Pulse Electrochemical Oxidative Destruction of PFAS:
A Simple Method for Improving Water Treatment Efficiency

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Faraday Technology, Inc.

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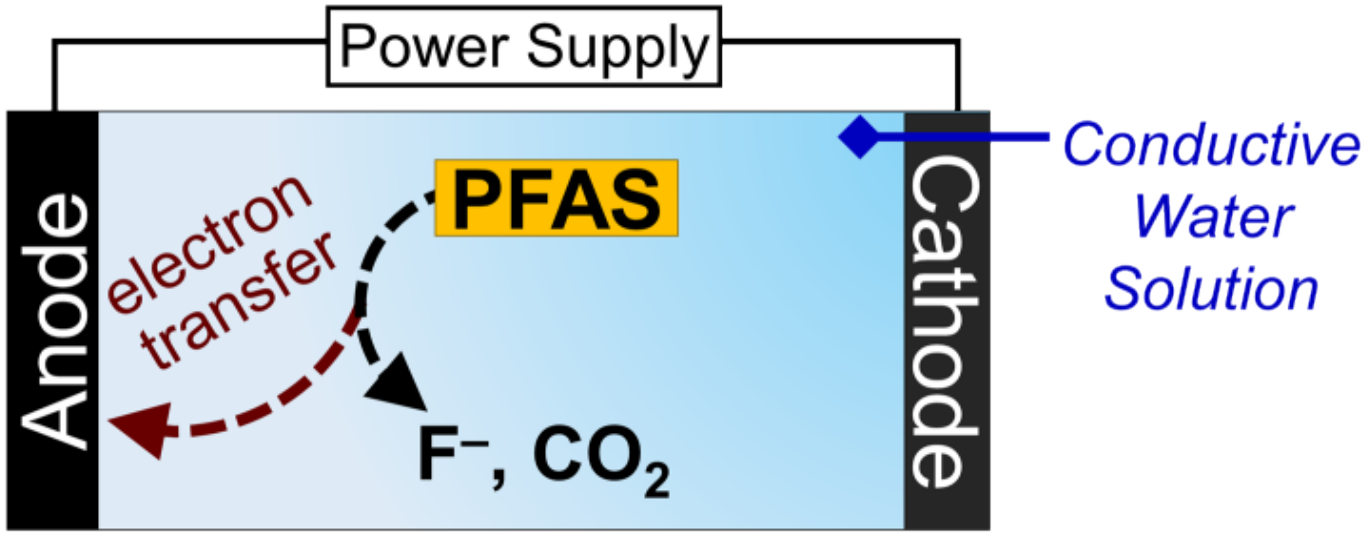
Electrochemical Oxidation for PFAS Destruction

- **Electrochemical Oxidation (EO):**
  - Complete mineralization of short- and long-chain PFAS in solution
  - Driven by direct /indirect electron transfer at anode

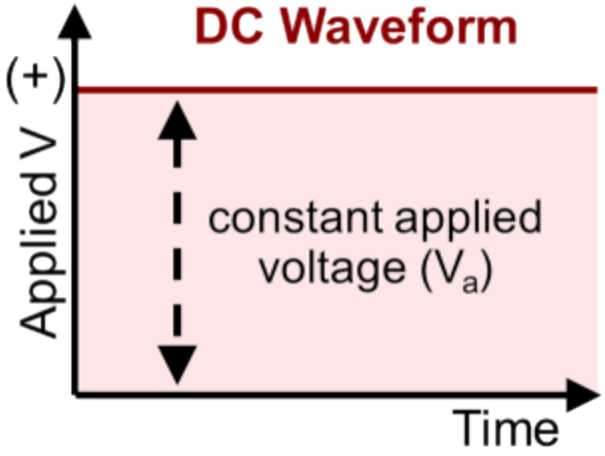


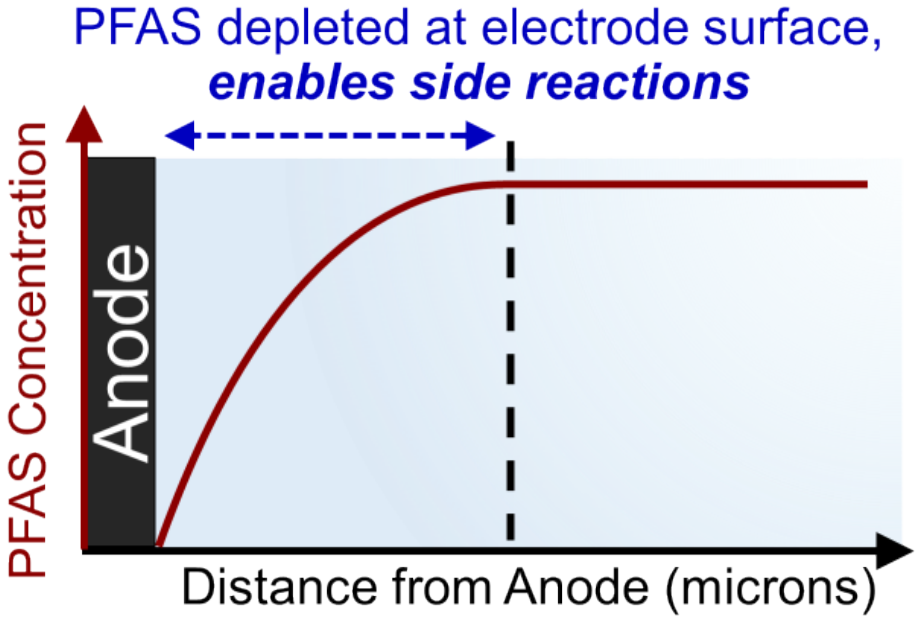
Advantages of EO:
- Ambient temperature/pressure
- No hazardous chemicals
- No solid or liquid waste generated

Challenge: Side reactions at anode
- Decrease energy efficiency
- Increase operating costs
- Can generate toxic by-products

DC Waveforms: PFAS depletion at electrode enables side reactions

- **Conventional Direct Current (DC) EO:**
  - Constant applied voltage or current
  - Depletes PFAS *at the electrode surface*, enables side reactions

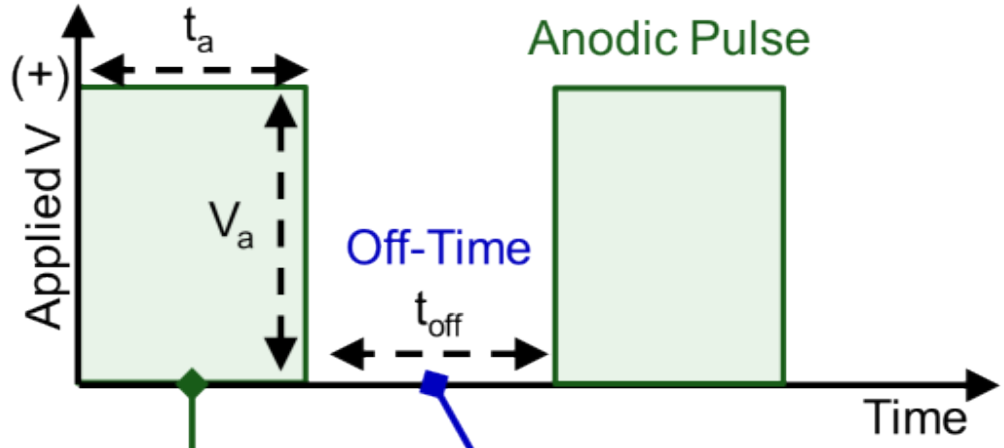




- **Common strategies to address this challenge:**
  - High concentrations of PFAS
  - Turbulence promoting reactor designs
  - 3D electrode architectures

