SAME Environmental COI

- Webinars covering a range of topics
  - *PFAS, NEPA, Climate Change and Resilience, Remediation*
  - To set up or for more information on webinars, contact Rick Wice wice@battelle.org
  - Monthly Call Third Wednesday of the Month 1500-1600 hrs Eastern (info on website – see below)
- Review JETC Abstracts
- Provide speakers for Post Meetings
- Industry and Government Exchange (IGE) PFAS Webinar Series and Fact Sheets
- Interact with Other COIs
  - Resilience
  - Energy and Sustainability
  - Health Engineering Task Force
- For more information contact Rick Wice, F. SAME, ECOI Chair- wice@battelle.org, or Ann Ewy, F. SAME, ECOI Vice-Chair- Ann Ewy - annewysame@gmail.com
  - Website https://www.same.org/Environmental-Community

Avoiding PFAS Information Overload:

Targeted Training for Operational Entities

SAME ECOI Industry – Government Engagement Project

Mission

Enable DoD personnel and contractors to effectively address PFAS issues by providing accurate, concise, tailored, and digestible PFAS knowledge

Upcoming Topics

- ✓ Mobility and Conceptual Site Models
- ✓ PFAS in NPDES Monitoring Programs
- ✓ PFAS Waste Management
- ✓ Cost/Performance Data for Treatment of PFAS

Products or deliverables provided:

- 1-hour webinars coordinated with the Environmental COI
- Timely (2-4 page) regulatory or technical Fact Sheets
- Spontaneous briefs during the ECOI Calls on current topics

Team:

- Project Lead: Bill DiGuiseppi, Jacobs
- DOD Advisors/Reviewers

~30 team members and trainers

Advances in Destructive Solutions for PFAS Water Treatment

Presenters:

- Michael Zafer, PE, Drinking Water Practice Leader
- Jeff Bamer, PE, Remedial Design Discipline Leader

Agenda

- PFAS Monitoring and Occurrence
- USEPA and State PFAS Regulations
- PFAS Removal Technologies
- Emerging PFAS Water Treatment Technologies

PFAS Monitoring and Occurrence

Unregulated Contaminants Monitoring Rule 3

Promulgated:
May 2, 2012

Monitoring:
2013-15

List 1:
- 21 CECs
- 6 PFAS
- All PWSs > 10,000
- 800 PWSs ≤ 10,000

UCMR 3 Contaminant List			
Assessment Monitoring (List 1 Contaminants)			
1,2,3-trichloropropane	bromomethane (methyl bromide)	chloromethane (methyl chloride)	bromochloromethane (Halon 1011)
chlorodifluoromethane (HCFC-22)	1,3-butadiene	1,1-dichloroethane	1,4-dioxane
vanadium	molybdenum	cobalt	strontium
chromium[1]	chromium-6[2]	chlorate	perfluorooctanesulfonic acid (PFOS)
perfluorooctanoic acid (PFOA)	perfluorobutanesulfonic acid (PFBS)	perfluorohexanesulfonic acid (PFHxS)	perfluoroheptanoic acid (PFHpA)
perfluorononanoic acid (PFNA)			
Screening Survey (List 2 Contaminants)			
17-β-estradiol	estriol	estrone	4-androstene-3,17-dione
17-α-ethynylestradiol	equilin	testosterone	
Pre-Screen Testing[3] (List 3 Contaminants)			
enteroviruses		noroviruses	

1. Monitoring for total chromium, in conjunction with UCMR 3 Assessment Monitoring, is required under the authority provided in Section 1445 (a)(1)(A) of SDWA.
2. Chromium-6 will be measured as soluble chromate (ion).
3. Monitoring for microbial indicators, in conjunction with Pre-Screen Testing, will be conducted, including: total coliforms, *E.coli*, bacteriophage, *Enterococci* and aerobic spores. EPA will pay for all sampling and analysis costs for the small systems selected for this monitoring.

https://www.epa.gov/sites/default/files/2015-10/documents/ucmr3_factsheet_general.pdf

USEPA UCMR 3 Program (2013 – 2015)

6 Million US residents receive PWS exceeding 70 ng/L

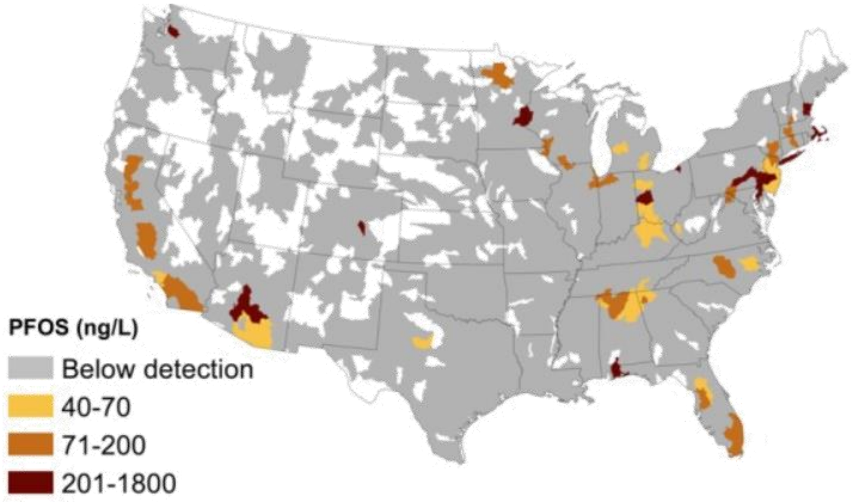
Point Sources

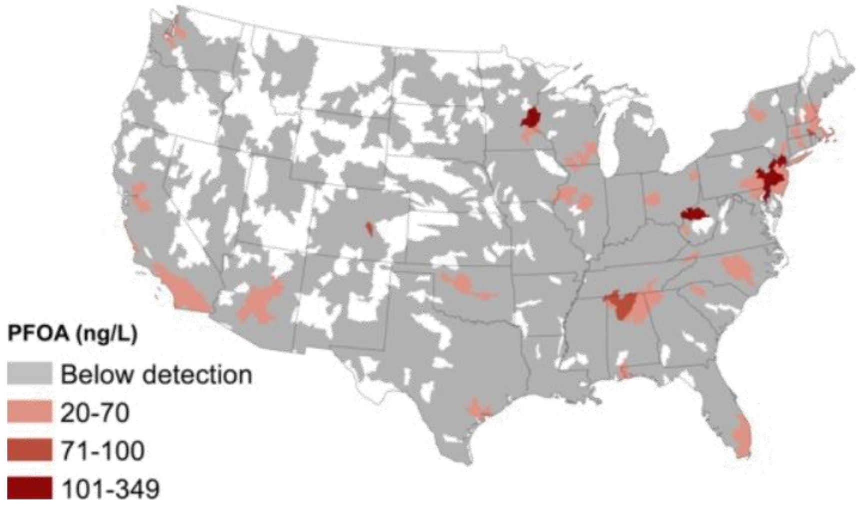
16 industrial sites listed in USEPA PFOA stewardship program

8,572 WWTP

664 military fire training sites

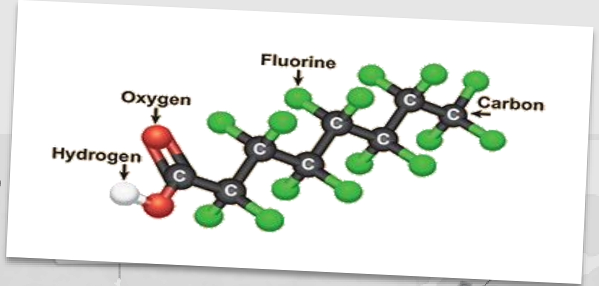
533 civilian airports

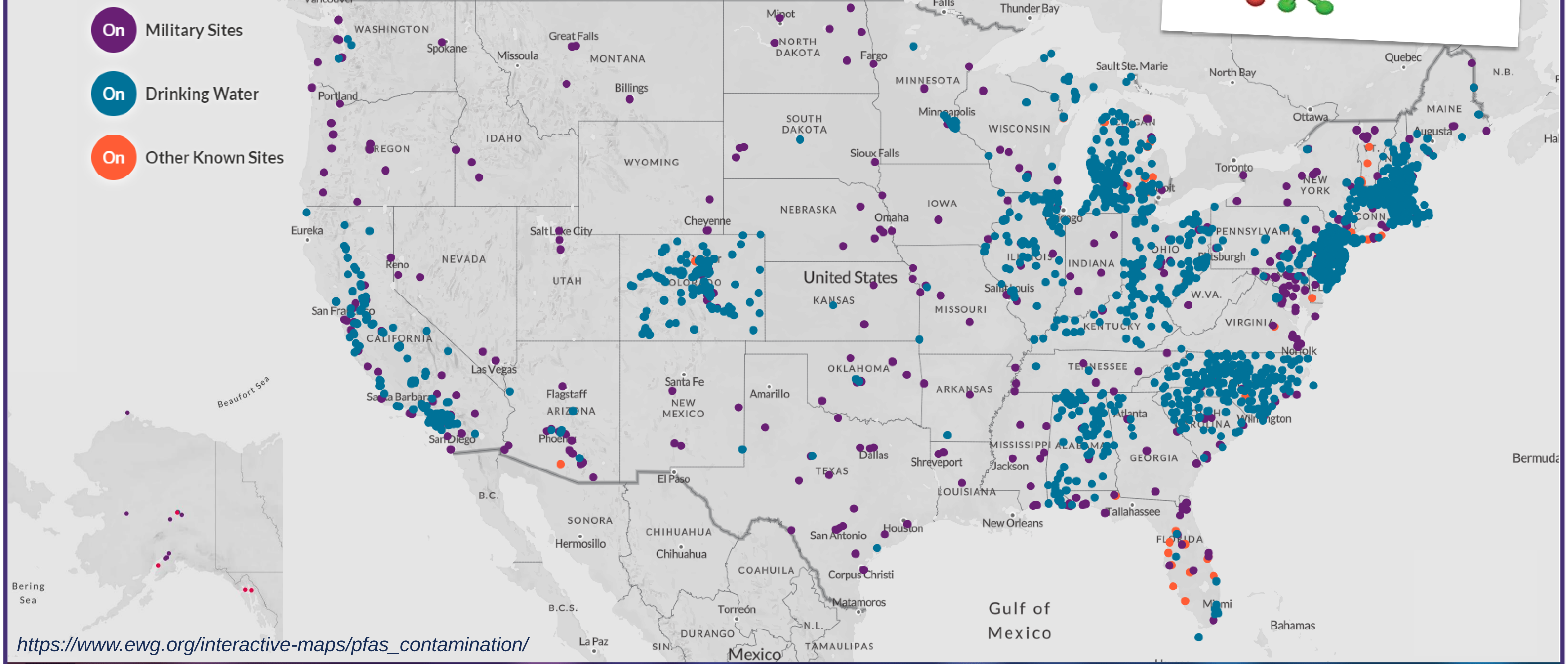




Environ Sci Technol Lett. 2016 Oct 11; 3(10): 344–350.

PFAS Contamination in the US (2022)





https://www.ewg.org/interactive-maps/pfas_contamination/

Unregulated Contaminants Monitoring Rule 5

Promulgated:
December 27, 2021

To Be Monitored:
2023-25

List 1:
- 29 PFAS + Lithium
- All PWSs > 3,300
- Representative PWSs ≤ 3,300

29 Per- and Polyfluoroalkyl Substances (PFAS)

11-chloroeicosafluoro-3-oxaundecane-1-sulfonic acid (11Cl-PF3OUdS)	perfluoro-4-methoxybutanoic acid (PFMBA)	perfluorooctanesulfonic acid (PFOS)
1H, 1H, 2H, 2H-perfluorodecane sulfonic acid (8:2 FTS)	perfluorobutanesulfonic acid (PFBS)	perfluorooctanoic acid (PFOA)
1H, 1H, 2H, 2H-perfluorohexane sulfonic acid (4:2 FTS)	perfluorobutanoic acid (PFBA)	perfluoropentanesulfonic acid (PFPeS)
1H, 1H, 2H, 2H-perfluorooctane sulfonic acid (6:2 FTS)	perfluorodecanoic acid (PFDA)	perfluoropentanoic acid (PFPeA)
4,8-dioxa-3H-perfluorononanoic acid (ADONA)[1]	perfluorododecanoic acid (PFDoA)	perfluoroundecanoic acid (PFUnA)
9-chlorohexadecafluoro-3-oxanone-1-sulfonic acid (9Cl-PF3ONS)	perfluoroheptanesulfonic acid (PFHpS)	n-ethyl perfluorooctanesulfonamidoacetic acid (NEtFOSAA)
hexafluoropropylene oxide dimer acid (HFPO-DA) (GenX)	perfluoroheptanoic acid (PFHpA)	n-methyl perfluorooctanesulfonamidoacetic acid (NMeFOSAA)
nonafluoro-3,6-dioxaheptanoic acid (NFDHA)	perfluorohexanesulfonic acid (PFHxS)	perfluorotetradecanoic acid (PFTA)
perfluoro (2-ethoxyethane) sulfonic acid (PFEESA)	perfluorohexanoic acid (PFHxA)	perfluorotridecanoic acid (PFTrDA)
perfluoro-3-methoxypropanoic acid (PFMPA)	perfluorononanoic acid (PFNA)	

1. Although the abbreviation used is ADONA, indicating the ammonium salt, 4,8-dioxa-3H-perfluorononanoic acid is the parent acid.

