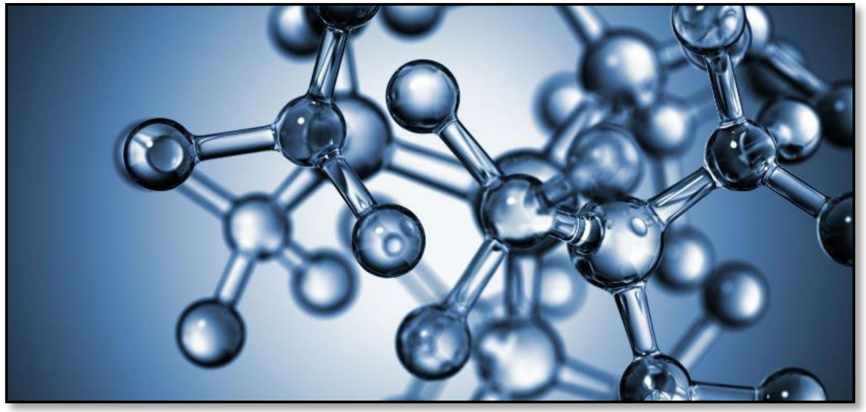
Management of PFAS Treatment Residuals

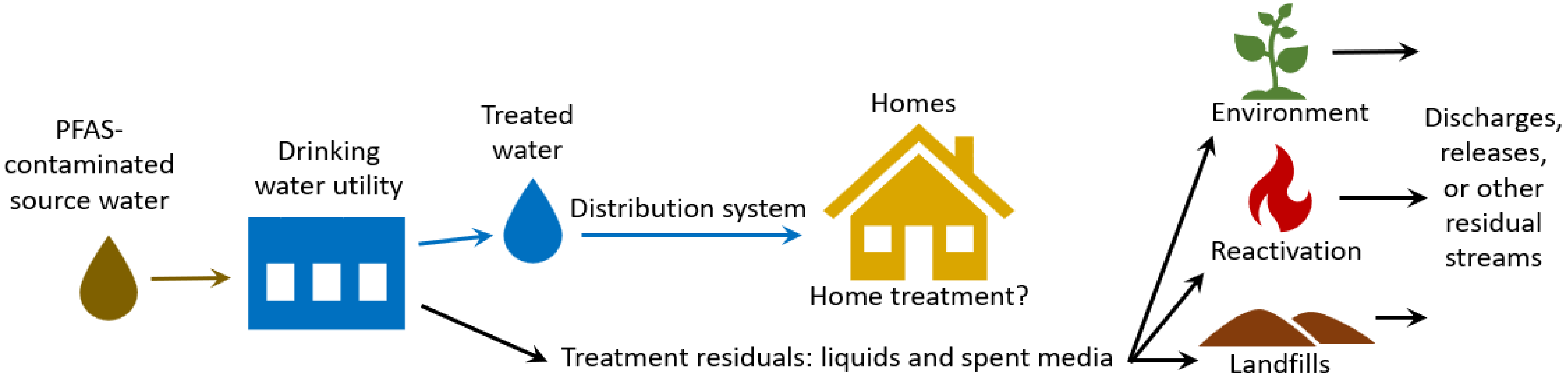
Thomas Speth
US EPA Office of Research and Development



Water Quality Division, Safe Drinking Water Section: PFAS Treatment for Engineers
November 2, 2023

Drinking Water Treatment

How do we remove PFAS from drinking water?



