MINNESOTA POLLUTION CONTROL AGENCY

PFAS Treatment Technologies

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Today's Speakers

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- ✓ Supporting clients, including MPCA, with PFAS since 2008
- ✓ Wood's PFAS Work Group Lead and has supported PFAS projects in 32 different states in 9 of the 10 USEPA regions as well as in Europe, Australia and Canada
- ✓ ITRC PFAS AFFF subgroup co-lead and PFAS AFFF and Risk Communication trainer
- ✓ NFPA Research Foundation, Project Technical Panel, Fire Fighting Foams: Fire Service Road Map

Dora Chiang, Ph.D., P.E.

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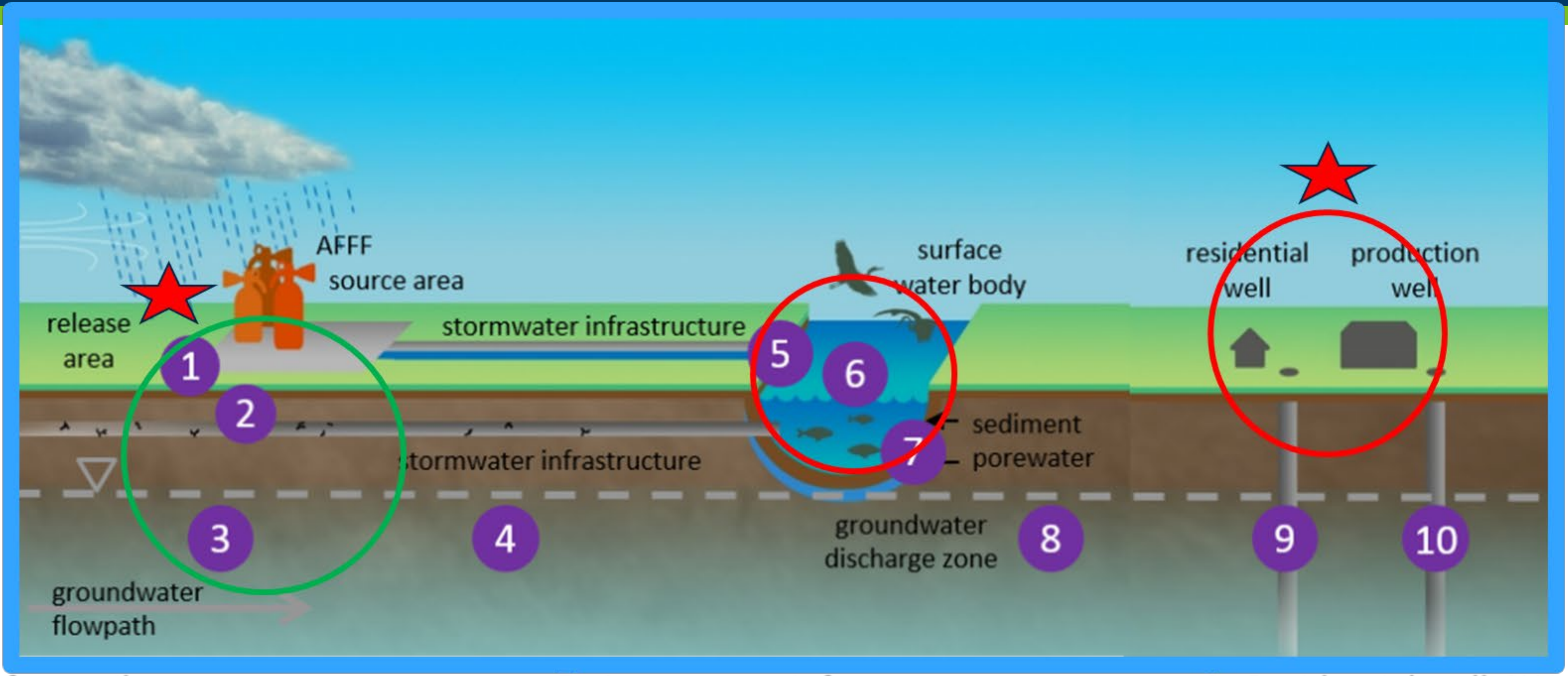
- ✓ Characterize and remediate PFAS since 2012
- ✓ PFAS practice leader for AECOM and CDM Smith between 2015-2021. Inventor of AECOM DeFluoro™ technology (patent pending)
- ✓ ITRC PFAS training subgroup co-lead and PFAS treatment technology trainer
- ✓ +100 PFAS presentations globally and 10+ peer reviewed publications on PFAS investigation and treatment
- ✓ Emerging PFAS treatment technology development and demonstration for Electrochemical oxidation, Supercritical water oxidation, Foam fractionation, Plasma destruction, Enzymatic degradation, Biodegradation, RemBind

Considerations on What to Treat



1. Surface soil
2. Subsurface soil
3. Source area GW
4. Downgradient GW containment
5. Stormwater infrastructure containment
6. Surface water
7. Sediment
8. Offsite GW impacted by surface water
9. Residential well GW treatment
10. Production well GW treatment

Agenda

- Drinking Water Treatment Updates
- Remediation Technology Updates
- Destruction Technologies
- Technology Selection and Closing Remark

