Microbial Fuel Cell Technologies--MxCs: Can they scale?

(Yes!)

Bruce E. Logan
Penn State University

Engineering Energy & Environmental Institute

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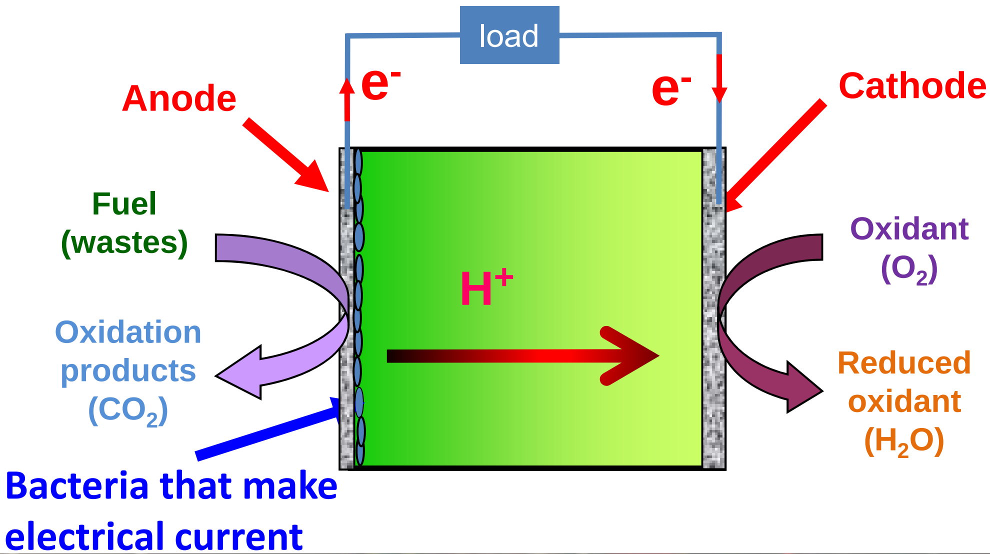
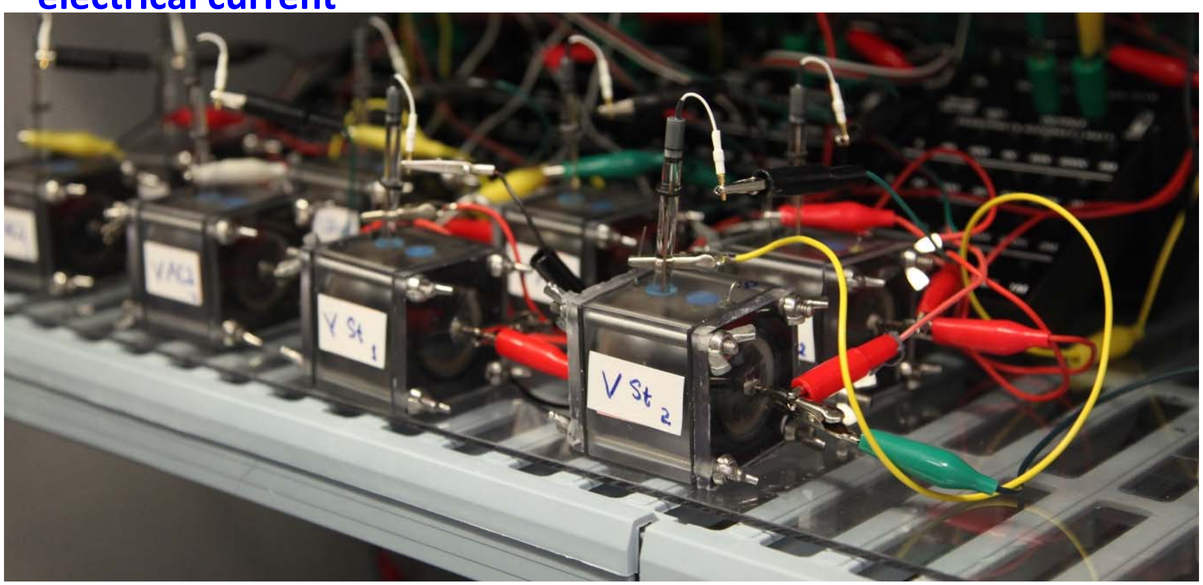
MFCs

Electrical power generation in a Microbial Fuel Cell (MFC) using exoelectrogenic microorganisms

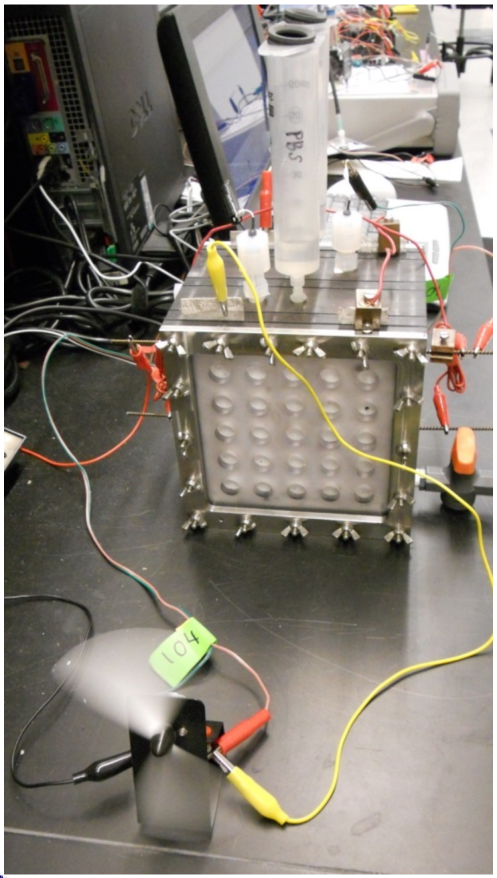


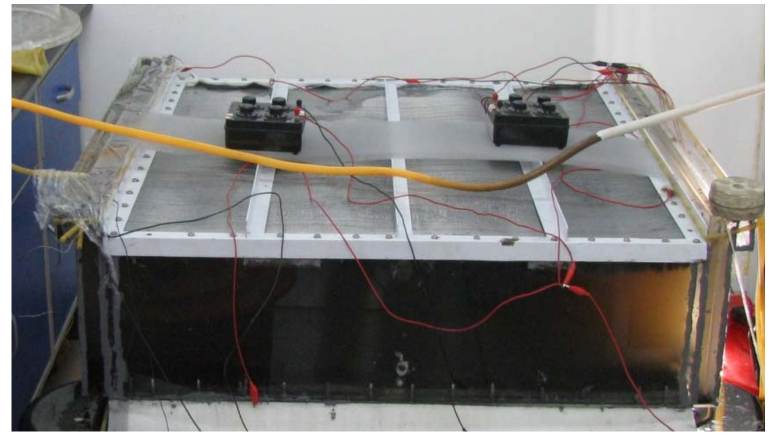


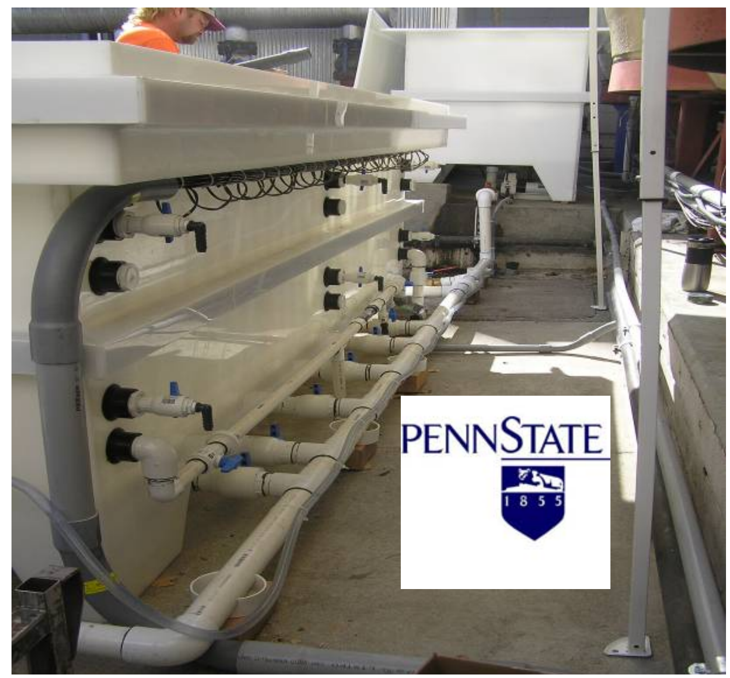
Liu et al. (2004) *Environ. Sci. Technol.*

