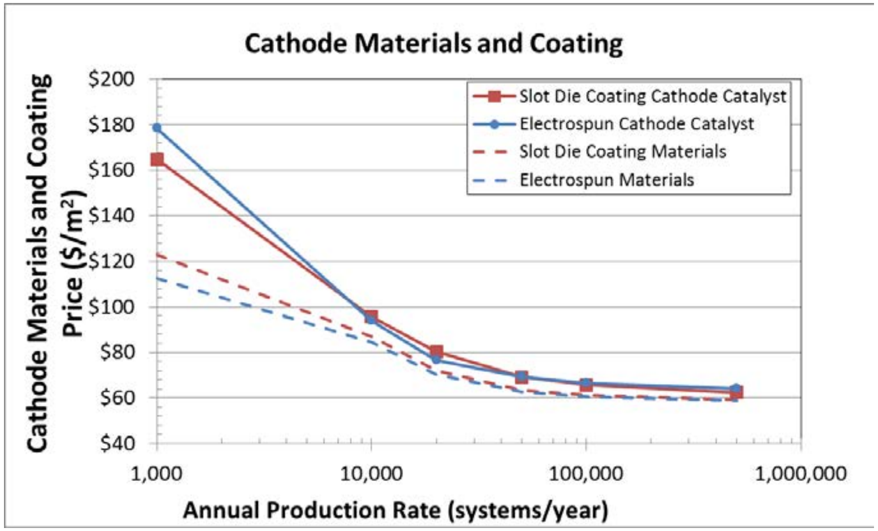
Electrode Application to Membrane (Anode and Cathode) (as alternative to slot-die coating)

Cathode Catalyst Application to Membrane

	Polymer [1]	Solvent [1]
Cathode Slurry	PtNi/C:Nafion:Polyacrylic Acid 55:30:15 (13.4wt% of slurry)	Isopropanol: water 2:1 (86.6wt% of slurry)

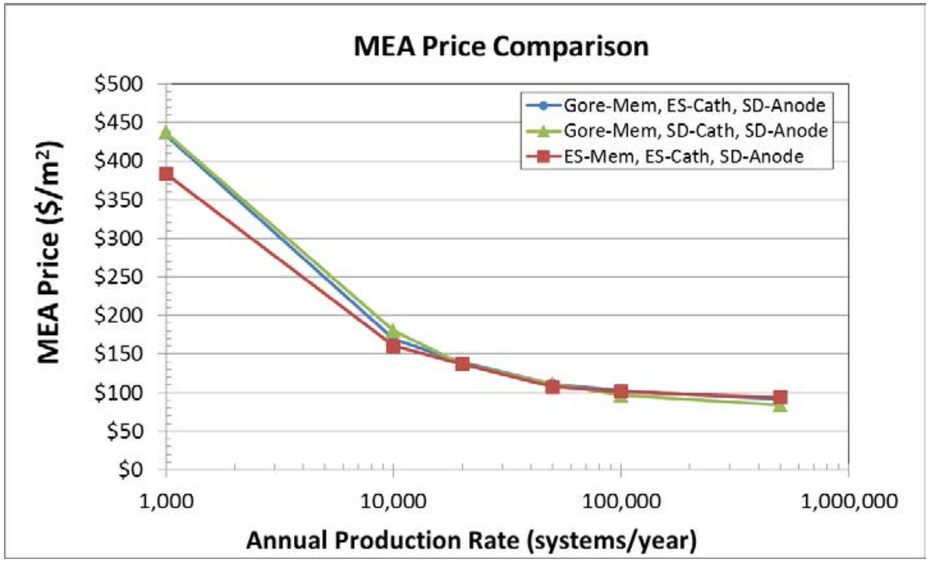
Electrospinning Machine: Inovenso Nanospinner

- 5.12 g/hr per nozzle x 154 nozzles = 788 g/hr
- 25 g/m2 (combined catalyst powder, ionomer, and PAA)
- Line Rate: 0.53m/min (3-25m/min for slot die coating)
- Web width: 1m



Comparison of Different MEAs

- ES: electrospun material
- SD: slot die coating (dual sided-coating when using SD on anode and cathode)
- Prices are nearly identical at high volume for $/m². Performance & durability will be the deciding factor



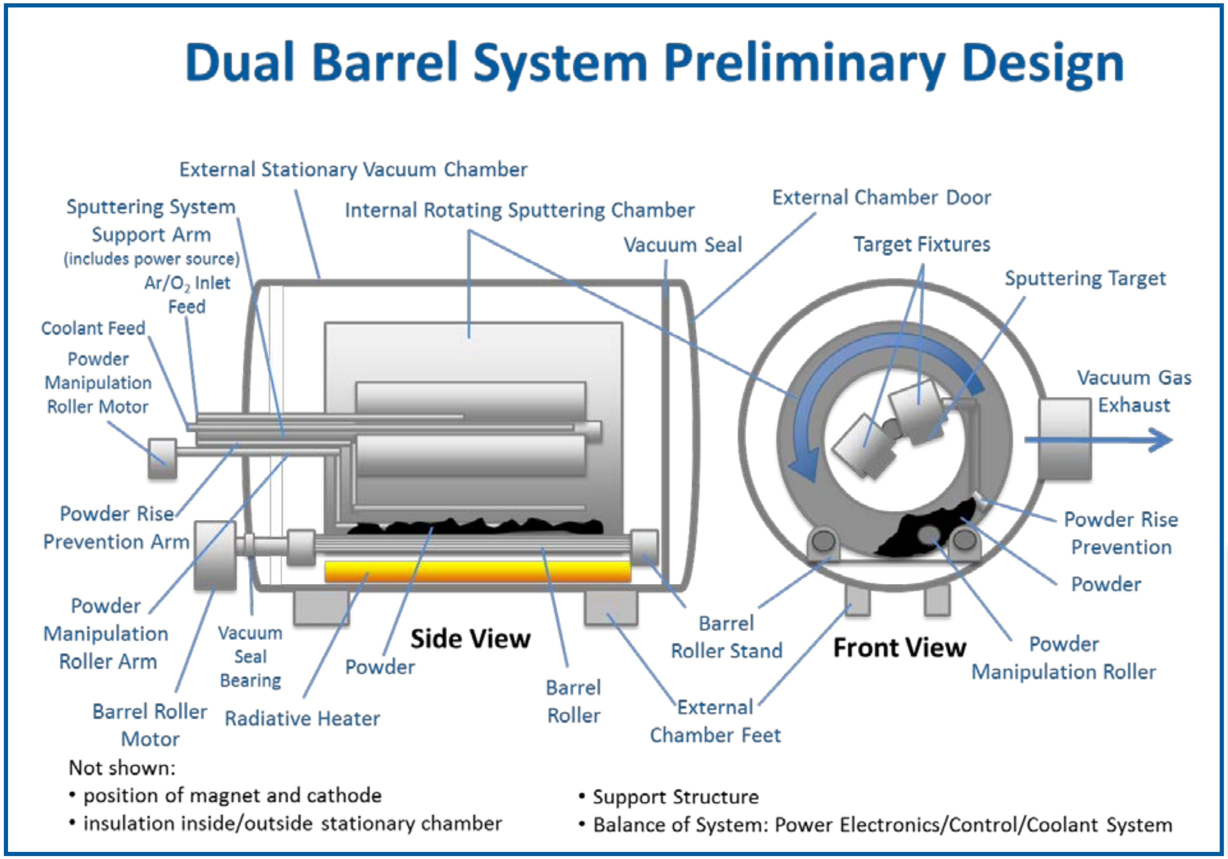
- **Next Step:** Incorporate performance of catalyst to obtain MEA price of stack for 80kW$_{net}$ vehicle.

[1] US Patent Application 2017/0250431 A1 "Polymer Solution, Fiber Mat, and Nanofiber Membrane-Electrode-Assembly Therewith, and Method of Fabricating Same".

Membrane prices similar: performance & durability will decide.