1 Metal/Pharmaceutical

lithium

https://www.epa.gov/dwucmr/fact-sheets-about-fifth-unregulated-contaminant-monitoring-rule-ucmr-5

USEPA and State PFAS Regulations

USEPA

2016: *Revised health advisory levels.*
PFOS: 70 ng/L and PFOA: 70 ng/L
PFOA+PFOS: 70 ng/L

2019: *Feb 14, 2019 EPA published the PFAS Action Plan.*

2019: *EPA begins designation proposals of PFOS and PFOA as hazardous substances under CERCLA.*

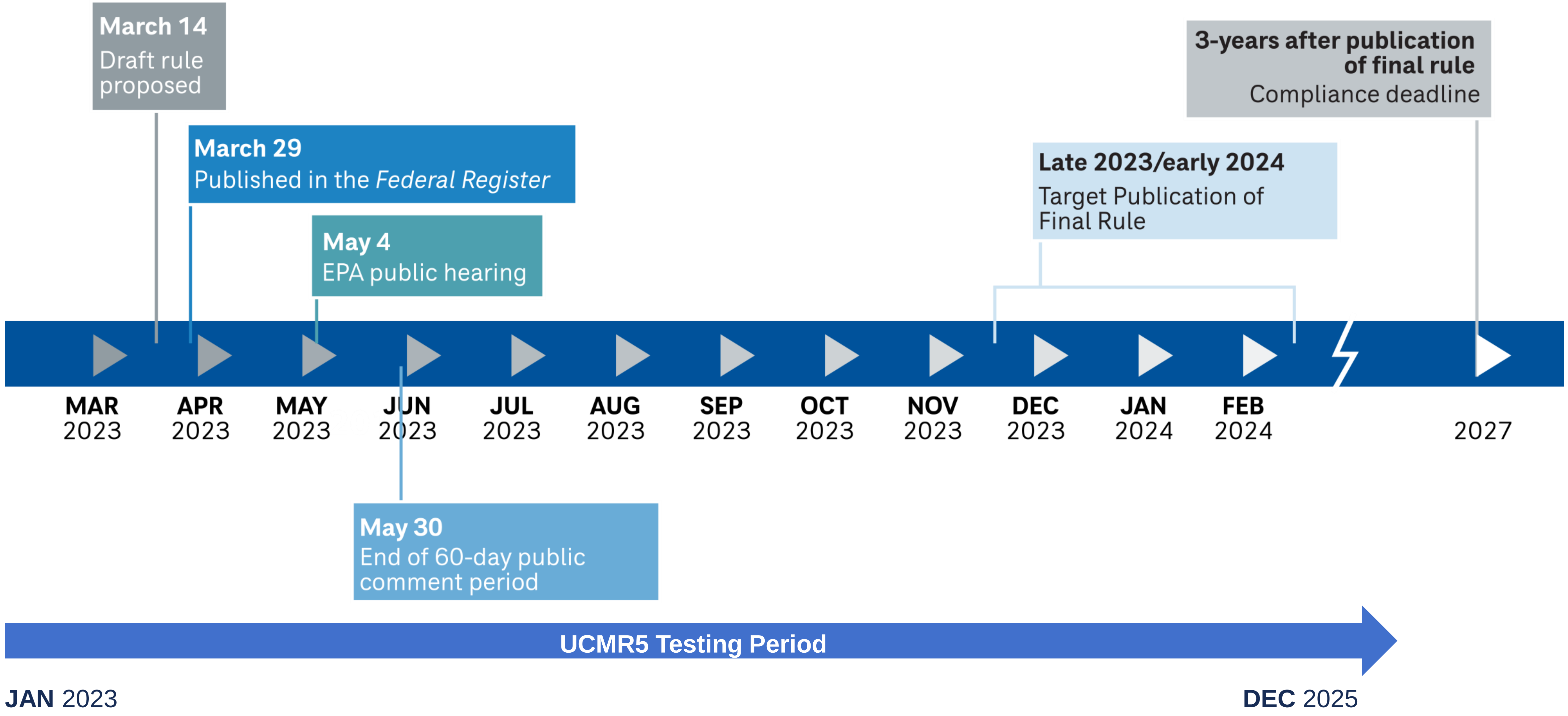
2020: *EPA announces the proposed decision to regulate PFOA and PFOS in drinking water.*

2022: *June 15, 2022, EPA revised Health Advisory Levels for PFOA = 0.004 , PFOS = 0.002 ppt, Gen-X = 10 ppt, and PFBS = 2000 ppt.*

2023: *EPA includes 29 PFAS compound to its UCMR5, which requires testing in 2023 – 2025.*

2023: *March 14, 2023, EPA proposed draft MCLs for PFOA = 4 ng/L and PFOS = 4 ng/L; and Hazard Index for PFNB, PFNA, PFHXs and Gen-X.*

Regulatory Timeline



Proposed Primary Standards (MCLs)

Numerical levels for compliance

- **4.0 ng/L** or ppt MCL **PFOA**
- **4.0 ng/L** or ppt MCL **PFOS**
- **1.0 (unitless, NOT 1 ppt)** Hazard Index (HI) for a mixture of **PFNA**, **PFHxS**, **PFBS**, and **GenX**

$$\frac{\text{GenX}}{10} + \frac{\text{PFBS}}{2000} + \frac{\text{PFNA}}{10} + \frac{\text{PFHxS}}{9} = \text{Hazard Index (HI)}$$

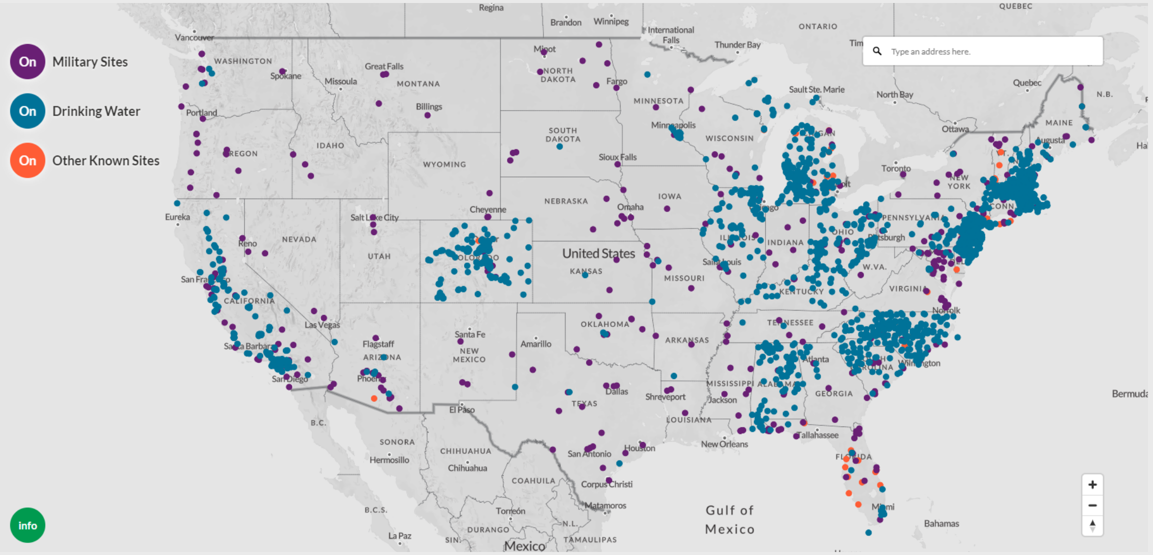
(all concentrations in ppt or ng/L)

HI Denominators are called Health-Based Water Concentrations (HBWC)

"Under the HI approach, additional PFAS can be added over time once more information on health effects, analytics, exposure and/or treatment becomes available, and merits additional regulation as determined by EPA."

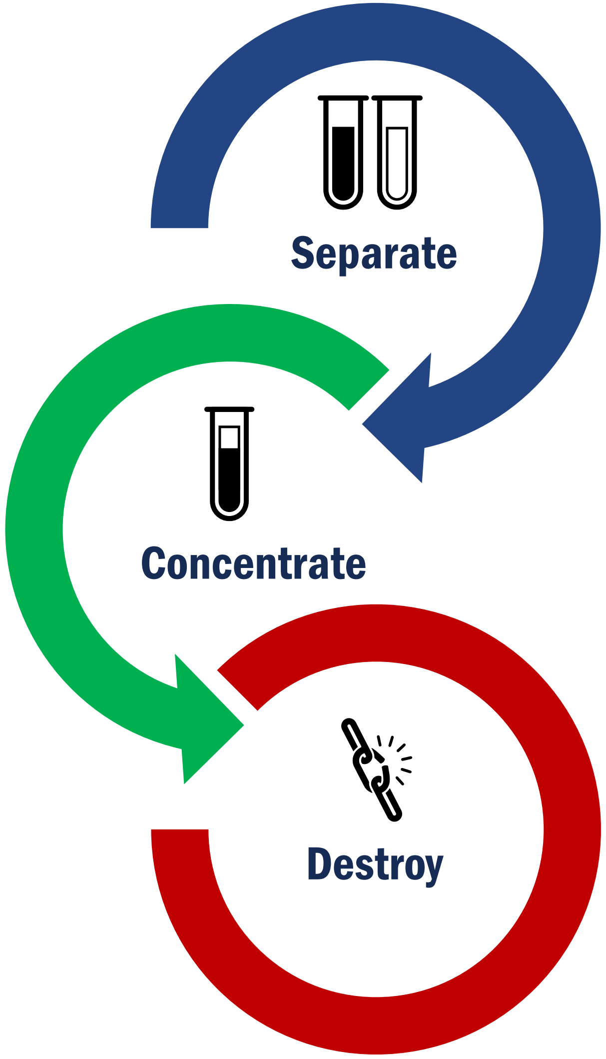
PFAS in Your Water Supply – *What's Next?*

- Temporarily or permanently remove sources
- Change water supply sources
- Blend sources temporarily or permanently
- Treatment to remove PFAS



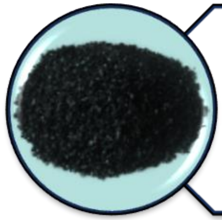
PFAS Removal Technologies

Treatment Trains – PFAS Management Solution

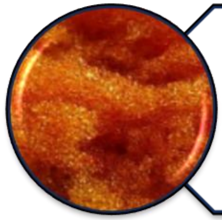


Treatment Goals	Focused Technologies
• Protect human health and the environment • Meet safe drinking water and discharge requirements	• Media separation: GAC or AIX • Liquid-liquid separation: Membrane filtration or foam fractionation
• Reduce waste stream volume	• Foam fractionation → PFAS foam concentrate • PerfluorAd® → flocculate and filter out anionic PFAS
• Zero PFAS waste discharge	• Electrochemical oxidation, UV reductive treatment, and others → complete destruction of PFAS

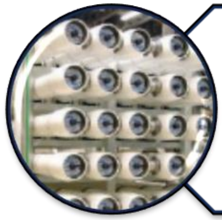
Proven Technologies for PFAS Removal



Granular Activated Carbon (GAC)



Anion Exchange (AIX)



NF and RO Membranes

Table 2-1. Summary of PFAS removals for various treatment processes.

Compound	Molecular Weight (g/mol)	Aeration	Coagulation/Dissolved Air Flotation	Coagulation/Flocculation/ Sedimentation/Granular Filtration or Microfiltration	Anion Exchange	Granular Activated Carbon Filtration	Nanofiltration	Reverse Osmosis	Permanganate/Ozone/ Hypochlorous/Hypochlorite/ Chloramination/UV photolysis
PFBA	214	● (assumed)	● (assumed)	●	●	●	■	■	●
PFPeA	264	●	●	●	●	▼	■	■	●
PFHxA	314	●	●	●	●	▼	■	■	●
PFHpA	364	●	●	●	▼	■	■	■	●
PFOA	414	●	●	●	▼	■	■	■	●
PFNA	464	●	Unknown	●	■ (assumed)	■ (assumed)	■	■	●
PFDA	514	●	Unknown	●	■ (assumed)	■ (assumed)	■	■	●
PFBS	300	●	●	●	▼	■	■	■	●
PFHxS	400	●	●	●	■	■	■	■	●
PFOS	500	●	▼	●	■	■	■	■	●
FOSA	499	Unknown	Unknown	●	Unknown	■ (assumed)	Unknown	■ (assumed)	Unknown
N-MeFOSAA	571	● (assumed)	Unknown	●	■ (assumed)	■ (assumed)	■ (assumed)	■	Unknown
N-EtFOSAA	585	●	Unknown	●	■ (assumed)	■ (assumed)	■ (assumed)	■	Unknown

From Dickerson & Higgins, 2016 (WRF, #4322)

● Removal <10% ▼ Removal 10-90% ■ Removal >90% ☐ Unknown ☐ Assumed

THE Water Research FOUNDATION

WRF 4322: Treatment Mitigation Strategies for PFCs

Raw Water Quality is Key to Selecting Treatment Technology

PFAS

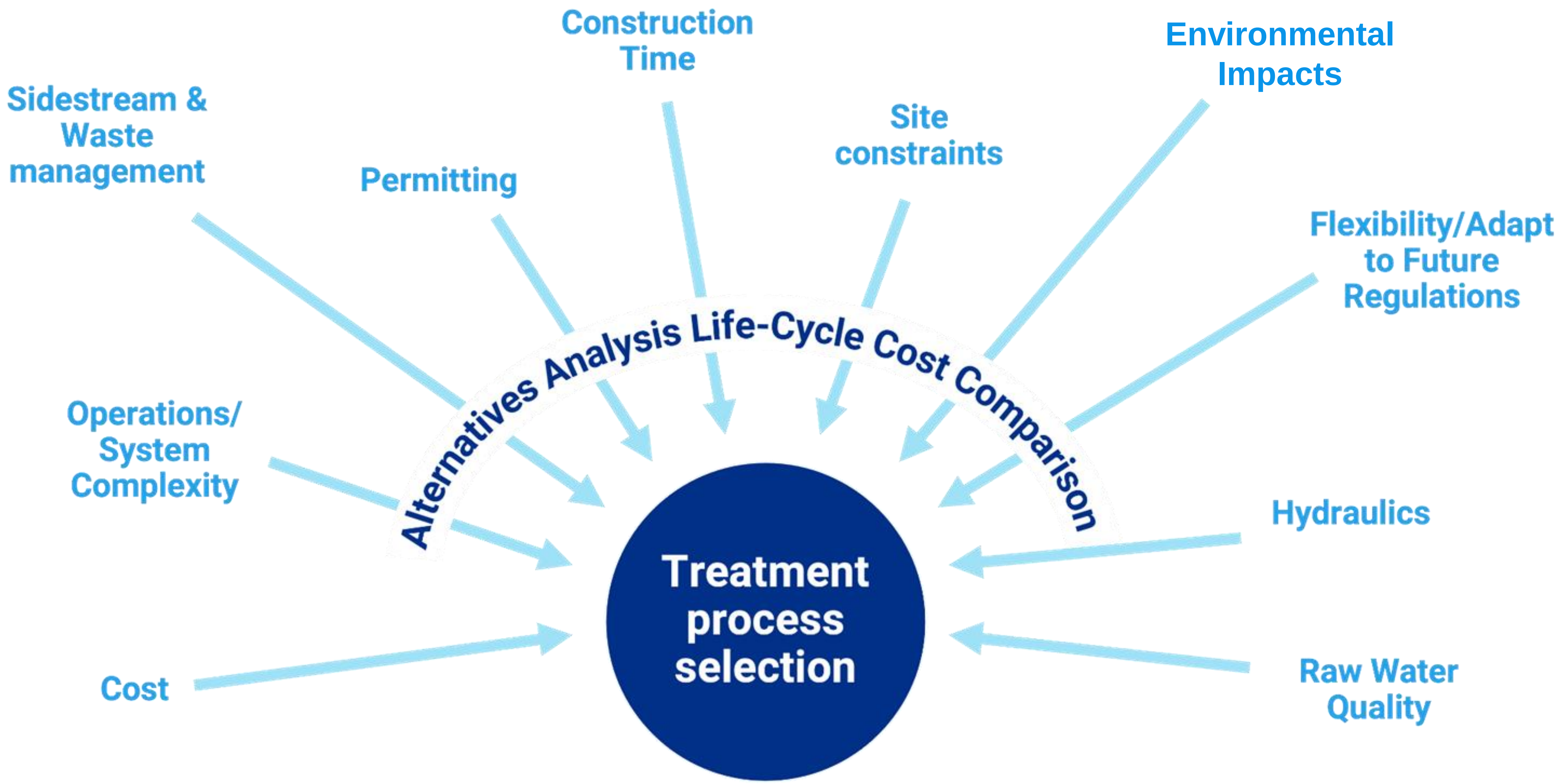
- *Which compounds are you treating for?*
- CA currently regulated: PFOA/PFOS/PFBS
- Flexibility for future MCLs and/or more compounds regulated

