



Hydrogen Fuel Cells for Unmanned Systems

Benjamin Gould, U.S. Naval Research Laboratory, Alternative Energy Section

Karen Swider-Lyons, U.S. Naval Research Laboratory
Head, Alternative Energy Section, Chemistry Division
Director, Laboratory for Autonomous Systems Research

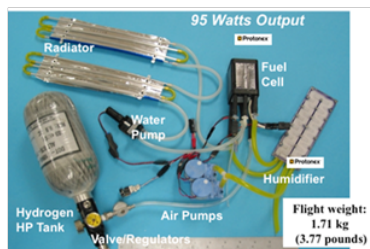
Yannick Garsany and Robert Atkinson, Excet Inc.

Keith Bethune, University of Hawaii, Hawaii Natural Energy Institute

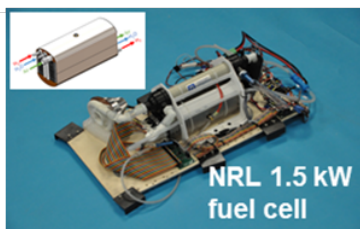
2021 DOE-AMR
Virtual
June 10, 2021

DISTRIBUTION A. Approved for public release: distribution unlimited.

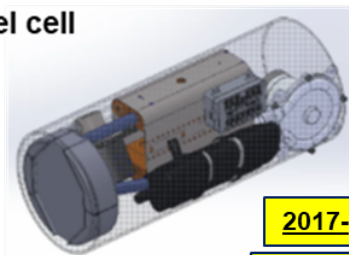
History of NRL Fuel Cells R&D



2002: 1st Protonex 100W fuel cell



NorthwestUAV 1.5 kW
fuel cell



2021- NRL's fuel cell becomes commercially available

2018- Publish methods for high power fuel cell membrane electrode assemblies

2017- Iron Fish prototype for H₂ and O₂ storage in large UUV

2016 First prototype of NRL built 1.5 kW modular fuel cell

2015 Field Hydranox Large Displacement UUV at NSWCCD

2013- Establish toolbox to enable scaling UAV/UAS propulsion systems between 500 and 5000W

2013 48 hour flight of Ion Tiger using liquid hydrogen

2013 Vertical launch of XFC/Sea Robin fuel cell UAV from USS Providence

2010 Start collaboration with General Motors and NSWCCD to use automotive hydrogen fuel cell in UUVs

2010 Publish methods for fuel cell electrocatalyst characterization

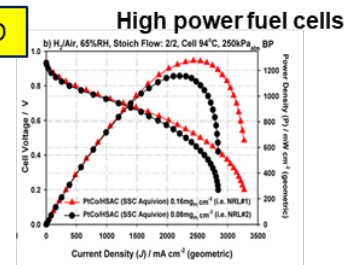
2009 Ion Tiger UAV breaks unofficial world record for fuel cell flight with 26-hour flight

2008 Develop lightweight heat rejection strategies for UAVS

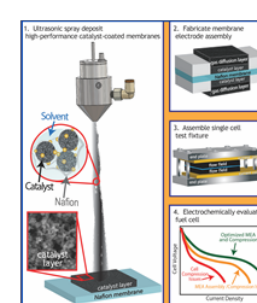
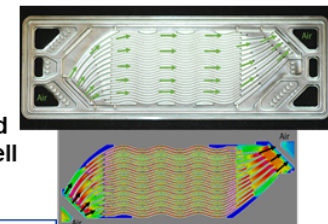
2007 Electrochemical protocols developed to remove air-borne poisons from fuel cell catalysts.

2003-2005 First hydrogen fuel cell UAV – Spider Lion

2001 KSL begins hydrogen fuel cell research with DOE grant on electrocatalysis



Computational fluid
dynamics of fuel cell
plates



Publications
establishing
fuel cell
methodology
and
benchmarks

2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021

Motivation for Fuel Cell in Unmanned Systems (UxVs)

Fuel cell advantages:

- Higher energy than batteries
- Higher efficiency than engines
Small engines ~10% efficient
Fuel cells ~45-60% efficient
- Better durability and reliability the small engines

Benefit to Navy:

- Long endurance electric UxVs
- For UAVs quiet flights for lower cost for longer times
- ***Big UAV missions with a small UAV***
 - “Nano-ization” of UAVs
 - Lower cost and maintenance
 - Less storage volume

Advantages of electric propulsion

- Near silent operation
- Instant starting
- Increased reliability
- Ease of power control
- Reduced thermal signature
- Reduced vibration
- No electric generator



Ion Tiger Design and Sizing – 26h in 2009



Ion Tiger

• Cruise Power	267w
– Propulsion	200 w
– Avionics	20 w
– Flight Controls	20 w
– Payload	20 w
– Conversion Losses	7 w

Dimensions

• Wing Area	16.9 ft ²
• Span	17.0 ft
• Aspect Ratio	17
• Length	7.9 ft
• L/D	17

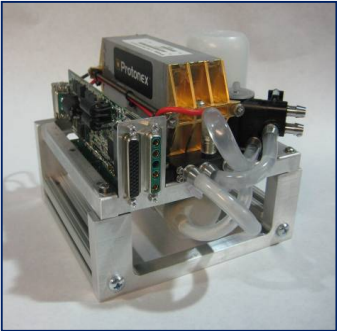
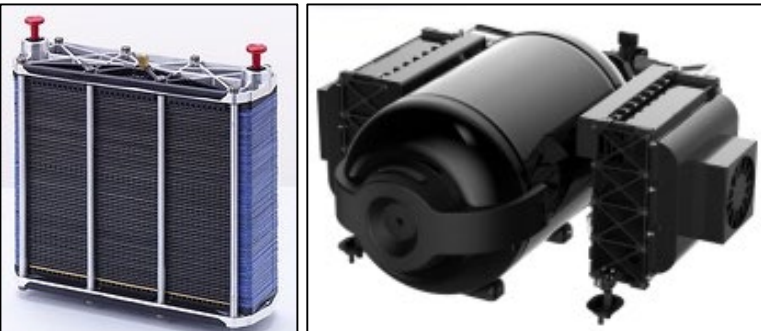
• TOGW	35.5 lbs
– Fuel Cell	2.2 lb
– Fuel Tank	8.0 lb
• Fuel	1.1 lb
– Regulator	0.4 lb
– Cooling System	1.5 lb
– Propulsion System	0.9 lb
– Avionics	1.0 lb
– Airframe	15.5 lb
– Payload	5.0 lb

Key design point – POWER to WEIGHT!!!

Status of Hydrogen Fuel Cells for UAVs

- Fuel cells are good enough to support UAVs with real utility
- H₂ infrastructure is still a gap to fielding in larger quantities

Numerous commercial offerings:

Liquid cooled Closed cathode	Air cooled Open cathode		Air cooled Closed cathode
 Honeywell	 Horizon Fuel Cell Technologies	 Intelligent Energy DOOSAN	 PLUG POWER

Issues with Commercial Fuel Cells

- **Inadequate cooling for hot conditions**
 - Several vendors sell air cooled systems
- **Inadequate blower for high altitudes**
- **Inadequate controls**
 - Start-up and shut-down sequences
- **Inadequate power electronics**
 - Components de-solder
- **Lack of CVM – cell voltage monitoring – for durability and control**
- **Coolant issues**
 - Glycol-based coolant can damage the catalyst
 - Vapor lock with DI water
- **Serviceability**

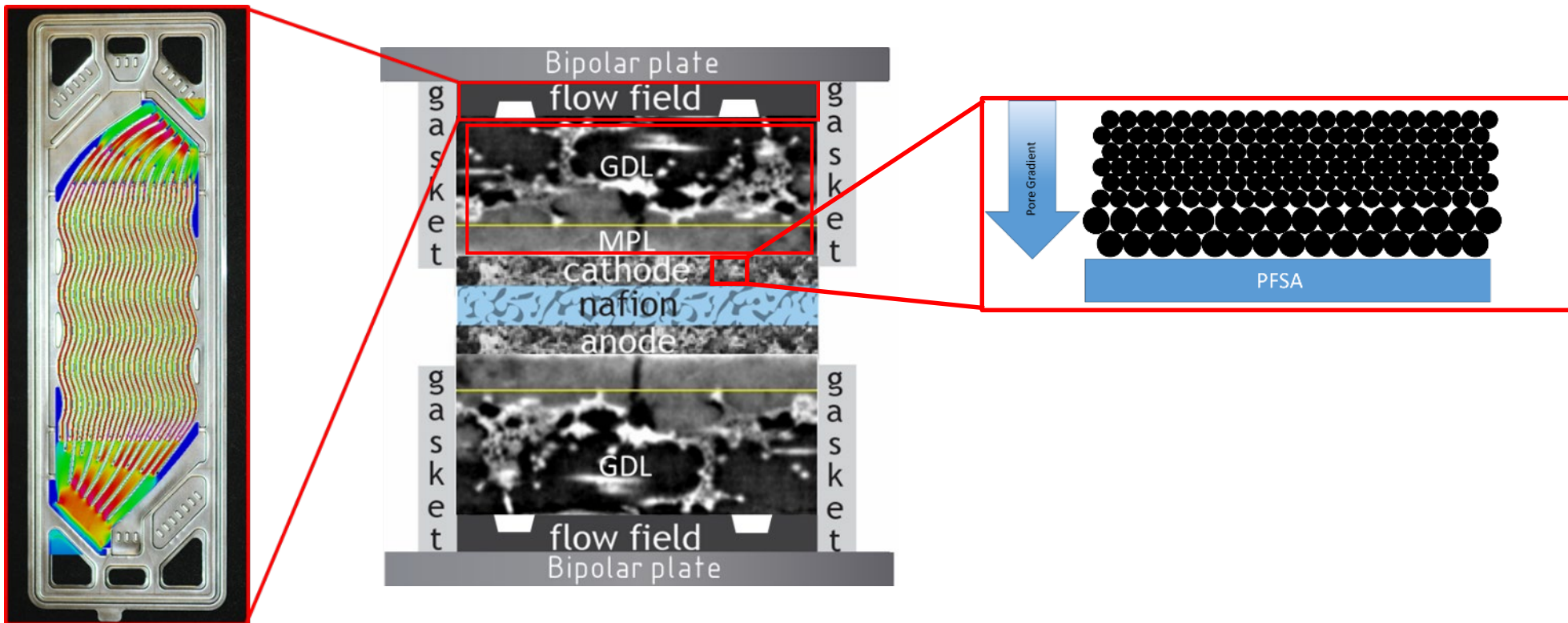
NRL is addressing through internal development and commercial partnership

