AECOM

Evaluation of PFAS Removal by Surface Active Foam Fractionation and Destruction by Electrochemical Oxidation

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REMTEC & EMERGING CONTAMINANTS SUMMIT
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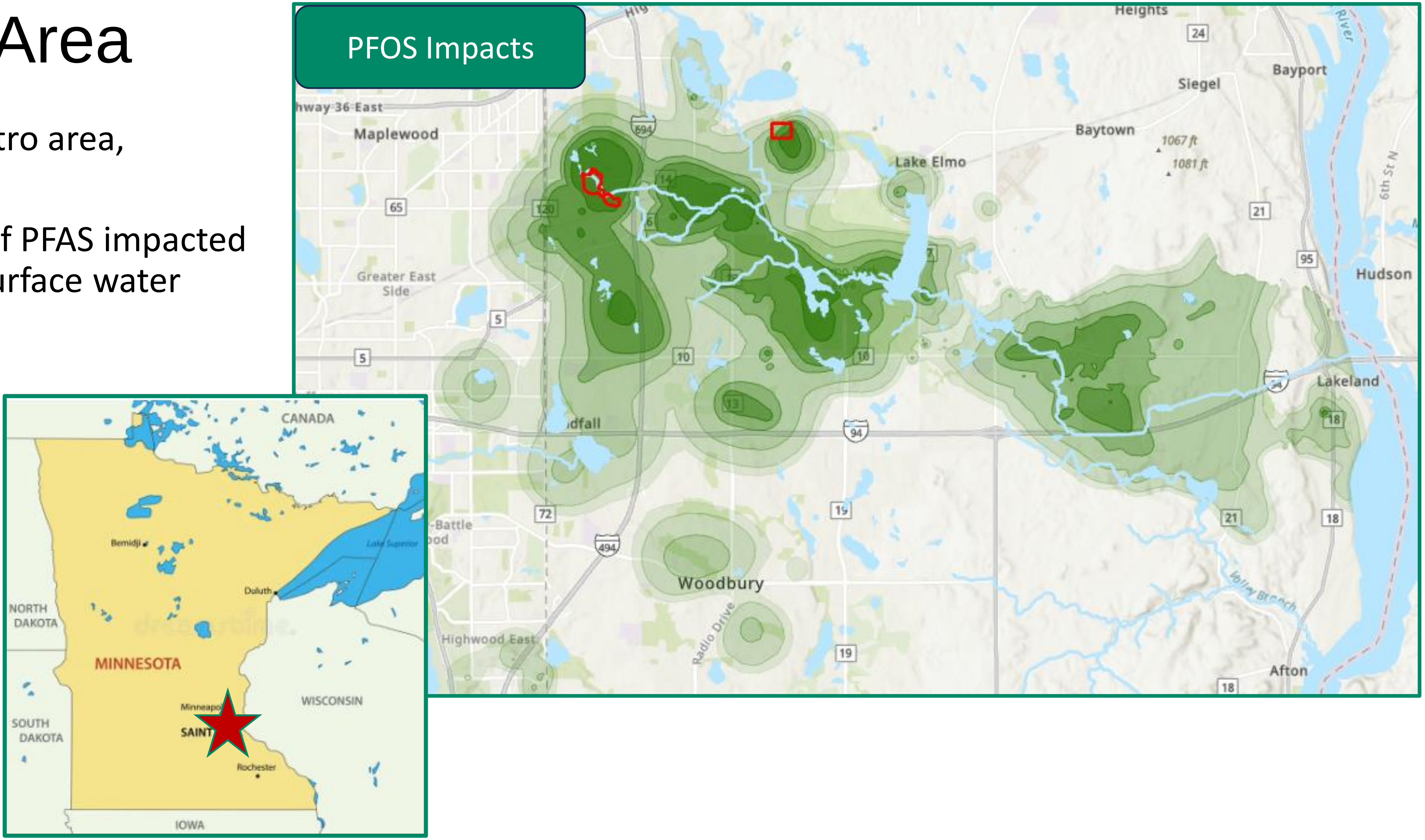
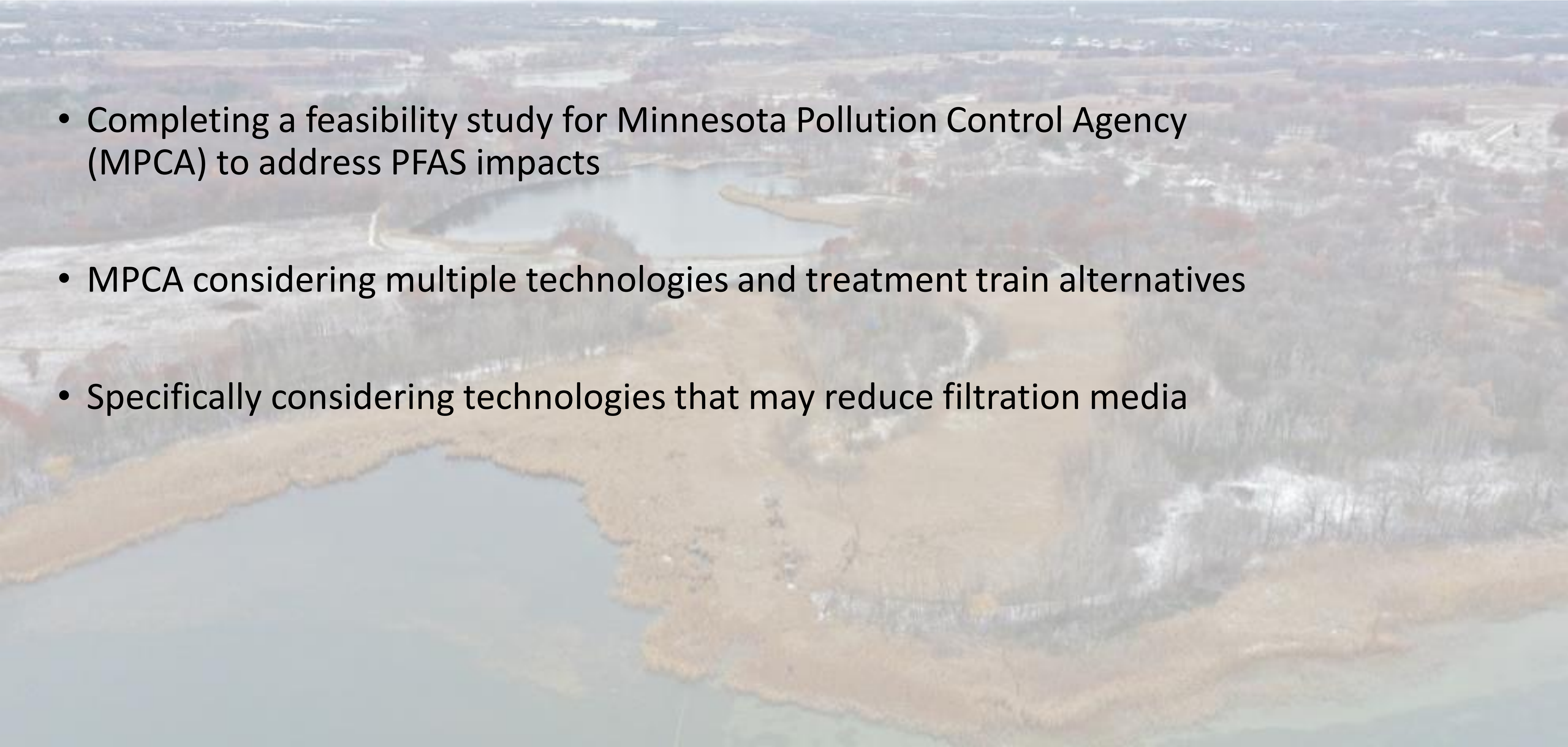
Project Area

- Twin Cities east metro area, Minnesota
- Over 125 sq miles of PFAS impacted groundwater and surface water

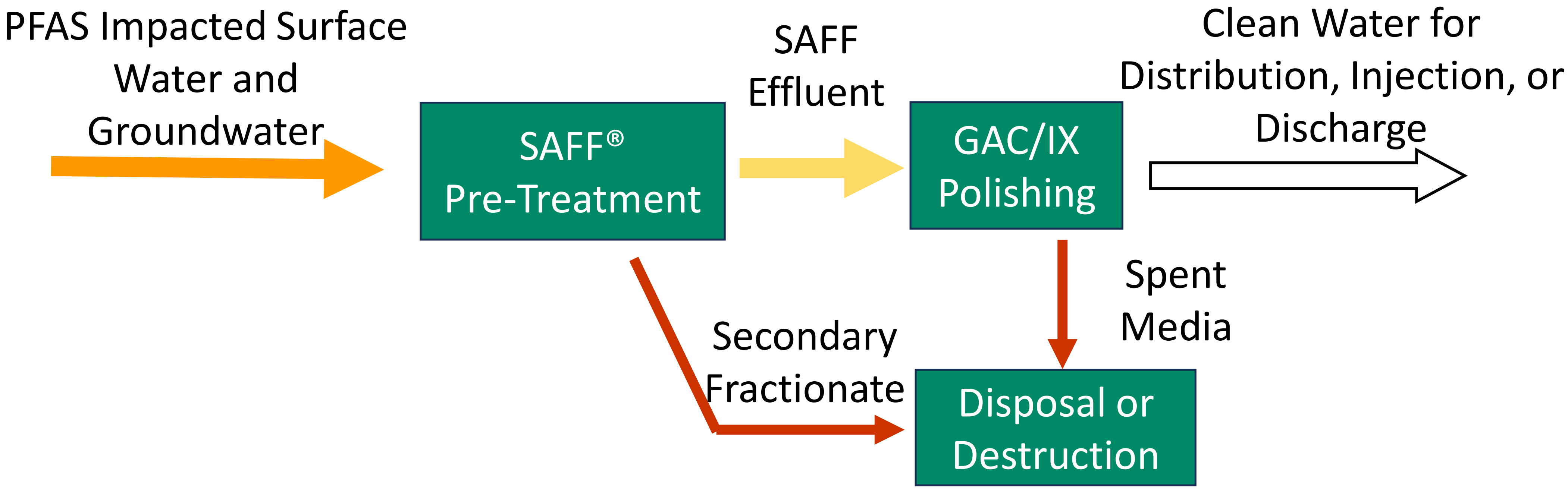

PFOS Impacts

Feasibility Study



- Completing a feasibility study for Minnesota Pollution Control Agency (MPCA) to address PFAS impacts
- MPCA considering multiple technologies and treatment train alternatives
- Specifically considering technologies that may reduce filtration media

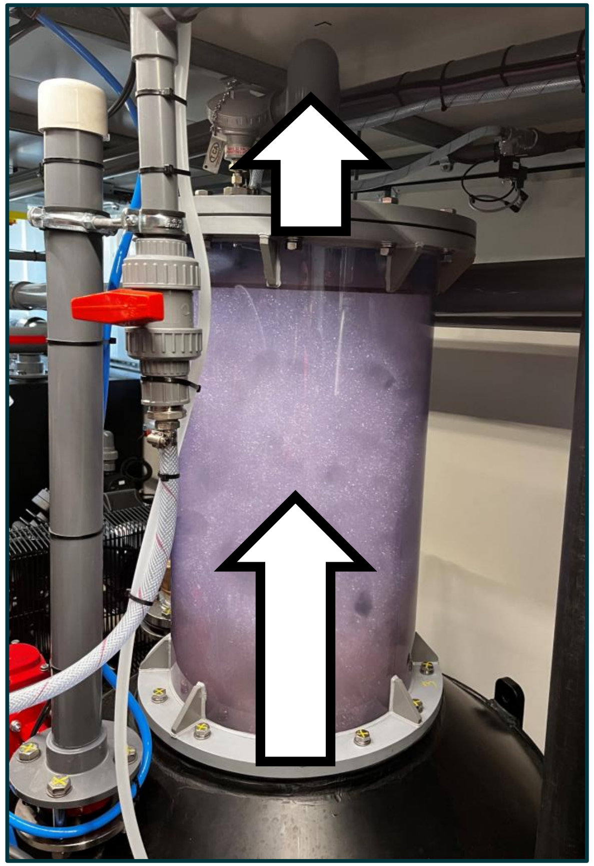
Possible Treatment Train



- Surface Active Foam Fractionation (SAFF®) one possible technology
- SAFF® could be used as a standalone technology or as pretreatment to filtration to reduce costs
- Pilot study focused on SAFF® Pre-Treatment followed by destruction of concentrate