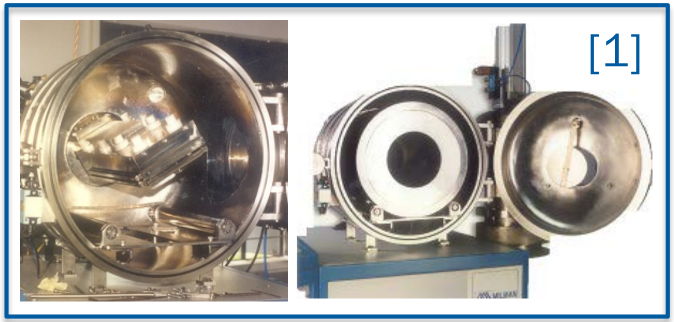
Catalyst Powder Coating with Physical Vapor Deposition (PVD)
(an alternative to aqueous synthesis and PVD/NSTF)

- Under DOE's award DE-EE0007675,
  - Ford Motor Co., Oakridge National Laboratory (ORNL), and Exothermics
  - Development of new catalyst powder synthesized by PVD coating: Pt and Nb onto carbon powder to form Pt/NbOx/C



Dual Barrel Design Properties

- External barrel fixed while internal concentric barrel rotates
- Motor external to vacuum
- Rotation wheels inside vacuum chamber
- Avoid vacuum seal bearings for the centerline components
- Possibly quicker change-out times (replacing one barrel for the next)



[1] Design loosely based on Milman Barrel Sputter Machine:
http://www.milmanthinfilms.com/barrel-sputtering-equipment/barrel-sputtering-equipment

Catalyst Powder Coating with Physical Vapor Deposition (PVD)

PVD Coating Operating Assumptions (single large-batch production facility)

- 70kg powder batches (nominal)
  - Considering a 30-70kg batch size range
- ~4 days/batch, 240 work-days/year, 63 batches per year
- Sputtering cycle times based on deposition rate of 6.6g/min for both Niobium and Pt
- Catalyst sufficient for ~100,000 vehicles/year (based on 44 grams-powder/vehicle)

Step#	Process Step	Time (hours)
1	Load internal chamber (with carbon) into vacuum chamber and refill targets as needed	2
2	Heat at 175°C to drive off moisture while drawing down vacuum to 10mTorr	12
3	Feed Ar and O_2 into chamber during Niobium deposition at >100°C (Ar/O_2 ratio between 10/1 and 20/1 (Argon using 26/1 ratio)	17.7
4	Raise temp to 200°C to off-gas Ar/O_2 mixture	3
5	Feed pure Ar while depositing Pt	44.2
6	Passivation step (run small % of O_2)	10
7	Re-pressurize to atmospheric conditions	5
8	Unload internal chamber from vacuum	2
	Total Cycle Time	95.9

Max Power Requirement: ~8kW

-Niobium higher power(if same deposition rate)
-52MJ over 17.7 hours
-Assumes 10% efficiency

Material Assumptions (nominal)				
	Carbon	Niobium	Pt	Totals
Composition (Wt%)	65%	10%	25%	100%
Densities (g/cc)	2.3	8.57	7.86	NA
Mass per batch (kg)	45.5	7	17.5	70
Volume per batch (L)	20.08	0.82	2.23	23.12

Coating System Configuration and Dimensions

- External Vacuum Chamber: 6ft OD, 5.5ft ID, 4ft length (based on 70kg batch size)
- Internal Sputtering Chamber: 4ft OD, 3ft 10in ID, 3.5ft length (based on 70kg batch size)
- Ratios based on approximate sizing from Exothermics image below
- Depth/Length → higher uncertainty (difficult to estimate from image)

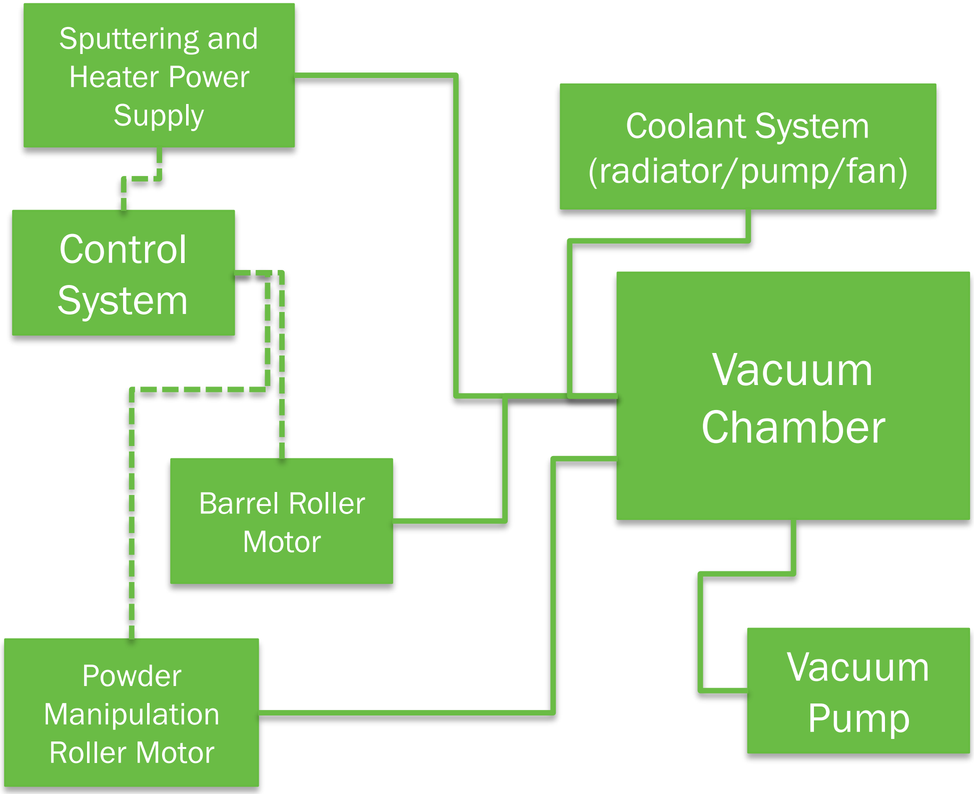
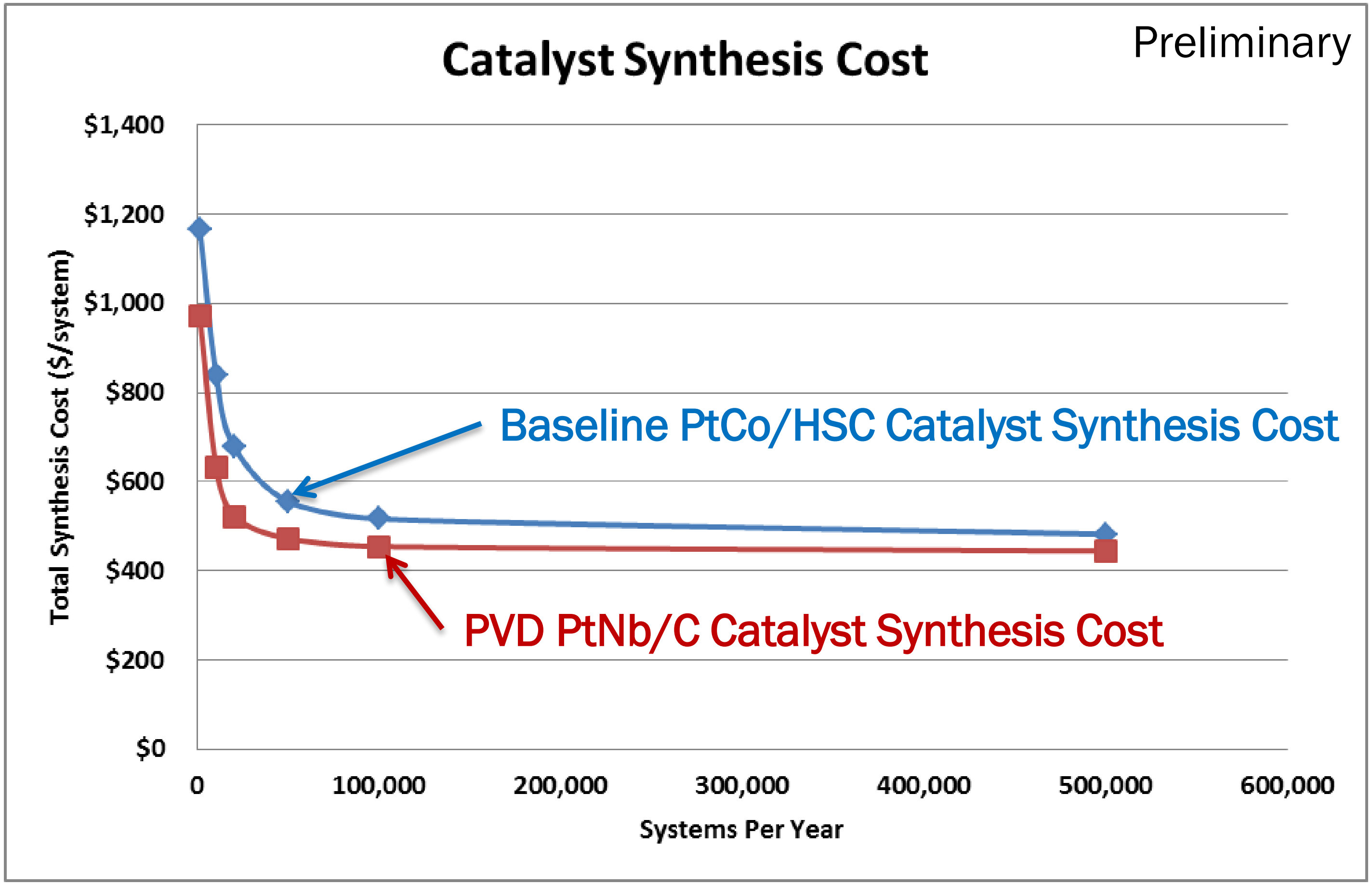