Hydrogen Fuel Cell Research

Bipolar plates (BPP)

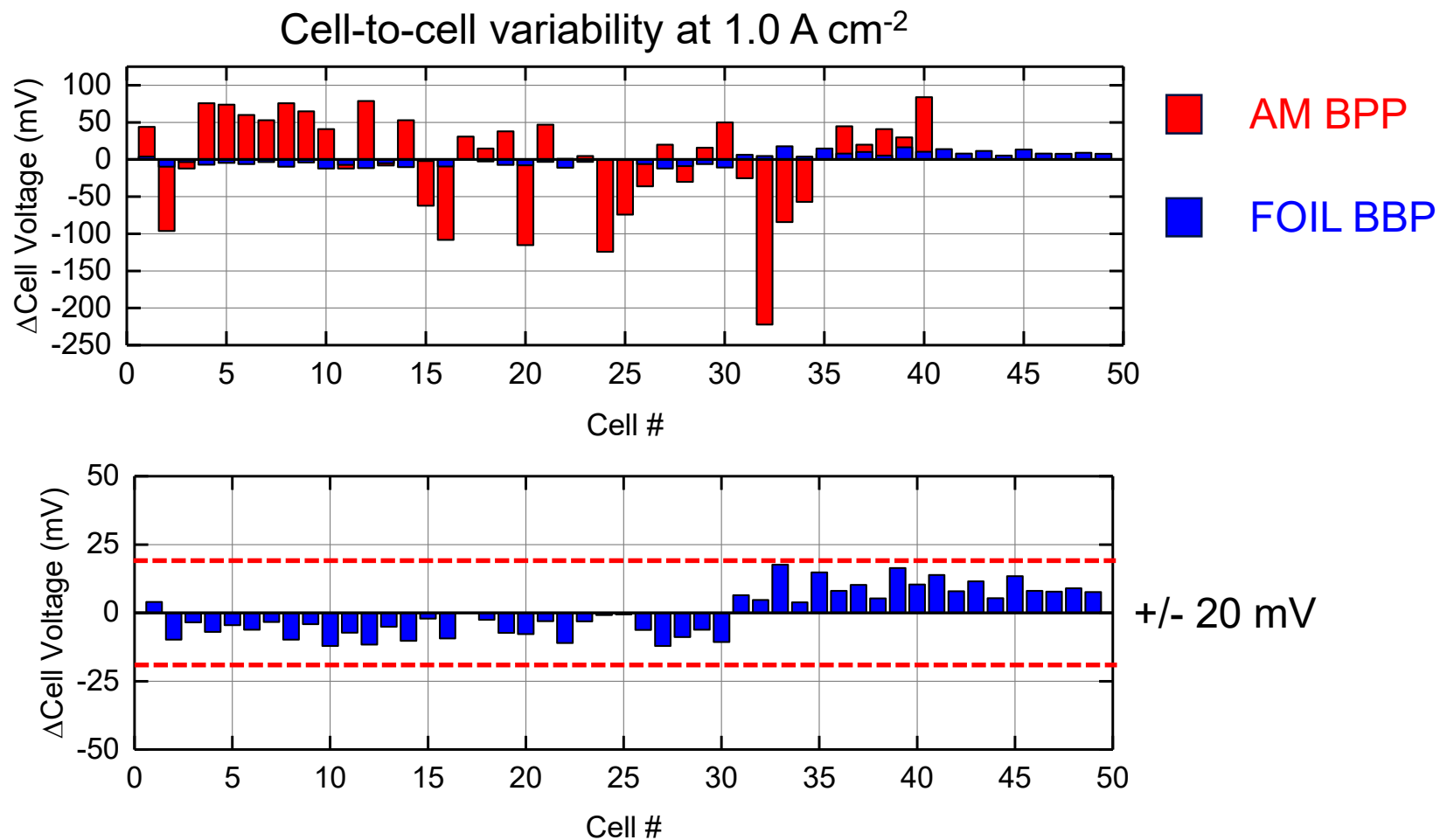
Gas diffusion media (GDM)

Catalyst layer (CL)



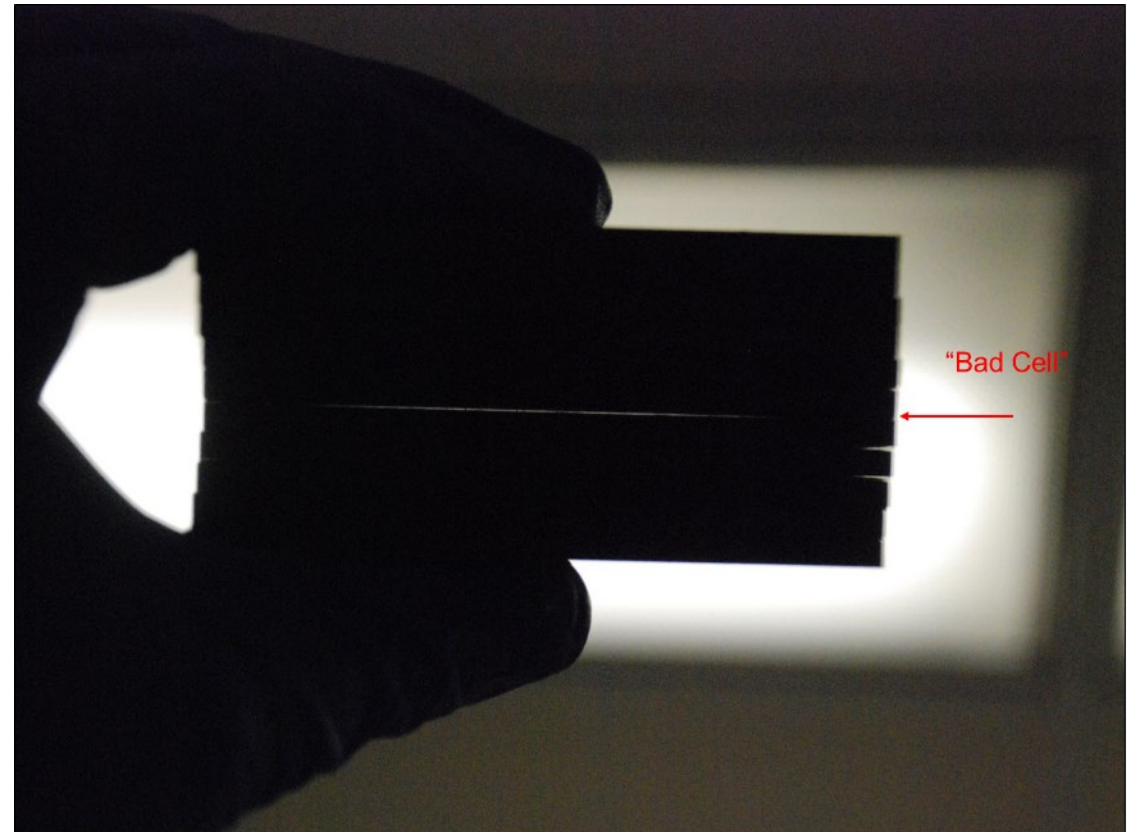
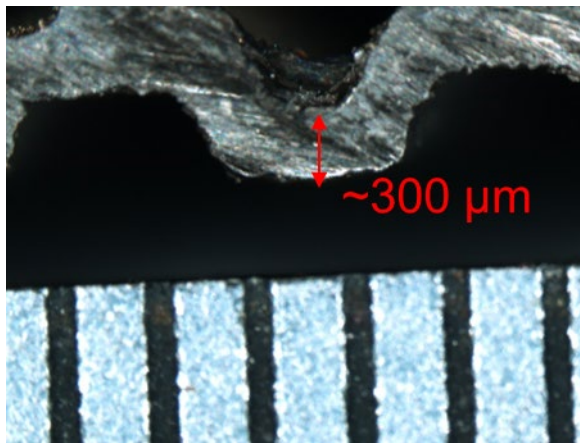
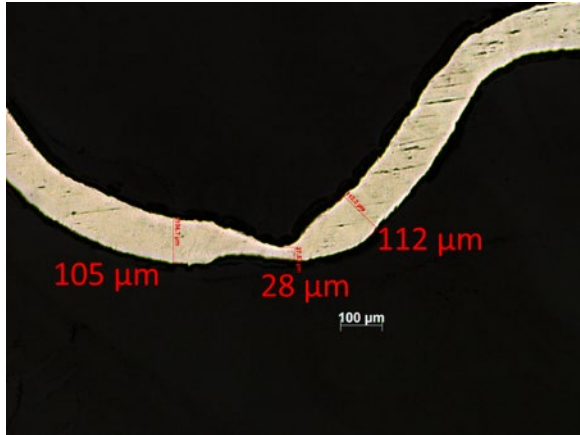
- Fuel cell design is a holistic problem
- NRL's fuel cell portfolio spans basic to applied (6.1 → 6.4)
- A fuel cell is a “water production machine”
- High power devices for unmanned systems requires water removal and oxygen transport to active sites

Comparison Between Foils and AM



- Large cell-to-cell variability in stack with AM bipolar plates: $\pm 53 \text{ mV}$, Max 222 mV
- Good cell-to-cell variability in stack with metal foil bipolar plates: $\pm 8 \text{ mV}$, Max 16 mV

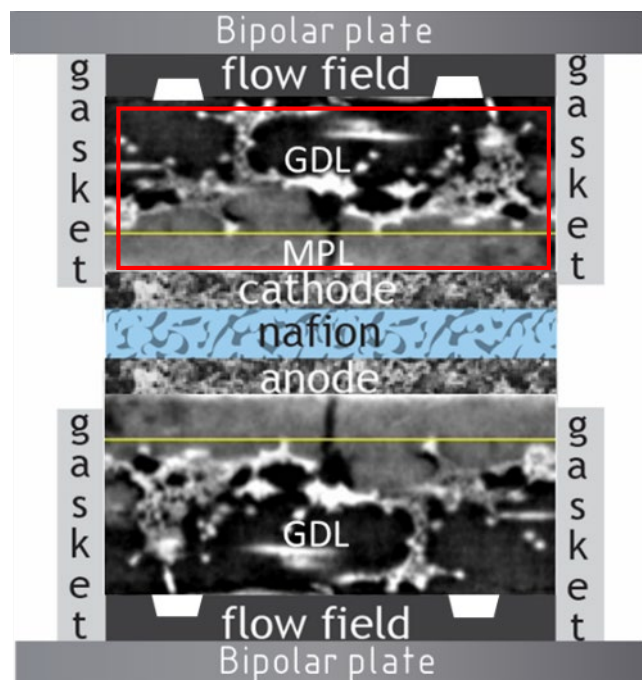
Comparison Between Foils and AM



- Cell-to-cell variability caused by manufacturing limits
- Features sizes, resolution, and post processing are limiting with AM
- Contact between interfaces is important!
- Structure matters: proper channels to reject water, proper interfaces