Surface Active Foam Fractionation (SAFF®)

1. **Inject air into water**
2. **PFAS foams**
3. **Remove foam**

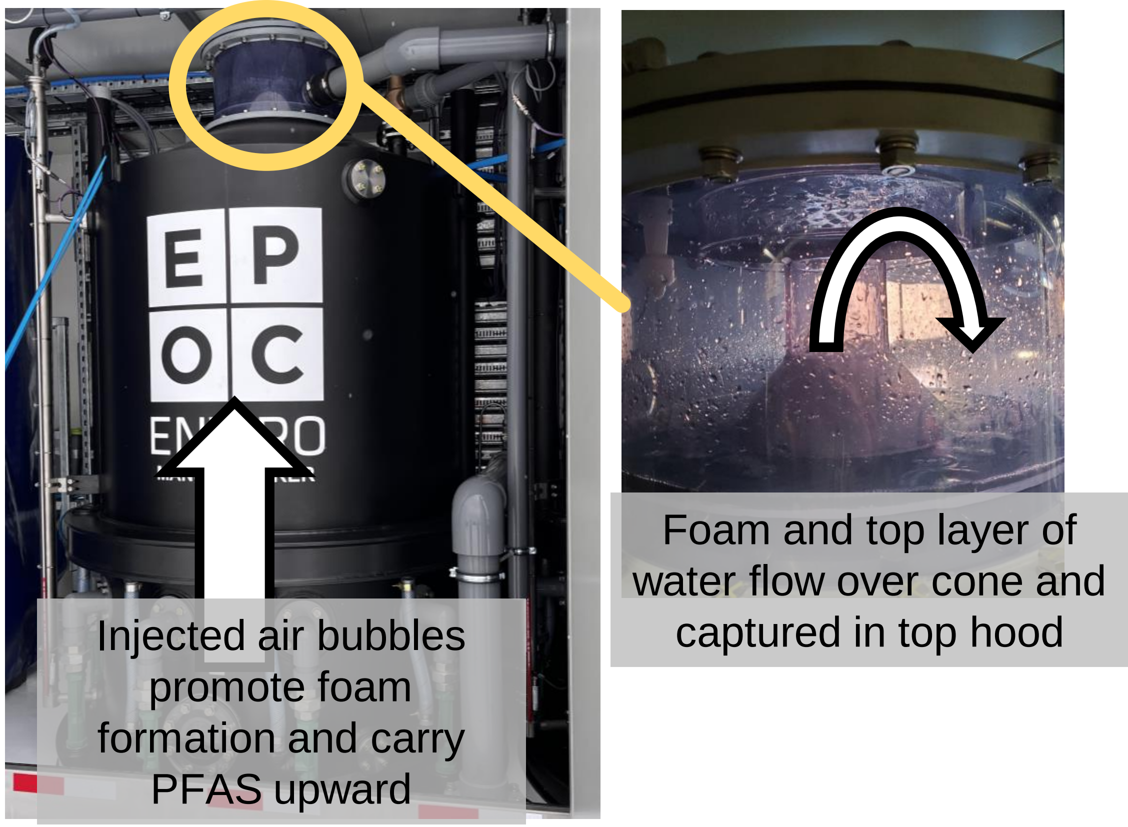


- Pilot study used a SAFF®20 from EPOC
- No surfactants used

SAFF®: Two Stages Process

Primary Fractionation

- **Goal:** Minimize PFAS concentration in effluent

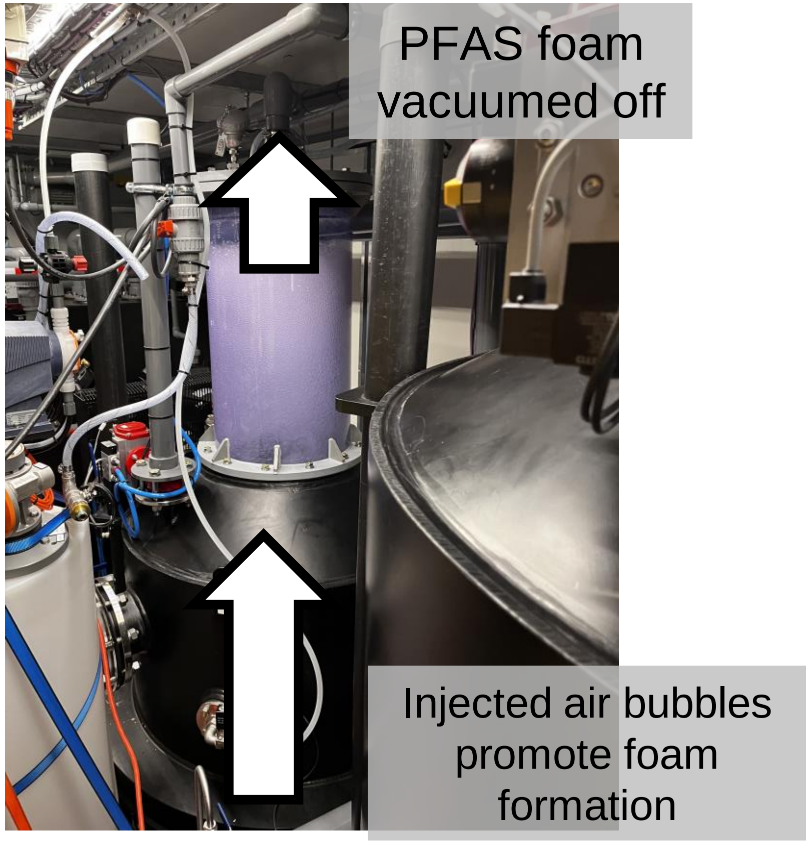


Injected air bubbles promote foam formation and carry PFAS upward

Foam and top layer of water flow over cone and captured in top hood

Secondary Fractionation

- **Goal:** Minimize volume of PFAS concentrate prior to destruction or disposal

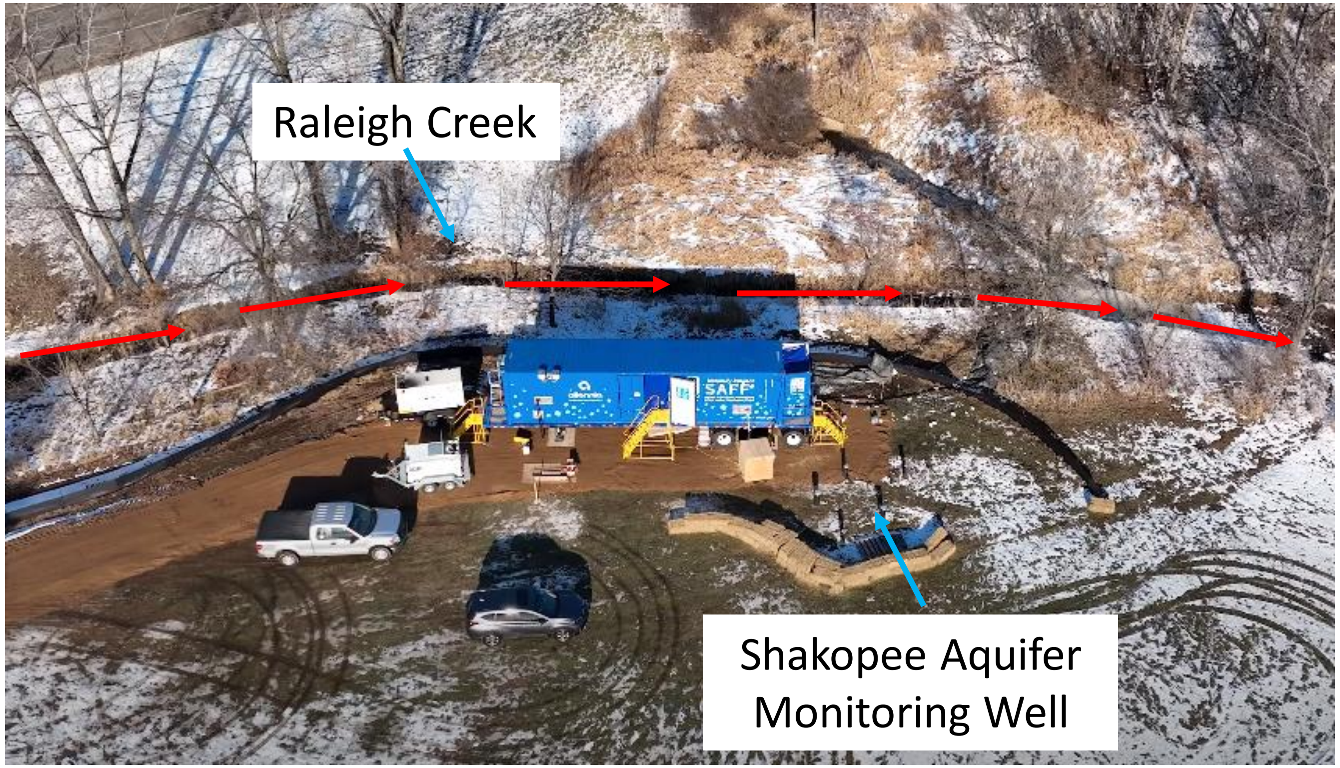


PFAS foam vacuumed off

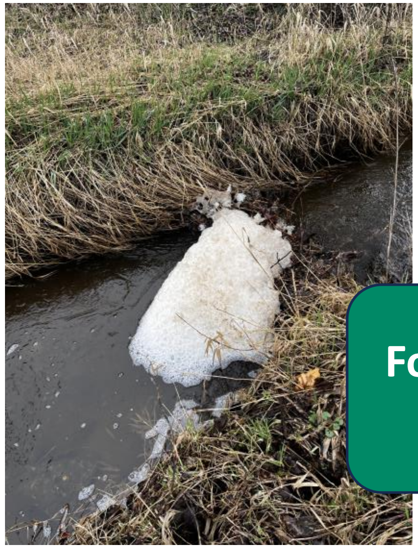
Injected air bubbles promote foam formation

Water Sources

Site selected because of access to impacted surface water and impacted aquifers



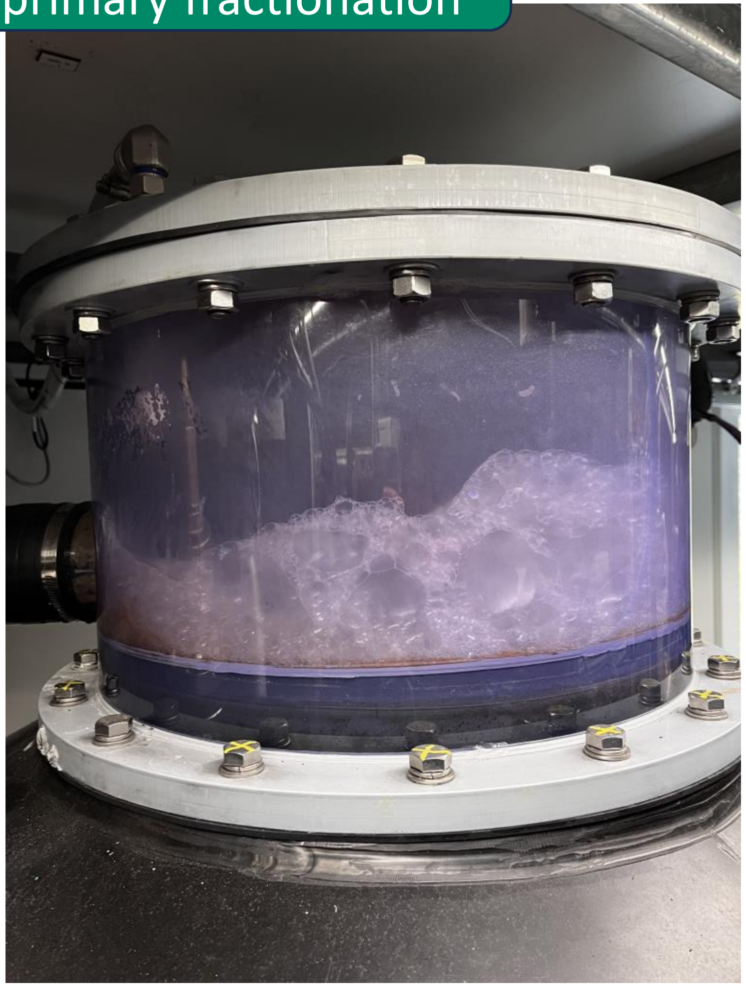
	PFOS	PFOA	Total Organic Carbon
Raleigh Creek	2,000-3,000 ng/L	700-900 ng/L	6.5 mg/L
Shakopee Aquifer	950 ng/L	330 ng/L	<0.5 mg/L
Jordan Aquifer	1 ng/L	22 ng/L	<0.5 mg/L

