Modeling Performance and Stability of Bipolar Plates for Automotive Fuel Cells

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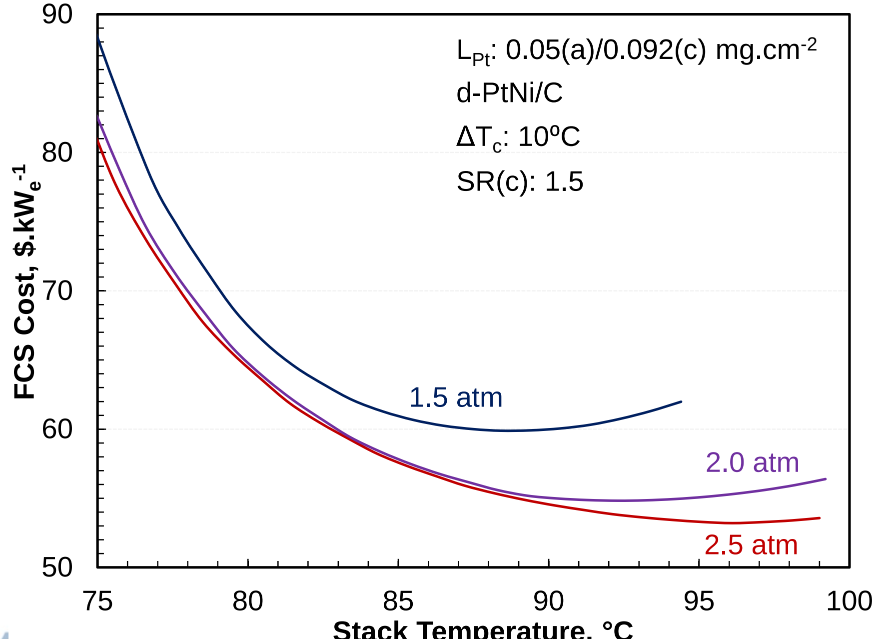
Stack Operating Conditions

Heat rejection constraint requires high performance stacks to run hotter and drier, but two-phase flow likely at part load and normal condition.

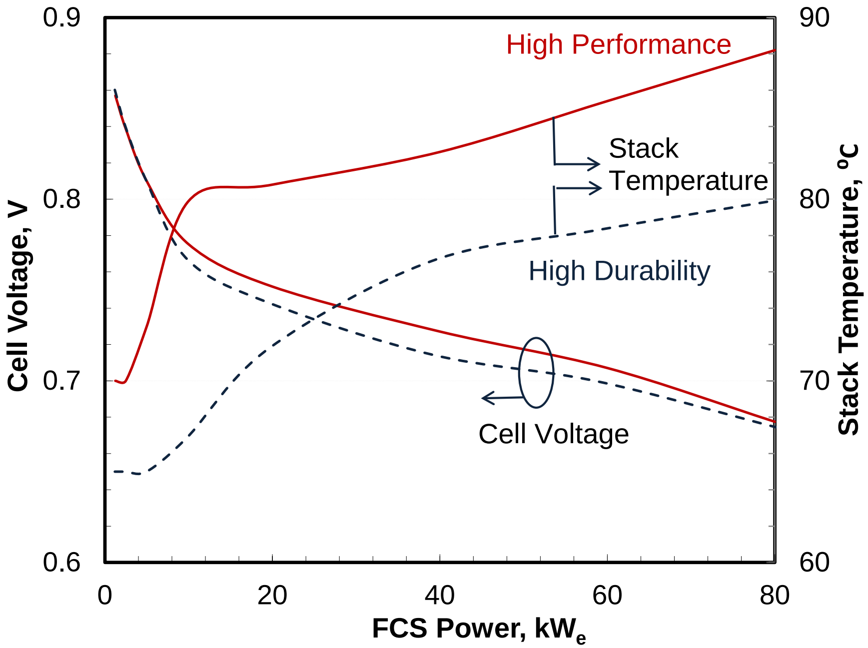
High Performance Design & Operation

- With Q/ΔT constraint, FCS cost is lowest for stacks with d-PtNi/C cathode catalysts at 2.5 atm stack inlet pressure, 95ºC, and 82%/103% RH at cathode inlet/outlet.
- Only small amount of liquid water in flow channels



High Durability Operation

- When performance is not absolutely critical (no Q/ΔT constraint), run stack at 65-80ºC for extended durability with 1-2% penalty in system efficiency
- Two-phase flow in flow channels

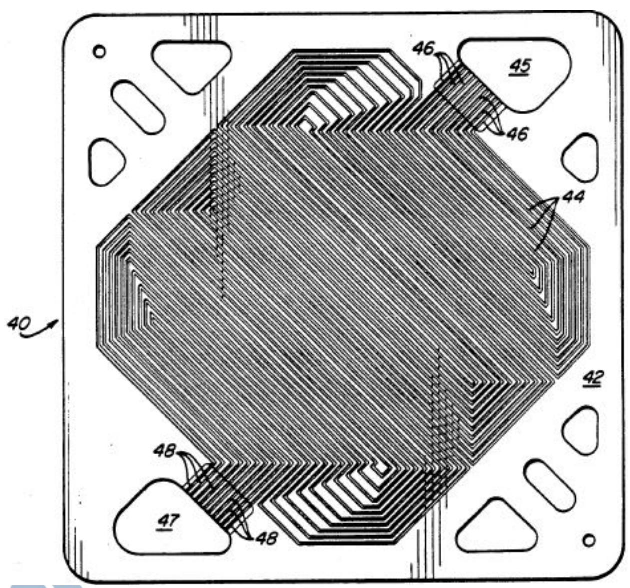


State-of-the-Art Flow Fields

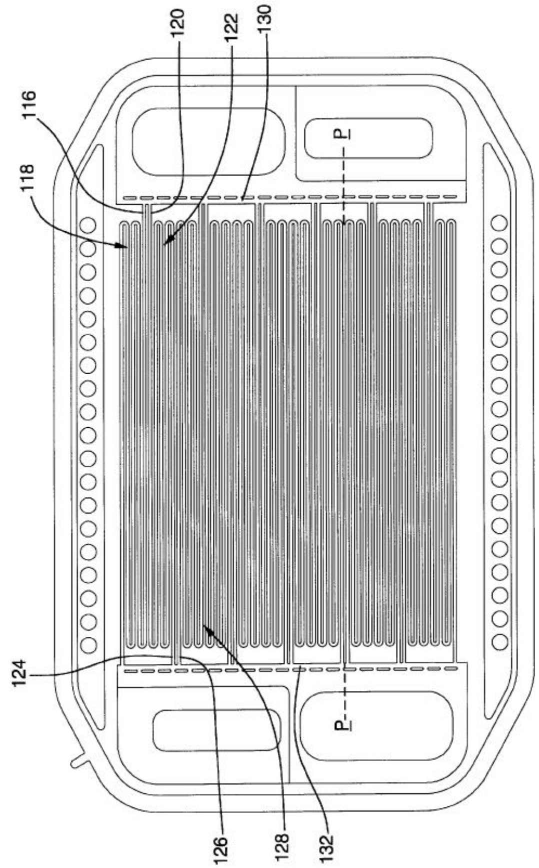
Current SOA: Metal bipolar plates with nearly straight flow channels