Treatment of Other Constituents

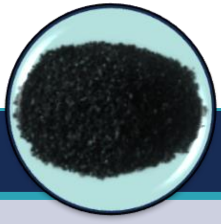
- Softening
- Iron/Manganese
- Nitrate
- VOCs
- Perchlorate
- Hexavalent chromium
- Emerging compounds – 1,4-dioxane
- *Others?*

Potential Interferences with Treatment Technologies

- Radionuclides
- Hardness
- Metals
- Sand/fine sediment
- Organics (including TOC/DOC)
- Entrained air (common in wells)


Construction Time
Environmental Impacts
Sidestream & Waste management
Permitting
Site constraints
Flexibility/Adapt to Future Regulations
Alternatives Analysis Life-Cycle Cost Comparison
Operations/ System Complexity
Hydraulics
Treatment process selection
Cost
Raw Water Quality

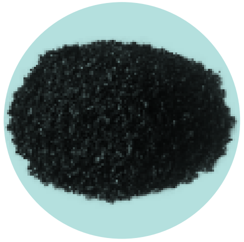
GAC vs. AIX



GAC	Single Use IX-R
7 – 20-minute EBCT	**2 – 3-minute EBCT**
Larger infrastructure footprint	Smaller infrastructure footprint
Typical bed life: 50,000 – 120,000 bed volumes	Typical bed life: 250,000 – 300,000 bed volumes
GAC media is less expensive	IX-R media is more expensive
Less effective for short chain PFAS	Effective for a wider range of PFAS, but less effective for PPCPs
Well established technology	Not as extensively practiced as GAC
Backwash is available	Backwash not recommended

- Life cycle costs for GAC and IX-R are often similar
- Both generate spent media requiring off-site reactivation (GAC) or incineration (IX-R)
- Pretreatment may be needed for both technologies to increase media life span

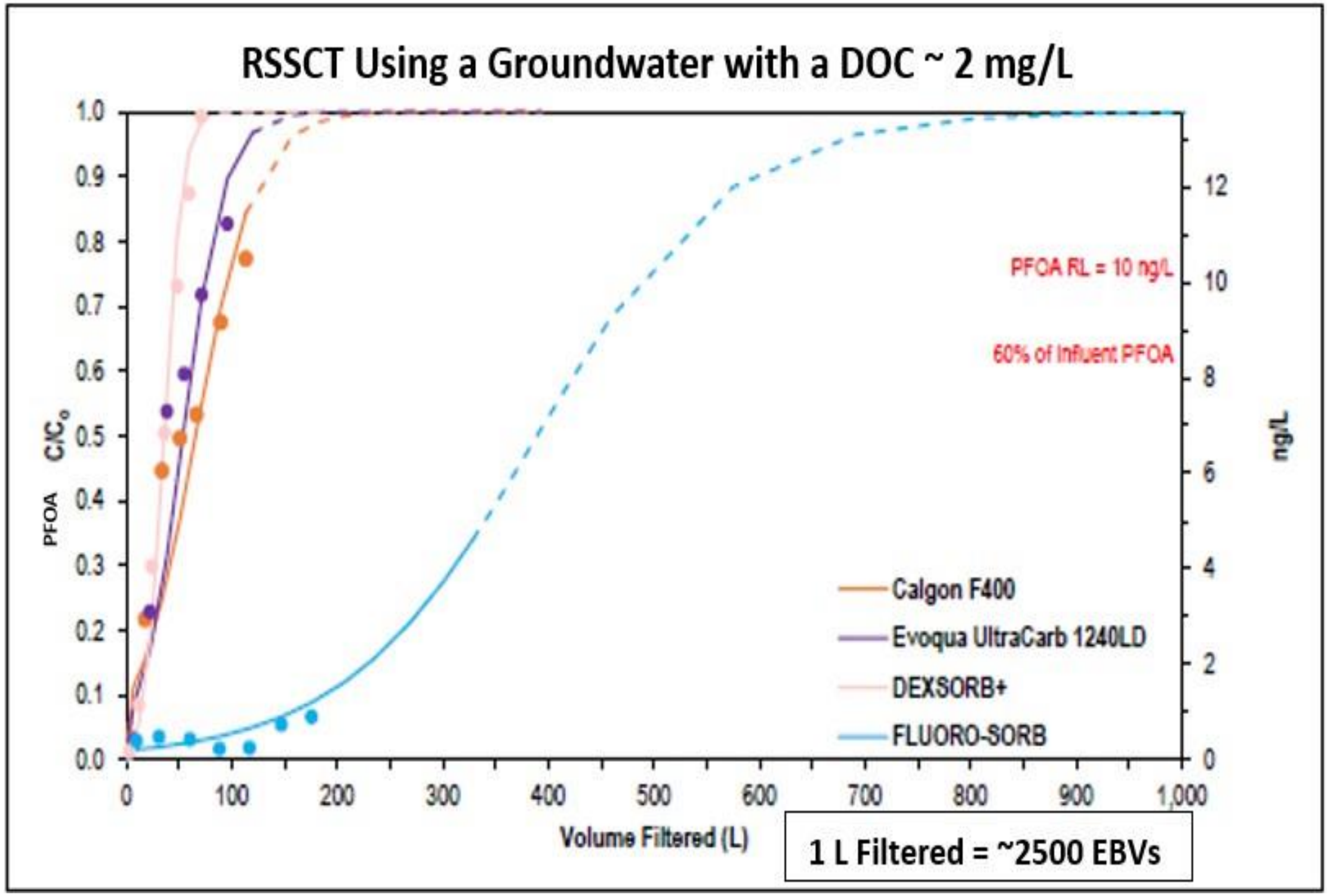
Advancements in Novel Adsorbents Show Promise



Granular Activated Carbon

Novel Adsorbents

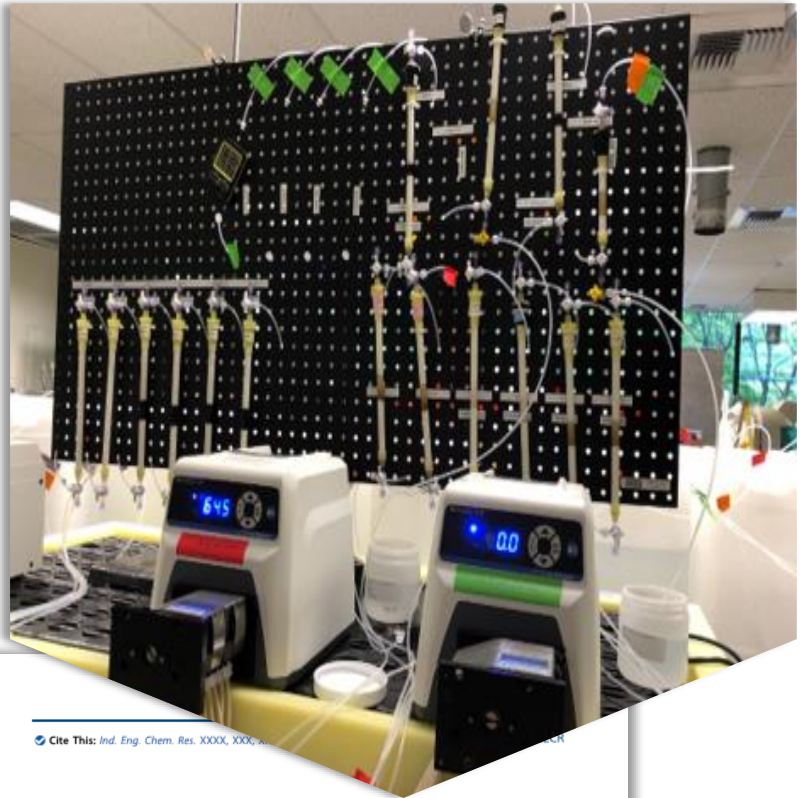
- Carbon (biochar)
- Clay (bentonite)
- Mixed minerals (aluminum oxide, iron oxide, silicates)



Treatment of Low-TOC and Low-PFAS Groundwater Using Conventional (Calgon F400 GAC and Ultracarb 1240LD GAC) and Novel (DexSorb+ and FLUORO-SORB®) Sorbents.
Data courtesy of Colorado School of Mines (Chris Bellona)

GAC and IX Resin: Rapid Small Scale Column Testing (RSSCT)

- Examine breakthroughs of short chain and long chain PFAS
- Compare PFAS removal effectiveness between GAC and ion exchange resin
- Evaluate performance of different commercial products
- Evaluate impact of *site-specific parameters* such as co-contaminants (VOCs), geochemical water quality (e.g., TOC, iron, pH), water treatment additives (e.g., chlorination, corrosion inhibitors) on PFAS removal effectiveness
- Evaluate need for pre-treatment



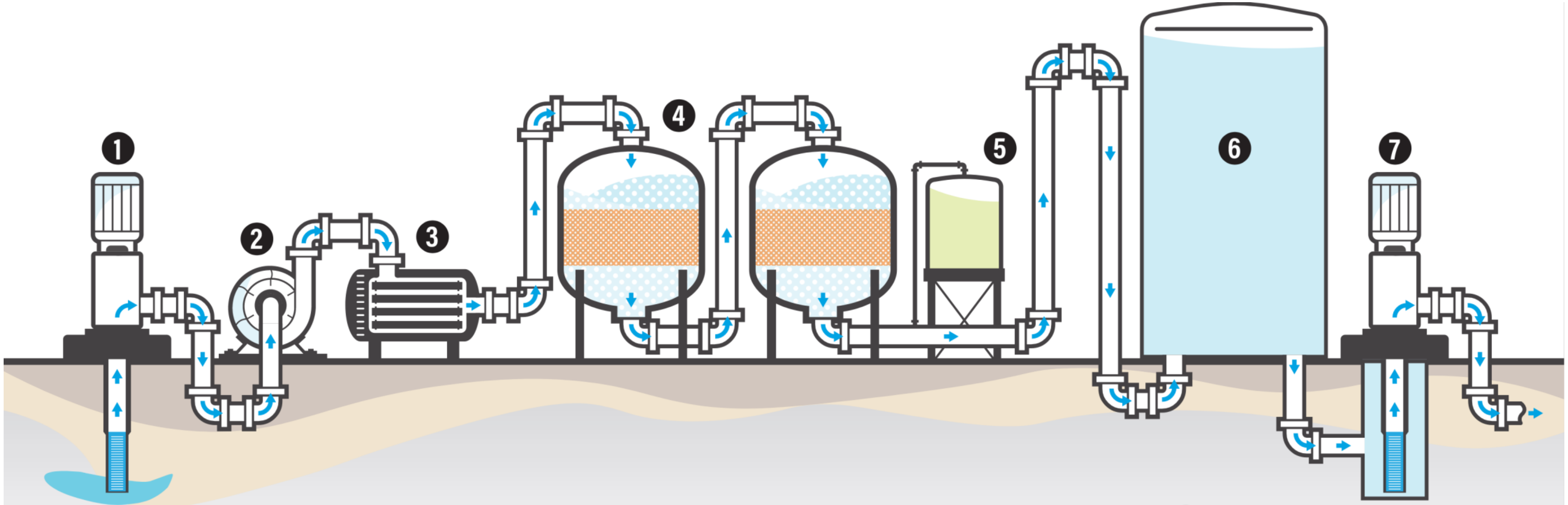
I&EC research
Industrial & Engineering Chemistry Research

Assessing Rapid Small-Scale Column Tests for Treatment of Perfluoroalkyl Acids by Anion Exchange Resin

Charles E. Schaefer,*[†] Dung Nguyen,[‡] Paul Ho,[‡] Jihyon Im,[§] and Alan LeBlanc[§]

[†]CDM Smith, 110 Fieldcrest Avenue, #8, Sixth Floor, Edison, New Jersey 08837, United States
[‡]CDM Smith, 14432 SE Eastgate Way, #100, Bellevue, Washington 98007, United States
[§]CDM Smith, 670 North Commercial Street, #208, Manchester, New Hampshire 03101, United States

Treatment Process Overview



1 Groundwater Wells

Water is sourced through groundwater wells. Each well is paired with a pump that provides the necessary power to draw out water from underlying aquifers.

2 Feed Pumps

Feed pumps provide the energy needed to push water through the treatment system.

3 Cartridge Filters

Cartridge filters provide essential pretreatment of source water to remove particulates prior to ion exchange treatment.

4 Ion Exchange Vessels

Ion exchange vessels are filled with tiny, positively charged resin beads that attract and remove the negatively charged PFAS contaminants.

5 Disinfection

Sodium hypochlorite is injected to ion exchange effluent for disinfection.

