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2019 DOE Hydrogen and Fuel Cells Program Review Presentation

Fuel Cell Systems Analysis

PI: Brian D. James

Strategic Analysis Inc.

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Project ID# FC163

Overview

Timeline

- Project Start Date: 9/30/16
- Project End Date: 9/30/21
- % complete: 45% of five year project (in Year 3 of 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 Funding Spent
  - ~$685,000 (through Feb. 2019, including Labs)
- Total DOE Project Value
  - $1.25M (over 5 years, including Labs)
  - 0% Cost share

Partners

- National Renewable Energy Laboratory (NREL)
- Argonne National Lab (ANL)

NREL NATIONAL RENEWABLE ENERGY LABORATORY Argonne NATIONAL LABORATORY

Relevance

Overall Project Objectives:

- Project current (2019) and future cost (2025) of automotive, bus, & truck fuel cell systems at high manufacturing rates.
- Project impact of technology improvements on system cost
- Identify low cost pathways to achieve the
  - DOE 2025 goal of $40/kW_{net}$ (automotive) at 500,000 systems per year
  - DOE Interim goal of $80/kW_{net}$ (MDV/HDV) at 100,000 systems per year
- Benchmark against production vehicle power systems
- Identify fuel cell system cost drivers to facilitate Fuel Cell Technologies Office programmatic decisions.

Impact since 2018 analysis final results:

- 2019 current system decreases $3/kW_{net}$ for 170 kW MDV System
- 2025 future MDV system cost decreases to < $75/kW_{net}$
  - Reaches DOE Interim MDV cost target but not Ultimate cost target $60/kW

Relevance: Timeline of Analyses

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~~ HDV Truck #1	Current (2019), ~~2020~~, 2025
		~~Buses~~ MDV Truck #2	Current (2019), ~~2020,~~ 2025
2020	4	LDV	Current (2020), 2025
		MD/HD Truck System #2 or #3	Current (2020), 2025
2021	5	LDV	Current (2021), 2025
		Update to Buses & Trucks as needed	Current (2021), 2025

- **Automotive LDV Cases** ***New Since 2018: All values in 2016$***
  - **As recommended by DOE, the LDV cases are deferred until 2020 for two reasons.**
    - The time period for advancement in technology often takes longer than a year and reporting a small cost change is not of major impact or usefulness to the fuel cell community.
    - Time & resources are better spent on MDV and HDV systems as they are of immediate interest to DOE.
- **2019 Project Analyses:**
  - **Medium & Heavy Duty Fuel Cell Truck Analysis**
  - **Current (2019) and Future Tech (2025) Analysis – 2020 year analysis removed**
- **Bus to be updated in Year 5**

Approach: Topics Examined Since 2018 AMR

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

2019/2025 Medium Duty and Heavy Duty Truck Systems

- **Questionnaire:** Use of feedback from MDV/HDV FC developers for cost modeling
- **Updated Operating Conditions:** Collaboration with ANL and FCPAD
- **Bipolar Plate Material:** Embossed flexible graphite/resin plates (Switch from metallic)
- **Coolant Gasket:** Replace welded BPPs with adhesive coolant gasket

2018/2019 Side Studies for Automotive/MDV/HDV System (not affecting baseline)

- **End of Life Disposal and Recycling Cost:** Pt catalyst and BPP coating recycle
- **Impact of Durability on Cost:** Outline of material and system solutions (ongoing)
- **Precors BPP Coating:** carbon-based pre-coating
- **2D Manufacturing:** R2R process for assembly of unitized cell

***Milestone 1: Validation Study* – Completed in 2017**

***Milestone 2,5,8: System Definition* – Completed for 2019/2025 MDV and HDV Systems**

***Milestone 3,6,9: DFMA® Cost Analysis* – Initiated for 2019/2025 MDV and HDV Systems**

***Milestone 4,7,10: Reporting of Cost Results* – (due Sept 2019) => Go/No-Go Decision**

Approach:

Fuel Cell Truck Analysis

- DFMA analysis of FC Medium Duty Vehicle (MDV) and Heavy Duty Vehicle (HDV)
- Leverage past work:
  - ANL studies (Ram Vijayagopal et al): 12 truck applications studied
  - 21st Century Truck
- Questionnaire sent out to FC truck developers (results still coming in)

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) [Class 6 Construction]

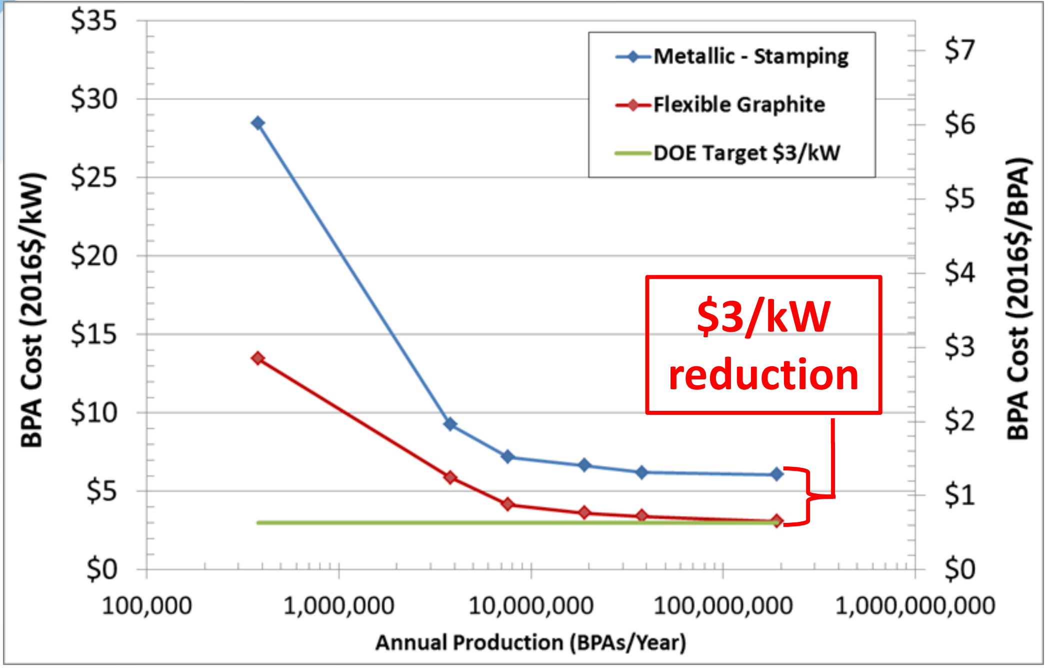
← HDV Baseline [Class 8 Linehaul]

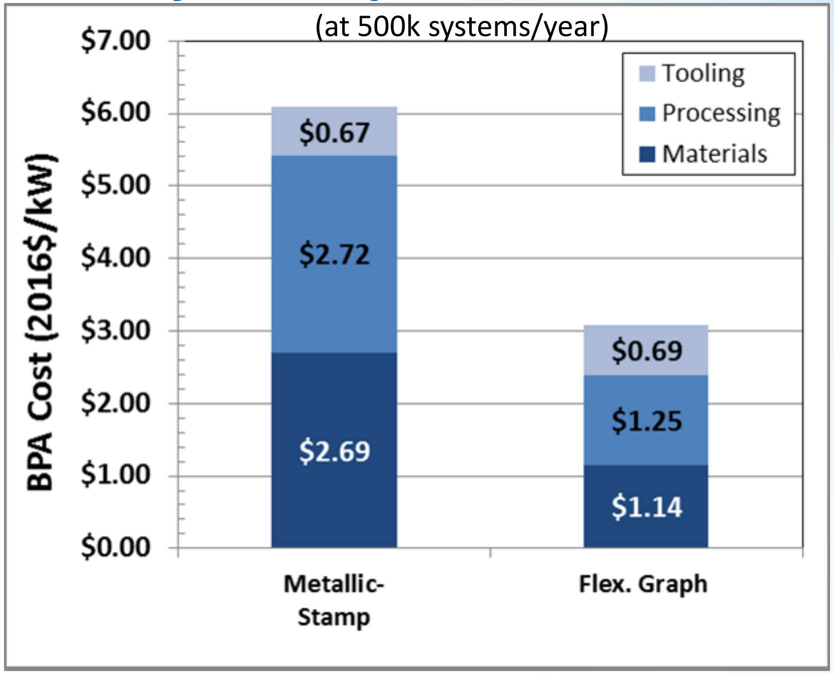
Accomplishments and Progress: MDV & HDV Operating Parameters