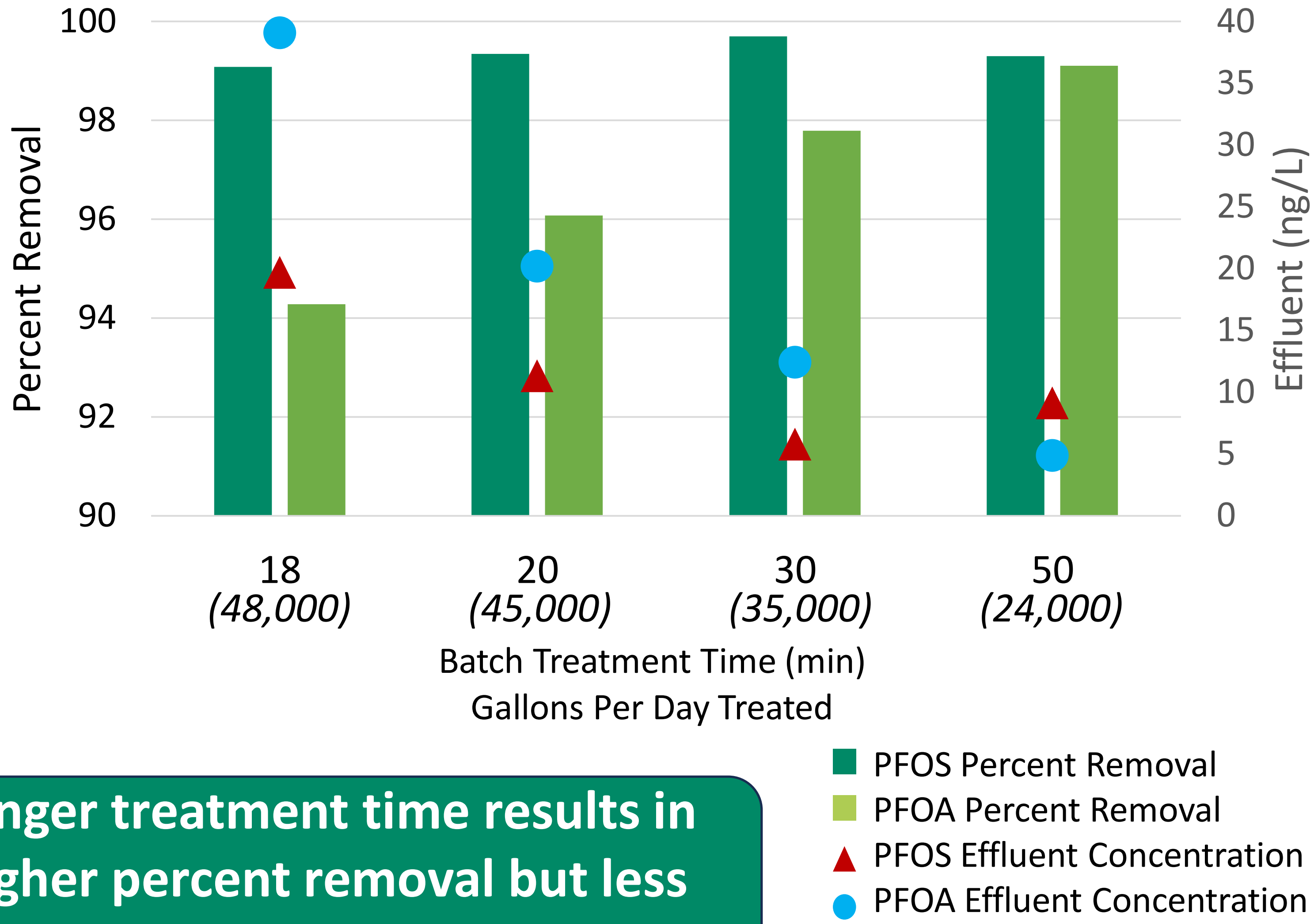


Foam readily forms on Raleigh Creek

Raleigh Creek Treatment

Foam formed during primary fractionation





Longer treatment time results in higher percent removal but less water treated per day

Raleigh Creek Optimized Results

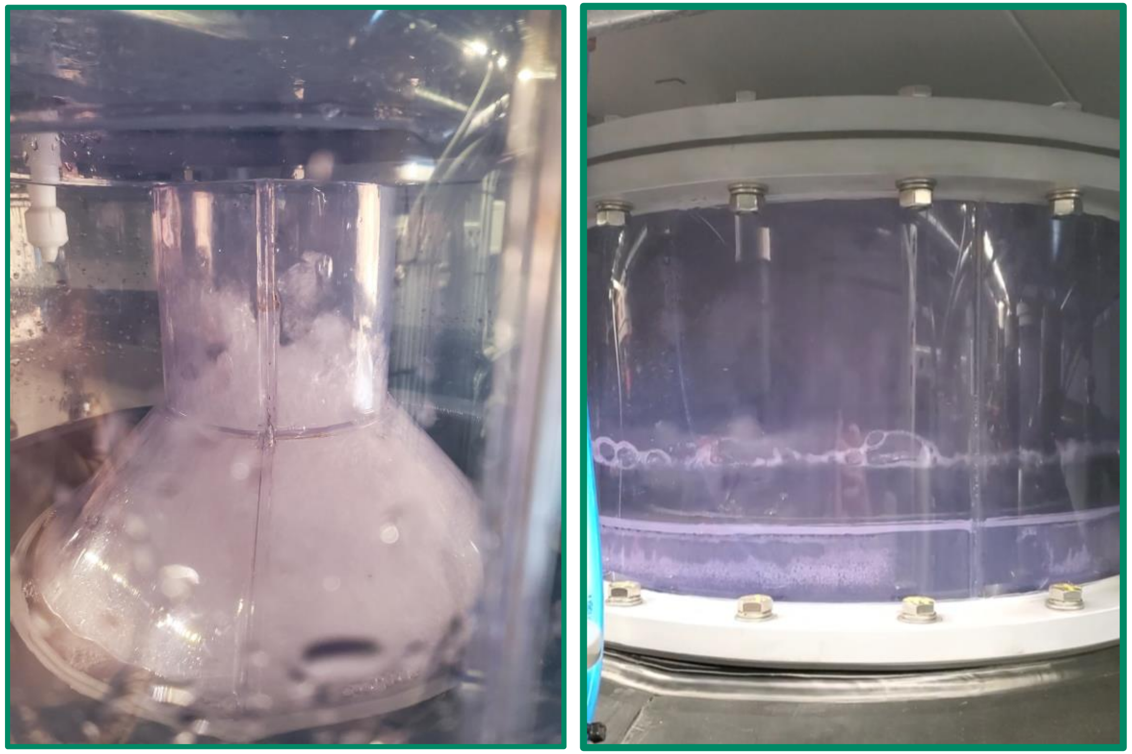
PFAS	Influent (ng/L)	Effluent (ng/L)	Percent Removal	Surface Water Quality Criteria (ng/L)
PFBA	303	175	42	5,700
PFHxA	51.5	22	57	220
PFOA	515	2.12	99	25
PFBS	18.4	8.08	56	140
PFHxS	41.1	1.69	96	20
PFOS	1570	1.8	99	0.05

Met criteria

Exceeded criteria

- Removal observed to be variable with changes in flow and PFAS concentrations
  - PFOS: 1.8-5 ng/L
  - PFOA: 2-4 ng/L

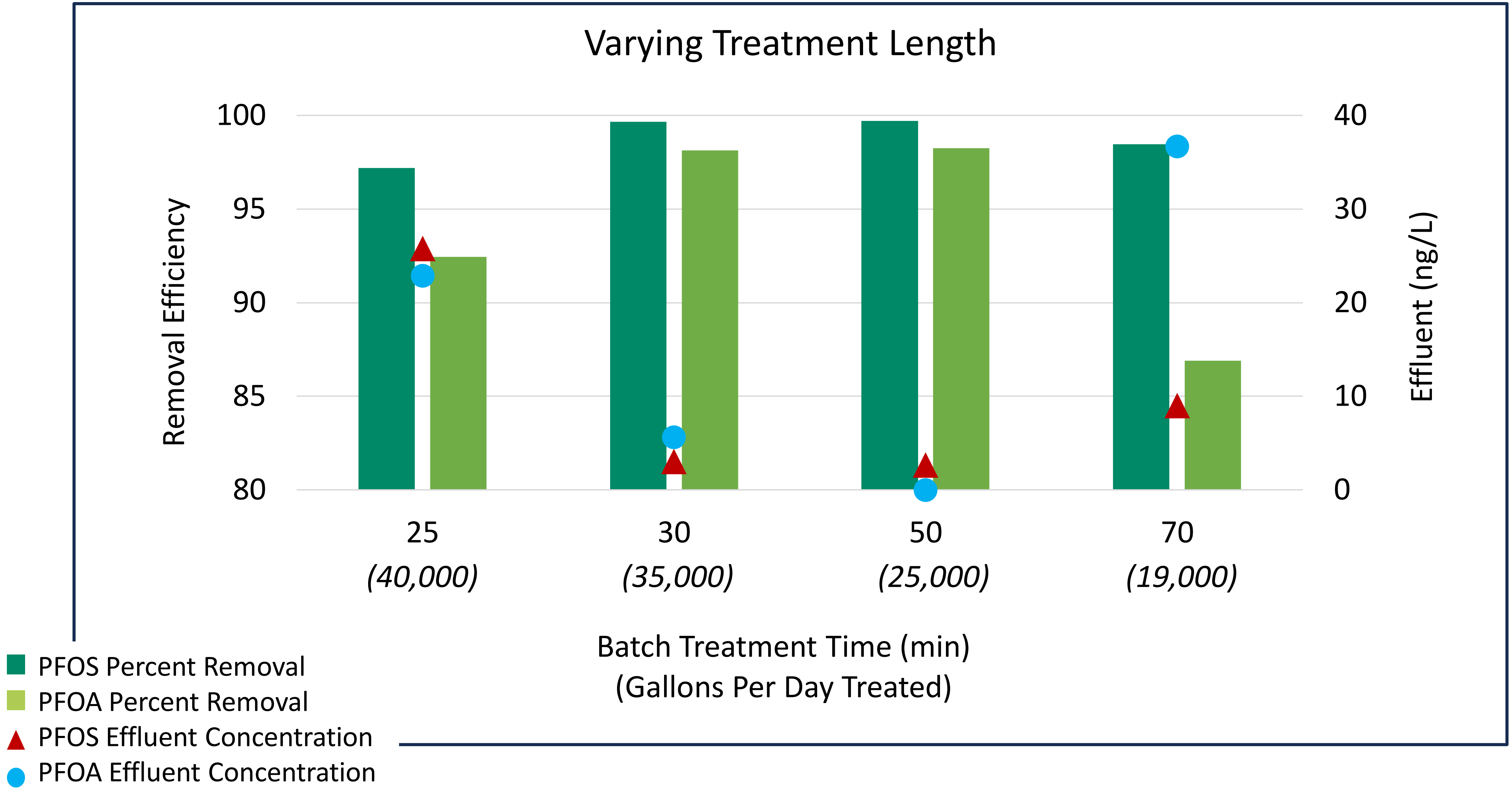
Shakopee Aquifer Treatment



No foam observed during primary fractionation

- Tested conditions to improve efficiency:
  - Higher air injection
  - Addition of clean water to push PFAS out of top cone
  - Dosing with PFAS concentrate
  - Oscillating between high and low air injection
- Able to achieved over 99% removal of PFOS and PFOA with oscillation method
- Removal by bubble fractionation