6 Treated Water Reservoir and 7 Booster Pump Station

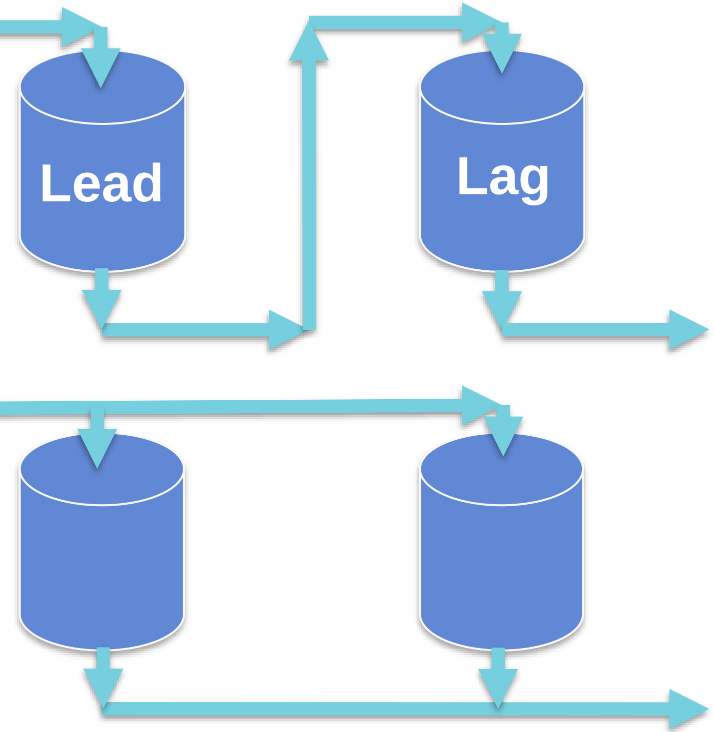
Treated water is stored in a 4 million gallon capacity reservoir. Two booster pump stations pump treated water to the 400-ft and 555-ft pressure zones of the distribution system to provide drinking water to the public.

Series (Lead-Lag) Operation for GAC and AIX

Provides More Safety/Redundancy than Parallel Treatment

Series
(Longer EBCT)

Parallel
(Greater throughput)



Case Study 1 – Owen District Road GAC Facility, Westfield, MA (4 MGD)

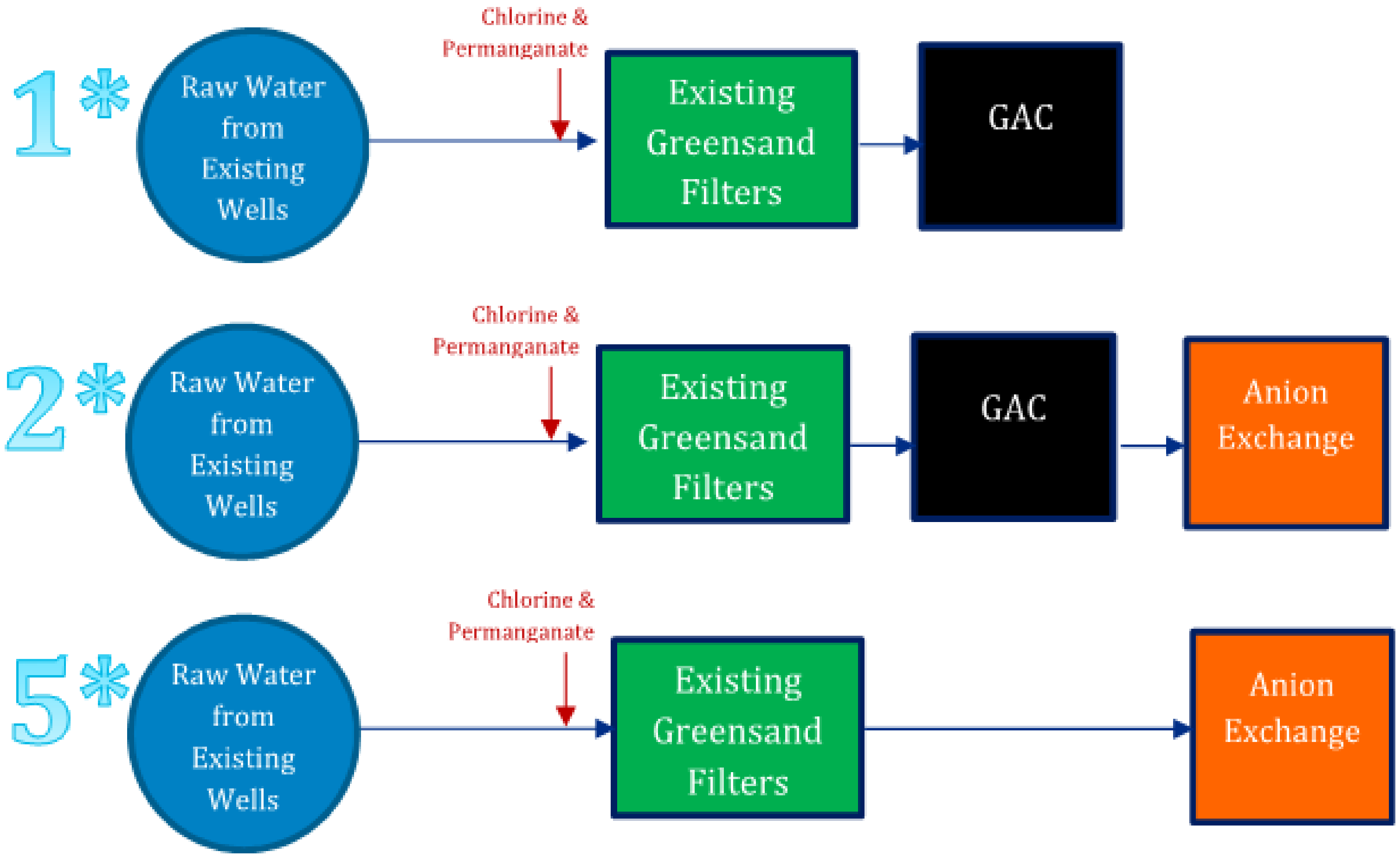
- GAC adsorbers with 20-minute EBCT (lead-lag)
- Parallel operation allowed by state to achieve seldom-used maximum flow
- Project Duration – approximately 30 months, $5.5 Million construction cost
- Operating for about 19 months – site is next to airfield, source water PFAS is 100s of ppt
  - *To date, non-detect for the six PFAS compounds regulated in MA*

Case Study 2 – Grove Pond AIX Facility, Ayer, MA (2 MGD)

- AIX with 3-min EBCT located next to Fe/Mn removal plant
- Project Duration will be approximately 24 months – treatment study, design, construct
- $3.1 million construction bid in June 2019, Startup in Q4 2020

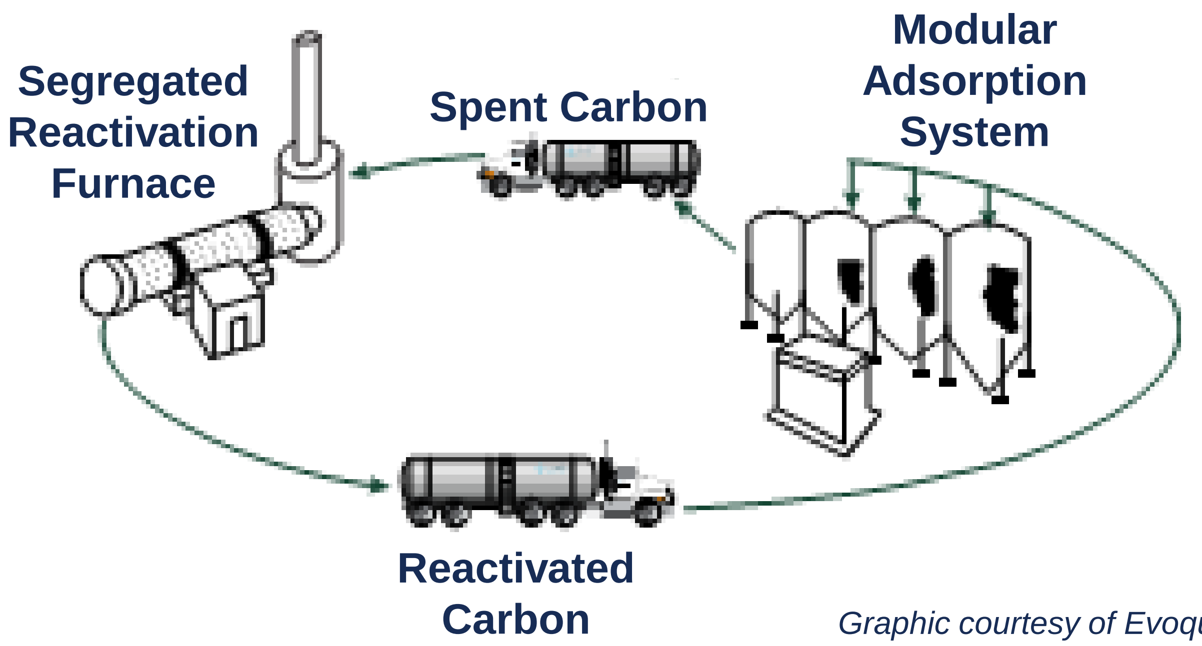
Bench Scale Testing: GAC versus Anion Exchange

- PFAS treatment process to be placed downstream of the existing greensand filters (post iron and manganese removal)



Options to Dispose of Spent Media

- Granular Activated Carbon
  - Landfill
  - Incineration
  - Reactivation / Reuse of Carbon



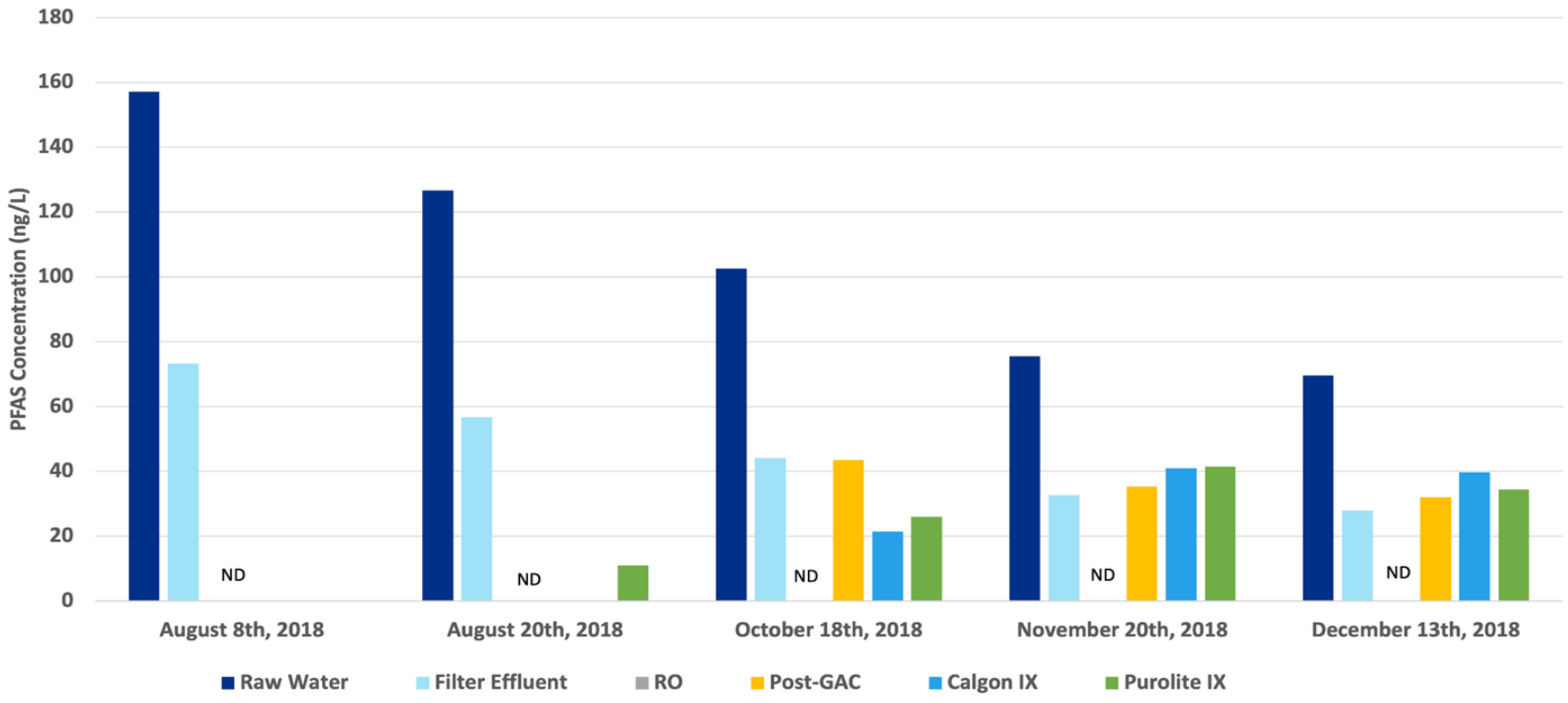
Graphic courtesy of Evoqua

- Single Use Anion Exchange Resin
  - Landfill
  - Incineration
  - No re-use of Anion Exchange Resin

Case Study 3 – Northwest WTP LPRO, Brunswick County, NC (41 MGD)

- Surface water treatment system – Cape Fear River
- Three-stage LPRO to remove PFAS and other CECs
- Project Duration – approximately 48 months
- $70 million construction for LPRO system
  - *lowest life-cycle cost*

NC Pilot Test Results – GAC, AIX, and LPRO for Treated Surface Water



LPRO Pilot – Example Test Results

Parameter	Filtered Water Concentration	RO Treated Water	Calculated Removal %
Sum (45) of PFAS Tested	423 – 892 ng/L	ND – 11 ng/L	--
1,4-Dioxane (industrial chemical)	3.2 µg/L	0.2 µg/L	94%
Carbamazepine (seizure medicine)	13 ng/L	ND	--
Atrazine (herbicide)	58 ng/L	ND	--
Cotinine (metabolite of nicotine)	15 ng/L	ND	--
DEET (insect repellant)	44 ng/L	ND	--
Simazine (herbicide)	57 ng/L	ND	--
Tris (1,3 dichloro-2-propyl) phosphate (pesticide, flame retardant)	120 ng/L	ND	--

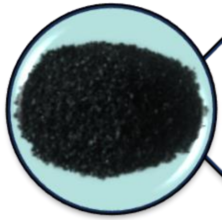
Identify an Equipment Procurement Approach to Avoid Potential Delays