	2018 MDV System ($160kW_{net}$)	2019 MDV System ($170kW_{net}$)	2019 HDV Line Haul System ($237kW_{net}$)
Annual Production (FC systems/year)	200-100k		
Target Stack Durability (hours)	25,000		
FC Conditions			
Gross Power (kW_{gross})	197	217	315
Power Density (mW/cm^2)	1,178	1,097	1,097
Total Pt loading ($mgPt/cm^2_{total\ area}$)	0.35		
System Voltage (cell voltage)	500V (0.68V)	500V (0.675V)	500V (0.675V)
Cells per Stack (Stacks per system)	368 (2 x 80kW stacks)	370 (2 x 85kW stacks)	247 (3 x 80kW stacks)
Operating Pressure (atm)	2.35	2.5	2.5
Stack Temp. (Coolant Exit Temp) (°C)	63	85 (peak temp. during 6% grade)	85 (peak temp. during 6% grade)
Air Stoichiometry	1.5		
$Q/\Delta T$ (kW_{th}/°C) ($T_{ambient}$=25 C)	4.2	3.1 (approx. diesel MDV value)	4.5 (approx. diesel HDV value)
Battery Conditions (not cost modeled)			
Battery Peak Power Req. (kW)	30	30	76
Battery Energy Req. (kWh)	0.8	0.8	28

- Change in power density, temp., and pressure from 2018 to 2019 MDV system
- New HDV System
  - 40% more FC power than MDV system
  - $Q/\Delta T$ based on ANL modeling and set to match heat rejection of diesel truck

Approach:
Flexible Graphite Plates Could Shift Bipolar Plates Closer to $3/kW DOE Target for LDVs at 500k Systems per Year





- Leverage LDV work conducted in collaboration with Ballard
- Bipolar Plate Assembly (BPA) cost includes base material/coating, forming, and joining of two individual bipolar plates at 315cm^2 total area
- Automotive plate sizing and production volumes, assuming the same performance
- Metallic plates utilizing SS316 have base material cost ~$2.70/kW
- Flexible Graphite expected to be slightly higher mass and volume than metallic

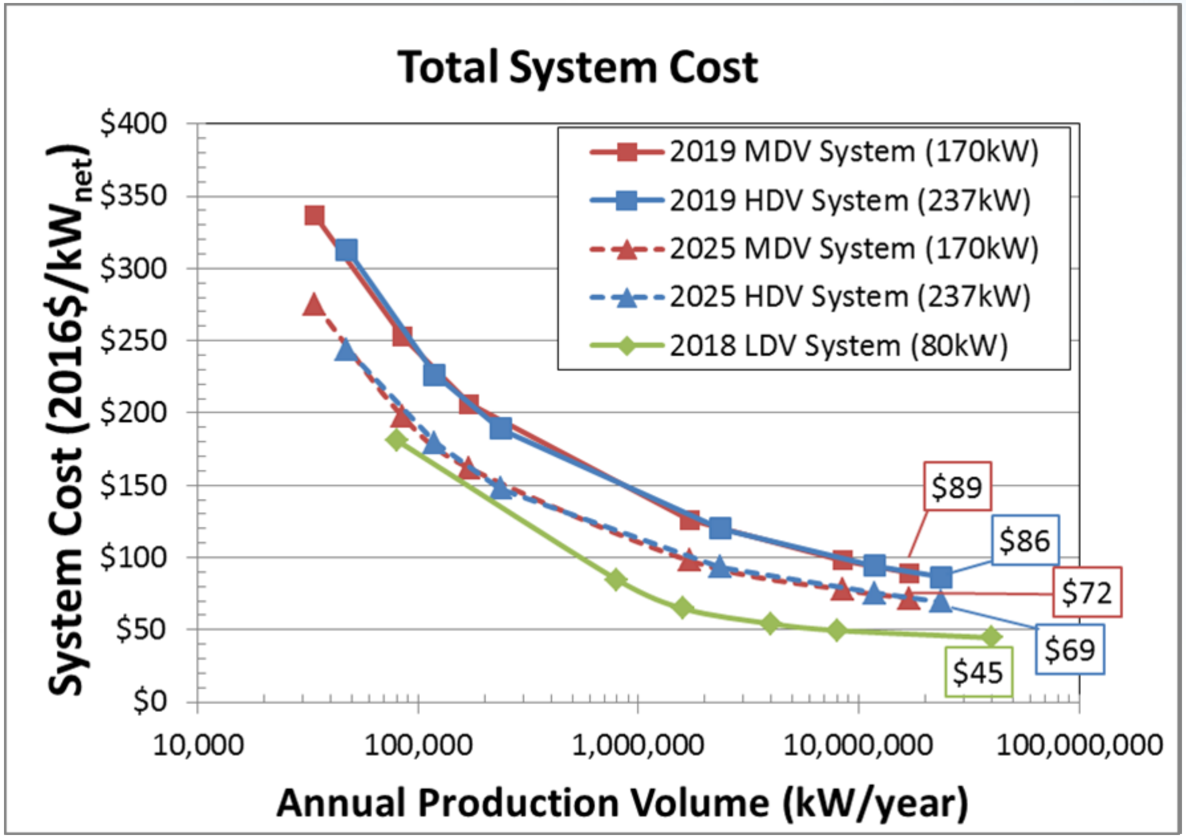
Approach: Flexible Graphite Plates Could Improve Durability While Reducing MDV System Cost by $5/kW at 100k systems/year

- Initial feedback from multiple FC developers suggest that carbon plates are more desirable than metallic plates , especially when trying to reach 25,000 hrs operation
- Increased FC power to $170kW_{net}$ and switched from PtCo/HSC to annealed Pt/C for improved durability

=> Reduced power density based on ANL modeling of higher Pt loading ($0.35mgPt/cm^2$)

Accomplishments and Progress:

Preliminary Cost Results for 2019 MDV & HDV Systems



- MDV/HDV cost curves more shallow than LDV due to low-volume manufacturing assumptions
- Large cost difference between LDV and MDV/HDV at 100k sys/year 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)

Accomplishments and Progress:

Quantifying the Cost Impact of Durability Measures

- Review of possible durability-enhancing actions
  - Collaborated with NREL, ANL, and LANL to create list of mitigation steps
  - List broken into two categories: Materials and System Solutions

Mitigation Step	Hardware	Other Impacts	Currently in Models?
Material Solutions			
Increase Pt loading	Increase total Pt loading to 0.35mgPt/cm^2	Enhances power density	✓
Use radical scavengers	Add 9 micrograms Ce/cm^2 (in form of CeO_2 nanopowder) to cathode catalyst ink		✓
Manage particle agglomeration	Novel catalyst geometries and formulations	Probable increase in synthesis costs. Potential water management issues.	X
Limit leaching	Mirai approach: use <10%mol Co (in cathode catalyst)		X
Bipolar Plate Base Material	LDV: Ti plates (used in Mirai) MDV/HDV: Graphite Plates	Ti material would increase material cost.	✓
Other material solutions	Eg. Use of high performance, inherently durable catalysts with high surface area carbon supports	Unknown	X

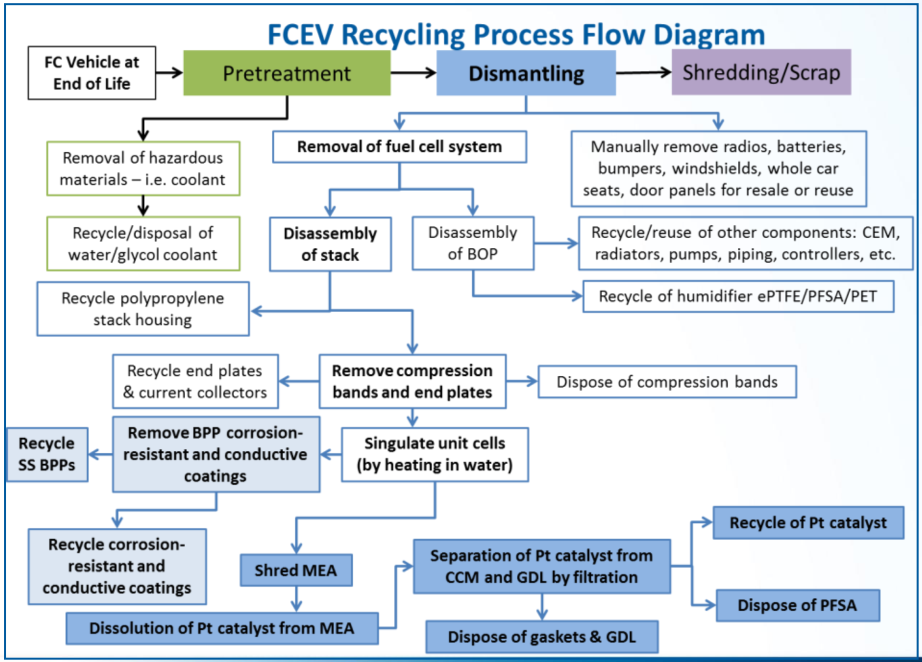
Accomplishments and Progress:
Quantifying the Impact of Durability on Cost