Image of Exothermics large batch systems.
Source: Waldecker, J., "Vapor Deposition Process for Engineering of Dispersed PEMFC ORR Pt/NbO$_x$/C Catalysts", Ford Motor Company presentation (FC162) for the 2017 US DOE Annual Merit Review Meeting, June 2017.

Preliminary Comparison of Baseline Catalyst Cost vs. PVD Catalyst Cost



PVD onto a powder substrate (carbon) may be a lower cost option for generating platinum based catalyst (assuming equivalent electrochemical performance).

Updates to Compressor-Motor-Expander (CEM) Unit

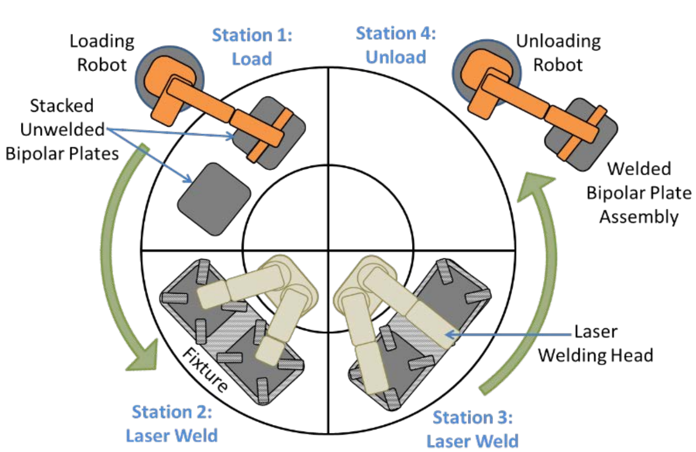
- **SA design is based on 2008 Honeywell concept**
  - ~3atm, 165krpm, centrifugal compressor, radial inflow expander, central motor, single (common shaft), air bearings
  - Size and cost scaling with pressure ratio, flow rate, and motor power
- **2018 re-evaluation of assumptions (with ANL and Honeywell input)**
  - Basic CEM design appropriate: No significant design changes needed
  - Updated air flow rate for air-bearing/motor-cooling
  - CEM re-sized for 2018 mass flows & motor power
  - Motor & Controller efficiency: increased to 90%
  - Inflation adjustment: Previously in 2008$: + Δ$1.32/kW_{net} in 2018$

	2017 Model Value	2018 Model Value
Compressor Efficiency	71%	71%
Expander Efficiency	73%	73%
Motor & Motor Controller Efficiency	80% combined	90% based on FCTT input, new/adv. design

Re-evaluation of Laser Welding Bipolar Plate Assumptions

- 2017 Welding Station assumptions re-evaluated after Vendor input
  - Lincoln Electric, other component vendor suppliers
- Capital costs increased
  - Most items increased, substantial weld-fixture cost added per industry feedback
- Index/Rotation time between stations increased: 1 sec (2017) to 4.5 sec (2018)

Top view of BPP laser welding turn-table system



		Station Configuration for Low Volume			Station Configuration for High Volume	
Parts per Station			1		4	
Number of Stations			1		2	
Number of Turn Table/Enclosures			1		1	
Number of Lasers per part			1		1	
Total Number of lasers			1		8	
Total Number of Focus Heads			1		8	
	From Vendor Estimates (used at lower production volumes)				Projected for >5 Systems Purchased (used at high prod. Vol.)	
Components/ Cost-Elements	**Min Component Cost**	**Max Component Cost**	**Min Subsys Cost**	**Max Subsys Cost**	**Component Cost**	**Subsystem Cost**
Laser Resonator	$ 50,000	$ 100,000	$ 50,000	$ 100,000	$ 35,000	$ 280,000
Focus Head	$ 30,000	$ 50,000	$ 30,000	$ 50,000	$ 30,000	$ 240,000
Base Sys & Integration	$ 150,000	$ 200,000	$ 150,000	$ 200,000	$ 75,000	$ 75,000
Material Handling	$ 112,500	$ 137,500	$ 112,500	$ 137,500	$ 100,000	$ 100,000
Robots	$ 86,722	$ 125,000	$ 173,444	$ 250,000	$ 86,722	$ 173,444
Parts Handling Fixtures	$ 60,000	$ 80,000	$ 60,000	$ 80,000	$ 112,500	$ 225,000
Weld Monitoring	$ 60,000	$ 125,000	$ 60,000	$ 125,000	$ 45,000	$ 360,000
Cost Contingency (20%)	NA	NA	$ 127,189	$ 188,500	NA	$ 290,689
Base system budgetary price (Total)			$ 763,133	$ 1,131,000		$ 1,744,133
2017 Analysis Station Cost			**$ 815,444**			**$ 1,031,444**
2018 Analysis Station Cost (Mid-Point)			**$ 947,066**			**$ 1,744,133**

\+ 16%   + 69%

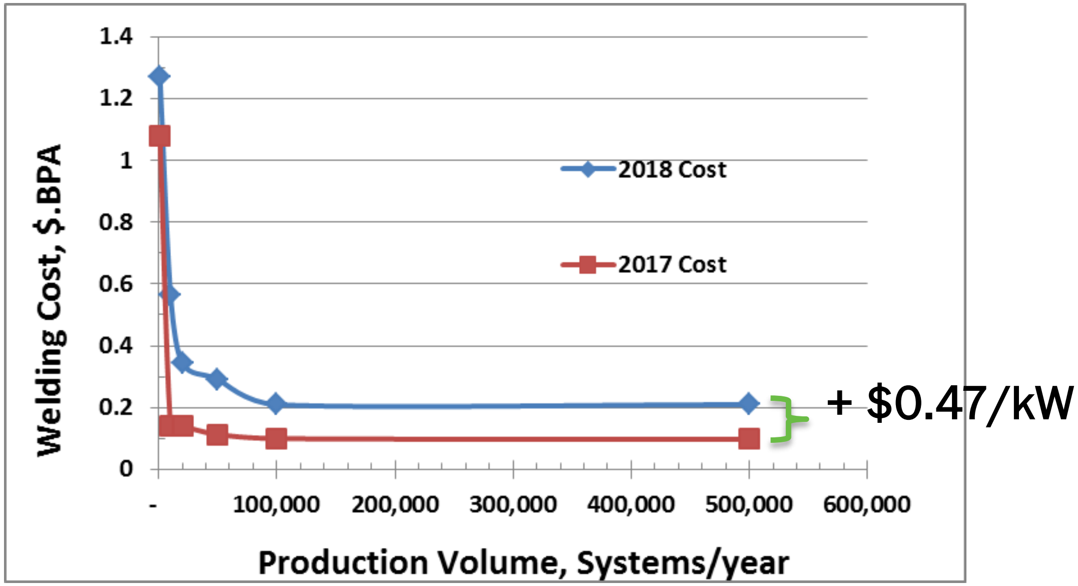
Updates result in higher (but more realistic) costs.