Now consider porosity of gas diffusion media

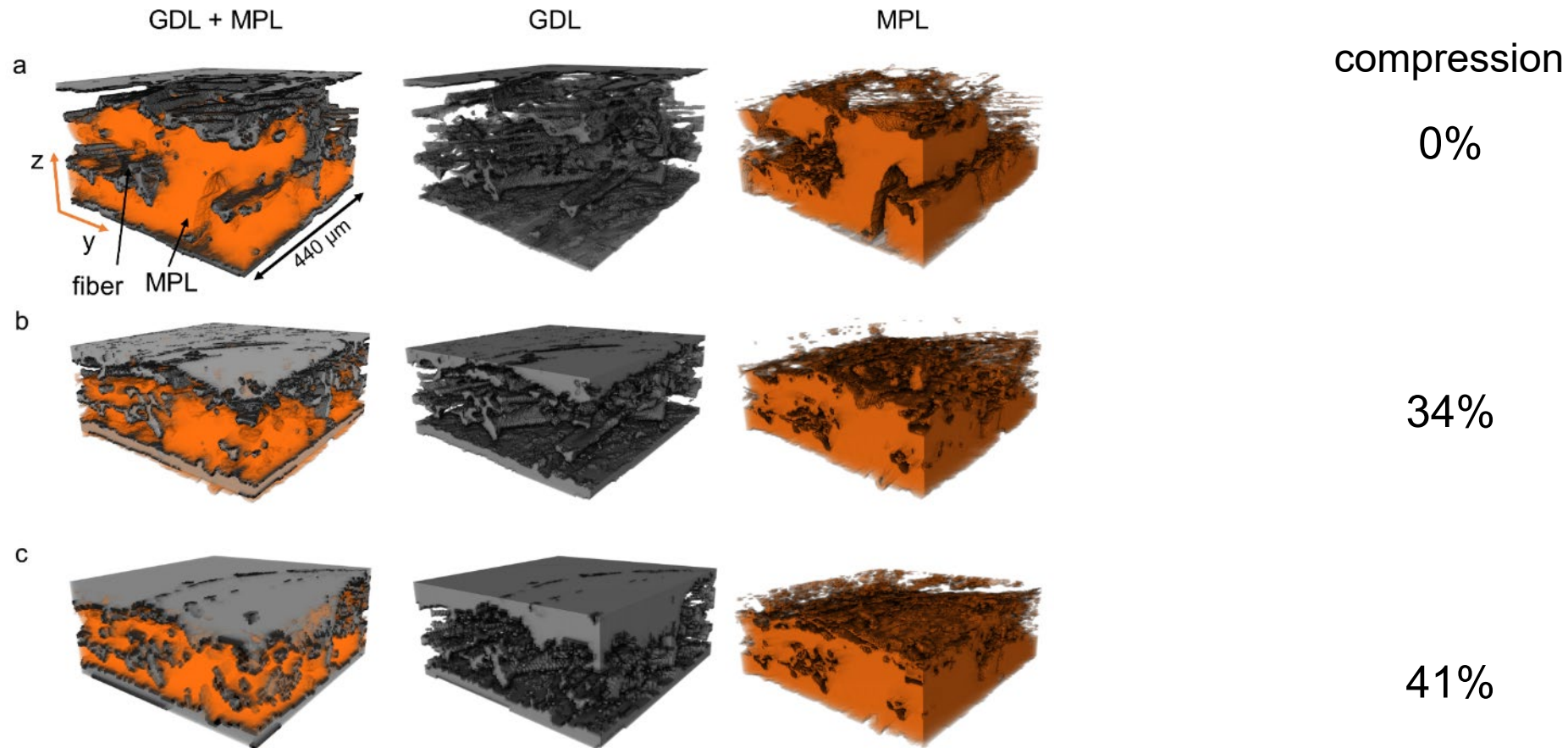
Gas diffusion media (GDM)



Compression and Morphology Determine Power

Computed tomography – with Prof. Iryna Zenyuk

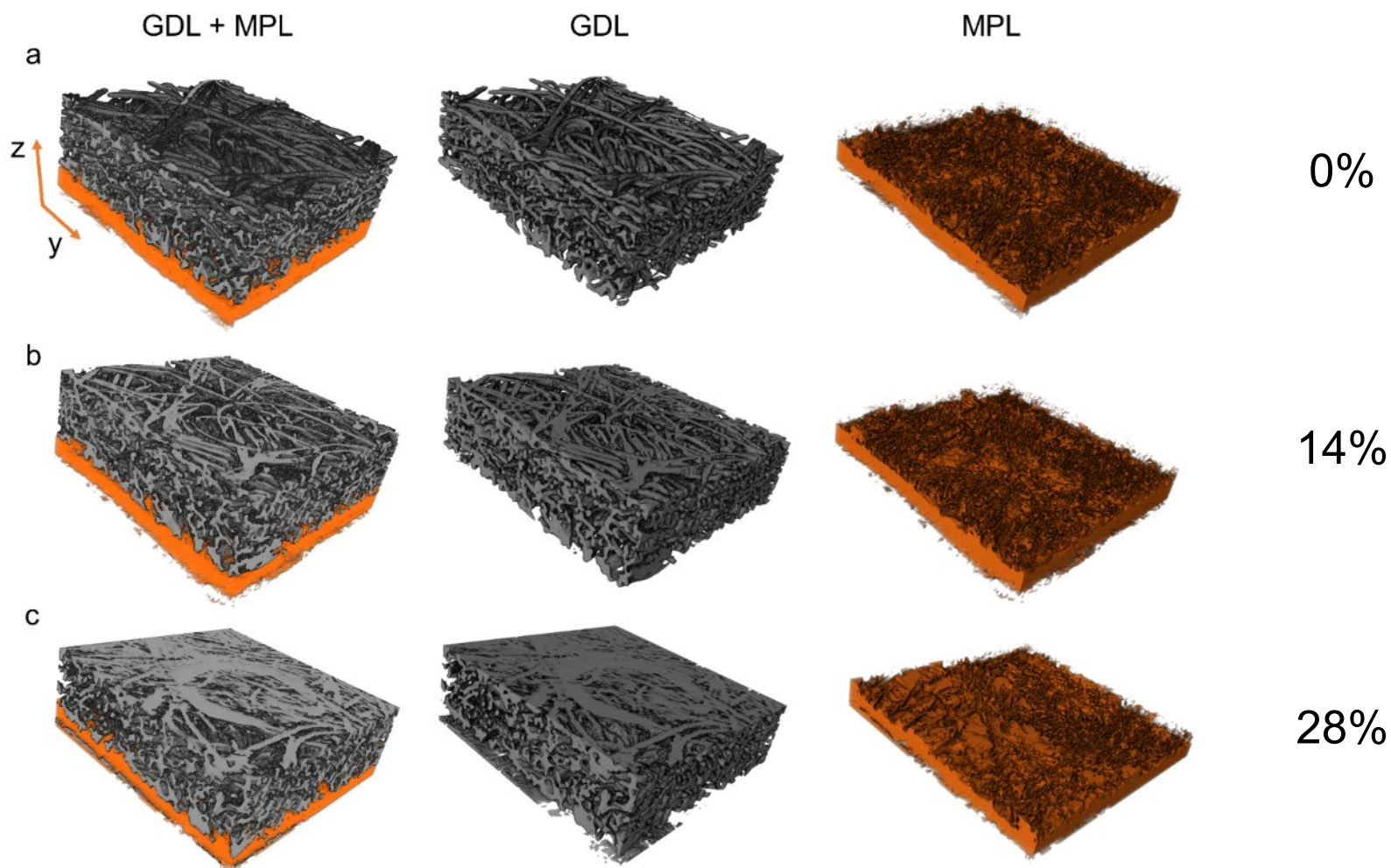
“Wet Laid” Gas Diffusion Media – SGL 29BC



- Wet Laid GDM affected by compression – MPL pushed into GDL

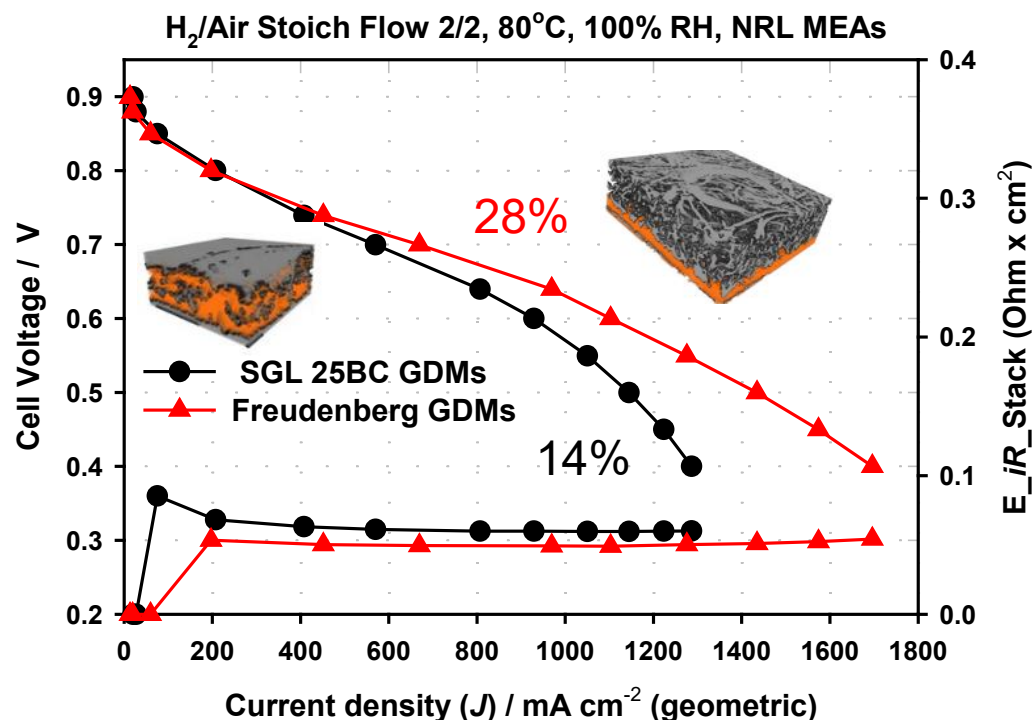
Compression and Morphology Determine Power

