NASDAQ: BLDP | TSX: BLD

An Industrial Perspective on Fuel Cell Electrocatalysts

July 27th, 2016

BALLARD POWER SYSTEMS

PUTTING FUEL CELLS TO WORK

The Power of Fuel Cells, Simply Delivered

BALLARD®

WWW.BALLARD.COM

Dustin Banham, Siyu Ye, Shanna Knights

Outline

1. **Introduction: Ballard's current markets and primary focus in the electrocatalyst space**

2. **Current status of most promising ORR electrocatalysts**

3. **Importance of catalyst layer strategies in meeting performance/durability targets**
   - Cathode example
   - Anode example

4. **Importance of Industry/Academia collaboration**

5. **Future outlook/opportunities**

Where is Ballard's Primary Expertise in Electrocatalysis?

MARKETS


Portable


Material Handling


Backup Power


Heavy Duty Motive

PRODUCTS

Portable Systems


Protonex
a Ballard® company

Squad Power Manager (SPM)

Fuel Cell Stacks


Air-cooled FCgen®-1020ACS
Liquid cooled FCvelocity®-9SSL

Stationary Systems


Hydrogen
FCgen®-H2PM Systems

Motive Modules


HD Power Module
(up to 200kW)

A broad product portfolio gives Ballard a unique understanding of electrocatalyst requirements for many applications

Where is Ballard's Primary Expertise in Electrocatalysis?

BALLARD®

DAIMLER

HONDA

NISSAN

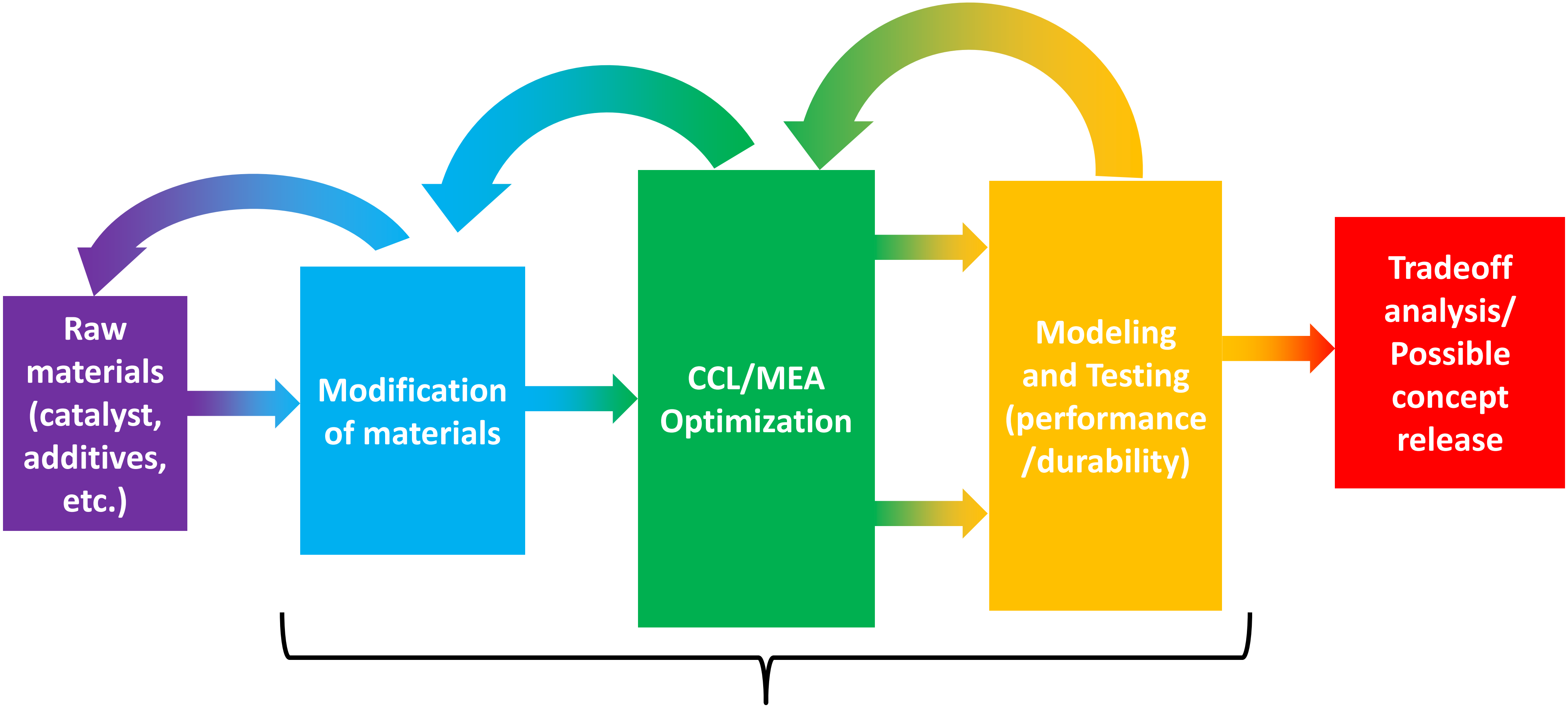
MITSUBISHI MOTORS

AUTOMOTIVE FUEL CELL COOPERATION®

Unnamed Global Auto OEMs

A deep understanding of requirements for electrocatalysis for automotive applications has been acquired through many previous and on-going TS contracts with major OEMs.

Approach to Support Programs and Technology Solutions



Raw materials (catalyst, additives, etc.)

Modification of materials

CCL/MEA Optimization

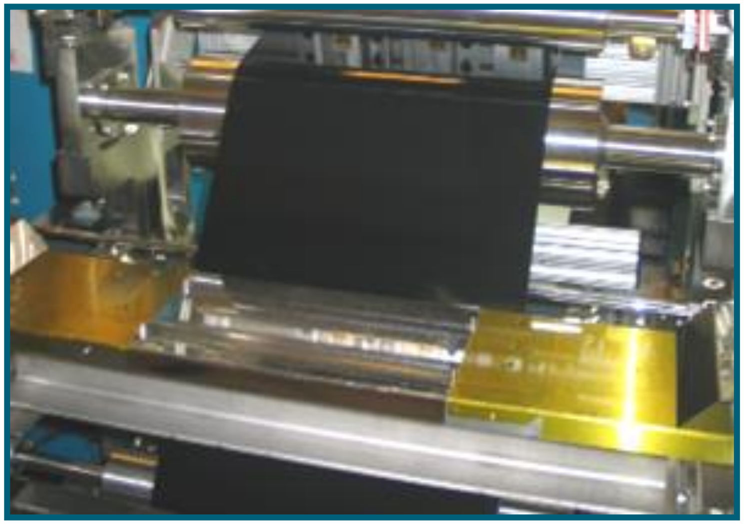
Modeling and Testing (performance /durability)

Tradeoff analysis/ Possible concept release

- Ballard’s largest effort in the electrocatalysis space is on integrating catalysts into high performance/durable CCLs.

Approach to Support Programs and Technology Solutions

Raw materials (catalyst, additives, etc.)