Mitigation Step	Hardware	Other Impacts	Currently in Models?
System Solutions			
Thicker membrane to delay failure due to membrane thinning	25 micron membrane (instead of <14 micron)	Lower power density	X
Limit temperature to <90°C	Larger radiator: at peak 85°C 18% increase (93°-40°)/(85°+40°)=1.18	Lower power-density/larger-stack	✓
Clip voltage at 0.85V/cell	No hardware change needed	Do not operate stacks at low powers where voltage exceed threshold. (rough est. 0.85V @50mA/cm2 is ~4% of peak power). May want to avoid/limit numerous FC on/off cycles by running in Range Extender mode. May need larger battery.	X
Limit voltage slew rate	No hardware change needed	Time delay expected to be ~1 second. Impact on battery sizing expected to be negligible.	X
Run wetter/ Run with less RH variability	Possibly larger humidifier. Ballard Bus approach: "run wetter" Approach: avoid RH swings that cause tearing/pin-holes at inlet and outlet	Impacts power density	X
Run load through shut down and don't let voltage go up	No hardware change needed		X
Oversize stack	Increase in stack size	Increase in stack size would increase cost but also increase fuel economy for much of vehicle life.	X
Accept >10% power degradation over system lifetime	No/limited hardware impact Approach: redefine "durability"	System will provide <90% rated power in later years of lifetime	X
Air purge of Anode at shut down (Not in use by OEMs)	Add 3-way valve, \$24-\$50 each, 1 per stack	Additional H_2 loss during each shutdown. Shutdowns more frequent than current/baseline system. Partially offset by reduced anode purges (of N_2 and water buildup)	X

Accomplishments and Progress:
End of Life Vehicle (ELV) Recycle and Disposal Cost Analysis

- Investigation of recycling or disposal of fuel cell system components
  - **Fuel Cell Stack**
    - MEA - Recycling of Pt. Multiple patented pathways (see backup slides).
    - Ionomer at EOL not expected to have much value due to degradation, however fluorine capture could be a lucrative business.
    - Recycling of bipolar plates and coatings: SS, Au, Ru, Ti, & TiO_2
  - **Balance of Plant Components**
    - Components similar to EV/ICE vehicles (so recycle/disposal is also the same)

- **Complex processes requiring specific separation methods**
  - Ideally have single stream process that can handle different stack designs
- **Extensive Pt/metals recycling currently conducted for autos**
  - FCV's would most likely leverage that recycling infrastructure
- **Plan to incorporate feedback from Pt experts**: Umicore, Johnson Matthey, Heraeus, AngloAmerican, etc.



Accomplishments and Progress:

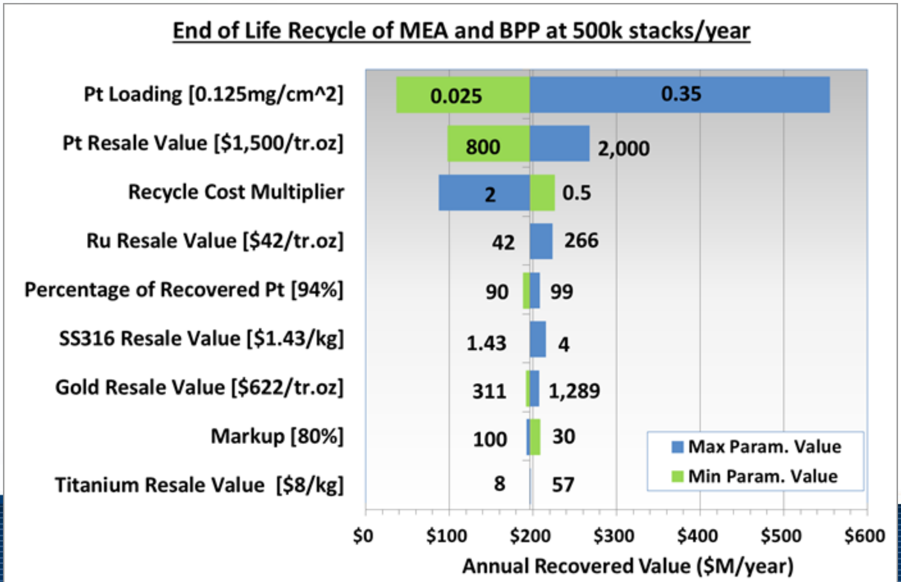
Recovered Value from Pt Recycle are Much Higher than Recycled BPP Materials

Values shown in nominal year dollars

Preliminary Results

Total Pt loading at 0.125mg/cm²		Fuel Cell Stack Recycling					
Annual System Recycling Rate	stacks/year	1,000	10,000	20,000	50,000	100,000	500,000
Annual Pt Recycled	kg/year	9	88	176	439	878	4,389
Cell Singulation & Separation Cost	$/year	($97,283)	($185,348)	($333,673)	($669,350)	($1,469,610)	($6,642,615)
Pt Recycle Cost	$/year	($618,593)	($1,121,964)	($1,781,337)	($2,701,757)	($3,970,012)	($14,331,416)
BPP Materials Recycle Cost	$/year	($801,230)	($2,386,491)	($1,545,541)	($2,165,246)	($4,234,868)	($19,745,009)
Revenue from Pt	$/year	$423,305	$4,233,053	$8,466,105	$21,165,264	$42,330,527	$211,652,636
Revenue from BPP Base Material and Coating	$/year	$51,256	$512,561	$1,025,122	$2,562,806	$5,125,611	$25,628,057
Total Annual Recovered Value	**$/year**	($1,042,545)	$1,051,811	$5,830,676	$18,191,716	$37,781,649	$196,561,654

Total Pt loading at 0.025mg/cm²		Fuel Cell Stack Recycling					
Annual System Recycling Rate	stacks/year	1,000	10,000	20,000	50,000	100,000	500,000
Annual Pt Recycled	kg/year	2	18	35	88	176	878
Cell Singulation & Separation Cost	$/year	($97,283)	($185,348)	($333,673)	($669,350)	($1,469,610)	($6,642,615)
Pt Recycle Cost	$/year	($533,080)	($737,479)	($876,846)	($1,560,146)	($2,198,064)	($4,547,673)
BPP Materials Recycle Cost	$/year	($801,230)	($2,386,491)	($1,545,541)	($2,165,246)	($4,234,868)	($19,745,009)
Revenue from Pt	$/year	$84,661	$846,611	$1,693,221	$4,233,053	$8,466,105	$42,330,527
Revenue from BPP Base Material and Coating	$/year	$51,256	$512,561	$1,025,122	$2,562,806	$5,125,611	$25,628,057
Total Annual Recovered Value	**$/year**	($1,295,676)	($1,950,146)	($37,717)	$2,401,116	$5,689,175	$37,023,287



- Above 1k stacks per year recycled, one can have net positive recovered value from recycling Pt at 0.125mgPt/cm²
- Recovered value of metals to be split between FCV owner, salvager, & recycler.
  - Split driven by market forces

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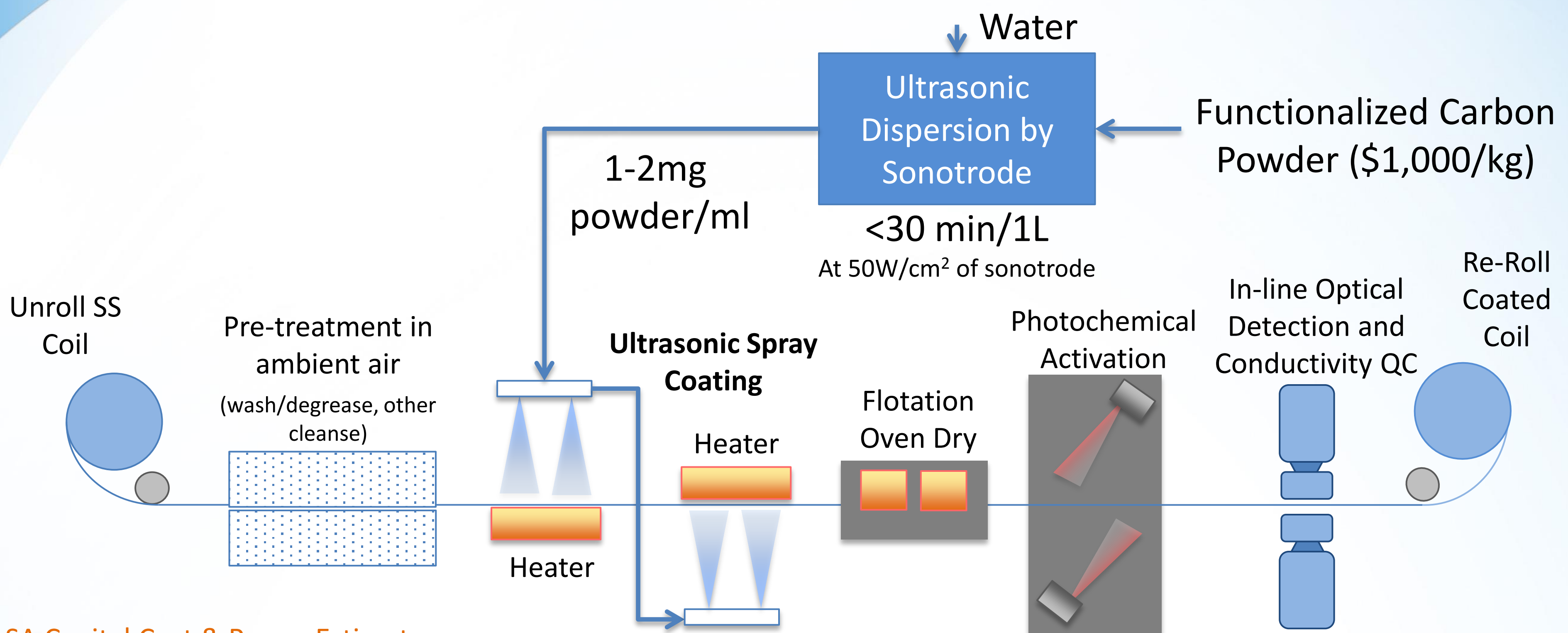
Accomplishments and Progress:
Precors BPP Coating: Deposition of Functionalized Carbon (High Volume)
Vacuum-free in-line process for pre-coating and post-coating