2018 Welding Cost

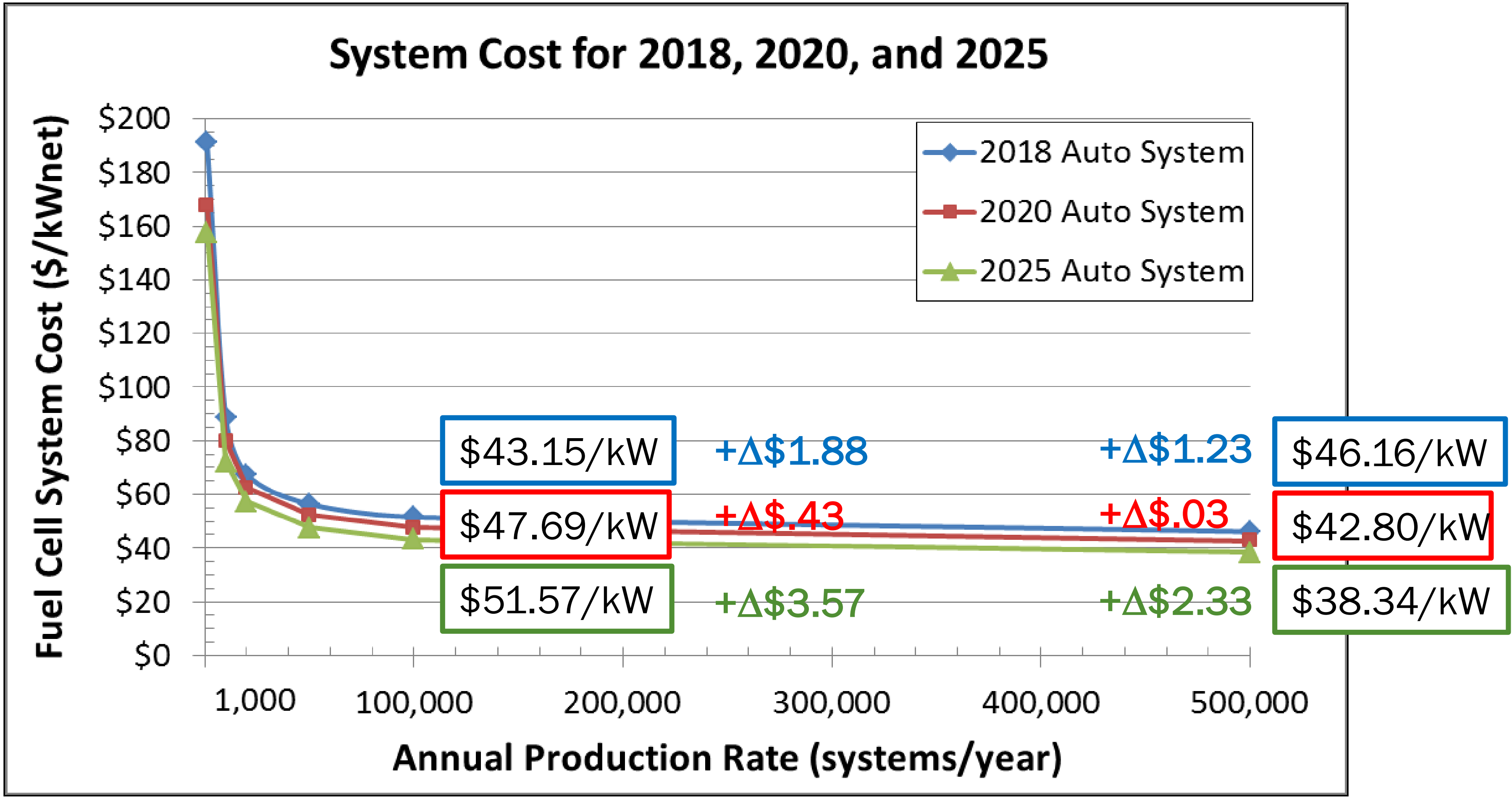
2018 Welding Station Assumptions

Process Parameters	Systems/year	1,000	10,000	20,000	50,000	100,000	500,000
Capital Cost ($/line)	$/line	$947,066	$1,238,066	$772,133	$1,126,133	$1,744,133	$1,744,133
Welding Stations	#	1	1	1	2	2	2
Parts per station	#/station	1	2	2	2	4	4
Lasers per part	#/part	1	1	1	1	1	1
Galvos per laser	#/laser	1	1	1	1	1	1
Total galvo heads simultaneously engaged	#	1	2	2	4	8	8
Laser Speed	m/s	0.125	0.125	0.125	0.125	0.125	0.125
Index Time Between Plates	sec	5	5	5	5	5	5
Duration of welding at each station (to be added to index time)	sec	11.43	11.43	11.43	5.72	5.72	5.72
Total index time (welding time + index time for mult. Parts)	sec	15.93	15.93	15.93	10.22	10.22	10.22
Effective Cycletime per Welded assembly	sec	15.93	7.97	7.97	5.11	2.55	2.55
Simultaneous Lines	#	1	3	5	8	8	40
Laborers per Line	#/line	0.50	1	1	1	1	1
Line Utilization	%	49.79%	82.98%	99.58%	99.77%	99.77%	99.77%
Effective Total Machine Rate ($/hr)	$/hr	$286.31	$252.48	$153.41	$202.43	$288.32	$288.32
Material Cost ($/kg)	$/kg	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

2018 Cost > 2017 Cost

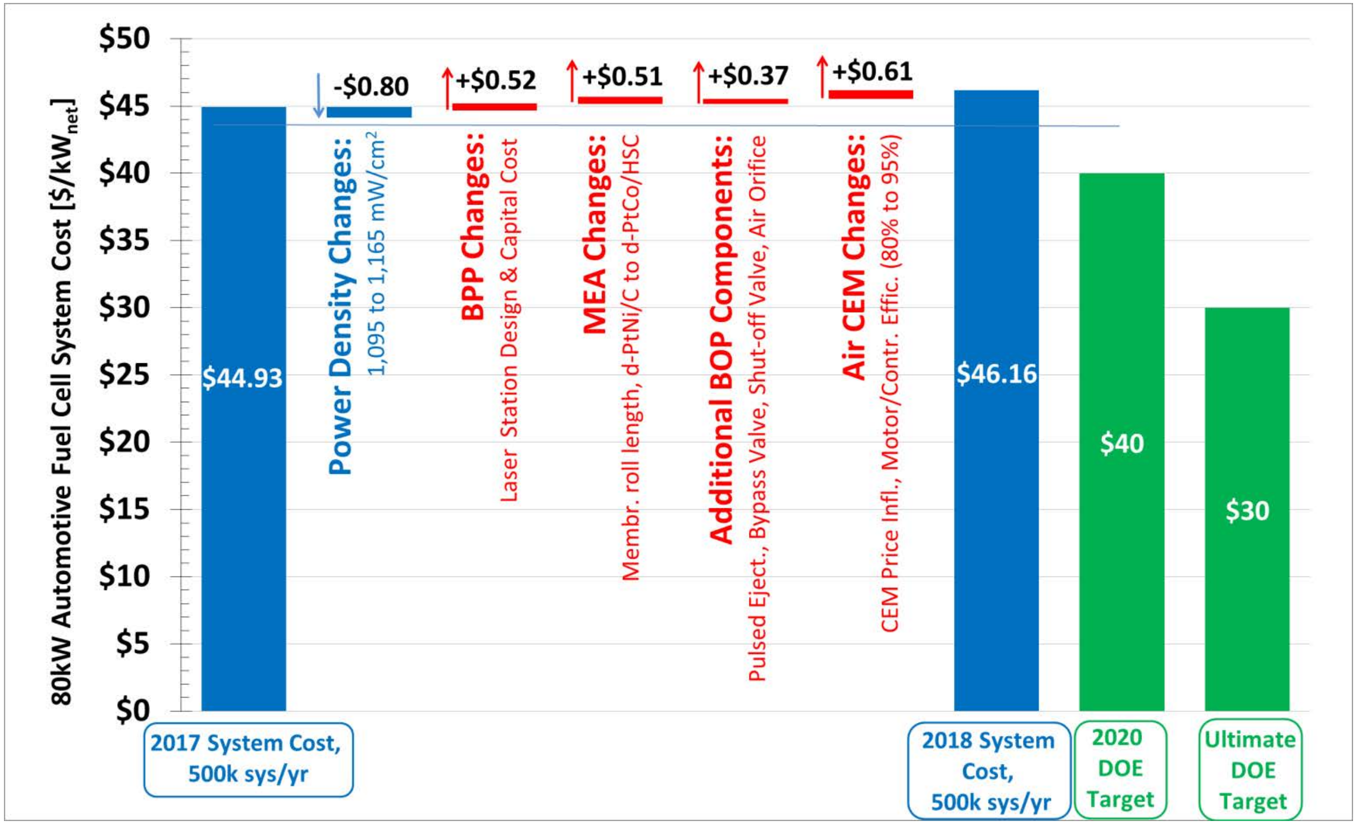


Cost Results for 80kW$_e$ Auto Systems



*Cost results shown for both 100,000 & 500,000 systems/year

Annual Updates of Automotive System Cost Preliminary 2018 Projection Compared to DOE Targets (2018 Baseline System at 500k systems/year)