Dry Laid GDM - Freudenberg H2315 C2 (H23C2)



- Dry Laid GDM fairly unaffected by compression

Compression and Morphology Determine Power

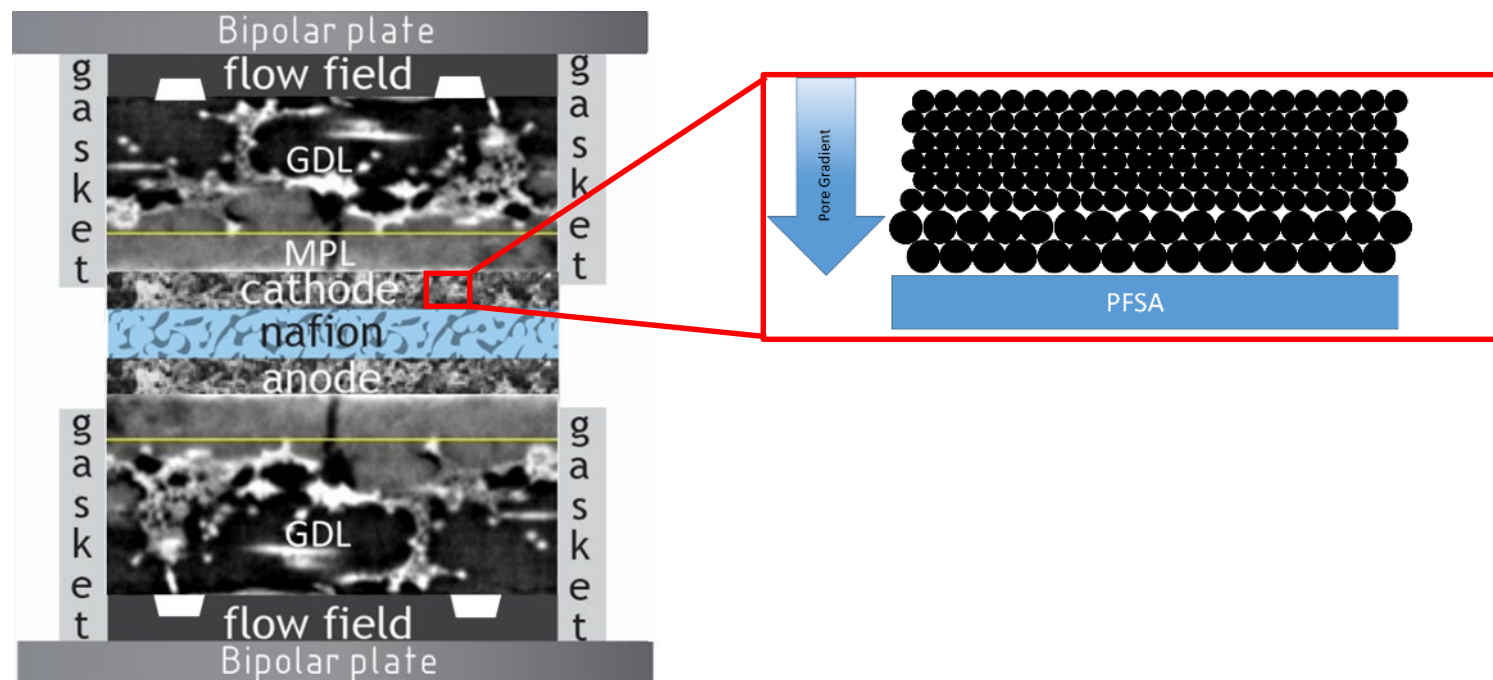


- Fuel cells made with dry laid GDM have much higher power compared to wet laid
- Lower resistance
- Better water management

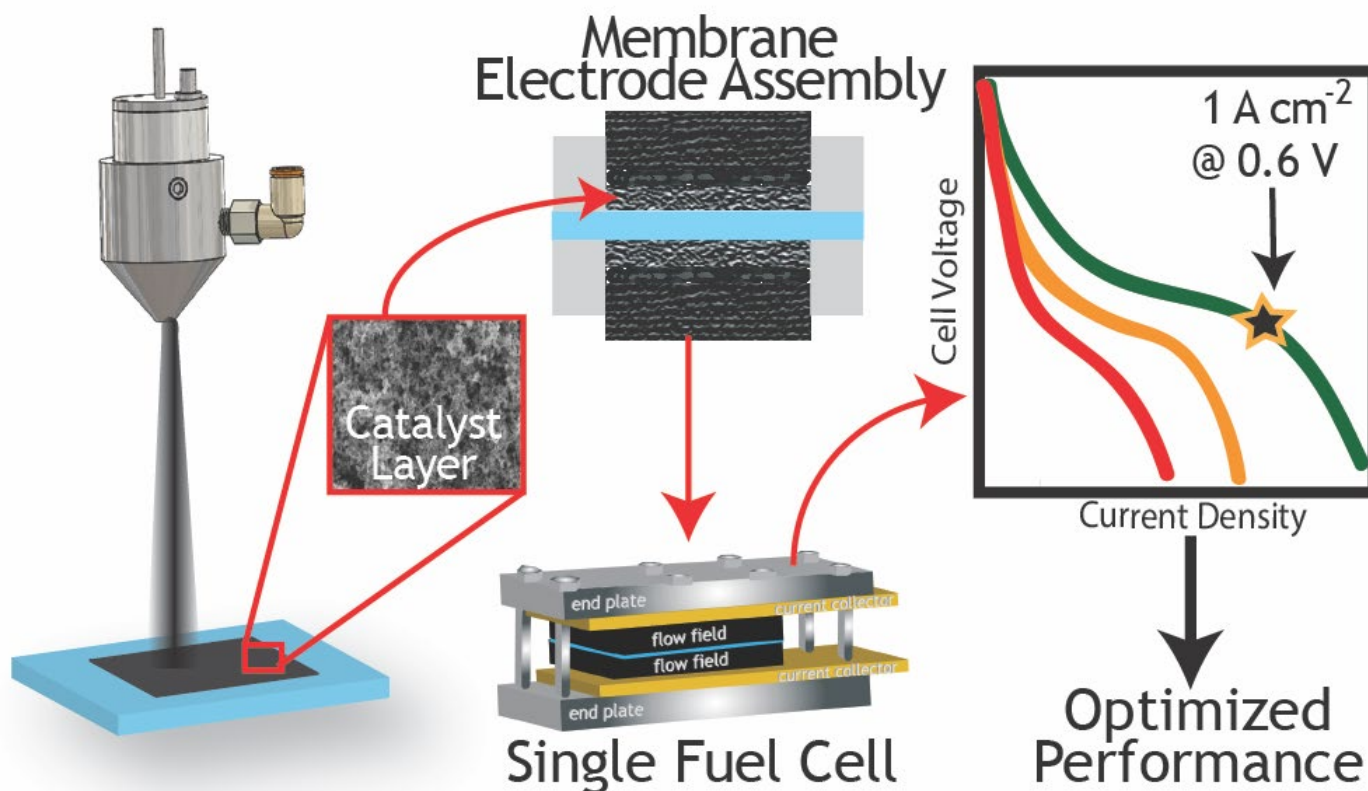
MEA ID	GDM	J @ 0.60V (mA cm ⁻²)	R @ 0.60V (Ω cm ⁻²)
NRL	Wet laid MPL	929	0.0599
NRL		1103	

Now consider porosity of catalyst layer

Catalyst layer (CL)



Spray coated catalyst coated membranes

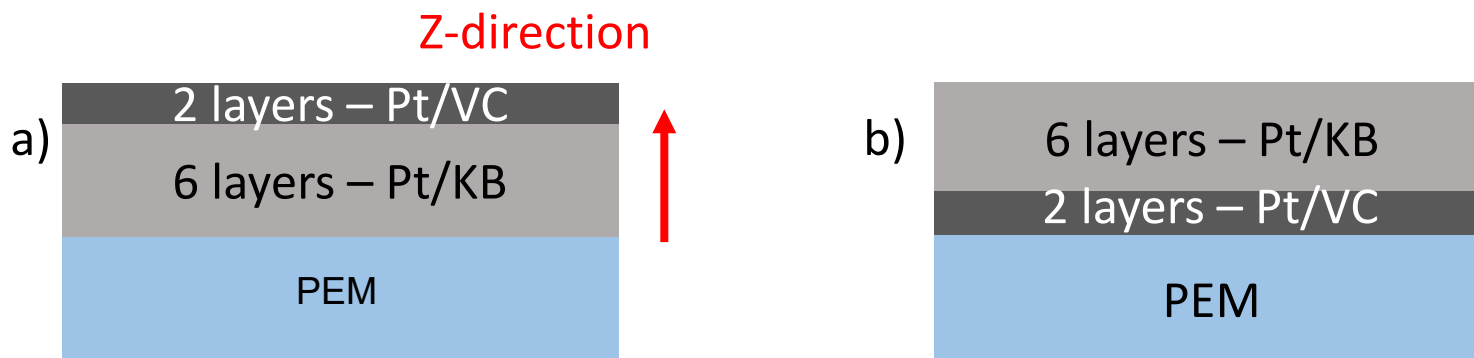


NRL creates by ultrasonic spray process
Tutorial with videos and details:

M. Sassin, Y. Garsany, B.D. Gould, K. Swider-Lyons, *Anal. Chem.*, **89**(1), 511 (2017).

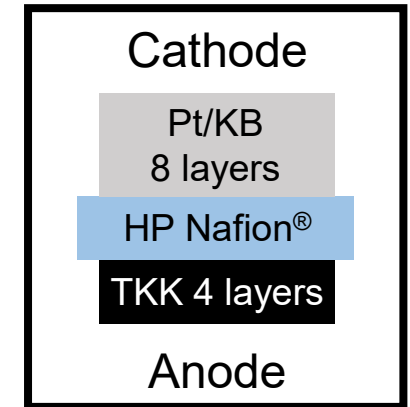
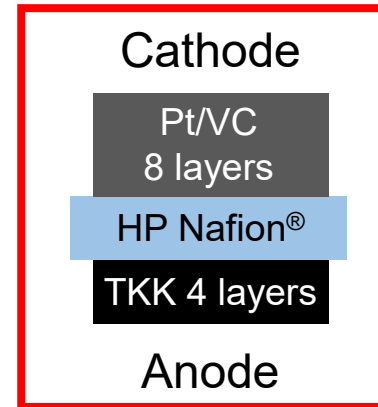
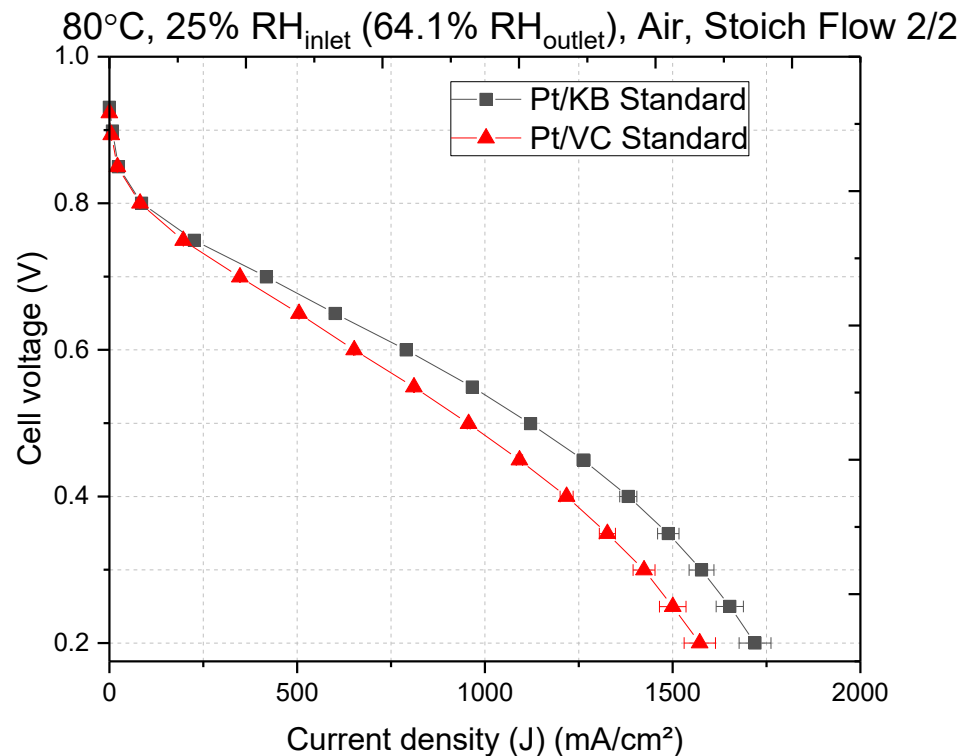
Approach to tune electrode structure by varying Carbon support

- We previously optimized catalyst layer thickness and Pt loading
 - 8 layers, Pt loading = $0.30 \text{ mg}_{\text{Pt}} \text{ cm}^{-2}$
 - 2 layers Pt/VC and 6 Pt/KB
- All CLs will be 8 layers. We vary the sub-layer thicknesses to total 8 layers.
 - (a) sub-layer 1 = 6 layers, sub-layer 2 = 2 layers
 - (b) sub-layer 1 = 2 layers, sub-layer 2 = 6 layers



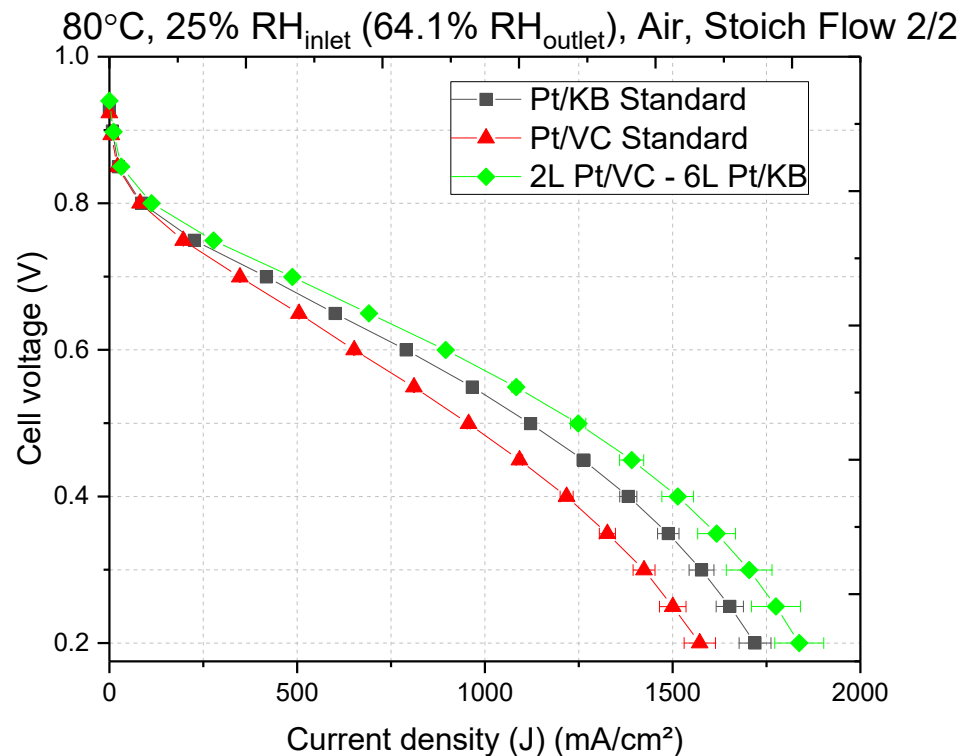
What is the preferred orientation in the Z-direction of sublayers?

NRL Graded Cathode Electrodes: Ordered vs. Disordered

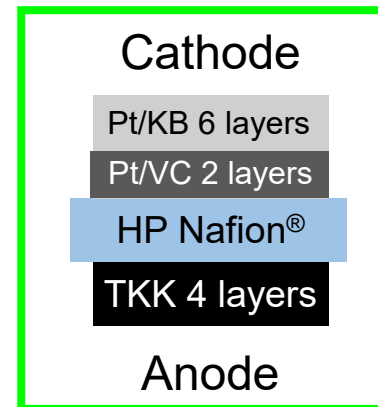
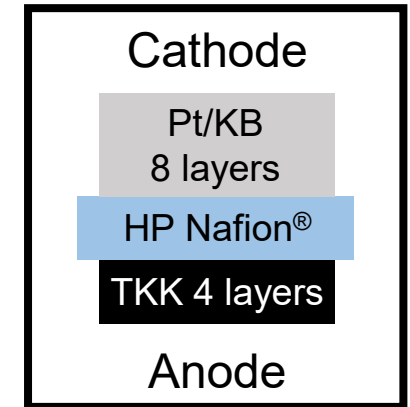
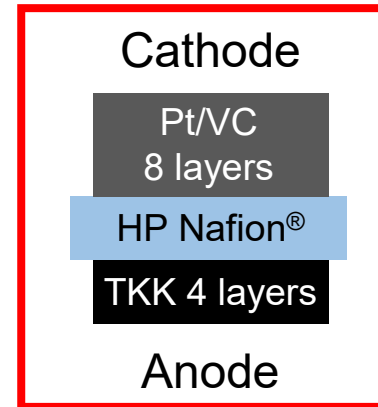


- Dry operation to examine water management
- Baseline materials show OK performance
- Pt/KB is higher performance than Pt/VC

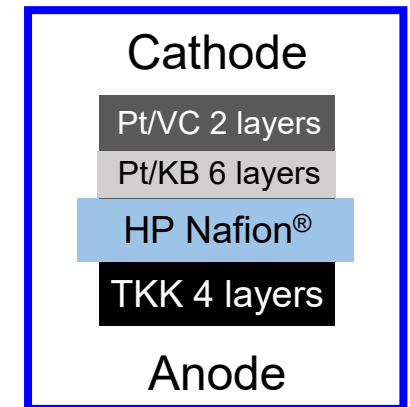
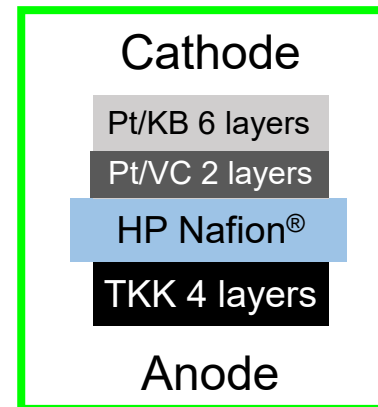
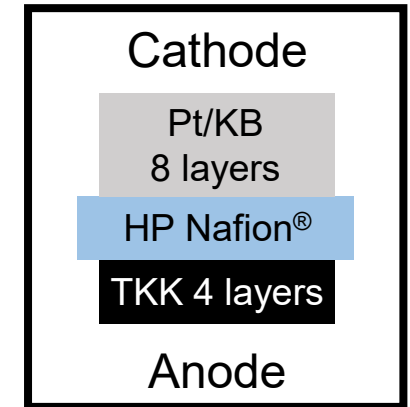
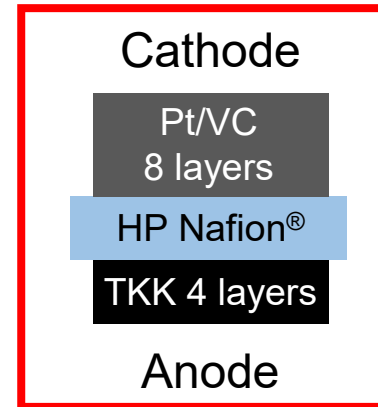
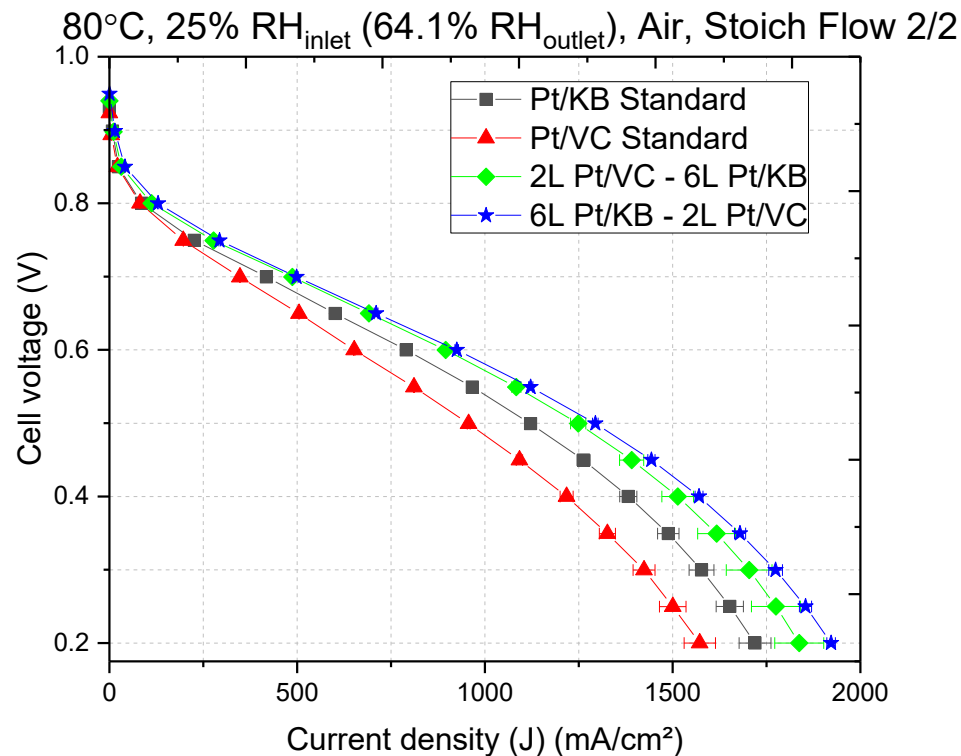
NRL Graded Cathode Electrodes: Ordered vs. Disordered