Scaling up MFCs & MECs

M**F**Cs= fuel cells, make electricity
M**E**Cs= electrolysis cells, make H_2







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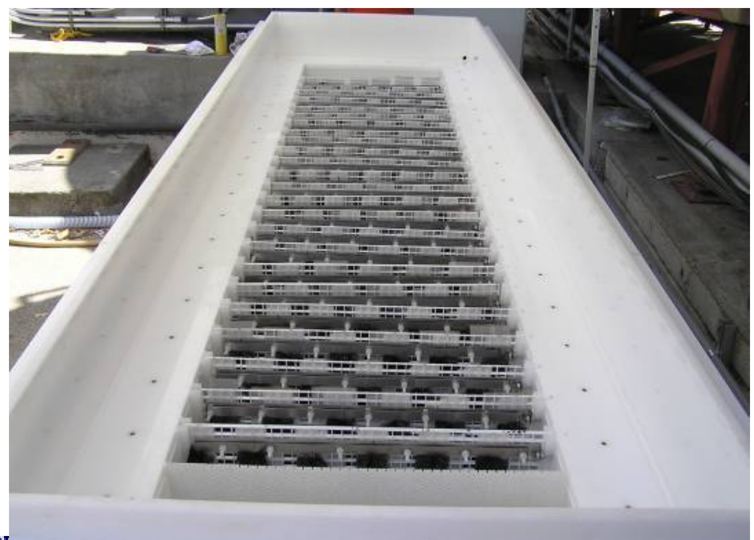
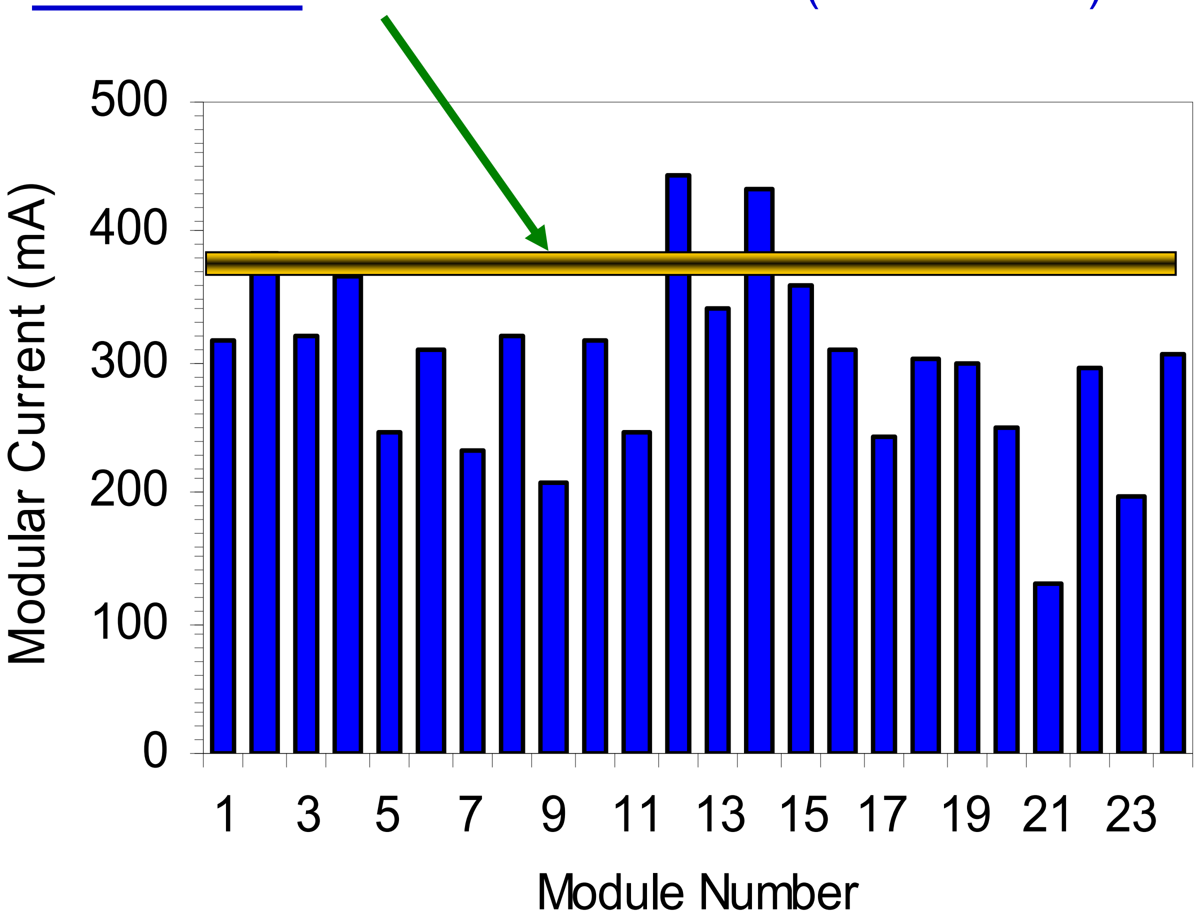
MEC Reactor that has 24 modules with a total of 144 electrode pairs (1000 L)



Cusick et al. (2011) *Appl. Microbiol. Biotechnol.*

Individual module performance of the MEC treating Wastewater

Predicted: 380 mA/module (total of 9.2 A)



H_2 initially produced, but it all was converted to CH_4

Elec. Energy input= 6 W/m³
Energy Out = 99 W/m³

16× more energy recovered than electrical energy put into the process

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Cusick et al. (2011) *Appl. Microbiol. Biotechnol.*

MFC Architecture

Estimates for MFCs

- **100 € /m² or $130/m²**

Estimates for MECs

- **100 € /m² or $130/m²**

CHEMSUSCHEM
ChemPubSoc Europe

DOI: 10.1002/cssc.201100732

Bioelectrochemical Systems: An Outlook for Practical Applications

Tom H. J. A. Sleutels,[a] Annemiek Ter Heijne,*[b] Cees J. N. Buisman,[a, b] and Hubertus V. M. Hamelers[a, b]

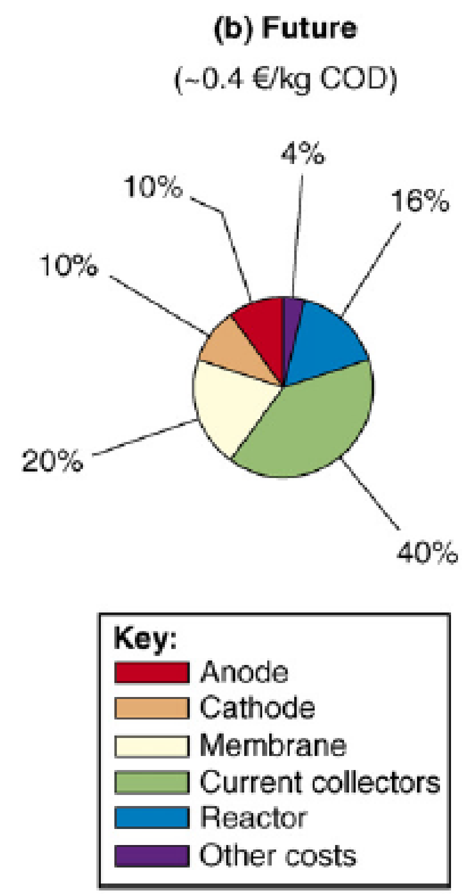
Bioelectrochemical systems (BESs) hold great promise for sustainable production of energy and chemicals. This review addresses the factors that are essential for practical application of BESs. First, we compare benefits (value of products and cleaning of wastewater) with costs (capital and operational costs). Based on this, we analyze the maximum internal resistance (in mΩm^2) and current density that is required to make microbial fuel cells (MFCs) and hydrogen-producing microbial electrolysis cells (MECs) cost effective. We compare these maximum resistances to reported internal resistances and current densities with special focus on cathodic resistances. Whereas the current densities of MFCs still need to be increased considerably (i.e., internal resistance needs to be decreased), MECs are closer to application as their current densities can be increased by increasing the applied voltage. For MFCs, the production of high-value products in combination with electricity production and wastewater treatment is a promising route.

Review
Cell PRESS

Towards practical implementation of bioelectrochemical wastewater treatment

René A. Rozendal[1,2,3], Hubertus V.M. Hamelers[2], Korneel Rabaey[1], Jurg Keller[1] and Cees J.N. Buisman[2,3]

[1] Advanced Water Management Centre, The University of Queensland, St. Lucia, QLD 4072, Australia
[2] Sub-department of Environmental Technology, Wageningen University, Bomenweg 2, P.O. Box 8129, 6700 EV Wageningen, The Netherlands
[3] Wetsus, Centre for Sustainable Water Technology, Agora 1, P.O. Box 1113, 8900 CC Leeuwarden, The Netherlands



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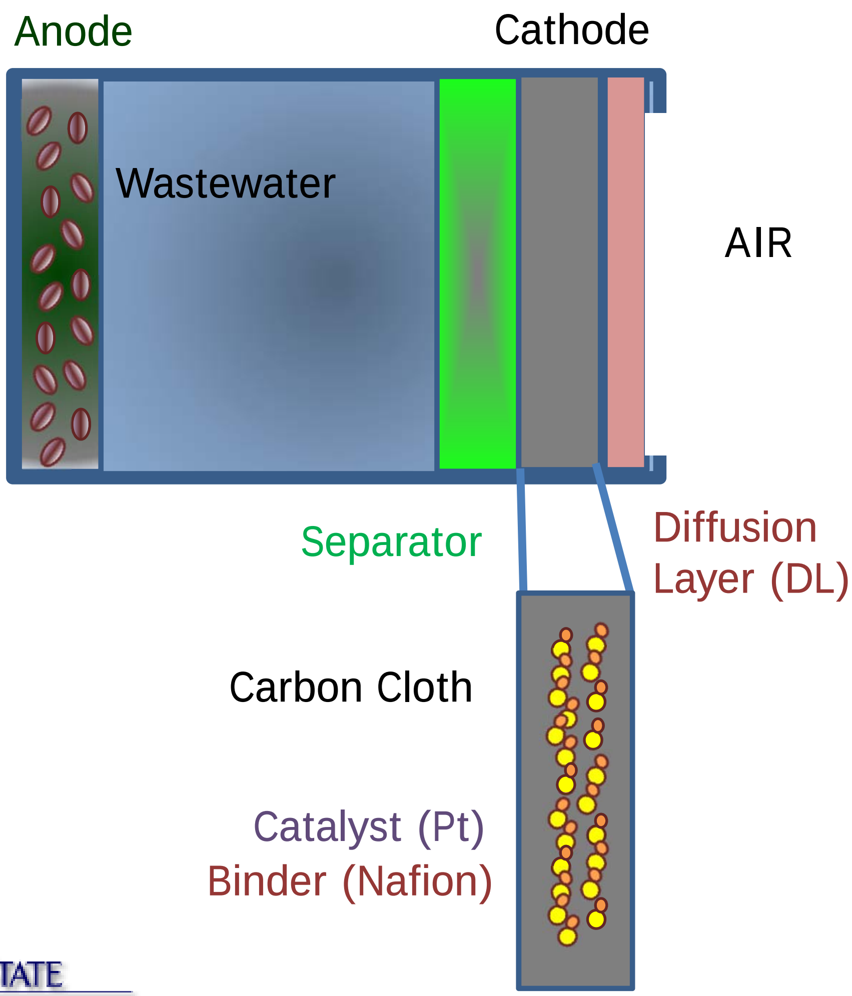
MFC Architecture



Original systems: $/m² (US)

- Carbon cloth~ $1,000
- Pt catalyst~ $ 500
- Binder~ $ 700
- DL (PTFE)~ $ 0.30
- Separator~ $ 1

TOTAL $2200

New systems: $/m² (US)

- Anode $20
- Cathode $15
  - SS + CB= $20
  - Catalyst (AC)=$0.40
  - Binder= $1.5
  - DL (PDMS)= $0.15
- Separator $ 1

TOTAL $36

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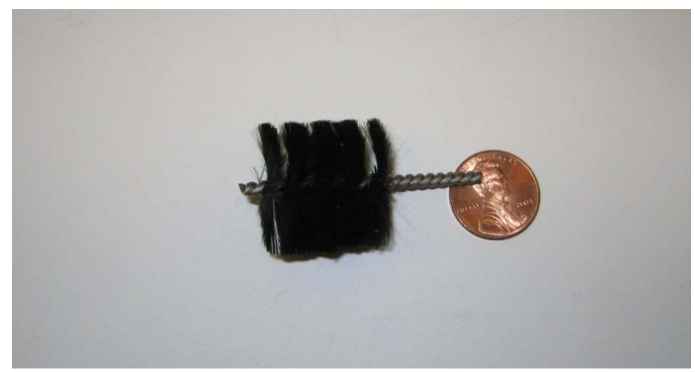
MFC Materials

