DE-FLUORO™

Electrochemical Degradation of PFAS: Mass in Redundant Stocks of AFFF Concentrate and First Flush Washwater – Pilot-Scaled Field Demonstrations

Rachael Casson, Shangtao Laing, Rebecca Mora

John Santacroce

PFAS

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Agenda

- PFAS Dilemma
- Introducing DE-FLUORO™
- The DE-FLUORO™ Journey
  - Proof of Concept
  - Real World Bench-Scale Trials
  - Wright-Patterson AFB Pilot Demonstration
  - MEG System Demonstration-First Flush
  - ORCA System Demonstration
- Q&A

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PFAS Dilemma

The PFAS Treatment Dilemma

- **Basics:**
  - Per- and polyfluoroalkyl substances (PFAS) contain C-F bonds
  - The C-F bond resists chemical, biological, and thermal destruction
  - USEPA draft guidance identifies current commercial PFAS disposal options as: landfilling, deep well injection, or incineration
- **The Dilemma:**
  - Commercial PFAS treatment is primarily separation
  - Destroying environmental contaminants is often favored because it is permanent and sustainable
  - Thermal destruction via incineration is under scrutiny for emissions issues
- **The Solution:**
  - Develop reliable destructive technologies that are commercially viable

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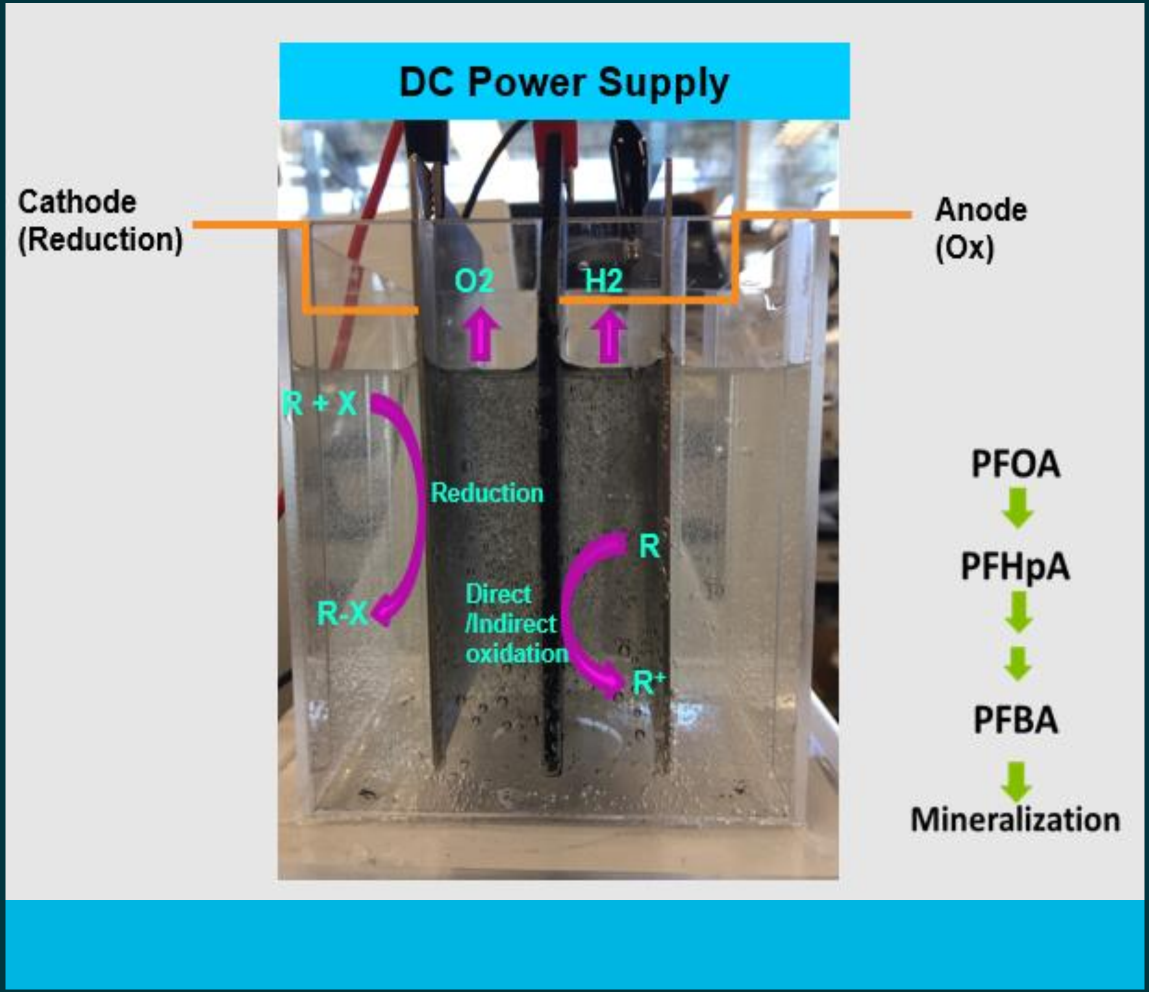
Introducing DE-FLUORO™