Effective Treatment Technologies for PFAS

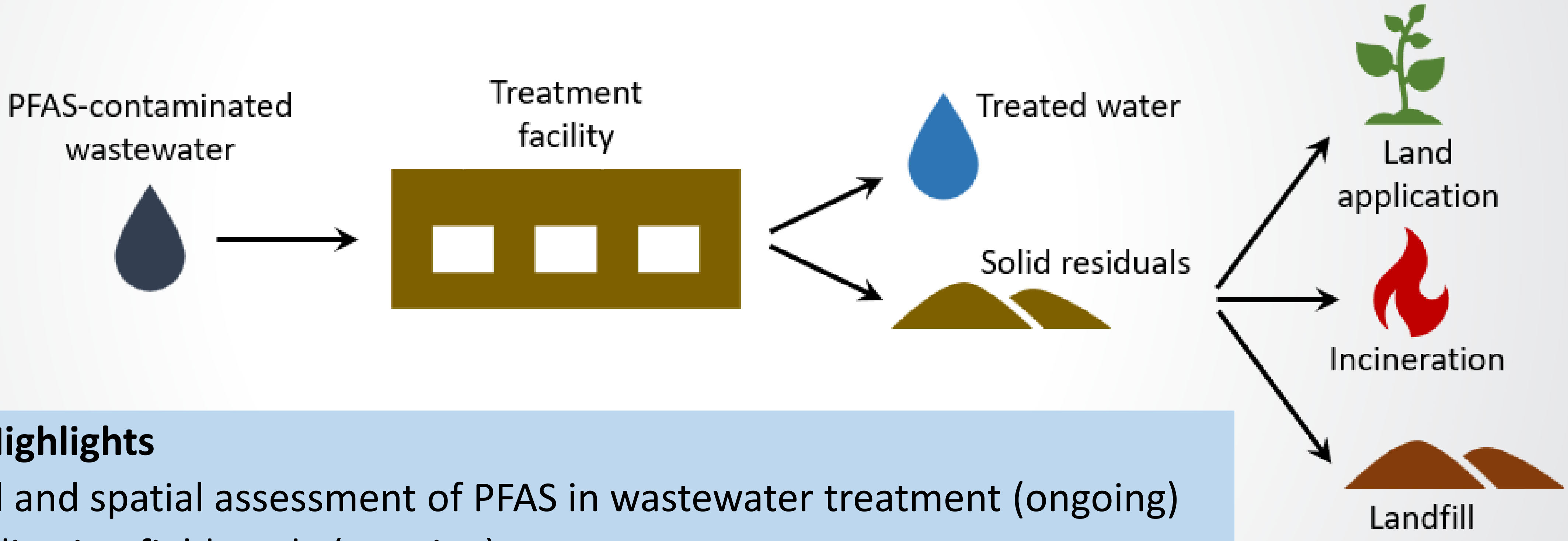
- Anion exchange resin, granular activated carbon (GAC), and membrane separation (RO) are generally effective at removing PFAS
- More effective for long-chain than short-chain PFAS
- Removal efficiencies and cost depend on source water characteristics and water system characteristics

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

PFAS in Wastewater and Biosolids

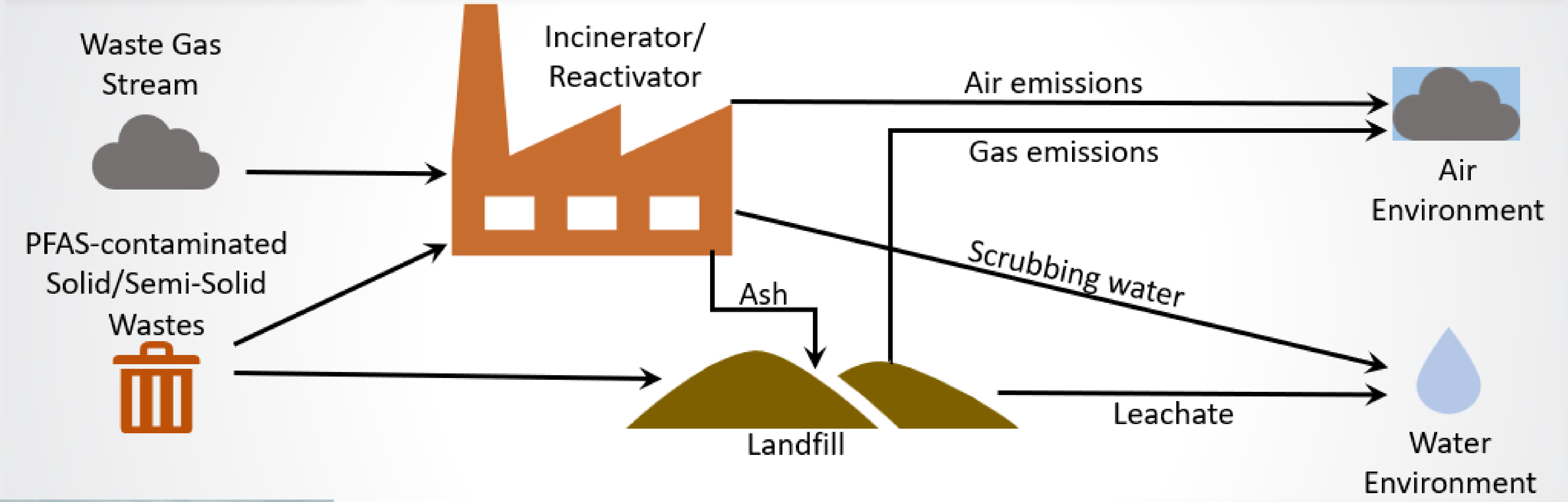
Land application of biosolids can release PFAS into the environment



Research Highlights

- Temporal and spatial assessment of PFAS in wastewater treatment (ongoing)
- Land application field study (ongoing)
- STAR: PFAS in landfills
- Upcoming RFA: PFAS in agriculture

Incineration



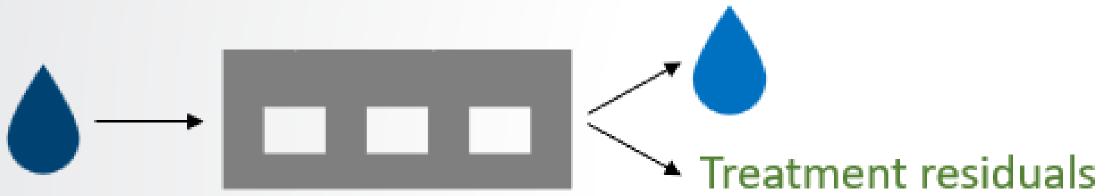
<u>PFAS Waste Destruction and Disposal</u>
There is a data gap regarding how the end-of-life management and ultimate disposal of PFAS-containing materials can impact PFAS concentrations in the environment.