Drinking water technologies Updates

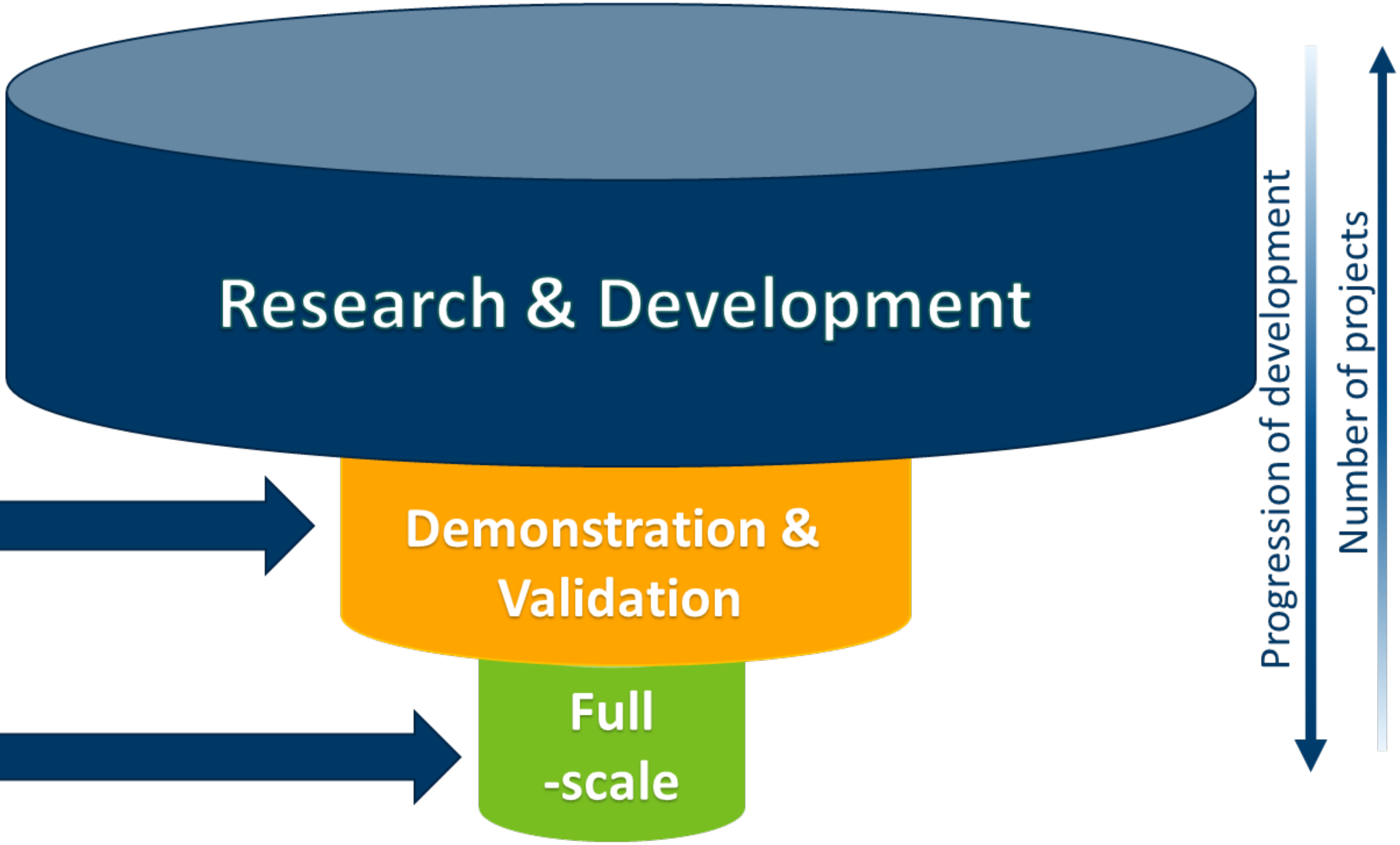
PFAS Treatment Technology Maturity for **Drinking Water** Treatment

How does technology move through development?

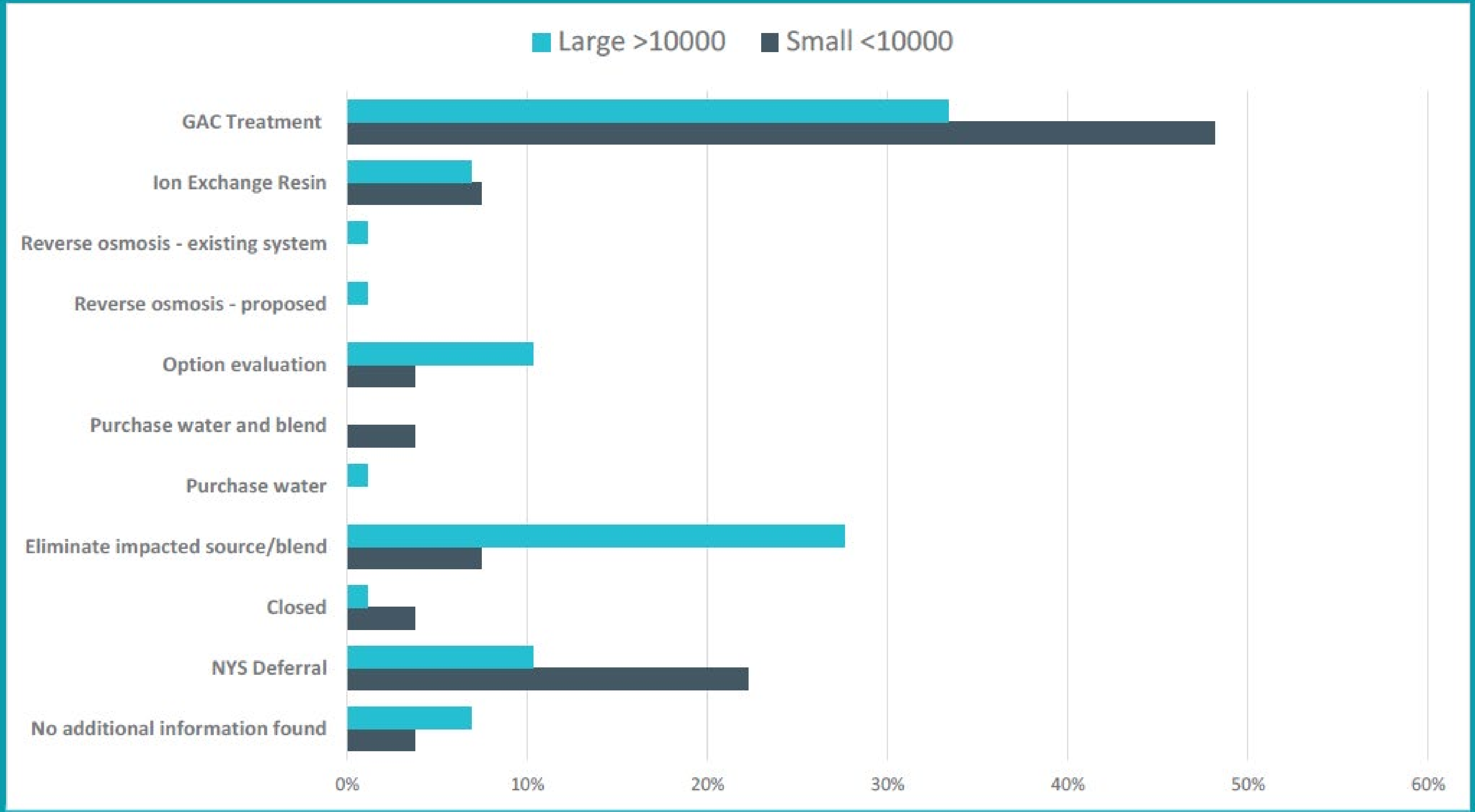
Focusing on destruction of PFAS waste streams and waste minimization approaches, not yet demonstrated for any field scale applications (too many of these)