Anode: Graphite brush electrode

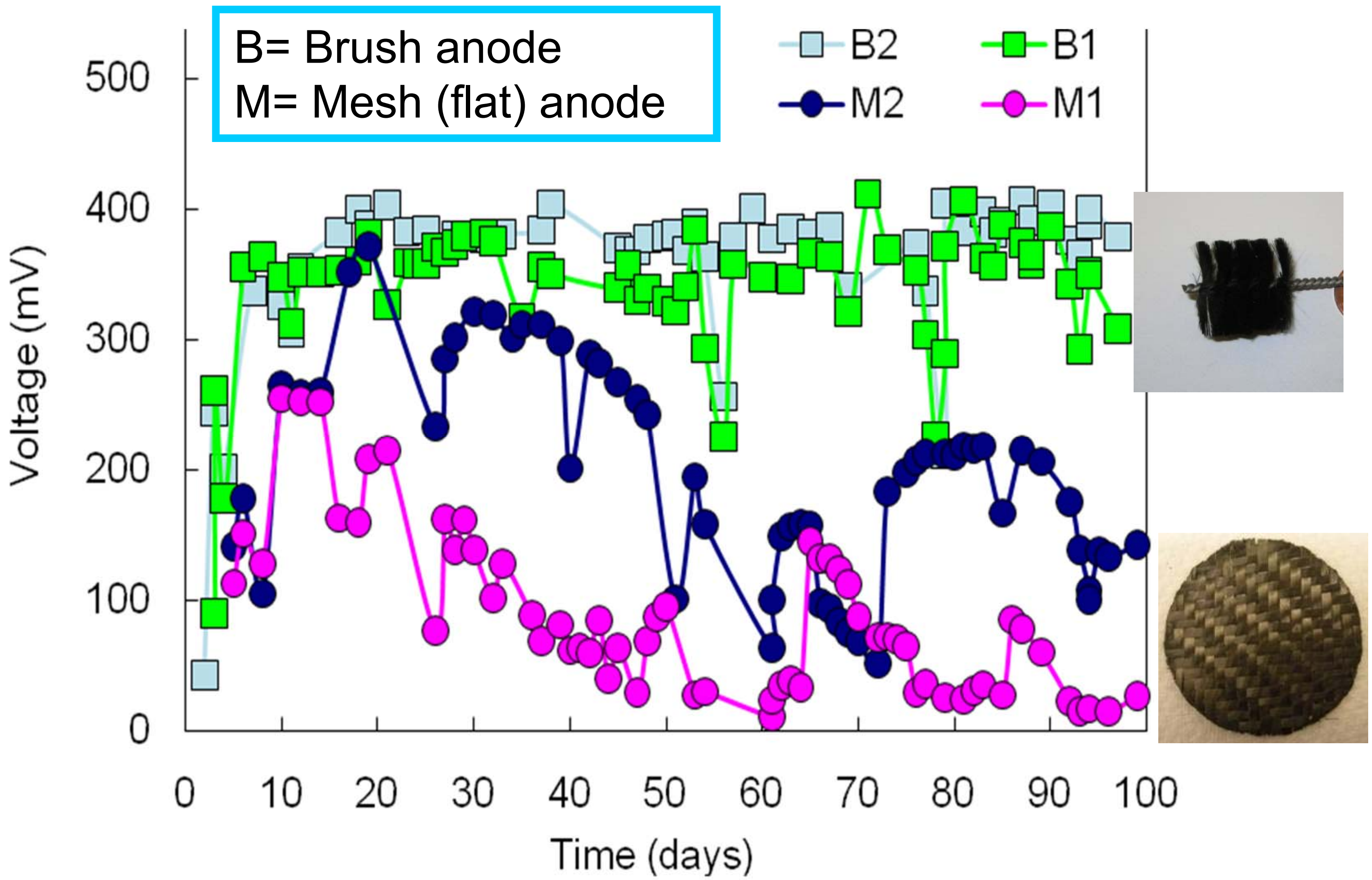
- Graphite fibers commercially available (used in tennis rackets, airplanes, etc.)
- Easy to manufacture
- Fiber diameter- 6-10 µm a good match to bacteria (~1 µm)
- High surface area per volume- Up to 15,000 m^2/m^3



Logan et al. (2007) *Environ. Sci. Technol.*

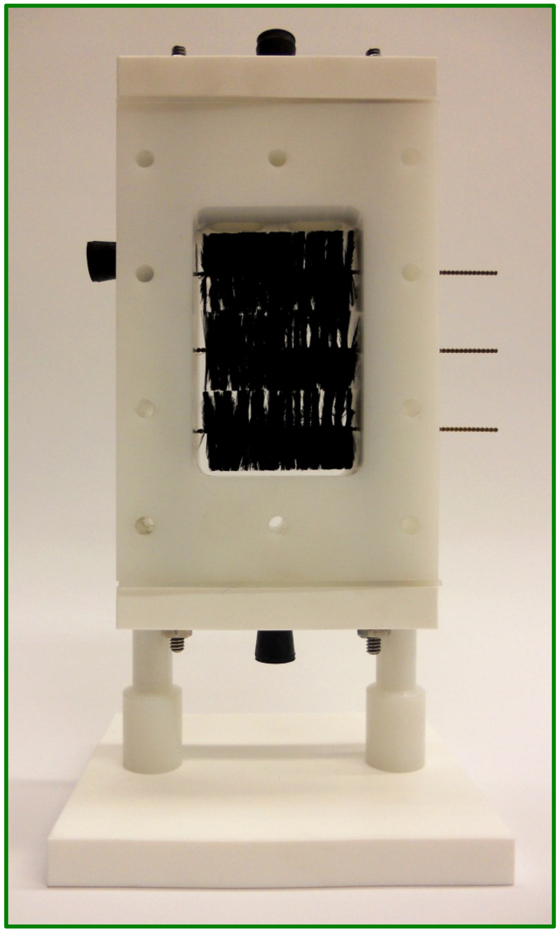
Voltage Production Results:

Brushes still work better than flat mesh

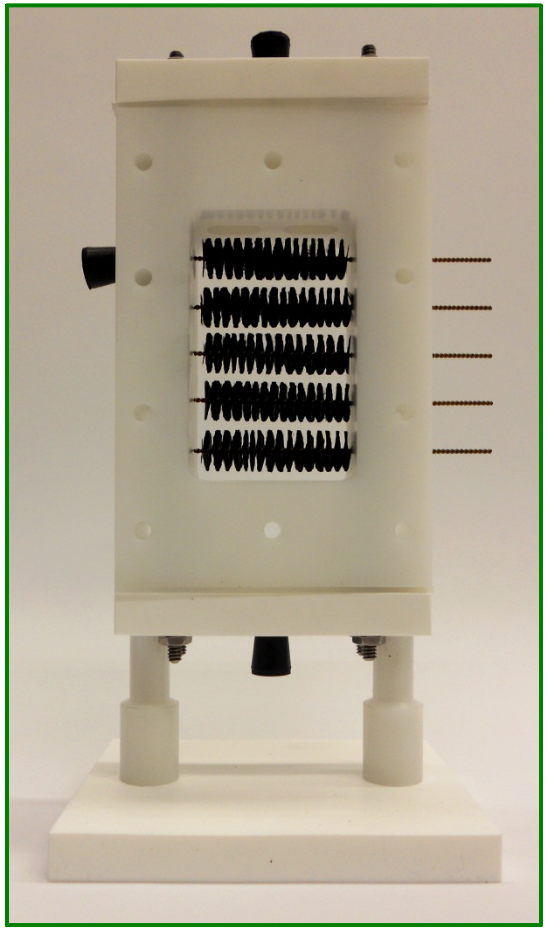


Hays and Logan (2011) *J. Power Sources*

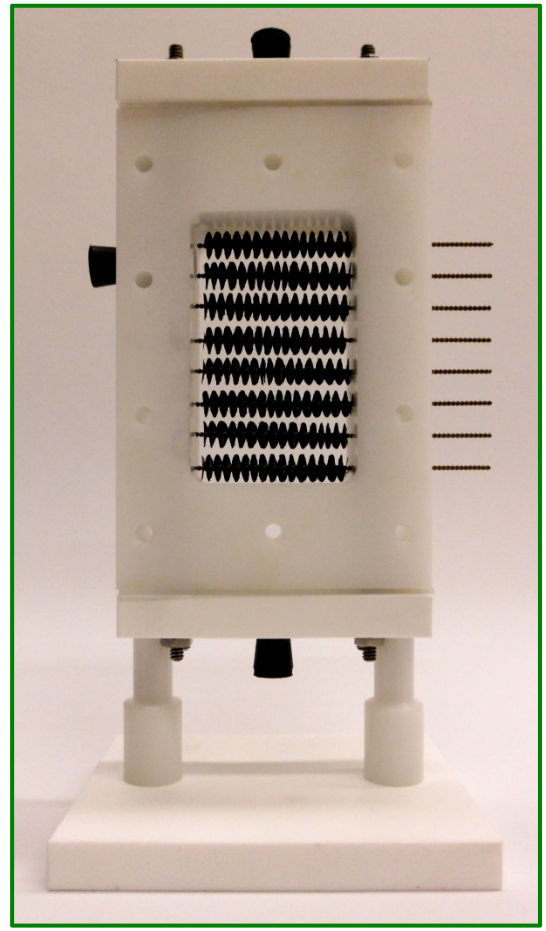
Multi-electrode MFCs



3 brushes (**R3**)
3500 m^2/m^3



5 brushes (**R5**)
2800 m^2/m^3



8 brushes (**R8**)
2900 m^2/m^3

Electrode area (2.5 cm diameter brush/chamber width = 40 m^2/m^3

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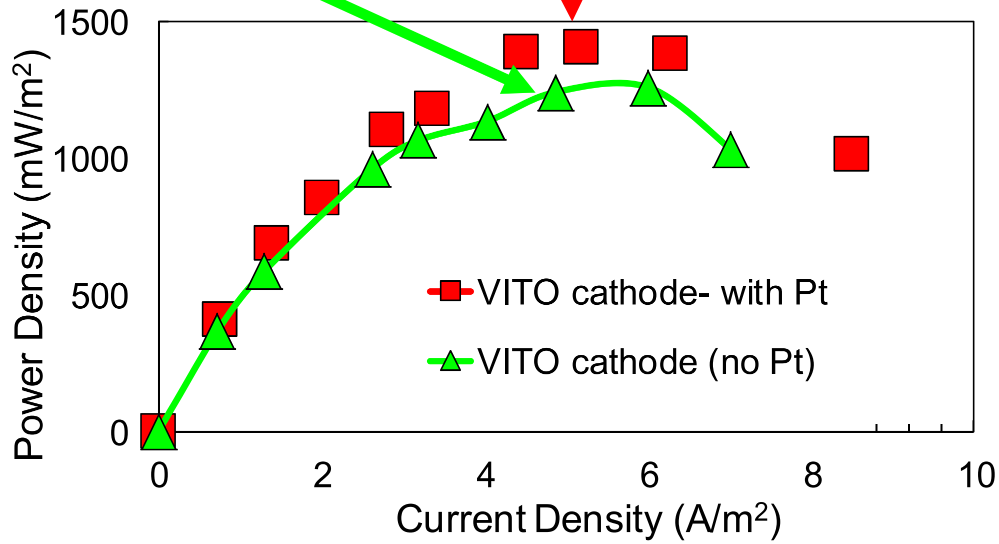
Lanas & Logan (2013) *J. Power Sources*

