PFAS Removal & Destruction

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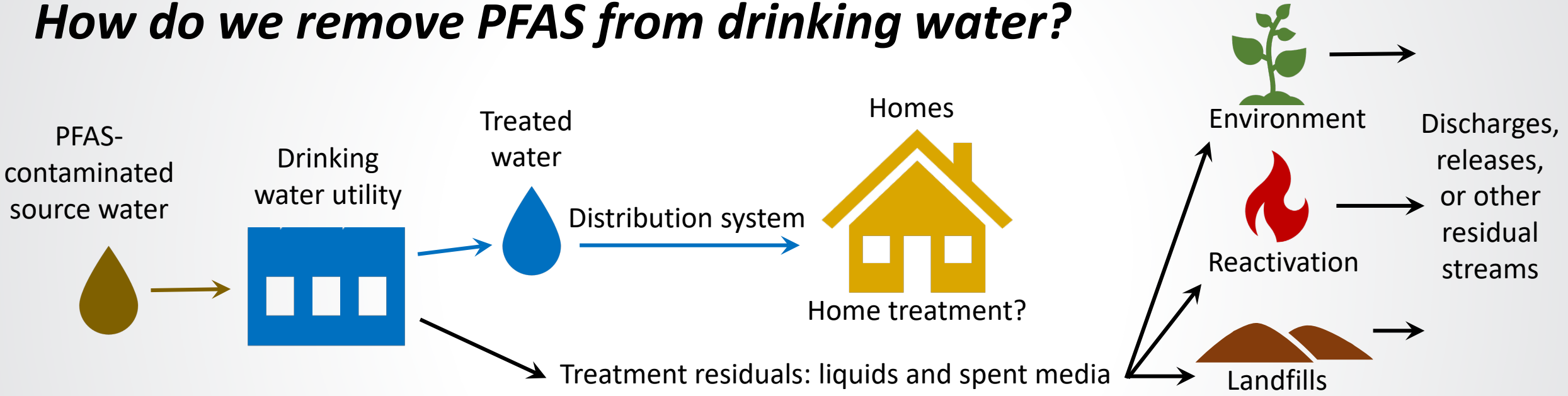
The views expressed in this presentation are those of the author and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

Drinking Water Treatment

How do we remove PFAS from drinking water?



Effective Treatment Technologies for PFAS

- Anion exchange resin, granular activated carbon (GAC), and membrane separation (RO) are generally effective at removing PFAS
- More effective for long-chain than short-chain PFAS
- Removal efficiencies and cost depend on source water characteristics and water system characteristics

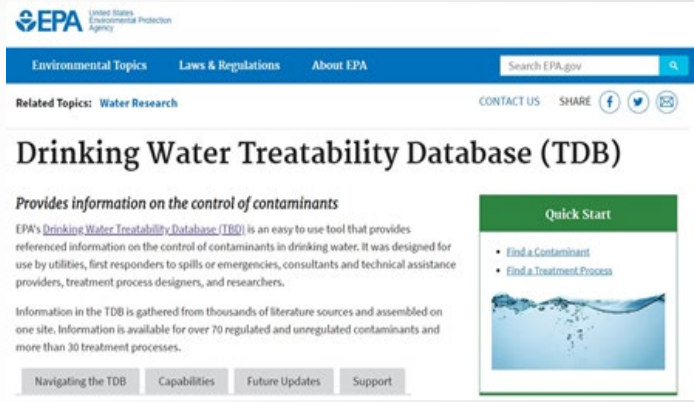
Treatment Residuals

- PFAS found in spent GAC and spent resin
- Spent media can be regenerated, landfilled, or incinerated with unknown releases of PFAS
- There are no known commercial treatments (mineralization) for RO concentrate streams or regenerant solutions

Treatment Information

Publicly Available Drinking Water Treatability Database

Interactive literature review database that contains more than 120 regulated and unregulated contaminants and covers over 35 treatment processes commonly employed or known to be effective (thousands of sources assembled on one site)



Currently available:

37 different PFAS
156 references

Contains treatment information to be used in performance or cost models

Updated yearly

Access EPA's Drinking Water Treatability Database.

Drinking Water Treatment for PFOS

Ineffective Treatments

- Conventional Treatment
- Low Pressure Membranes
- Biological Treatment (including slow sand filtration)
- Disinfection
- Oxidation
- Advanced Oxidation

PAC Dose to Achieve

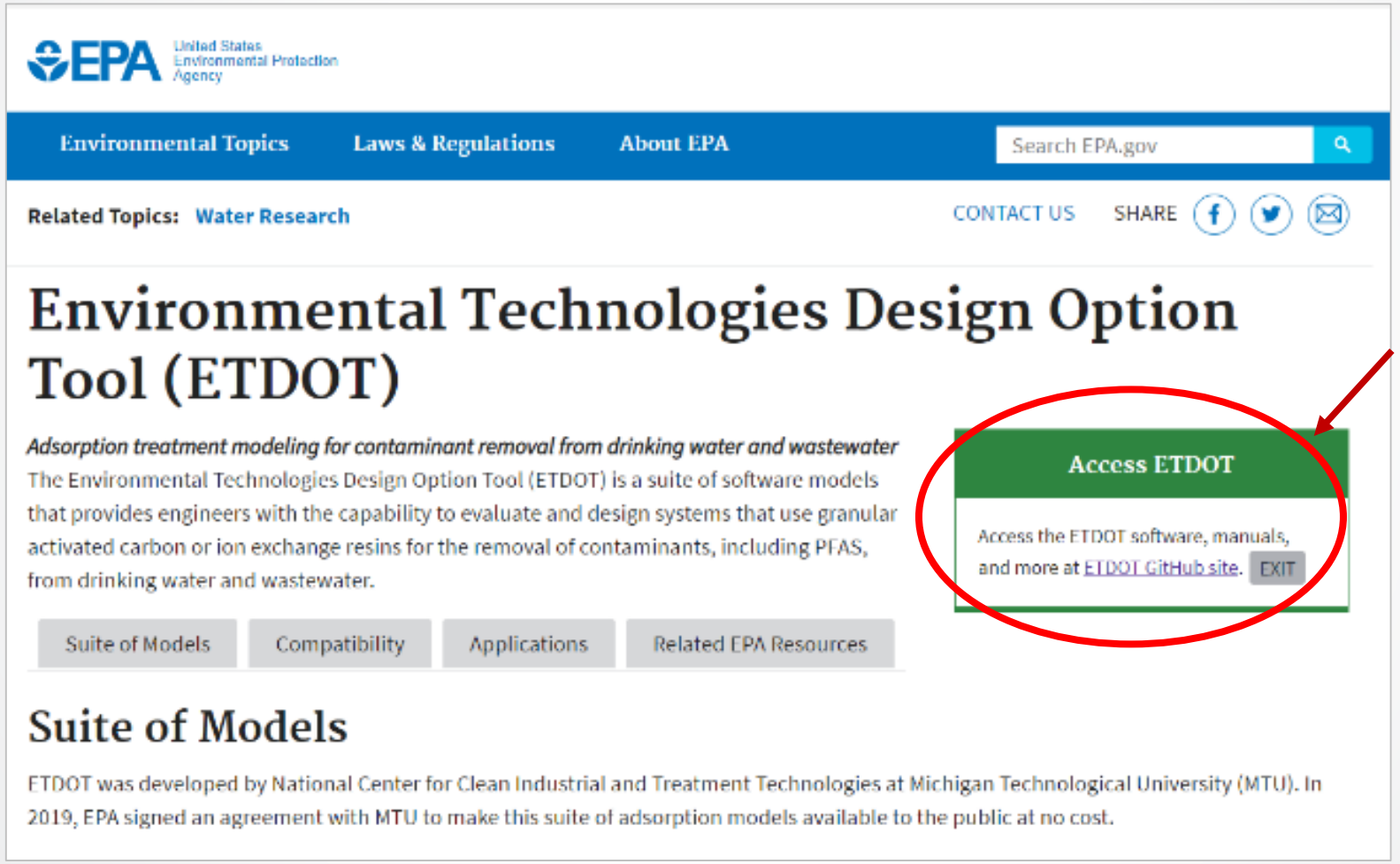
50% Removal	16 mg/l
90% Removal	>50 mg/L

Dudley et al., 2015

Effective Treatments

	Percent Removal	
Anion Exchange Resin (IEX)	90 to 99	- **Effective**
High Pressure Membranes	93 to 99	- **Effective**
Powdered Activated Carbon (PAC)	10 to 97	- **Effective for only select applications**
Granular Activated Carbon (GAC)		
• Extended Run Time	0 to 26	- **Ineffective**
• Designed for PFAS Removal	> 89 to > 98	- **Effective**