- ~\$0.8/kW_{net} cost reduction from new optimized operating conditions of PtCo/HSC catalyst (major improvement of \$7.5/kW observed last year in switch to PtCO/HSC)
- Pulsed Ejector implement to allow adequate recirculation at low power
- Multiple analysis improvements/refinements
- Preliminary 2018 system cost: ~\$46/kW_{net}

Medium Duty Vehicle (MDV) Outline

- Results of scoping study on system architecture and power level
- System schematic for three timeframes considered
- System definitions (catalyst loading, materials selection, etc.) for three timeframes
- System operating conditions
- Projected MDV/HDV costs

Fuel Cell Truck Analysis

- DFMA analysis of FC Medium Duty Vehicle (MDV) or Heavy Duty Vehicle (HDV)
- Leverage past work:
  - ANL studies (Ram Vijayagopal et al): 12 truck applications studied
  - 21st Century Truck

Two powertrain architecture options can be considered:

1. Battery powered electric vehicle with fuel cell range extender
2. Fuel cell dominant system with battery for peak acceleration events

Selected for analysis

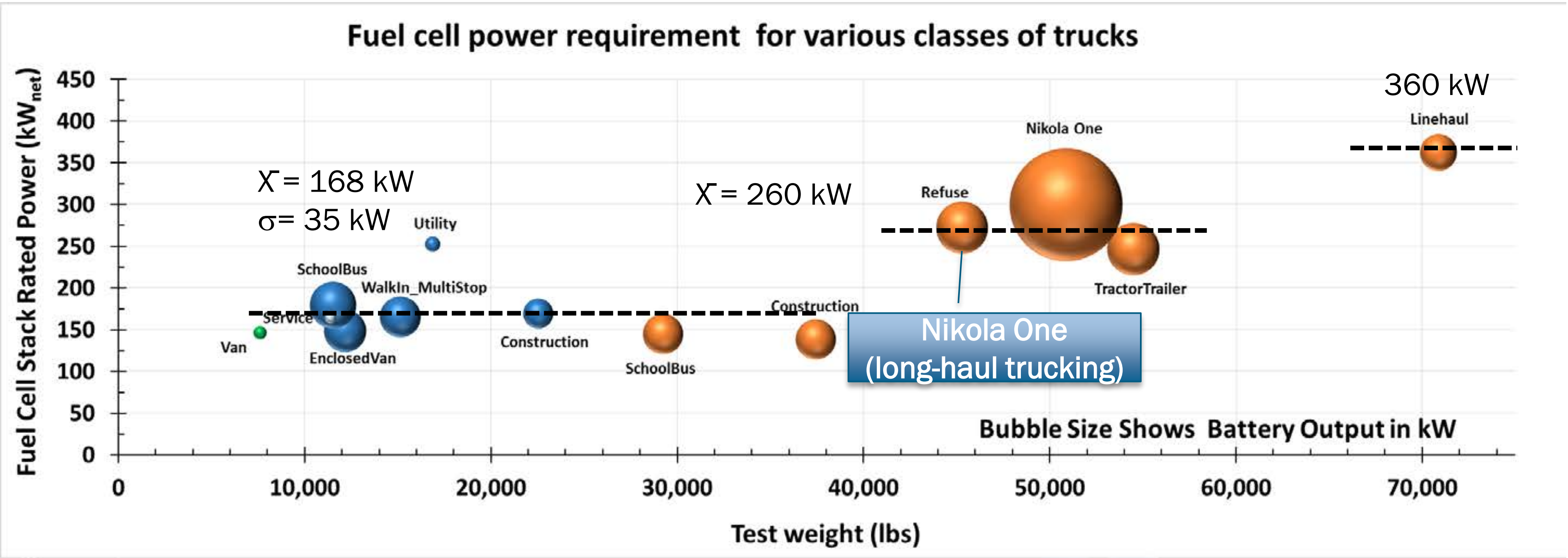
	Class and Vocation	FHA Vehicle Class Definition	ANL Analysis Assumption/Results TestWeight (lbs)	Fuelcell (kW)	Battery (kW)
Light Duty	Class 1	Class 1: < 6,000 lbs	Not eval.	Not eval.	Not eval.
	Class 2 Van	Class 2: 6,001 - 10,000 lbs	7,588	147	6
Medium Duty	Class 3 Service	Class 3: 10,001 - 14,000 lbs	11,356	165	4
	Class 3 SchoolBus	Class 3: 10,001 - 14,000 lbs	11,512	180	76
	Class 3 EnclosedVan	Class 3: 10,001 - 14,000 lbs	12,166	149	62
	Class 4 Walk-In, Multi-Stop	Class 4: 14,001 - 16,000 lbs	15,126	166	59
	Class 5 Utility	Class 5: 16,001 - 19,500 lbs	16,860	253	8
	Class 6 Construction	Class 6: 19,501 - 26,000 lbs	22,532	170	30
Heavy Duty	Class 7 SchoolBus	Class 7: 26,001 - 33,000 lbs	29,230	145	56
	Class 8 Construction	Class 8: >33,001 lbs	37,429	139	57
	Class 8 Refuse		45,291	273	94
	Class 8 Nikola One		50,870	300	446
	Class 8 TractorTrailer		54,489	247	95
	Class 8 Linehaul		70,869	363	47

21st Century Truck

MDV Baseline (approximation)