Cathode: Activated Carbon Catalysts

VITO cathode (no Pt)

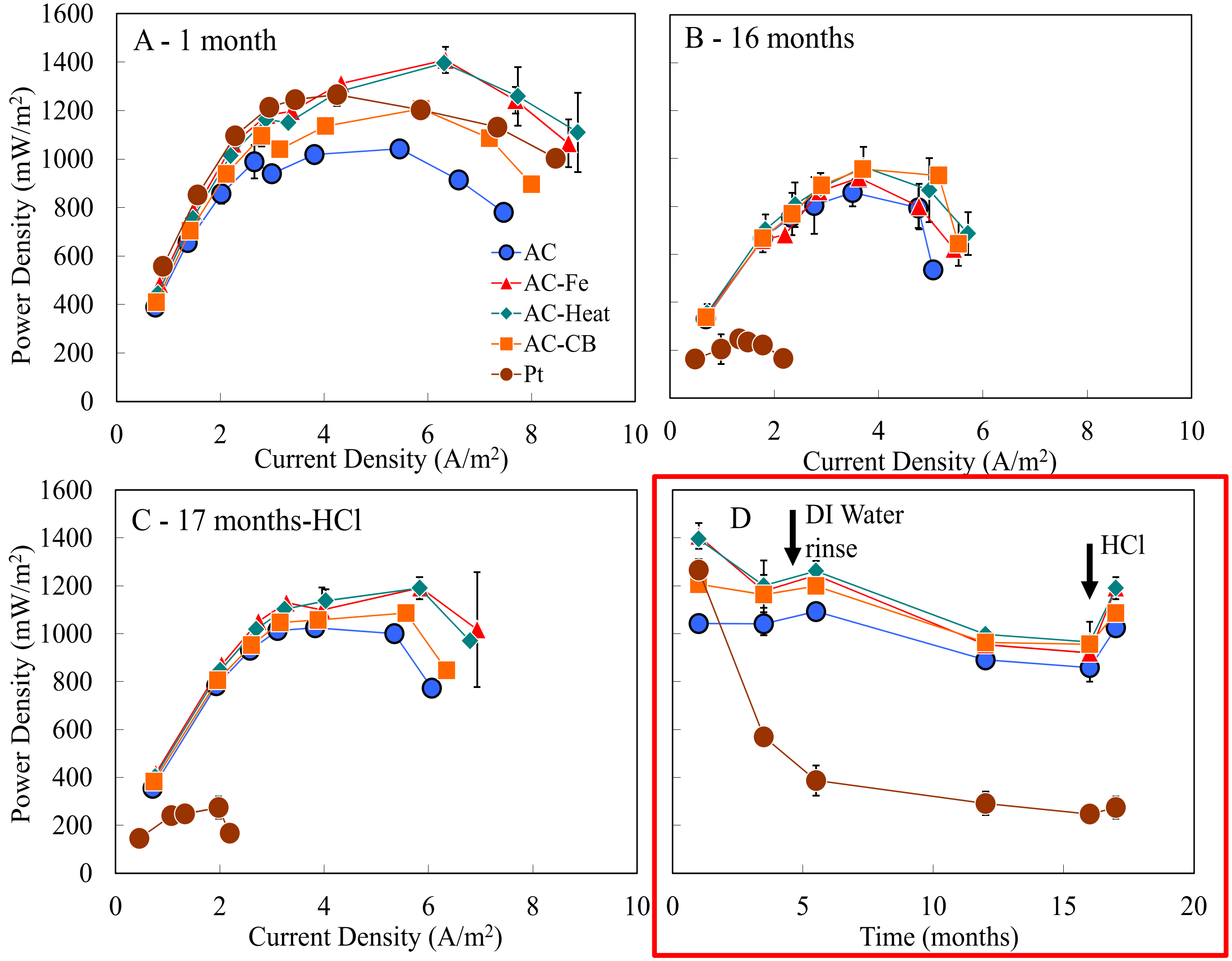
Carbon cloth with Pt

Activated carbon cathode works almost as well as Pt catalyst



Zhang, Cheng, Van Bogaert, Pant & Logan (2009) *Electrochem. Commun.*

Activated Carbon Cathodes- (Manufactured by VITO)



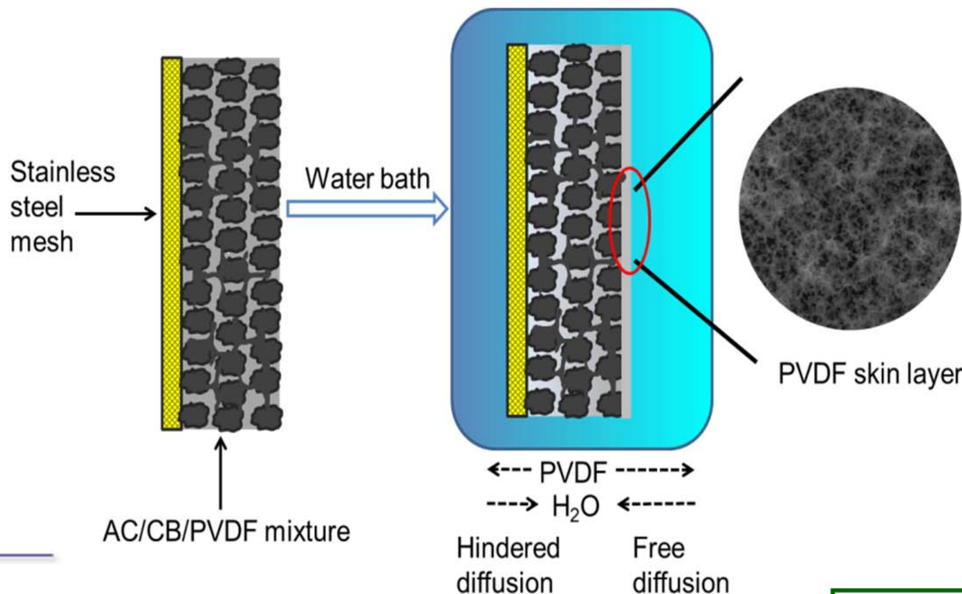
Performance over 16 months:

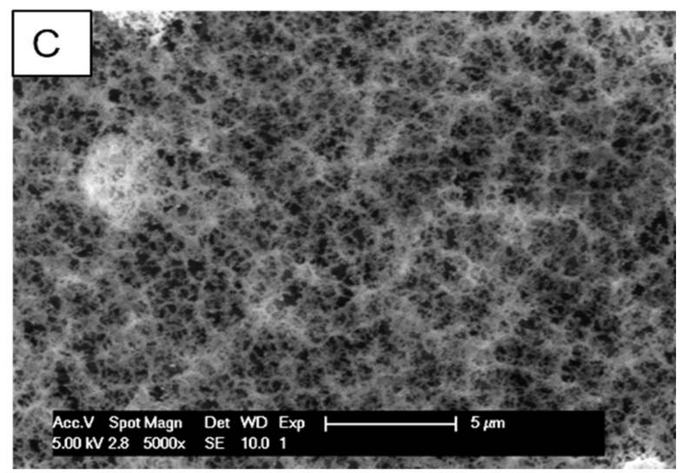
Original power nearly restored using acid (HCl) wash.

Zhang, Pant, Zhang, Liu, Logan (2014) *Chem. Electro. Chem.*

New Binder for Activated Carbon: PVDF

- Using a PVDF binder is simple and effective
  - 1- apply to SS mesh; 2- phase inversion in water
  - Make at room temperature
  - Amenable to continuous rolling process
  - No separate gas diffusion layer (GDL) needed
  - Cost: \$15 m^{-2} (\$12 m^{-2} for SS mesh, \$3 m^{-2} for catalyst and binder)





Yang, He, Zhang, Hickner, Logan (2014) *ES&T Letters*

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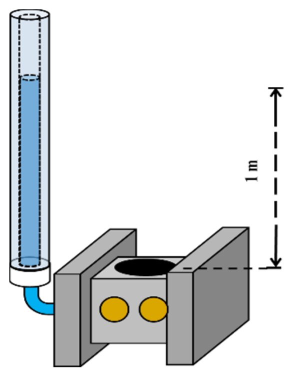
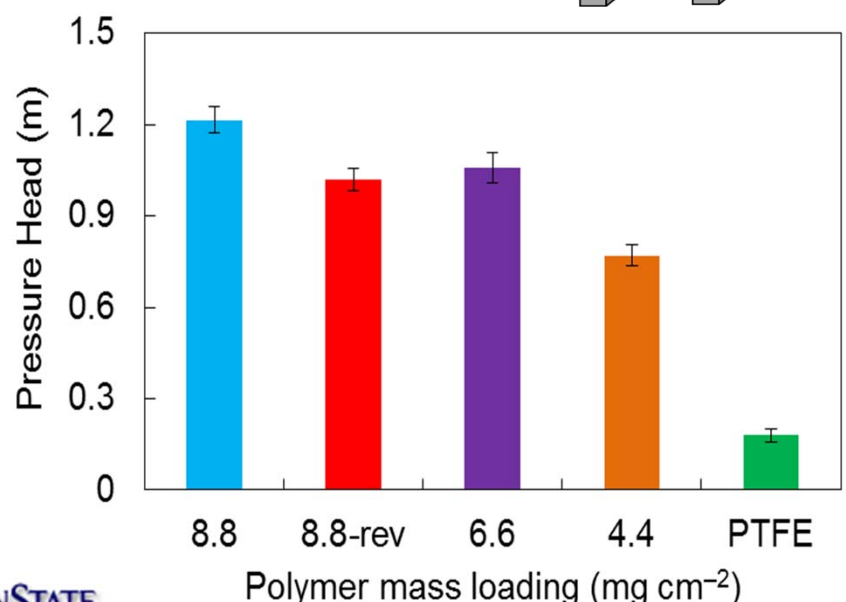
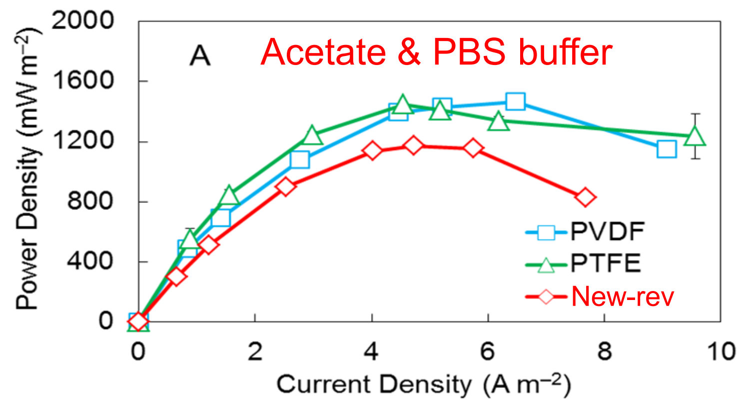
PVDF Binder