<u>Treatment Residuals</u>
PFAS are found in ash, scrubbing waters, and subsequent leachates

Risk Management Research

Water Treatment

Goal: Remove or reduce PFAS in drinking water and wastewater

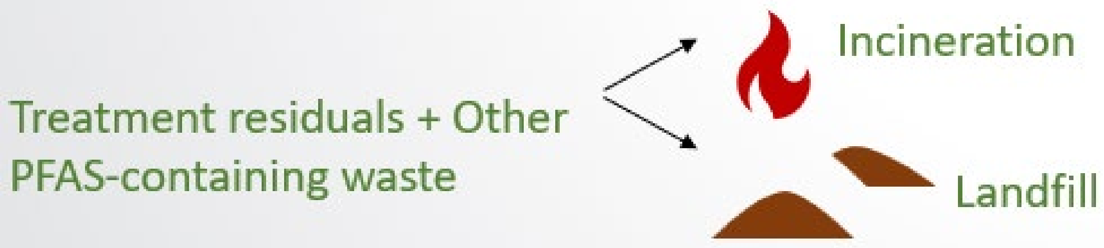


Research Highlights

- Polanyi adsorption potential theory for estimating PFAS treatment with activated carbon (2023)
- Drinking Water Treatability Database

Destruction and Disposal

Goal: Prevent re-introduction of PFAS into the environment through destruction or containment



Research Highlights

- A critical review of PFAS landfill disposal in the US (2023)
- Pilot-scale thermal destruction of PFAS in a legacy AFFF (2023)
- PFAS Thermal Treatment Database

Thermal Destruction Technologies

Incineration

Granular activated carbon reactivation

Pyrolysis

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/

Reference

- Author
- Publication year
- Source
- Reference type

Scope

- Treatment process
- Scale (lab, pilot, full)
- Matrix treated (e.g., soil, sludge)

Condition

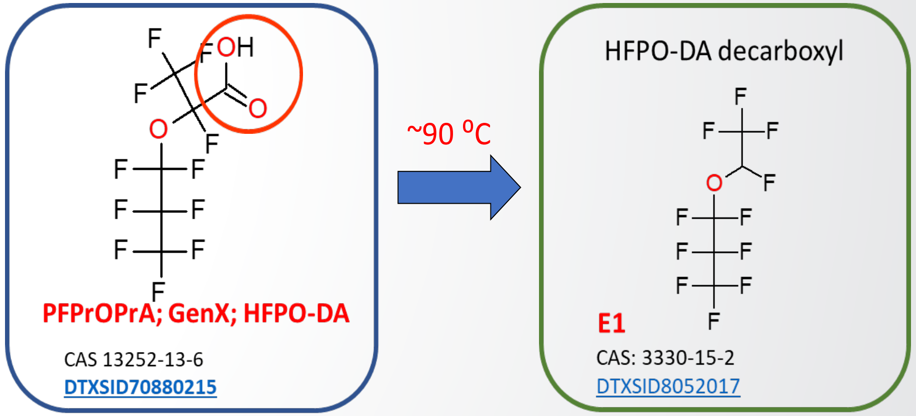
- Temperature
- Time
- Other details (e.g., atmosphere, amendments)

Results

- Analyte
- Effectiveness
- Initial concentration
- Post-treatment concentration
- Off-gas concentration
- Additional details

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)
    - Destruction pathway is not fully understood
  - 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