- Engineered electrode with ordered orientation of catalyst layers 13% better than either baseline material!

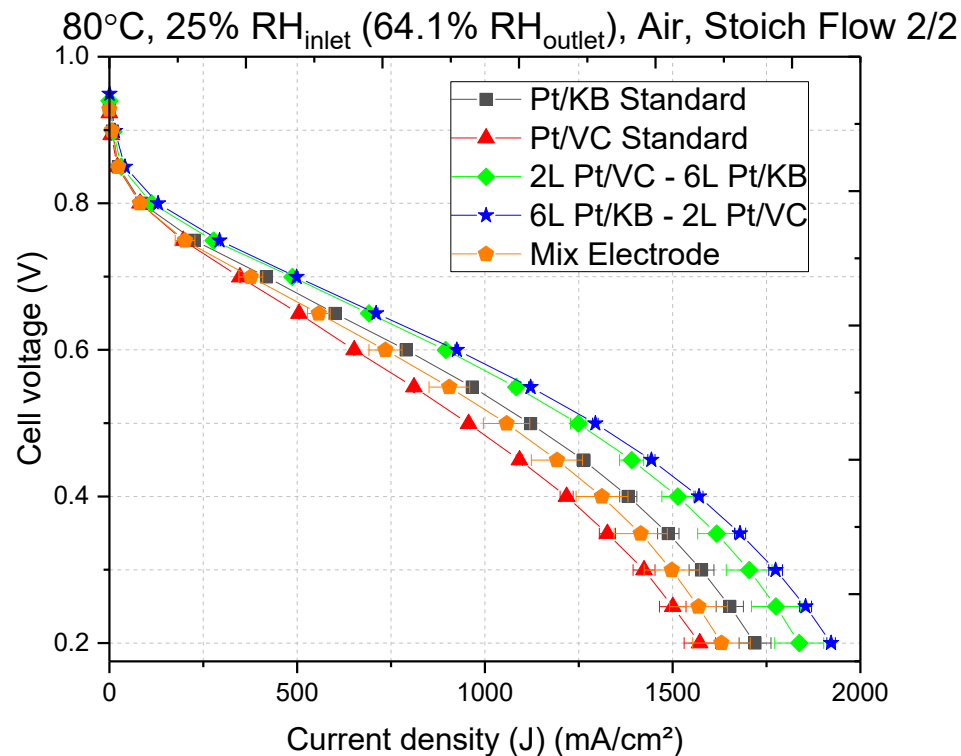


NRL Graded Cathode Electrodes: Ordered vs. Disordered

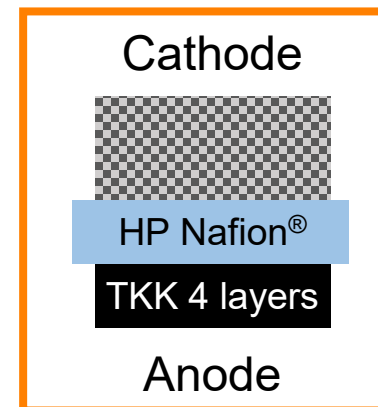
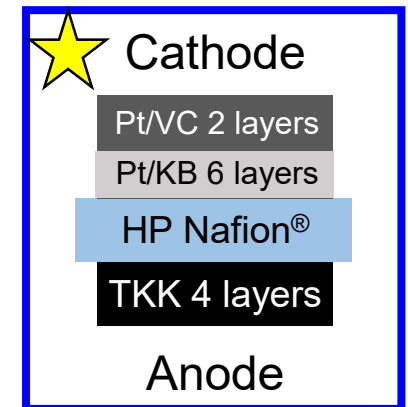
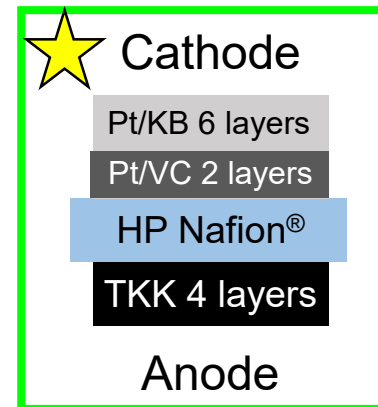
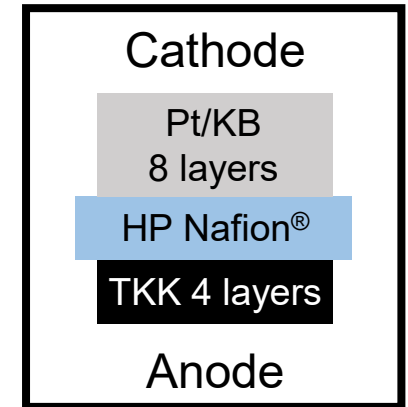
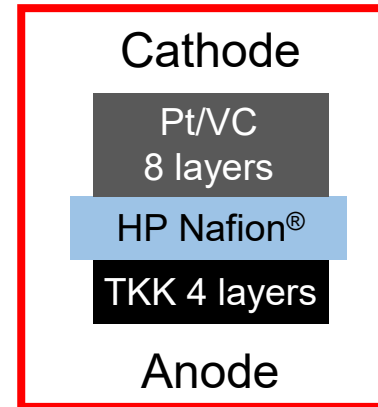


- Orientation matters slightly
- Importance of buried interface???

NRL Graded Cathode Electrodes: Ordered vs. Disordered

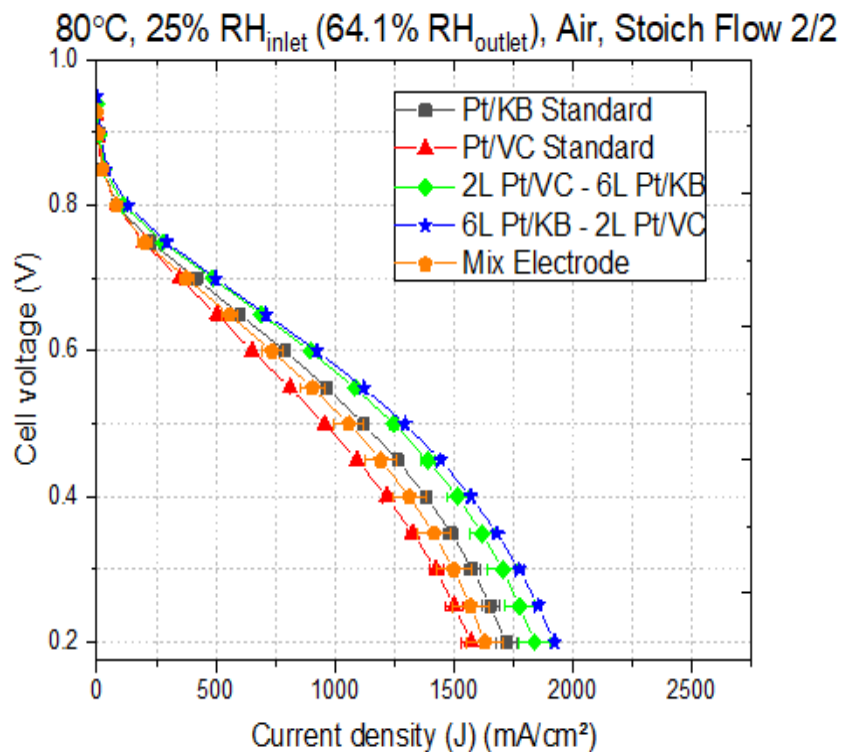


- Random mixture of materials is an average of the two baseline materials

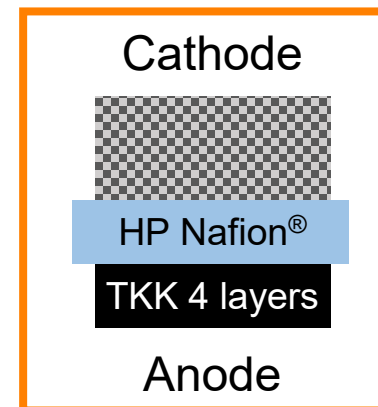
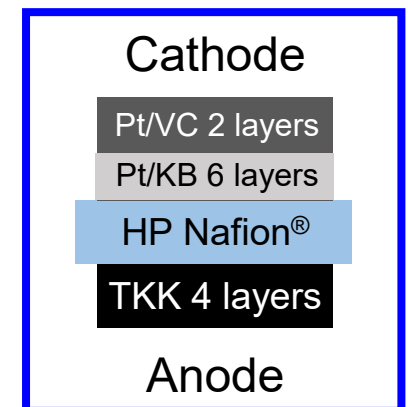
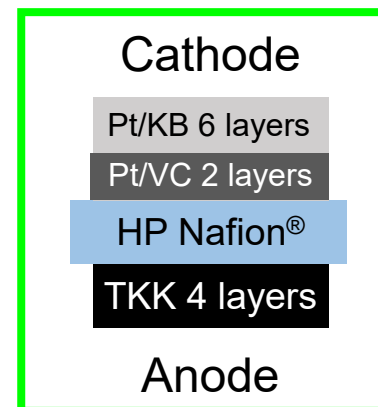
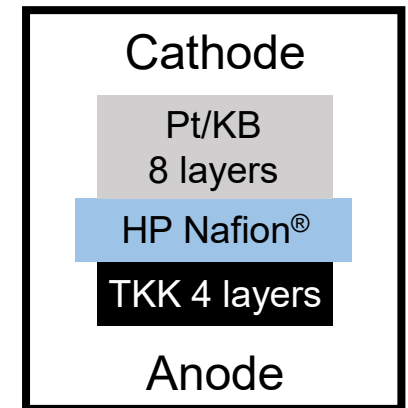
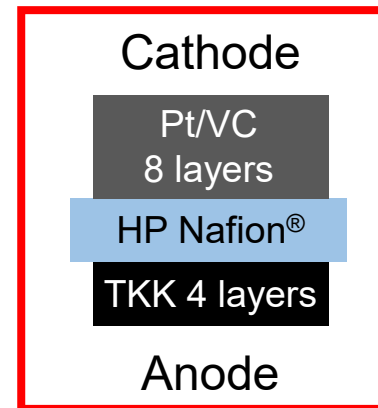