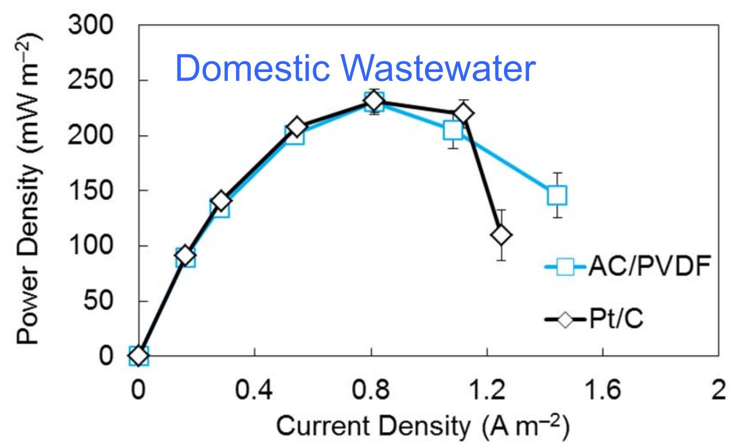
- Water pressure up to 1.2 m (vs 0.2 m for PTFE)





Power the same as PTFE applied to carbon cloth/Pt





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Yang, He, Zhang, Hickner, Logan (2014) *ES&T Letters*

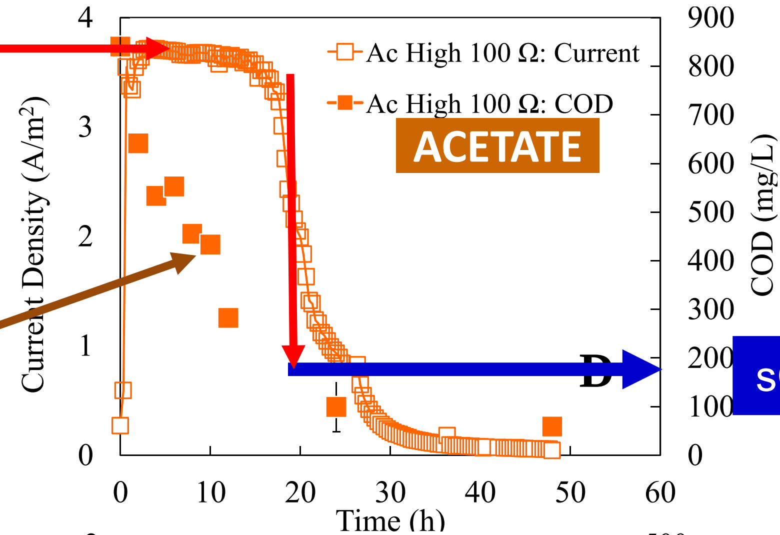
MFCs and MECs for Wastewater Treatment

…and why MxCs alone cannot accomplish wastewater treatment

Low sCOD limits current generation!

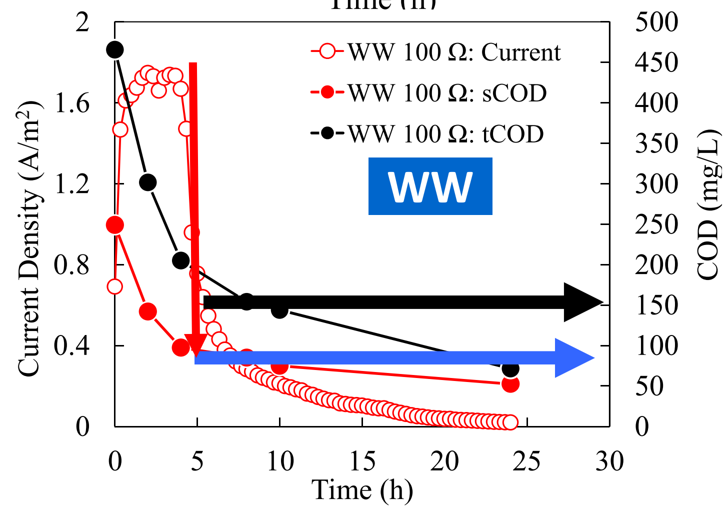
Current very stable, then it suddenly decreases

COD removal constant (first-order kinetics)



sCOD ~ 180 mg/L

In both cases, COD continues to be removed, so treatment continues without electricity generation, but ww cannot be discharged due to high COD



tCOD ~ 150 mg/L

sCOD ~ 100 mg/L

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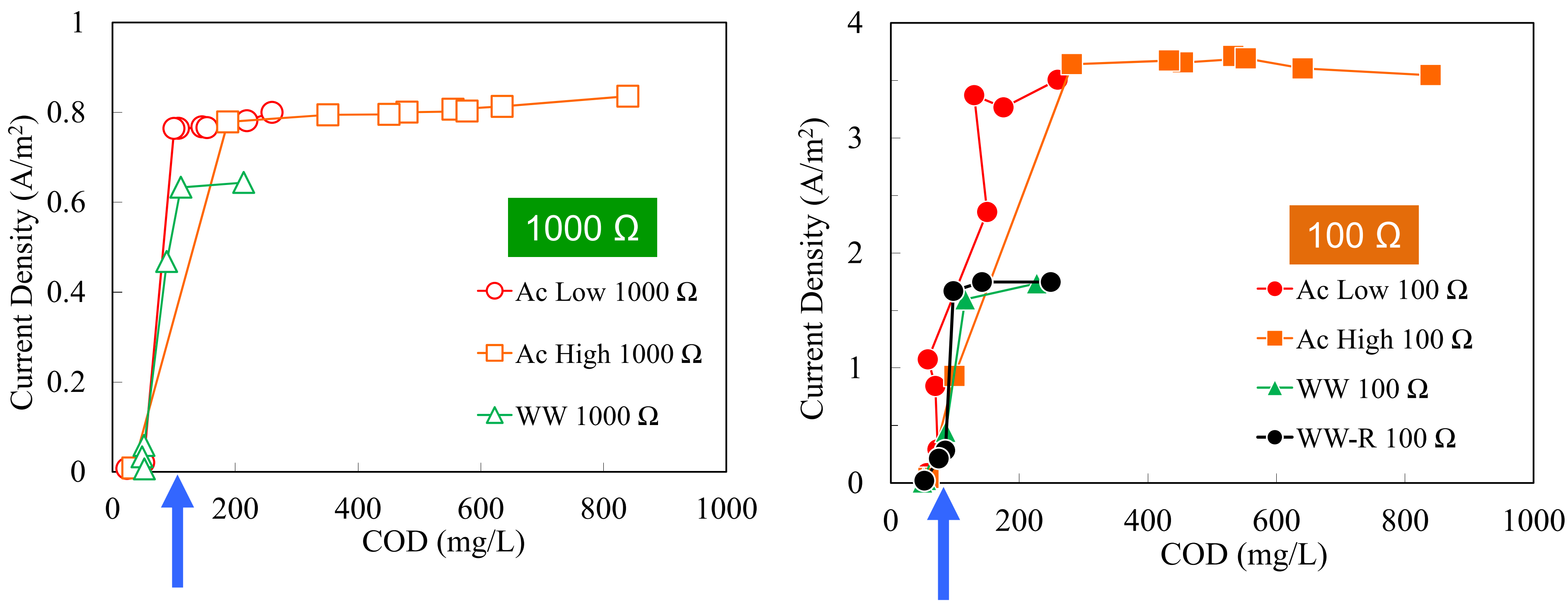
Zhang, He, Ren, Evans, Logan (2015) *Biores. Technol.*

Current density vs soluble COD (sCOD)

Current rapidly drops off at ~100 mg/L sCOD



In both cases, current rapidly decreases when sCOD is still high (~100 mg/L)

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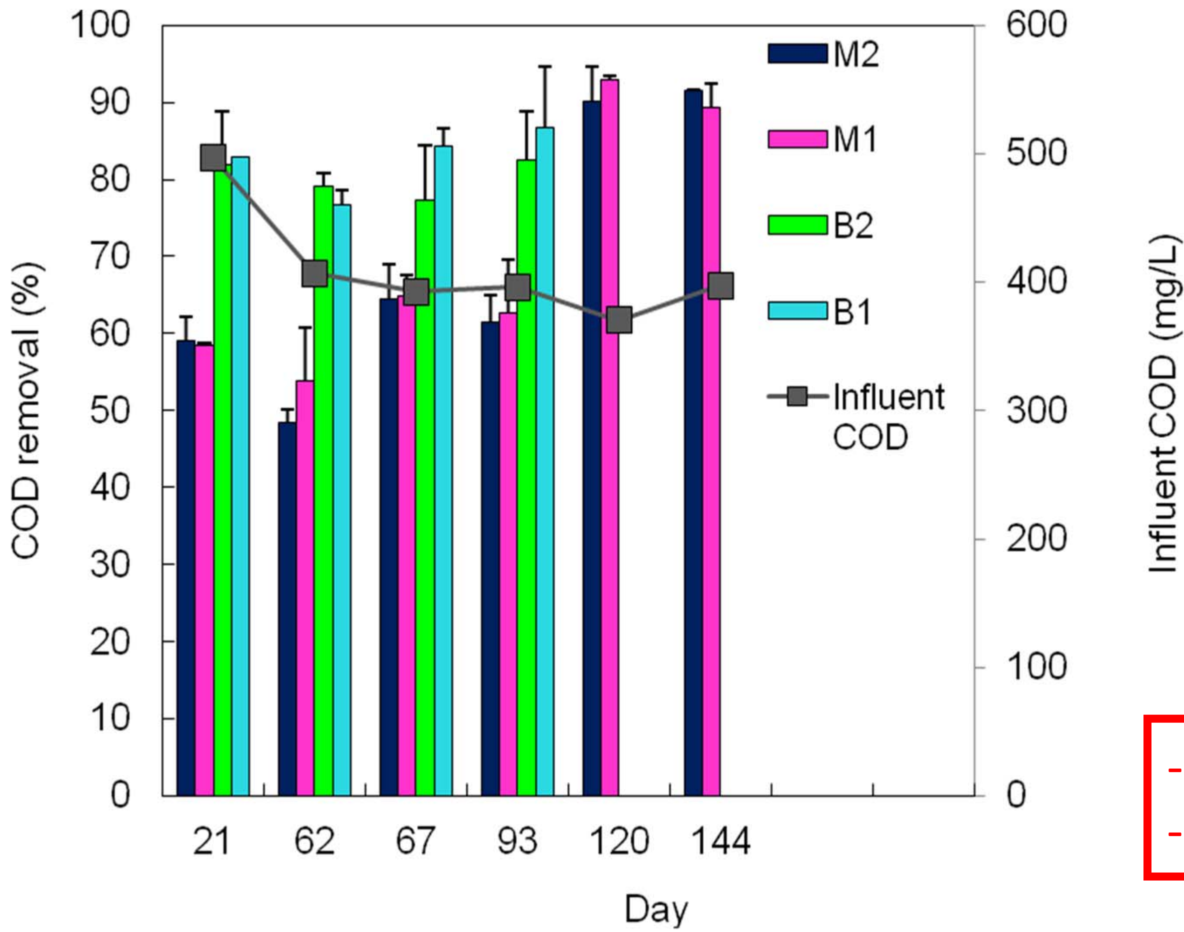
Zhang, He, Ren, Evans, Logan (2015) *Biores. Technol.*