- ❑ Serpentine Channels: 75-90% active area, no flow distributor needed
- ❑ Straight Channels: 40-60% active area, flow distributor required

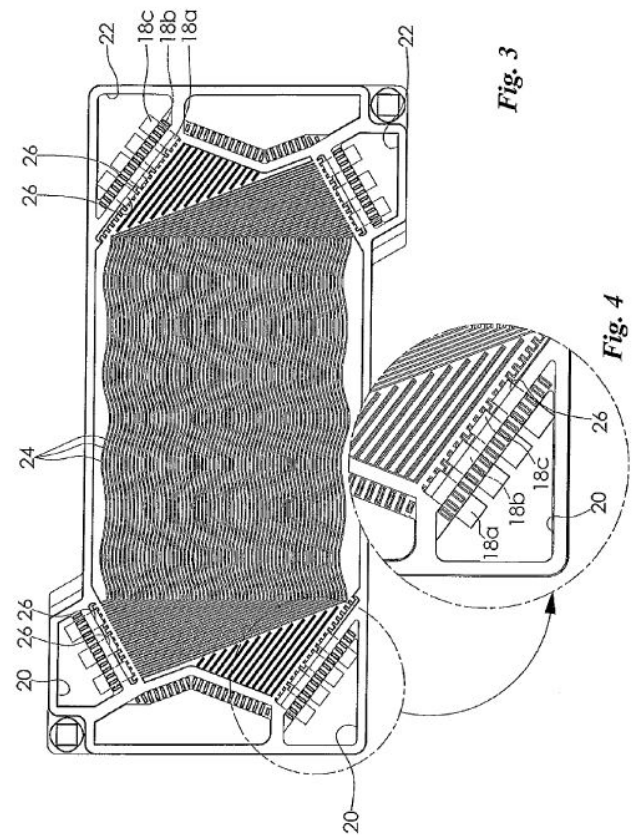
Serpentine Graphite Bipolar Plate, US Patent 5,108,849, Apr. 28, 1992



Serpentine Metal Bipolar Plate, US Patent 6,099,984, Aug. 8, 2000



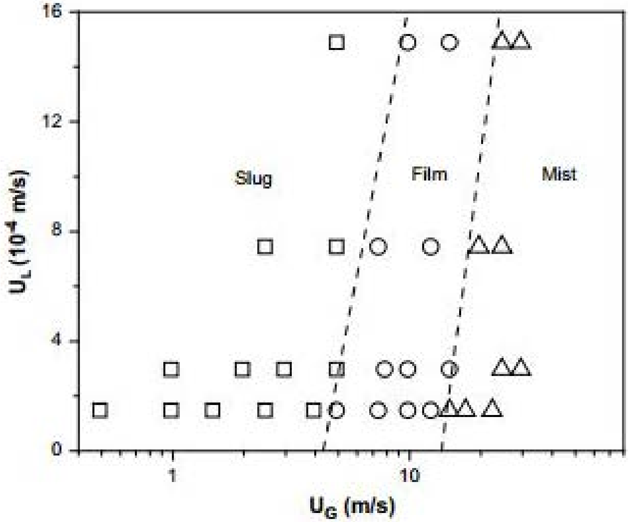
Straight Metal Bipolar Plate, US Patent 8,501,364, Aug. 6, 2013



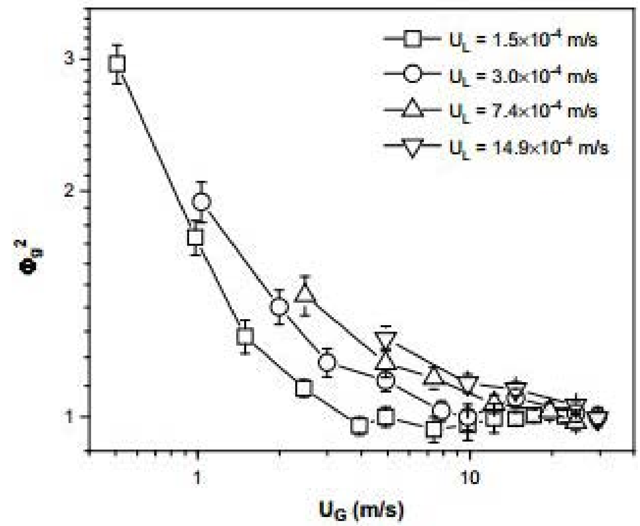
Two Phase Flow Map and Pressure Drop in Micro Channels

Z. Lu, S.G. Kandlikar, et al, “Water Management Studies in PEM Fuel Cells, Part II: Ex Situ Pressure Drop and Two-Phase Flow Patterns in Gas Channels,” International Journal of Hydrogen Energy, 34(2009), 3445-3456.