2:6 Blend of Pt/VC : Pt/KB
8 layers

NRL Graded Cathode Electrodes: Ordered vs. Disordered

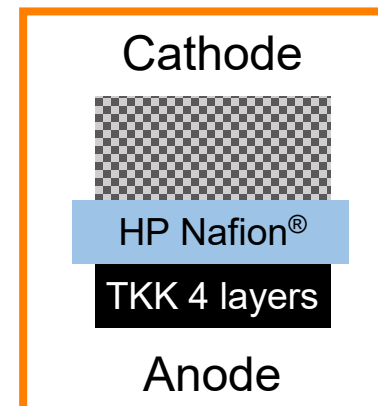
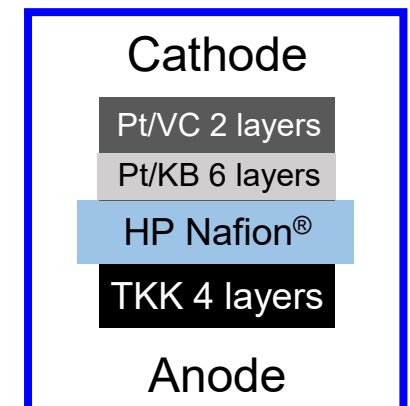
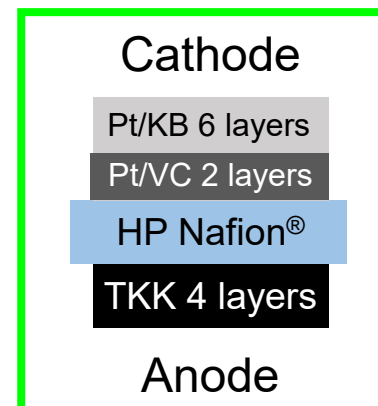
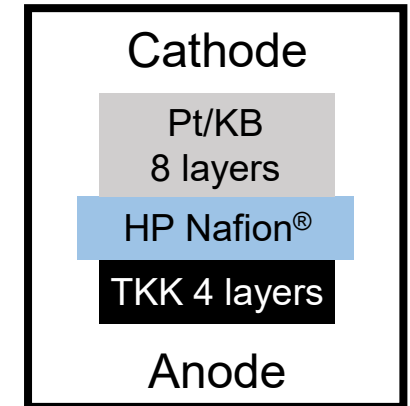
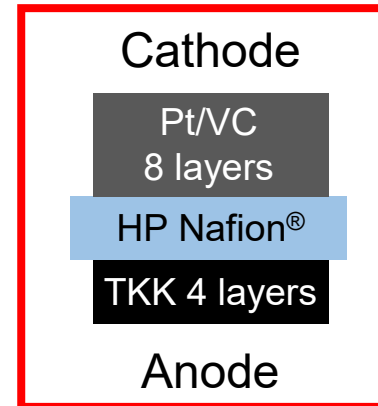
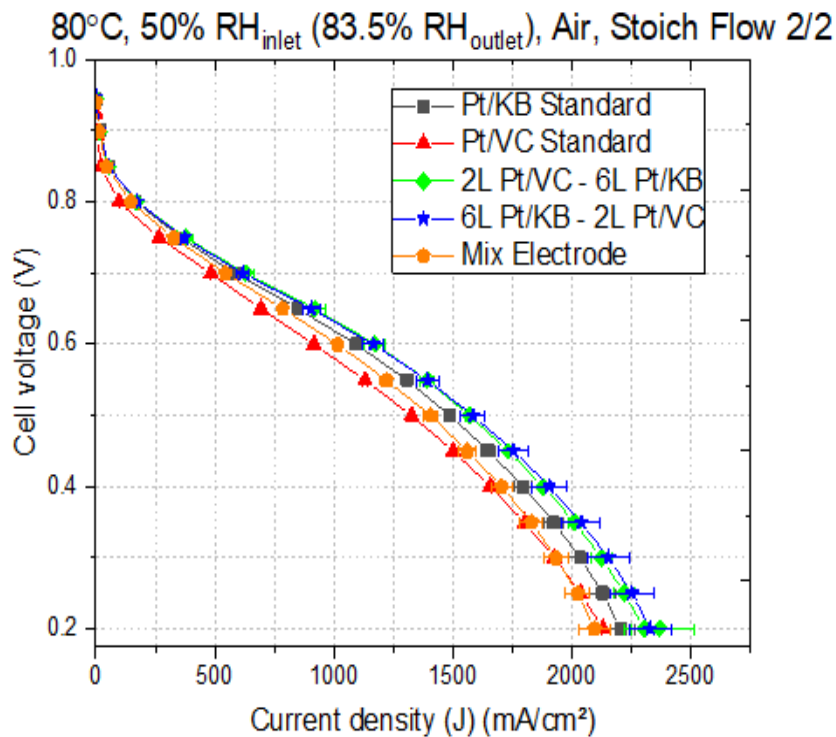