Available Modeling Tools



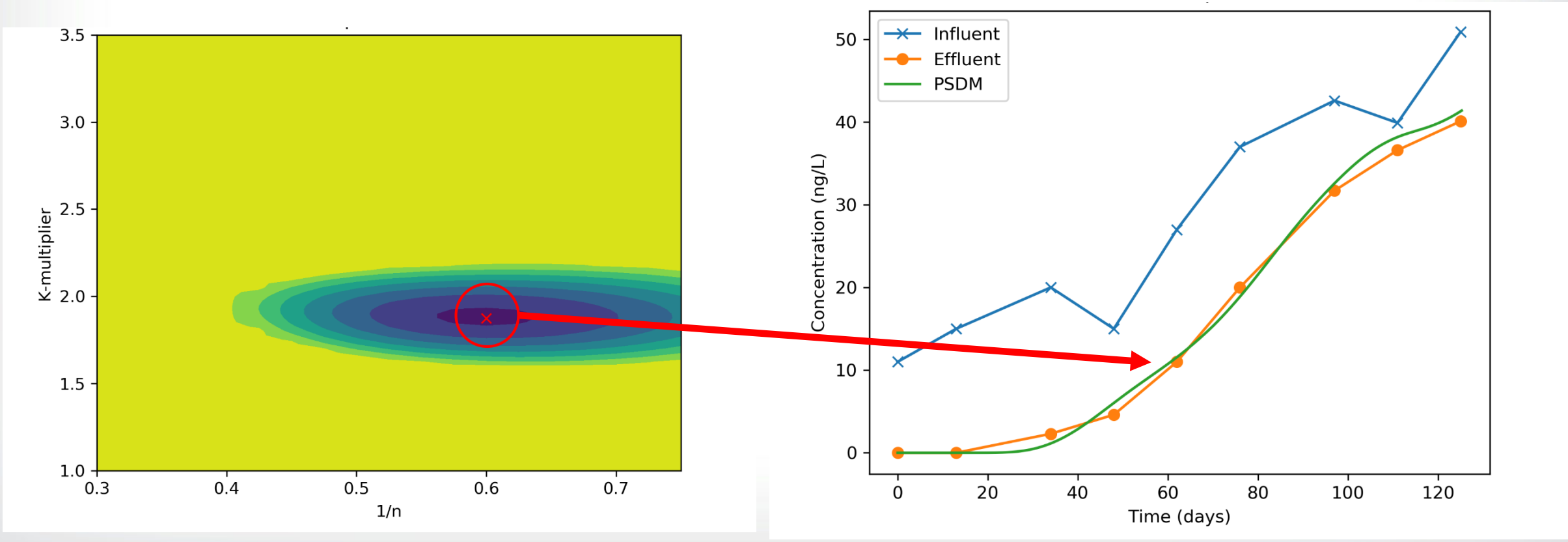
GitHub Site

[Access the Environmental Technologies Design Option Tool](#) **(ETDOT)** or search EPA ETDOT.

Model Fitting of Pilot Data

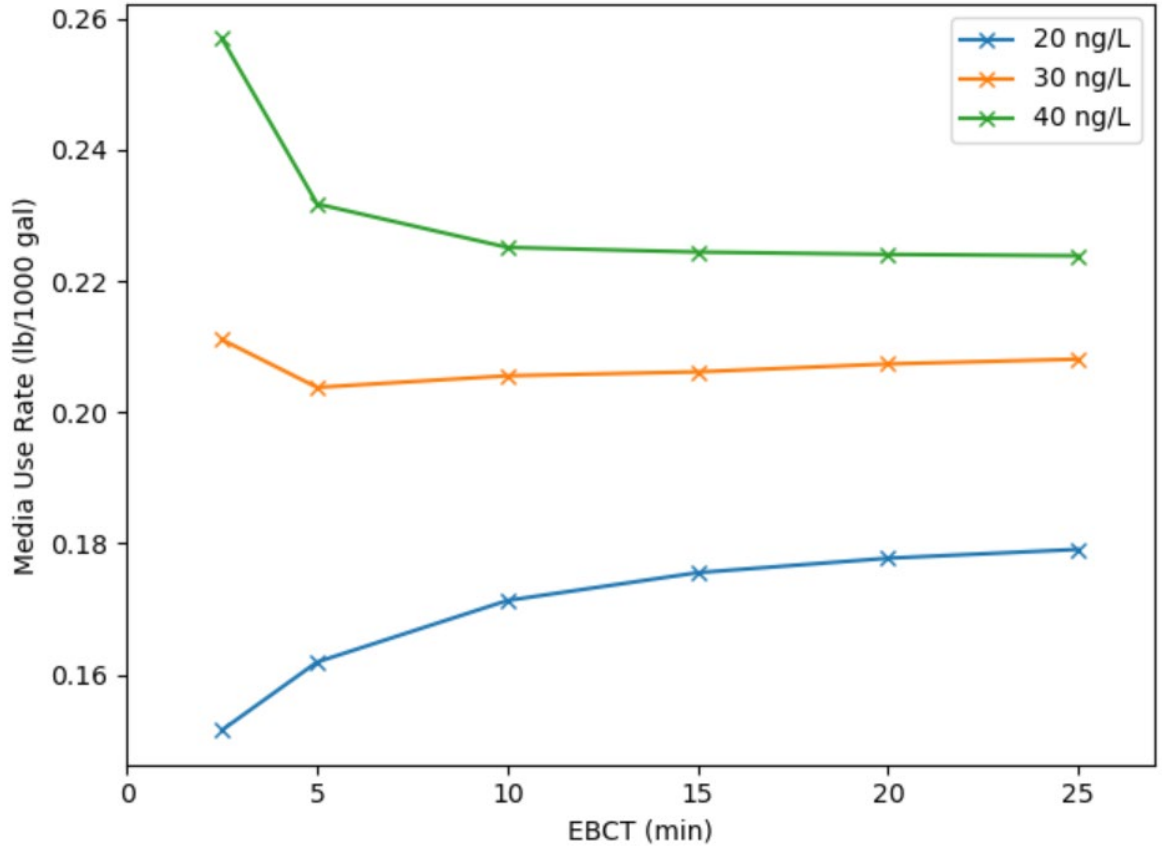
Automated Fitting

Automated fitting of Freundlich isotherm parameters based on field data:
doi.org/10.1061/(ASCE)EE.1943-7870.0001964