- Expect ongoing market price volatility and delays in equipment fabrication:
  - Pressure vessels – in high demand
  - Electrical gear (MCCs, breakers)
  - VFDs
- Pre-purchase of equipment can reduce construction duration by several months.
  - Contractor can proceed without having to wait for shop drawings approval
  - Owner would own risk of potential equipment delays
- Consider alternative delivery for implementation

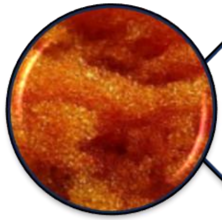
Emerging PFAS Water Treatment Technologies

Limitations of “Conventional” PFAS Treatment

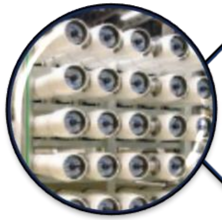
1. High volume of spent media/waste stream requiring waste management
2. Significant pretreatment often required to remove competing solutes
3. High concentrations of PFAS can lead to inefficient target compound removal
4. Overall high costs for removing small mass of contamination (down to trace ppt levels)



Granular Activated Carbon (GAC)

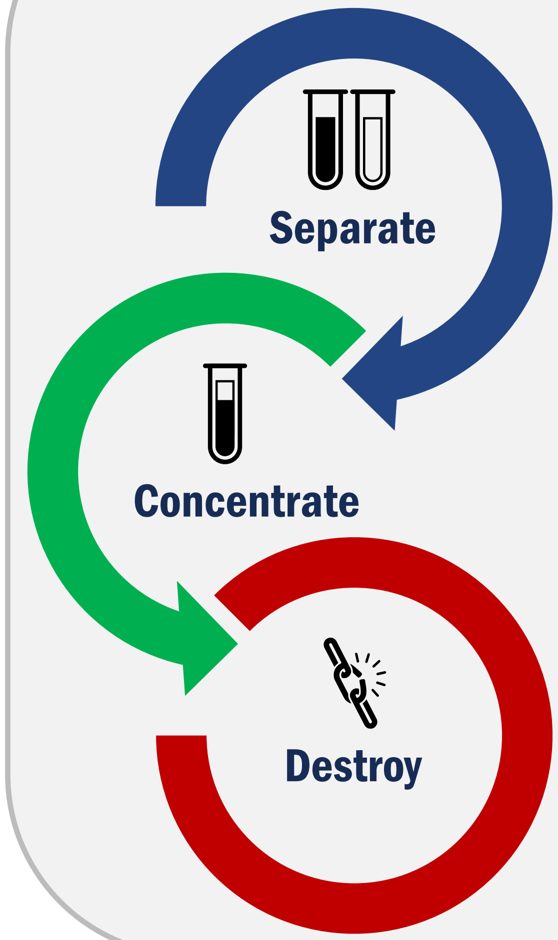


Anion Exchange (AIX)



NF and RO Membranes

Present and Future of PFAS Treatment



Focused Technologies

- **Media separation:**
  GAC, AIX, and novel adsorbents
- **Liquid-liquid separation:**
  Membrane filtration or foam fractionation
- Foam fractionation → PFAS foam concentrate
- PerfluorAd® → flocculate and filter out anionic PFAS
- Electrochemical oxidation (ECO), UV reductive treatment, and others → complete destruction

SERDP DOD • EPA • DOE
ESTCP
WORLD ECONOMIC FORUM
AUSTRALIAN DEFENCE FORCE
The Water Research Foundation
NGWA The Groundwater Association
AIR FORCE CIVIL ENGINEER CENTER
INTERSTATE TECHNOLOGY REGULATORY COUNCIL ITRC

Many challenges remain for municipal application of PFAS concentration and destruction.

PFAS Destructive Water Technologies

Research and Development: Bench

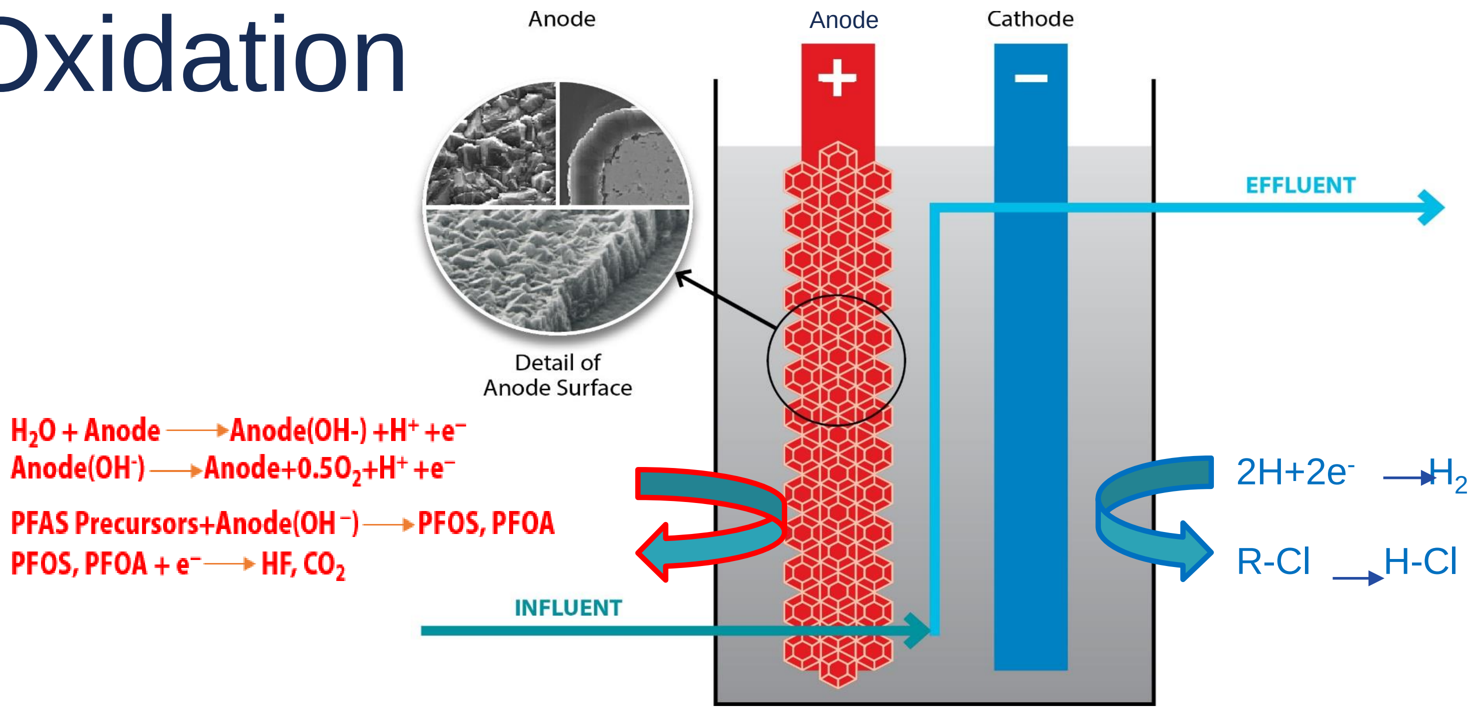
- Hydrothermal
- Photolysis/Photocatalytic
- High-energy Electron Beam
- Radiolytic

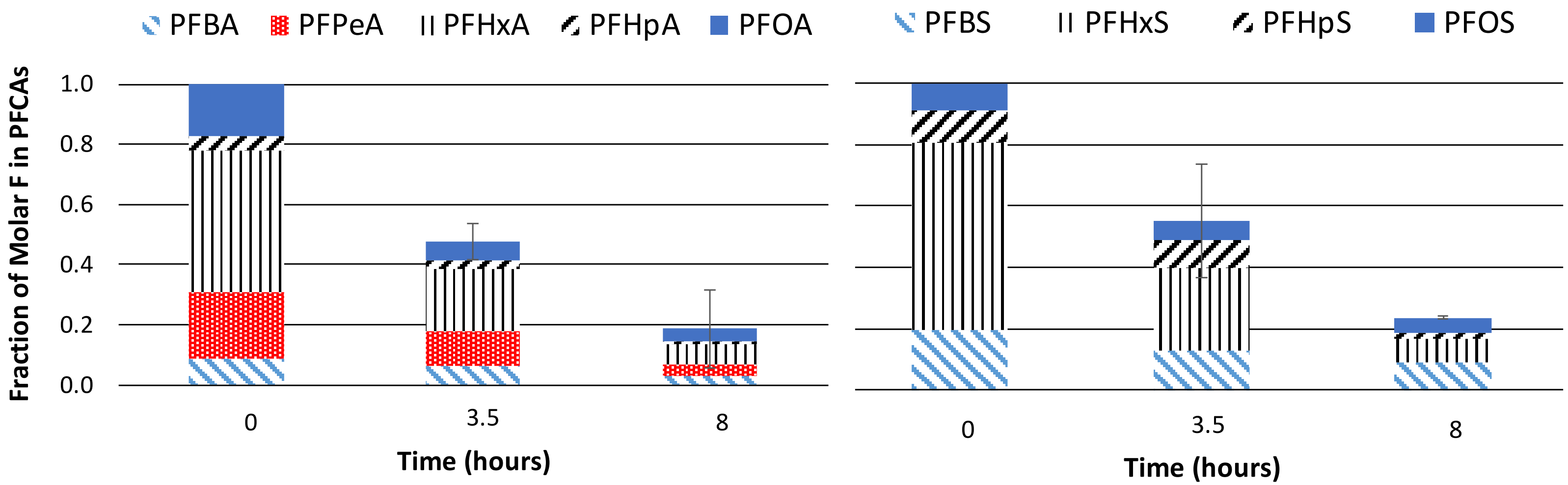
Demonstrated at the Bench and Pilot/Field Scale

- Electrochemical Oxidation
- Plasma
- UV-Hydrated Electrons
- Sonochemical

Electrochemical Oxidation

- Applicable for groundwater, AFFF, AIX or NF reject, IDW
- Direct (on anode) and indirect (in solution) oxidation
- PFAS are mineralized to F^- and CO_2 in hours
  - 80% Reduction of PFCAs and PFSAs in 8 hrs
- Generates perchlorate (requires additional treatment)





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Electrochemical Transformations of Perfluoroalkyl Acid (PFAA) Precursors and PFAAs in Groundwater Impacted with Aqueous Film Forming Foams

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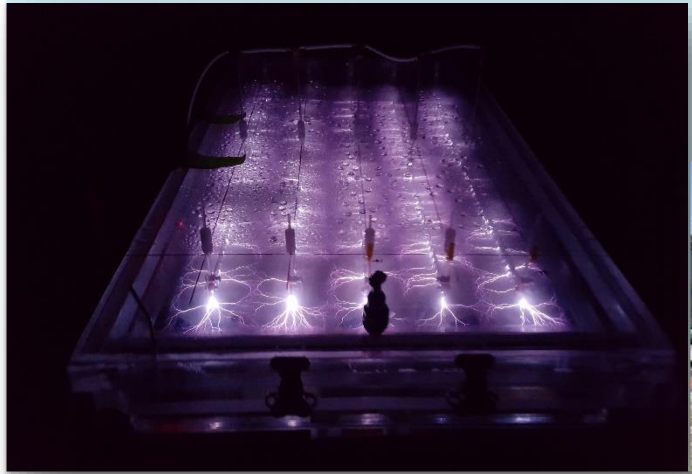
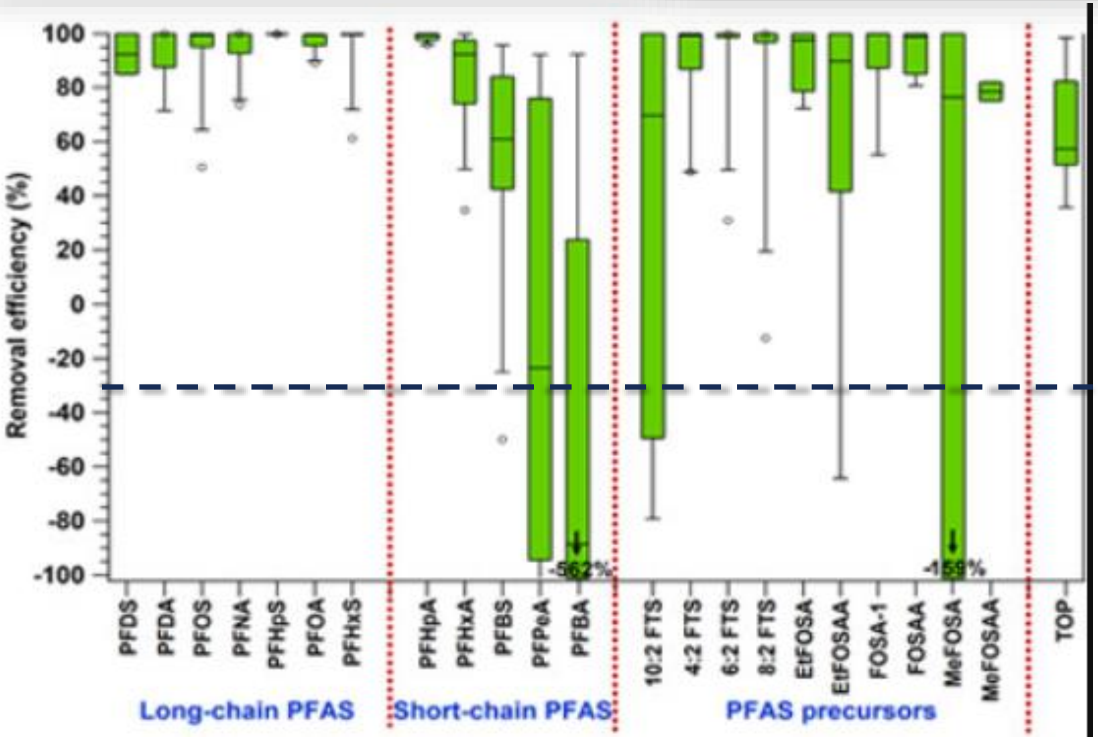
Plasma

- Applicable for groundwater; AFFF; AIX and NF reject; IDW
- Electrically-generated plasma
- Argon bubbles to enhance PFAS contact with plasma
- Less sensitive to co-contaminants
- Shorter (minutes) reaction time
- Less effective for shorter chain PFAS
- Partial destruction leads to accumulation of some PFAS