FARADAYIC® EO: pulsed waveform prevent PFAS depletion

- **Faraday's Strategy:** Pulsed-Waveform FARADAYIC® EO
  - Anodic pulse periodically interrupted by an off-time where no voltage is applied
  - Anodic Pulse – PFAS at electrode destroyed
  - Off-Time – Replenishes PFAS concentration at electrode

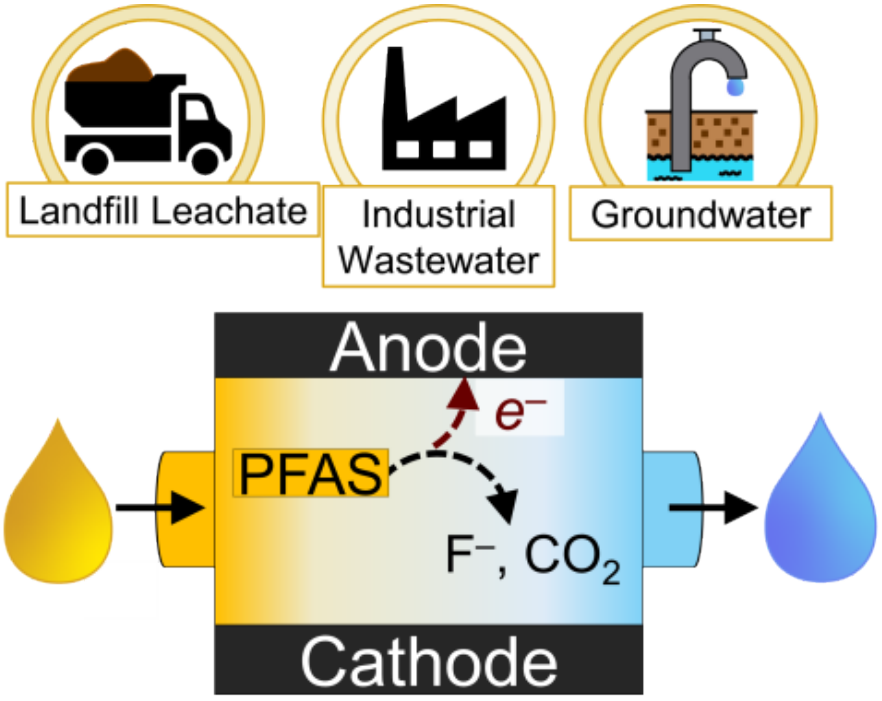


Anodic Pulse tuned to:
- Maximize PFAS destruction
- Minimize side reactions

Off-time tuned to:
- Prevent PFAS depletion at electrode
- Minimize energy demand
- Prevent by-product formation

Faraday's R&D Programs on PFAS Destruction

Prior Work:
Aqueous Effluents and Groundwater



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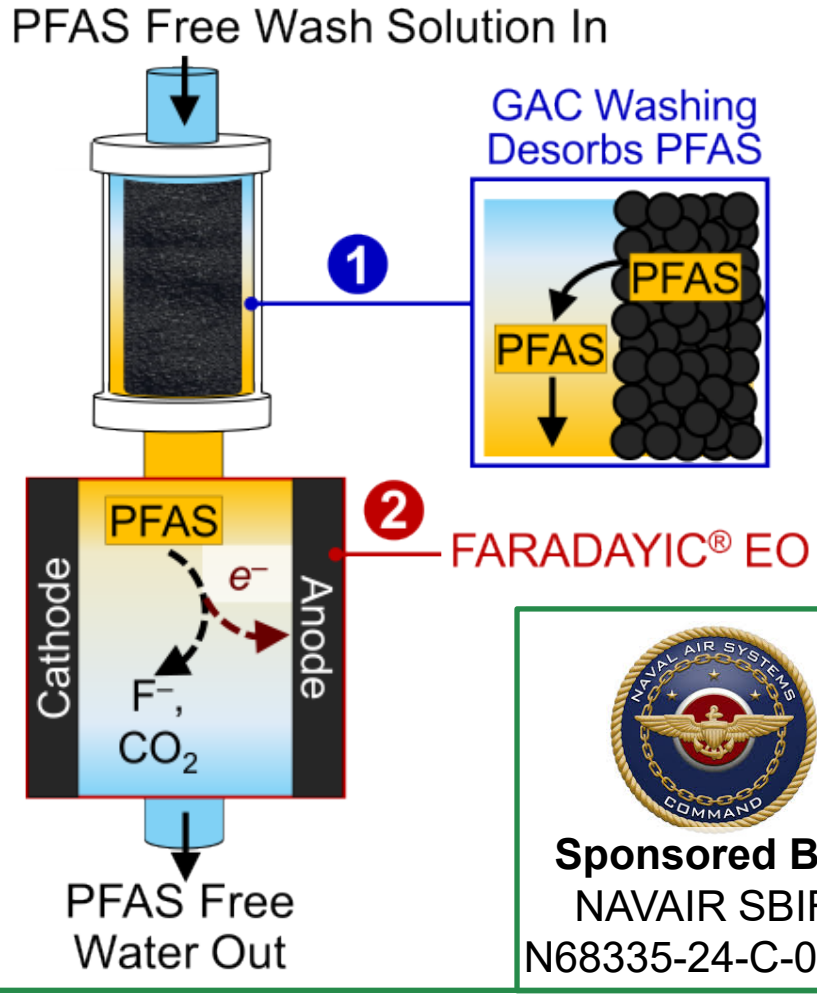
Ongoing Work:
GAC Regenerant

axine WATER TECHNOLOGIES



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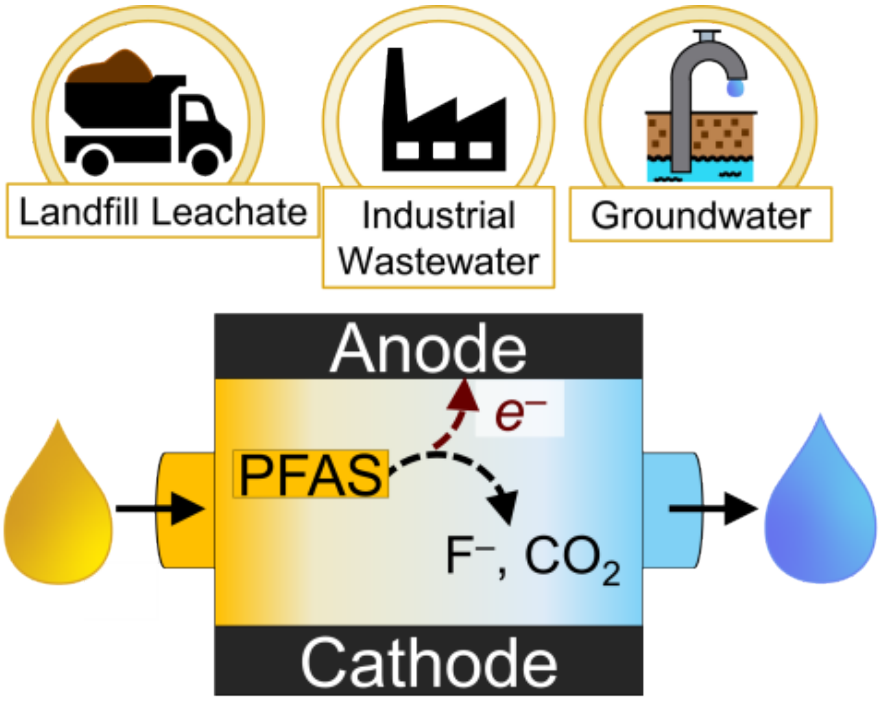
Today's Discussion