Shakopee Aquifer Treatment



Varying Treatment Length

Shakopee Aquifer: Optimized Results

PFAS Analyte	Influent Concentration (ng/L)	Effluent Concentration (ng/L)	Percent Removal	MDH HBV/HRL (ng/L)
PFBA	372	361	2.96	7,000
PFHxA	44.3	36.1	18.51	200
PFOA	281	<0.887	>99.68	0.0079
PFNA	2.12	<0.887	>58.16	
PFBS	15.4	13.5	12.34	100
PFHxS	34.1	1.62	95.25	47
PFOS	939	2.67	99.2	2.3

- Variations observed in long term study
    - PFOS: 2 to 5 ng/L
    - PFOA: ND to 7 ng/L
- Adjustment of settings results in decreased PFOS effluent concentration but increased PFOA effluent concentration

Low foaming water can be effectively treated with SAFF

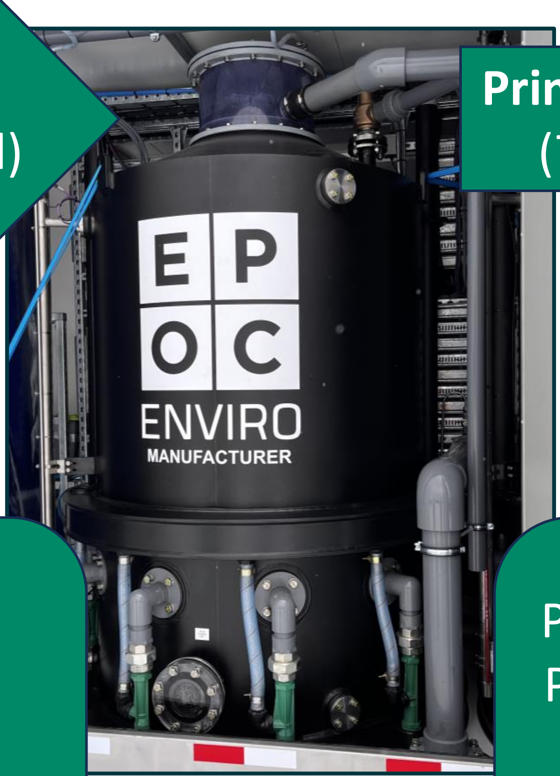
Jordan Aquifer: Optimized Results

PFAS Analyte	Influent Concentration (ng/L)	Effluent Concentration (ng/L)	Percent Removal	HBV/HRL (ng/L)
PFBA	392	391	0	7,000
PFHxA	6.35	5.84	8	200
PFOA	26.5	4.95	81	0.0079
PFHxS	0.791	<0.402	>49	47
PFOS	0.92	<0.402	>56	2.3

PFAS removal occurs with low concentrations but less effective

Optimizing Secondary Fractionation: Concentration Factor Comparison

Influent
(30,000-40,000 gpd)



Primary Concentrate
(700-1,300 gpd)

Secondary Concentrate
(<0.5 gpd)

Raleigh Creek
PFOA: 0.9 ug/L
PFOS: 2.5 ug/L

Shakopee Aquifer
PFOA: 0.33 ug/L
PFOS: 0.95 ug/L

Raleigh Creek
PFOA: 24 ug/L (27X)
PFOS: 72 ug/L (29X)

Shakopee Aquifer
PFOA: 11 ug/L (34X)
PFOS: 35 ug/L (36X)

Raleigh Creek
PFOA: 9,020 ug/L (10,000 X)
PFOS: 19,100 ug/L (8,000X)

Shakopee Aquifer
PFOA: 6360 ug/L (20,000 X)
PFOS: 19100 ug/L (21,000 X)

SAFF Lessons Learned

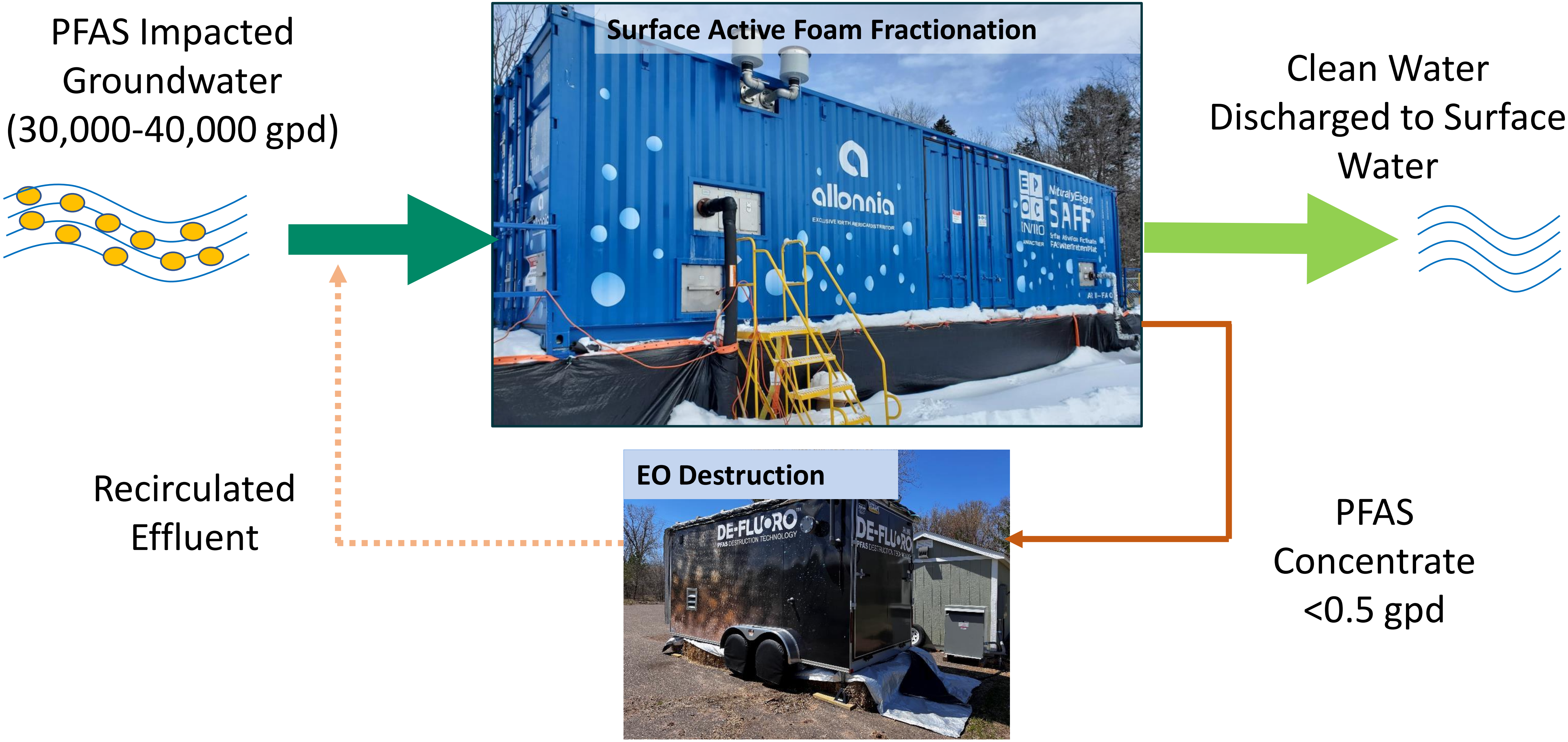
- Effective removal and concentration of PFAS even when foam is not formed
  - Polishing may be required to achieve treatment objectives
  - Rapid Small Scale Column Studies in progress to determine media savings
- Air emissions control is needed as some PFAS is likely being aerosolized
- Operations and maintenance will be simplified when the system is no longer in a shipping container

Bench Scale Testing of Destruction Technologies with SAFF Concentrate

- Plasma
  - Onvector (Plasma Vortex)
- Photochemical
  - Claros (Elemental)
  - Enspired (PFASigator)
- Supercritical Water Oxidation
  - 374 Water (AirSCWO)
  - General Atomics (iSCWO)
  - Revive Environmental (PFAS Annihilator)
- Electrochemical Oxidation
  - Axine
  - DE-FLUORO® (Pike)

Initial field demonstration with DE-FLUORO because of ability to rapidly deploy

Field Demonstration of Electrochemical Oxidation



PFAS Impacted Groundwater (30,000-40,000 gpd)

Surface Active Foam Fractionation

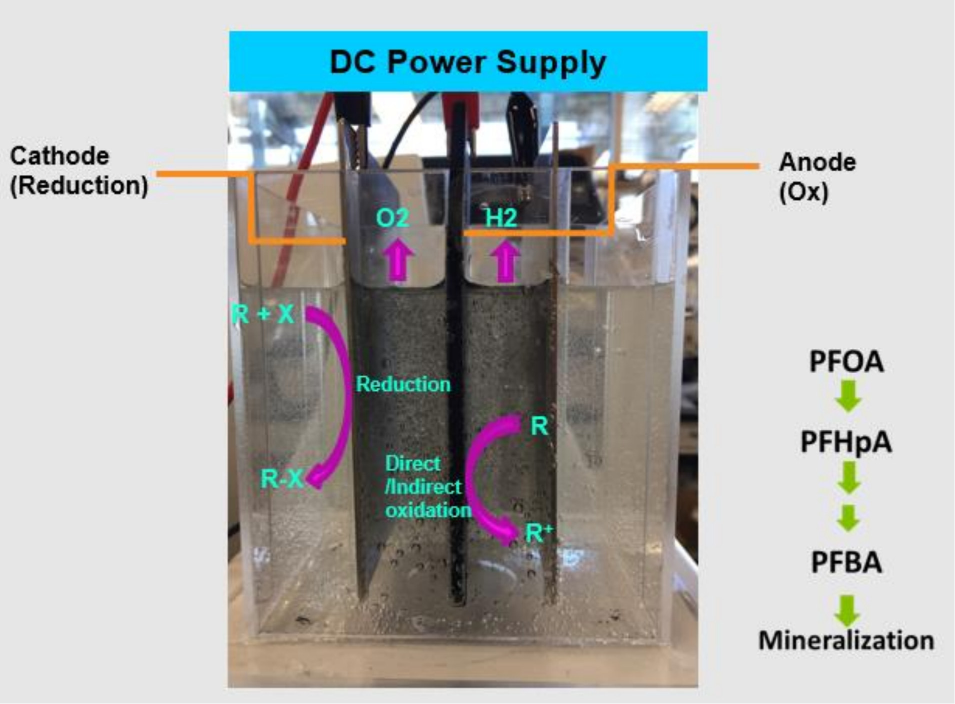
Clean Water Discharged to Surface Water

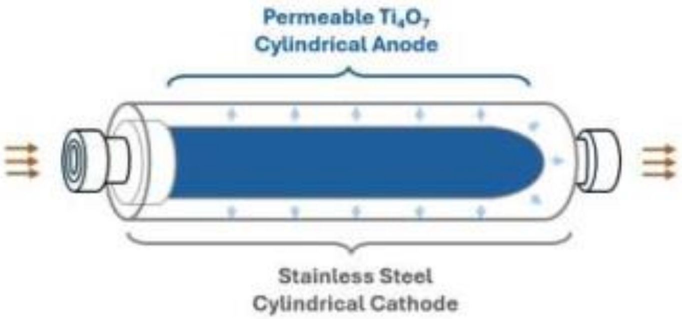
PFAS Concentrate <0.5 gpd

EO Destruction

Recirculated Effluent

Destruction by Electrochemical Oxidation





- Current applied across anode-cathode pair
- Direct oxidation as electrons are transferred from PFAS via direct contact at the anode
- Additional advanced oxidation mediated by hydroxyl radicals generated in reactor
- Electron transfer sequentially defluorinates PFAS leading to complete mineralization (formation of carbon dioxide and fluoride)
- Transitioned early on to reactive electrochemical membrane (REM) electrodes
- High surface area, durable, flow-through operation, commercially available
- Proof of concept began at bench-scale