Partially demonstrated at contaminated sites, showing promising but not proven yet for WTPs (e.g., foam fractionation)

Full-scale applications to treat regulated PFAS and meet criteria (i.e., GAC, IX, RO)



Assessment of 114 PWS



Chosen Treatment Options

Commercially Available PFAS Treatment Technology for **Drinking Water**

Technology	GAC	Single use IX	RO	Foam fractionation
Full-scale operation of drinking water treatment	Yes	Just started	No	No
Design build construction	Yes	Yes	Yes	No
Time-critical interim treatment	Yes	Yes	No	No
Waste generated	Spent GAC (solid)	Spent IX (solid)	RO reject concentrate (liquid)	Foam concentrate (liquid)
Waste management	Reactivation	Landfill, incineration, media not regenerable	Rejects not treated and discharged	Incineration, landfill, on-site destruction
Regulatory acceptance	Yes	Pre-design study needed	RO reject management plan needed	New to regulators
PFAS not efficiently treated by the technology	PFBA	PFBA, cationic PFAS	Limited data reported	Short chain PFAS unless surfactant additive is added

What's New on PFAS Drinking Water Technologies

- **Adaptive design**
  - → Design flexible systems that can be switched into different media when a novel media is ready to go
- **Removal of shorter chain PFAS** using novel sorbents
  - → NSF-certified Fluoro-Sorb®
  - → Biochar identified by NJIT, less proven as primary treatment technology
- **Precursor treatment**
  - → Concerns of converting precursors into PFAAs when AOP is part of treatment process

Considerations from MDH – New technology approval

- New technology approval process generally includes:
  - request for approval of new technology,
  - pilot study and report showing that the new tech works at the intended treatment location, and
  - design information for the specific technology.
- Then MDH responds with comments, and eventually approval/denial.
- MDH **doesn’t do wholesale approval of a new technology for the whole state** (due to varying water qualities/designs);
- However, other communities in the East Metro can use Cottage Grove’s final IX pilot report
  - The requesting community will need to provide additional information on their water quality compared to the pilot location.

Considerations from MDH – New technology approval

What is needed for MDH to review use of IX for PFAS removal?

Specific project submittal for PFAS treatment

- The specific resin(s) being proposed. The resin(s) must have been previously piloted for PFAS removal.
- Sampling results of PFAS compounds and ideally their trending values at the proposed site.
- A full set of water quality parameters at the proposed site.
- Note any potential interference from ions found at the proposed site that were not present in roughly the same concentration at the pilot site.
- Provide data on resin selectivity if available from other work or the manufacturer.

Final pilot study report for specific IX product(s)

- Product name and manufacturer for each resin.
- Testing results for various PFAS compounds
- Water quality parameters at the pilot site
- Any other relevant data (breakthrough, unique events during the pilot, etc.)
- Data on other contaminant removal occurring throughout the IX systems

General requirements for WTPs

- Plan Review Fee Sheet (PDF)
- see:https://www.health.state.mn.us/communities/environment/water/planreview/treatmentplants.html


DEPARTMENT OF HEALTH

Office Use Only
Plan No.__________
Deposit No.__________
Deposit Date__________

Plan Review Fee Sheet

- Watermains
  - 1 set of plan and specifications are required
- Wells, storage, booster stations, and water treatment plants
  - 2 sets of plans and specifications are required
- Interconnections
  - 1 interconnection plan and hydraulic analysis are required

Plans and Specifications Must Be Signed by a Professional Engineer registered in the State of Minnesota