Prior Work:
Aqueous Effluents and Groundwater



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Goal: Demonstrate that FARADAYIC® EO can enhance the PFAS destruction performance (relative to DC EO) of commercially available reactors.

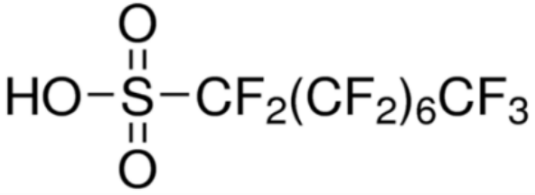
Approach:

- Develop landfill leachate surrogate for initial case study
- Select commercially available reactor
- Baseline performance with DC waveforms
- Compare to performance with FARADAYIC® EO
- Extend FARADAYIC® EO to other complex solutions

Worked with commercial partner to develop landfill leachate surrogate composition

- Worked with U.S. Ecology to develop landfill leachate surrogate solution
- Initial case study spiked PFOS into solution

US ecology

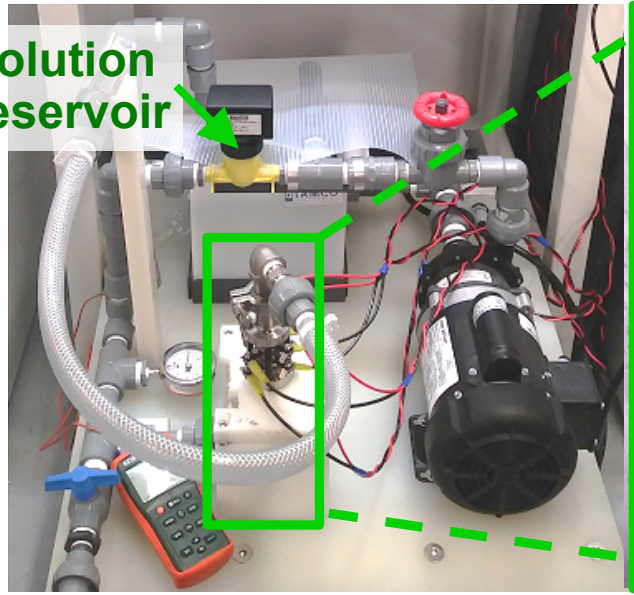


Component	Concentration
NaH_2PO_4	2.5 mM
KH_2PO_4	4.4 mM
Na_2HPO_4	5.2 mM
Na_2CO_3	0.2 mM
$NaNO_3$	0.5 mM
NaCl	8.8 mM
NH_4Cl	2.5 mM
$CaCl_2$	0.2 mM
$MgCl_2$	3.3 mM
Na_2SO_4	0.5 mM
pH	6.5

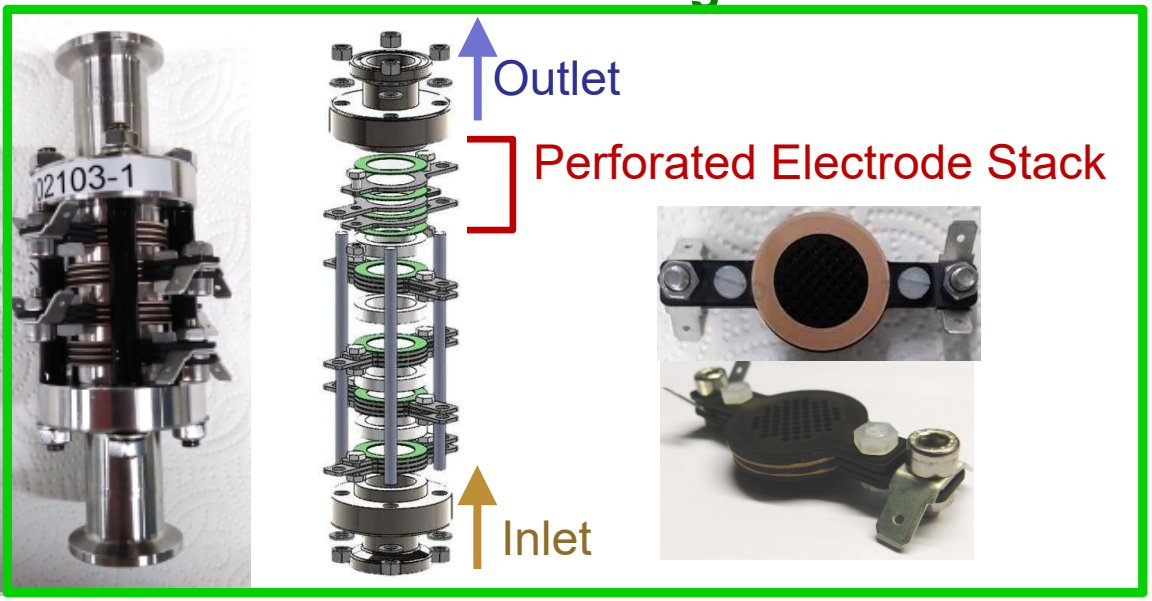
Commercial CONDIACELL® reactor used for initial case study

- Lab-Scale Experimental Set-Up
  - Closed-loop, multi-pass system
  - CONDIACELL® flow-through reactor
  - Boron doped-diamond (BDD) electrodes