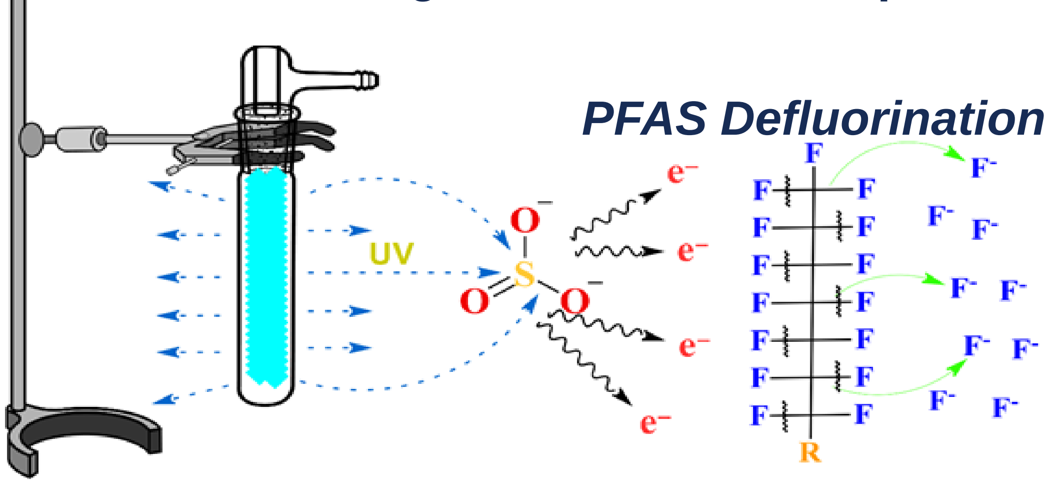


Pilot-scale plasma reactor for IDW treatment *(Singh et al, ES&T, 2019)*

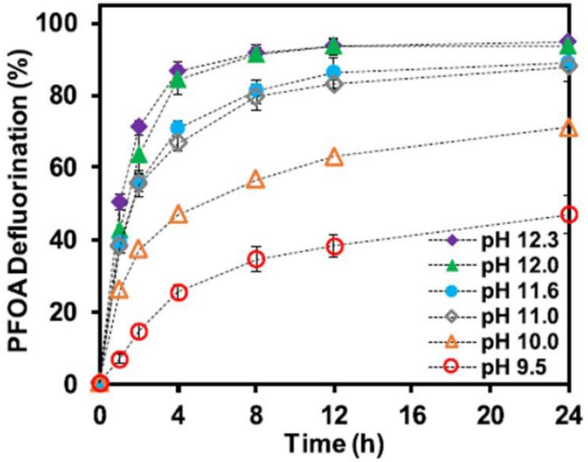


UV-Hydrated Electrons (Sulfite)

- Applicable to groundwater; AFFF; AIX or NF reject; IDW
- Easy to operate and implement in water/wastewater facilities
- PFAS half-lives depend on the PFAS (few hours to days)
- Highly impacted by water quality parameters and UV scavengers
  - Turbidity, dissolved organic carbon (DOC), alkalinity, nitrate and others which slow PFAS degradation



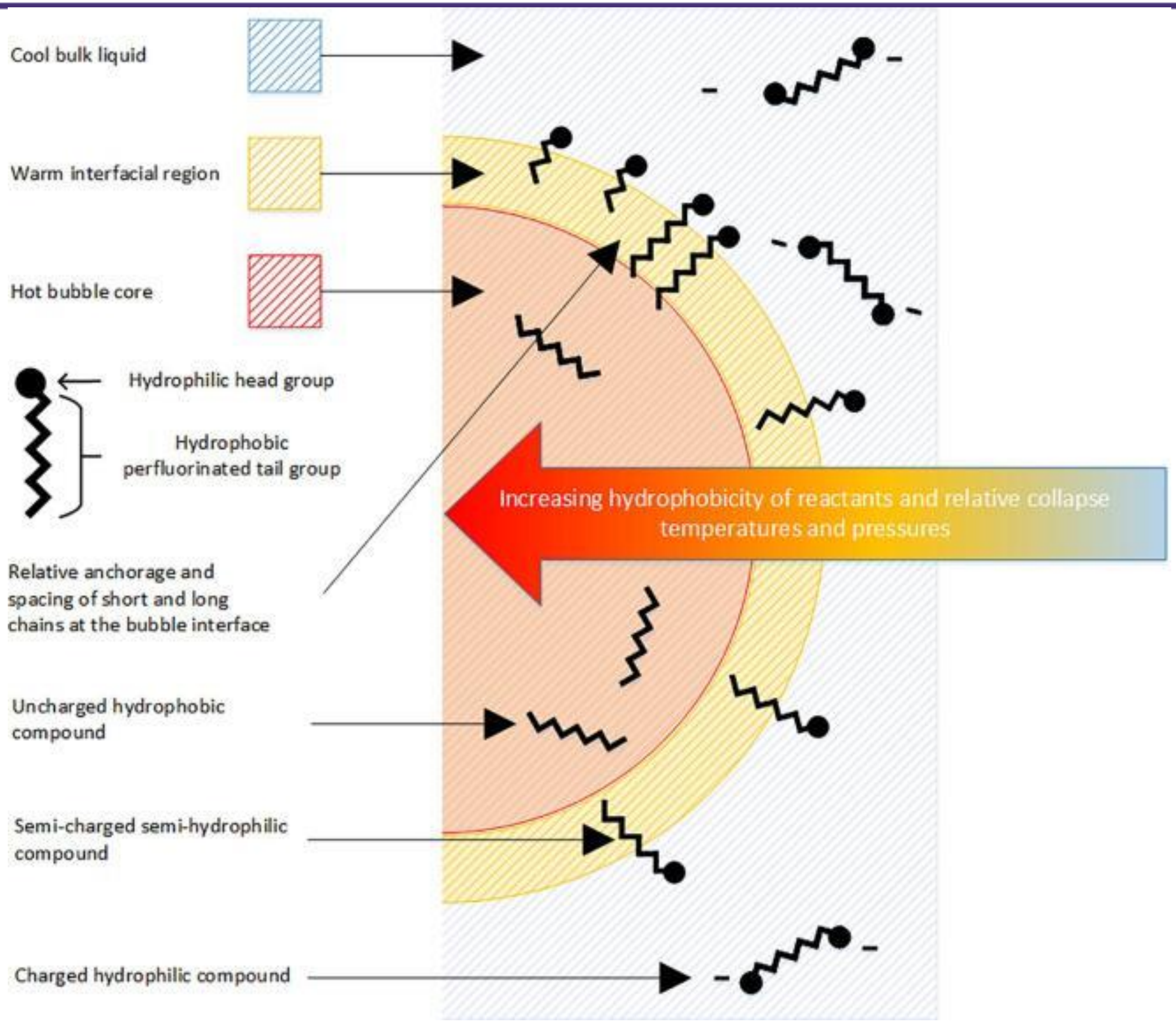
UV + Sulfite → Hydrated electrons (e_{aq}^-)+ Sulfate/bisulfate (nontoxic)



Bentel et al., *ES&T Letters*, 2020

Sonochemical

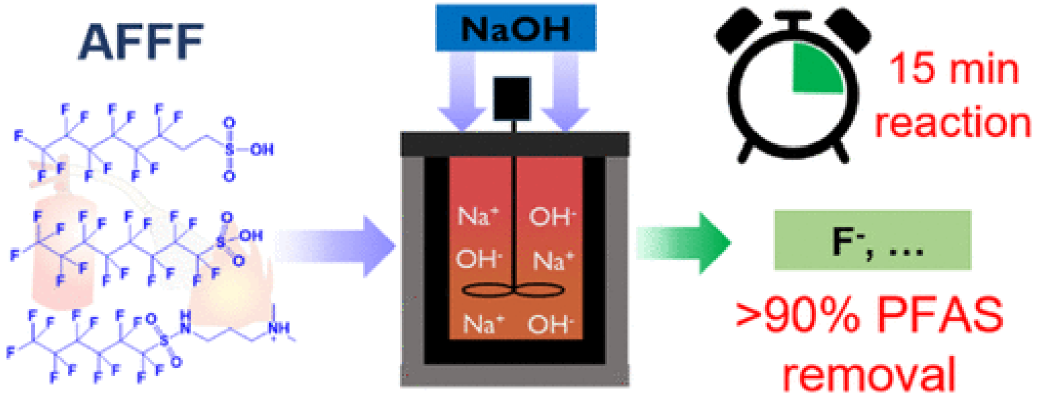
- Applicable for: concentrated wastes, AFFF, IDW, soil slurries, in situ GW
- Requires:
  - Ultrasonic waves → cavitation
  - Elevated temperature (60-80°C)
  - low pH (~4)
- Results:
  - Localized thermal treatment (5000K; combustion and pyrolysis)
  - Formation of reactive radicals
  - Near-complete defluorination of PFASs in AFFF mixtures in seconds
  - Nitrate and peroxide
- Mechanism and mass balance work ongoing



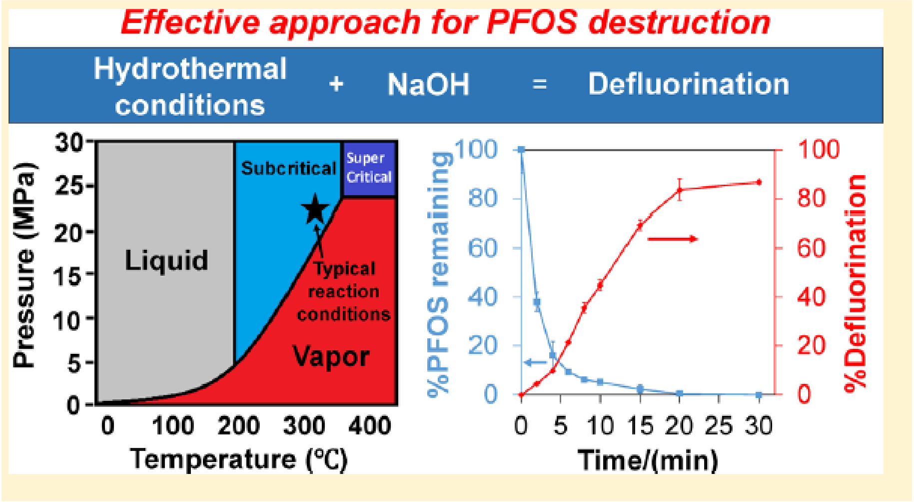
Sidnell et al, *Ultrasonics Sonochemistry*, 2022

Hydrothermal Alkaline Treatment (HALT)

- Applicable for: concentrated wastes, AFFF, IDW, concentrated source materials
- Requires:
  - High temperatures (up to 350°C or 660°F)
  - High pressure (290 to 2400 psi)
  - pH ~ 11
- Results:
  - Near-complete defluorination of PFAS in AFFF mixtures in minutes (e.g., 30) to hours
  - Can generate HF
- Mass balance work ongoing



Hao et al, Environ. Sci. Technol. 2021, 55, 5, 3283-3295

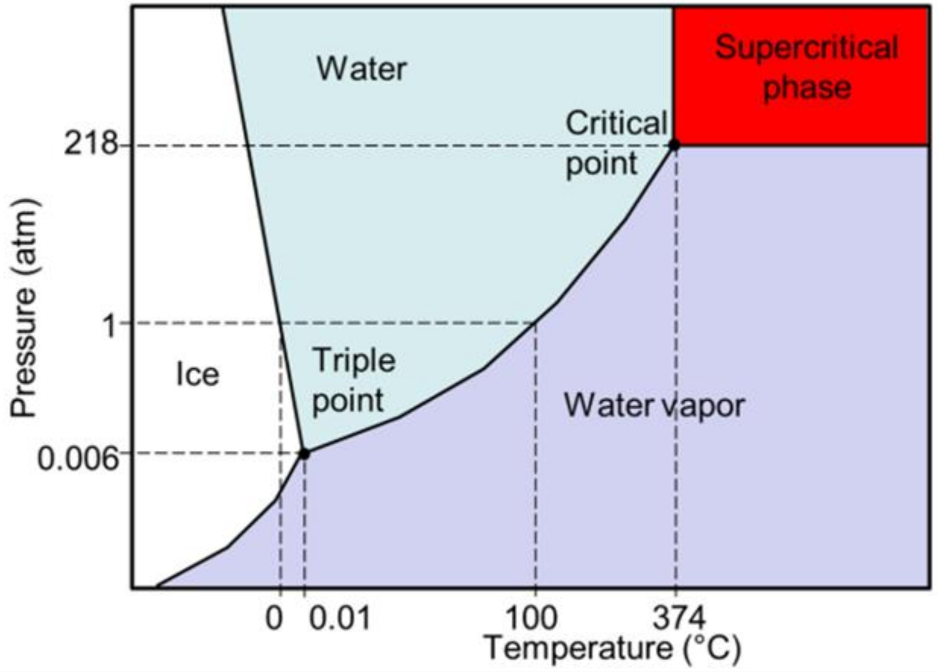


Wu et al, ES&T Letters, 2021, 2019, 6, 10, 630−636

Supercritical Water Oxidation

$$\mathbf{PFAS} + O_2\ (\text{air}) \xrightarrow[\sim 240\ \text{bars}]{>374\ ^\circ\text{C}} CO_2 + \mathbf{F^-} + \underbrace{\mathbf{CaF_2}}_{\text{solid}} + \text{heat}$$

- Applicable for concentrated wastes, AFFF, IDW, concentrated source including slurries and biosolids
- Requires:
  - High temperatures (>374°C or 705°F)
  - High pressure (>3,200 psi)
  - An oxidant (e.g., oxygen, air)
- Results:
  - Water and salts (no organics)
  - Near-complete defluorination of PFAS in AFFF mixtures in seconds (e.g., 30)
  - Corrosive conditions (generates HF)
- Mass balance work ongoing



ESTCP Project ER20-5350

- Treated 30-300 dilute AFFF
- > 95 – 98% decrease in TOF

Treatment Efficiency

where P is the power (kW), t is the treatment time (h), V is the water volume (m^3), and C_0 and C_t are the initial and final concentrations, respectively.

$$E_{EO}\left(\frac{kWh}{m^3}\right) = \frac{P\,t}{V\,\log\left(\frac{C_0}{C_t}\right)}$$