- Let's examine the influence of RH



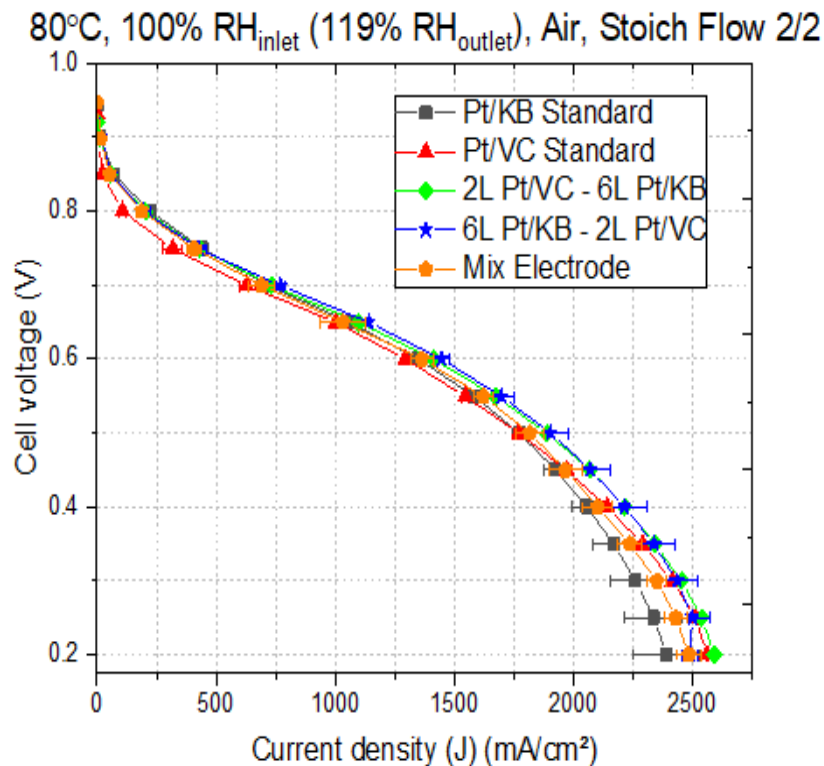
2:6 Blend of Pt/VC : Pt/KB
8 layers

NRL Graded Cathode Electrodes: Ordered vs. Disordered



2:6 Blend of Pt/VC : Pt/KB
8 layers

NRL Graded Cathode Electrodes: Ordered vs. Disordered



Cathode

Pt/VC
8 layers

HP Nafion®

TKK 4 layers

Anode

Cathode

Pt/KB
8 layers

HP Nafion®

TKK 4 layers

Anode

Cathode

Pt/KB 6 layers
Pt/VC 2 layers

HP Nafion®

TKK 4 layers

Anode

Cathode

Pt/VC 2 layers
Pt/KB 6 layers

HP Nafion®

TKK 4 layers

Anode

Cathode



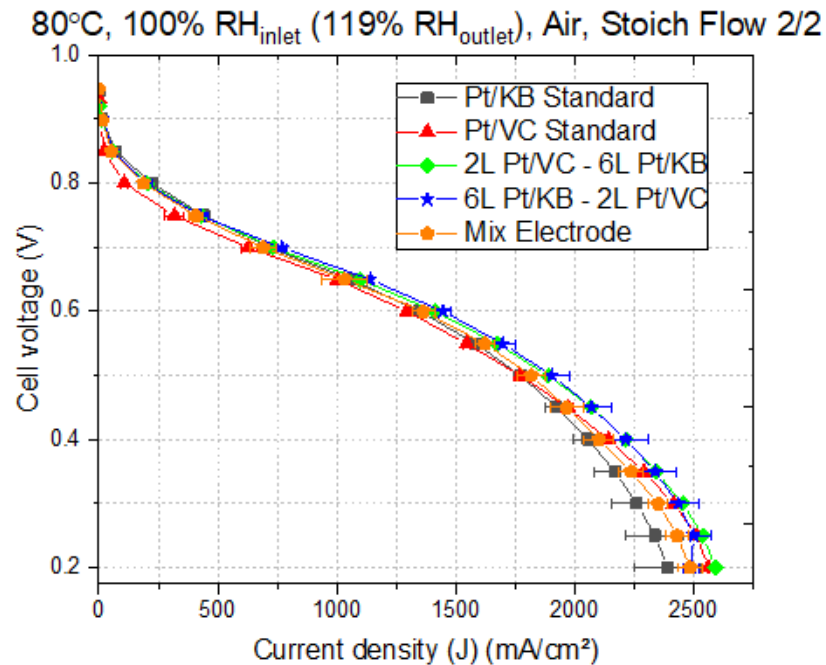
HP Nafion®

TKK 4 layers

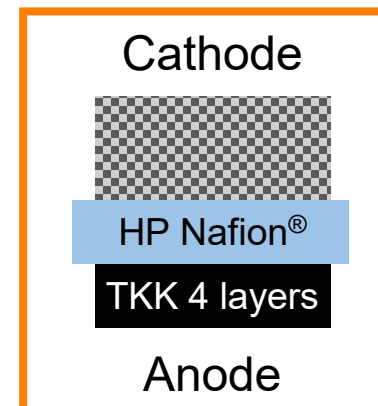
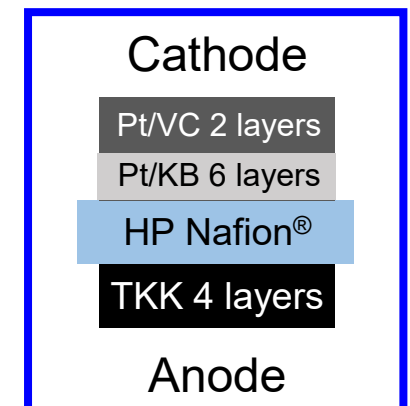
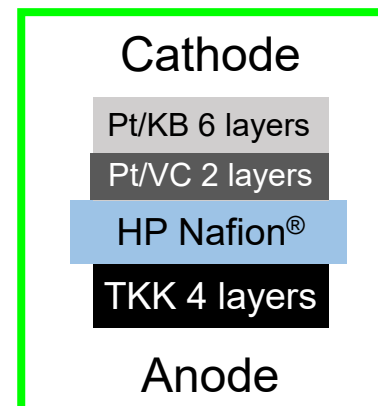
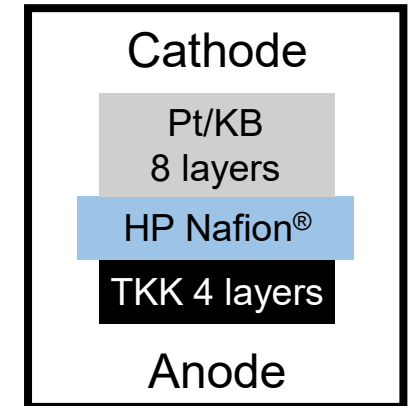
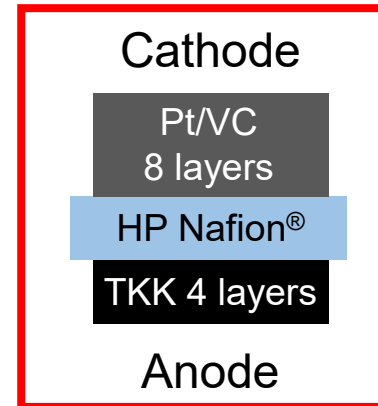
Anode

2:6 Blend of Pt/VC : Pt/KB
8 layers

NRL Graded Cathode Electrodes: Ordered vs. Disordered

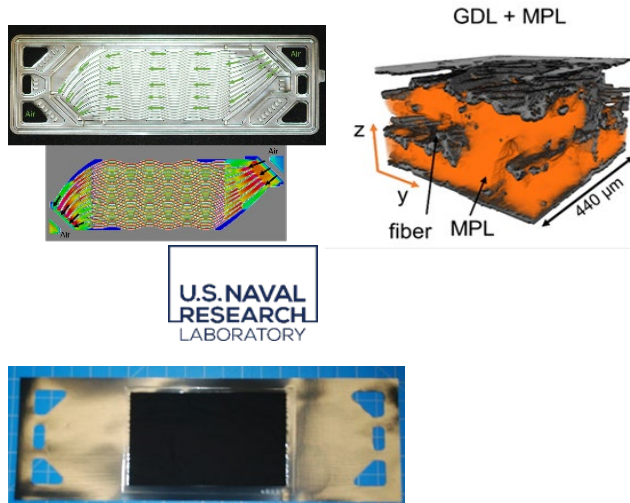


- Rank order of structure is the same over a range of RH
- Benefit of structure diminishes as RH increases
- CLUE: Catalyst layer structure influences cell hydration



2:6 Blend of Pt/VC : Pt/KB
8 layers

Manufacturing Development



MRL 4 → 7

World-class S&T



NWUAV PROTON EXCHANGE MEMBRANE (PEM) FUEL CELL FOR UNMANNED SYSTEMS

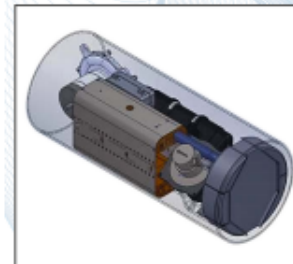
Clean and Reliable Energy

Why Use a Fuel Cell?

- Low maintenance
- Low operating cost
- Low audible signature
- Instant on – remote operation
- Clean power with a low thermal signature
- More energy efficient compared to other energy sources

How Does a Fuel Cell Work?

Hydrogen flows through passages to the anode, the catalyst allows the hydrogen molecules to separate into protons and electrons. Protons pass through the membrane to the other side of the cell. Electrons follow a path to the cathode; this produces the electricity. Then the electrons react with oxygen and the protons that moved through the membrane at the cathode producing water.

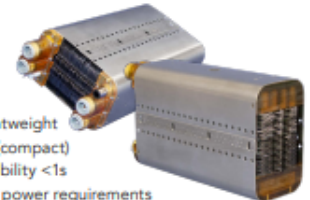


Each cell in the stack generates 1 volt of electricity and when combined in series they produce all of the power for your unmanned system.



Features:

- Reliable and lightweight
- Small envelope (compact)
- Quick start capability <1s
- Scalable to your power requirements
- System layout is customizable to fit your physical space
- Long term storage capable in fueled condition (1+years)



PEM SPECIFICATIONS

Model	NWFC-1500
Rated Power (Net)	1500 W
Rated Performance	24V @ 50A
Number of Cells	48
Hydrogen Consumption at Rated Power	1.7 g/min (10.2 lpm) 2.7 gpm
Hydrogen Consumption at Cruise Power (500 W)	0.5 g/min (2.9 lpm) 0.8 gpm
Hydrogen Supply Pressure	10-20 psi 69-138 kPa
Weight*	9.1 lbs 4128 grams
System Dimensions (Diameter x Length)	6.8 x 16 in 17.3 x 40.6 cm
Sound Rating (Max)	66 db
Power-to-Weight Ratio	360 W/kg
System Efficiency at Cruise (500 W)	53%
Ambient Operating Temperature	23°F to 113°F -5° to 45°C
Time Between Overhaul	500 hours
Service Life	1500 hours

* Excludes fuel tank. Includes balance of plant and radiator, and in flight cell voltage monitoring.
NOTES: This product is under development, a reduction in weight, improvements to the power-to-weight ratio, and increased TBO and service life are expected.
High-performing Membrane Electrode Assembly (MEA) under development.

Northwest UAV
A GLOBAL COMPANY

REV D AS9100 | ISO9001 Certified

11160 SW Durham Lane, Suite 1 | McMinnville, OR 97128
Office: 503.434.6845 | Fax: 503.217.6080 | www.nwuav.com

Where Precision and Reliability Soar!

The materials contained in this brochure are provided for information only, "as is" without any warranties, express or implied, including warranties of merchantability, fitness of purpose and non-infringement of third-party intellectual property. While every effort is made to ensure that the information and specifications are accurate, the scope of information is limited by nature. Northwest UAV Propulsion Systems reserves the right to make changes to the Products and Proven described in the Product Brochure at any time, without notice. The application of our products is dependent upon the operating mission, environmental conditions, loads and other factors, none of which can be guaranteed by this brochure. Any technical advice or information obtained from this Product Brochure is given in good faith and without charge, and such advice and information is provided by Northwest UAV Propulsion Systems without assumption of liability or obligation. This brochure and the information it contains is the work product of Northwest UAV Propulsion Systems ("NWUAV"). All title, ownership rights and intellectual property rights in and relating to this brochure is owned by NWUAV or used by NWUAV through preauthorization by third parties and cannot be used without its express prior written permission.

Conclusions

- Structure (porosity) is really important!
- Proper channel design in bipolar plates needed to reject water
 - Repeatable structure needed for good stack performance
- Compression of gas diffusion media has very large impact on performance at 0.6 V
 - Affects water management through changes in pore sizes
 - The design of the GDM also has a profound affect.
- Control of porosity in the catalyst layers is also really important
 - Controlled through the selection of ionomer
 - Fabrication process
 - Mixtures of porous catalysts
- New methods such as computed tomography very useful
- Holistic approached needs for high power systems

The future of flight?



<https://www.skai.co/>

NRL Research On Compression/MEA Optimization

- C. Netwall, B. D. Gould, J. A. Rodgers, N. J. Nasello, K. Swider-Lyons, *J. Power Sources*, **227**, 137 (2013).
- M. B. Sassin, Y. Garsany, B.D. Gould, K. Swider-Lyons, *J. Electrochem. Soc.*, **163**, F808 (2016).
- M. Sassin, Y. Garsany, B.D. Gould, K. Swider-Lyons, *Anal. Chem.*, **89(1)**, 511 (2017).
- R. W. Atkinson III, M. W. Hazard, J. A. Rodgers, R. O. Stroman, B. D. Gould, *ECS Trans.*, **75(14)**, 531 (2016).
 - JECS 2018, 165 (11), F1002.
- R. W. Atkinson III, Y. Garsany, B. D. Gould, K. E. Swider-Lyons, I. V Zenyuk, *ACS Appl. Energy Mater.*, **1(1)**, 191 (2018).
- Y. Garsany, et al, Short side chain ionomers, JECS, 165 (5) F381-F391 (2018)
- Y. Garsany, et al, Journal of Power Sources 408 (2018) 38–45.

Acknowledgements



Prof. Iryna Zenyuk – UC Irvine - for MicroCT work
ONR/NRL Summer Faculty Member

Megan Sassin
Chris Netwall