High Volume Catalyst Coating Process

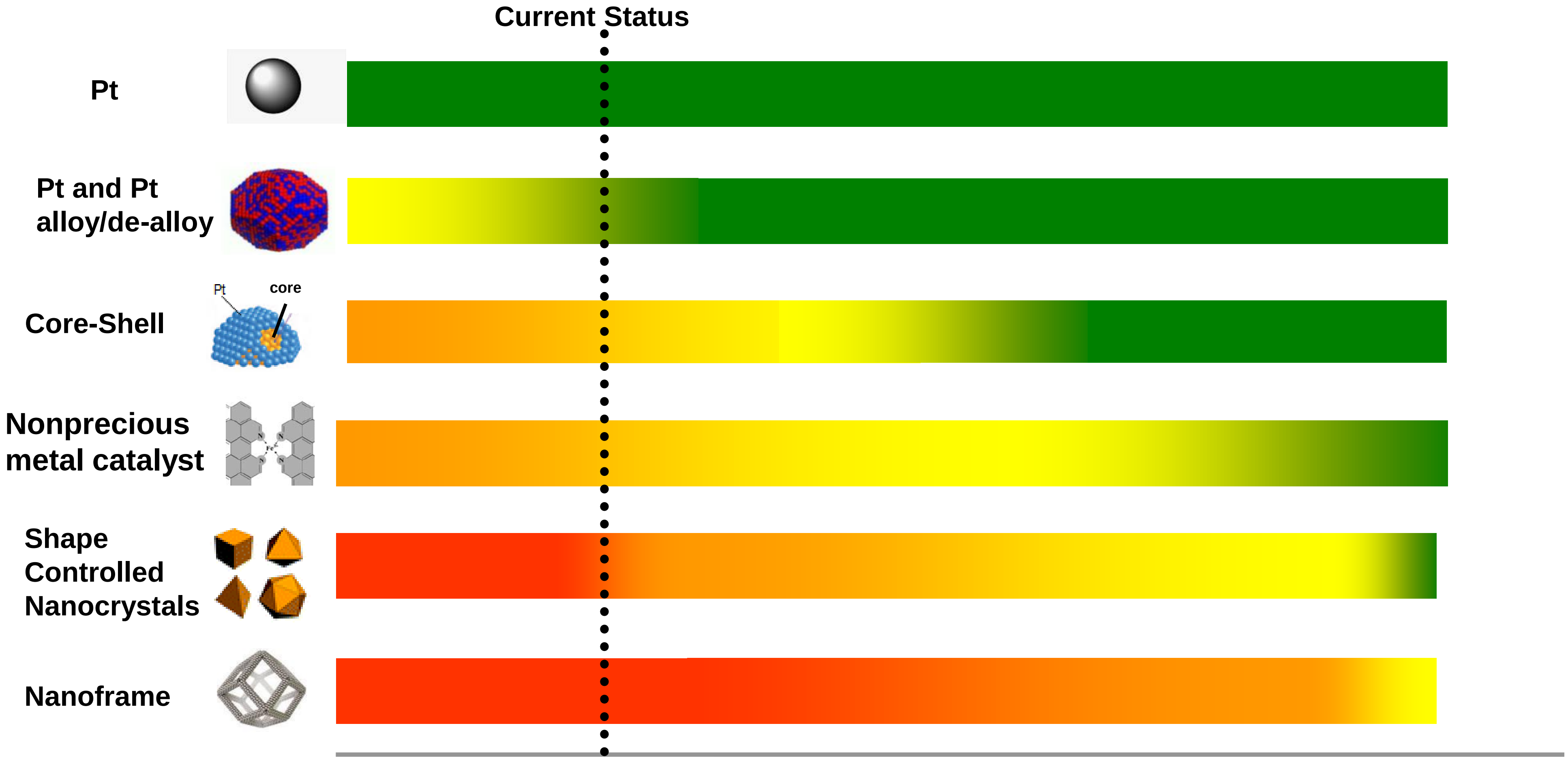
Modeling and Testing (performance /durability)

Tradeoff analysis/ Possible concept release

- Ballard's l on integrating catalysts into high performan

Real-world test protocols
(Ballard Test Facility – up to 333 kW test stations)

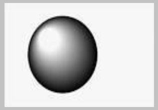
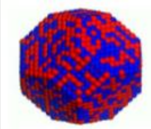
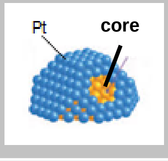
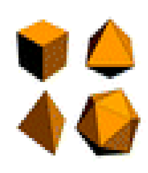
Current Status – Advanced Catalyst Technology Development Timeline



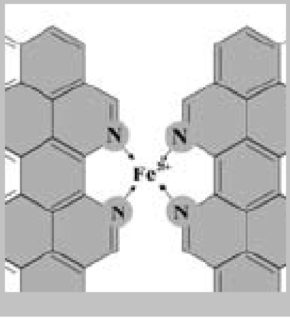
🟥 R&D Phase (RDE)
🟧 Scale-up (small scale MEA testing)
🟨 Validation phase (short stack testing)
🟩 Production phase/use in product

- Timeline is product dependent.
- Catalyst ‘maturity’ depends on targeted application (e.g. NPMC may be nearly ready for backup power, but still far from meeting automotive targets).

Current Status – Tradeoffs Among Leading ORR Electrocatalysts

Catalyst Type	Benefit	Remaining Challenges
Pt 	1) Mature technology	1) Unable to meet long term automotive Pt loading and catalyst layer durability targets
Pt alloy/de-alloy 	1) Mature technology 2) Improved performance over Pt/C 3) Enhanced membrane/MEA durability	1) Difficult to meet long term automotive Pt loading target
Core-shell  	1) Improved mass activity over Pt alloy 2) Improved durability over Pt/C 3) Very high ECSA	1) Difficult to maintain quality of 'shell' 2) Dissolution of 'core' still a concern
Shape controlled nanocrystal 	1) Significantly higher mass activity (~ 15 x) over Pt 2) Chemical synthesis (vs. electrochemical) may allow for easier scale up vs. core-shell	1) Scale up is at an early stage 2) Conflicting data on stability 3) MEA performance has not been demonstrated yet
Nanoframe/nanocage 	1) Significantly higher mass activity (~ 15 x) over Pt 2) Highly stable (improved durability over Pt/C)	1) Scale up is at an early stage 2) Ionomer penetration into nanocage will likely be difficult 3) MEA performance at high current density may be challenging

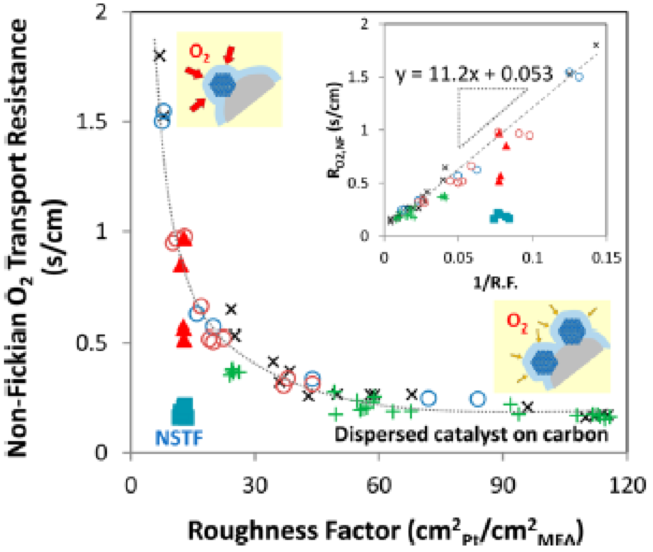
Current Status – Tradeoffs Among Leading ORR Electrocatalysts

Catalyst Type	Benefit	Remaining Challenges
Non-precious metal catalyst  	1) Potentially offer the largest benefit (significant cost reduction)	1) Still far from meeting performance, durability, and stability requirements for automotive applications. 2) Stability still a concern for even the least demanding applications.

PGM Catalysts – What Challenges Remain?