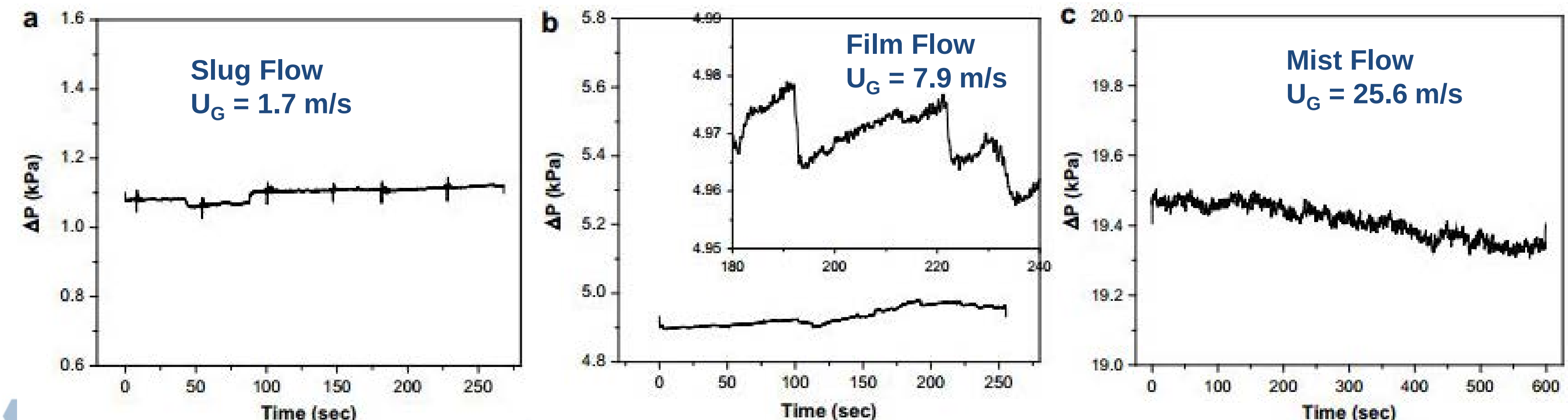
Flow Regime Map of Two-Phase Flow



Two-Phase Flow Pressure Drop Multiplier



Pressure Drops at Superficial Water Velocity (U_L) of 3.0×10^{-4} m/s



Liquid Accumulation, Distribution and Transport

A. Turhan, S. Kim, M. Hatzell, and M.M. Mench, "Impact of Channel Wall Hydrophobicity on Through-Plane Water Distribution and Flooding Behavior in Polymer Electrolyte Fuel Cell," Electrochimica Acta 55 (2010) 2734–2745.

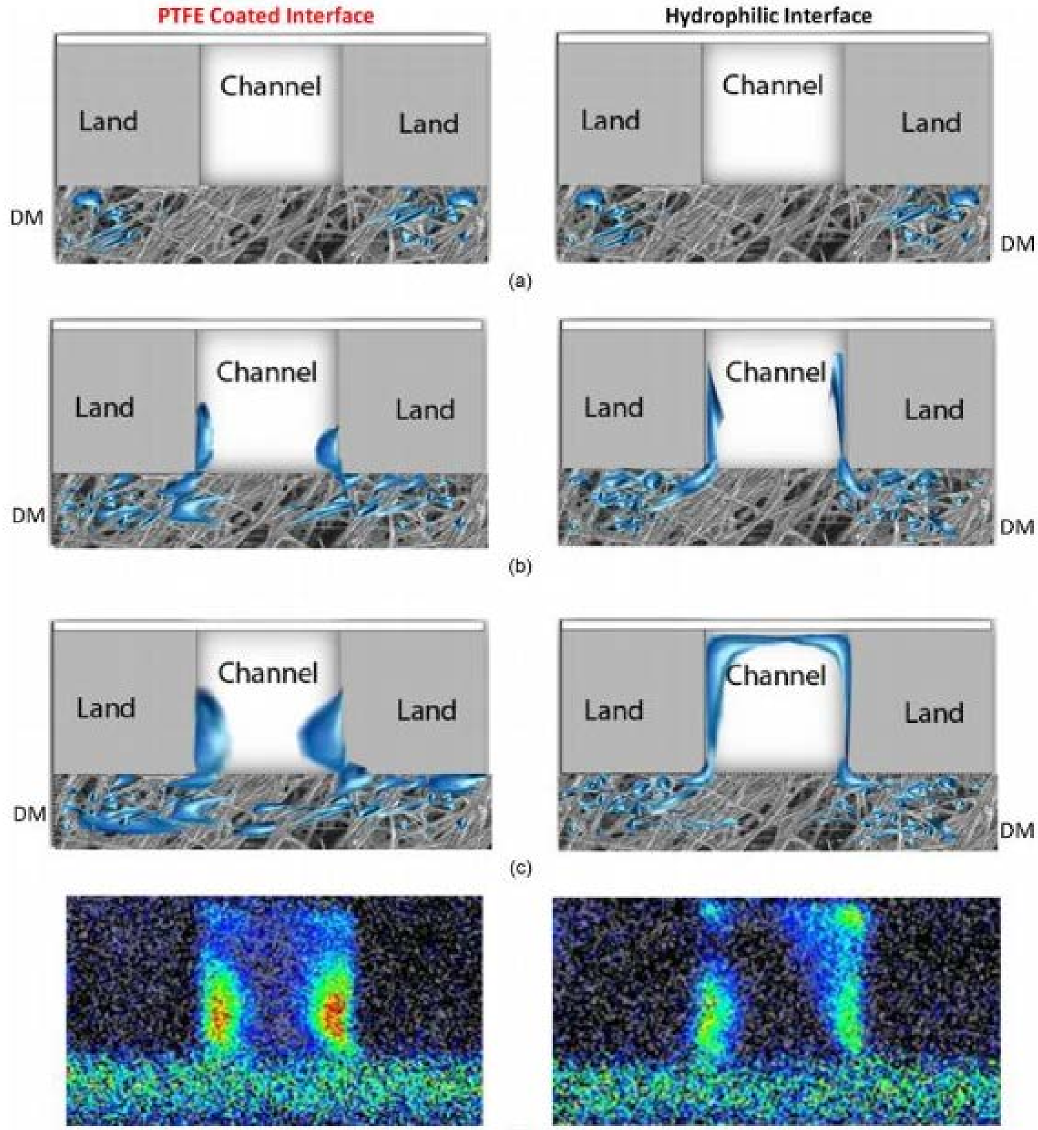
Schematic of Liquid Water Transport and Removal with Coated Channels and Uncoated Channels