How much COD removal can we get from domestic WW?
~80-90%, but final COD is too high



- Influent

  COD = 400 mg/L or
  BOD_5 = 200 mg/L
- Effluent

  BOD_5 35-40 mg/L

  (like a Trickling Filter)

Removal >80%

- Why isn't more COD removed?
- What is "fate" of COD?

Hays and Logan (2011) *J. Power Sources*

MFC Performance using Domestic Wastewater

Wastewater and Design Considerations

- Acetate + Phosphate buffer ≠ Synthetic wastewater
  - Acetate concentrations are usually too high to represent WW
  - PBS used is artificially conductive:7-20 mS/cm (vs 1 mS/cm for WW)
- Domestic wastewater
  - COD of ~300-500 mg/L (50% BOD_5)
  - Composition is variable!... So lots of oxygen contamination of the anode over time; can have anode limitations on performance
- Reactor design
  - Can't have too narrow space between electrodes (it will clog)
  - Must take into account volume demands of air cathodes
- Final effluent quality
  - If domestic ww used + need to discharge = Need AFMBR
  - If industrial, may only need to get to level suitable for discharge to sewers (no secondary process needed in this case)

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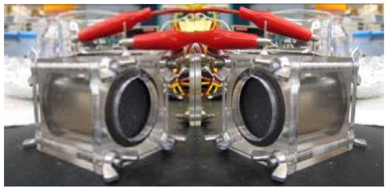
MFC Architecture



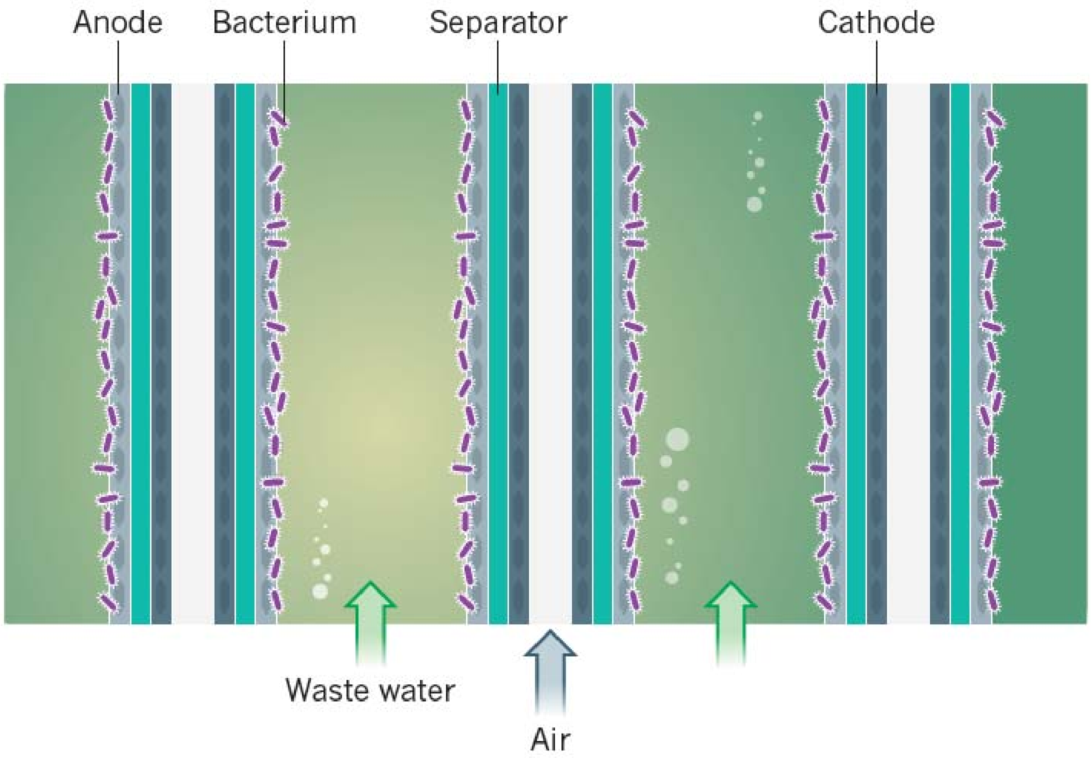


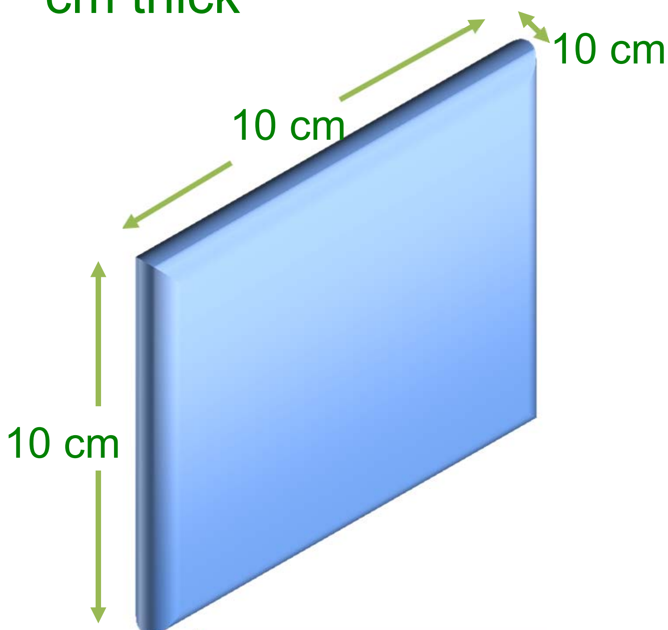
Figure 3 | An MFC stack. MFCs are arranged close together to reduce internal resistance and form compact reactors. Within the stack the electrodes consist of repeating units of an anode coated in a mat of bacteria, or biofilm, an insulating separator and a cathode. Waste water flows over the anodes and air over the cathodes. The individual anode and cathode are connected by a wire (not shown).

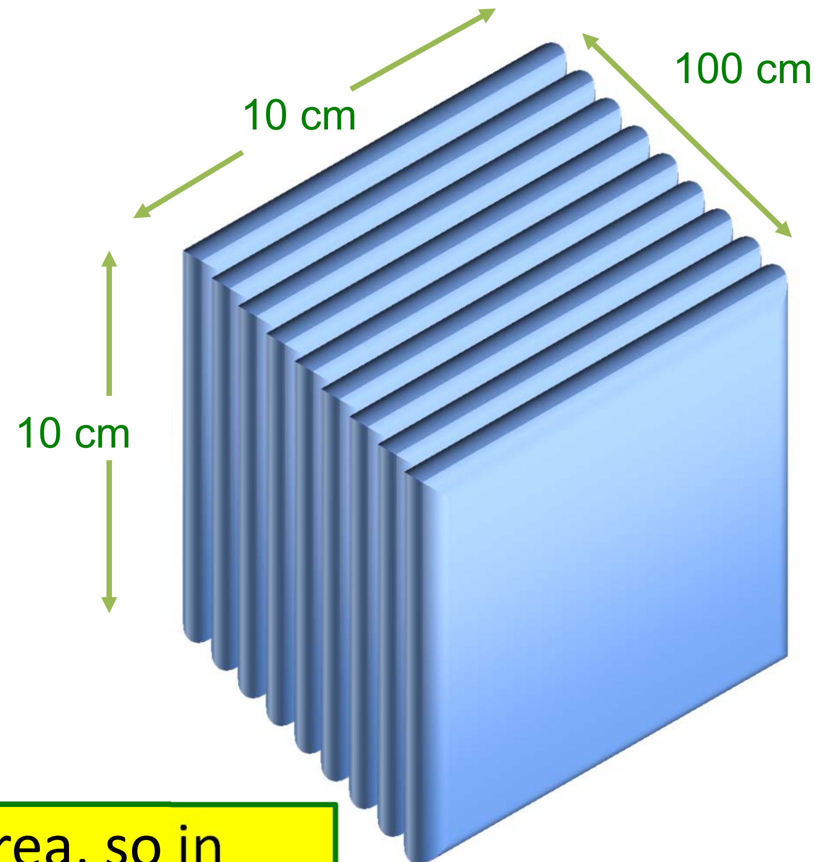
Logan & Elimelech (2012) *Nature*

Overall goal: compact reactor design

Result: 10 modules = 10 m^2

Assume: One anode-cathode module is 1 m^2 projected area (height x width) and 10 cm thick