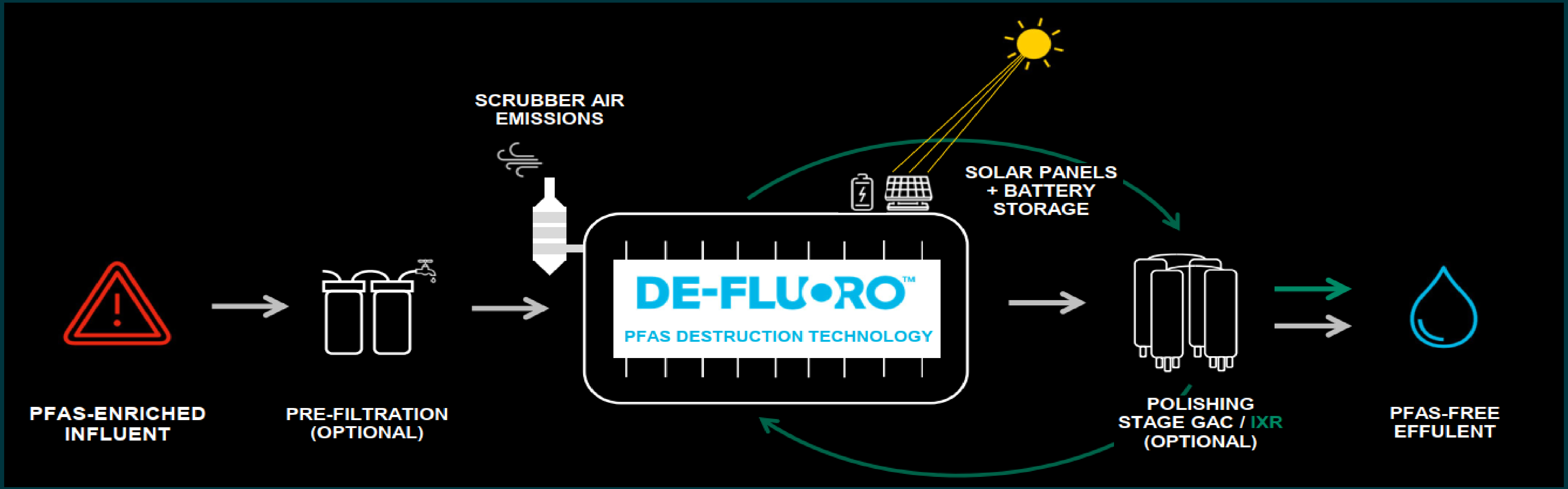
Introducing DE-FLUORO™ Electrochemical Oxidation Technology

- Electrochemical oxidation (EO) defluorinates and mineralizes short-chain and long-chain PFAS
- DE-FLUORO™ utilizes a proprietary, high durability and low-cost electrode that can be in different sizes, forms and shapes for different applications
- **DE-FLUORO™** : **D**egradation and **E**lectrochemical oxidation of per- and poly**fluoro**alkyl substances
- A compact, highly efficient, cost-effective mobile treatment unit for on-site PFAS destruction treatment
- It reduces environmental liability of transporting PFAS-impacted waste off site for treatment/disposal



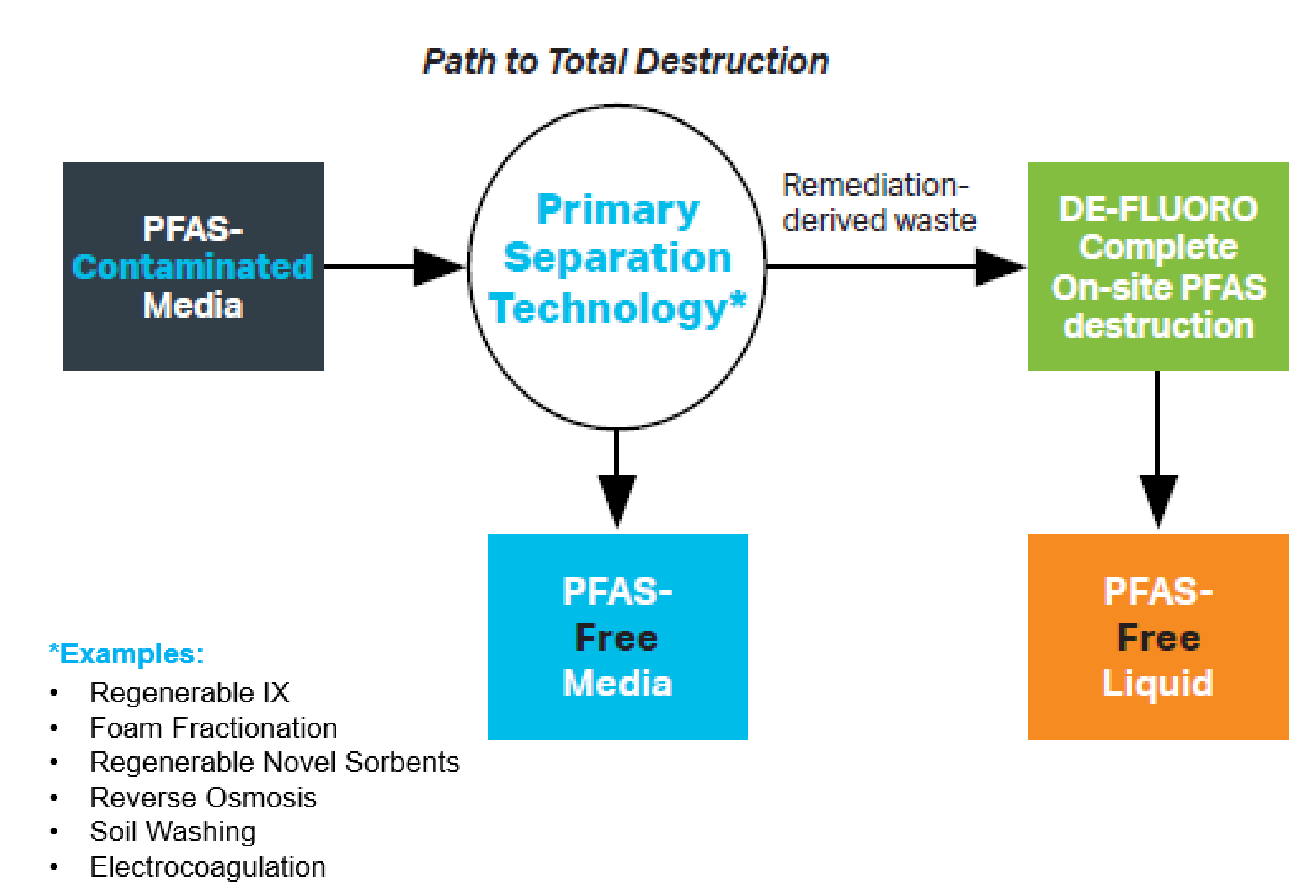
DE-FLUORO™ as Primary Treatment Technology