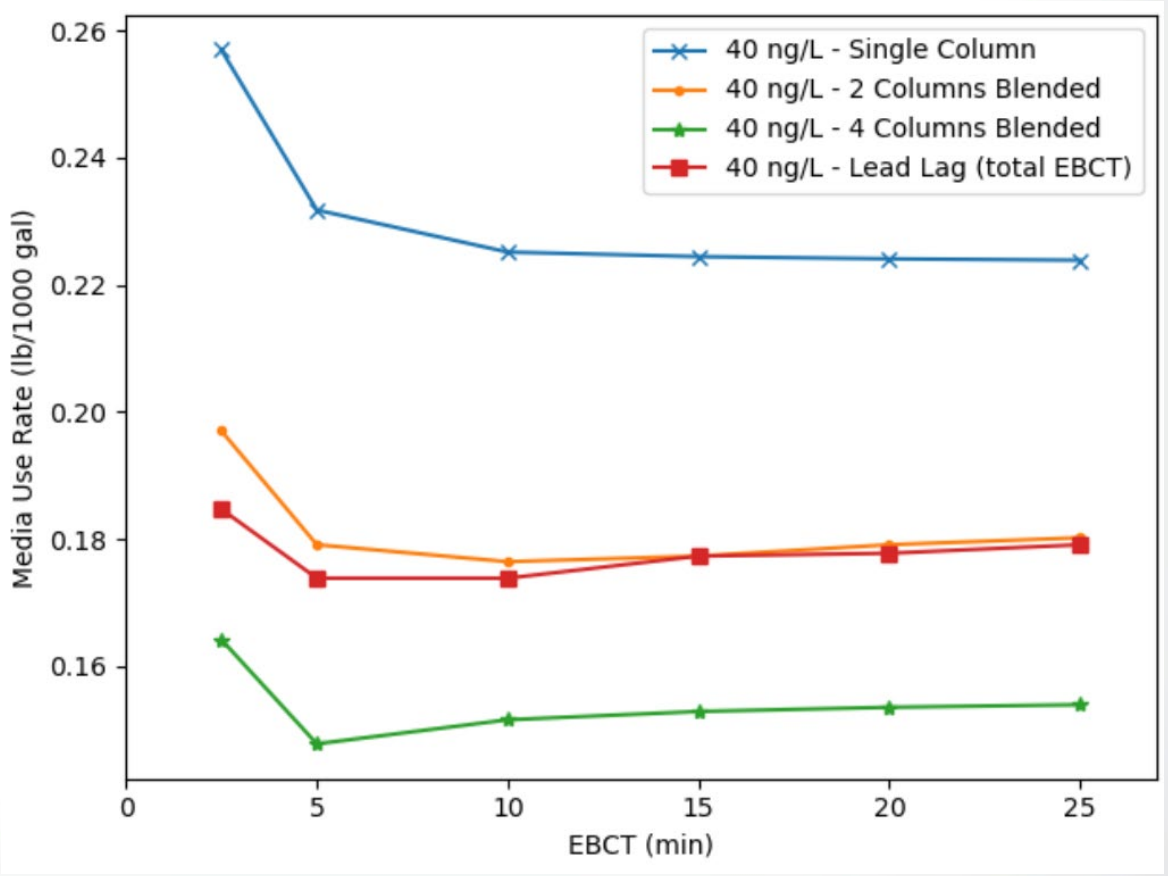


Predicting Operating Conditions

Impact of Influent Concentration on GAC Use Rate

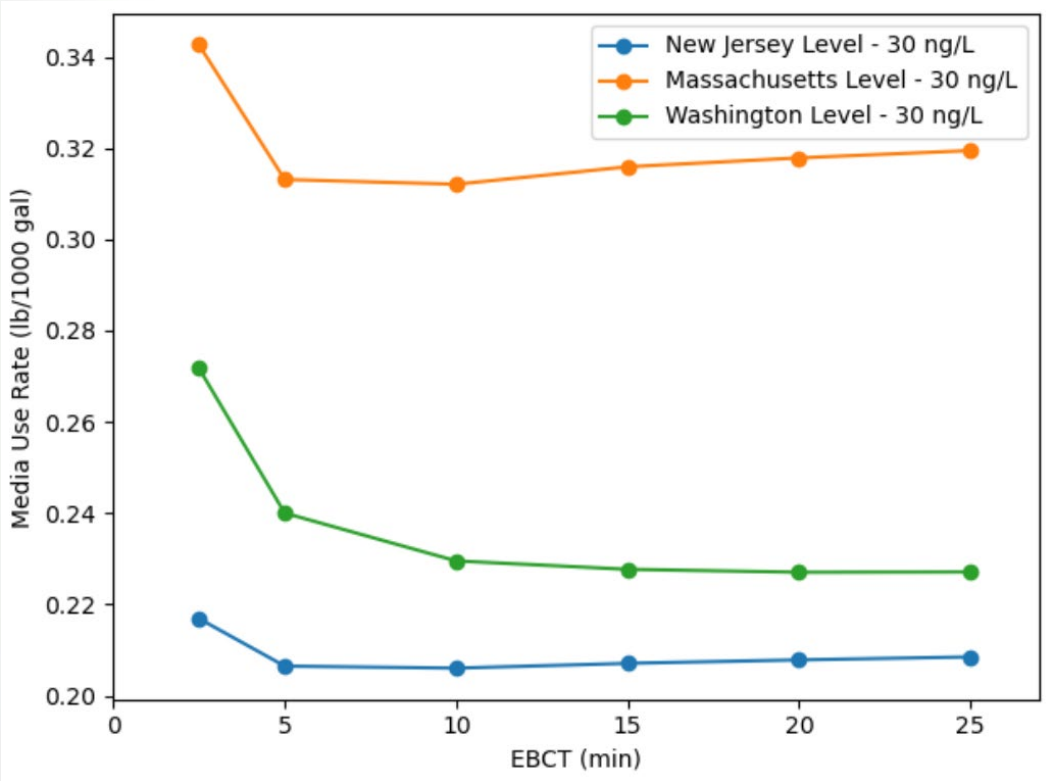


Impact of Column Configuration on GAC Use Rate

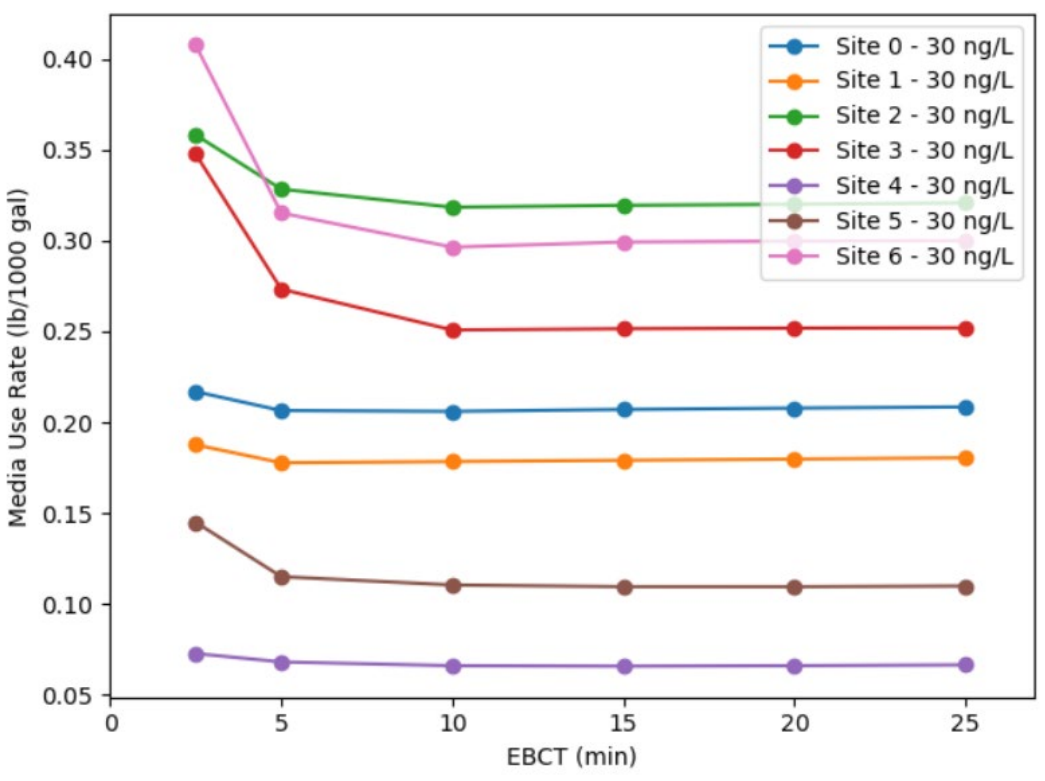


Multi-Site Considerations

Same System – Different State Levels (Reg. or AL)