System	PFAS	Volume (L)	OOM	Time (hr)	E_{EO} (W-h/L)	Defluorination (%)	Source
Electrochemical Oxidation	PFOS, PFOA, dilute AFFF, RO	20	3-5	8	46-140	86-99.9%	Chaplin, 2020, Schaefer, 2017, 2019,2020
Plasma				1	9-84	~33-133%	Singh et al. 2019
UV-Sulfite					15-50	90%	Jassby, 2020, Rao, 2020, Su 2019
Hydrothermal Alkaline					127	70-99%	Strathman, 2020
Sonochemical					250-1500	90-99%	Kulkarni, 2022

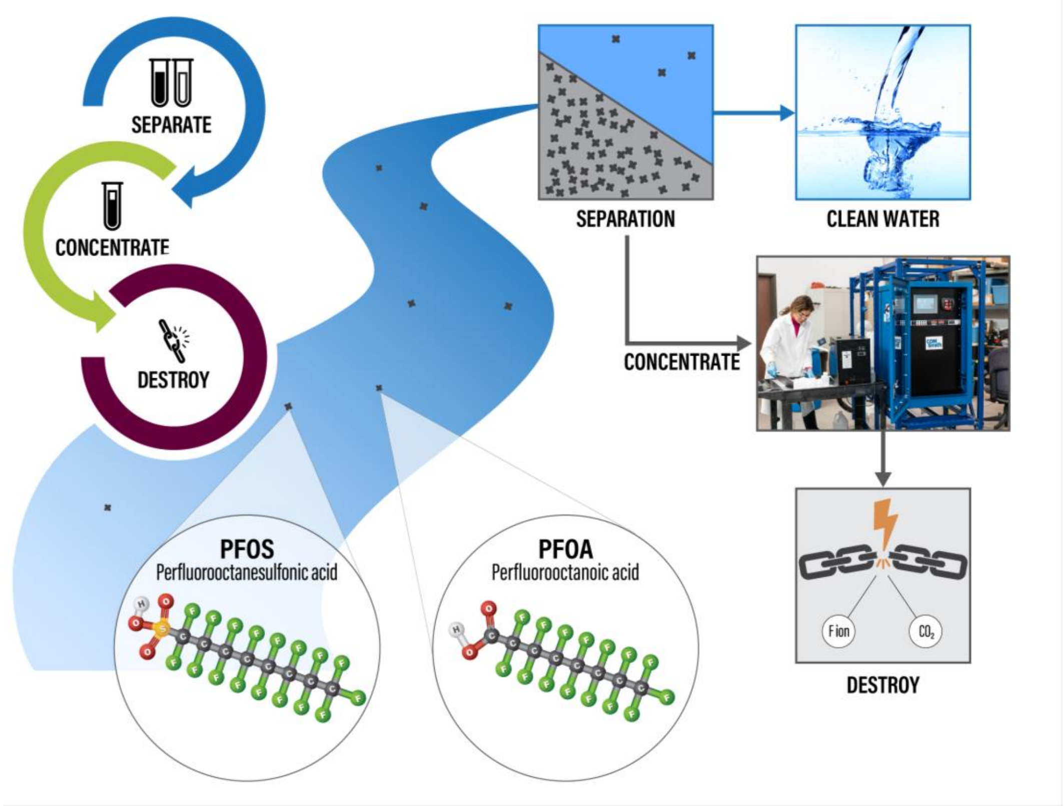
Separation Technologies:
Reverse Osmosis – 0.4 W-h/L
Ion Exchange – 0.01 W-h/L

MGD = 160 kL/h
If E_{EO} is 10 W-h/L, that's 1.6 MW of power per MGD

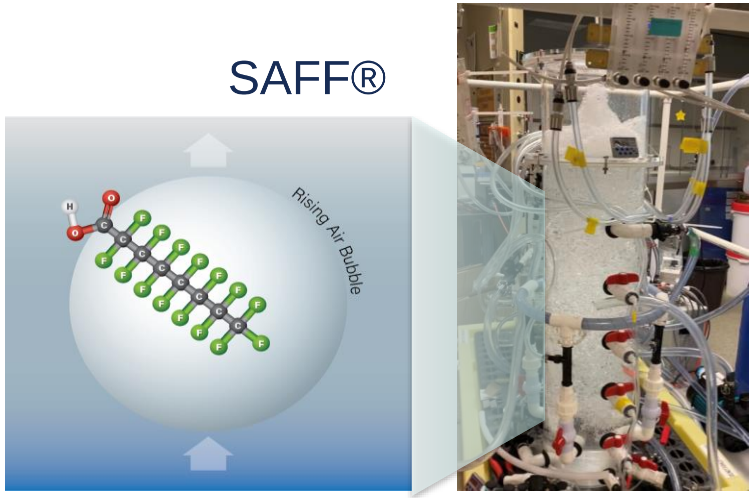
Takeaways

- Future PFAS solutions will focus on PFAS destruction with zero waste discharges
- Most destructive technologies are impractical for dilute streams – best suited for low-volume, high-strength PFAS concentrates
- Effective PFAS destruction that checks all the boxes for full-scale applications is going to be challenging and will take years to develop
- More pilot-scale demonstrations for PFAS destruction in side-by-side comparisons for different treatment streams
- When water matrix is complex, shorter chain PFAS and precursors are present, complete defluorination remain problematic for nearly all destruction technologies

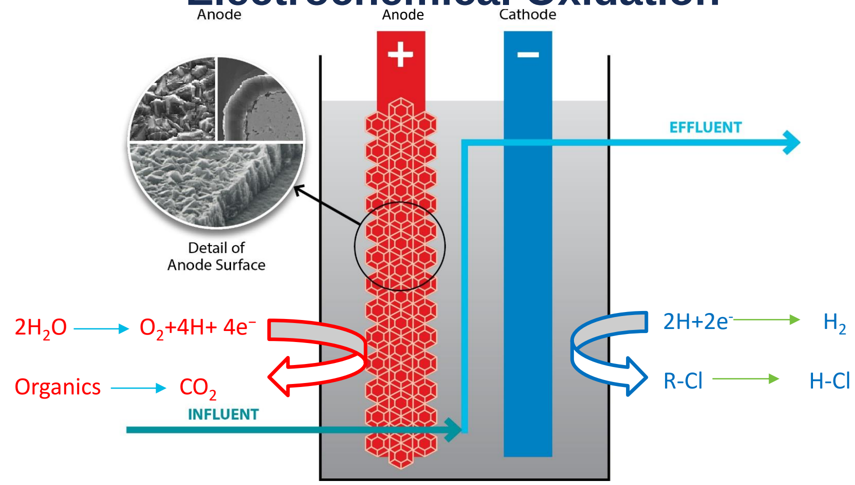
Separate-Concentrate-Destroy



SAFF®

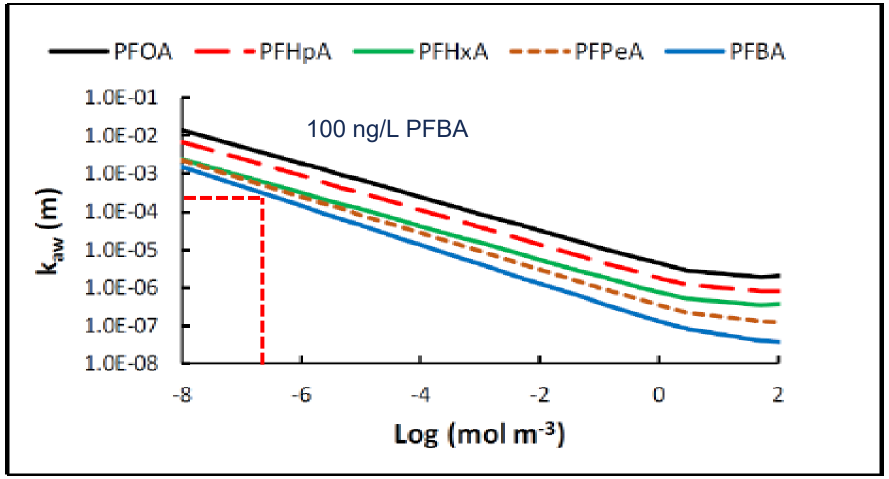


Electrochemical Oxidation



Surface Active Foam Fractionation (SAFF®)

- Applicable for groundwater, surface water, wastewater and leachate treatment
- Technology developed by EPOC Enviro (Australia)
- Separates PFAS using bubble formation
- Concentrates PFAS at the bubble-water interface → PFAS foam concentrate
- Capable of removing PFAS to low levels
- Short chain PFAS takes longer to remove (lower Kaw)



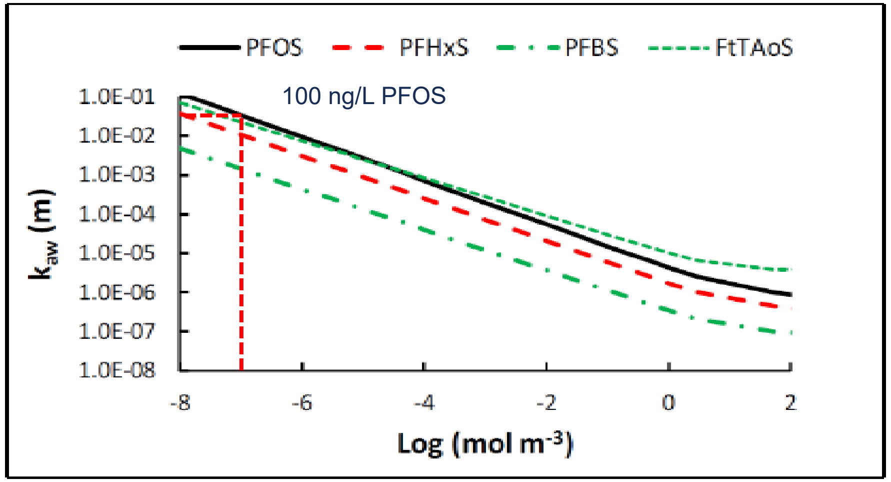
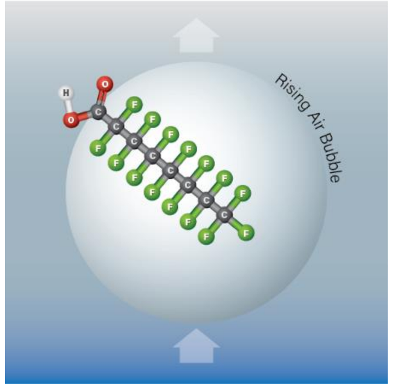
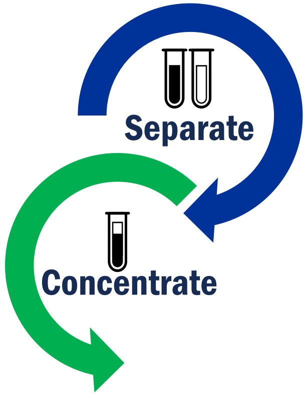


Figure courtesy of Schaefer et al., 2019





SAFF® Configuration

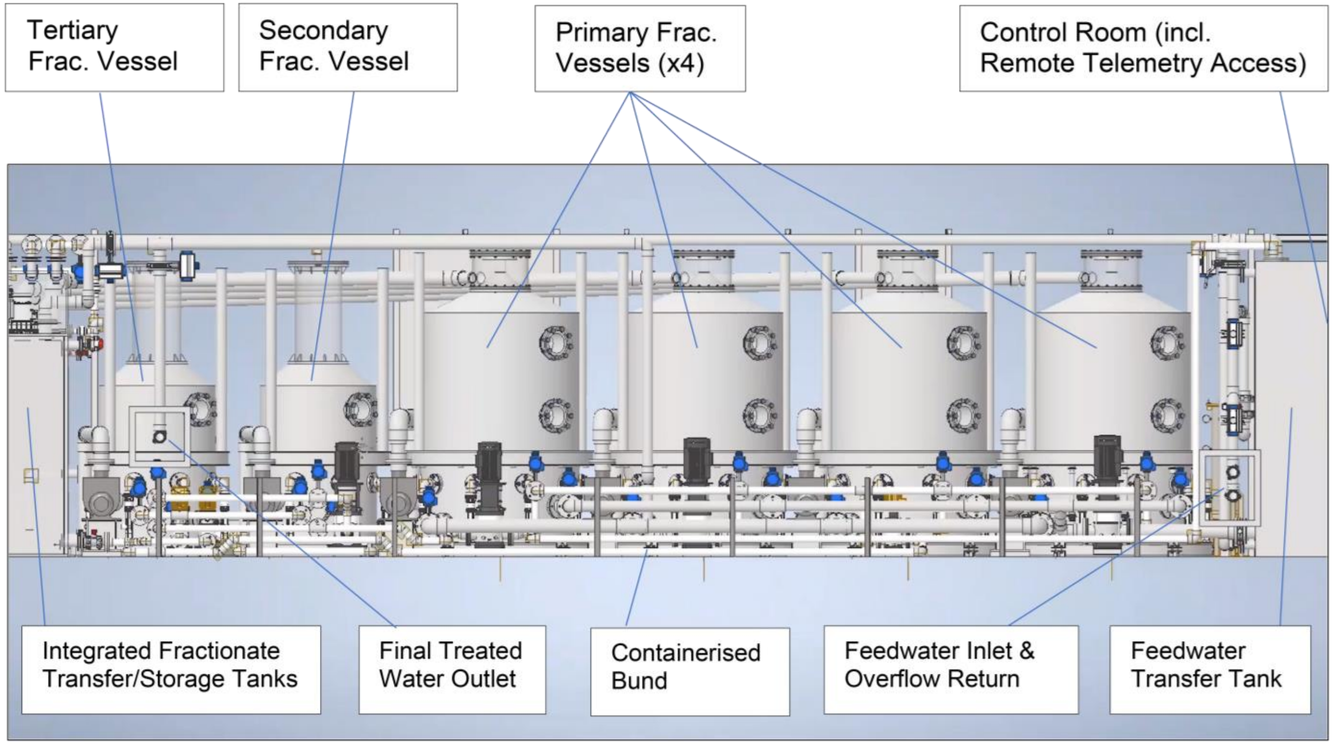


Figure courtesy of EPOC Environmental

- Aeration through venturis
- 480V / 100 amp service
- 100 gpm nominal capacity
- Requires good foaming
- Can be optimized via foaming agents and operational changes