- Applicable for smaller volumes and higher PFAS concentrations (e.g., AFFF concentrate, AFFF rinsate, wastewater from FTAs, etc.)
- Can treat in batch or flow-through mode
- Polishing may be required to reach strict (single digit ppt) discharge levels



Coupling DE-FLUORO™ with Separation Technologies

- Applicable for larger volumes and lower PFAS concentrations (e.g., groundwater, landfill leachate, etc.)
- Primary technology separates PFAS from the waste stream
- Primary technology typically generates a concentrated waste stream, with higher PFAS
- DE-FLUORO™ destroys PFAS in the concentrated waste stream



Coupling Approach

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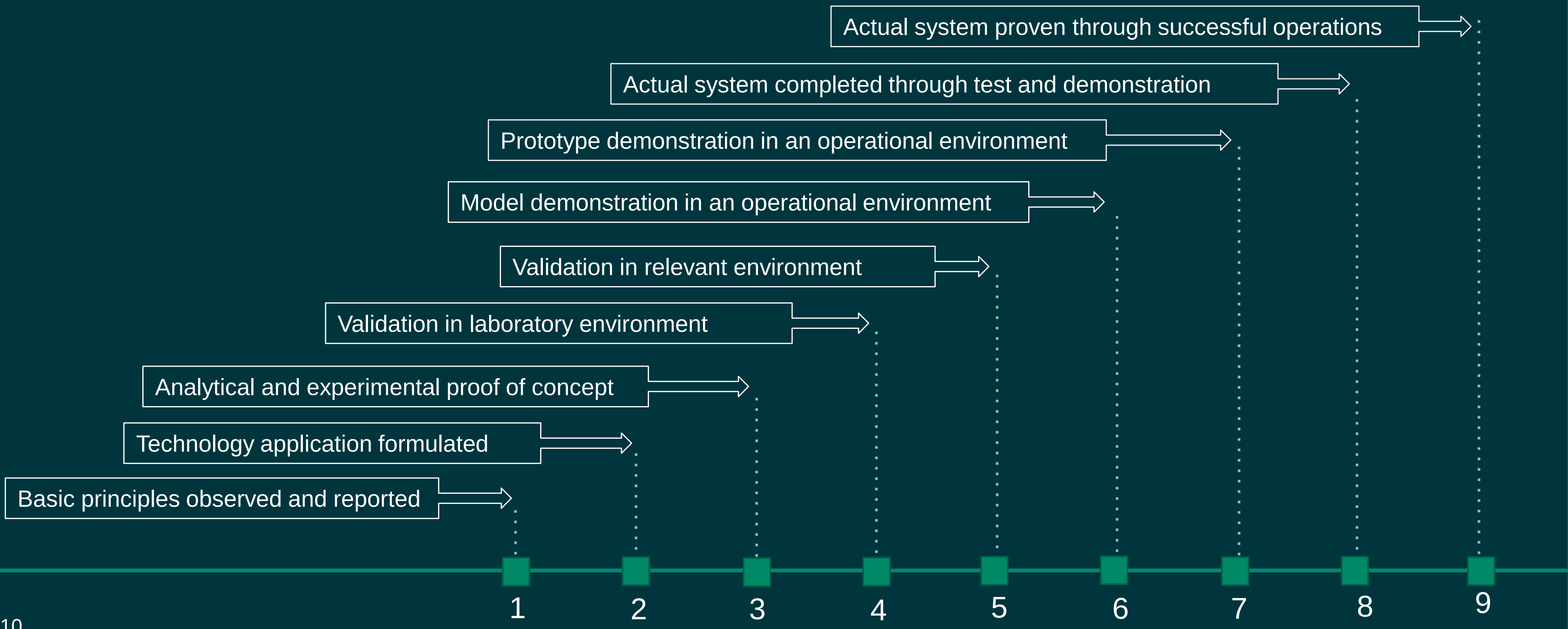
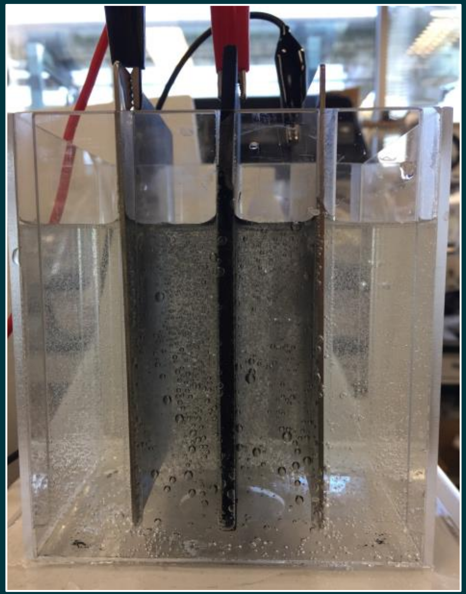
The DE-FLUORO™ Journey