Design: Limited by cathode area, so in this example we achieve 10 m^2/m^3

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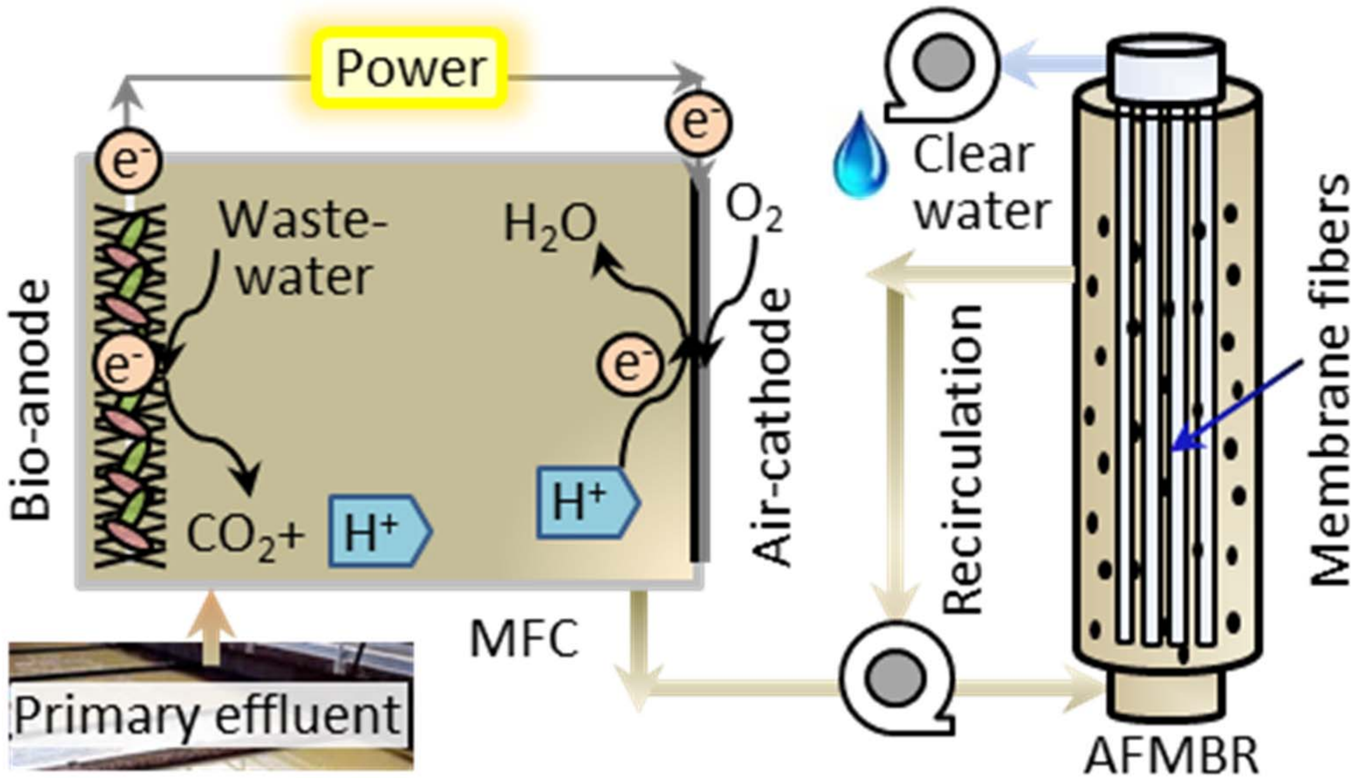
Logan (2012) *Chem. Sus. Chem.*

MFC + AFMBR

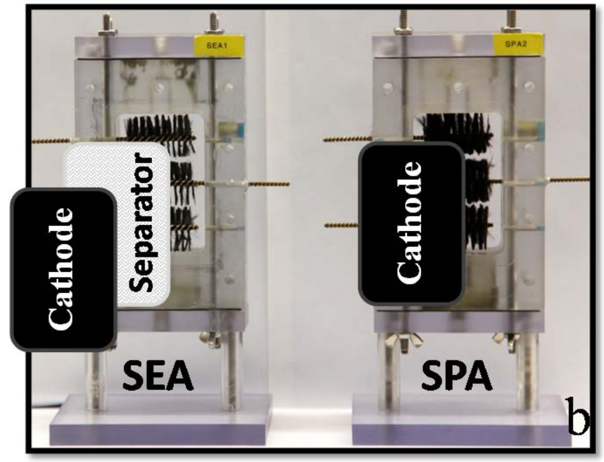
(Anaerobic Fluidized Bed Membrane Bioreactor)



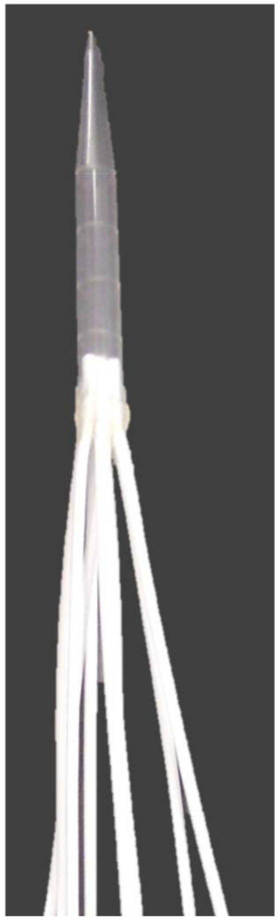
Ren, Ahn & Logan (2014) *Environ. Sci. Technol.*

Generation I: MFC configuration

- SEA: Separator electrode assembly
  - Trimmed graphite fiber brush, one side flat
  - Separator between brush anode and cathode placed together
- SPA: Spaced electrode assembly
  - Brush placed distant from cathode so it can't touch it
- Two reactors used in series
  - 2 × 4 h HRT = 8 h HRT
- Total of 4 MFCs (2 SEA, 2 SPA)



Ren, Ahn & Logan (2014) *Environ. Sci. Technol.*

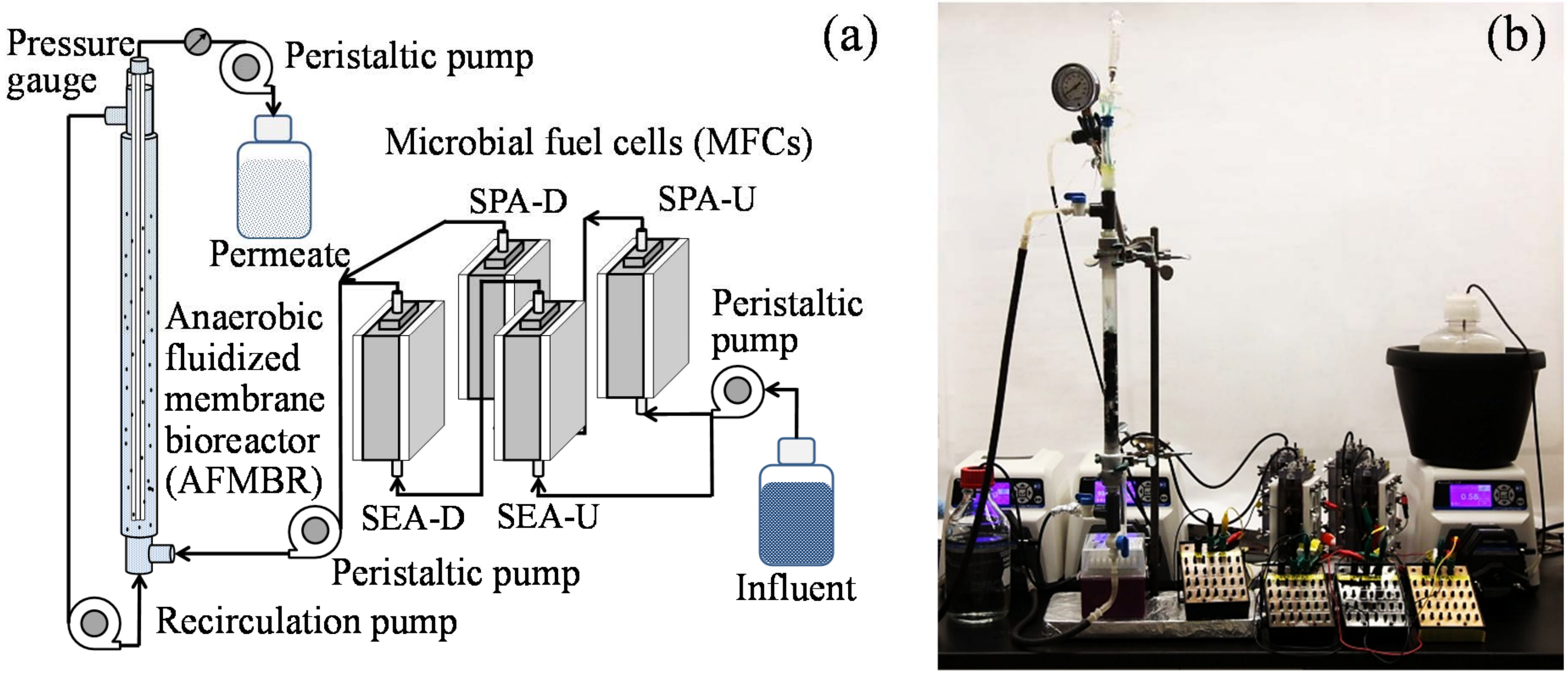


AFMBR Construction

- Idea of AFMBR first published by Chae et al. (ES&T). Used as a second stage to granular fluidized bed anerobic digester
- AFMBR consists of a reactor body + ultrafiltration membrane + granular activated carbon (GAC)
- GAC fluidized by recirculation
- In tests here, used with a hydraulic retention time of 1 hour

Ren, Ahn & Logan (2014) *Environ. Sci. Technol.*

Experimental Setup: MFC+AFMBR



Reactor HRTs: MFC=4 h (each); AFMBR=1 h
"F"= Granular activated carbon (GAC), fluidized, used for biofilm support and membrane cleaning (scour)
"MBR": PVDF hollow fiber membranes
MFC types: SEA (separator); SPA (spaced, no separator)