	PGM Mass Activity (A/mg)	Durability
Huang et al., Science, 348 (2015) 1230-1234	6.98	5.5 % loss*
Chen et al., Science, 343 (2014) 1339-1343	5.7	0 %*
Choi et al, ACS Nano, 8 (2014) 10363-10371.	1.6	1.7%*

* See references for details on voltage cycling



Largest remaining challenges

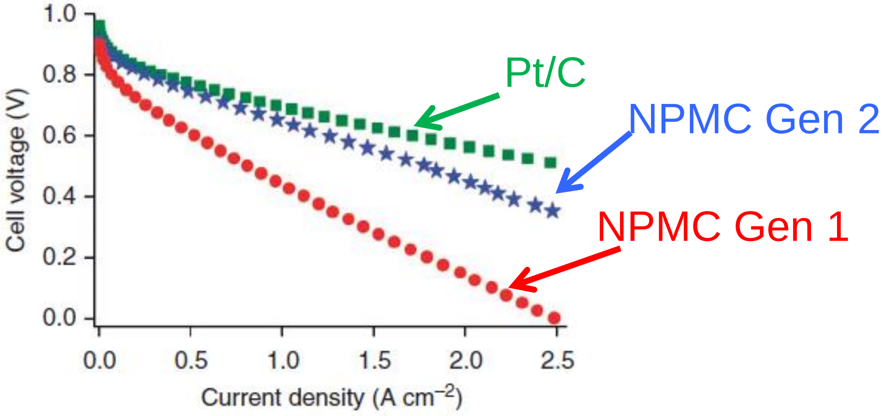
- At the RDE level, mass activity and durability targets have already been greatly exceeded.
- Additionally, these catalysts would appear to have sufficient ECSA (all > 60 m^2/g) to avoid the ‘oxygen transport’ problems observed at low PGM loadings.

Scale-up, and incorporation into high performance/durable CCLs must now be top priority.

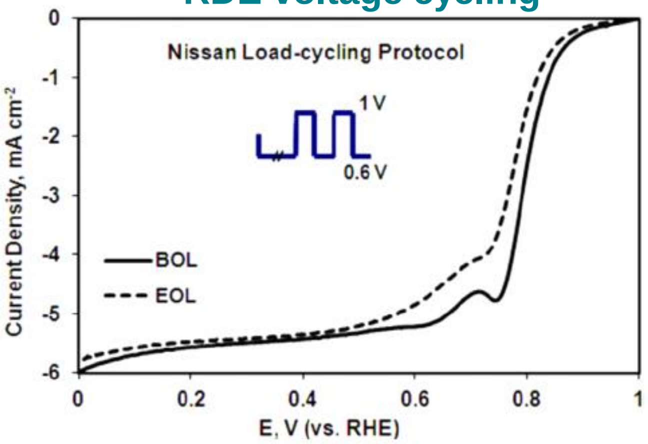
A. Kongkanand, M. Mathias, J Phys Chem Lett, 7 (2016) 1127-1137

Non PGM Catalysts – What Challenges Remain?

O_2 polarization curves[1]



RDE voltage cycling[2]

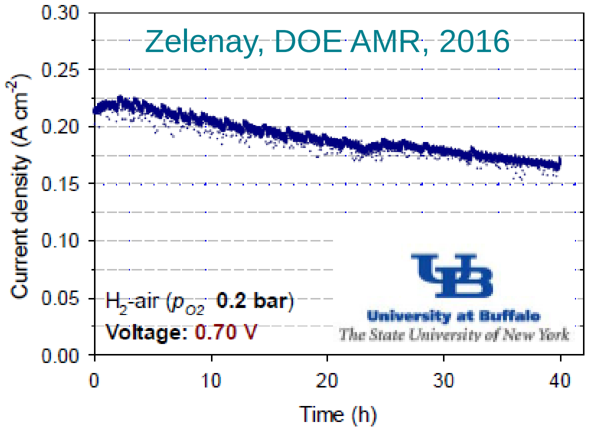


- Due to great advances in activity, the performance of NPMCs has reached a stage at which they can be considered for some (non-automotive) applications.
- Additionally, these catalysts have shown impressive durability during voltage cycling.

D. Banham, et al., J. Power Sources, 285 (2015) 334-348.

Stability – Performance loss during galvanostatic/potentiostatic experiments

Durability – Performance loss during voltage cycling experiments



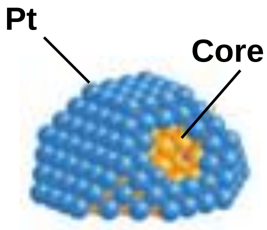
The **stability** of NPMCs is presently too low for any commercial PEMFC applications.

[1] Proietti et al., Nature Communications, 2 (2011).

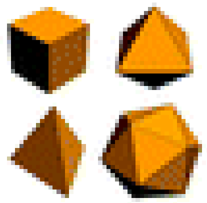
[2] Serov et al., Nano Energy, 16 (2015) 293-300.

Strategies to Achieving Performance and Durability Targets at the MEA Level

Question: Is it possible to achieve performance and durability targets with a ‘catalyst only’ approach?



Core-Shell[1]



Shape Controlled Nanocrystals[2]

Nanoframe[3]

Answer: Despite remarkable advances in electrocatalysts, remaining technical targets will only be achieved by:

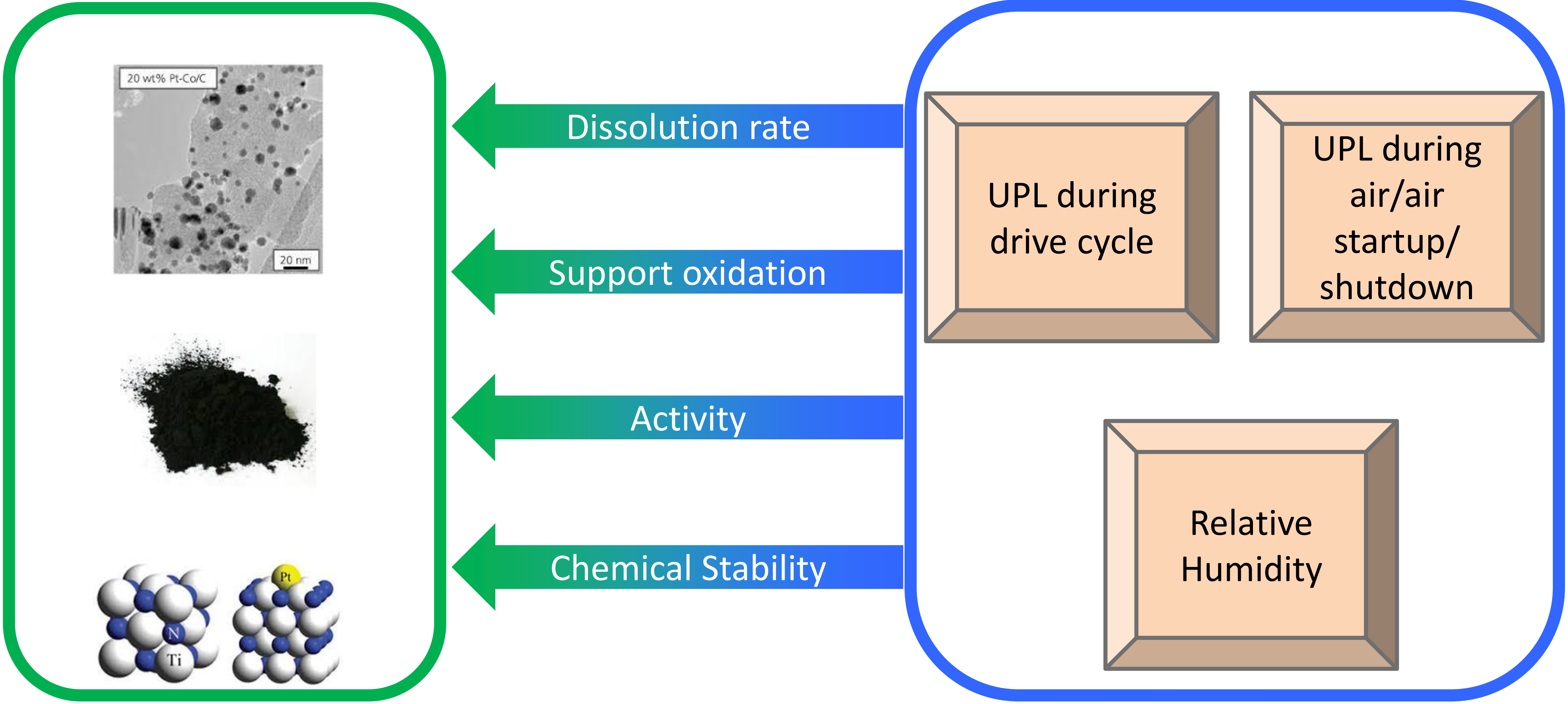
1) **Optimization of stack/system with consideration to interdependency between materials and operating conditions/modes.**
2) **Advanced catalyst layer design strategies to close remaining gaps at the materials level.**