CONDIAS
CONDUCTIVE DIAMOND PRODUCTS



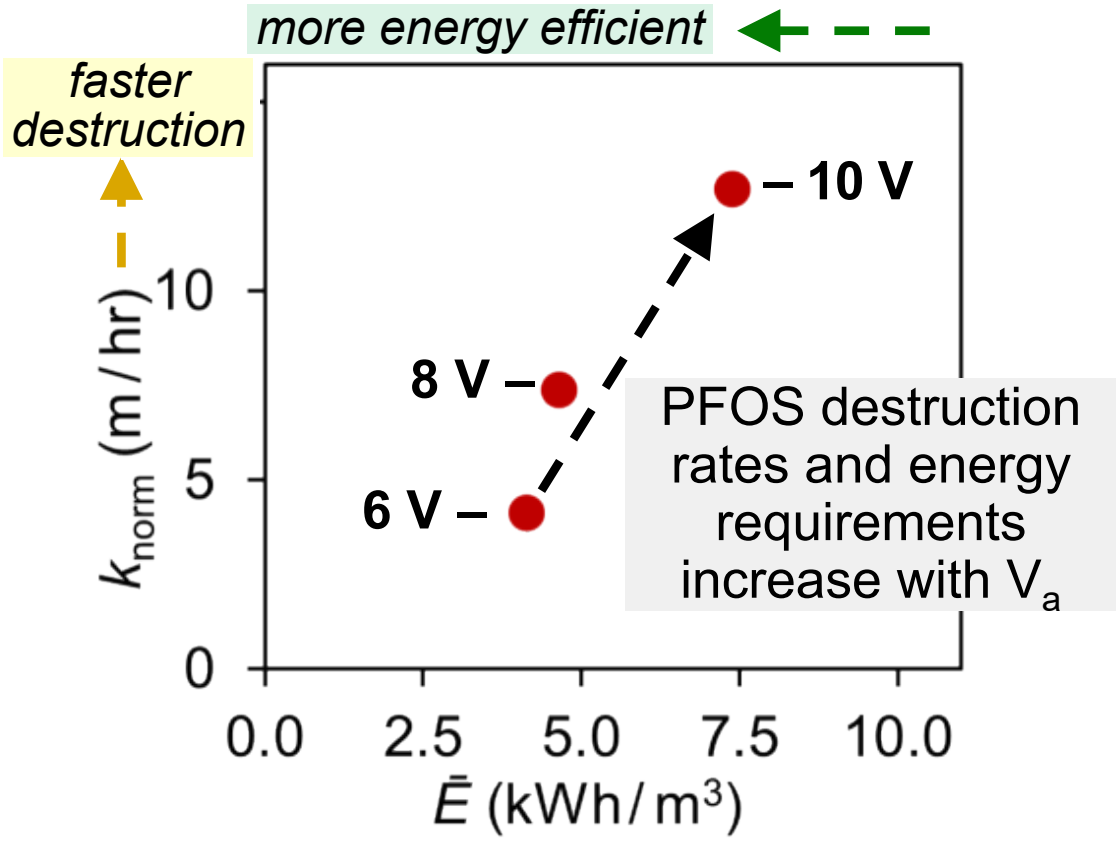
CONDIACELL® Flow-Through Reactor



While this program has focused on BDD, the benefits of the FARADAYIC® EO are expected to translate to other electrode materials

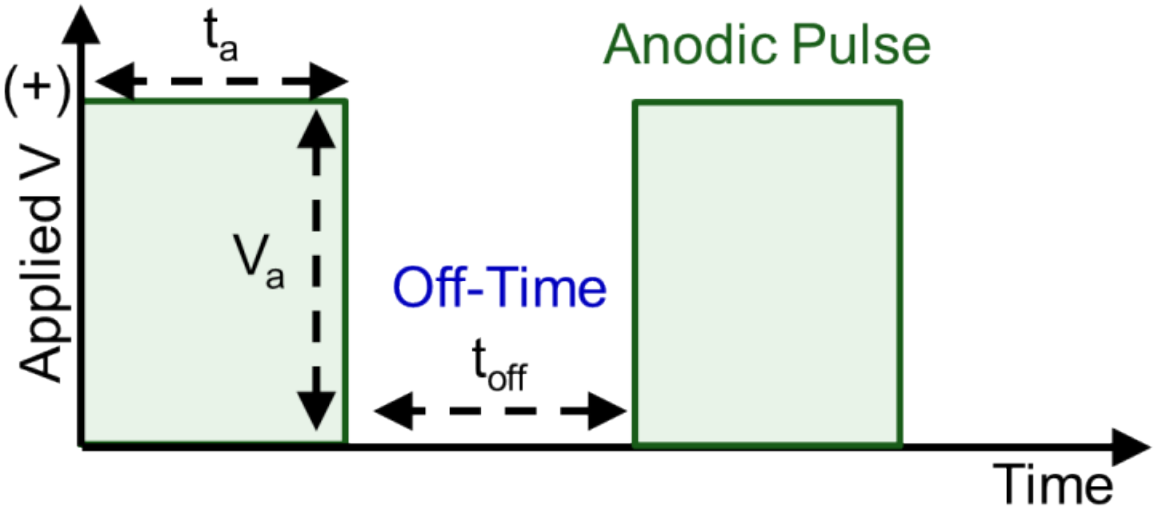
Baseline trials highlight limitations of DC waveforms

- DC waveforms with voltages ranging from 6–10 V
- Increasing the voltage:
  - Increased rate of PFOS destruction (k_{norm})
  - Increased energy demand ($\bar{E}$)



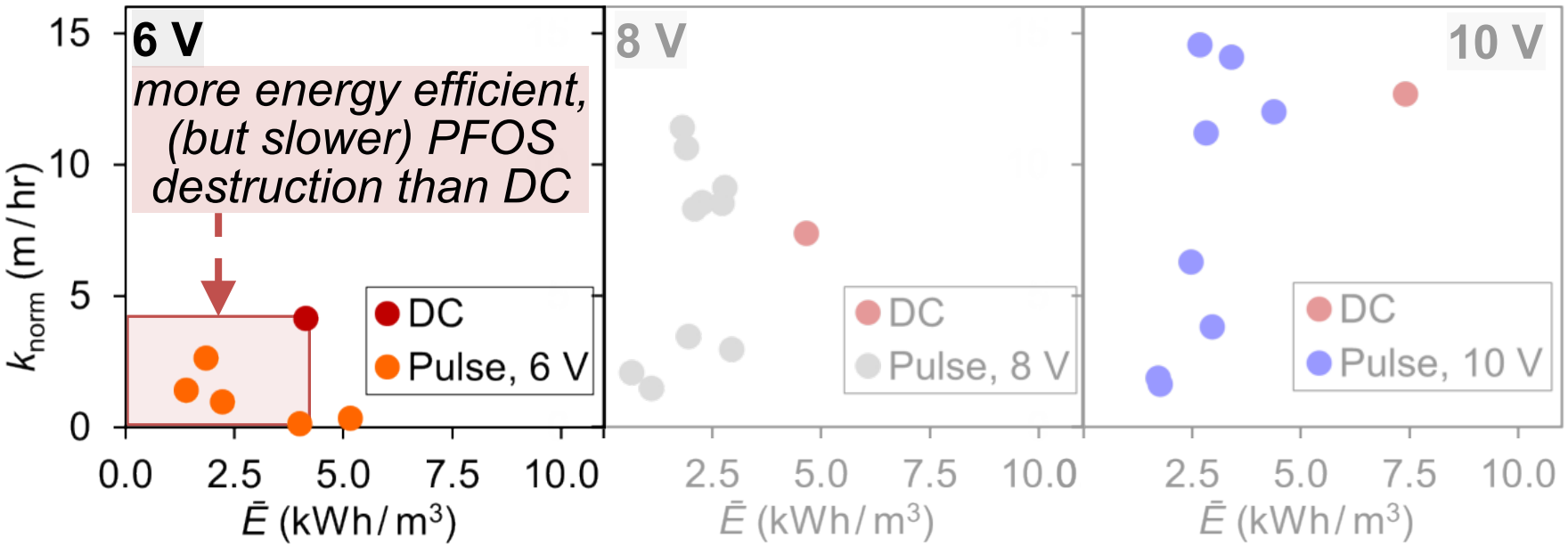
Evaluated a range of pulse waveforms over 30-minute treatment periods