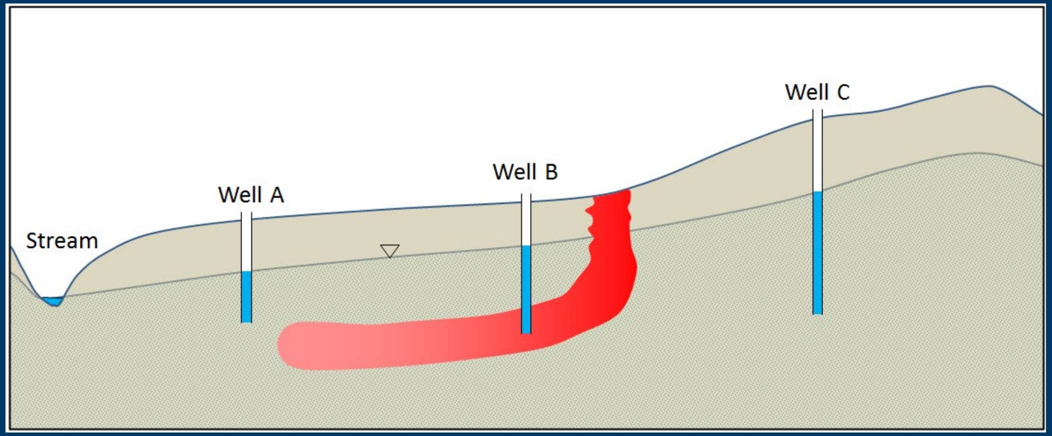
What's New on PFAS Drinking Water Technologies

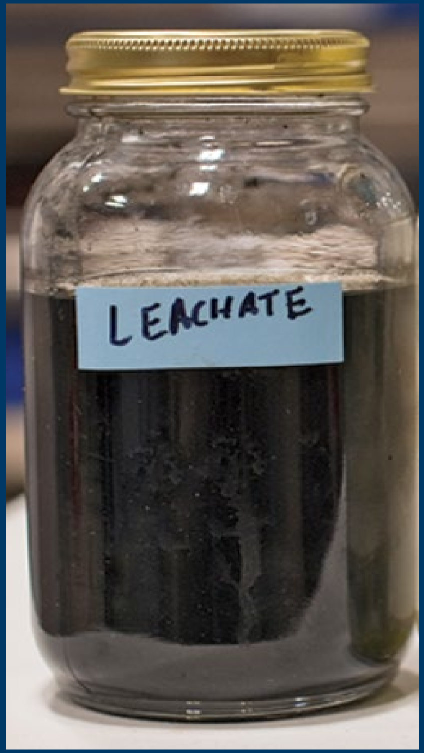
Membrane filtration/Reverse Osmosis

- One system underway – PFAS removal specifically
- Old technology with new applications
- Limited full-scale applications
- PFAS are "detoured" not "treated"
  - No mass reduction
- Effective on removing all PFAS
- Issues:
  - Environment (waste, energy, available resources, etc)
  - Management of RO concentrate (SAFF?) – 4x higher concentration
  - High capital and O&M costs (immediate and long term)

Piloting RO for PFAS removal has not been previously implemented in MN and would be required before full-scale implementation.

- ✓ **Membrane Processes**
  - **High pressure membrane**
  - **High energy usage**
  - **Reject water disposal**
  - **Typically used on lower flow rates**
- ✓ **Effective for PFAS**
- ✓ **Removes a wide range of constituents:**
  - **Including hardness, dissolved solids, as well as VOCs and PFAS**
- ✓ **Costly**
  - **Capital**
  - **Operating**





PFAS Remediation Technologies

Non-potable water treatment

PFAS Separation Technologies

- Foam Fraction
- Fluor-Sorb® by CETOCO
- β-cyclodextrin Polymer Adsorbents (Dexsorb® by Cyclopure)
- Electrocoagulation
- PlumeStop
- Other Carbon based media (biochar, RemBind, etc)
- PerfluorAd
- Thermal desorption

Surface Active Foam Fractionation (SAFF^{TM})

- Separates + Concentrates PFAS
- 'AIR IN – PFAS OUT'
- SAFF is not dissolved air flotation (DAF)
- No chemical additions (just air) for PFAS > 100 µg/L
- Process generates small volume of foam concentrate

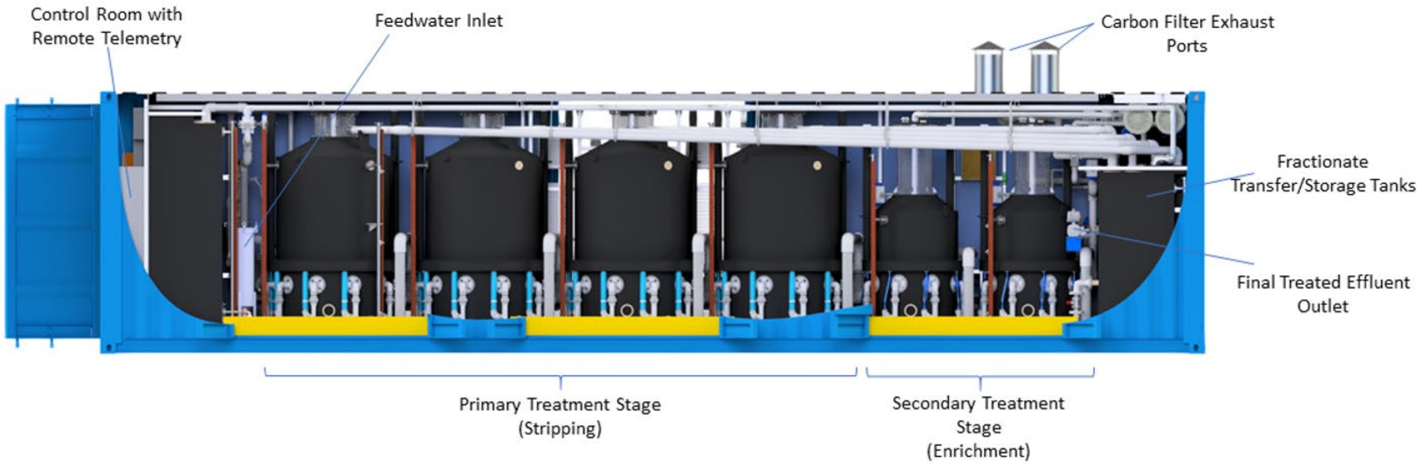
Broad applications with limited demonstrations as of today