Start-Up

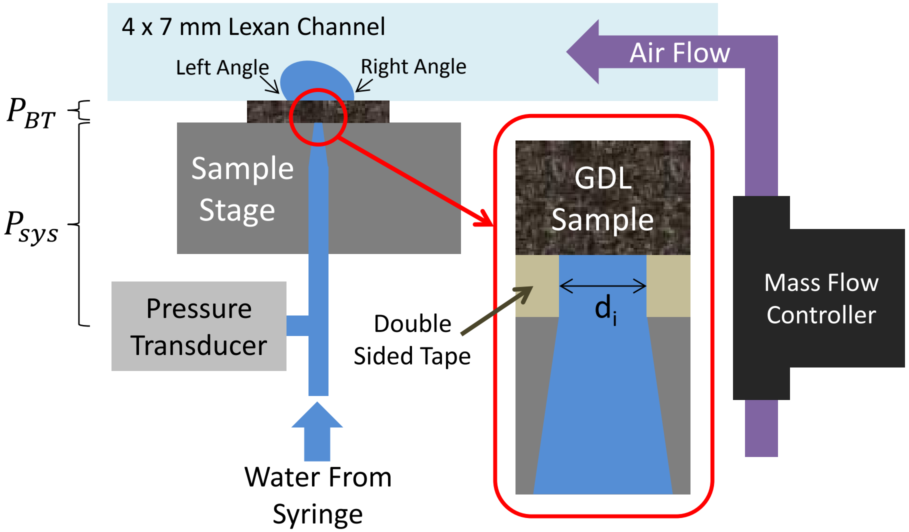
After Couple Minutes of Operation

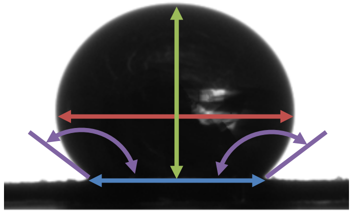
After Significant Liquid Build-Up

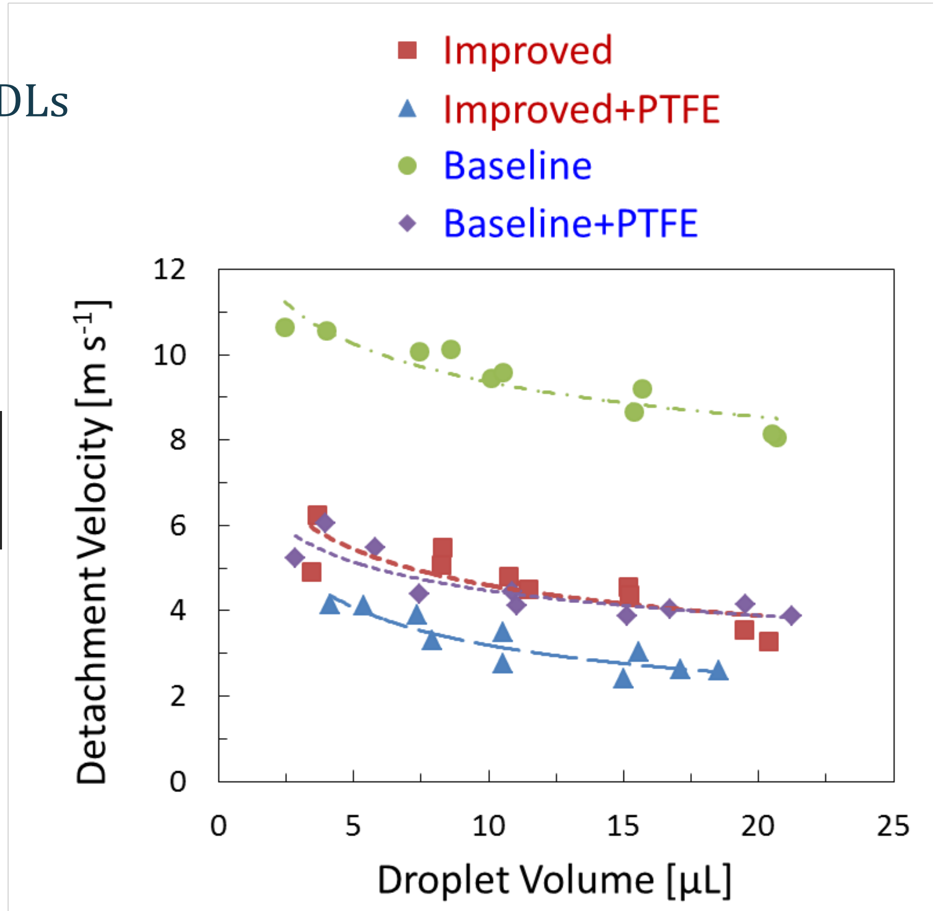
Real-Time Neutron Images



- **Detachment velocity**
  - Improved GDL also shows lower value
    - Correlates to better water removal
  - Can be possible screening tool for new GDLs







A. D. Santamaria, P. K. Das, J. C. MacDonald, A. Z. Weber, *J. Electrochem. Soc.*, 161 (12), F1184-F1193 (2014).

IEA Annex 34 Meeting on Metal Bipolar Plates for Automotive PEM Fuel Cells (Nov. 2015)

Performance Requirements of Bipolar Plates for Automotive Fuel Cells, *R. K. Ahluwalia, ANL*

Effect of Potential and Temperature on Electrochemical Corrosion of Metallic Bipolar Plates for HT-PEFCs, *Vitali Weißbecker, FZ Jülich*

Interconnectors, *Christian Bienert, Plansee*

Recent Developments in Water Management – Pressure Drop, Water Removal, Droplet Dynamics and Transient Performance, *Satish Kandlikar, Rochester Institute of Technology*

Bipolar Plates for PEM Electrolysis: Challenges vs. Fuel Cells, *Kathy Ayers, Proton OnSite*

Metal Bipolar Plate Coating for PEM Fuel Cells, *Conghua Wang, TreadStone Technologies*

R&D for Automotive Fuel Cell Systems – Bipolar Plates, *Shinichi Hirano, Ford Motor Company*