- Design of experiments with pulse waveforms:
  - Voltages: 6, 8, and 10 V
  - Systematically varied on-time/off-time length
  - 30-minute total treatment times
- Performance compared to DC waveform with the same voltage



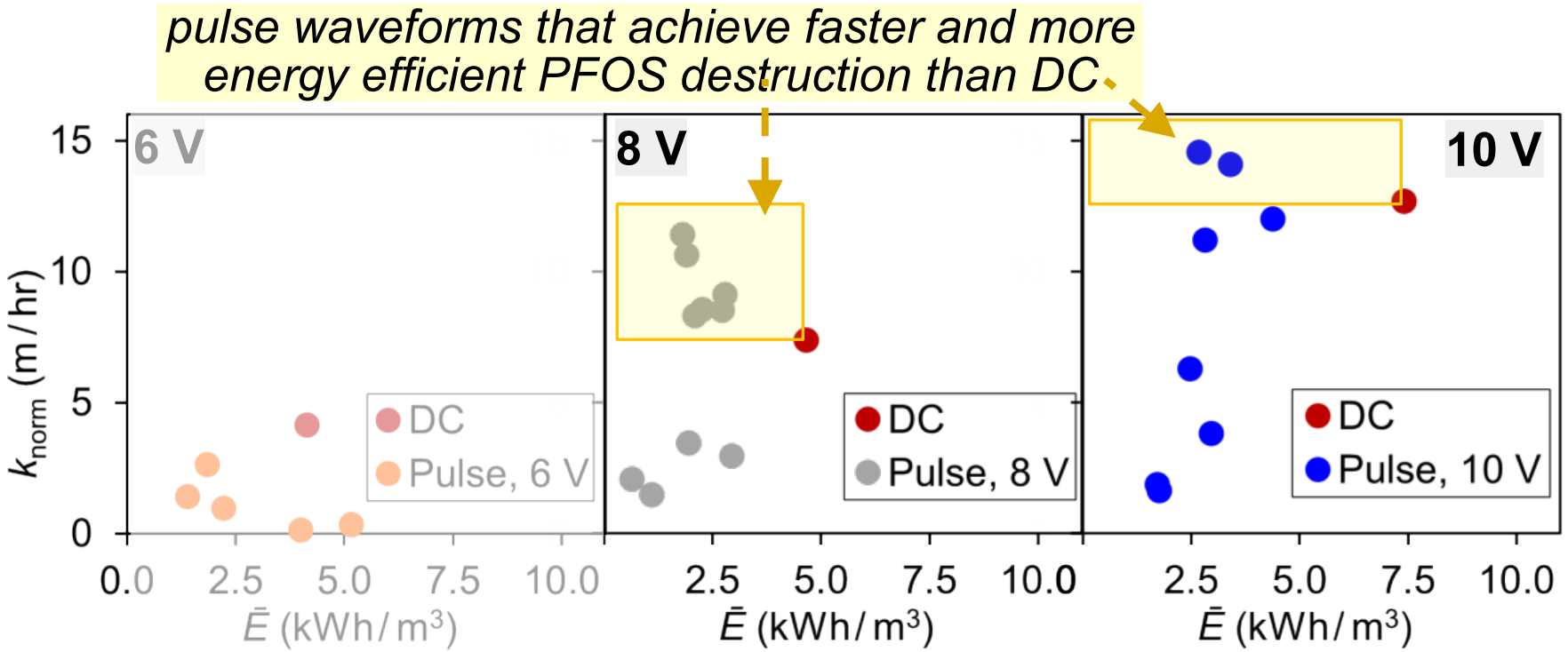
At 6 V, pulse waveforms improve energy efficiency

- At 6 V, pulse waveforms:
  - Improve energy efficiency (lower $\bar{E}$)
  - Decrease rate of PFOS destruction (lower k_{norm})



At 8 and 10 V, pulse can improve efficiency and kinetics

- At 8 V and 10 V, pulse waveforms identified that:
  - Improve energy efficiency (lower $\bar{E}$) ***and***
  - Increase rate of PFOS destruction (lower k_{norm})



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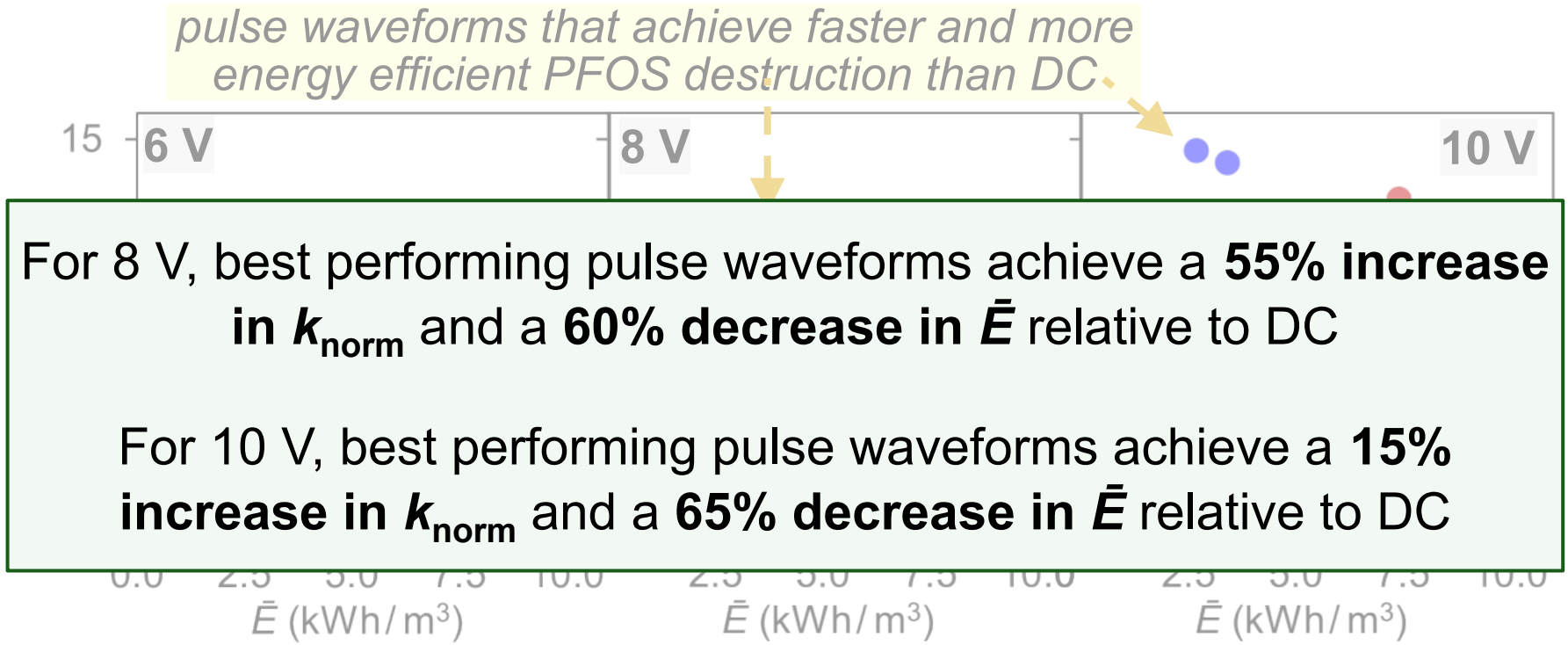
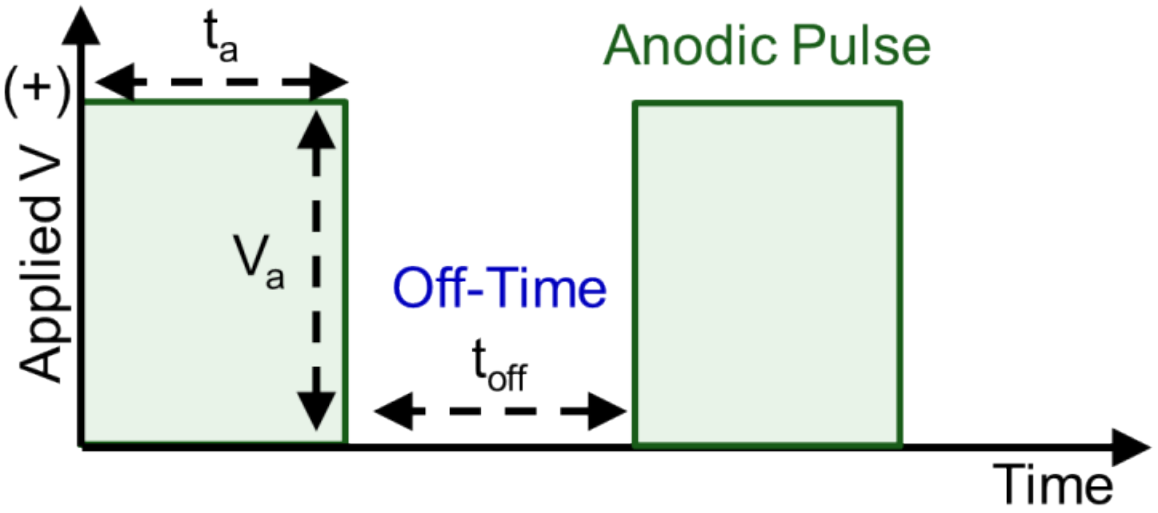