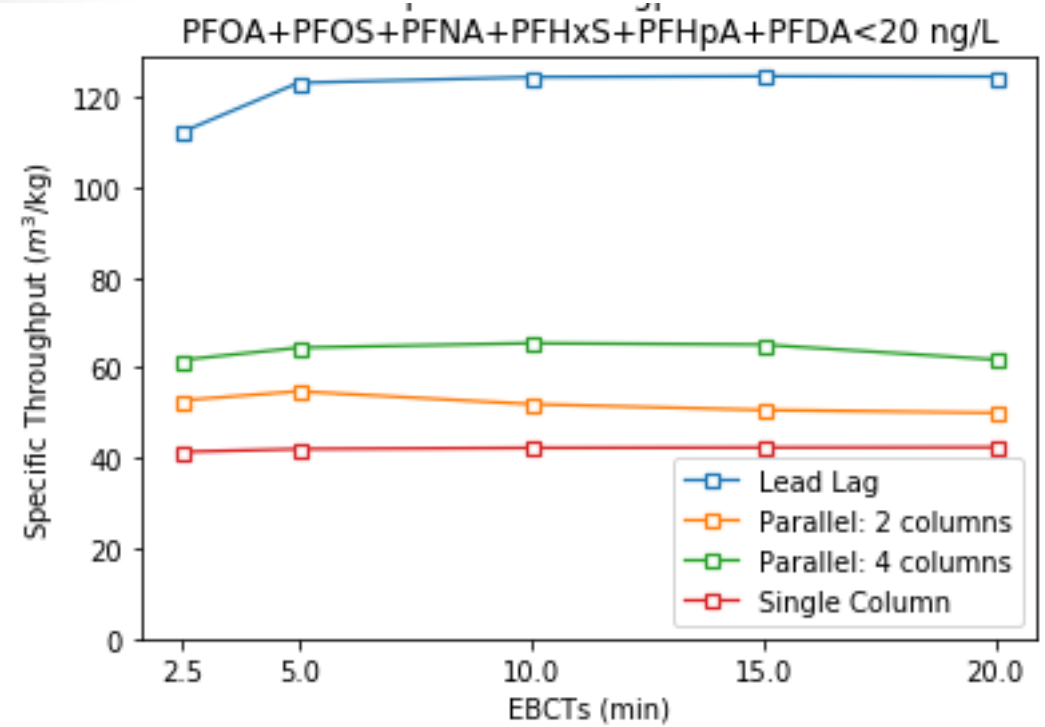


Same State Level – Different Site Effective Capacities

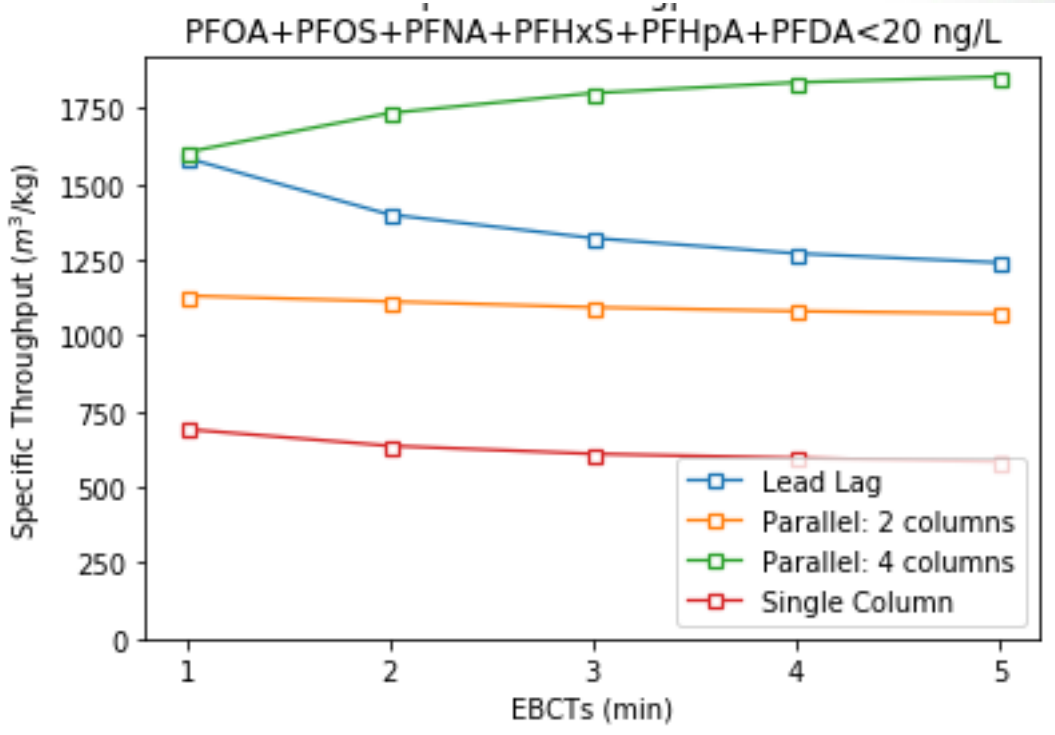


Comparing Various Configurations

GAC



IX



EPA's Drinking Water Cost Models

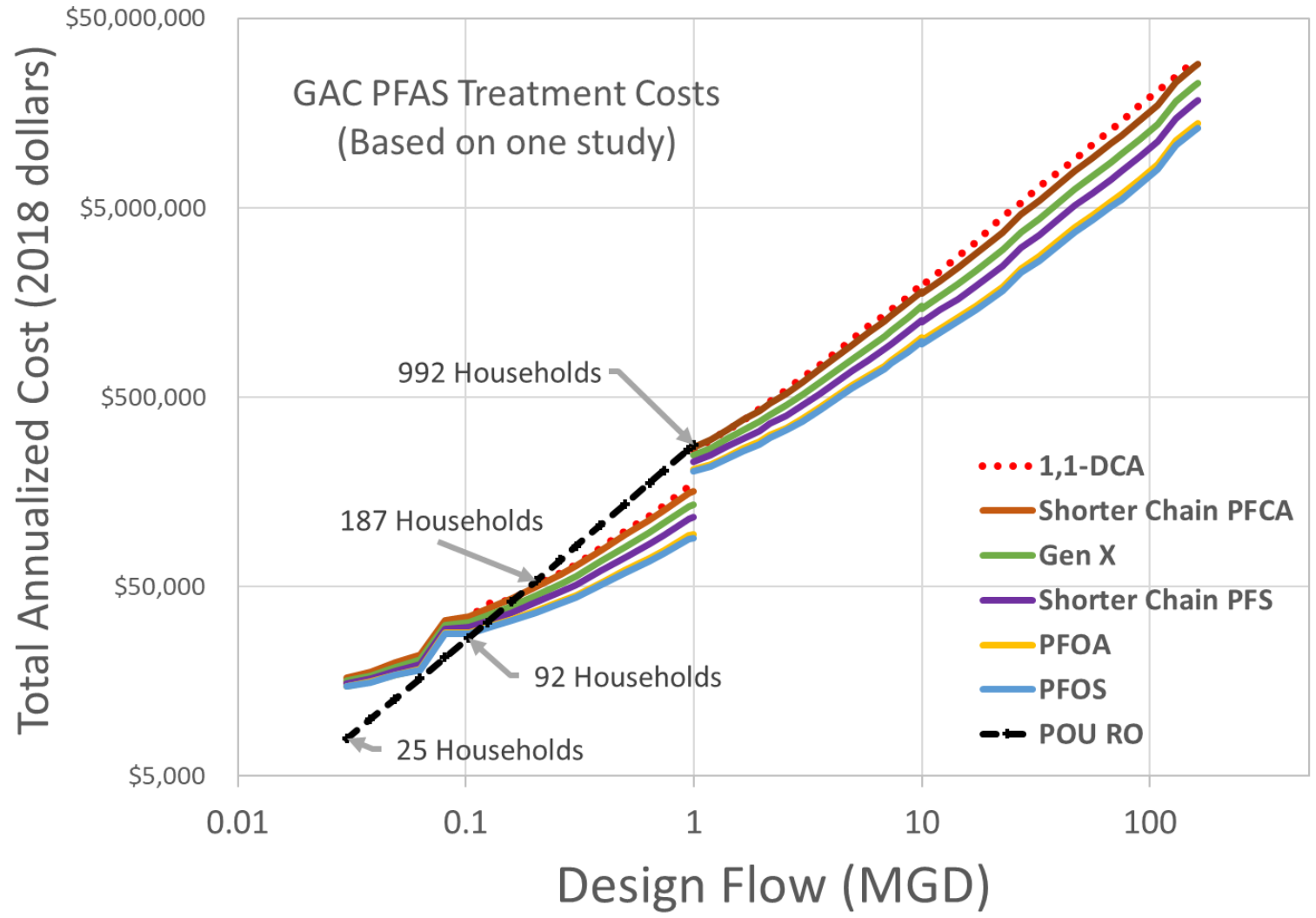
- Adsorptive media
- **Anion exchange***
- Biological treatment*
- Cation exchange
- **GAC***
- Greensand filtration
- Microfiltration / ultrafiltration
- Multi-stage bubble aeration*

- Non-treatment
- Packed tower aeration
- **POU/POE#**
- **Reverse Osmosis / Nanofiltration**
- UV disinfection
- UV Advanced Oxidation

***Search: EPA WBS** https://www.epa.gov/sdwa/drinking-water-treatment-technology-unit-cost-models

 # For POU/POE search: EPA small system compliance help
http://water.epa.gov/type/drink/pws/smallsystems/compliancehelp.cfm

Costs for PFAS Treatment: One GAC Example



Costs can be generated for various sizes, contaminants, and even POU scenarios

Primary Assumptions:

- Two vessels in series
- 20 min Empty Bed Contact Time (EBCT) Total
- Bed Volumes Fed
  - 1,1-DCA = 5,560 (7.5 min EBCT)
  - Shorter Chain PFCA = 4,700
  - Gen-X = 7,100
  - Shorter Chain PFS = 11,400
  - PFOA = 31,000
  - PFOS = 45,000
- 7% Discount rate
- Mid-level cost

Destruction Technologies for Water Streams

Incineration (limited liquid sources)

Pyrolysis (limited liquid sources)

Granular activated carbon reactivation

Supercritical water oxidation

Hydrothermal liquefaction

Hydrothermal oxidation

Sub-critical water oxidation

Plasma

Sono-chemical oxidation

Zero-valent iron

Electron beam

Solvated electrons

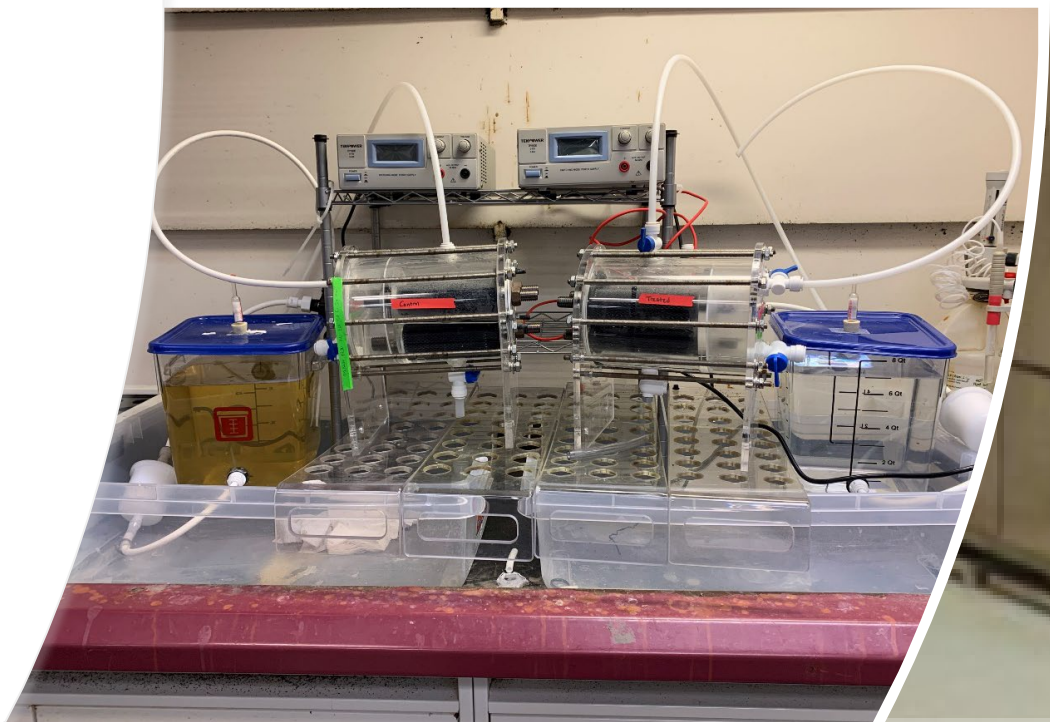
Advanced oxidation

Photocatalysis

Ultraviolet irradiation

Activated persulfate

Biological



Thermal Destruction Technologies

Incineration (limited liquid sources)