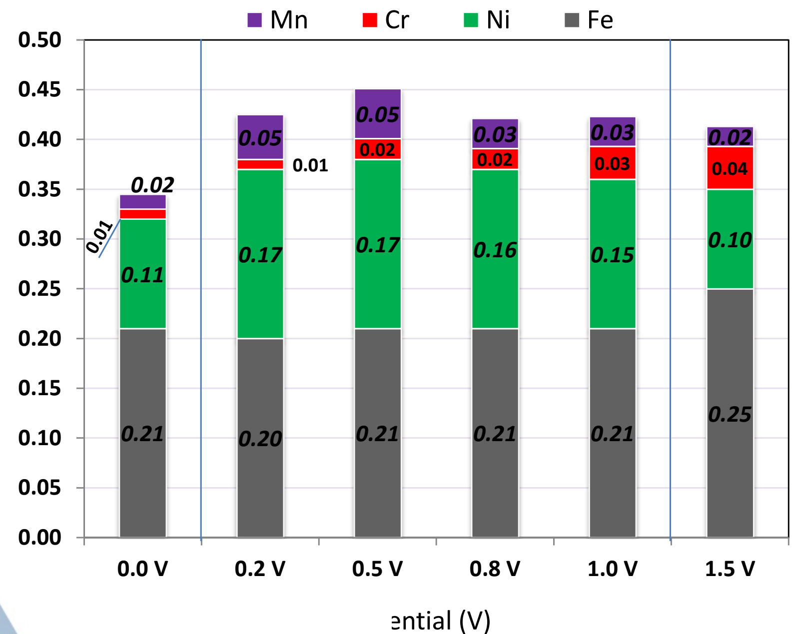
Sandvik Surface Technology - Commercializing bipolar plate production, *Hanna Bramfeldt, Sandvik*

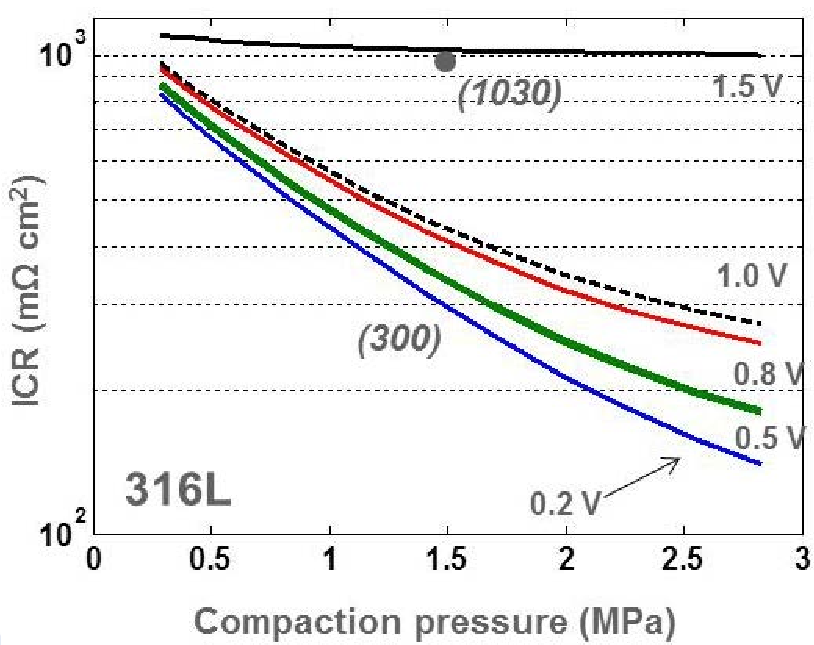
Ceramic MaxPhase™ - a highly conductive, low cost, and corrosion resistant coating on metal bipolar plates for PEM fuel cell, *Henrik Ijungcrantz, Impact Coatings*

SS 316L Requires Coatings

Corrosion currents < 1 μA/cm², but ICR >> 5 mΩ.cm². Coating needed to prevent formation of the passivating but resistive oxide film.

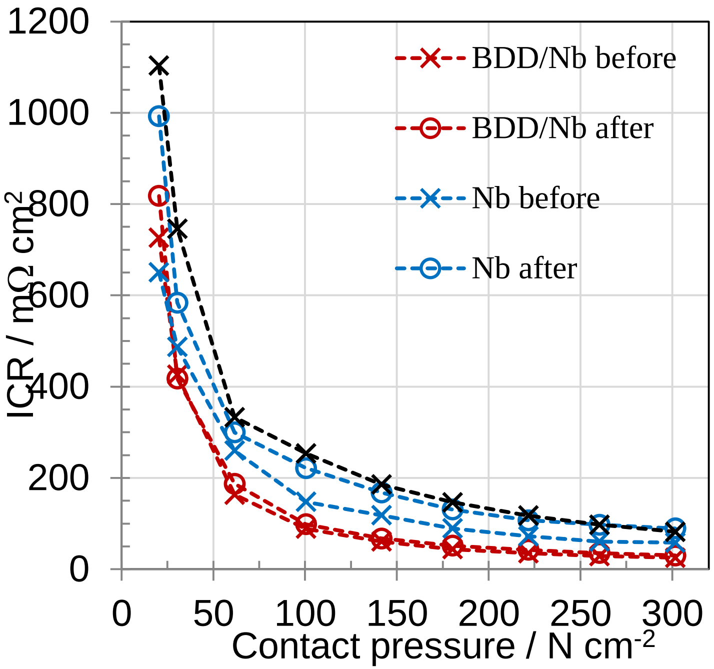
- Region I: Passive H_2 environment
- Region II: Passive air environment, Cr-rich film at potentials <1 V.
  Cr film dissolves at all potentials (0–1 V), rate function of pH
- Region III: Transpassive air environment, Fe-enriched film at potentials >1.5 V
- Potentiostatic release rates
  Fe > Ni >Mn > Cr
- 316L ICR as function of potential (0.2 – 1 V) correlates well with modeled changes in oxide layer thickness (passive film)
- ICR values shown are subject to experimental uncertainties because only one side was exposed to electrolyte

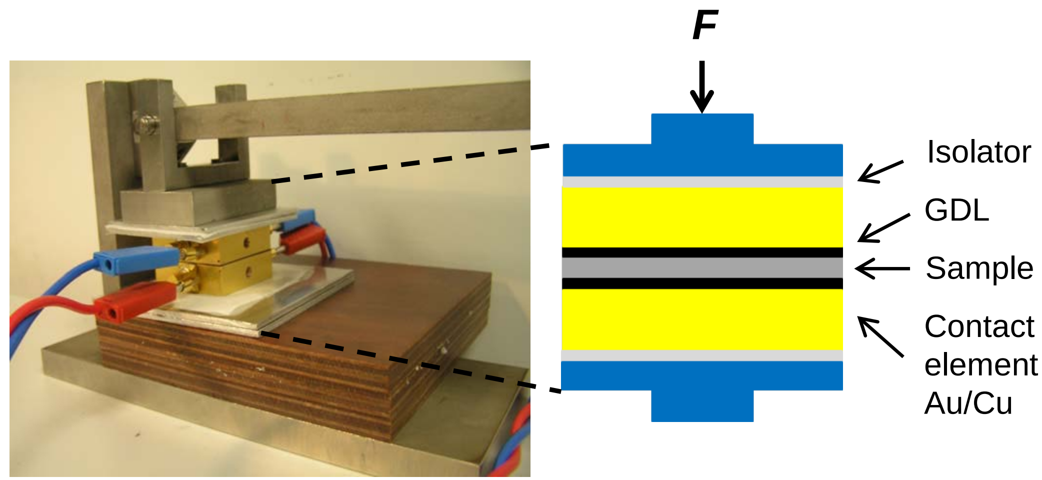




Interfacial Contact Resistance (ICR)

ICR before and after exposure to 85 % H_3PO_4 at 160 °C for 4 d.