[1] Adzic et al. Angew Chem Int Ed Engl, 49 (2010) 8602-8607.

[2] Y. Xia et al., Nano Letters, 13 (2013) 3420-3425.

[3] V.R. Stamenkovic et al., Science, 343 (2014) 1339-1343.

Interdependency of Materials/Operating Modes



Materials

Conditions/Operating Modes

Dissolution rate

Support oxidation

Activity

Chemical Stability

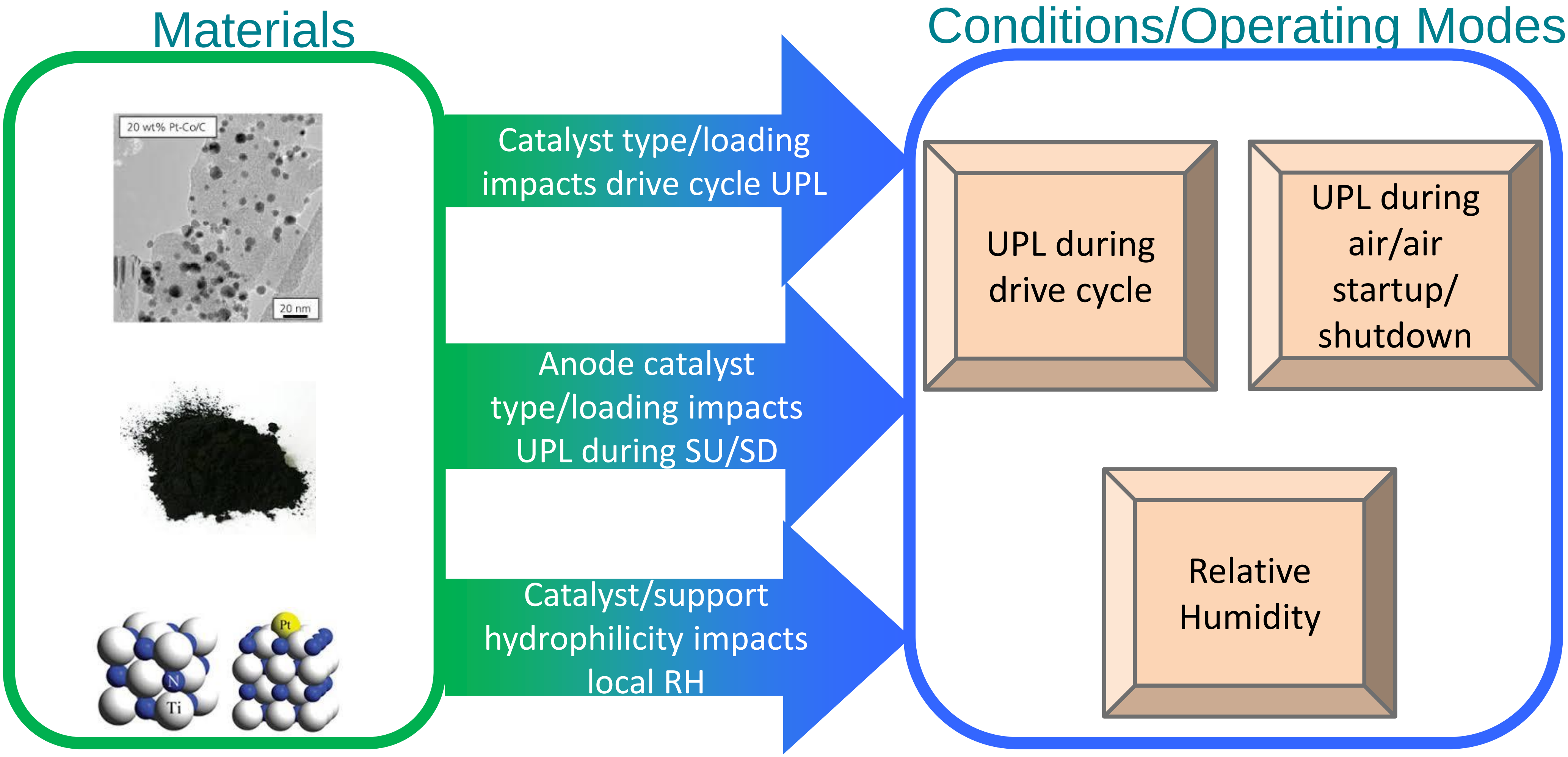
UPL during drive cycle

UPL during air/air startup/ shutdown

Relative Humidity

- We typically think about how PEMFC conditions will impact materials.

Interdependency of Materials/Operating Modes



Materials

Conditions/Operating Modes

Catalyst type/loading impacts drive cycle UPL

Anode catalyst type/loading impacts UPL during SU/SD

Catalyst/support hydrophilicity impacts local RH

UPL during drive cycle

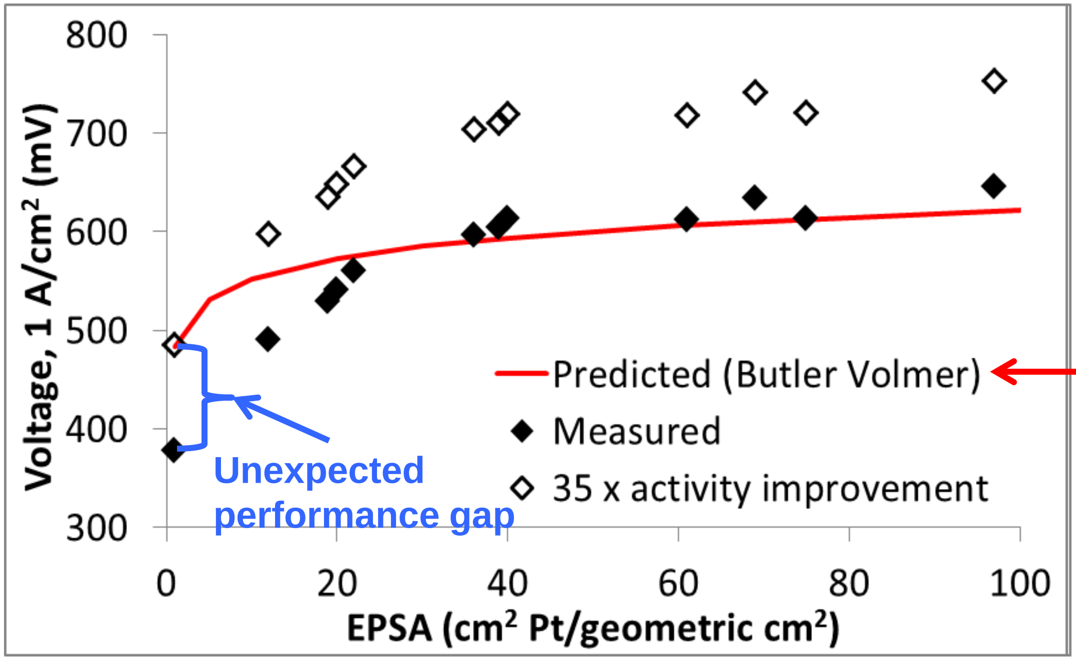
UPL during air/air startup/ shutdown

Relative Humidity

- We typically think about how PEMFC conditions will impact materials.
- However, we must also consider how materials can impact PEMFC conditions/operating modes.