HDV Baseline

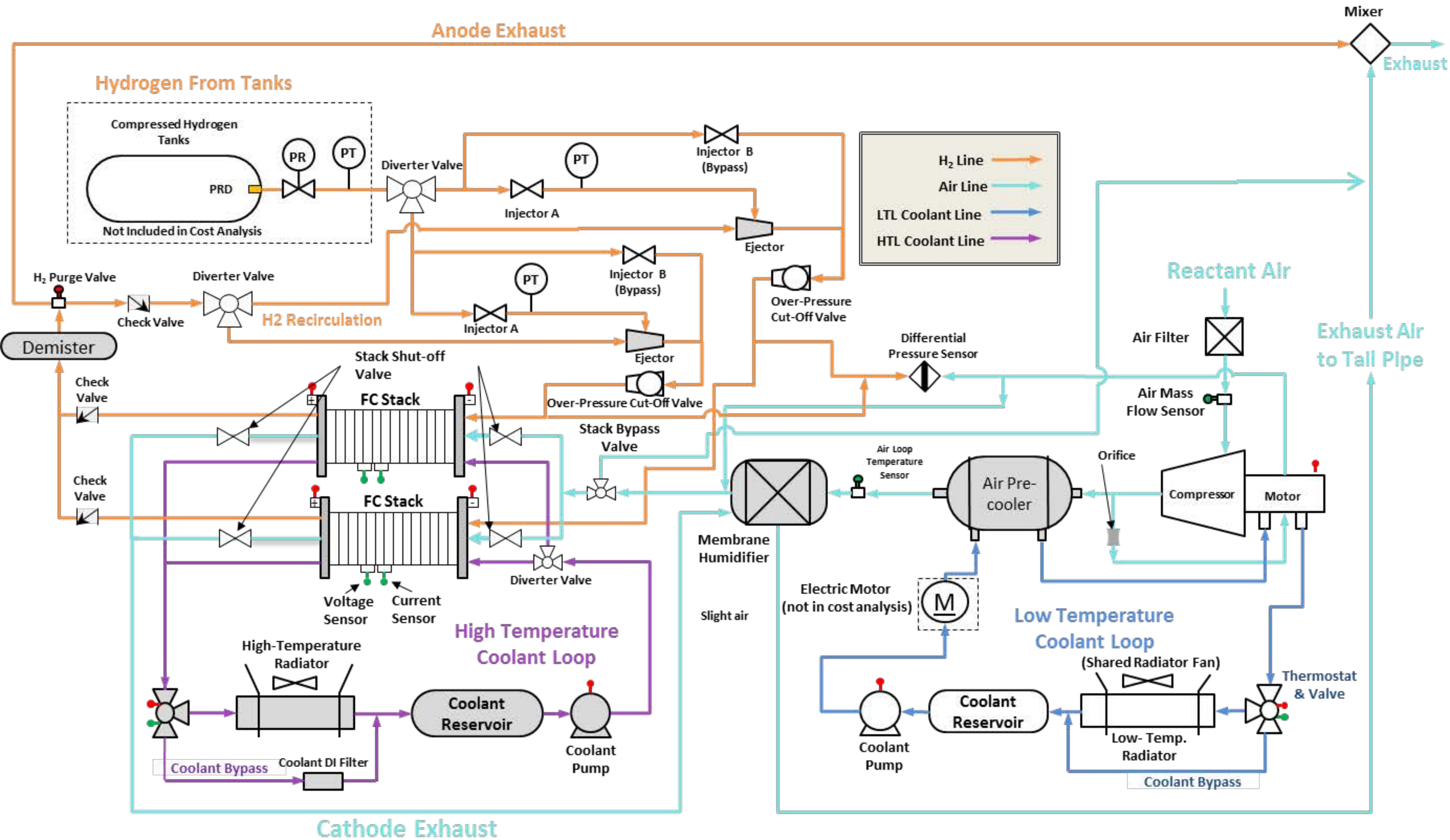
MDV/HDV Fit into 3 Power-Level Bins



<u>ANL Study Findings:</u> - Two power levels capture most MDV/HDV applications

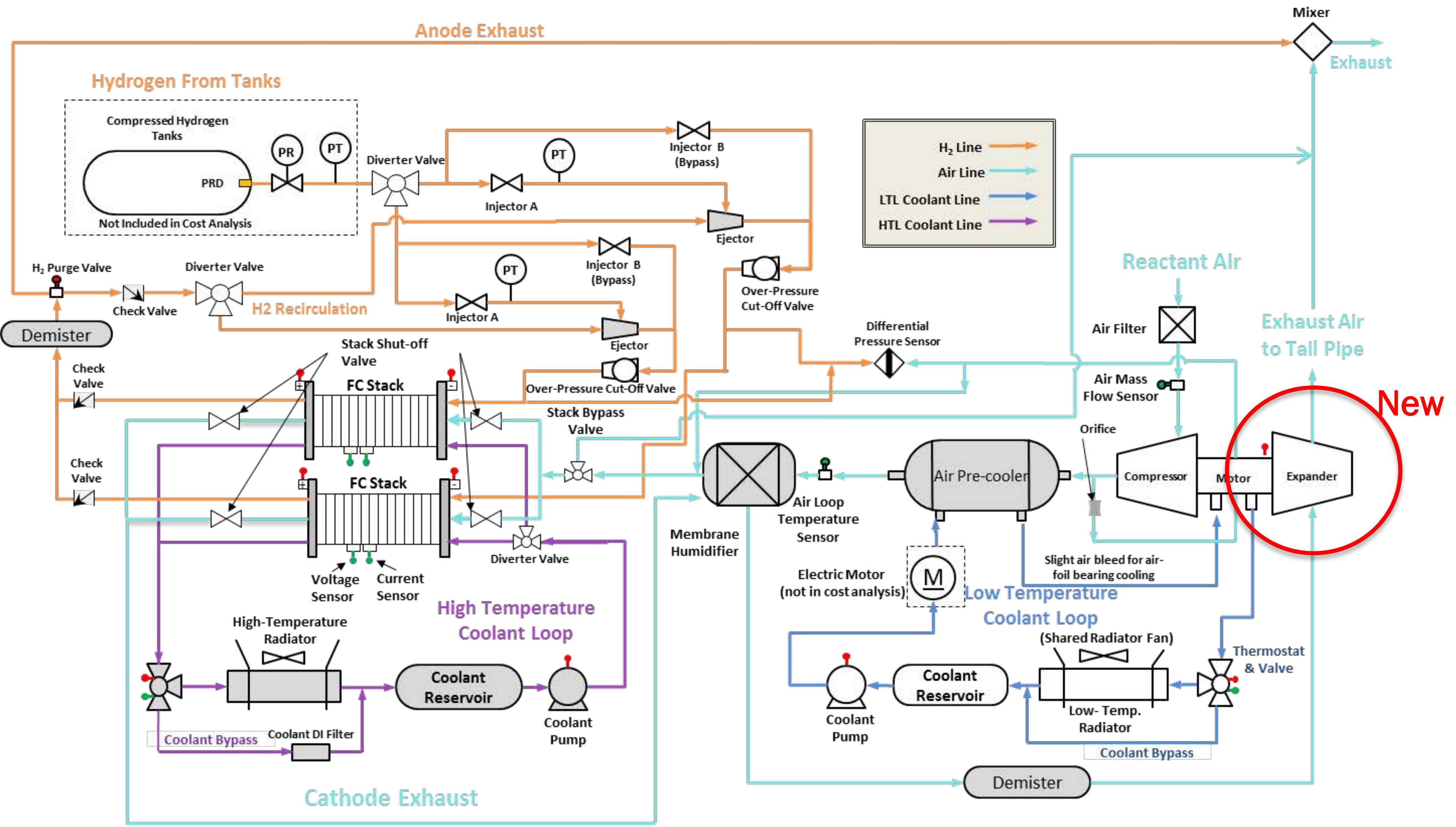
- Stacks can be built-up from ~80 kW modules

2018 MDV System (Diagram shows system components included in baseline cost analysis model)



2020/2025 MDV System

(Diagram shows system components included in baseline cost analysis model)



MDV System Definition- Part 1
(Configuration, Operating, and Manufacturing Parameters)

	2016 Bus System	2018 MD Truck System	2020 MD Truck System	2025 MD Truck System
Power Density (mW/cm^2)	739	1,178	1,200	1,350
Total Pt loading (mgPt/cm^2)	0.5	0.35	0.35	**0.3**
Pt Group Metal (PGM) Total Content (g/kW$_{gross}$)	0.719	**0.321**	**0.316**	**0.242**
Net Power (kW$_{net}$)	160	160	160	160
Gross Power (kW$_{gross}$)	194.7	**196.5**	**189.3**	**183.4**
Cell Voltage (V)	0.659	**0.68**	0.68	0.68
Operating Pressure (atm)	1.9	**2.35**	2.35	2.35
Stack Temp. (°C) (Coolant Exit Temp)	72	**63**	63	63
Air Stoichiometry	1.8	**1.5**	1.5	1.5
Q/ΔT (kW$_{th}$/°C)	5.4	**7.2**	**6.9**	**6.7**
Active Cells	758	**736**	736	736
Total System Voltage	500 - 720	500 **- 700**	500 - 700	500 – 700
Active to Total Area Ratio	0.625	0.625	0.625	0.65
Membrane Material	20-micron Nafion (1100EW) supported on ePTFE	**14-micron Nafion (850EW) supported on ePTFE**	14-micron Nafion (850EW) supported on ePTFE	**14-micron Nafion (850EW) supported on electrospun support**
Radiator/ Cooling System	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler	Aluminum Radiator, Water/Glycol Coolant, DI Filter, Air Precooler
Bipolar Plates and Coating	SS 316L with TreadStone LIteCell™ Coating (Dots-R)	**SS 316L with PVD Gold Coating**	**316SS with Vacuum Coating (modeled as TreadStone TIOX)**	316SS with Vacuum Coating (modeled as TreadStone TIOX)

Green font indicates a change from the column to the left.

MDV System Definition- Part 2

(Configuration, Operating, and Manufacturing Parameters)

	2016 Bus System	2018 MD Truck System	2020 MD Truck System	2025 MD Truck System
BPP Forming/Joining	Progressive Stamping/Welding	Progressive Stamping/Welding	**Hydroforming or HVIF**	Hydroforming or HVIF
Air Compression	Eaton-Style Multi-Lobe Compressor, Without Expander	Eaton-style compressor (no expander)	**Eaton-style compressor, Eaton-style expander**	**Centrifugal Compressor, Radial-Inflow Expander**
Gas Diffusion Layers	Carbon Paper Macroporous Layer with Microporous Layer (DFMA® cost of Avcarb GDL)	**150 microns (105 µm GDL, 45 µm MPL, uncompressed)**	150 microns (105 µm GDL, 45 µm MPL, uncompressed)	150 microns (105 µm GDL, 45 µm MPL, uncompressed)
Catalyst & Application	Slot Die Coating of: Cath.: Dispersed 0.4 mgPt/cm^2 Pt on C Anode: Dispersed 0.1mgPt/cm^2 Pt/C	**Slot Die Coating of: Cath.: Dispersed 0.3 mgPt/cm^2 d-PtCo/HSC-e Anode: Dispersed 0.05mgPt/cm^2 Pt/C**	Slot Die Coating of: Cath.: Dispersed 0.3 mgPt/cm^2 d-PtCo/HSC-f Anode: Dispersed 0.05mgPt/cm^2 Pt/C	**Slot Die Coating of advanced perf. Catalyst cost modeled as: Cath.: Dispersed 0.25mgPt/cm^2 d-PtCo/HSC Anode: Dispersed 0.05mgPt/cm^2 Pt/C**
CCM Preparation	No acid wash	**Gore Direct-Coated Membrane with dual-side slot-die coated electrodes, acid washing**	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes, acid washing	Gore Direct-Coated Membrane with dual-side slot-die coated electrodes, acid washing

Green font indicates a change from the column to the left.