$ICR\ (\Omega\ cm^2) = ½\ (R - R_{Sys})\ A$

BDD/Nb shows lowest values:

65 mΩ cm^2 at 150 N cm^{-2}
30 mΩ cm^2 at 300 N cm^{-2}

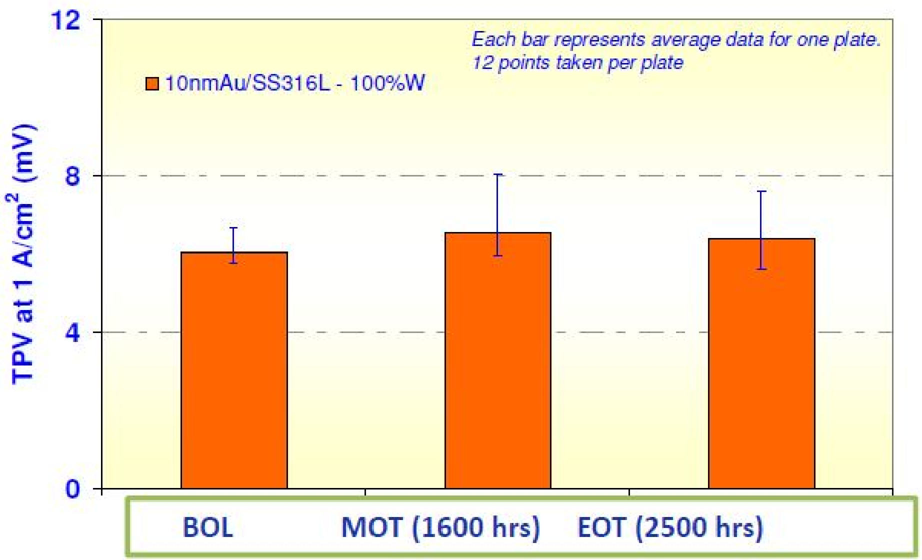
(DOE: < 20 mΩ cm^2)

ICR of alloy 625 too high to be measured after exposure

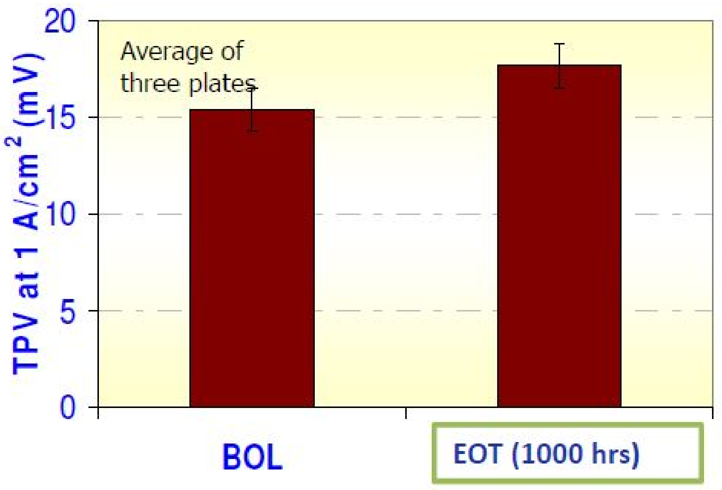
BDD-coatings exhibit high stability with no underlying passivation!

In-situ Durability Test

Au-nanoclad® 20-cell Stack



Au Dot 10-cell Stack

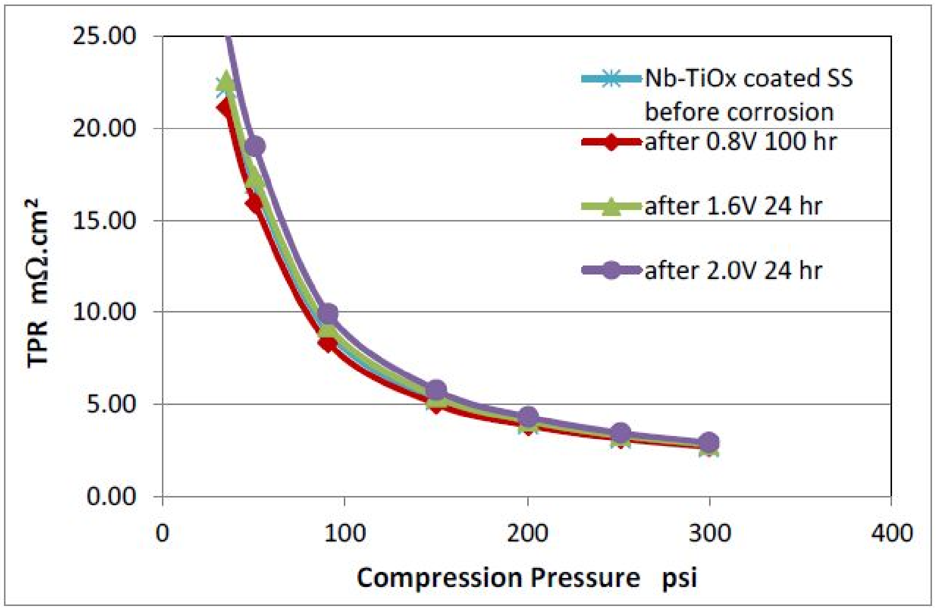


- No significant increase in plate area specific resistance was observed during in-situ durability test.
- Post analysis revealed no significant corrosion issues. Metal cations in the stack effluent water (anode, cathode, and coolant) were below the detectable limit of Inductively Coupled Plasma (ICP) analyzer (~ppm).