- ✓ Landfill leachate
- ✓ Wastewater
- ✓ Groundwater
- ✓ Surface water

OPEC SYSTEMS

EPOC ENVIRO

(https://epocenviro.com/)



SAFF™ for Landfill Leachate and Wastewater

- Confidential data indicate that PFAS in leachate were removed at % reduction similar to full-scale groundwater treatment system (previous slide)
  - 99%-100% removal for long-chain PFAS (C>6)

Bench-scale leachate treatment

40-ft OPEC system for landfill leachate treatment in Sweden

Information provided by OPEC, Australia

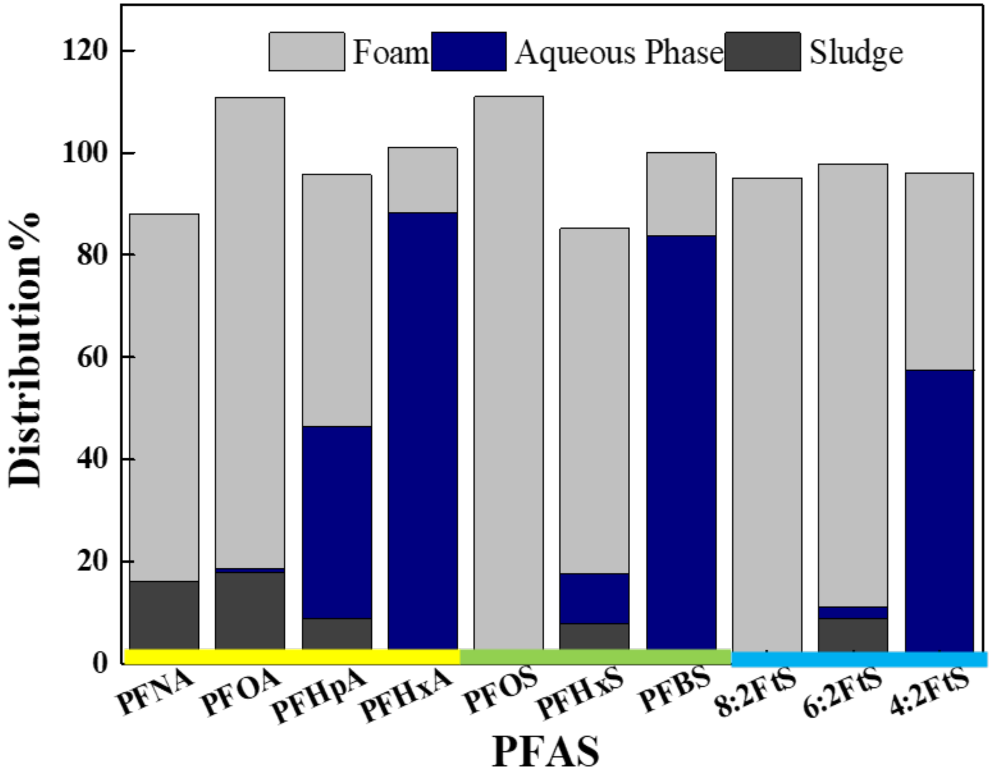
Coagulation

- **PerfluorAd**
  - It is claimed to interact with **PFAS only**
  - Large scale pilot tested in Europe and commercially available in the US
  - Only **simple mixing** process is required
  - Low reagent cost
  - Applicable as pre-treatment technology
  - Demonstrated as potential cleaning reagent for decontamination of fire trucks during foam transition

Electrocoagulation Treatment, Spiked Solution

High PFAS, High Current Density

- High LC-PFAS partition into foam driven by electrochemical processes
- Lower PFAS partition into flocs when foam is present



PFAS	Aqueous Phase (%)	Foam (%)	Flocs (%)	Total mass recovery (%)
PFNA	0.1	71.9	16.0	88
PFOA	0.9	92.2	17.8	110.9
PFHpA	37.6	49.3	8.7	95.6
PFHxA	88.2	12.7	0	101
PFOS	0.2	110.8	0	111
PFHxS	9.8	67.7	7.8	85.2
PFBS	83.8	16.2	0	100
8:2FtS	0	95.0	0	95
6:2FtS	2.2	86.7	8.8	97.7
4:2FtS	57.4	38.5	0	95.9

The mass distribution of 10 PFAS in different phases after EC treatment (C_0 = 0.5 μM, current density = 5.0 mA cm $^{-2}$, 20 mM Na_2SO_4)

PFAS Destruction Technologies

PFAS Destructive Technologies

- Electrochemical Oxidation
- Plasma
- UV-Hydrated Electrons
- Hydrothermal
- Supercritical water oxidation ★
- Gasification ★
- Sonochemical
- Photolysis/Photocatalytic
- Mechanochemical (Ball-milling)
- High-energy electron beam
- Enzymatic degradation
- Biodegradation

★Technology destroy PFAS-containing solid waste

Electrochemical Oxidation

- Electrochemical cells containing reactive anodes and cathodes (the electrodes) are used to destroy PFAS concentrates
- Electrode materials matter (Boron-doped diamond, MMO, titanium suboxide, etc.)
- Uses direct current (DC) to mineralize PFAS
- Best for low volume high concentration liquids
- Limitations include flow rate, co-contaminants, shorter chain PFAS generation from longer chain PFAS destruction, less effective for shorter chain PFAS
- Field pilot scale demonstration at limited sites

Source: ITRC PFAS Treatment Training Slide

Plasma Treatment

- Electricity used to convert water into mixture of highly reactive species
    - $OH^{\bullet}$, O, $H^{\bullet}$, $HO_2^{\bullet}$, $O_2^{\bullet-}$, H_2, O_2, H_2O_2 and aqueous electrons (e^{-}_{aq})
- Plasma formed by means of electrical discharge between one high voltage and one groundwater within or contacting the water
- Argon gas pumped through diffuser
    - Produces bubble layer on surface that concentrates PFAS

Photos courtesy of Selma Mededovic, Clarkson.