Technology Readiness Level Advancement

Reference: https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf



Technology Readiness Level Advancement



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Actual system proven through successful operations

Actual system completed through test and demonstration

Prototype demonstration in an operational environment

Model demonstration in an operational environment

Validation in relevant environment

Validation in laboratory environment

Analytical and experimental proof of concept

Technology application formulated

Basic principles observed and reported

1 2 3 4 5 6 7 8 9

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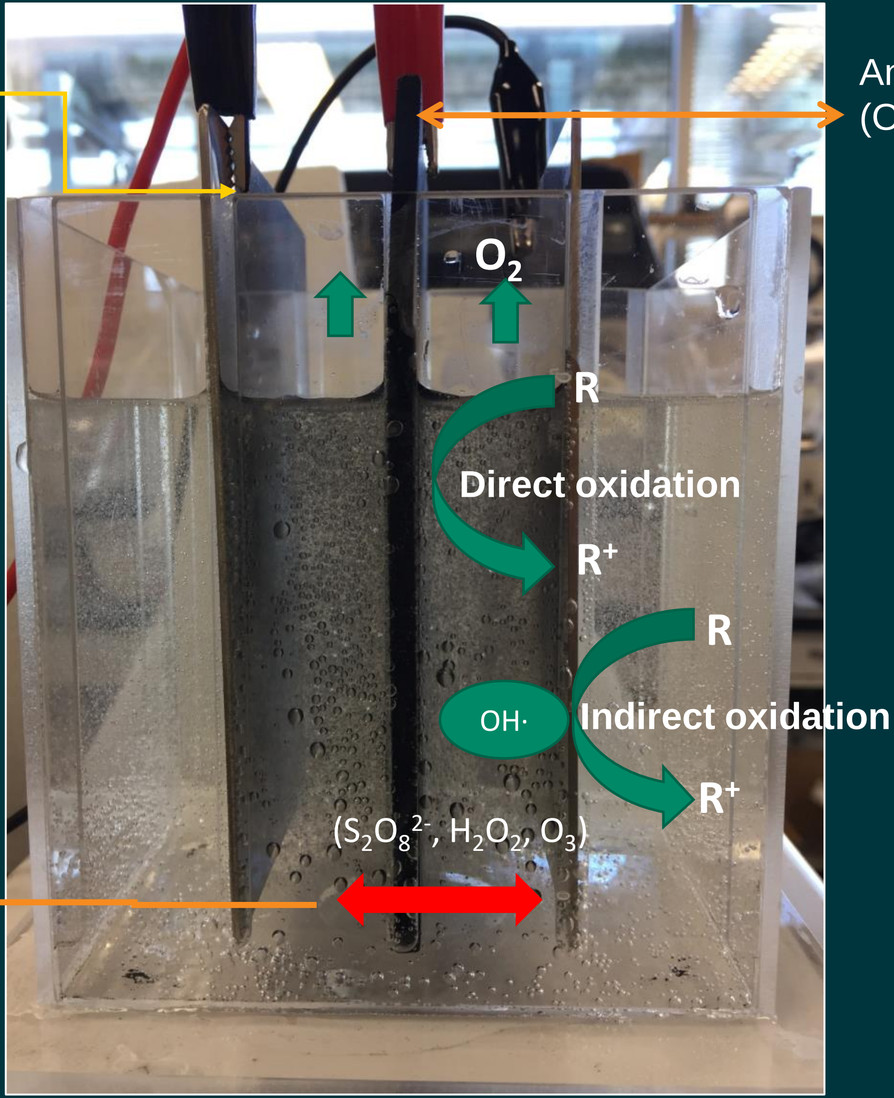
DE-FLUORO™ – Proof of Concept

DC Power Supply

Cathode (Red)

Anode (Ox)



Mixing to increase mass transfer

PFOA

PFHpA

PFBA

Mineralization

$CO_2 + F^-$

PUBLICATIONS

- Lin, Hui, et al. "Development of macroporous Magnéli phase Ti4O7 ceramic materials: As an efficient anode for mineralization of poly-and perfluoroalkyl substances." **Chemical Engineering Journal** 354 (2018): 1058-1067.
- Liang, Shangtao, et al. "Electrochemical oxidation of PFOA and PFOS in concentrated waste streams." **Remediation Journal** 28.2 (2018): 127-134.
- Schaefer, Charles E., et al. "Electrochemical Transformations of Perfluoroalkyl Acid (PFAA) Precursors and PFAAs in Groundwater Impacted with Aqueous Film Forming Foams." **Environmental science & technology** (2018).
- Niu, Junfeng, et al. "Electrochemical oxidation of perfluorinated compounds in water" **Chemosphere** 146 (2016) 526-538
- Schaefer, Charles E., et al. "Electrochemical treatment of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) in groundwater impacted by aqueous film forming foams (AFFFs)." **Journal of hazardous materials** 295 (2015): 170-175.
- Lin, Hui, et al. "Highly efficient and mild electrochemical mineralization of long-chain perfluorocarboxylic acids (C9–C10) by Ti/SnO2–Sb–Ce, Ti/SnO2–Sb/Ce–PbO2, and Ti/BDD electrodes." **Environmental Science & Technology** 47.22 (203): 13039-13046.