SA Capital Cost & Power Estimates

$29k, ~2kW | $240k, ~10kW | $820k, ~200kW | $800k, 40kW | $1.2M, 36kW | $400k, ~2kW | $26k, ~2kW

Total = $3.5M, 290kW

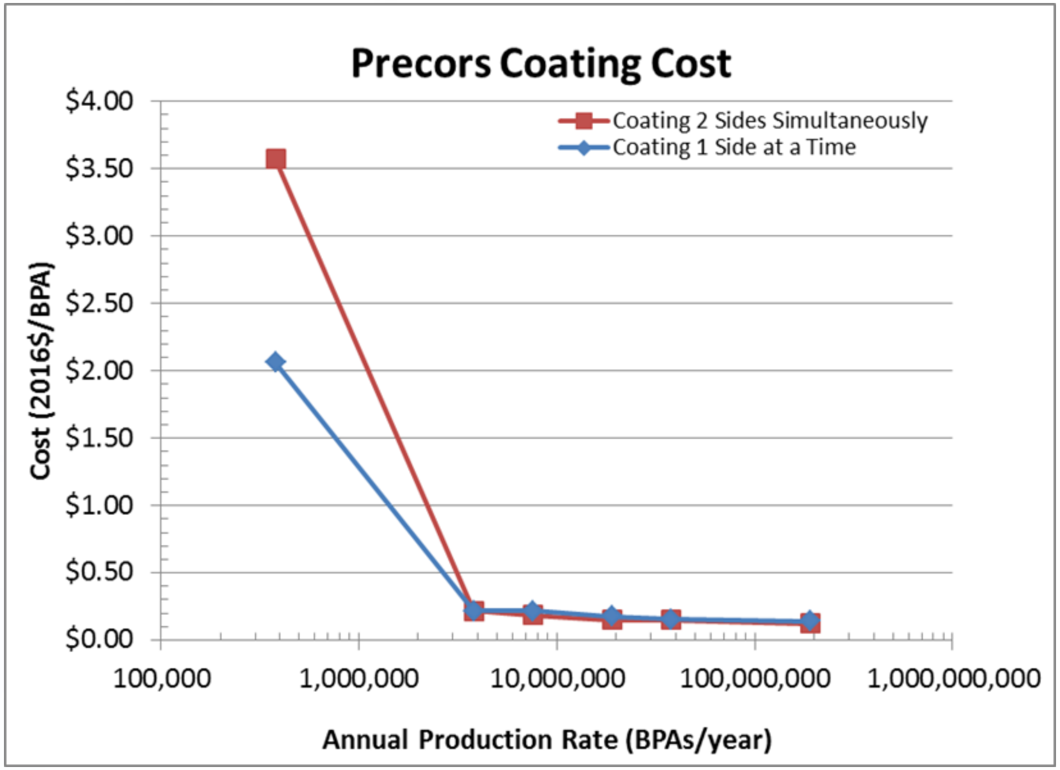
- Final coating
  - 10nm thick coating is ~0.02g carbon/m^2
- Projected high volume process coats both sides simultaneously.
  - one-sided coating demonstrated (currently building R2R two-sided coating line)

STRATEGIC ANALYSIS INC

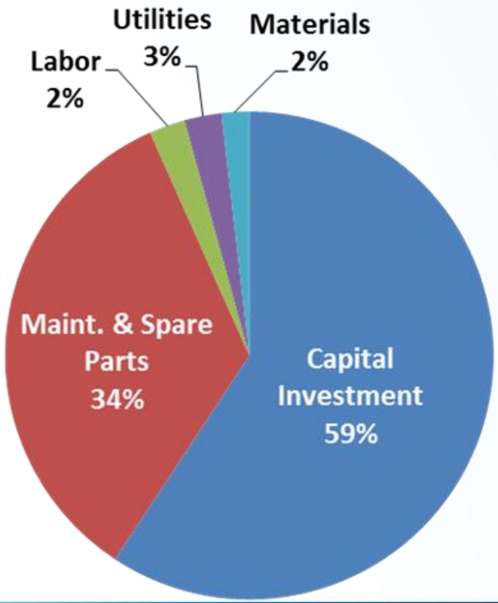
Accomplishments and Progress:
Project Low Cost for Precors BPP Coating at High Volume

$0.58/kW at high production volume (**assuming same performance** as baseline system)

- $0.12/bipolar plate assembly (BPA) (coated on both sides simultaneously)
- High cost at low production due to low utilization of equipment
- Above 4M BPAs/year, lower cost to use $3.5M machinery for 2-sided coating
- Majority of cost associated with capital investment (minor material cost)
- Maintenance & Spare Parts assume 15% of capital cost per year



Breakdown in Cost per BPA at 500k systems/year



Accomplishments and Progress:
Possible Cost Reduction with High Volume 2D Manufacturing Concept

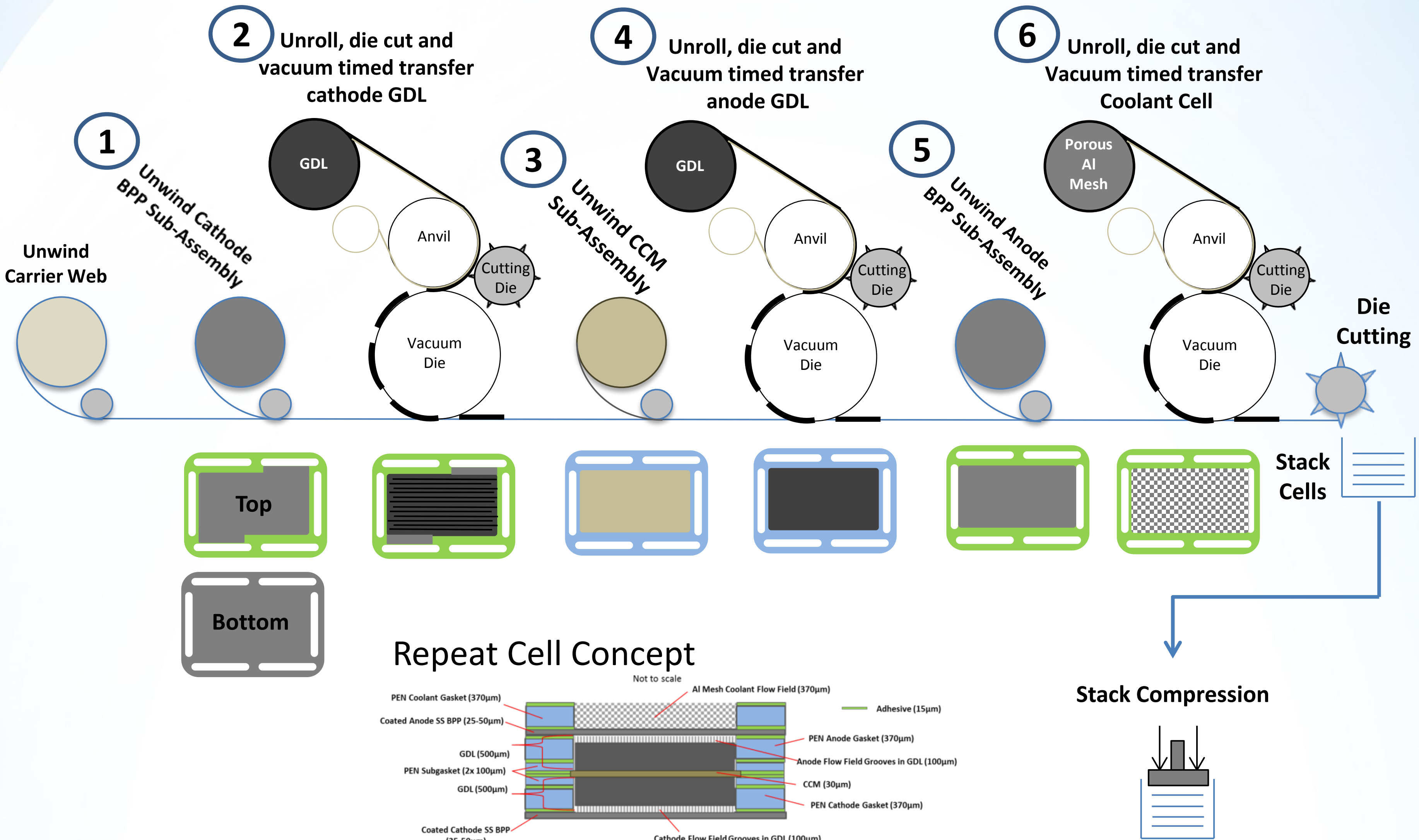
- Concept from Takuya Hasegawa of Nissan
  - Batteries and fuel cells assemblies can benefit from fast line speeds
  - Currently has lab in Oppama, Japan, making 4kW stacks
- Features of roll-to-roll operation for unit cell fab/assembly
  - Avoid 3D stacking of individual pieces and long cycle-time batch processes
  - Delay singulation as long as possible to minimize handling of parts
  - **Flow field formation on the MEA/GDL would be an enabling technology**
  - **Mechanical forming of flow fields can be avoided => Thinner separators (1-2mils rather than 3mils thick) reduce stack weight and modestly reduces cost**
- Many different conceptual ideas to explore
- SA chose one design pathway, vetted the design with NREL and industry, and conducted a DFMA® analysis of the R2R concept