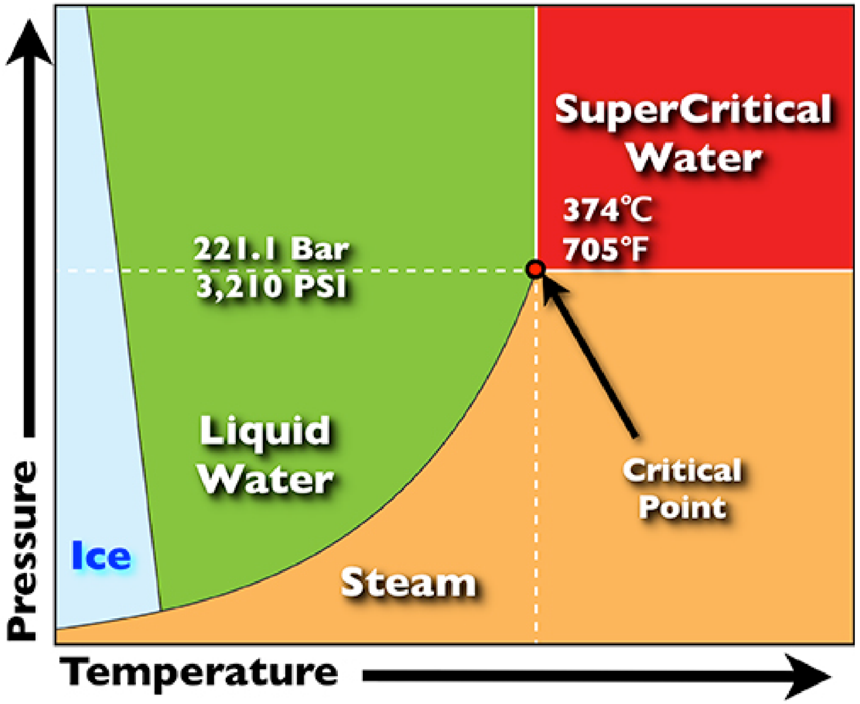
Stratton, G.R., et al. (2015). Chemical Engineering Journal, 273: 543-550.

Stratton, G. R., et al., (2017). Environmental Science & Technology 2017, 51(3):1643-1648.

Source: ITRC PFAS Treatment Training Slide

Supercritical Water Oxidation (SCWO)

- Water >374ºC and pressure of 221.1 bar is considered "supercritical"
- Under these conditions, certain chemical oxidation processes are accelerated
- Technology established for other recalcitrant organics
- Technology proven to destroy sludges and biosolids
- Bench tested successfully for destroying PFAS and even PFAS-containing spent media
- Pilot and full-scale applications in development

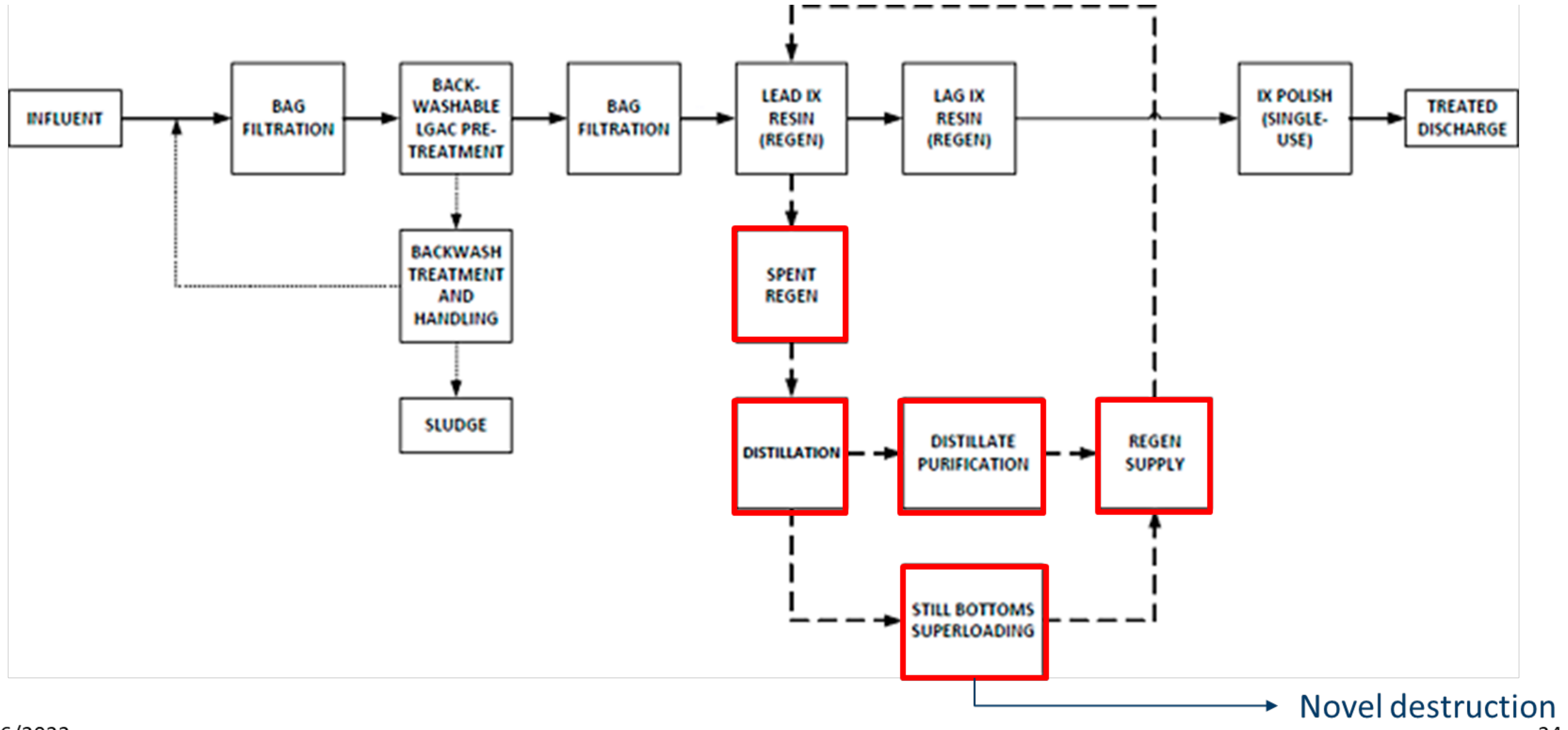


One of a few technologies with potential promise to destroy PFAS in oxidation.