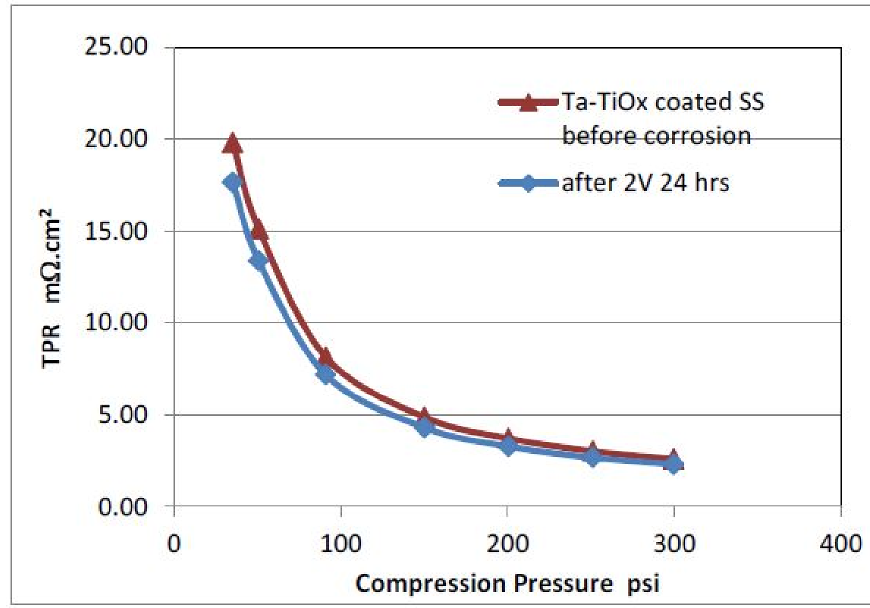
Doped TiO_x Coating Stability Test in Extreme Conditions

in pH 3 H_2SO_4 + 0.1 ppm HF at 80°C

316L SS with Nb-TiO_x coating before and after corrosion tests



316L SS with Ta-TiO_x coating before and after corrosion tests



- Doped TiO_x coated SS has low surface electrical contact resistance.
- The coated SS has superior corrosion resistance for PEM fuel cell applications.
- The extreme corrosion condition (@ 1.6V_{NHE} or 2 V_{NHE}) *ex-situ* tests are not included in regular standard, but it is very attractive to OEMs because of the concerns of stack transient operation conditions.

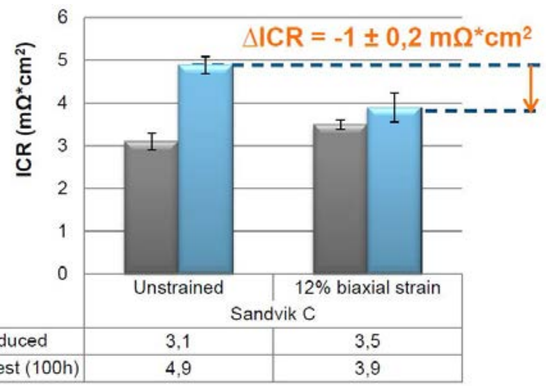
Sandvik Pre-Coated Graphite-Like Carbon (GLC) Coatings

Requirements

- Prevent formation of oxide scale on SS
- Low contact resistance (ICR?ASR)
- Good corrosion behavior
- Good formability / coating adhesion

Sanergy LT Coating

- Graphite-like carbon (GLC) coating
- Metallic interlayer

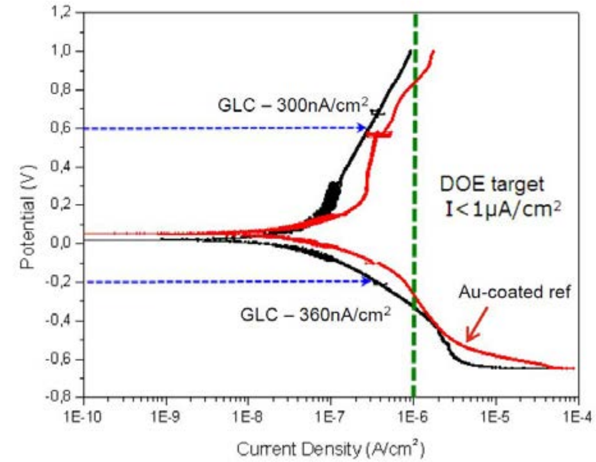


Forming of Coil-Coated Material

- Forming operation produces cracks in the coating: No negative impact on ICR
- Coating adhesion is the key
- Choice of substrate important
- Long standing relationships with OEMs, indication of stable performance

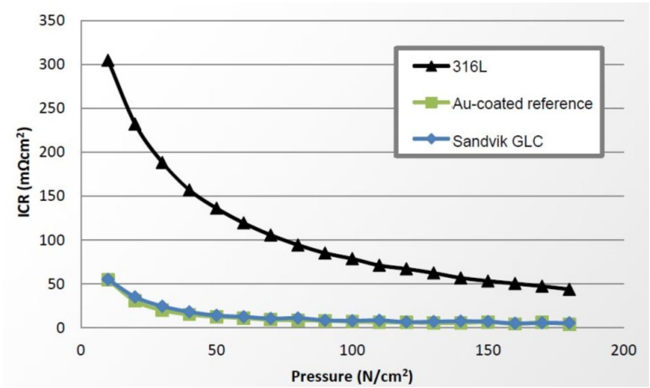
Corrosion Resistance

GLC coated AISI 304L: currents are in the passive region between 0.6 V and -0.2 V, well below the target, < 1 μA/cm²



Contact Resistance

GLC coating comparable to Au-coating: ICR = 3-6 vs. 1.5-2.0 mΩ.cm² at 14 bar

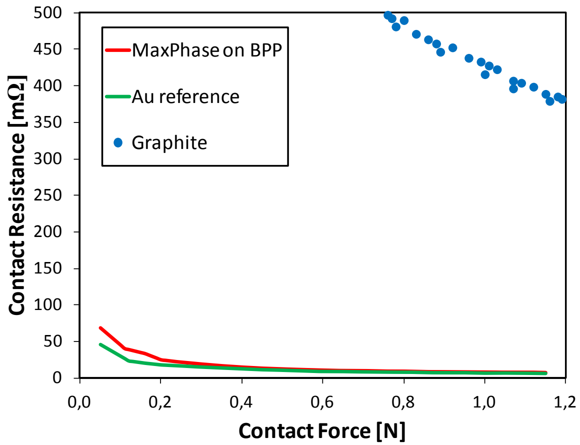


Impact Coatings AB

- ❑ Volume production solutions for coating of fuel cell metal bipolar plates
- ❑ Ceramic MaxPhase™
  - – Low cost and high-performance coating
  - – Exceeds US DOE requirements
- ❑ Turn-key PVD equipment for volume production
- ❑ Coating Services for prototyping