For 8 V, best performing pulse waveforms achieve a **55% increase in k_{norm}** and a **60% decrease in $\bar{E}$** relative to DC

For 10 V, best performing pulse waveforms achieve a **15% increase in k_{norm}** and a **65% decrease in $\bar{E}$** relative to DC

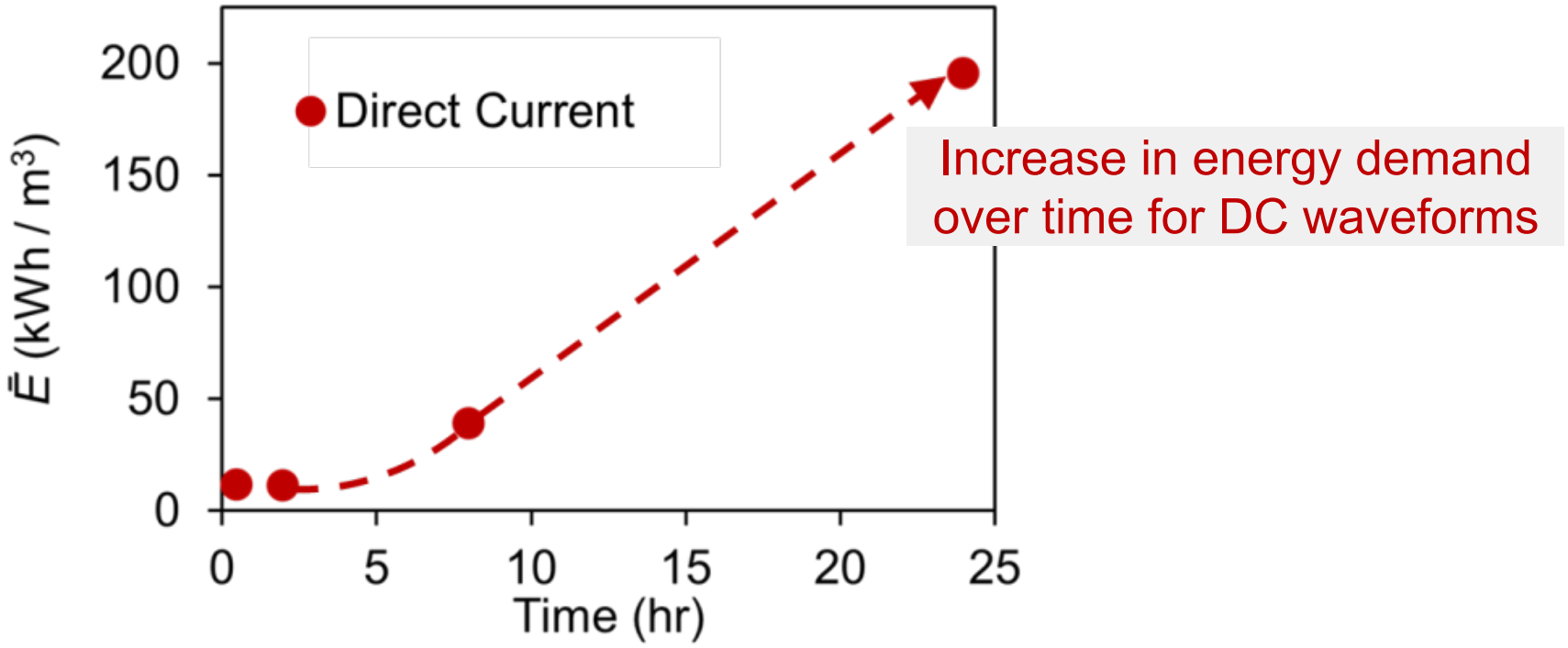
Does FARADAYIC® EO improve performance over longer timescales?

- Down-selected to a DC and pulse waveform with the same voltage
- 24 hour total treatment trials
- Aliquots of solution taken at 0.5, 2, 8, and 24 hours
- Monitored energy demand as a function of time