Source: ITRC PFAS Treatment Training Slide

Coupling Regenerable IX Treatment with On-site PFAS destruction

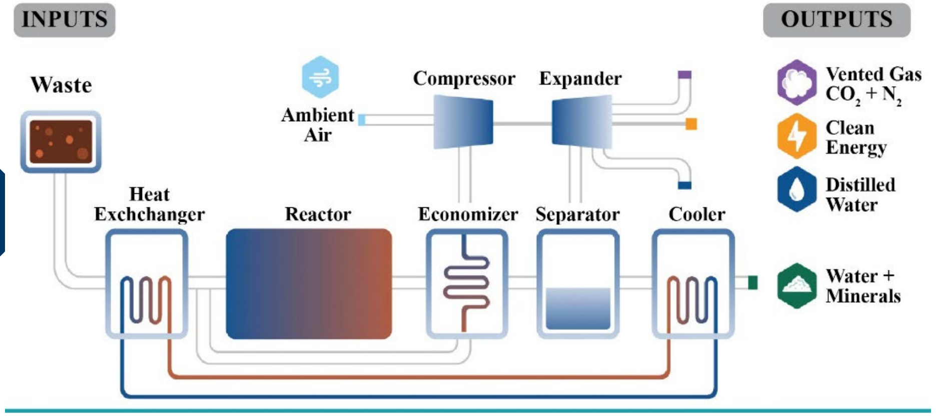
Example: Regeneration of regenerable IX



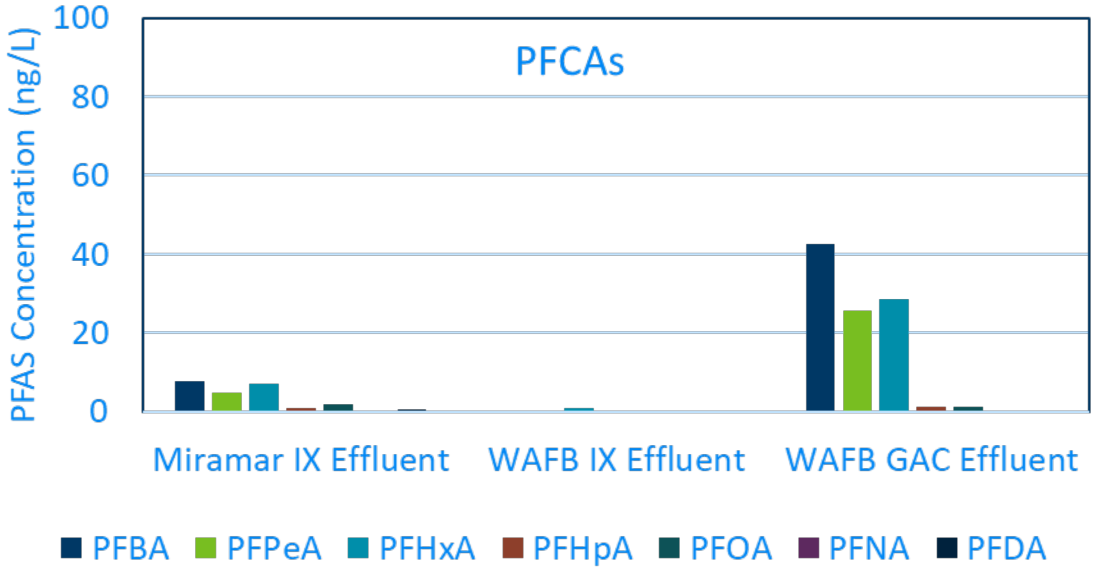
Coupling with GAC or Single Use Treatment with On-Site Destruction Technologies for Solid Wastes

Spent media

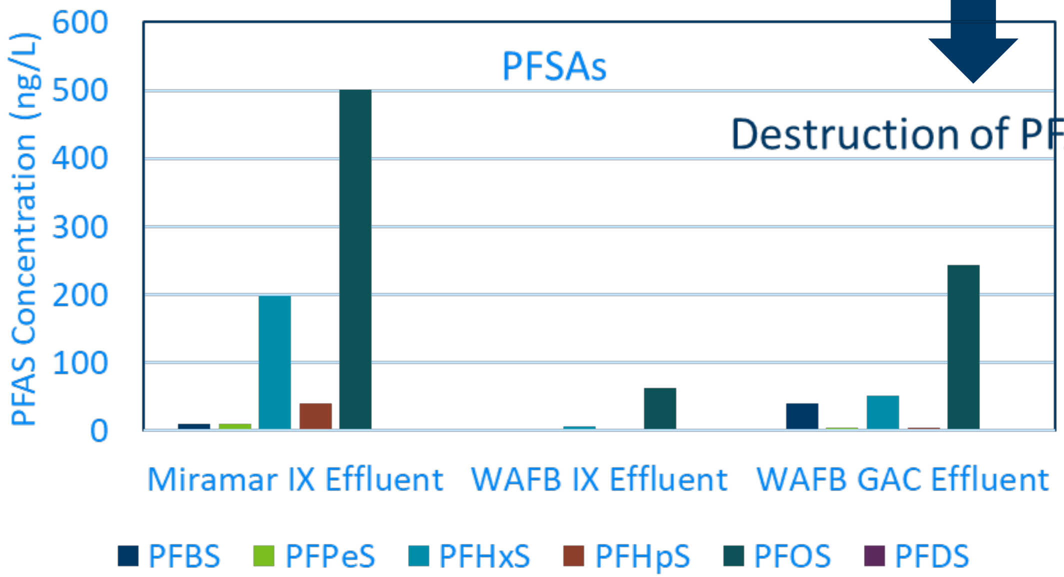
374Water



Converting spent media into water



Destruction of PFAS



Technology Programs- Advancements and Investments

✓How can we stay up to speed on new developments?