<u>Other work and patents on similar process</u>

- American Fuel Cell 2018 SBIR: Over-Molded Plate for Reduced Cost and Mass PEM Fuel Cells
- 2007 Horizon Fuel Cell Patent Application: Lamination for R2R fab
- 2010 US Patent Application from Power Cell (US 2010/0108236 A1)

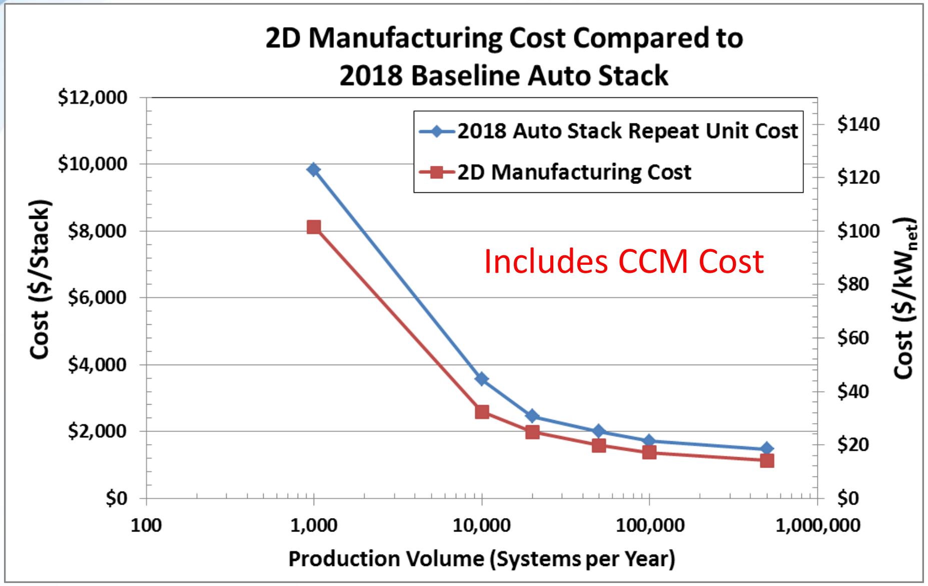
Accomplishments and Progress: SA's Roll-to-Roll Manufacturing Concept Final Cell and Stack Assembly

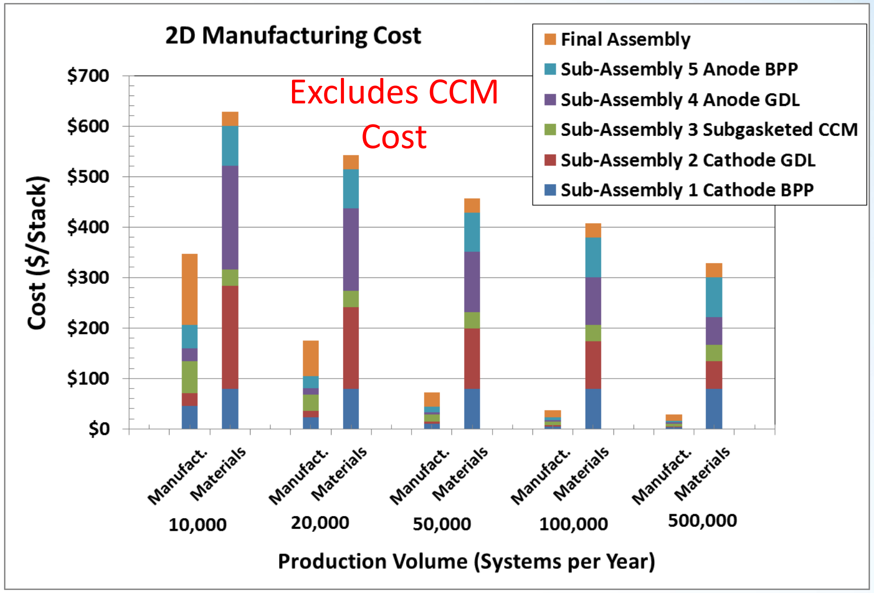
All 6 sub-assembly components are combined together in a R2R process to form a repeat cell. Repeat cells are stacked to form a FC stack.



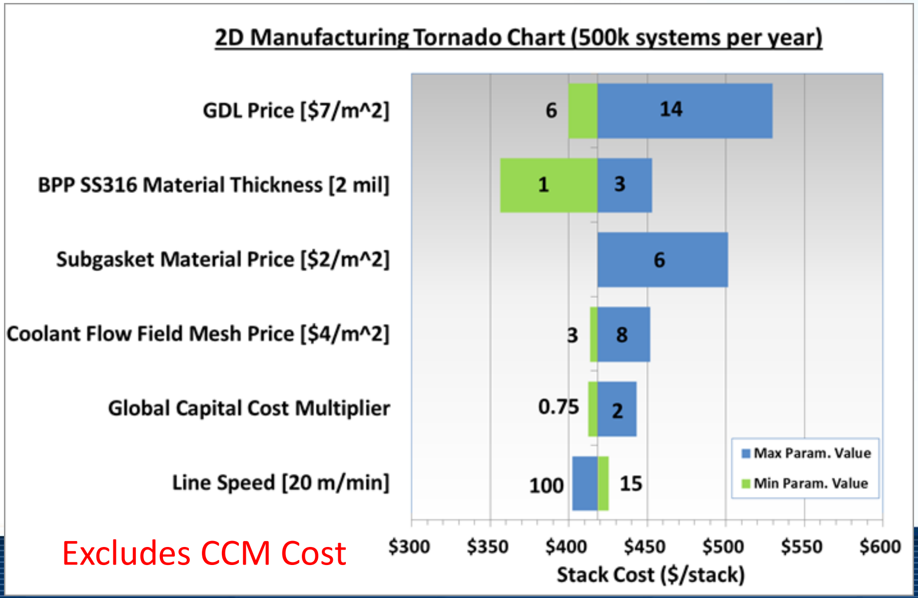
Accomplishments and Progress:

Cost Reduction Based on 2D Manufacturing Concept is Highly Dependent on Material Selection and Pricing





- **<u>2D Manufacturing can be ~$3.50/kW lower cost than 2018 baseline system</u>**
- Final Assembly has the largest manufacturing cost and it's driven by capital cost ($3.5M)
- Material assumptions have the greatest impact on final cost



Accomplishments and Progress:

Responses to Previous Year's Reviewers' Comments

2018 Reviewer's Comments	Response to Reviewer's Comment
"The model should also integrate system durability and take into account the impact of "degraded modes" on the performance and cost."	SA is working with ANL, LANL (both part of FCPAD) to identify sources of degradation. We are currently assessing the cost impact by altering stack materials or system operating techniques that can improve durability. See slides 11-12.
"The team should revisit seals and gasket costs because SA's current projections are too low. "	Feedback from multiple sources have similar concerns. SA evaluated the difference between PET and PEN material for MEA subgaskets for 2019. PET degrades under FC operating conditions while PEN does not. From one supplier, PEN is currently 4-5x the cost of PET. Further investigation of PEN cost and alternative low cost gasket materials is planned.
"Ways to further reduce system complexity, such as removing the humidifier or using only a compressor instead of a compressor/expander module, should be taken into consideration."	1. In collaboration with ANL, SA has looked into removing the air humidifier and shows minimal cost reduction within current system (see slide 13 of 2018 AMR presentation: FC017_Ahluwalia_2018_0) 2. Removing the expander for an LDV system is not ideal because of the significant increase in gross power. For lower pressure systems like the bus or MDV/HDV systems, the expander is removed.