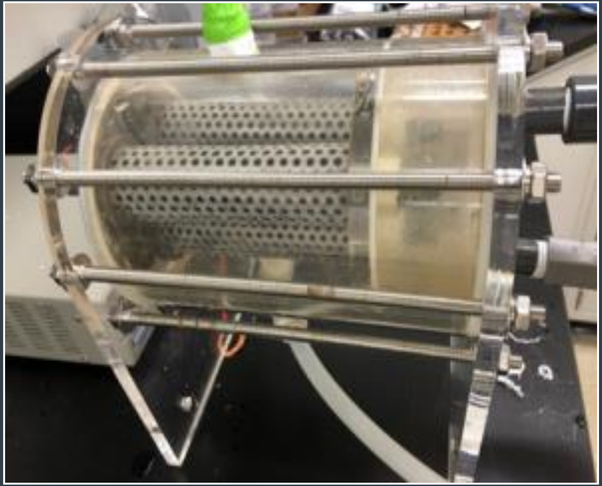
DE-FLUORO™ – Bench-Scale Reactors

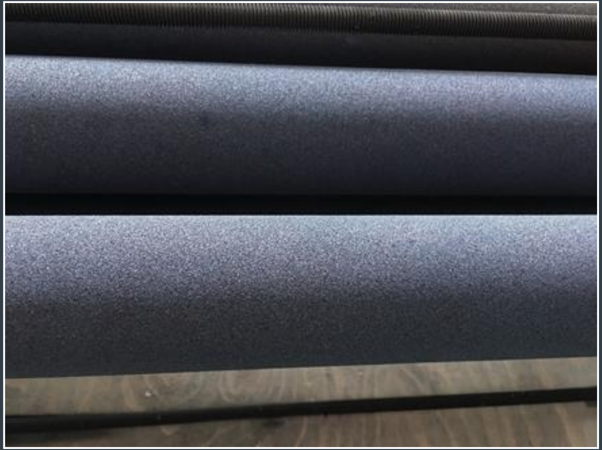
DE-FLUORO™ Model 1 - NEMO

Plate Electrodes

- Batch mode
- Large Surface Area
- High reactivity

DE-FLUORO™ Model 2 - JAWS





Membrane Electrodes

- Flow-through mode
- Large surface area
- Scalable

DE-FLUORO™ – Validation in laboratory environment Summary of Results

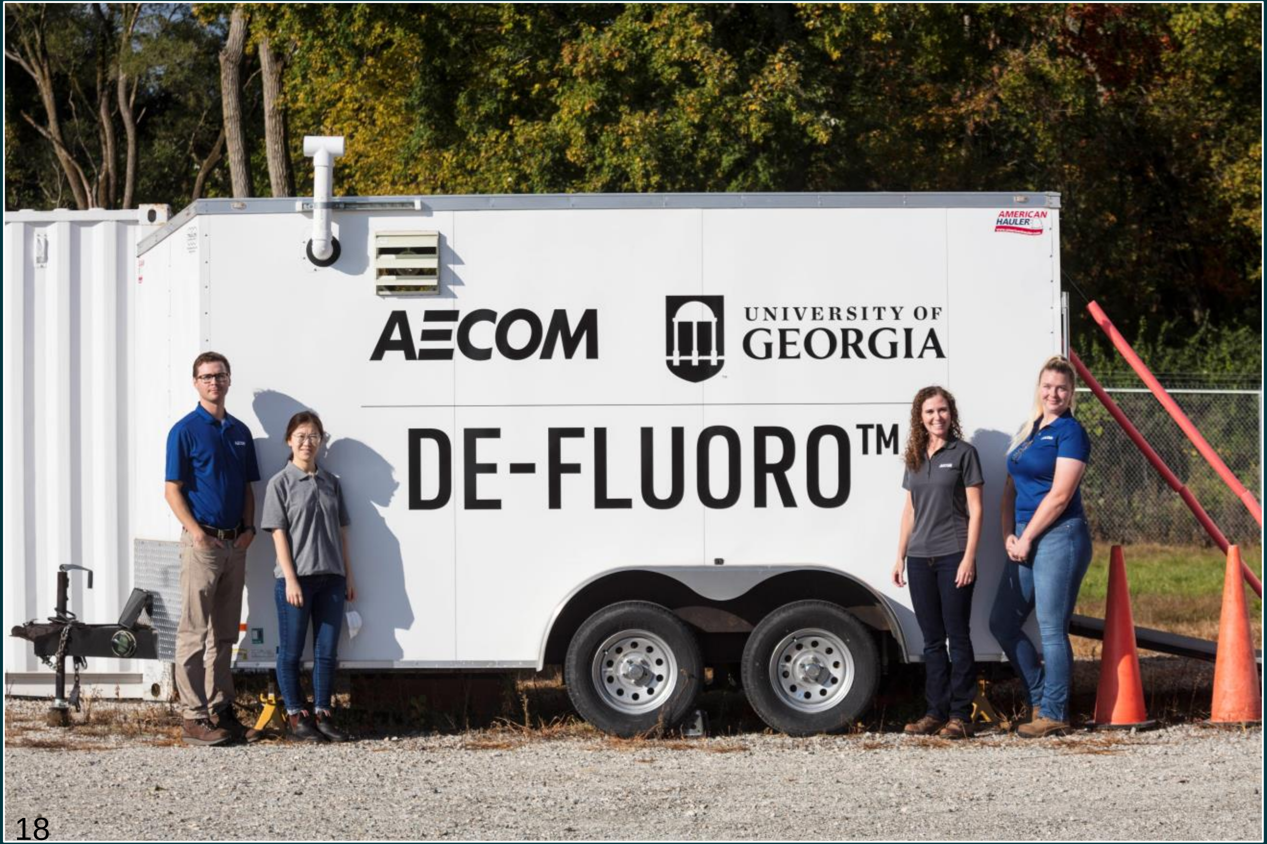
Trial #	Sample Description	Initial Total PFAS Concentration (ug/L)*	(PFOA + PFOS) Mass Reduction	Total PFAS Mass Reduction*
1	AFFF concentrate / product	6,380,000	42.7%	60.0%
2	IX-R regenerant waste (brine)	408,590	98.5%	92.9%
3	Remediation derived wastewater-soil washing	13,600	100%	99.2%
4	Spent C6 AFFF solution	4,620	80.5%	83.3%
5	Remediation derived wastewater-ozone fractionation	1,590	98.9%	90.7%
6	Source area groundwater 1	455	100%	99.7%
7	Industrial groundwater	411	100%	99.5%
8	Source area groundwater 2	27.3	98.3%	83.8%