Importance of Catalyst Layer Strategies: Low PGM Loadings

At low PGM loadings, a large gap exists (moderate to high current densities)



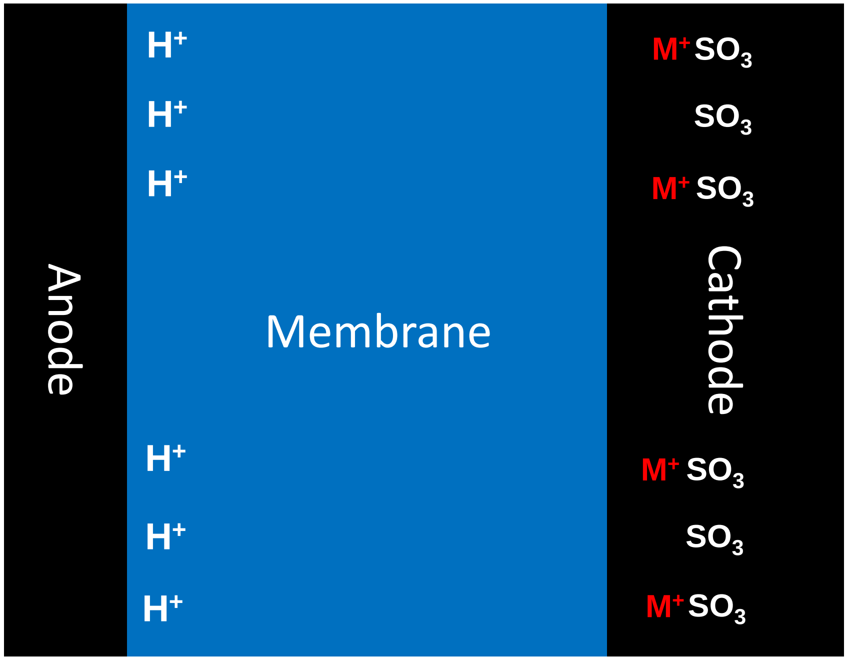
$$\Delta\eta = \frac{RT}{\alpha F}\ln\left(\frac{A_1 i_o}{A_2 i_o}\right)$$

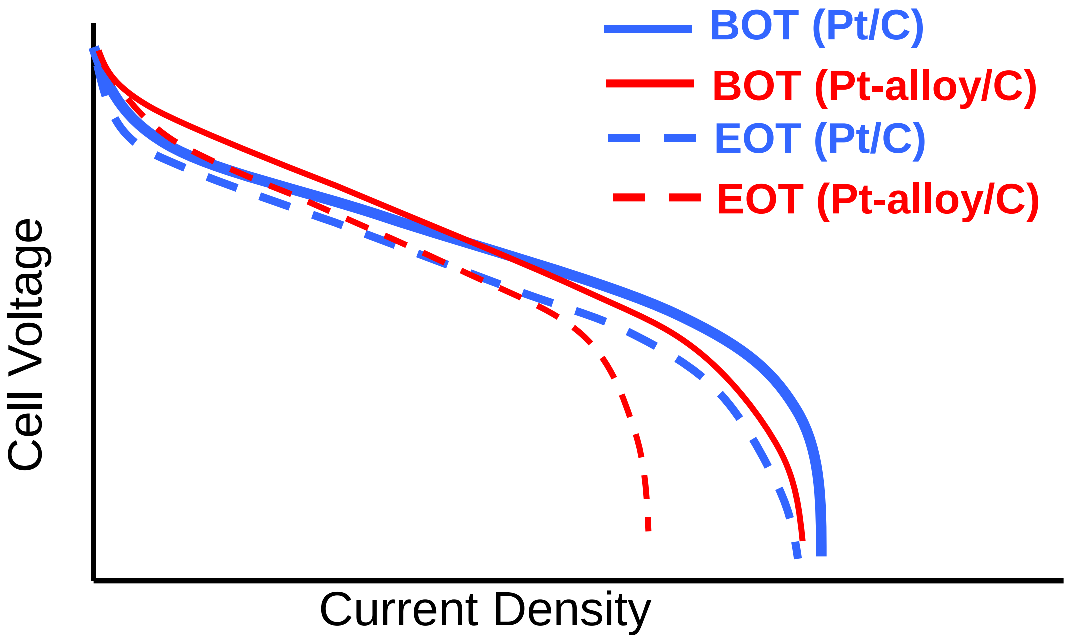
- Recent catalysts have shown up to 30x higher mass activity vs. Pt/C.
- Is this enough to overcome the performance gap at high current densities?

Answer: A ‘Catalyst only’ approach is unlikely to be successful

- (35x higher mass activity would be required even at **moderate** current densities).
- GM demonstrated that core-shell catalysts (large ECSA) can overcome this problem, but these catalysts suffer from some degree of base-metal dissolution.