Pyrolysis (limited liquid sources)

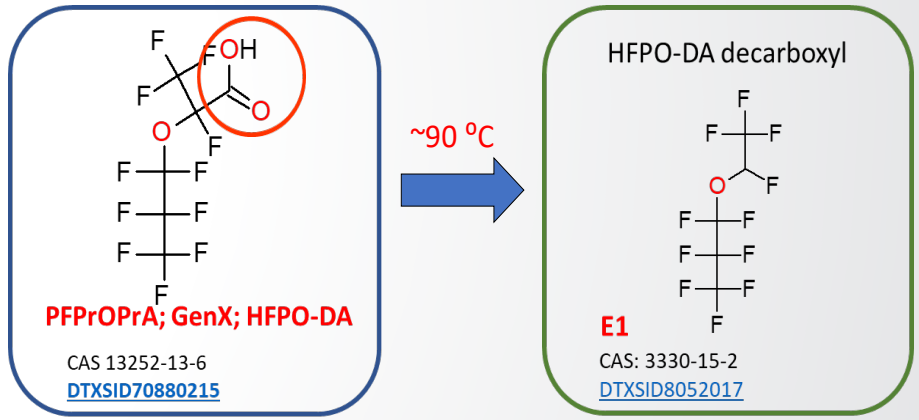
Granular activated carbon reactivation

Example Liquid PFAS Sources for Thermal Processes

- Wastewater biosludge and biosolids
- Aqueous film forming foam (AFFF)- concentrate, spent AFFF
- Landfill leachate
- Other low volume liquid/sludge streams
- Spent granular activated carbon, anion exchange resins

Challenges of Thermal Treatment of PFAS

- **Complicated chemistry -** Greater than 4,700 produced/used since 1950
- Efficacy of thermal treatment
  - Highly electronegative F makes C-F bonds particularly strong, requiring high temperatures for destruction
    - CF_4 requires 1,440 °C for >1 sec to achieve 99.99% destruction (Tsang et al., 1998)
    - CF_4 and C_2F_6 may be a useful surrogates (Krug et al., 2022)
    - Inhibited flame propagation
  - Field data are lacking
  - Historical laboratory research on "destructibility" lacks information about products of incomplete combustion (PICs)
    - PICs from F radicals more likely than for other halogens
  - Emission sampling and analytical methods are under development
    - Volatile, non-volatile, polar, non-polar
    - Limited number of analytical standards available



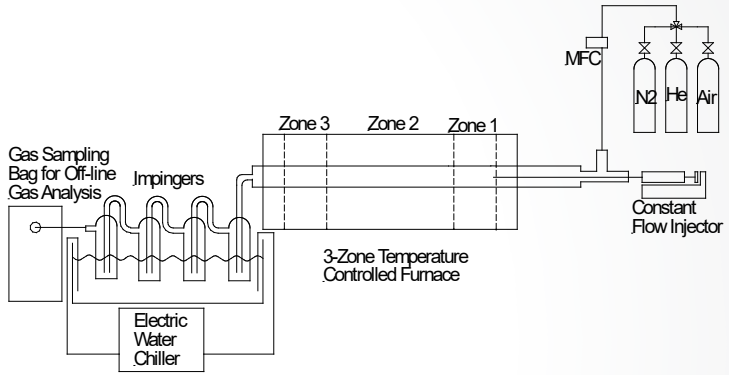
Wastewater Sludge Incineration

Goal: determine PFAS fate during wastewater treatment and sewage sludge incineration

Action:

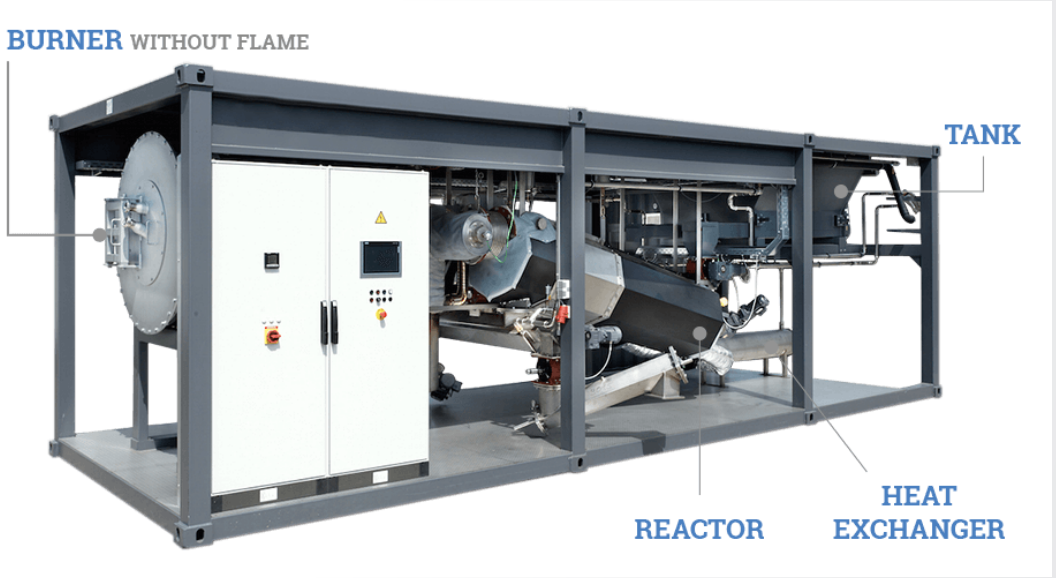
- Bench-scale work being conducted with NIST domestic sludge Standard Reference Material 2781.
- Full-scale sampling event to sample solids/liquids along treatment process and gas-phase emissions from sludge incineration
  - Targeted analysis for most common PFAS compounds
  - Non-targeted analysis for products of incomplete combustion (PICs)
  - Further develop sampling methods