* Based on measurable PFAS (27 PFAS compounds)

DE-FLUORO™ – Model Demonstration in an Operational Environment

Wright-Patterson AFB Field Pilot

Coupling with Concentration Technology



WPAFB - Field Pilot for Groundwater Treatment

- IX-R groundwater treatment flow rate: 2 to 5 gpm
- Designed to treat 5,000 – 15,000 ppt total PFAS
- Treatment goal: PFOS + PFOA < 70 ppt (Hangar) and ND for PFOS (FTA)
- Treated ~500,000 gallons of groundwater over 5 months at two sites

WPAFB Field Pilot - Separation & Concentration

Feed Groundwater

Discharge

Resin Regeneration and Distillation Equipment

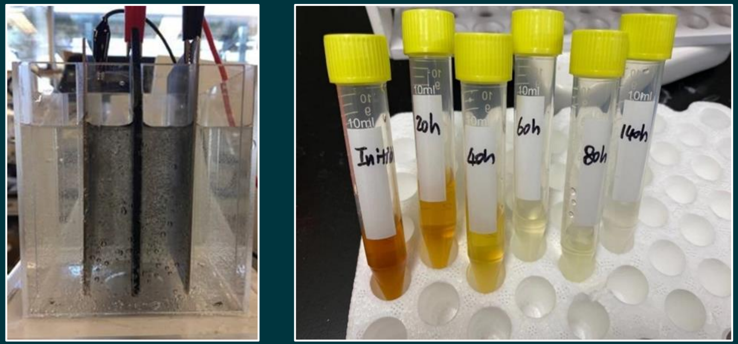
Still Bottom Waste

WPAFB Field Pilot - Destruction

Still Bottom Waste

On-site pilot treatment

UGA Bench Treatment

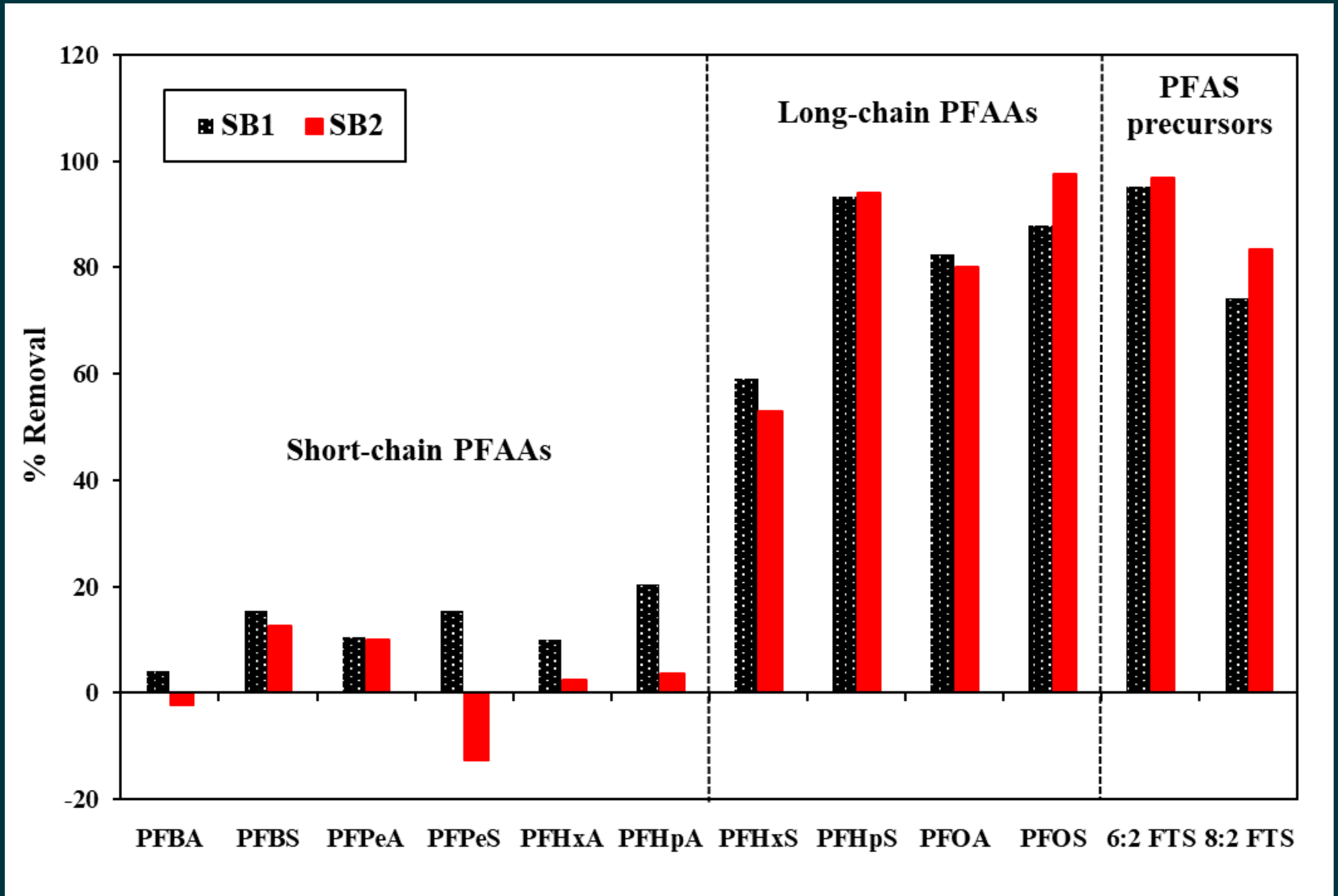


Bench EO Reactor

Pilot EO Reactor

WPAFB Field Pilot - Results

Liang et al., 2022. *Field demonstration of coupling ion-exchange resin with electrochemical oxidation for enhanced treatment of per- and polyfluoroalkyl substances (PFAS) in groundwater*. Chemical Engineering Journal Advances V9, 100216



% Reduction $(C_t-C_0)/C_0$		
	SB1	**SB2**
PFBA	-4%	2%
PFBS	-15%	-13%