Collaboration & Coordination

*Additional Collaborations Listed in Reviewer Slides

Partner/Collaborator/Vendor	Project Role
National Renewable Energy Laboratory (NREL) (sub on contract)	• Provided knowledge and expertise on QC systems for FC manufacturing lines. • Reviewed and provided feedback on SA's assumptions for MEA & R2R processing and techniques (2D Manufacturing for 2019). • Provided feedback on current 2019 and 2025 analysis systems and manufacturing processes. • Participates in researching the affect of durability on cost.
Argonne National Laboratory (ANL) (sub on contract)	• Supplied detailed modeling results for optimized fuel cell operating conditions (based on experimental cell data). • Provided SA with model results for system pressure, mass flows, CEM η, and membrane area requirements for optimized system. • Provided feedback and small modeling efforts on 2025 systems. • Provided modeling data on durability for various Pt loadings.
2018/2019 Collaborators	• Ballard supplied information on cutting-edge graphite bipolar plate design and manufacturing methods. • Mike Yandrasits (3M) and Matt Fronk (former GM, now consultant) provided detailed reviews of 2D Manufacturing analysis. • Vitali Weissbecker at Precors gave processing and capital cost information on carbon coating for metallic bipolar plates.
Vendors/Suppliers	See back-up material for list of ~30 other companies with which we have consulted.

Remaining Barriers and Challenges

- Gasket material cost: Low-cost PET material degrades under FC conditions. Polyethylene Naphthalate (PEN) is a recommended alternative, but may lead to ~$5/kW cost increase.
- PFSA ionomer cost uncertainty: Some in industry suggest ionomer may be ~$500/kg even at high volumes. May require alternative formulation or fabrication process.

Automotive System

- BPP material cost: Base material 316SS contributes ~$3/kW$_{net}$ making it difficult to reach DOE's 2025 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: Advancements projected for 2025 fuel cell system cost aligns with DOE's 2025 $40/kW target cost.
- $30/kW DOE target even harder to achieve: Projections for 2025 analysis suggest the DOE ultimate target of $30/kW may be difficult to achieve and will require much lower material costs (75% of stack cost).
- 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/HDV Study

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

Proposed Future Work

- Incorporate feedback from MDV/HDV questionnaire (system diagrams and preferred vocation)
- Continue to investigate ways to incorporate durability into cost modeling
- Investigate the value of recovering fluorine from waste ionomer
- Investigate synthesis cost of PFSA ionomers
- Synthesis cost analysis of PGM-Free catalyst
- Conduct sensitivity analyses for MDV and HDV systems
- Document in 2019 Final Report: Report due September 2019

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

Technology Transfer Activities

Not applicable for SA's Cost Analysis

Summary of Findings

- **MDV 170kW$_{net}$ System**
  - Interim results: ~\$89/kW$_{net}$ (current 2019) and ~\$72/kW$_{net}$ (2025) at 100k sys/year
- **HDV Line Haul 363kWnet System**
  - Interim results: ~\$86/kW$_{net}$ (current 2019) and ~\$69/kW$_{net}$ (2025) at 100k sys/year
- **Impact of Durability on Cost**
  - Material and System Solutions (qualitative and quantitative) incorporated into system cost models
  - Further FCPAD testing results will help quantify the impact of some solutions
- **Recycle and Disposal Cost Analysis**
  - Pt recycling is profitable for greater than 1,000 stacks recycled per year
  - Pt is more profitable than BPP base material and coating
- **Precors Bipolar Plate Coating**
  - Potentially lower cost functionalized carbon pre-coating for metallic bipolar plates
  - May be restricted to non-welded plates
- **2D Manufacturing**
  - Current SA design projected to reduce stack cost by ~\$3.50/kW
  - Most uncertainty in material selection and pricing

Project Summary

- **Overview**
  - Exploring subsystem alternative configurations and benchmark cost where possible
  - In year 3 of 5 year project
- **Relevance**
  - Cost analysis used to assess practicality of proposed power system, determine key cost drivers, and provide insight for direction of R&D priorities
  - Provides non-proprietary benchmark for discussions/comparison
- **Approach**
  - Process-based cost analysis methodologies (e.g. DFMA®)
  - Full transparency and open discussion of assumptions and results
- **Accomplishments**
  - 2018 Automobile analysis documented (report available)
  - MDV and HDV 2019 & 2025 fuel cell systems analysis results (LDV updated every other year)
  - Side Analyses:
    - Impact of Durability on Cost
    - Recycle and Disposal of Fuel Cell System components
    - Precors Bipolar Plate Coating
    - 2D Manufacturing
- **Collaborations**
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
  - Extensive discussions, interviews, feedback with 30+ industry vendors/suppliers
- **Future Work**
  - Continue to incorporate durability into cost analysis, evaluate cost of ionomer synthesis, initiate PGM-free catalyst cost analysis, and draft 2019 final report.

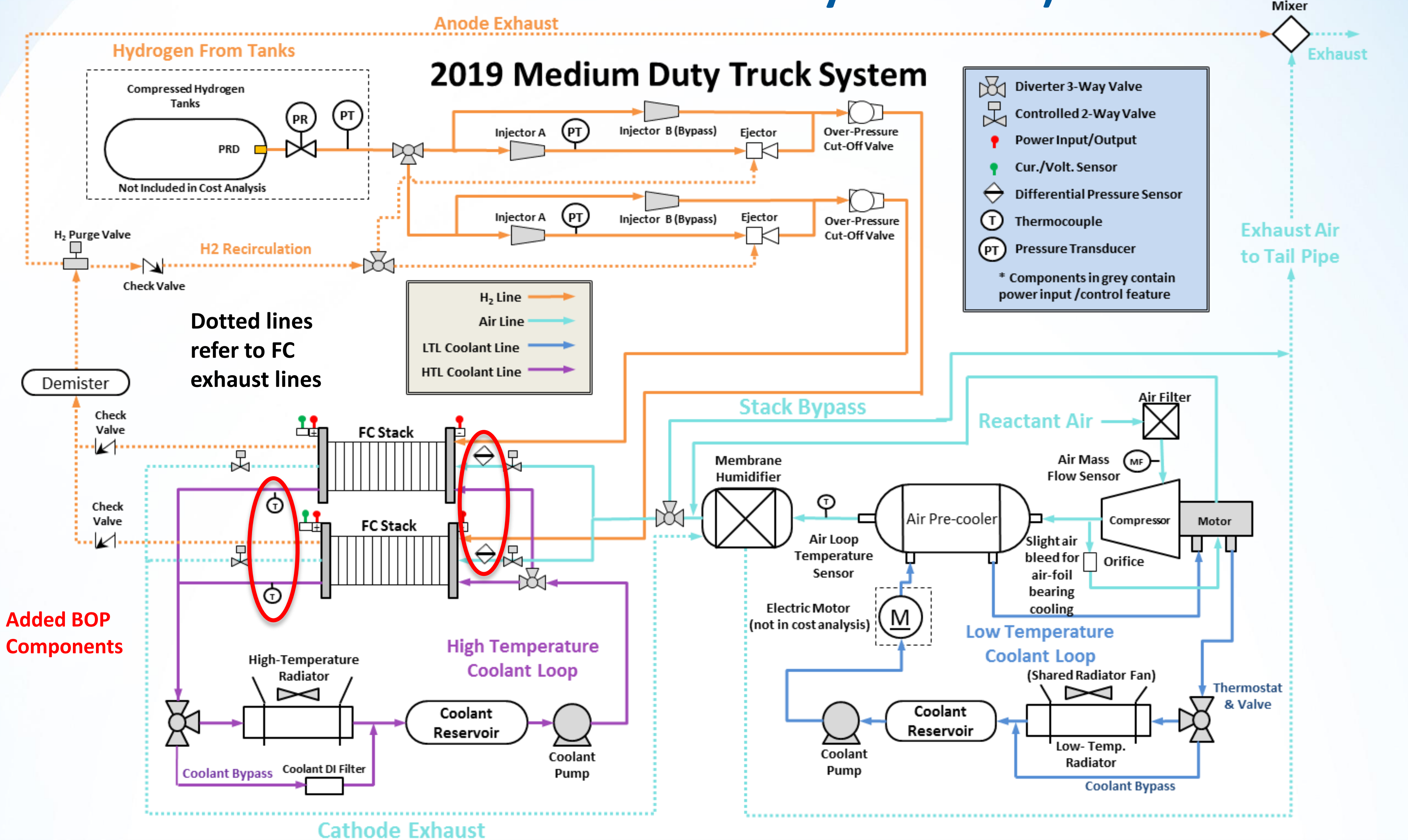
Thank you!

Questions?