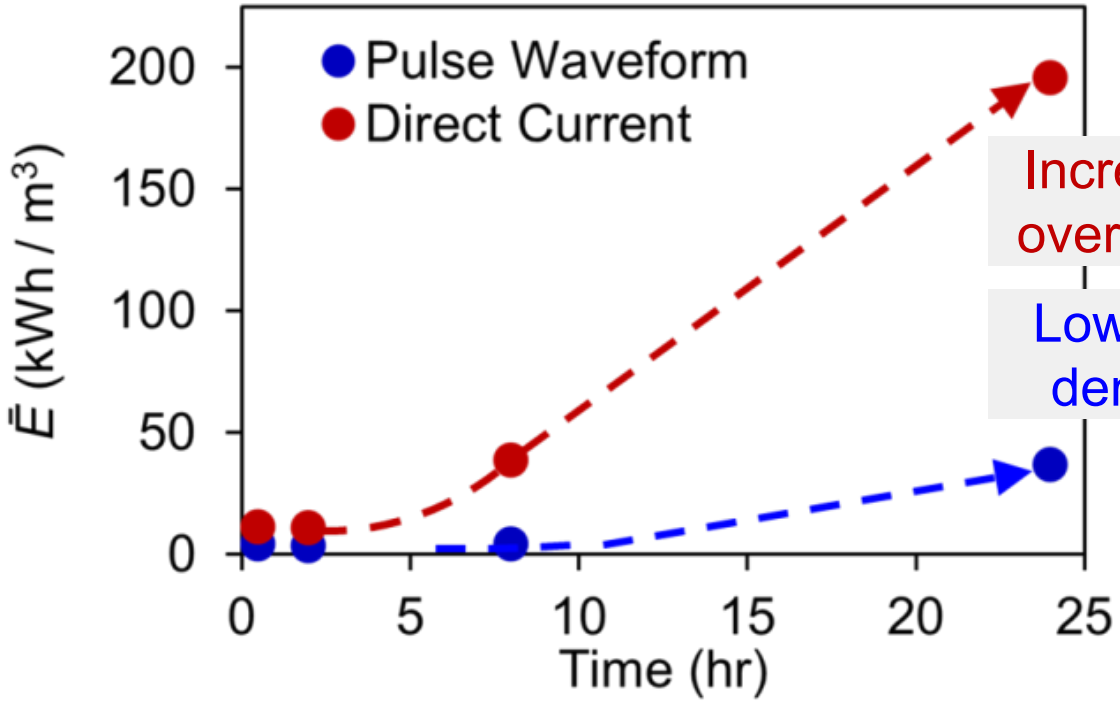
DC Waveforms: Large increase in energy demand after 2 hours

- Over 24 hours, both DC and pulse achieved > 99.9% PFAS destruction
- For DC waveforms:
  - Rapid increase in energy demand observed after 2 hours



Pulse Waveforms: lower, more stable energy demand

- Over 24 hours, both DC and pulse achieved > 99.9% PFAS destruction
- Pulse waveforms achieve the same PFAS destruction levels with:
  - Lower energy demand (than DC) at all timepoints
  - No increase in energy demand over first 8 hours
  - Smaller increase in energy demand at later timepoints



Increase in energy demand over time for DC waveforms

Lower and more stable energy demand for pulse waveforms

FARADAYIC® EO extended to foam fractionate and highly saline groundwater surrogates

- FARADAYIC® EO demonstrated in other complex solutions, including:
  - **Foam fractionate** from a landfill leachate site (provided by EPOC Enviro)
  - Highly saline **groundwater surrogate** solution

Component	Groundwater Surrogate
NaH_2PO_4	15 mM
KH_2PO_4	15 mM
$NaNO_3$	40 mM
KCl	40 mM
NaCl	100 mM
$CaCl_2$	15 mM
$MgCl_2$	15 mM
Na_2SO_4	15 mM
pH	4

DC and FARADAYIC® EO evaluated in foam fractionate derived from real landfill leachate

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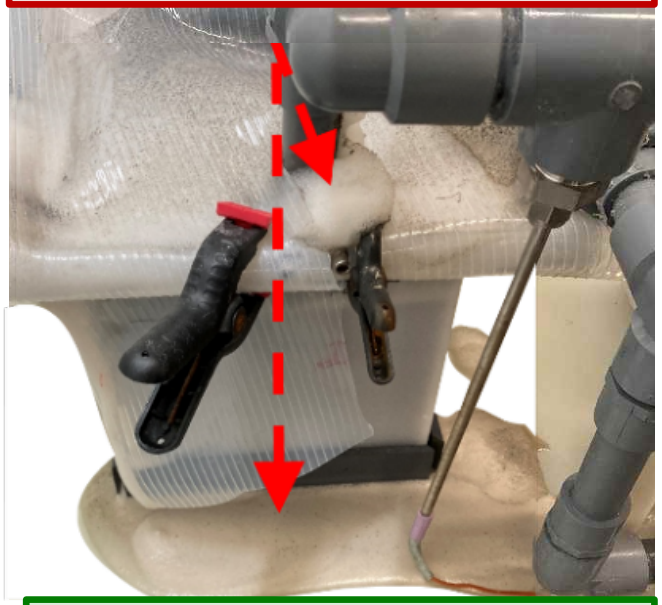
$MgCl_2$	15 mM
Na_2SO_4	15 mM
pH	4

FARADAYIC® EO enabled safe treatment of foam fractionate

- DC waveforms **could not** safely treat foam fractionate from EPOC Enviro
  - Aggressive solution foaming observed in under 15 minutes
  - Foaming led to reactor overflow

- FARADAYIC® EO **could** safely treat foam fractionate
  - Minimal foaming enabled treatment over long timescales
  - After 24 hours, achieved up to 65% PFOS destruction and 30% PFOA destruction

DC EO: aggressive foaming prevented safe treatment of foam fractionate



FARADAYIC® EO: foaming minimized, enabled safe treatment

EPOC ENVIRO

DC and FARADAYIC® EO evaluated in highly saline groundwater surrogate

- FARADAYIC® EO demonstrated in other complex solutions, including:
  - **Foam fractionate** from a landfill leachate site (provided by EPOC Enviro)
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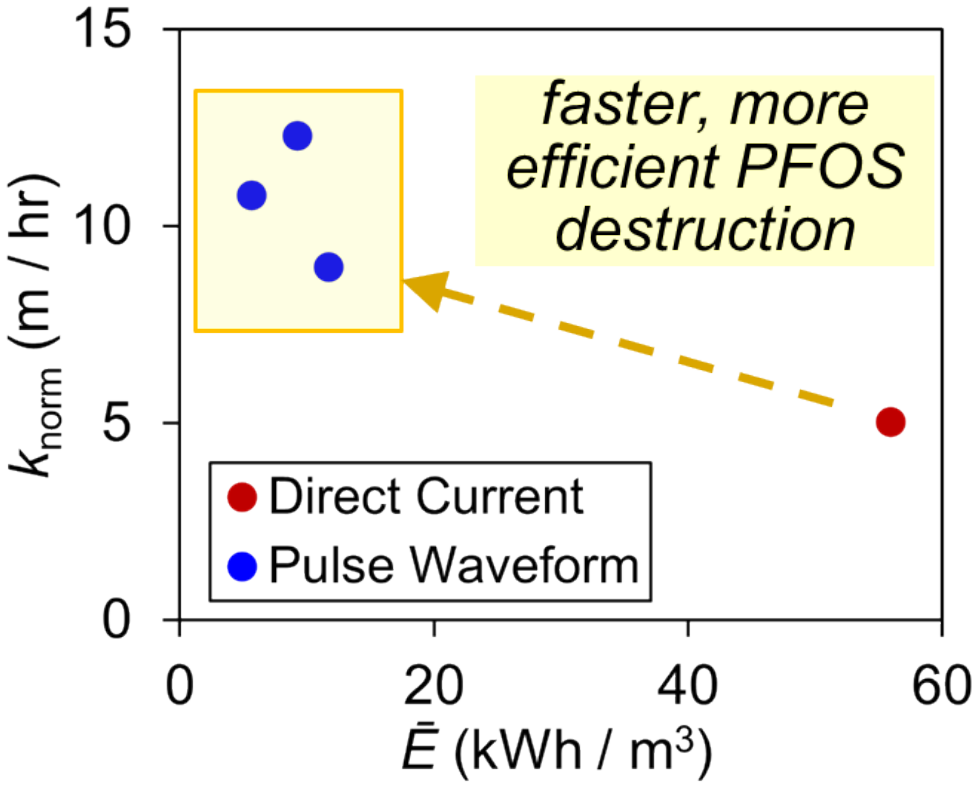
NaCl	100 mM
$CaCl_2$	15 mM
$MgCl_2$	15 mM
Na_2SO_4	15 mM
pH	4