PFPeA	-10%	-10%
PFPeS	-16%	13%
PFHxA	-10%	-2%
PFHpA	-20%	-4%
PFHxS	-59%	-53%
PFHpS	-93%	-94%
PFOA	**-82%**	**-80%**
PFOS	**-88%**	**-98%**
6:2 FTS	-95%	-97%
8:2 FTS	-74%	-83%

- Up to 82% reduction of PFOA and 98% reduction of PFOS using NEMO reactor
- Degradation of short-chains was slower due to decarboxylation of long-chains and precursors
- Good replicability between batches
- With coupling approaches, DE-FLUORO™ effluent can be metered back to the influent of the primary technology

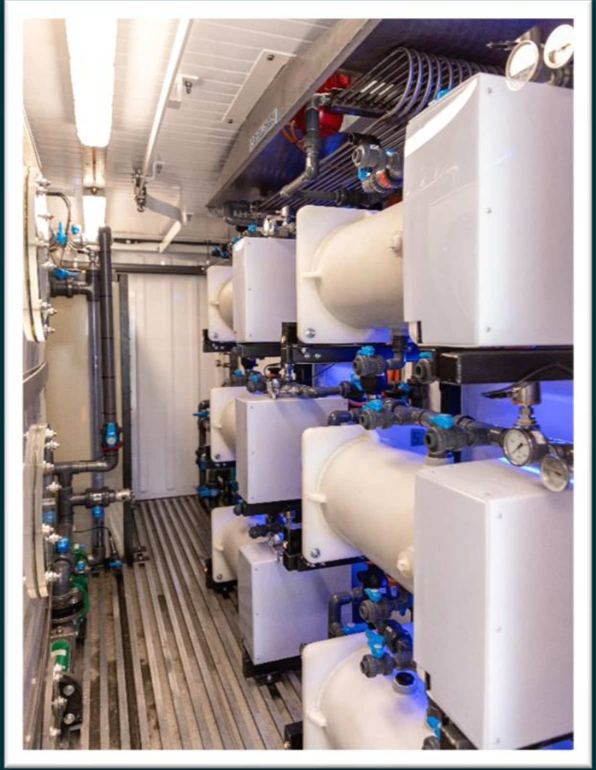
DE-FLUORO™ – Prototype Demonstration in Operational Environment

<u>Demonstration Systems:</u>

Used to optimize or for full-scale treatment

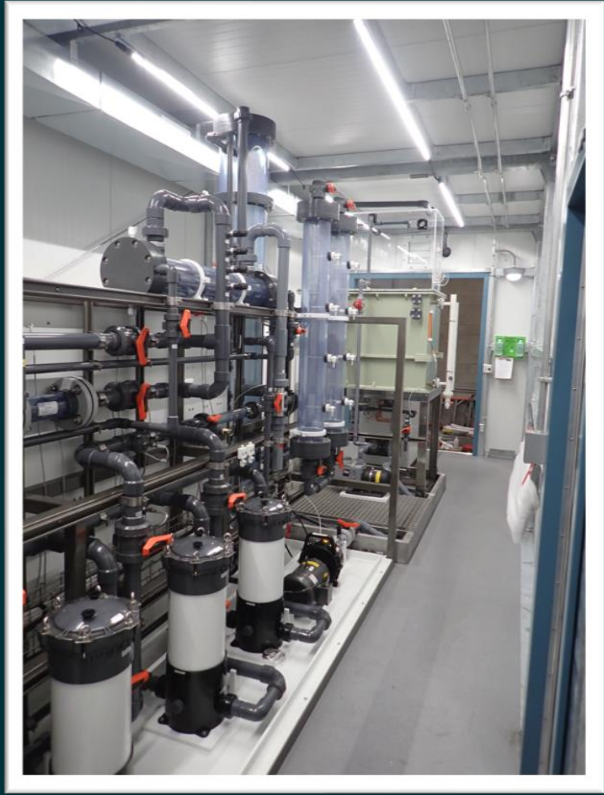
Megalodon Batch System

Mobile 20-foot container
240-liter reactors
100-300 amps



Orca Flow Through System

Mobile 40-foot container
300-liter reactor
1000-3000 amps
EO/ER modes



DE-FLUORO™ – Prototype Demonstration in Operational Environment

Client: Australian Defence

Treatment Solutions:
- First flush wastewater
- AFFF Concentrate

Origin of Solutions: Foam transition program

Objective: Treat to levels suitable for discharge to onsite water treatment system