Impact: waiting on analytical results, serves as a model for future studies



Pyrolysis of Biosolids

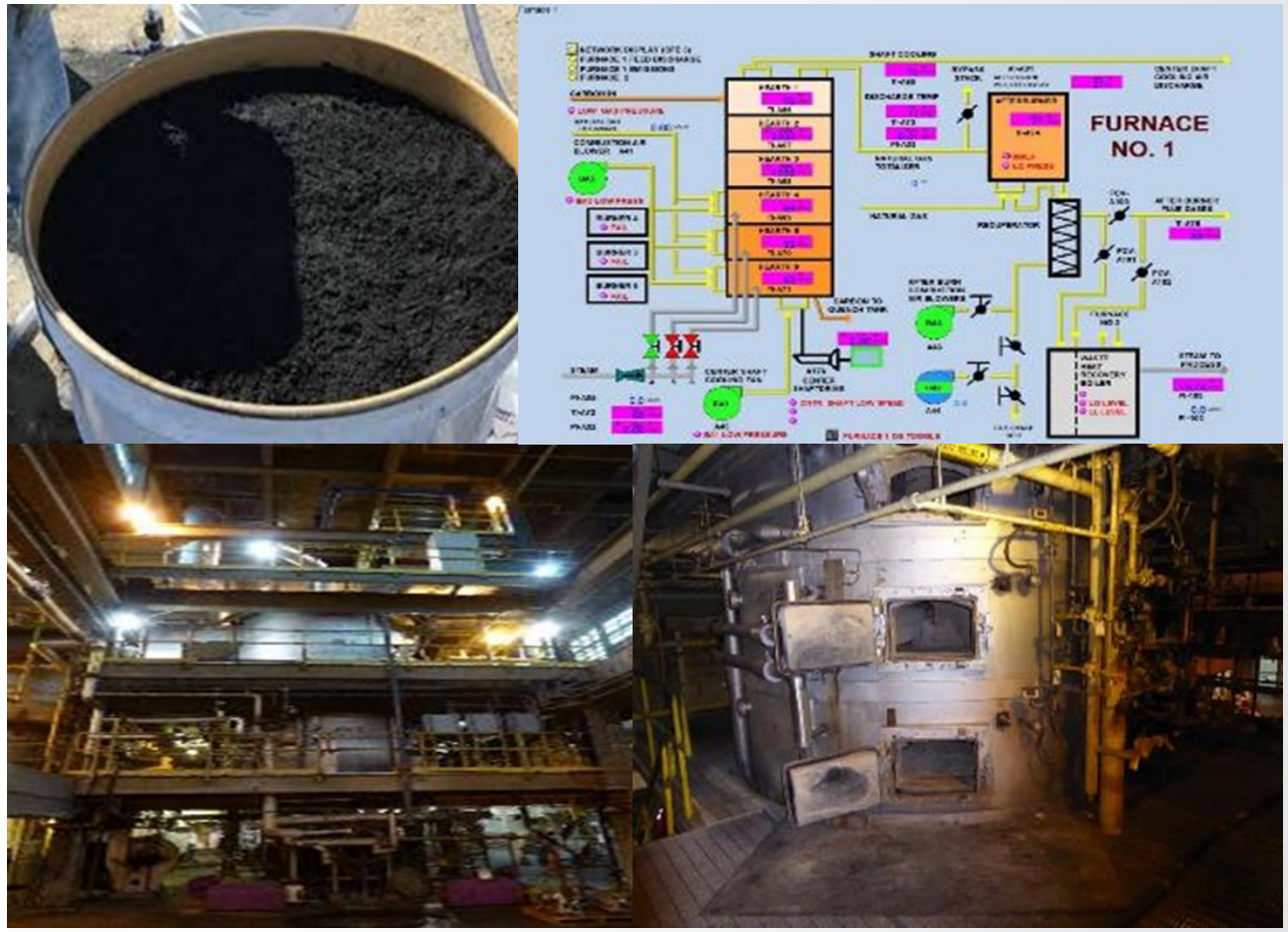
- San Francisco, CA field study with BioForceTech
- Facility not known to be impacted by PFAS (chosen for operating tech)
- FTIR analysis for fluorine in gas-phase (no tracer used)
- Limited scope: analyzed PFAS in influent (biosolids) and effluent (biochar)
- Thoma et al., 2022



Source: https://www.bioforcetech.com/

Granular Activated Carbon (GAC) Reactivation

- GAC used in water treatment for PFAS removal, then either incinerated or reactivated for repeated use
- Bench-scale research
  - Efficient decomposition (>99.9%) of PFOA and PFOS on GAC occurred at 700 °C or higher, accompanied by high mineralization of fluoride ions (>80%). *Xiao et al., 2020.*
  - Additional research being completed at North Carolina St. in conjunction with SERDP
- Pilot study completed
  - Waiting on results
- Searching for partners to evaluate full-scale carbon reactivation facilities



Spent Resin: Cement Kiln Incineration

Cement kilns are operated under different operating conditions

- Gas temperatures of up to ~2,000 °C
- Gas residence times of up to 10 seconds
- Solid residence time of up to 30 minutes

EPA is actively looking for partners for sampling of cement kiln incinerators

Source: Purolite presentation and case study. F. Boodoo et al.

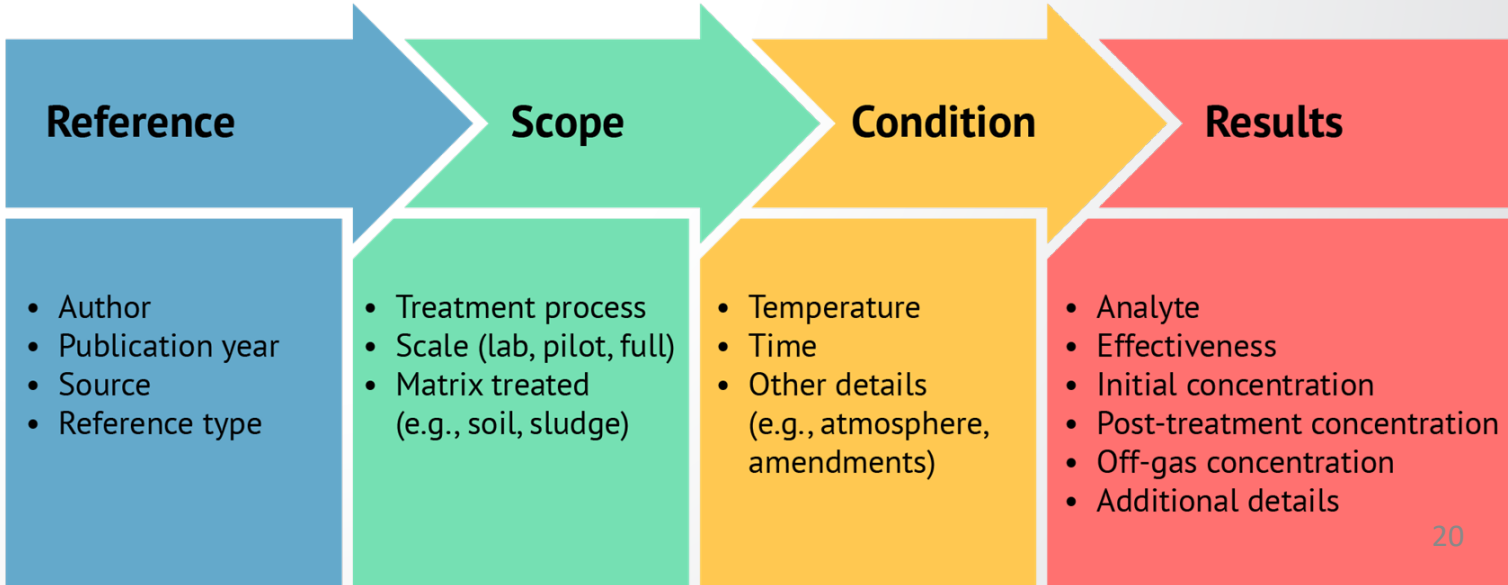
Thermal Treatment Database

- The PFAS Thermal Treatment Database (PFASTT) is a publicly-available database that contains over 2,000 records of 80 sources documenting the treatability of PFAS in different media via various thermal processes.
- Sources cited in the database include peer reviewed and non-peer reviewed journals, government reports, conference reports, and other types of publications.

Focuses on…

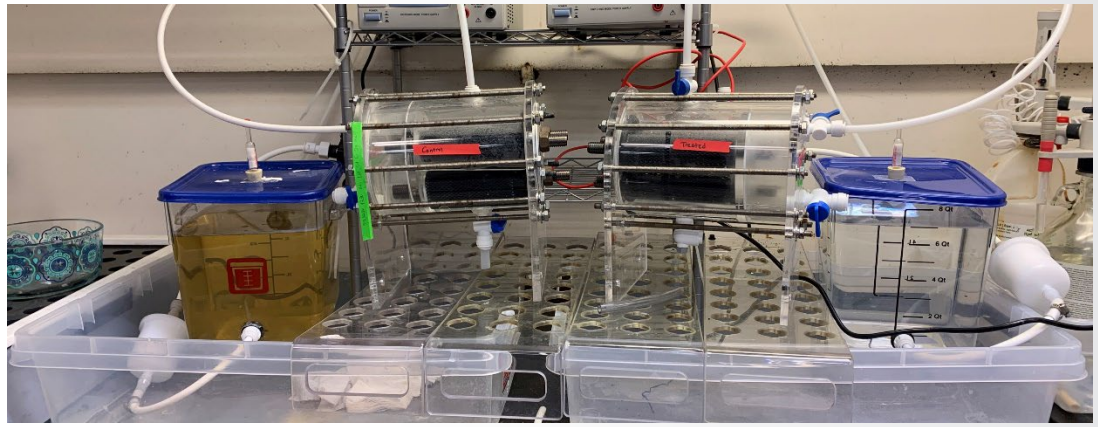
- Calcining
- Granular activated carbon reactivation
- Gasification
- Hydrothermal
- Incineration
- Indirect thermal desorption
- Pyrolysis
- Smoldering