Real-world Requirements for PEMFC Electrocatalysts: Cathode

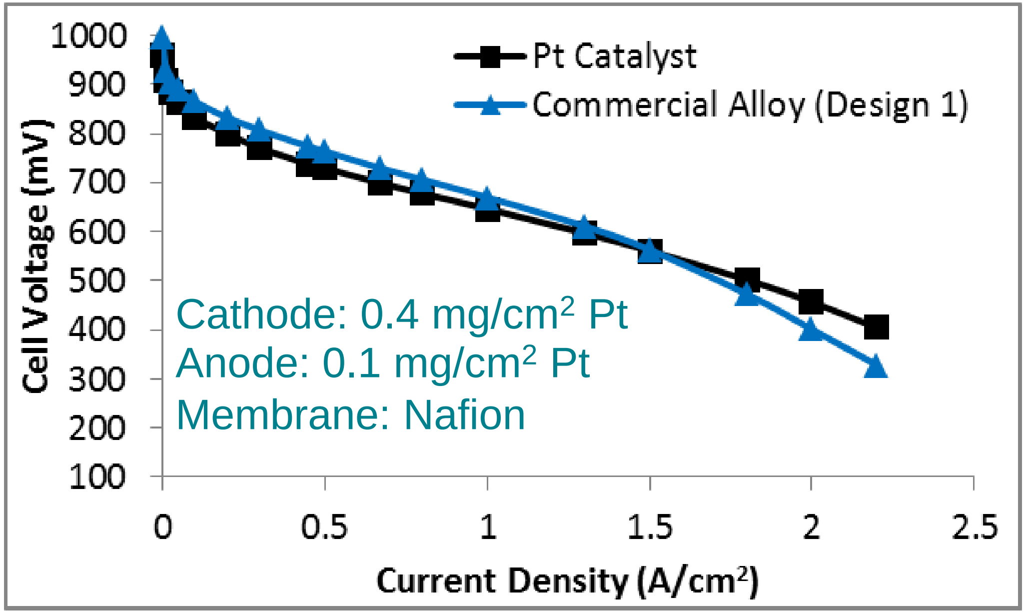




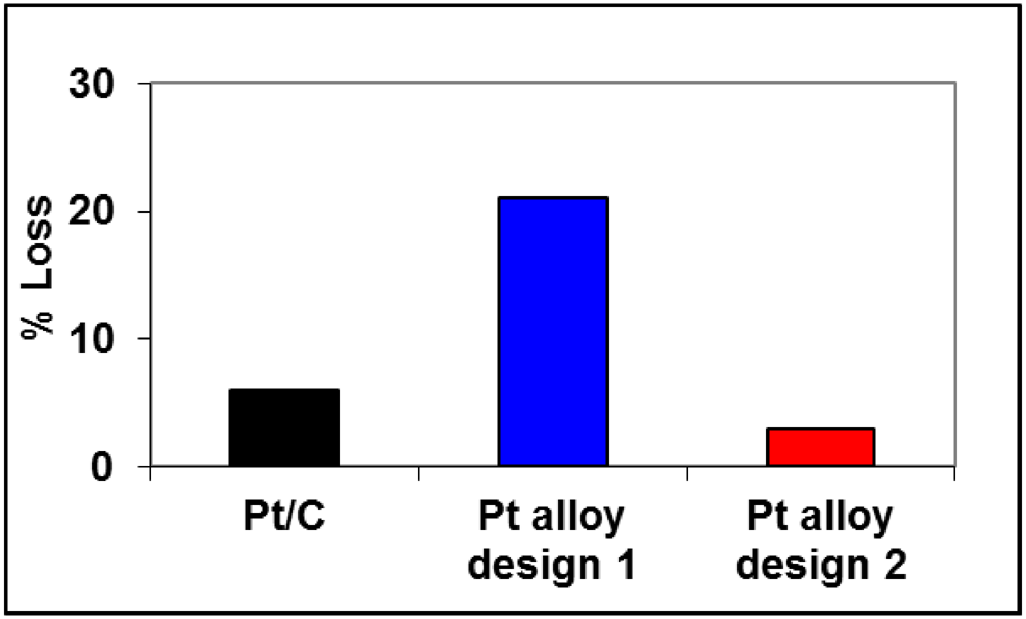
- PGM-alloy catalysts typically show improved performance (kinetic benefit) vs. Pt/C at BOL, but often show higher ohmic/mass transport losses.
- During voltage cycling, a Pt/C will lose performance due to traditional degradation mechanism (i.e. dissolution, agglomeration, Ostwald ripening).
- However, ionomer contamination due to PGM-alloy dissolution (M^+) results in significant additional performance loss at high current densities.

Can this challenge be overcome at the CCL level?

Catalyst Layer Design Strategies for Overcoming Performance/Durability Gaps: Cathode



100% RH, 5 psig, 75°C

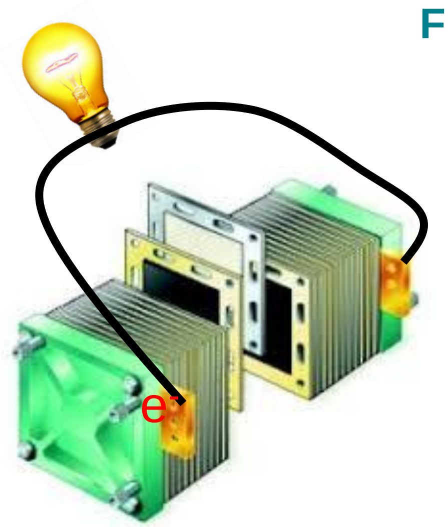


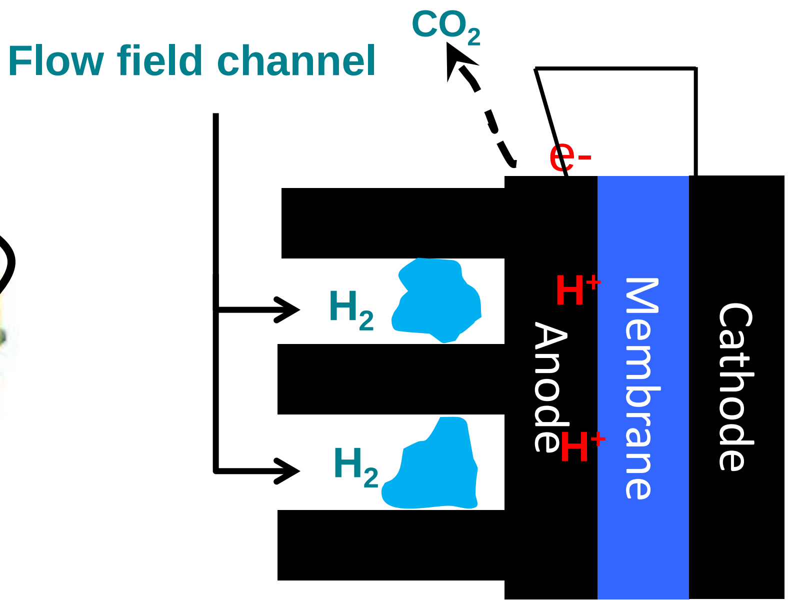
0.6-1.2 V, 2100 Cycles

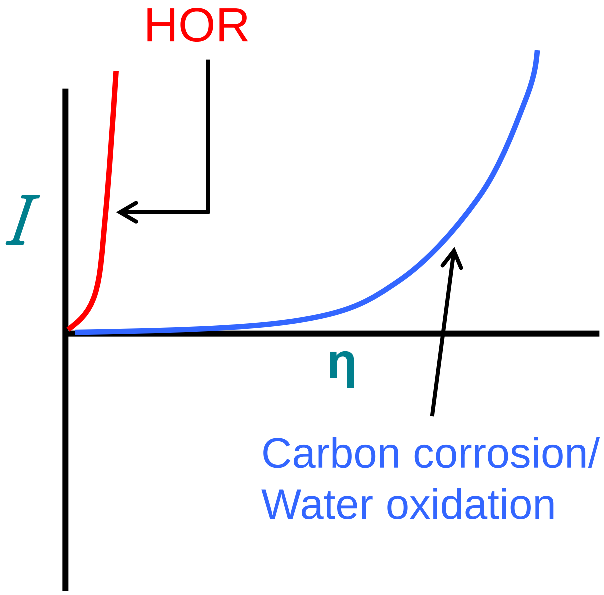
- Due to their high mass activities, Pt-alloy catalysts typically show high performance at low current densities.
- However, these catalysts suffer from performance at high current densities due to even trace base-metal dissolution.
- This loss is even more significant following voltage cycling which promotes dissolution.

Fortunately, appropriate CCL designs can help close remaining gaps in performance/durability.