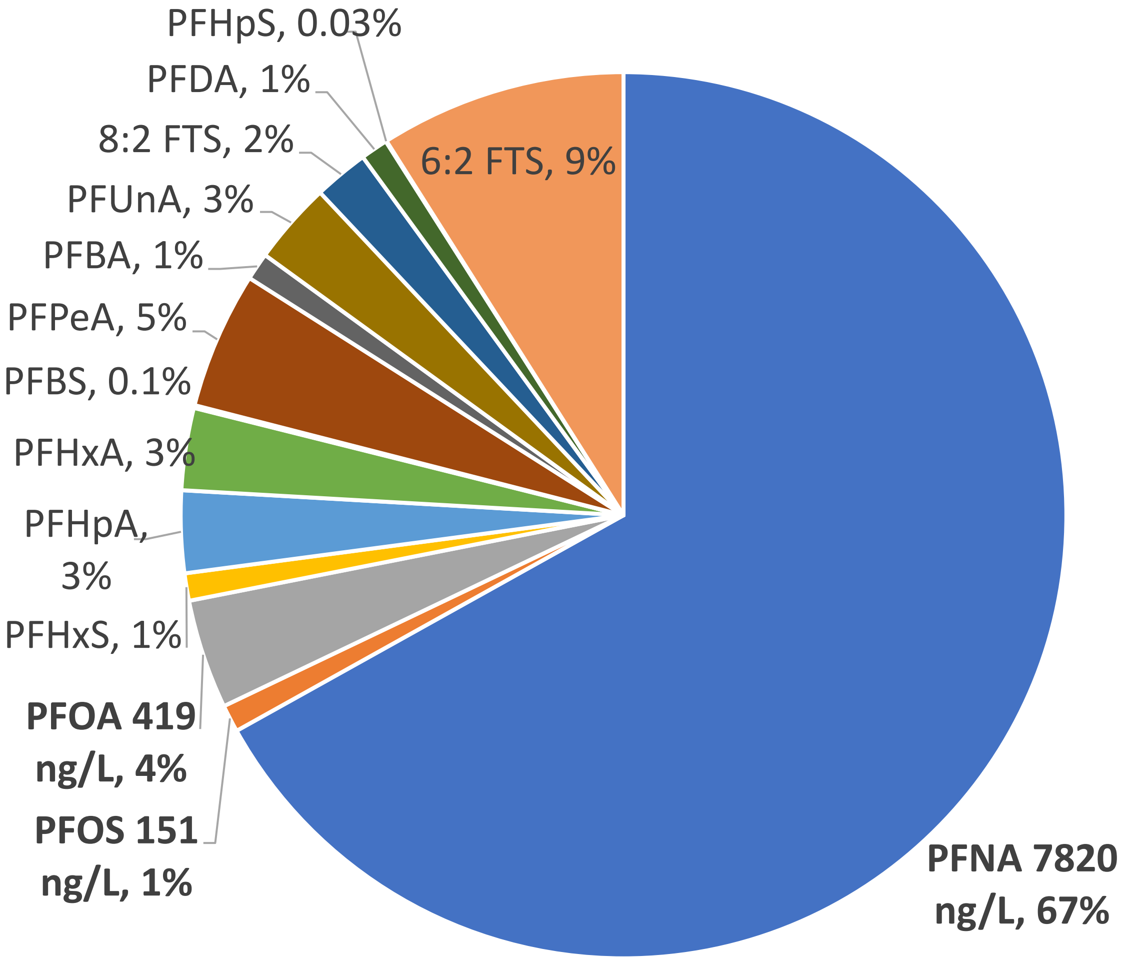
Primary Fractionators

Secondary Fractionators

Final (tertiary) Concentrate Tank

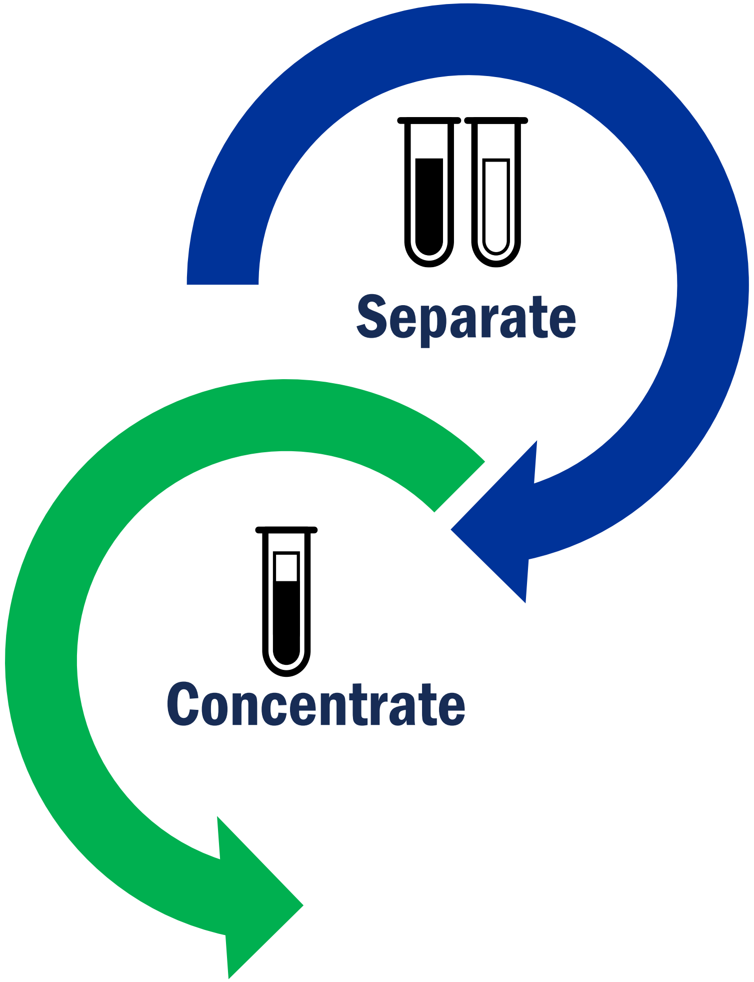
Pilot Site: Groundwater Impacts

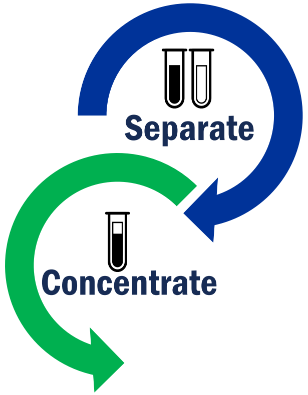
- Groundwater impacts
  - AFFF release from site drain line
  - Legacy chlorinated volatile organic compound (CVOC) impacts
- Existing groundwater treatment facility (GTF)
  - 250 gpm extraction
  - Discharge to surface water (state permit)
- Existing interim PFAS treatment system uses ion exchange (IX) resin
  - Discharge Criteria (LCMRL - Lowest Concentration Minimum Reporting Level)
    - PFOA: 5.1 ng/L
    - PFOS: 6.5 ng/L



Overall Technical Approach

- Test foam fractionation technology with site water at Bench Scale
- Field Pilot Test to determine SAFF® ability to remove PFAS
  - GTF effluent (~500 ng/L PFAS)
  - Source Area Groundwater (~11,000 ng/L PFAS)
- Objectives:
  - Determine site-specific operational settings for each water type
  - Assess the need for, and impacts of foaming agent to remove short-chain compounds
  - Confirm PFAS concentration reduction
  - Evaluate energy consumption per gallon treated





SAFF® Pilot Results

Separate

- Two groundwater sources tested
- Total PFAS removal: 51 – 81%
- Total PFAS removal with foaming agent: 97% - 98% (optimized)

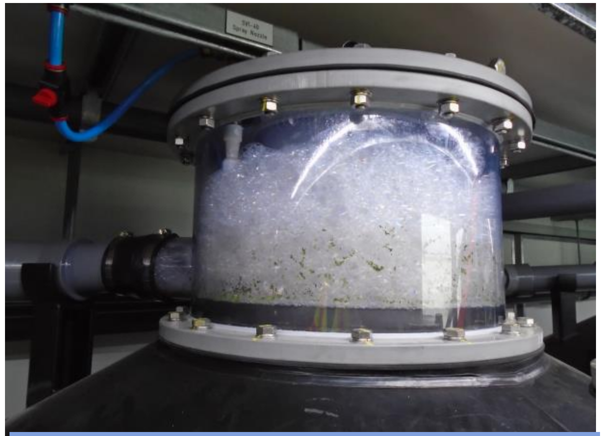
Concentrate

- ~265,000 gallons treated → 3 gallons of fractionate
- 90,000X concentration factor
- ~1.8 kWh / 1,000-gal electrical consumption

Destroy (Offsite Electrochemical Oxidation)

- 16 hours: 100X to 10,000X PFAS reduction, 99% TOF removal

Primary Fractionation
Without foaming agent



Primary Fractionation
With foaming agent

Treatment System Comparison

- Treatment system for air stripper effluent
- Design flow rate of 330 gpm
- Includes gravel pad area, trailer, piping with heat trace, power and PLC controls
- IOX – feed pump, bag filter skid
- SAFF – foaming agent system

	SAFF	IOX	GAC
Construction	$1.4M	$1.2M	$0.9M
O&M	$350K	$650K	$475K
1-year operation	$1.75M	$1.85M	$1.38M
5-year operation	$3.15M	$4.45M	$3.28M

What's Next for SAFF?

- Bench and/or Pilot Optimization is needed for this technology
- Limited treatment of short-chain PFAS – Amendment addition timing and length of aeration should be evaluated
- Regulatory acceptance of foaming agent could be a challenge – Need more case studies showing foaming agent is removed during treatment
- Unable to close the mass balance – Need additional sample ports and evaluation
- Lifecycle cost needs continued refinement

Destroy

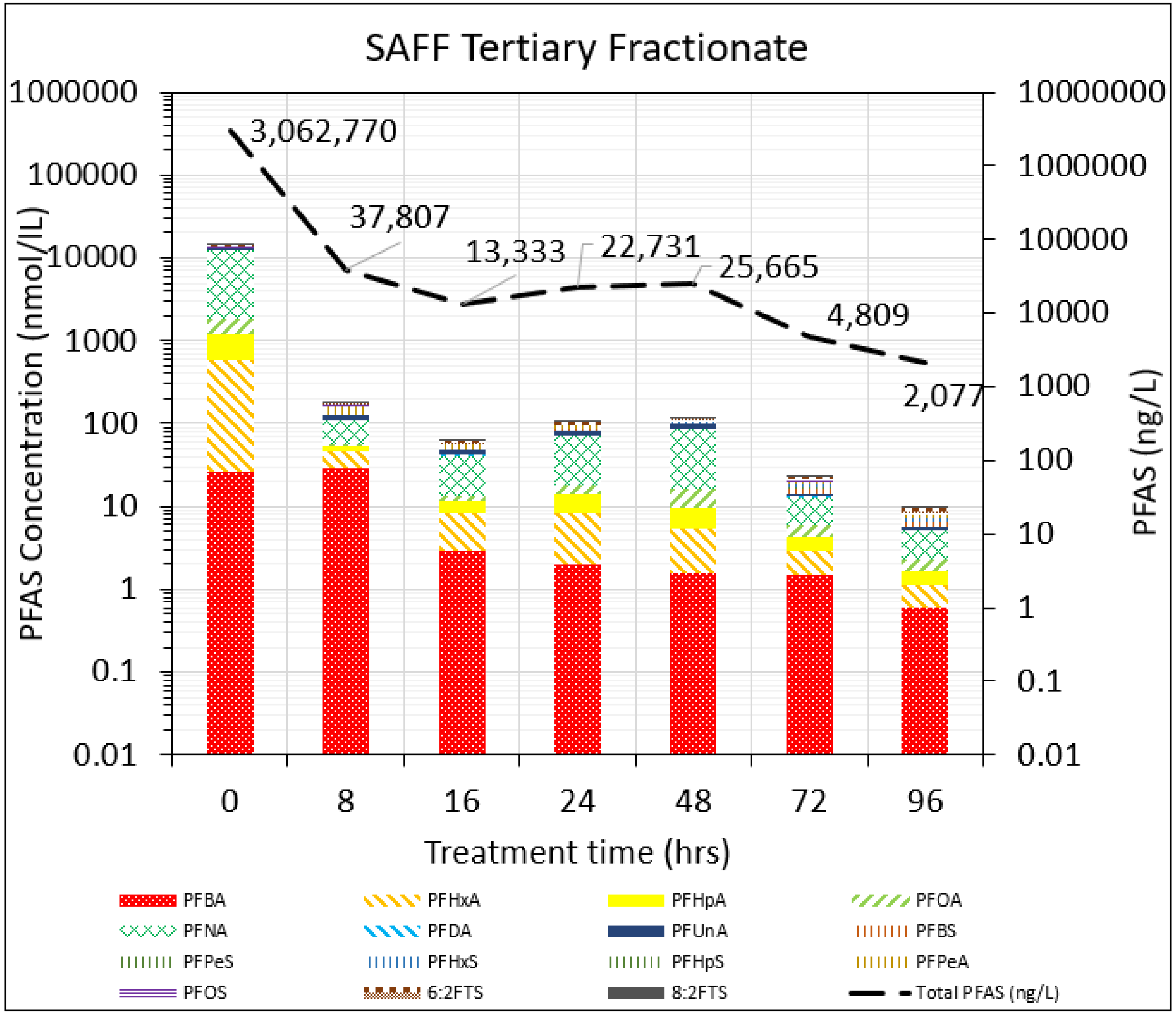
Pilot ECO System

- Proprietary electrodes
- Anti-scaling feature
- 3-8 GPM flow
- Adjustable power
- Gas detection sensor
- Leak detection system

Increases electrode surface area by >100X

Destruction of PFAS in SAFF Concentrates

- Secondary Fractionate removal rates: 100X – 10,000X
  - PFOS < 68 ng/L
  - PFOA < 14 ng/L
  - PFNA < 100 ng/L
  - 99% total fluorine removal (TOF)
- E_{EO} = 132 W-h/L
- Foaming agent – degraded/removed



Next Steps for Destructive Treatment Trains

- Demonstrate treatment effectiveness under variable conditions
- Obtain data to understand scalability and compatibility
- Compare technologies with different treatment streams to understand niches
- Develop effective automated controls for continuous operation
- Develop parameters to understand operations, maintenance and life-cycle costs
- Mitigate or manage undesirable by-products, such as HF, perchlorate and halogenated organics
- Optimize processes for a given PFAS stream

Q&A

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