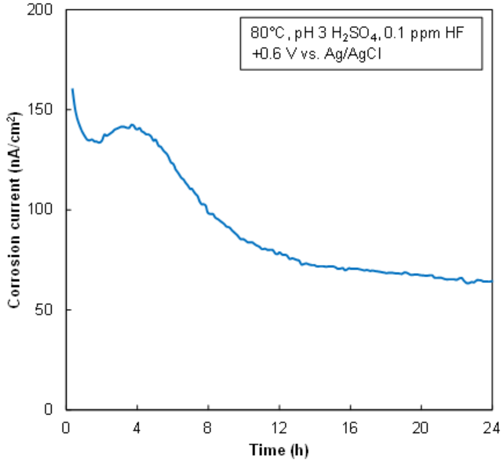
Single point Au probe contact resistance and ex-situ corrosion resistance

- Contact resistance close to Au reference coating
- No detectable surface oxidation



24 hour corrosion test

- Ceramic MaxPhase™ on SS304
- Current < USDOE Target 1000 nA/cm^2



- Ceramic MaxPhase coated BPPs showed stable performance for 5000 h in in-situ short stack tests at PowerCell with reformate fuel: 25 ppm CO, 500 mA/cm^2, 70^{o}C, 80% RH
- Possible to have post-coatings for low cost, high performance, or pre-coatings for lowest cost, medium performance

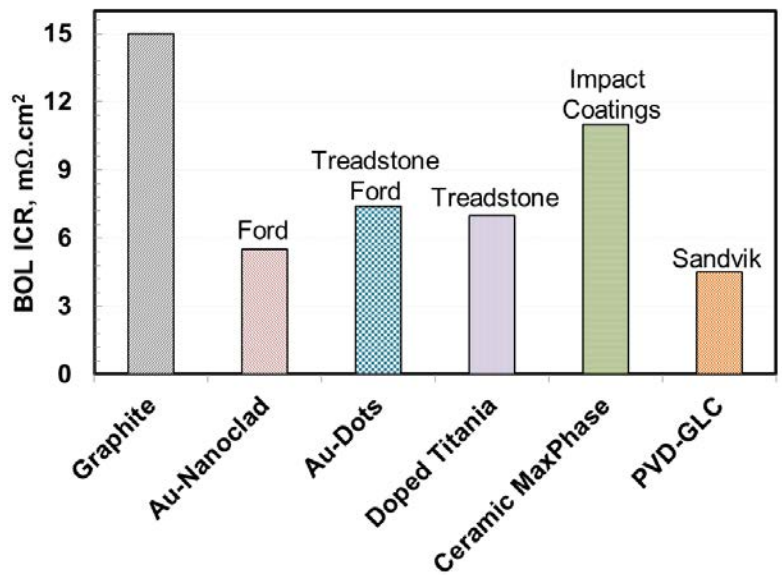
Annex 34 Bipolar Plates Meeting: Summary

Cost of bipolar plates is one of the largest contributor to the overall cost of the fuel cell stack. Cost reduction of BPP materials/process is still required.

Retention of electrical conductivity under fuel cell operational conditions is a key performance metric.

Wide range of *ex-situ* corrosion tests (potentiodynamic, potentiostatic for both anodic and cathodic conditions) can help to understand material characteristics for real world conditions. *In-situ* stack level durability test is imperative to verify material's durability.

Flow field design configuration is a key to the performance of fuel cells. Formability is an important attribute in the design space.



Characteristic	Units	2020 Targets	ANL, LANL, ORNL, NREL	UTRC	Ford	Ford, Treadstone	Treadstone	Impact Coatings	Sandvik
Plate or Coating Material			**SS-316L**	**Graphite**	**Au-Nanoclad**	**Au-Dots**	**Doped Titania**	**Ceramic MaxPhase**	**PVD-GLC**
Coating			Uncoated	Uncoated	Pre-Coated	Post-Coated			Pre-Coated
Plate Cost[b]	$ / kW	3							
Plate Weight	kg/kW	0.4				<0.3			
Plate H_2 permeation coefficient[c]	Std $cm^3/(s\ cm^2 Pa)$ @ 80°C, 3 atm 100% RH	$<1.3 \times 10^{-14}$ [d]							
Corrosion, anode[e]	$\mu A / cm^2$	<1	0.3		No active peak	No active peak	No active peak		<1
Corrosion, cathode[f]	$\mu A / cm^2$	<1	0.4		~1.0	~0.1	<0.02	~0.075	
Electrical conductivity	S / cm	>100				3400			
Areal specific resistance[g]	$m\Omega\text{-}cm^2$	10	420	~15	5-6	8.4-6.4	6-8	~11	3-6
Flexural strength[h]	MPa	>25							
Forming elongation[i]	%	40				53-64			

Metal Bipolar Plates – Research Needs

1. **Fluid mechanics of two-phase flow in SOA metal bipolar plates and flow fields**
   - Pressure drops (Effect of bipolar plate materials and coatings)
   - Liquid accumulation, distribution and transport (especially in flow distributors)
   - Flow transients (Effect on robustness)
   - Role of GDL in determining water distribution and removal
2. **Corrosion mechanisms**
   - Material and coating specific corrosion mechanisms as function of potential
   - Alternative substrate materials
   - Material characterization by understanding corrosion currents in ex-situ potentiodynamic tests
   - Effect of potential cycling on corrosion (metal dissolution) rates
   - Effect of defects and imperfections in coatings
   - Design of protocols for developing bipolar plate durability models
   - Correlating in-situ and ex-situ corrosion rates
3. **Transport of bipolar plate corrosion products (metal ions)**
   - Effect of cations on electrode performance
   - Effect of cations on membrane performance
4. **Interfacial contact resistance**
   - ICR as function of contact pressure, potential and exposure