DE-FLUORO$^{\text{TM}}$ Field Deployment

PREDICTION

- Bench-scale testing & analysis at Testing Facility
- Prompt data for decision making

CONFIRMATION

- Demonstration program - On or Offsite
- Informs design of a full-scale treatment program

Application for this project

DESTRUCTION

- Customized system deployment to meet treatment objectives
- Turn-key destruction solution
- Lease, operation & maintenance plans available

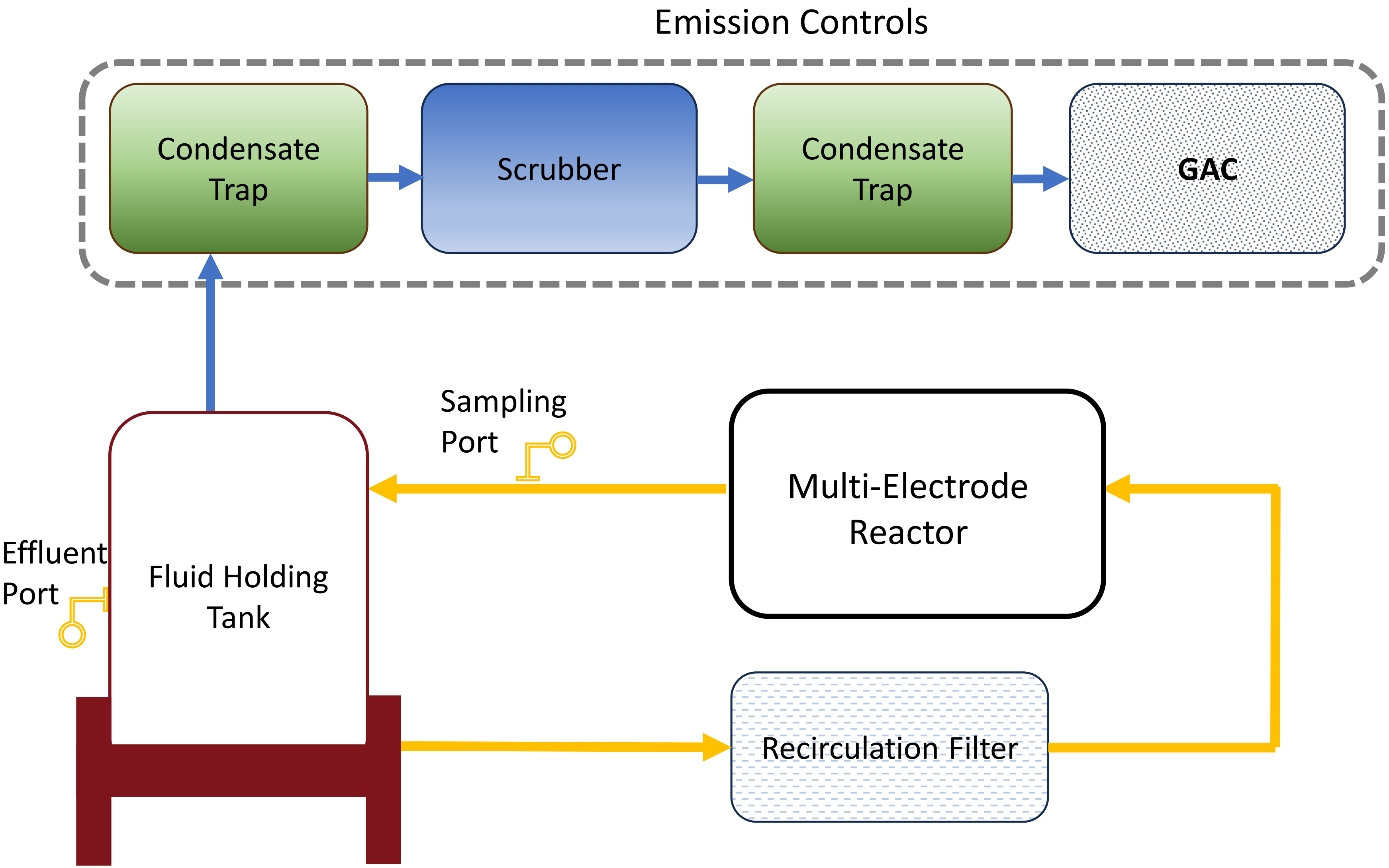
PFAS Concentrate from SAFF

	PFOA	PFOS	PFHxS	Total PFAS	TOF
	Nanograms per liter (ng/L)				
Shakopee Aquifer Groundwater	281	939	34.1	2,254	2,100
SAFF Concentrate 1	100,000	474,000	6,420	595,929	580,000
SAFF Concentrate 2	110,000	436,000	6,390	562,164	490,000

TOF: Total Organofluorine


SAFF® PFAS Concentrate

DE-FLUORO^{TM} Self-Contained System - Process Flow



Emission Controls

Condensate Trap

Scrubber

Condensate Trap

GAC

Sampling Port

Multi-Electrode Reactor

Effluent Port

Fluid Holding Tank

Recirculation Filter

GAC: Granular Activated Carbon

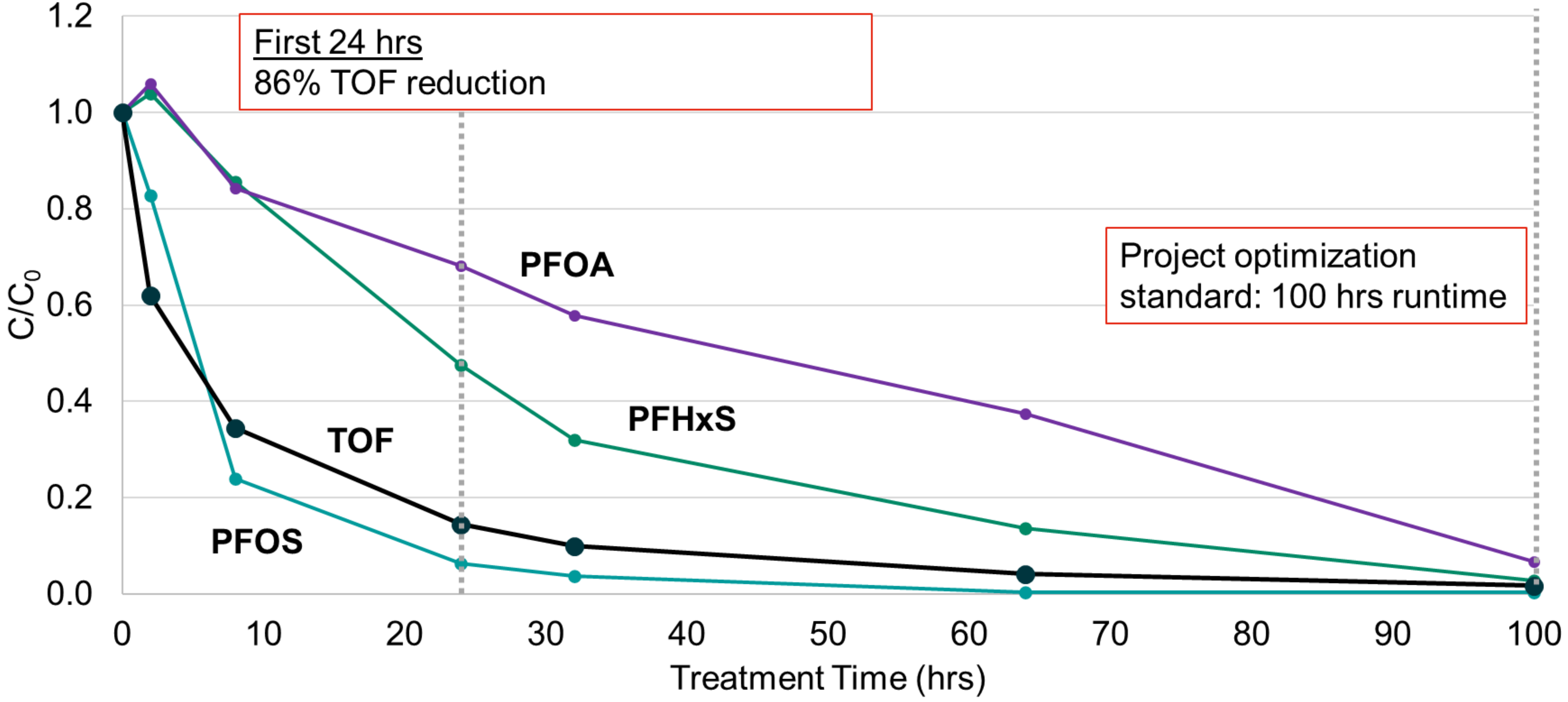
Demonstration Control Parameters

Field optimization of following parameters:

- Air flow rate across holding tank
- Electrode current
- pH and electrolyte additives--feed rates and locations
- Temperature

✓ Results inform full-scale implementation

Process Optimization: PFAS Reduction



First 24 hrs
86% TOF reduction

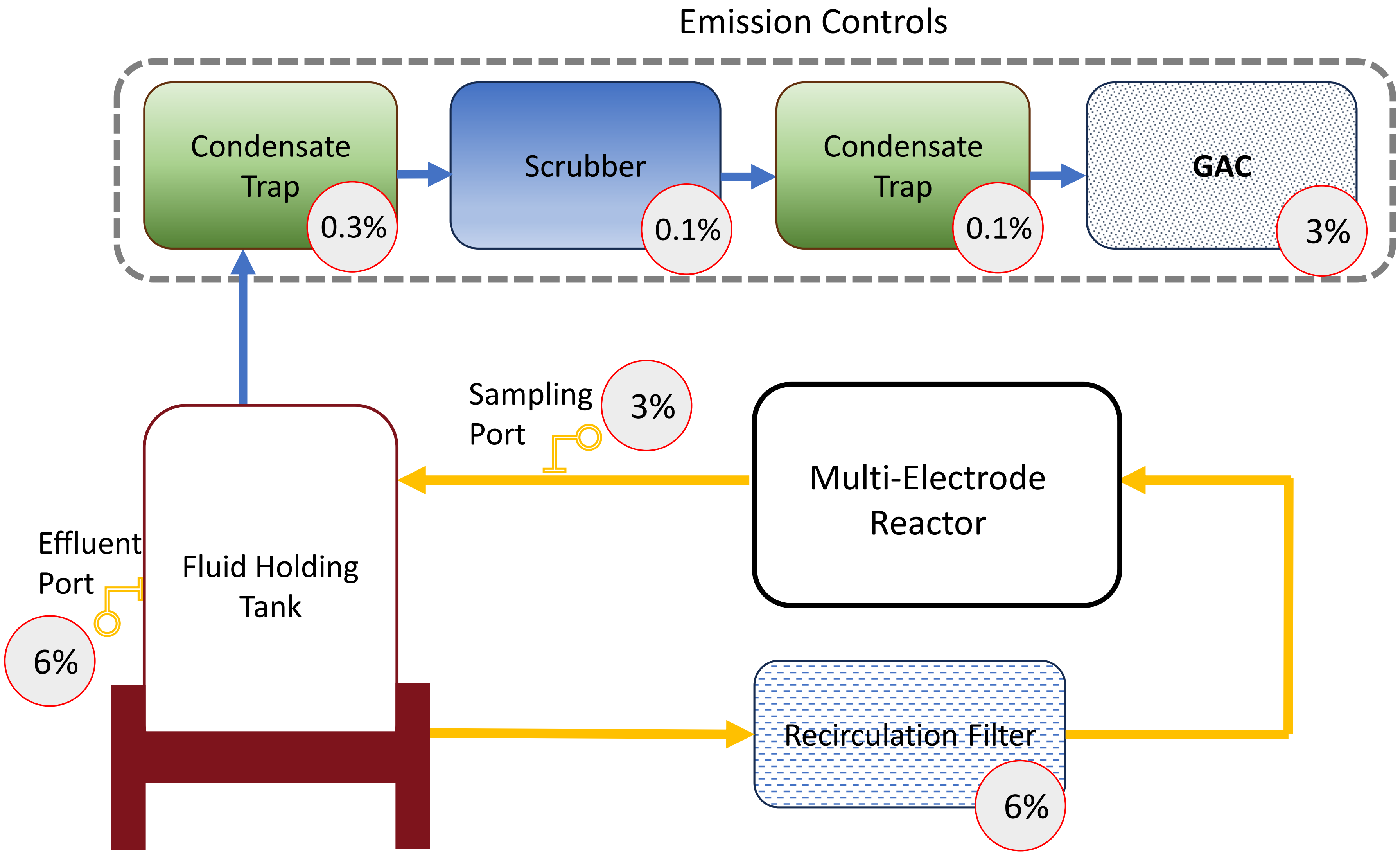
Project optimization standard: 100 hrs runtime