Technical Back-up Slides

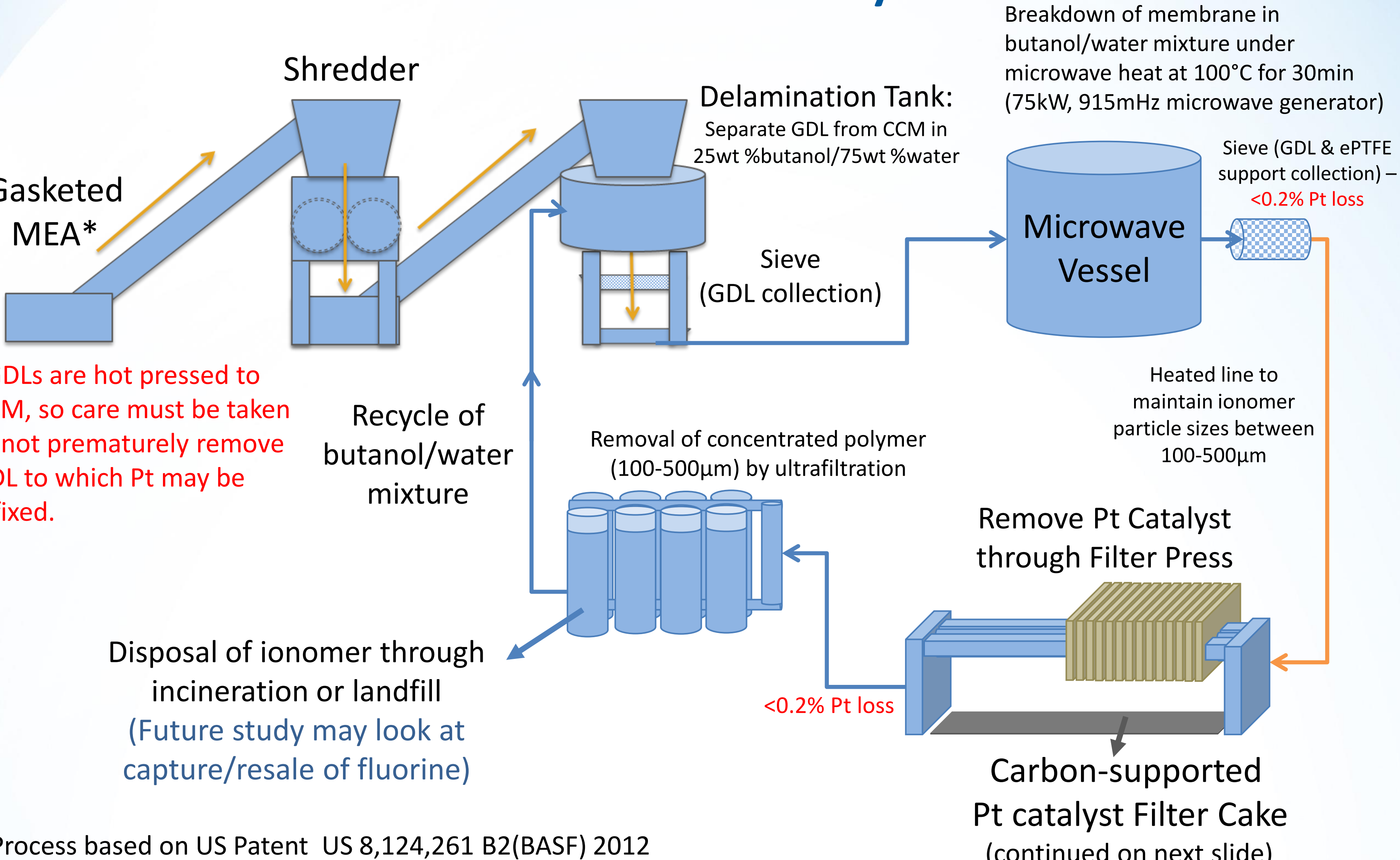
2019 MDV System

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



Accomplishments and Progress:

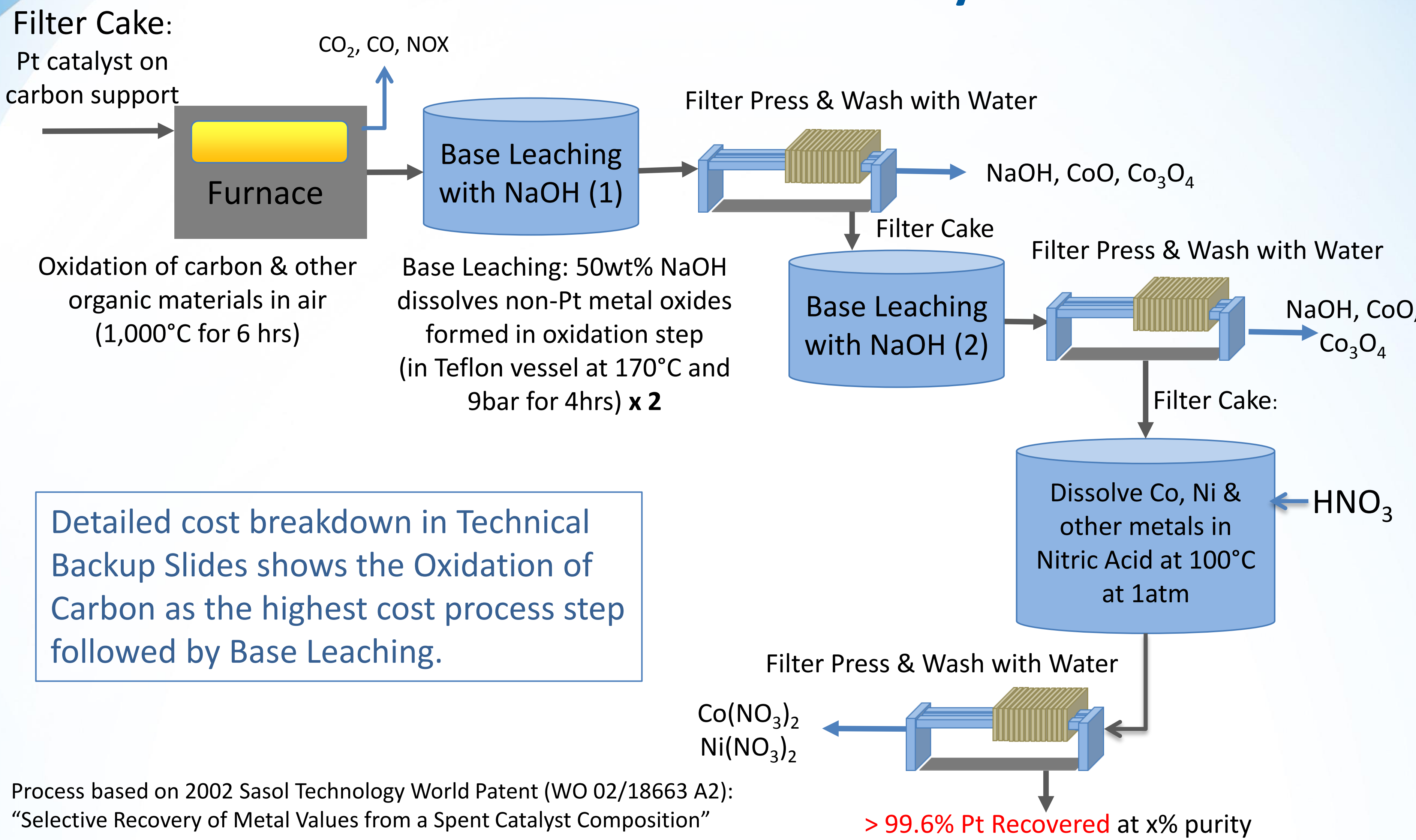
Detailed Process Flow Diagram of Pt & PFSA Recovery



*GDLs are hot pressed to CCM, so care must be taken to not prematurely remove GDL to which Pt may be affixed.

Process based on US Patent US 8,124,261 B2(BASF) 2012

Detailed Process Flow Diagram of Pt & PFSA Recovery



Detailed cost breakdown in Technical Backup Slides shows the Oxidation of Carbon as the highest cost process step followed by Base Leaching.