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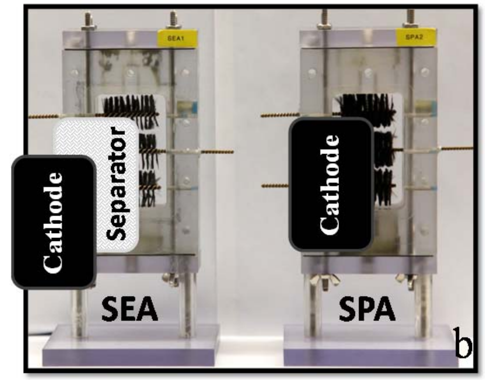
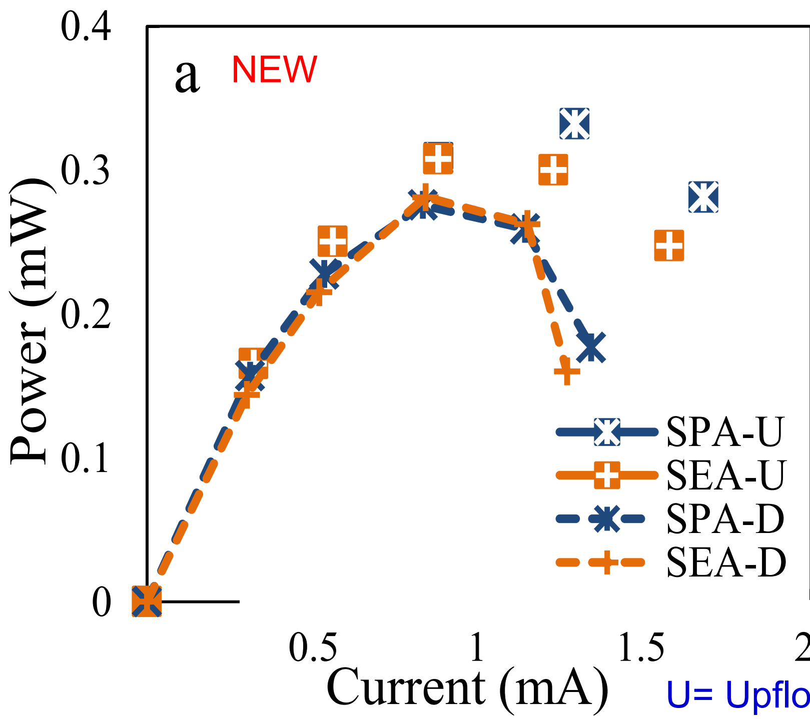
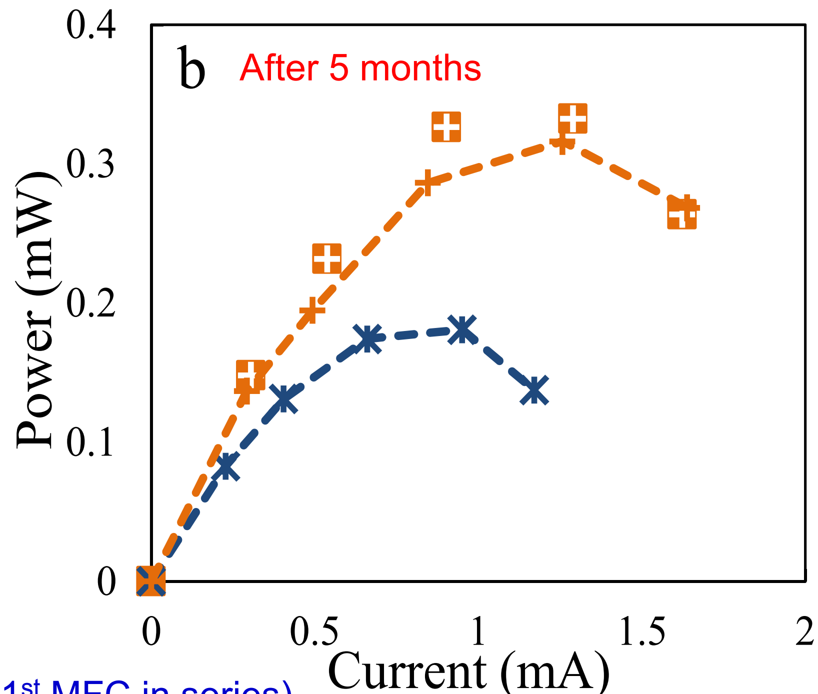
Ren, Ahn & Logan (2014) *Environ. Sci. Technol.*

Comparison of performance of SEA and SPA MFCs over time

- Initially: similar performance
- After 5 months: SEA>> SPA
- Separator needed for long term performance!







U= Upflow (1st MFC in series)
D=downflow (2nd MFC in series)

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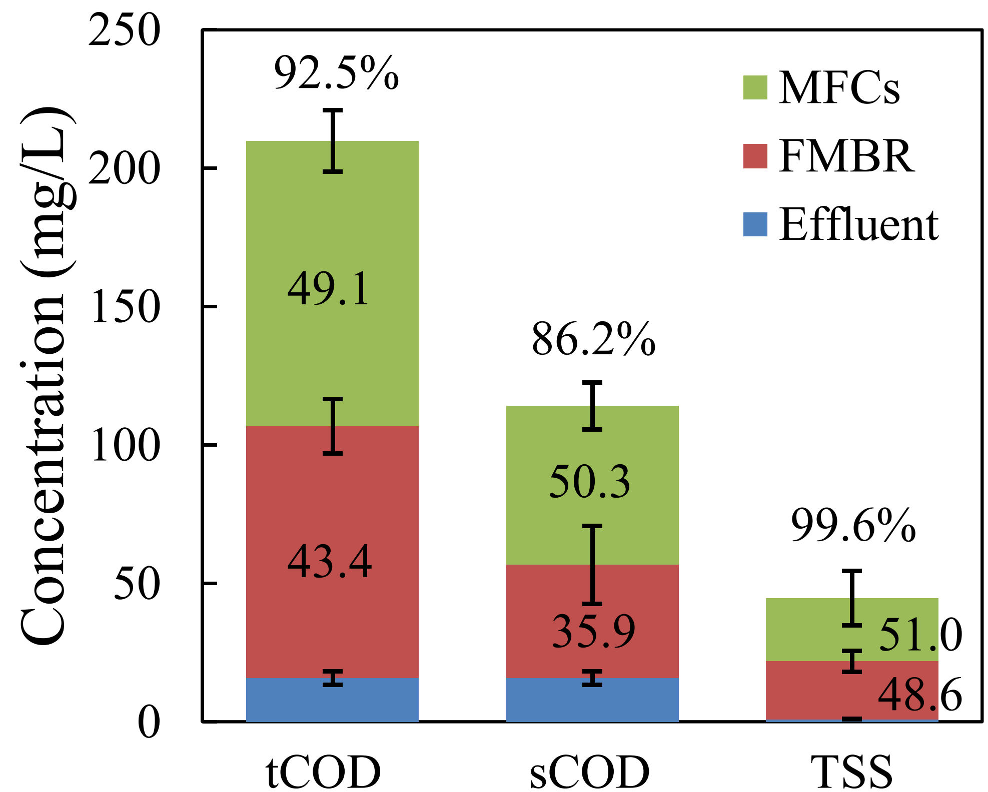
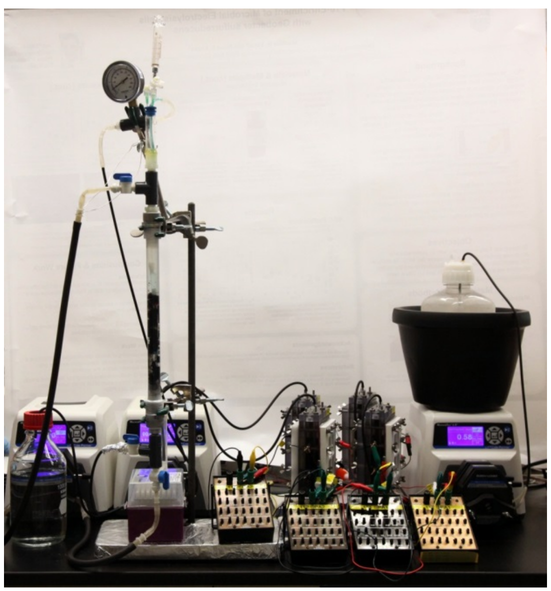
Ren, Ahn & Logan (2014) *Environ. Sci. Technol.*

Effluent reduced to 16 mg/L tCOD

- Two trains of MFC (HRT = 4 h) to AFMBR (HRT = 1 h)
- Membrane flux 16 L/m^2/h
- 50 days performance
- Energy balanced

 (MFC produced = AFMBR used)





WW in FMBR Permeate

- Effluent COD = 16 mg/L
- Effluent TSS <1 mg/L

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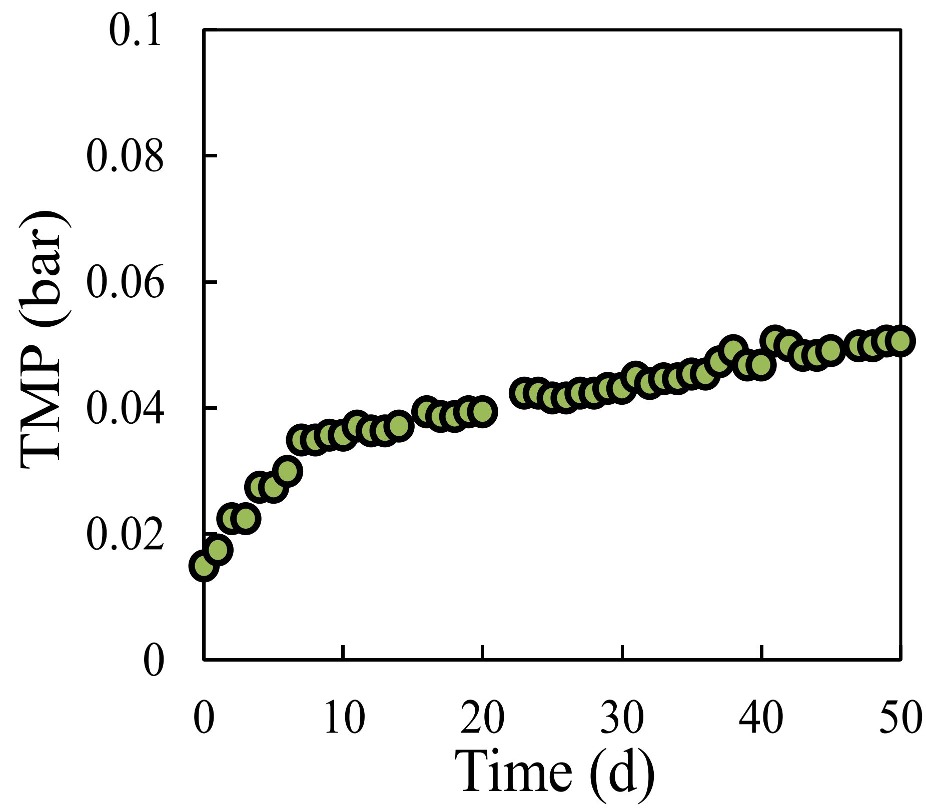
Ren, Ahn & Logan (2014) *Environ. Sci. Technol.*

Key to AFMBR success: Little fouling

- First 10 days, initial rapid increase in transmembrane pressure (TMP)
- Days 10-50, only slight increase in TMP
- Flux of 16 LMH much greater than that in previous studies with anaerobic fluidized bed reactors (AFBRs)
  - AFMBR: 6-7 LMH at start
  - 4-11 LMH at start



Ren, Ahn & Logan (2014) *Environ. Sci. Technol.*

Conclusions

- **Microbial Fuel Cell Technologies-- MxCs: Can they scale?**

→Yes!

MET Companies

- Emefcy (Israel) , www.emefcy.com/
- Cambrian Innovations (Boston, MA), http://cambrianinnovation.com/

- ArbSource (with Arizona State University), www.arbsource.us/
- Waste2Watergy (with Oregon State University), advantage.oregonstate.edu/clients/waste2watergy

- Living Power (with Harvard University)
- Quantum Intelligence (San Jose, CA)
- Electroarchae: www.electroarchae.com
- MicroOrganic (New York), http://microrganictech.com/technology/
-

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Thanks to students and researchers in the MxC team at Penn State!

Current research sponsors

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International Collaborations

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للعلوم والتقنية
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Water Desalination and
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STANFORD
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1949

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