TOF: Total organofluorine

TOF Used to Evaluated Fate of PFAS

- Total Organofluorine by Method MLA-119
- Accounting for TOF demonstrates destruction effectiveness
- System elements are monitored

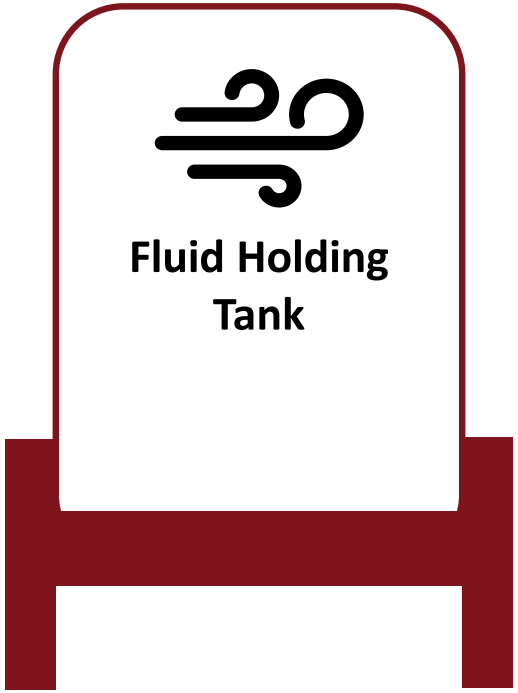
TOF	Percentage
Initial	**100%**
∑Components	13%
Effluent	6%
Balance	81%



GAC: Granular Activated Carbon

EO Lessons Learned: Air Emission System

Aerosolization can be minimized through operational settings



Optimization

- Managed emissions of H_2 and HF
- Controlled aerosolization of PFAS

In air emission system GAC and scrubber:

- Experiment 1: 6% of initial total PFAS
- Experiment 2: 3.5% of initial total PFAS

EO Lessons Learned: Foam

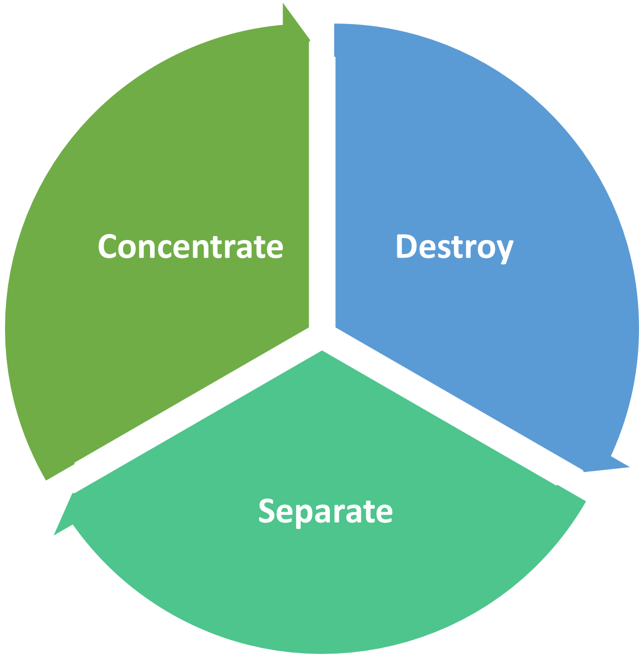
Minimizing foam ensures PFAS are being destroyed and not transferred into foam

- If foam is not dissipated, effluent concentrations do not reflect destruction
- In practice we incorporated foam management and controls

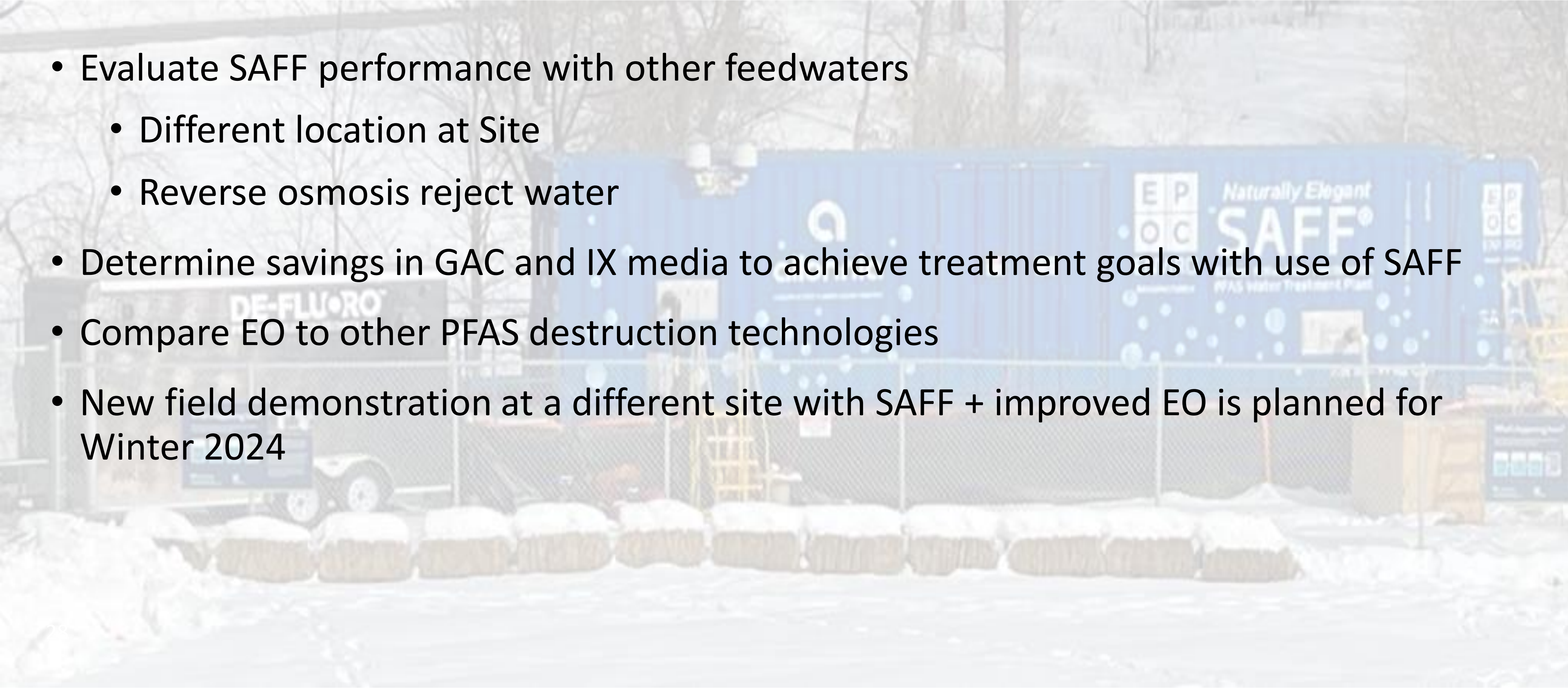
EO Lessons Learned: Closed Loop Operation

Closed loop treatment train enables flexibility in PFAS treatment optimization

- Optimizes performance
- Controls by-products
- Reduces overall energy consumption by limiting destruction within optimal range
- PFAS waste does not leave the site (reducing liability)



Next Steps



- Evaluate SAFF performance with other feedwaters
  - Different location at Site
  - Reverse osmosis reject water
- Determine savings in GAC and IX media to achieve treatment goals with use of SAFF
- Compare EO to other PFAS destruction technologies
- New field demonstration at a different site with SAFF + improved EO is planned for Winter 2024

Acknowledgements

Project Team

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THANK YOU!

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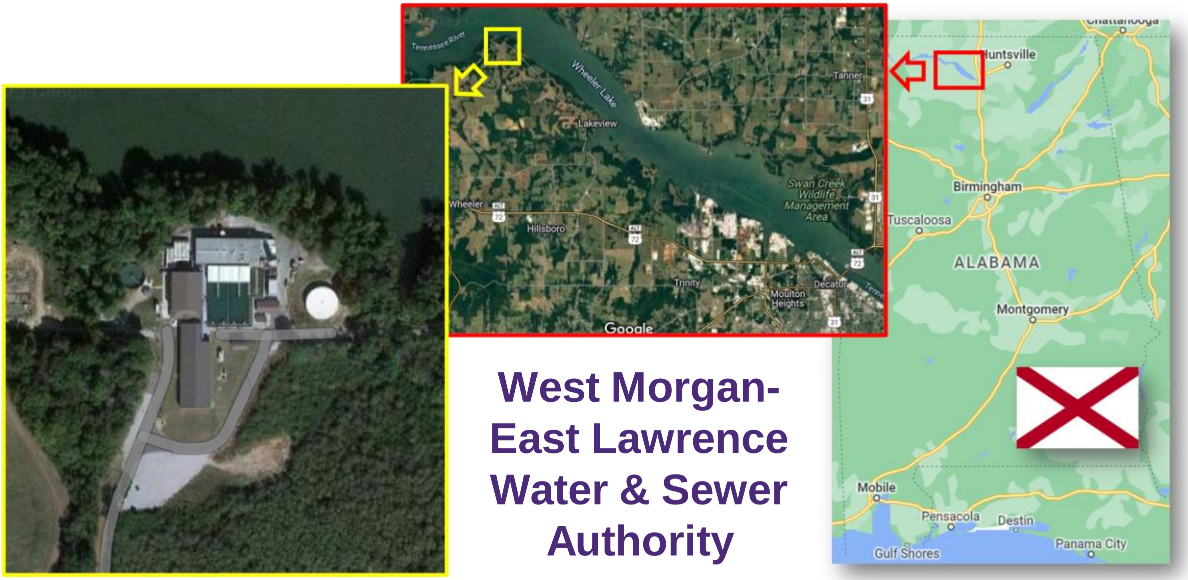
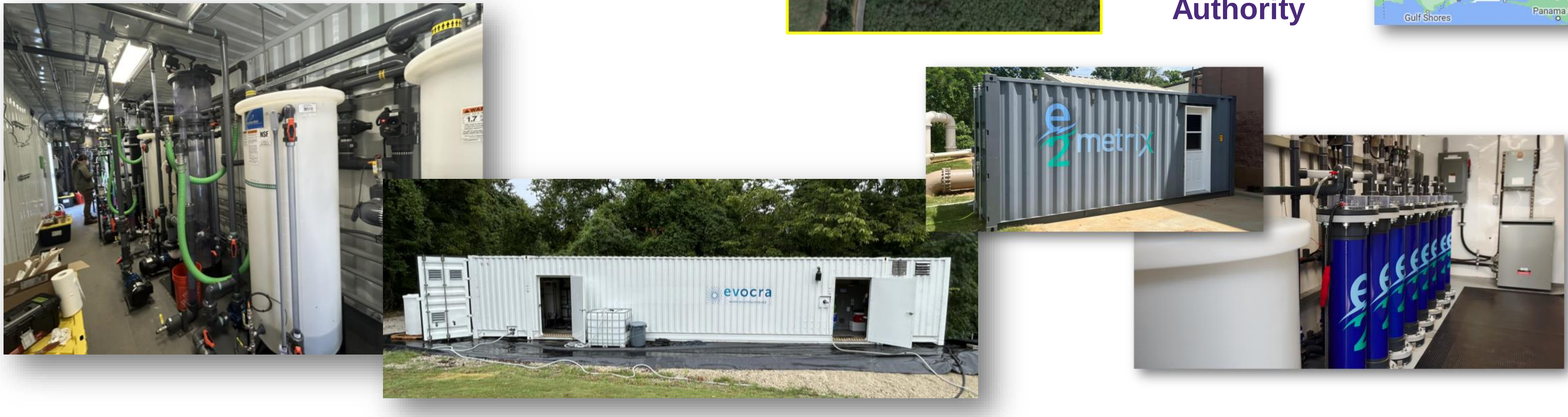
Poster:

"Piloting Foam Fractionation on an RO Concentrate Stream as part of Ovivo's Integrated Solution for Onsite PFAS Destruction with Electro-oxidation"



West Morgan-East Lawrence Water & Sewer Authority



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Enhanced PFAS Removal with Advanced Granular Activated Carbons (GACs)

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Objectives

1. Evaluate the effectiveness of advanced engineered GACs for PFAS adsorption.
2. Draw thermodynamic/adsorption behavioral tie lines and identify factors that disrupt tie lines between GAC adsorption performance in equilibrium isotherms and Rapid Small Scale Column Tests (RSSCT)s.
3. Identify key activated carbon properties contributing to leading adsorption mechanisms

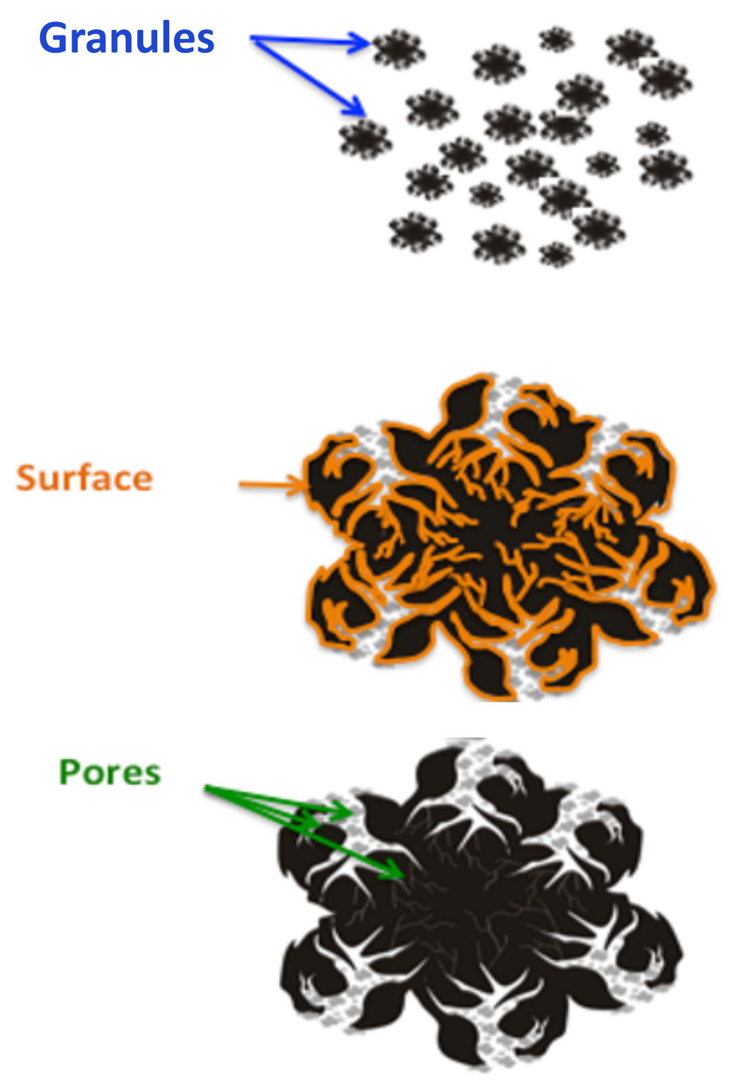
Test Methods

Test	Water Matrix(s)	Other Test Conditions
RSSCT	Spiked City of Golden Colorado tap water (0.9ppm TOC) spiked to equimolar concentrations of each PFAS at ~100ppt	RSSCT designed using constant diffusivity to simulate 10-minute Empty Bed Contact Time (EBCT)
Equilibrium	Spiked City of Golden Colorado tap water (0.9ppm TOC) spiked to equimolar concentrations of each PFAS at ~100ppt and at ~1000ppt	Equilibrium for each water used 7-day contact time
Kinetic	Spiked City of Golden Colorado tap water (0.9ppm TOC) spiked to equimolar concentrations of each PFAS at ~100ppt	Adsorption measured at contact times ranging from 5 minutes to 7 days

PFAS	MCL or HI (ppt)
PFBS	2000*
PFHxS	10
PFOS	4
PFPeA	N/A
PFHxA	N/A
PFOA	4
PFNA	10

Maximum Contaminant Level (MCL)
*Health Index (HI) sum < 1 for of 4 PFAS

Tunning Reagglomerated Bituminous GAC Properties

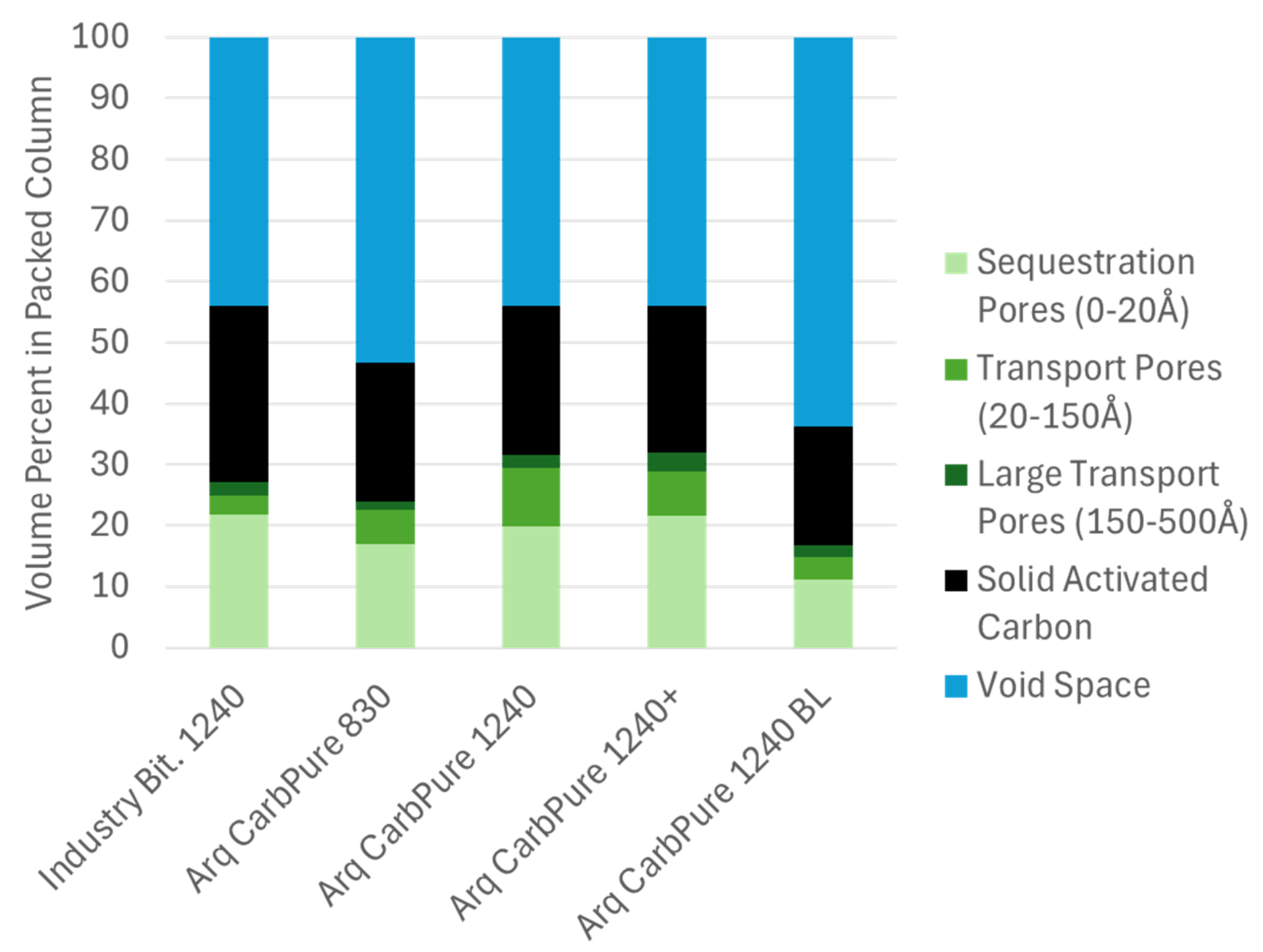


Arq CarbPure RG 1240
Generation 1 - 12X40 GAC
Produced from purified bituminous coal waste

Arq CarbPure RG 830
Generation 1 - 8X30 GAC
Produced from purified bituminous coal waste

Arq CarbPure RG 1240 BL
Generation 2 - 12X40 GAC
Produced from purified bituminous coal waste with enhanced surface character for targeting PFAS

Arq CarbPure RG 1240+
Generation 2 - 12X40 GAC
Produced from purified bituminous coal waste with enhanced pore character for targeting PFAS



DESCRIPTION	Apparent Density (g/mL)	Iodine Number (mg/g)	Total Pore Volume (0-500Å) (cc/g)	Sequestration Pore Volume (0-20Å) (cc/g) (vol%)	Transport Pore Volume (20-150Å) (cc/g) (vol%)	Slurry pH (high pH indicates net positive surface charge)	Ash (dry wt%)	TGA wt loss 400-750C (wt%) (low wt loss indicates low surface functional groups)
Industry Bit. 1240	0.59	837	0.46	0.37 (80%)	0.05 (11%)	10.3	5.7	0.64
Arq CarbPure 830	0.47	913	0.51	0.36 (67%)	0.12 (22%)	11.0	10.1	0.61
Arq CarbPure 1240	0.51	1034	0.62	0.39 (63%)	0.19 (31%)	10.8	12.7	0.46
Arq CarbPure 1240+	0.50	1098	0.64	0.43 (67%)	0.15 (23%)	10.7	12.5	0.65
Arq CarbPure 1240 BL	0.41	726	0.41	0.27 (66%)	0.09 (22%)	11.9	16.0	