MDV System Definition- Part 3
(Configuration, Operating, and Manufacturing Parameters)

	2016 Bus System	2018 MD Truck System	2020 MD Truck System	2025 MD Truck System
Air Compressor/Expander/ Motor Efficiency	Compr.: 58% (multi-lobe) Expander: NA Motor/Controller: 95%	Compr.: 58% (multi-lobe) Motor/Controller: 95%	**Compr.: 58% (multi-lobe) Exp.: 59% (multi-lobe) Motor/Controller: 95%**	**Compressor: 71% (centrifugal) Expander: 73% (radial in-flow) Motor/Controller: 90%**
Air Humidification	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)	Plate Frame Membrane Humidifier (with 5 micron ionomer membranes)
Hydrogen Humidification	None	None	None	None
Anode Recirculation	2 fixed geometry ejectors	**Pulse ejector with bypass**	Pulse ejector with bypass	Pulse ejector with bypass
Exhaust Water Recovery	None	None	None	None
MEA Containment	Screen Printed Seal on MEA sub-gaskets, GDL hot pressed to CCM	R2R sub-gaskets, hot-pressed to CCM	R2R sub-gaskets, hot-pressed to CCM	R2R sub-gaskets, hot-pressed to CCM
Coolant & End Gaskets	Laser Welded(Cooling)/ Screen-Printed Adhesive Resin (End)	**Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)**	Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)	Laser Welded(Cooling)/ Screen-Printed Polyolefin Elastomer (End)
Freeze Protection	Drain Water at Shutdown	Drain Water at Shutdown	Drain Water at Shutdown	Drain Water at Shutdown
Hydrogen Sensors	3 for FC System[1]	**1 for FC System[2]**	1 for FC System	1 for FC System
End Plates/ Compression System	Composite Molded End Plates with Compression Bands	Composite Molded End Plates with Compression Bands	Composite Molded End Plates with Compression Bands	Composite Molded End Plates with Compression Bands
Stack Conditioning (hrs)	2	2	2	**1**
Stack Lifetime (hrs) (before replacement)	Not specified	25,000	25,000	25,000

[1] There are a total of 3 hydrogen sensors on-board the 2016 FC bus fuel cell cost estimate (1 more than in the 2016 auto system).
[2] In the 2017 and 2018 auto cost analyses, the number of sensors in the fuel cell compartment of the automobile was reduced to zero (from a previous level of 2). Consequently, the MDV sensor estimate is one more than the auto and is thus set at one sensor (for all three technology years).

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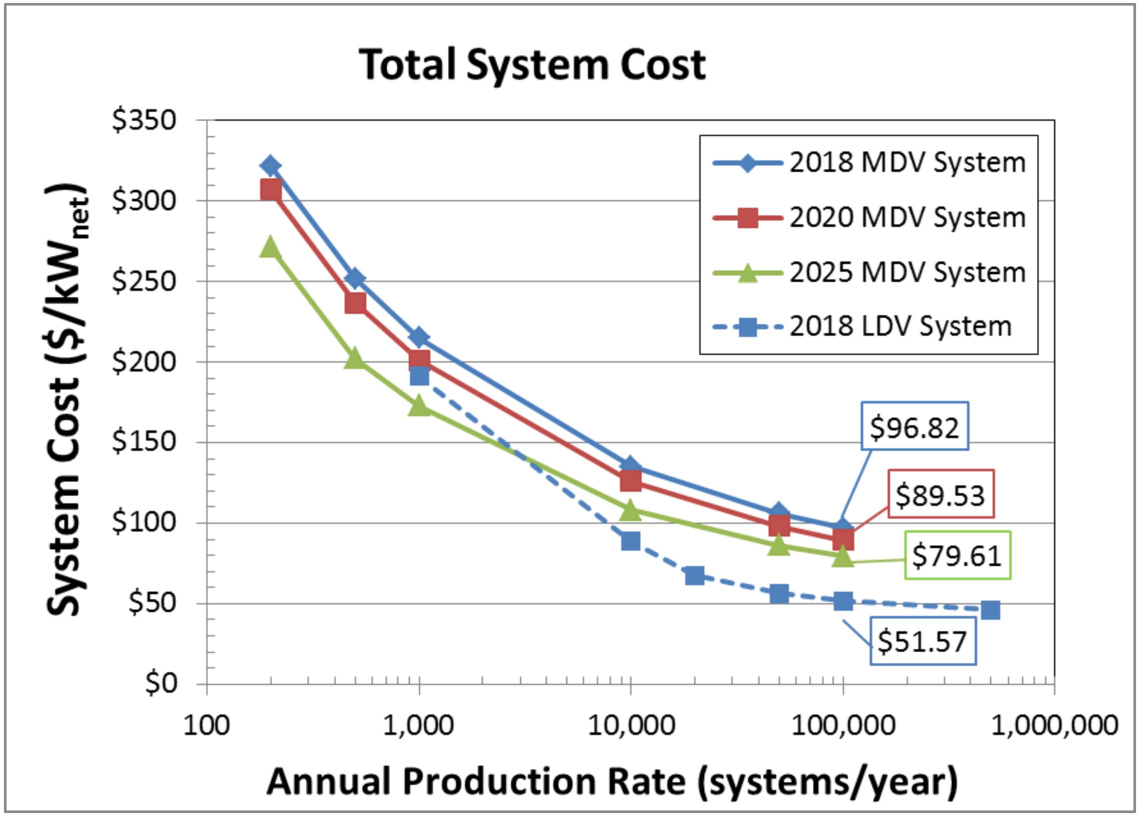
MDV Operating Parameters

	2018 LDV System	2016 Bus System	2018 MDV System	2020 MDV System	2025 MDV System
Annual Production (fuel cell systems/year)	1,000-500,000	200-1,000	200-100k[1]	200-100k[1]	200-100k[1]
Configuration	Centrifugal Compressor, Radial-Inflow Expander	Multi-Lobe Compressor	Multi-Lobe Compressor	Multi-Lobe Compressor and Expander	Centrifugal Compressor, Radial-Inflow Expander
Target Stack Durability (hours)	5,000	25,000[2]	25,000[2]/5,000[3]	25,000[2]/5,000[3]	25,000[2]/5,000[3]
Power Density	1,165	739	1,178	1,200	1,350
Total Pt loading ($mgPt/cm^2{}_{total\ area}$)	0.125	0.5	0.35	0.35	0.3
Pt Group Metal (PGM) Total Content (g/kW_{gross})	0.114	0.719	0.321	0.316	0.242
Cell Voltage (V/cell)	0.663	0.659	0.68	0.68	0.68
Net Power (kW_{net})	80	160	160	160	160
Gross Power (kW_{gross})	88	194.7	196.5	189.3	183.4
Operating Pressure (atm)	2.5	1.9	2.35	2.35	2.35
Stack Temp. (Coolant Exit Temp) (°C)	94	72	63[4]	63[4]	63[4]
Air Stoichiometry	1.5	1.8	1.5	1.5	1.5
$Q/\Delta T$ ($kW_{th}/°C$)	1.45	5.4	7.2	6.9	6.7

1. VTO Market Report Chapter 3: Heavy Trucks (http://cta.ornl.gov/vtmarketreport/pdf/2015_vtmarketreport_full_doc.pdf)
2. DOE Ultimate Bus Target (https://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf)
3. CAFCP Action Plan (http://cafcp.org/sites/default/files/MDHD-action-plan-2016.pdf)
4. Lower temperature selected for durability