Operator Requirement: Single operator supported through telemetry system

MEG

DE-FLUORO™ – Prototype Demonstration in Operational Environment

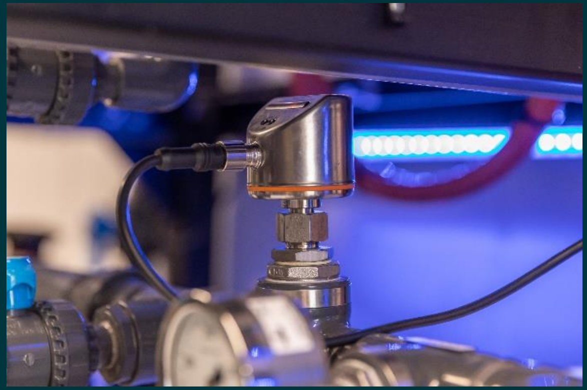
Experiment #	Treatment Sample	Initial (T0) TOF Mass	Initial (T0) regulated PFAS mass	Mass Reduction DE-FLUORO™	Pilot Efficacy Meet (~*90% - 99% destruction rate*)?
1	First Flush	6.975 g	PFOS – 0.020 g PFOA – 0.004 g PFHxS – 0.003 g	TOF – 81.1 % PFOS – 99.5% PFOA – 11.1 % PFHxS – 92.1 %	☒ ☑ ☒ ☑
2	First Flush	2.565 g	PFOS – 0.013 g PFOA – 0.001 g PFHxS – 0.004 g	TOF – 62.1 % PFOS – 99.1% PFOA - -278 % PFHxS – 85.8 %	☒ ☑ ☒ ☒
3	First Flush	3.719 g	PFOS – 0.042 g PFOA – 0.002 g PFHxS – 0.012 g	TOF – 96.4 % PFOS – 99.9 % PFOA – 94.3 % PFHxS – 99.3 %	☑ ☑ ☑ ☑
4	AFFF Concentrate	3,870 g (3.87 kg)	PFOS – 0.275 g PFOA – 0.282 g PFHxS – 0.038 g	TOF – 76.9 % PFOS – 78.8 % PFOA - -794 % PFHxS – 71 %	☒ ☒ ☒ ☒

Successes

- Significant mass reduction within first 8 - 24 hours (suitable for discharge to WTP).
- Potential to run 24/7 with minimal to no supervision.
- Energy consumption 3-5 kilowatt hour/day. Possible to operate on solar power supplemented with a battery (contributing to ESG compliance and lower operational costs).
- Electrodes appear very durable.

Challenges

Batch System	Mitigation	Flow Through System
Excessive foaming	Sprinkler, antifoaming agent, vacuum extraction	Amended
Filter build up	Increase filtration, possible pre-treatment	Enhanced
Complex PFAS Chemistry (Transition PFAS (PFOA))	ER/EO sequential treatment, increase residence time and amperage input	Enhanced
Air emissions	Enhance vapour emission capture	Amended



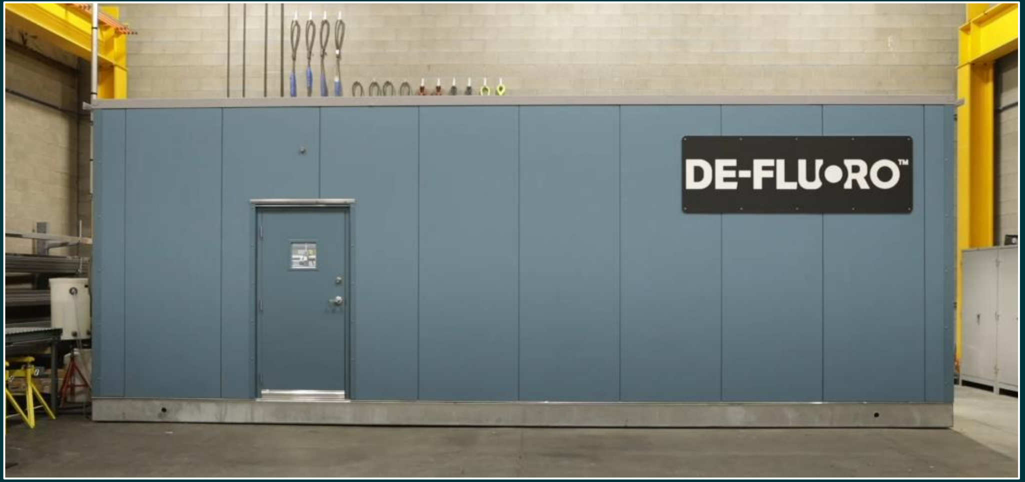
DE-FLUORO™ – Prototype Demonstration in Operational Environment

Client: US DOD

Treatment Solutions:

- FTA wastewater
- Evaporator brine
- AFFF Concentrate

Origin of Solutions: Active fire training area



Objective: Treat increasingly complex AFFF-related wastes with very high PFAS concentrations

Operator Requirement: Single operator supported through telemetry system

What have we learned and what's next?

- Demonstration learnings
  - Coupling with concentration technologies makes groundwater treatment possible
  - Stockpiled AFFF foaming requires careful flow management
  - Energy supplementation via sustainable solar power and batteries is attractive
  - Complex solutions containing PFAS can be treated
- What's Next?
  - Complete US ORCA system demonstration
    - Fluorine mass balance, optimal treatment times, energy usage evaluation
  - Promote application as fixed or mobile units
  - Develop models for deployment to broad range of client needs
  - Expand understanding through additional advanced field demonstrations, based on treatability testing

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THANK YOU.

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John.Santacroce@aecom.com