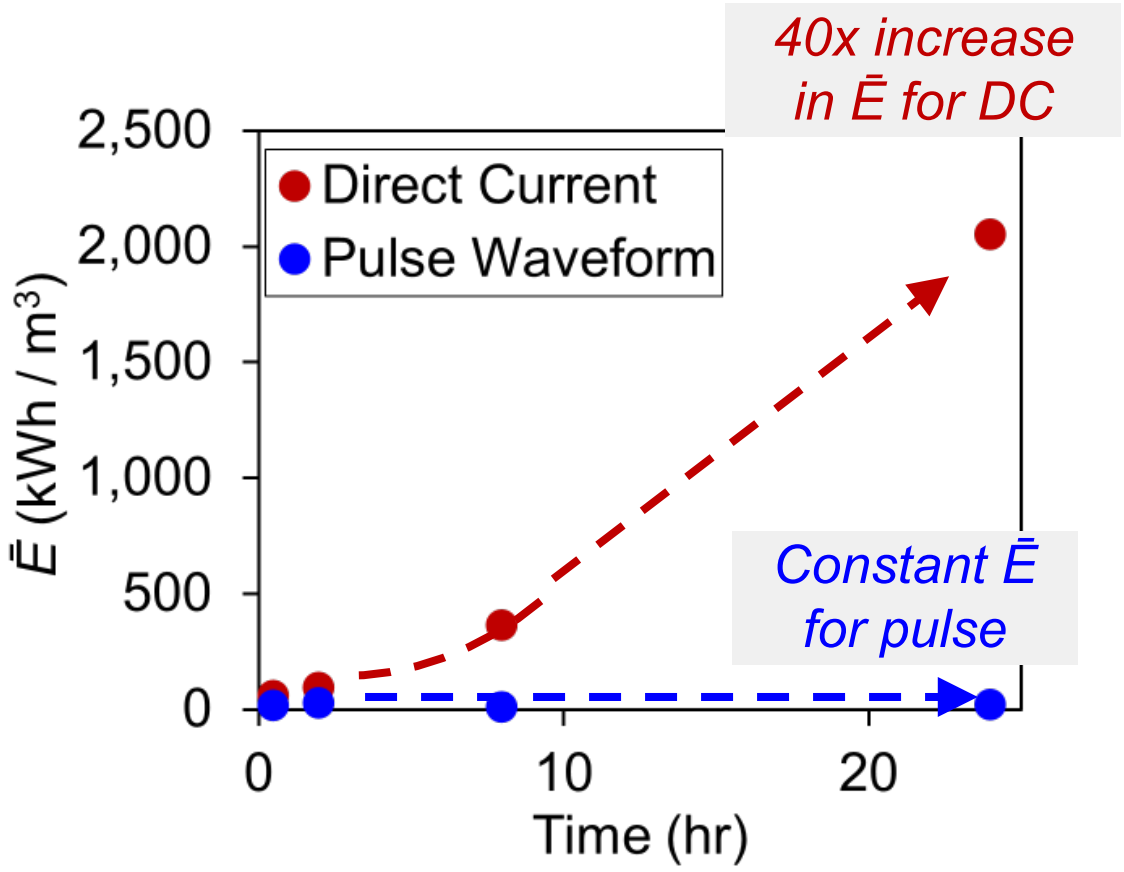
Groundwater Surrogate: FARADAYIC® EO improves rate, energy efficiency

- During 30-minute trials, pulse waveforms identified that:
  - Improve energy efficiency (lower $\bar{E}$) ***and***
  - Increase rate of PFOS destruction (lower k_{norm})



Groundwater Surrogate: FARADAYIC® EO prevents 40-fold increase in energy over longer timescales

- Over 24 hours:
  - DC: 40x increase in energy demand
  - Pulse waveforms: constant energy demand



Groundwater Surrogate: FARADAYIC® EO mitigates electrode fouling

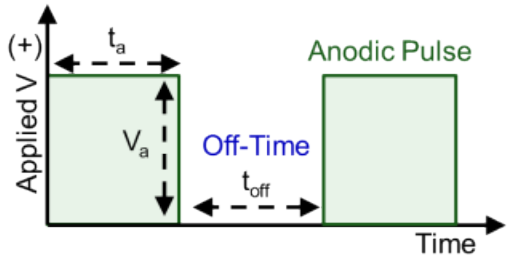
Additional Long-Term Performance Benefits

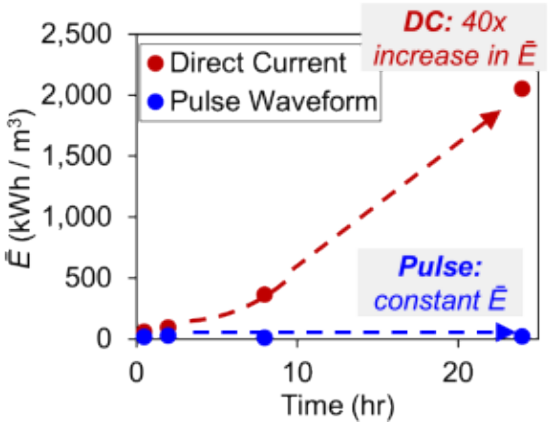
- **DC EO:**
  - pH increase after 10 minutes
  - Led to precipitation of a white solid/obstruction of solution flows
- **FARADAYIC® EO:**
  - pH increase/precipitation not observed for 8–24 hours (depending on pulse conditions)

Summary and Ongoing Work

Summary:

- FARADAYIC® EO:
  - Pulse-waveforms improve PFAS destruction performance
  - Validated in CONDIACELL® reactor with BDD electrodes
- FARADAYIC® and DC EO compared in landfill leachate and groundwater surrogates:
  - FARADAYIC® EO improved PFAS destruction rate and energy efficiency
  - FARADAYIC® EO prevented increase in energy demand over 24-hour treatment times
- Additional benefits identified in other complex solutions:
  - Foam Fractionate: FARADAYIC® EO prevented foaming/solution overflow; enabled safe treatment
  - Highly Saline Groundwater Surrogate: FARADAYIC® EO prevented pH swings, salt precipitation, electrode fouling





Ongoing Work: FARADAYIC® EO with GAC regenerate in Axine reactor

- PFOS, PFOA, PFNA, PFHxS, PFBS, GenX
- Compare energy efficiency and rate of FARADAYIC® EO and DC EO
- Evaluate potential to suppress by-product (e.g., perchlorate) formation

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Thank you for your attention! Questions?

For additional information, please contact:

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