https://pfastt.epa.gov/



Non-Thermal Destruction Technologies

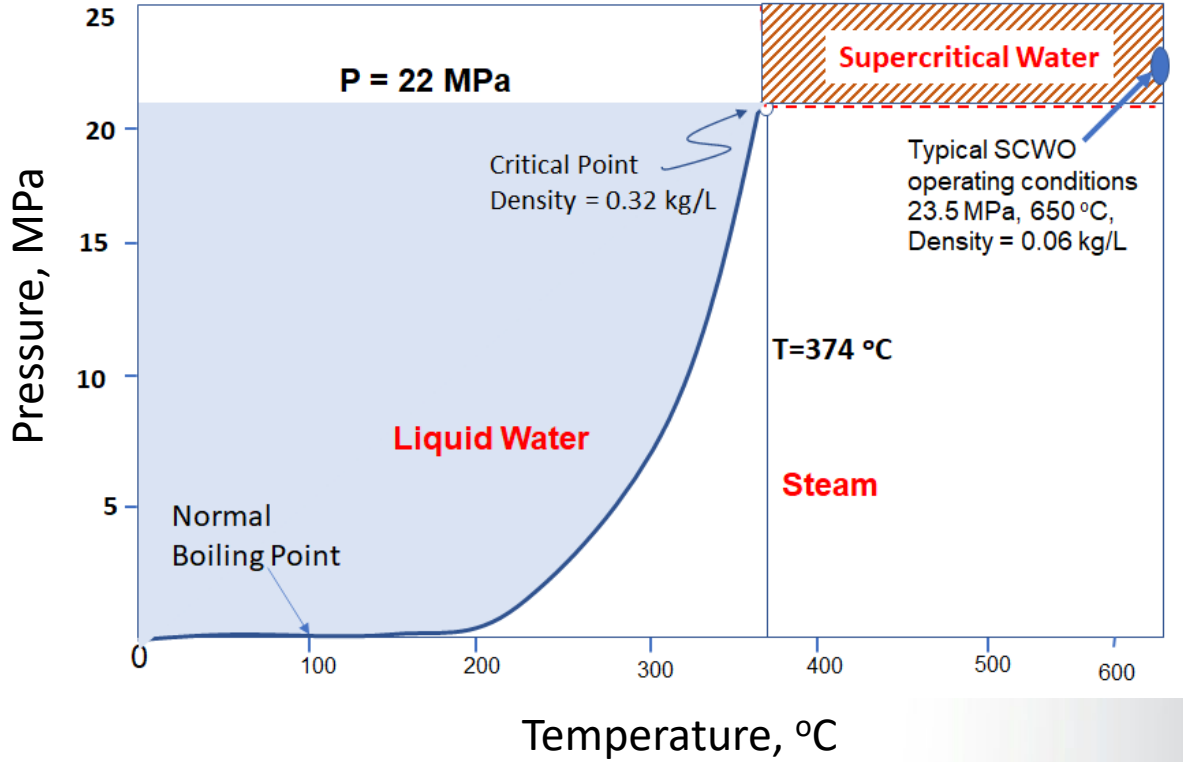
- Supercritical water oxidation
- Hydrothermal liquefaction
- Hydrothermal oxidation
- Sub-critical water oxidation
- Plasma
- Sono-chemical oxidation
- Zero-valent iron
- Electron beam
- Solvated electrons
- Advanced oxidation
- Photocatalysis
- Ultraviolet irradiation
- Activated persulfate
- Biological

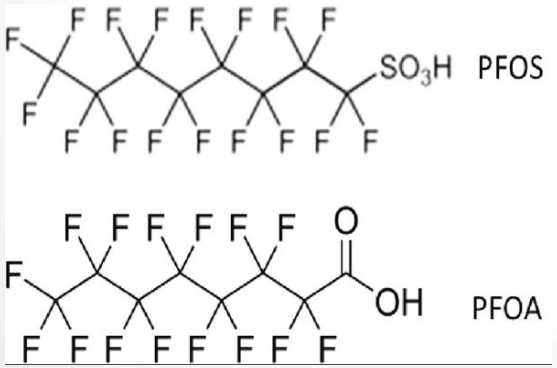


Source: https://aquarden.com

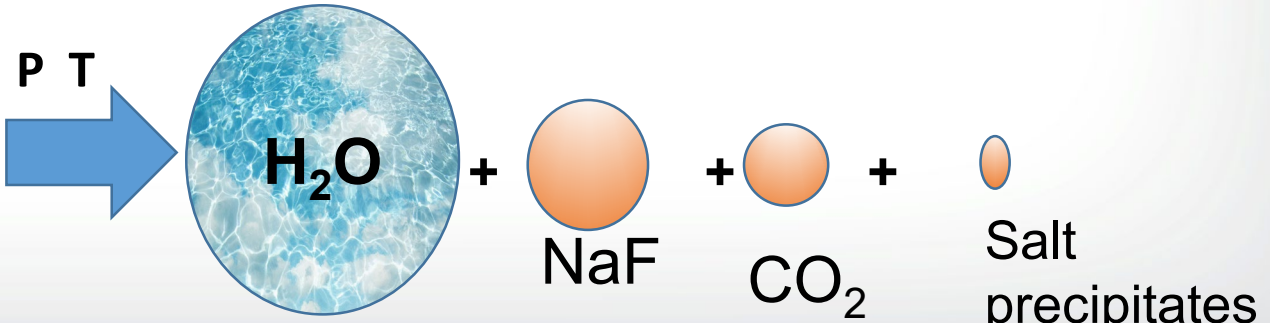
Supercritical Water Oxidation (SCWO) of PFAS

- Short residence time (< 10 sec) is required
- Can handle high feed concentrations and organic co-contaminates
- Relatively low operating temperatures → does not generate SOx, NOx
- Generates little waste





\+ Oxidant
NaOH
(Neutralization)



Supercritical Water Oxidation (SCWO)

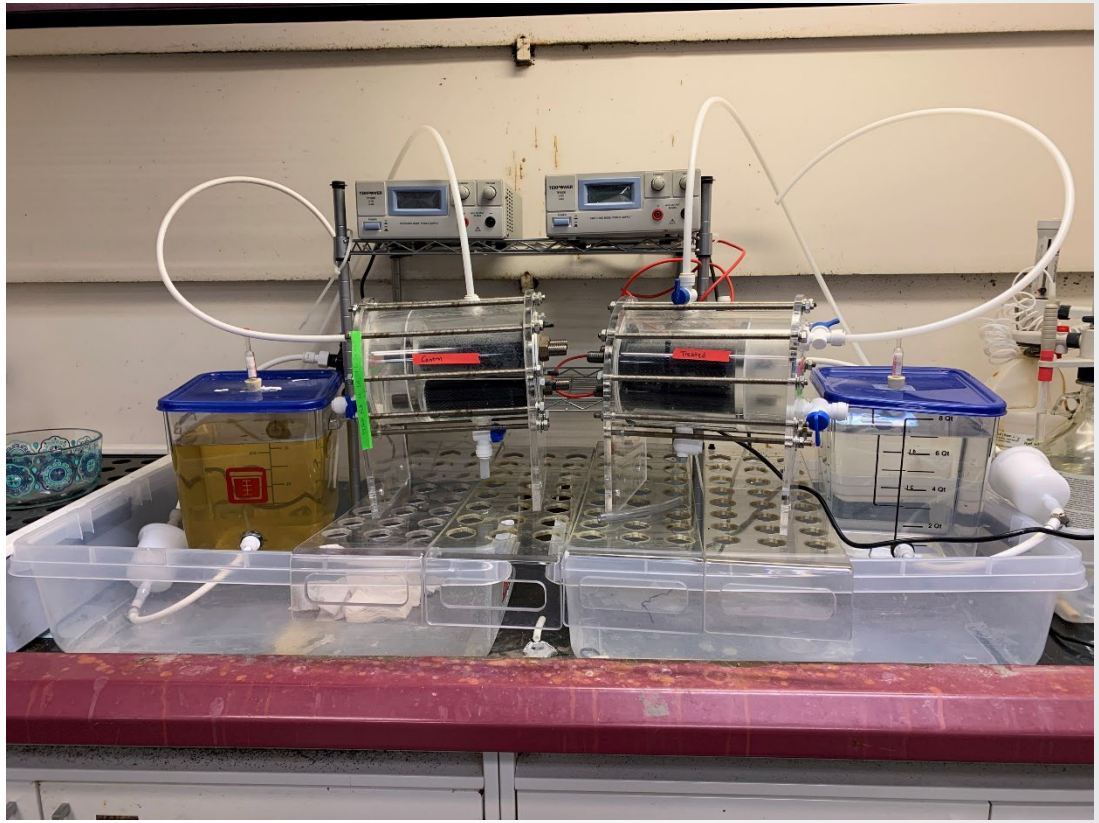
- Case studies performed with four separate SCWO operators
  - Aquarden (Denmark)
  - 374Water (Durham, NC)
  - Battelle (Columbus, OH)
  - General Atomics (San Jose, CA)
- Tested SCWO on dilute AFFF
- Analyzed for PFAS, TOF, fluoride, and COD
  - Some gas-phase PFAS sampled w/General Atomics
- Results showed greater than 99% reduction of the targeted PFAS Krause et al., 2022