Process based on 2002 Sasol Technology World Patent (WO 02/18663 A2): "Selective Recovery of Metal Values from a Spent Catalyst Composition"

Accomplishments and Progress:

Pt Catalyst Recycling

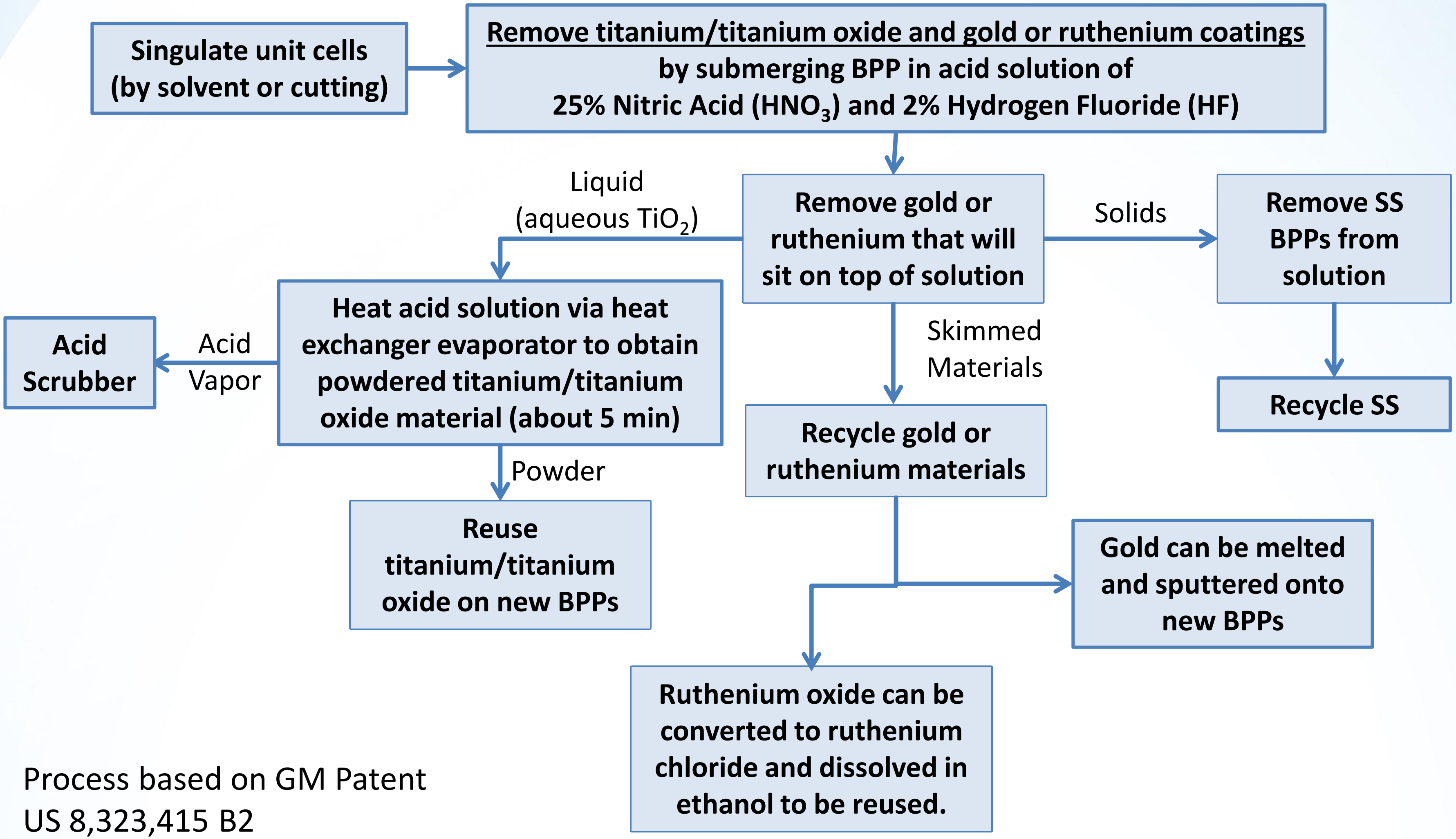
Preliminary Cost Results

PtCo/HSC Cathode Catalyst Recycling		Annual System Recycling Rate (stacks/year)					
Component Costs per gram of Pt recycled		1,000	10,000	20,000	50,000	100,000	500,000
Step 1: Shred and Delamination	**$/g**	($11.87)	($1.31)	($0.79)	($0.40)	($0.22)	($0.08)
Step 2: Microwave Dissolution	**$/g**	($18.70)	($1.99)	($1.08)	($0.88)	($0.45)	($0.11)
Step 3: Pt Catalyst Filtration	**$/g**	($3.95)	($0.40)	($0.21)	($0.09)	($0.06)	($0.03)
Step 4: Ultrafiltration	**$/g**	($4.69)	($0.56)	($0.35)	($0.33)	($0.26)	($0.16)
Step 5: Combustion of HSC	**$/g**	($4.62)	($1.40)	($1.40)	($0.90)	($0.84)	($0.68)
Step 6: Base Leaching with NaOH (1)	**$/g**	($2.60)	($1.19)	($1.10)	($0.65)	($0.55)	($0.48)
Step 7: Leaching Filter Press (1)	**$/g**	($3.30)	($0.63)	($0.50)	($0.30)	($0.25)	($0.20)
Step 8: Leaching Wash (1)	**$/g**	($2.14)	($0.52)	($0.52)	($0.24)	($0.15)	($0.12)
Step 9: Base Leaching with NaOH (2)	**$/g**	($2.60)	($1.19)	($1.10)	($0.65)	($0.55)	($0.48)
Step 10: Leaching Filter Press (2)	**$/g**	($3.30)	($0.63)	($0.50)	($0.30)	($0.25)	($0.20)
Step 11: Leaching Wash (2)	**$/g**	($2.14)	($0.52)	($0.52)	($0.24)	($0.15)	($0.12)
Step 12: Dissolution in Nitric Acid	**$/g**	($1.56)	($0.50)	($0.42)	($0.30)	($0.24)	($0.21)
Step 13: Nitric Acid Filter Press	**$/g**	($3.08)	($0.47)	($0.34)	($0.17)	($0.11)	($0.08)
Step 14: Nitric Acid Wash	**$/g**	($1.95)	($0.42)	($0.35)	($0.20)	($0.12)	($0.09)
Step 15: Dry	**$/g**	($3.97)	($1.04)	($1.00)	($0.52)	($0.34)	($0.25)
Total Catalyst Recycling Cost	**$/g**	($70.47)	($12.78)	($10.15)	($6.16)	($4.52)	($3.27)
Total Catalyst Recycling Cost	**$/year**	($618,593)	($1,121,964)	($1,781,337)	($2,701,757)	($3,970,012)	($14,331,416)
Pt Price	$/g	$48.23	$48.23	$48.23	$48.23	$48.23	$48.23
Total Annual Revenue of Recycled Pt	$/year	$423,305	$4,233,053	$8,466,105	$21,165,264	$42,330,527	$211,652,636
Recovered Value per gram of Pt	$/g	($22.25)	$35.44	$38.08	$42.07	$43.70	$44.96
Total Annual Recovered Value	$/year	($195,288)	$3,111,089	$6,684,768	$18,463,507	$38,360,515	$197,321,220

Values shown in nominal year dollars

- Cost includes ionomer disposal in landfill
- Profit based on Pt resale price of $1,500/tr.oz at all recycling volume rates and 0.125mgPt/cm^2 loading (9.3g/system)
  - Current Pt price is ~$800/tr.oz.

Detailed Process Flow Diagram of Removal of Corrosion-Resistant and Conductive Coatings on Bipolar Plates



Process based on GM Patent US 8,323,415 B2

Bipolar Plate Recycling
Preliminary Cost Results

Bipolar Plate Base Material and Coating Recycling		Annual System Recycling Rate (stacks/year)					
		1,000	10,000	20,000	50,000	100,000	500,000
Step 1: BPP Coat Removal	**$/system**	($205.79)	($117.64)	($43.26)	($36.62)	($36.62)	($36.68)
Step 2: Acid Solution Evaporation	**$/system**	($595.45)	($121.01)	($34.02)	($6.68)	($5.73)	($2.81)
Total Bipolar Plate Recycle Cost	**$/system**	($801.23)	($238.65)	($77.28)	($43.30)	($42.35)	($39.49)
Total Bipolar Plate Recycle Cost	**$/year**	($801,230)	($2,386,491)	($1,545,541)	($2,165,246)	($4,234,868)	($19,745,009)
Total Annual Revenue of Recycled SS	*$/year*	$20,937	$209,371	$418,743	$1,046,857	$2,093,714	$10,468,572
Total Annual Revenue of Recycled Gold	*$/year*	$20,238	$202,377	$404,753	$1,011,883	$2,023,766	$10,118,828
Total Annual Revenue of Recycled Ruthenium	*$/year*	$10,073	$100,734	$201,467	$503,668	$1,007,336	$5,036,682
Total Annual Revenue of Recycled Ti	*$/year*	$8	$79	$159	$397	$795	$3,975
Total combined revenue of recycled materilas	*$/year*	$51,256	$512,561	$1,025,122	$2,562,806	$5,125,611	$25,628,057
Total Annual Recovered Value	**$/year**	($749,974)	($1,873,930)	($520,419)	$397,559	$890,743	$5,883,048

Values shown in nominal year dollars

- Stainless Steel, although having a low recycle price, makes up the majority of BPP revenue due to the sheer mass of material recycled.
- Although gold coating is quite small amount, makes up almost the same amount of revenue as SS.
- Titanium purchase price is extremely high for 99.9% purity PVD target

Material	Purchased Price ($/kg)	Recycled Price ($/kg)
316 SS	$13.19	$1.43
Gold	$42,439 ($1,320/tr.oz)	$20,000 ($622/tr.oz)
Ruthenium	$1,620 ($50/tr.oz)	$1,350 ($42/tr.oz)
Titanium	$230	$17.64