Real-World Requirements for PEMFC Electrocatalysts: Anode





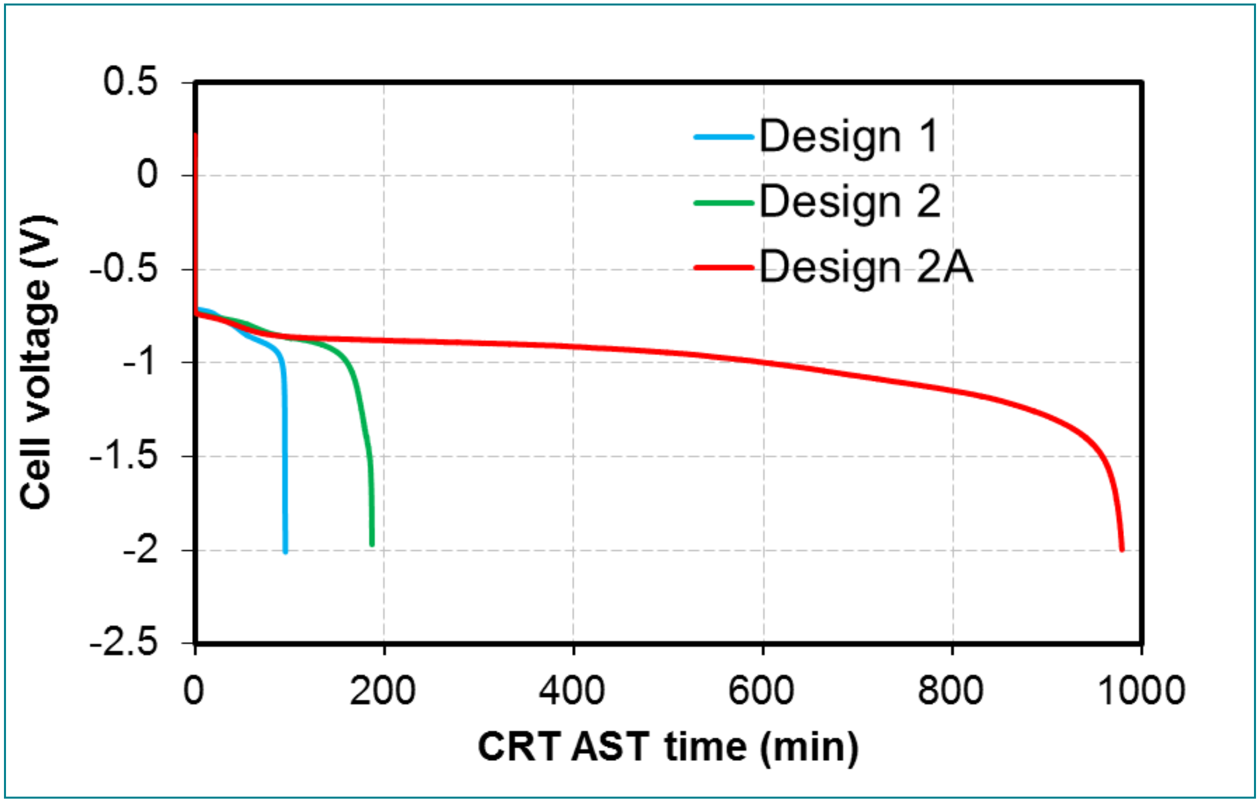


- During normal operation in a stack, hydrogen passes through the flow fields and is oxidized at the anode.
- If a flow field becomes blocked, current is still forced through the malfunctioning cell by the rest of the stack.
- Materials within the anode (carbon, catalyst, water) are then oxidized to supply the necessary electrons.
- This leads the anode potential to reach high anodic values (> 1.5 V), and can rapidly degrade the anode catalyst layer.

http://www.ptonline.com/articles/fuel-cells-jolt-plastics-innovation

Catalyst Layer Design Strategies for Overcoming Performance/Durability Gaps: Anode

- **45cm^2 MEA**
- **75^{o}C,**
- **100%RH,**
- **5psig,**
- **0.2A/cm^2 reversal current**



- Design 1 to design 2 represents a change in both catalyst type and catalyst layer design.
- Design 2 and design 2A have the same catalyst, but with a modified catalyst layer design.

Ballard has developed advanced anode catalyst layer designs capable of withstanding extreme cell reversal events.

How Can Industry Help Guide/Accelerate Catalyst Development in Academia?

- Long term goals
- Government funding/significant R&D resources
- Specialists/narrow focus

Commercialize Technology!

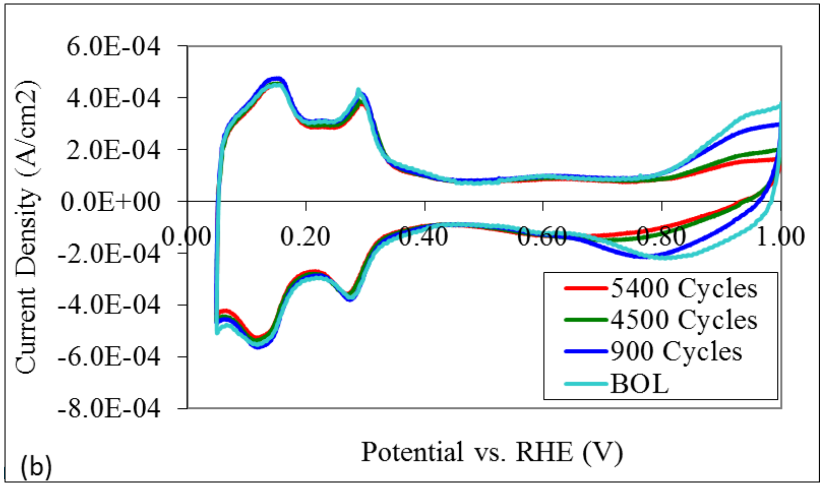
- Scale up capabilities
- Knowledge of real-world requirements
- Broad knowledge/focus

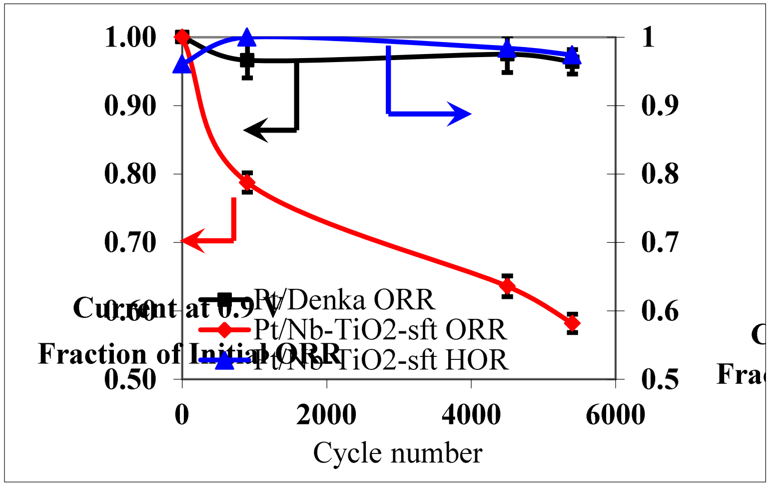
Academia/Industry typically have different skill sets which makes for a great partnership in trying to commercialize technology!

Selected Examples from Ballard's Collaborations

BALLARD®

Project	Partner/Role		Outcome
	BALLARD®	SUNY POLYTECHNIC INSTITUTE	
HOR Selective Catalyst	- Identified HOR selectivity - Proposed mechanism	- Synthesized catalyst - Optimized particle size	- Nano Energy, 27 (2016) 157-166.