Source: https://aquarden.com

Source: https://www.ga.com

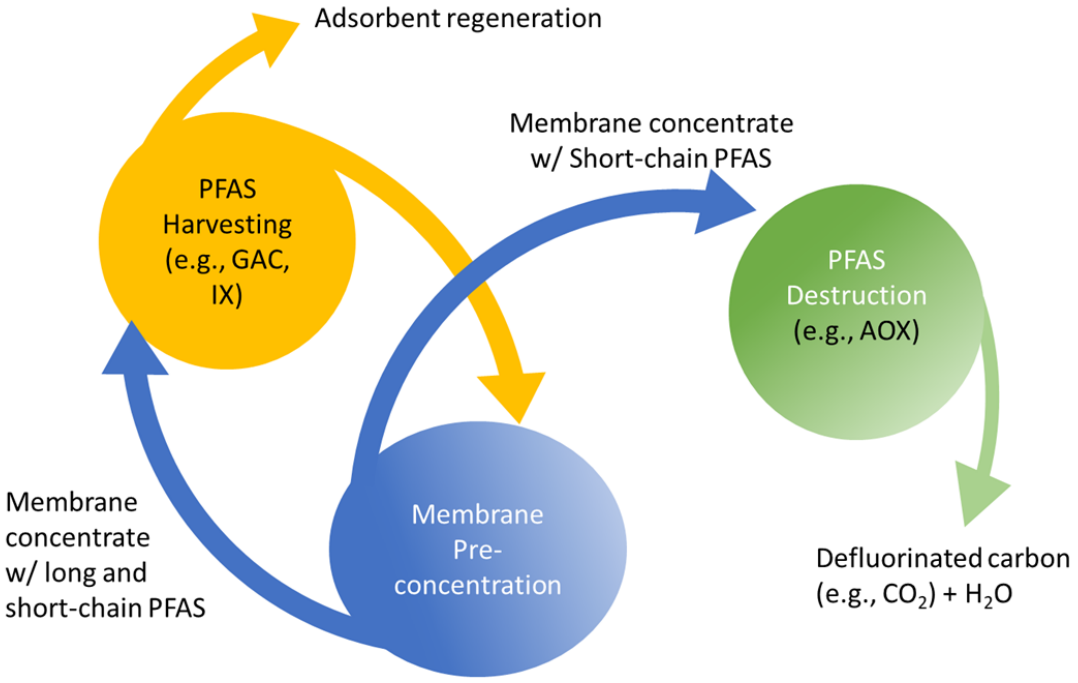
Electrochemical Oxidation

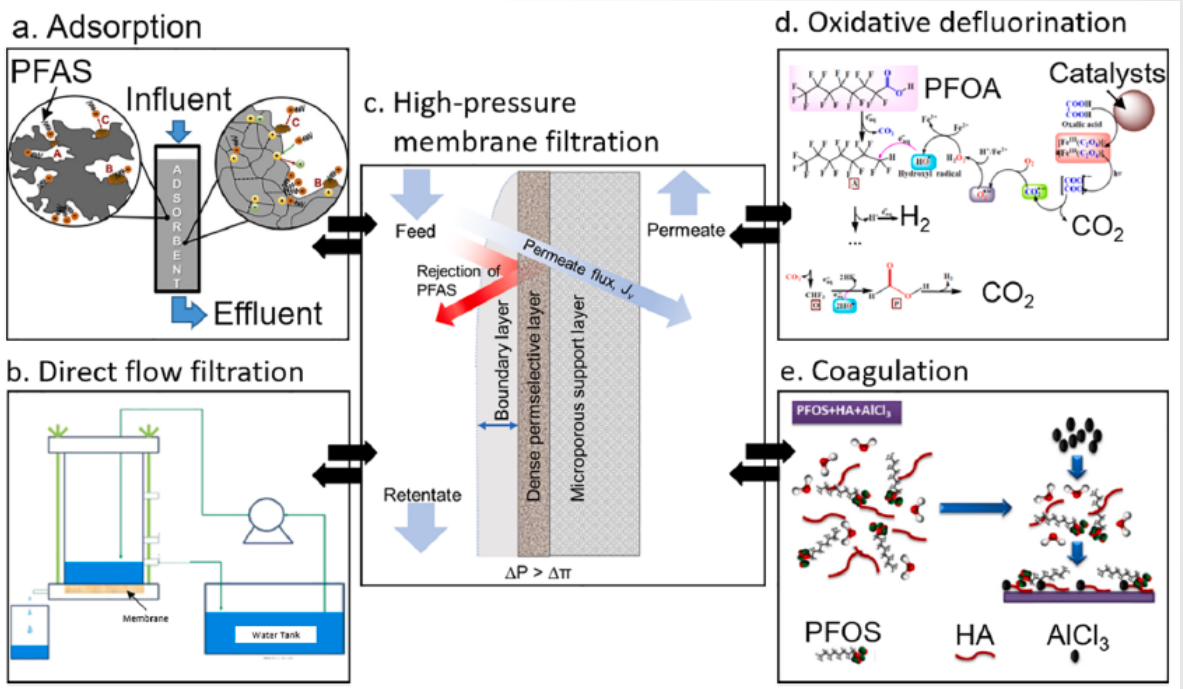
- In conjunction with AECOM
- Site visit and lab-scale experiment
- Tested EO on high-PFAS wastewater (AFFF)
- Analyzed for 24 PFAS, total adsorbable organofluorine (TOF), fluoride, and chemical oxygen demand (COD)
- Results to be published 2023



Source: Max Krause (2020)

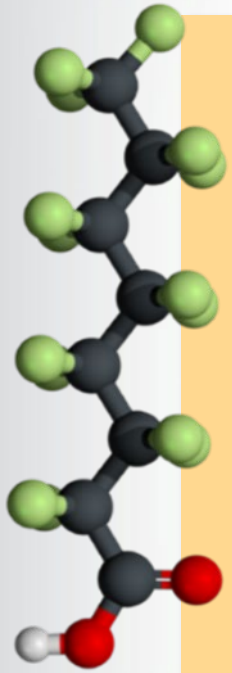
RO in combined system (RO/GAC/AOX)





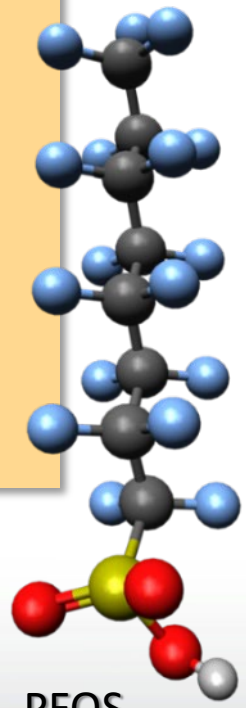
Likely very expensive, but combined (hybrid) system approach can be complementary or overcome treatment shortcomings

Water Infrastructure Technical Assistance Project



PFOA

To support states, tribes, territories, and communities **to identify and implement cost-effective treatment of emerging contaminants, with a focus on PFAS**



PFOS

The project is in direct support of the Drinking Water State Revolving Fund (DWSRF) as authorized by the Bipartisan Infrastructure Law. It will:

- Promote optimal/efficient use of DWSRF resources through:
  - Direct technical support
  - Development of "best practices" guides and performance/cost estimating tools to support communities using DWSRF resources in the future
- Include public water systems serving small, underserved, and/or disadvantaged communities from different regions of the U.S.
- Sample for years to generate long-term performance and cost data
- Work with states and communities to identify and apply appropriate treatment optimization tools
- Link data, materials, and tools to EPA's Drinking Water Treatability Database to facilitate future use

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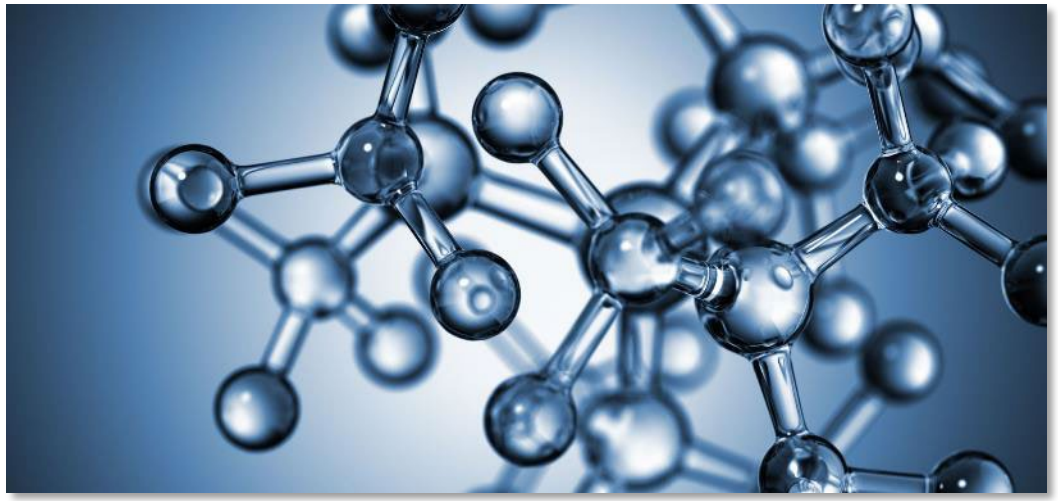
QUESTIONS?



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EPA PFAS Activities – www.epa.gov/pfas

PFAS Research and Development – www.epa.gov/chemical-research/research-and-polyfluoroalkyl-substances-pfas