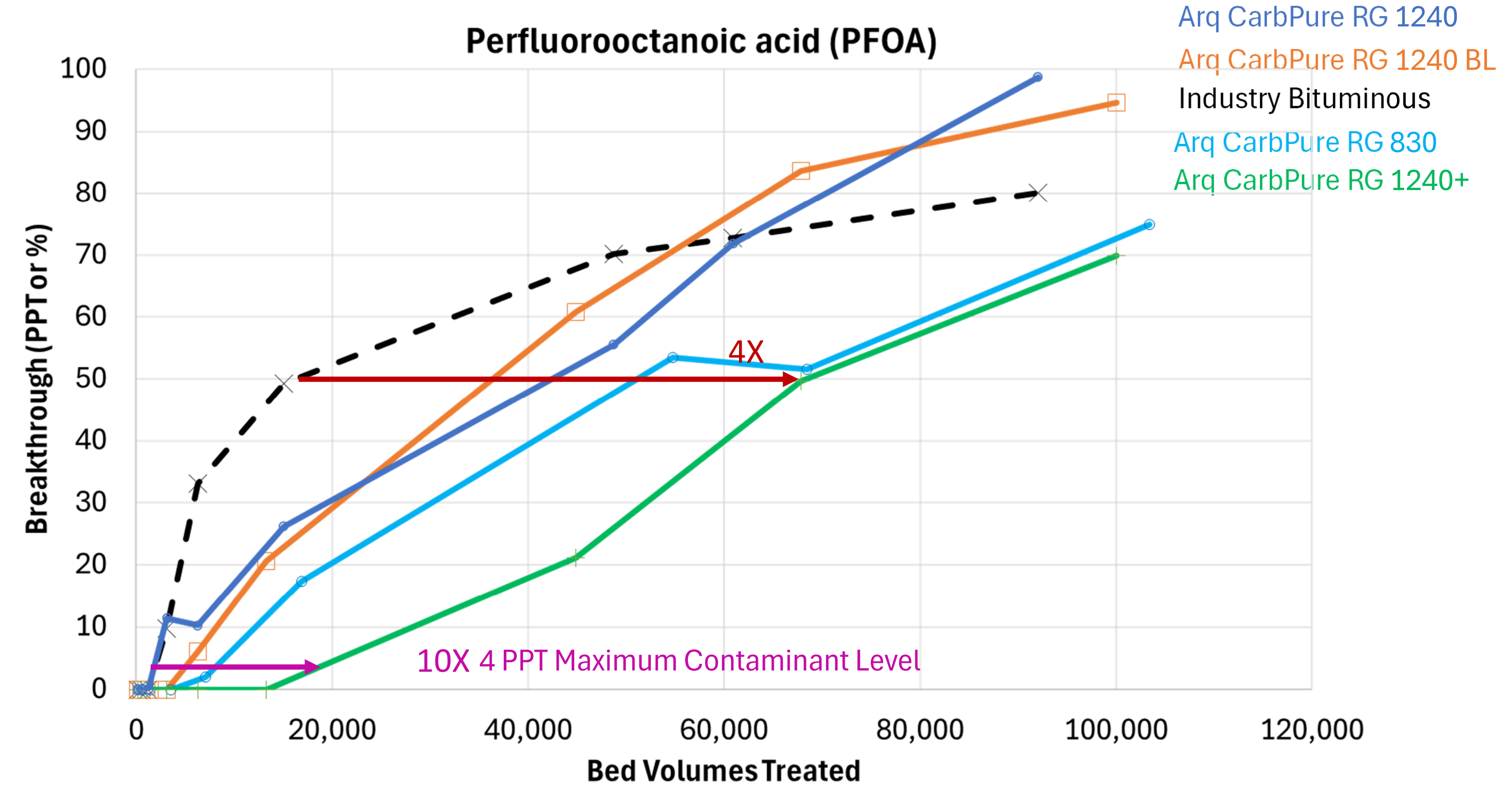
Enhanced PFAS Removal in Rapid Small Scale Column Test Results

Water Treated at MCL Breakthrough

PFAS		PFBS	PFHxS	PFOS	PFPeA	PFHxA	PFOA	PFNA
Average Influent, ppt		96	98	96	104	108	106	102
% Breakthrough at MCL		N/A	10%	4%	N/A	N/A	4%	10%
GAC	Iodine Number	Bed Volumes Treated at Max Contaminant Level (MCL) (Improvement over Industry Bituminous)						
Industry Bituminous 1240	837	-	3,400	2,600	-	-	2,000	3,400
Arq CarbPure GAC 1240	995	-	7,600 (2.2X)	6,200 (2.4X)	-	-	2,000 (1.0X)	7,800 (2.3X)
Arq CarbPure GAC 830	883	-	15,000 (4.4X)	11,600 (4.5X)	-	-	8,400 (4.2X)	15,400 (4.5X)
Arq CarbPure GAC 1240+	1098	-	38,400 (11X)	23,000 (8.9X)	-	-	19,200 (9.6X)	35,000 (10.3)
Arq CarbPure GAC 1240 BL	726	-	10,000 (2.9X)	9,000 (3.5X)	-	-	5,200 (2.6X)	10,000 (2.9X)

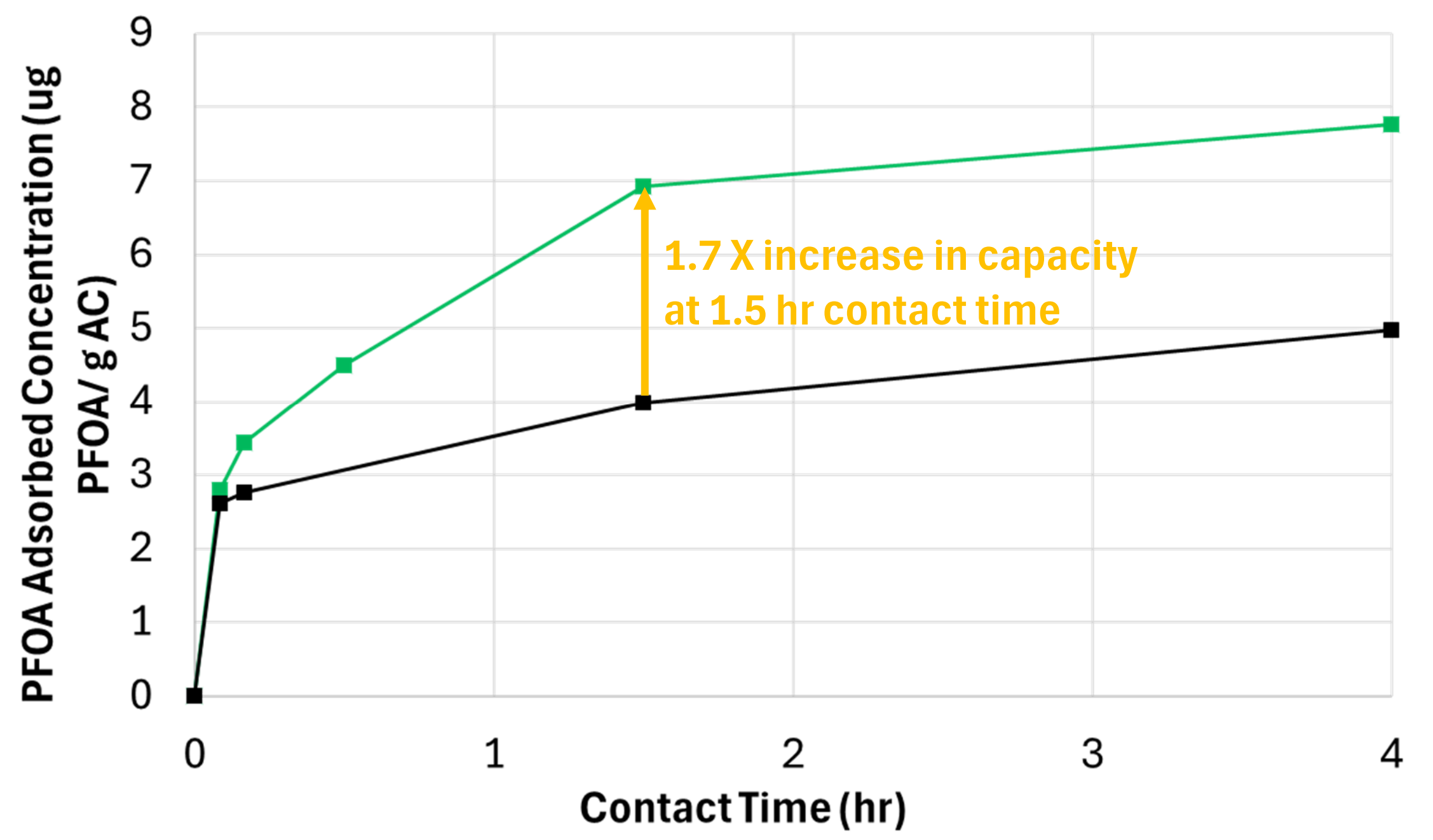
Water Treated at 50% Breakthrough

PFAS		PFBS	PFHxS	PFOS	PFPeA	PFHxA	PFOA	PFNA
Average Influent, ppt		96	98	96	104	108	106	102
% Breakthrough at MCL		50%	50%	50%	50%	50%	50%	50%
GAC	Iodine Number	Bed Volumes Treated at 50% Breakthrough (Improvement over Industry Bituminous)						
Industry Bituminous 1240	837	25,000	38,000	58,000	5,000	16,000	17,000	32,000
Arq CarbPure GAC 1240	995	49,000 (2.0X)	60,000 (1.6X)	62,000 (1.1X)	8,000 (1.6X)	25,000 (1.6X)	42,000 (2.5X)	52,000 (1.6X)
Arq CarbPure GAC 830	883	40,000 (1.6X)	101,000 (2.7X)	120,000 (2.1X)	19,000 (3.8X)	31,000 (1.9X)	52,000 (3.1X)	83,000 (2.6X)
Arq CarbPure GAC 1240+	1098	65,000 (2.6X)	109,000 (2.9X)	135,000 (2.3X)	26,000 (5.2X)	39,000 (2.4X)	68,000 (4.0X)	103,000 (3.2X)
Arq CarbPure GAC 1240 BL	726	30,000 (1.2X)	50,000 (1.3X)	67,000 (1.2X)	10,000 (2.0X)	25,000 (1.5X)	37,000 (2.2X)	49,000 (1.5X)



Tuning particle, pore, and surface properties of reagglomerated bituminous GACs can increase the volume of water treated for PFOA by up to 10X at the 4 ppt MCL and up to 4X at 50% breakthrough

Adsorption Kinetics



- Enhancement in adsorption kinetics doesn't fully account for RSSCT performance enhancement
- Exploring how to utilize improved adsorption kinetics

Equilibrium Adsorption Capacity

Test		Equilibrium	RSSCT	Equilibrium	RSSCT
Contact time		1 wk	Simulated 10 min EBCT	1 wk	Simulated 10 min EBCT
Performance Evaluation Concentration, ppt		4	4	100	100
Adsorbed Capacity (ug PFOA/g)	Industry Bituminous	2.7	0.4	75	9.1
	CarbPure GAC 1240+	3.5	4.1	81	16.0
Performance Factor (wt CarbPure 1240+ / wt industry bituminous needed to achieve performance evaluation conc.)	Industry Bituminous	1.0	1.0	1.0	1.0
	CarbPure GAC 1240+	0.8	0.1	0.9	0.6

- Isotherm comparisons at both full utilization (100ppt) and initial breakthrough (4ppt) over predict adsorption capacity in RSSCT
- Properties of CarbPure GAC 1240+ (enhanced transport pores and/or surface characteristics) lead to moderate performance enhancements in isotherm testing (10-20%) but significant performance enhancements in RSSCT (40-90%)
- Opportunity to overcome inefficiencies in RSSCTs that are preventing achieving equilibrium

Key Findings

1. Surface, pore, and particle properties of reagglomerated bituminous GACs can be tuned to enhance PFAS removal capacity and adsorption rate.
2. Equilibrium adsorption capacities indicate that column adsorption doesn't approach equilibrium entitlement leaving significant room to improve kinetic adsorption performance.
3. Mechanisms impacting GAC adsorption performance: 1.) Equilibrium adsorption capacity 2.) Adsorption kinetics 3.)Adsorption selectivity 4.) Competitive adsorption (contaminants and natural organic matter)