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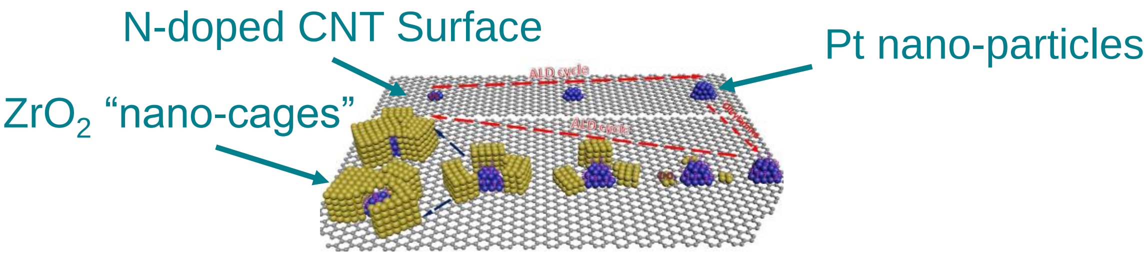
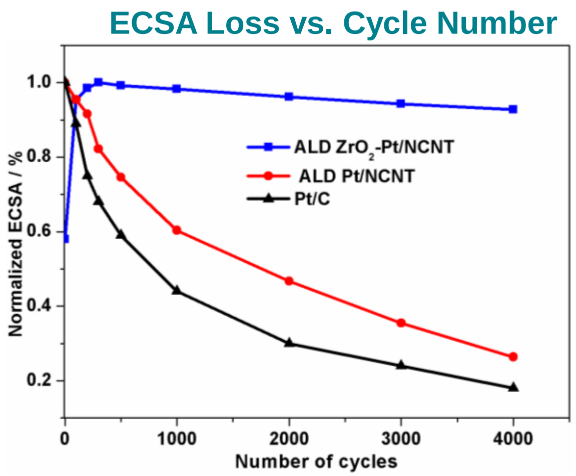
HOR Selective Catalyst	• Identified HOR selectivity • Proposed mechanism	• Synthesized catalyst • Optimized particle size	• Nano Energy, 27 (2016) 157-166.
	BALLARD	Western UNIVERSITY · CANADA	
ZrO stabilized Pt	• Identified possible benefits for PEMFCs • Proposed electrochemical testing protocols	• Developed the ALD method • Prepared all materials	• Adv Mater, 27 (2015) 277-281.

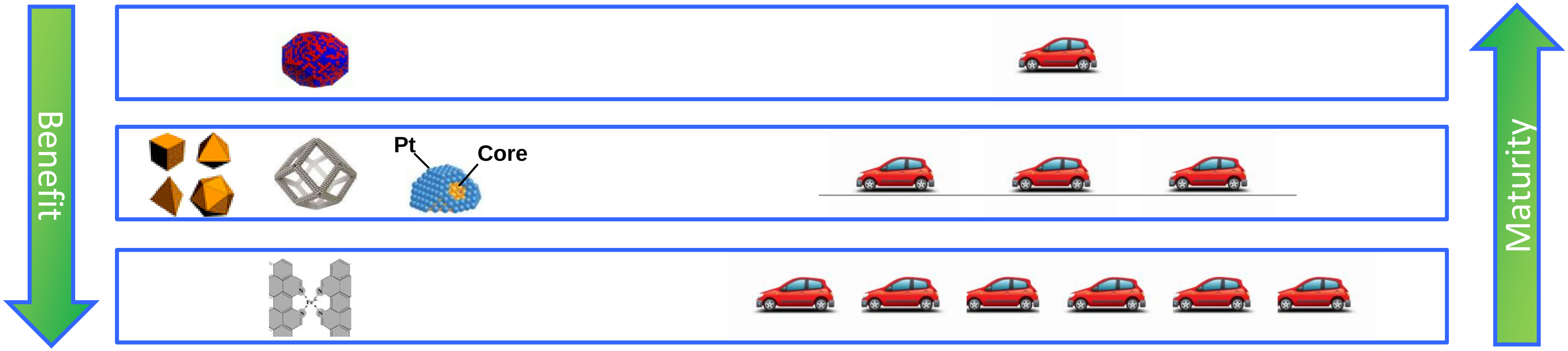


- By selective deposition of Pt, followed by ZrO_2, it may be possible to stabilize Pt nanoparticles against agglomeration.

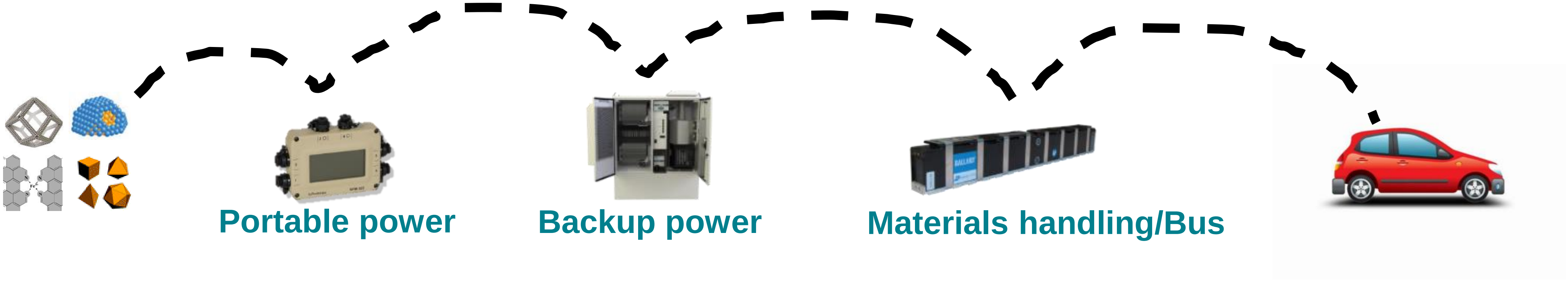


Future Outlook

- A strong pipeline of next-gen electrocatalysts should allow for wide-spread adoption of PEMFCs for automotive applications.



- Non-automotive applications offer an excellent steppingstone for some of these next-gen catalysts on their way to automotive applications



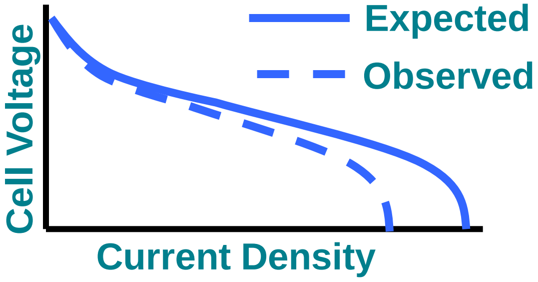
Portable power

Backup power

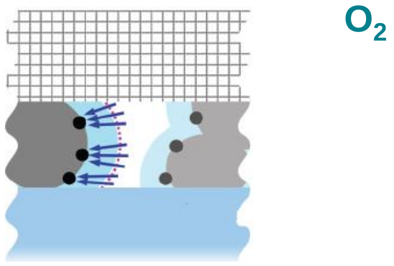
Materials handling/Bus

Remaining Challenges/Opportunities for PGM and non-PGM Catalysts

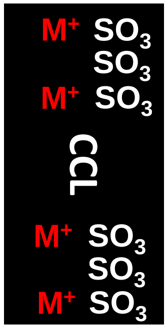
- For PGM catalysts, the mass activity targets have mostly been met, and focus should now shift to integration into advanced CCLs.



CCL Challenges

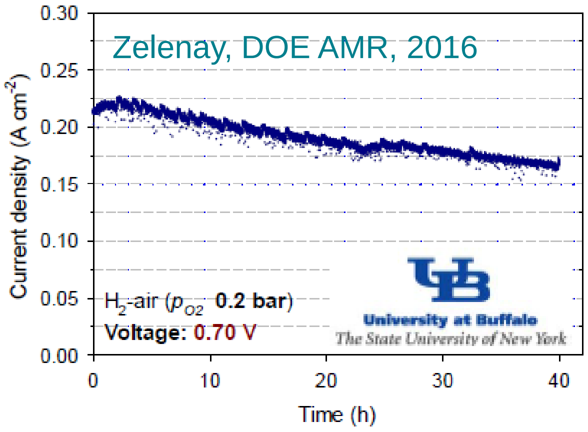


O_2 transport resistance



Ionomer contamination

- Non-PGM require further improvements (particularly in stability) before automotive targets can be met.


Zelenay, DOE AMR, 2016

Good progress, but even the least demanding applications would still require > 1000 h stability!

N. Nonoyama, S. Okazaki, A.Z. Weber, Y. Ikogi, T. Yoshida, *J. Electrochem. Soc.*, 158 (2011) B416-B423.

Thank You!

Questions?