Preliminary Cost Results for MDV Systems



- MDV cost curves more shallow due to low-volume manufacturing assumptions/criteria representative of the bus system.
- Large cost difference between LDV and MDV at 100k sys/yr due to:
  - Pt loading (0.125 Vs 0.35mgPt/cm^2)
  - CEM/gross power
  - Non-vertical integration (application of extra markup and job shop for truck)

Summary of Findings

- Auto cost results show small adjustments from 2017 analysis:
  - ~$46/kW$_{net}$ (2018, +Δ$1.23), $43/kW$_{net}$ (2020, +Δ$.03), $38/kW$_{net}$ (2025, +Δ$2.33)
- Moderate improvement (6%) in performance using latest PtCo/HSC-e cathode catalyst
- Bipolar plate base material 316 SS cost alone is the same as the DOE 2020 target of $3/kW. (~3,000mW/cm^2 power density would be required to reach DOE target.)
- At very high BPP production volume, it's difficult to avoid massively parallel processing lines
  - 2-D/Roll-to-Roll processing may be practical and economic solution
- Multiple BPP coating approaches examined and appear viable:
  - Each generation of TreadStone BPP coating shows lower cost (TIOX is <$1/kW)
  - Sandvik pre-forming coating provides advantage of reduced parts handling
- Pulsed-ejector H_2 recirculation adopted as lowest cost, full-performance option.
- Projected cost for 2020 does not meet DOE Target of $40/kW (but is close).
- 160kW Medium Duty Vehicle (MDV truck) selected for analysis.
  - Stacks very similar to auto except higher Pt loading, run cooler, for longer life.
  - Projected costs are $97/kW$_{net}$, $90/kW$_{net}$, and $80/kW$_{net}$ for 2018/2020/2025
  - Potentially high production rates (up to 100k's/year) but with higher markup due to business structure

Remaining Barriers and Challenges

Automotive System

- PFSA ionomer cost uncertainty: Some suggest that ionomer may be ~$500/kg even at high volumes. May require alternative formulation or fabrication process.
- BPP material cost: Base material 316SS contributes ~$3/kW$_{net}$ making it difficult to reach DOE's 2020 cost target of $3/kW total BPP (material/forming/coating).
- Ammonia contamination: Presence of ammonia in air feed of FC vehicles presents difficulty in maintaining membrane air humidifier performance.
- $40/kW* DOE target difficult to achieve: Current projected advancements are not able to meet DOE's $40/kW target cost. Out-year projections suggest much lower material costs (75% of stack cost) may be required.
- Massively parallel BPP forming lines: Even with ~2sec/plate forming speed, many parallel BPP production lines are needed for 500k systems/year. This presents part uniformity problems.

MDV Study

- Better understanding of FCV truck preferred operation mode (how much hybridization).

* Note that cost targets in the FY2019 budget request are $40/kW by 2025.

Proposed Future Work

Automotive Systems

- Continue investigating ways to incorporate durability into cost modeling
- Model cost of PFSA/PFIA ionomers
- Review end-of-life disposal costs for auto system
- Conduct DFMA analysis of 2D manufacturing of cells
- Investigate Precors BPP non-vacuum pre-coating process
- Conduct cost sensitivity studies on 2018/2020/2025 systems

Medium/Heavy Duty Truck

- Incorporating feedback from DOE planned MDV/HDV truck workshop
- Conduct cost sensitivity studies on 2018/2020/2025 systems

Document in 2018 Final Report

- Report due September 2018

*Any proposed future work is subject to change based on funding levels.

Acknowledgement

- This work is sponsored by the Department of Energy Fuel Cell Technologies Office under award numbers DE-EE0007600
- Project Partners: Argonne National Lab (ANL) and National Renewable Energy Lab (NREL)
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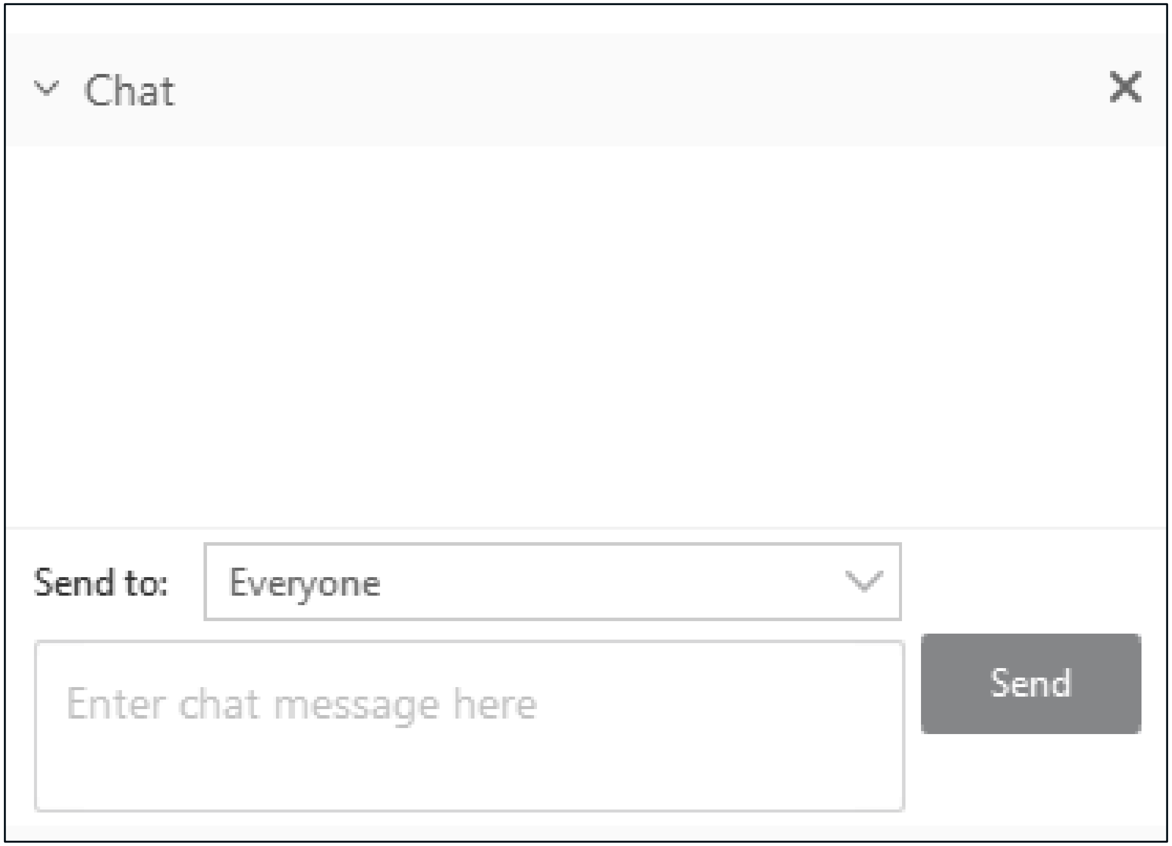
  - Mike Yandrasits (3M)
  - Jim Waldecker (Ford)
  - Anusorn Kongkanand (GM)
- Industrial partners who generously contributed insight and feedback on equipment, materials, and processes

Question and Answer

- Please type your questions to the chat box. **Send to: (HOST)**



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Thank you

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Backup Slides

Timeline of Analyses being Conducted

Year	Project Year	Technology	Proposed Analyses
2017	1	80kW Light Duty Vehicle (LDV)	Current (2017), 2020, 2025
		Med/Heavy Duty Truck	Scoping Study
		LDV System or Stack Component	Validation Study
2018	2	LDV	Current (2018), 2020, 2025
		MD/HD Truck #1	Current (2018), 2020, 2025
2019	3	LDV	Current (2019), 2020, 2025
		Buses	Current (2019), 2020, 2025
2020	4	LDV	Current (2020), 2025
		MD/HD Truck System #2 or update of #1	Current (2020), 2025
2021	5	LDV	Current (2021), 2025
		Update to Buses & Trucks as needed	Current (2021), 2025

- Project Analyses:
  - Auto and Medium & Heavy Duty Fuel Cell Truck Analysis
  - Current and Future Tech 2020 & 2025 Analysis
    - 2020 Systems: based on projected 2020 laboratory demonstrated technologies.
    - 2025 (High Innovation) Systems: based on projected 2025 technology advances that are expected to be achievable from a well-funded, focused, and successful program.
- Bus updates in Year 3 and 5 (not annually)