1. Track key funding research entities i.e. ESTCP/SERDP

2. Track key researchers

3. Track key collaboration organizations

Questions to Ask Technology Providers

PFAS Treatment Technology Selection Checklist

- Regulatory acceptance and NSF certification
- Changeout frequency
- System footprint
- Documented levels of reduction (logs of reduction) vs criteria
- Feasibility and cost of waste management
- Which PFAS and concentration ranges for treatment
- Treatment capacity- Low vs high vs fluctuation of volume/flow
- Pre-treatment needs for co-contaminant interference
- Applications on the types of waters (drinking water, groundwater, leachate, wastewater)
- Technology maturity
- Availability in different regions
- Life cycle Cost
- Flexibility to adopt novel media
- Whether it destroys PFAS

Top considerations

- Cost
- Reliability
- Flexibility
- Waste generation and management

Closing Thoughts

- There is no silver bullet solution. Pre-design study is needed.
- GAC, AIX and RO are proven effective on removing PFAS but all generate waste streams. PFAS waste destruction methods remain very limited.
- Modified sorbents demonstrate opportunities to be regenerated and remove broader range of PFAS
- Liquid-liquid separation technologies (e.g., foam fractionation) can be groundbreaking but not yet ready for drinking water treatment
- Some PFAS destruction technologies are under development, and some are scaling up. They are most applicable for low-volume PFAS concentrates
- “Separate, Concentrate and Destroy” is the best PFAS mitigation practice when treatment is needed. This approach is not just interesting, it is needed.
- There are MANY technology and sorbent providers in the PFAS market, validate any new information that have not been peer-reviewed

References

Chiang, D. and Salter-Blanc Alexander "PFAS Sources" **Enviro WIKI**, https://www.enviro.wiki/index.php?title=PFAS_Sources

Chang, Y., **Chiang, D.,** Smith, F. and Bohlen, A (2021) PFAS treatment challenges, solutions and considerations, ***Ohio AWWA 2021 Spring Newsletter***, pg 5-9.

Shi, H., **Chiang, S-Y. D**., Wang, Y., Wang, Y., Liang, S, Zhou, J., Fontanez, R., Gao, S., Huang, Q. (2021) An electrocoagulation and electrooxidation treatment train to remove and degrade per- and polyfluoroalkyl substances in aqueous solution, ***Science of the Total Environment***, 788 (20):147723

Rodowa, A. E., Knappe, D. R. U., **Chiang, S-Y. D**., Pohlmann, D., Varley, C, Bodour, A and Field, J. A (2020) Pilot scale removal of per- and polyfluoroalkyl substances and precursors from AFFF-impacted groundwater by granular activated carbon, ***Environmental Science: Water Research & Technology***, 6:1083-1094.

Shangtao Liang, Randall "David" Pierce Jr., Hui Lin, **Sheau-Yun (Dora) Chiang**, Qingguo "Jack" Huang (2018) Electrochemical oxidation of PFOA and PFOS in concentrated waste streams, ***Remediation***, 28 (2): 127-134

Paul M. Dombrowski, Prasad Kakarla, William Caldicott, Yan Chin, Venus Sadeghi, Dorin Bogdan , Francisco Barajas-Rodriguez, **Sheau-Yun (Dora) Chiang** (2018) Technology review and evaluation of different chemical oxidation conditions on treatability of PFAS, ***Remediation***, 28 (2): 135-150.

Rachael Casson and **Sheau-Yun (Dora) Chiang** (2018) Integrating total oxidizable precursor assay data to evaluate fate and transport of PFASs, ***Remediation***, 28(2**):** 71-87.

Luo, Qi, Wang, Z., Feng, M, **Chiang, D**., Woodward, D., Liang, S., Lu, J., Huang, Q.. "Factors Controlling the Rate of Perfluorooctanoic Acid Degradation in Laccase-Mediator Systems: The Impact of Metal Ions." ***Environmental Pollution***, vol. 224, 2017, pp. 649–657., doi:10.1016/j.envpol.2017.02.050.

Zhang, Di, Lup, Q., Gao, B., **Chiang, S-Y. D**., Woodward, D., Huang Q. (2016) "Sorption of Perfluorooctanoic Acid, Perfluorooctane Sulfonate and Perfluoroheptanoic Acid on Granular Activated Carbon." ***Chemosphere***, vol. 144, Feb. 2016, pp. 2336–2342., doi:10.1016/j.chemosphere.2015.10.124.

Luo, Qi, Lu, J., Zhang, H., Wang, Z., Feng, M., ***Chiang, S-Y,. D.,*** Woodward, D., Huang, Q (2015) "Laccase-Catalyzed Degradation of Perfluorooctanoic Acid." ***Environmental Science & Technology Letters***, vol. 2, no. 7, 2015, pp. 198–203., doi:10.1021/acs.estlett.5b00119.

Patent pending US2019/0185352A1 Use of electrochemical oxidation for treatment of per-and polyfluoroalkyl substances (pfas) in waste generated from sorbent and resin regeneration processes

Closing