Cement Kiln Incinerators

Cement kilns are operated under different operating conditions

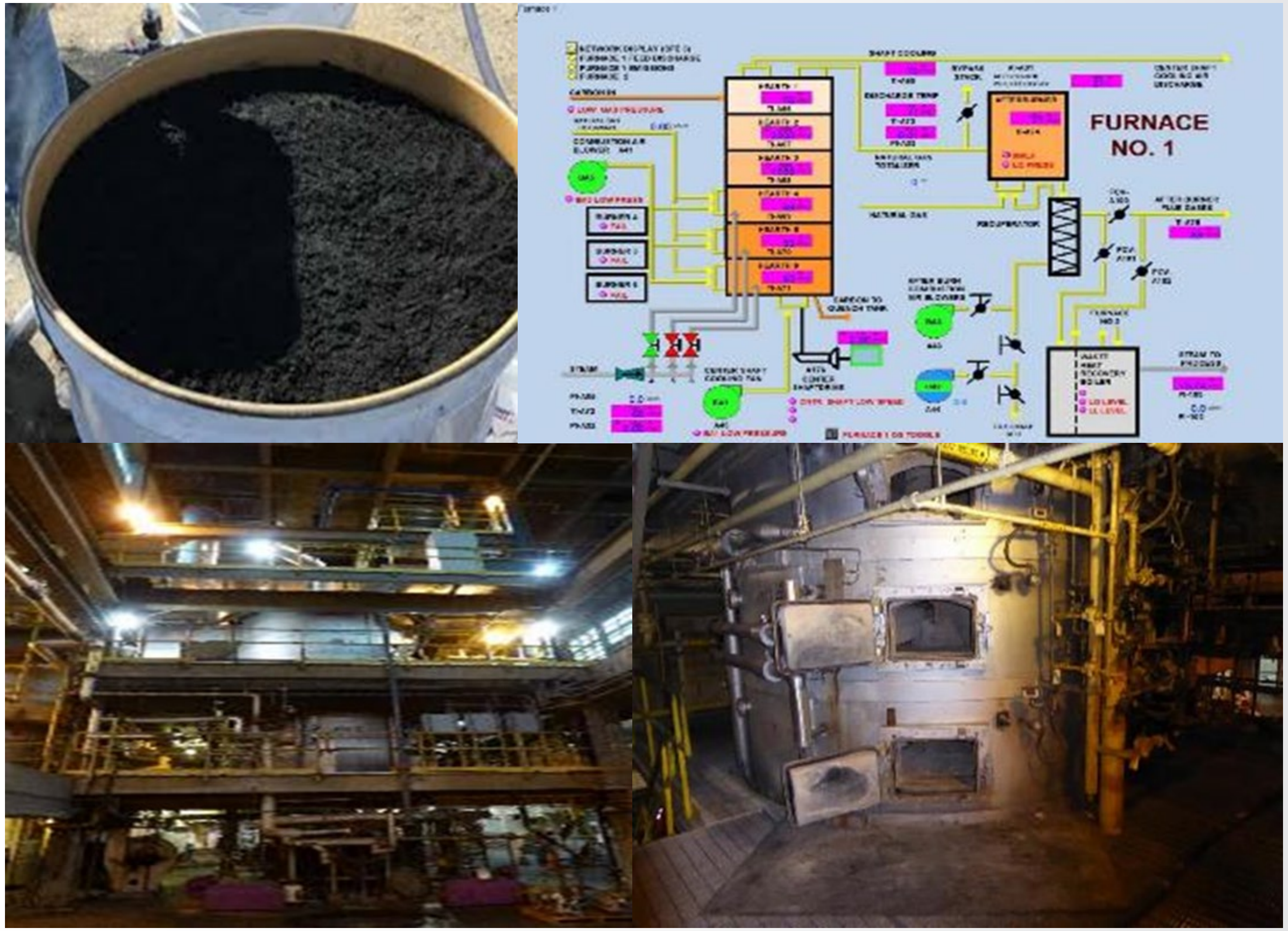
- Gas temperatures of up to ~2,000 °C
- Gas residence times of up to 10 seconds
- Solid residence time of up to 30 minutes

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

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

Granular Activated Carbon (GAC) Reactivation

- GAC used in water treatment for PFAS removal, then ideally reactivated
- 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 State Univ. in conjunction with SERDP
- Pilot study completed
  - Waiting on results
- Completed a full-scale reactivation study in June, 2023.
  - Waiting on results
- Searching for more partners to evaluate full-scale carbon reactivation facilities
- Calgon Carbon publication (DiStefano et al., 2022)



Treating Membrane Concentrates

Managing and treating per- and polyfluoroalkyl substances (PFAS) in membrane concentrates

- Outcome of collaboration among the Membrane Processes and Research Committee (MPRC)
- Many of the following slides are from Ladner et al., (2022) with permission

Received: 16 April 2021 | Revised: 15 June 2021 | Accepted: 8 July 2021
DOI: 10.1002/aws2.1233

AWWA WATER SCIENCE

REVIEW
TOPICAL COLLECTION ON PFAS ANALYTICS AND TREATMENT

Managing and treating per- and polyfluoroalkyl substances (PFAS) in membrane concentrates

Emily W. Tow[1] | Mahmut Selim Ersan[2] | Soyoon Kum[3] | Tae Lee[4] | Thomas F. Speth[4] | Christine Owen[5] | Christopher Bellona[6] | Mallikarjuna N. Nadagouda[4] | Anne M. Mikelonis[7] | Paul Westerhoff[2] | Chandra Mysore[8] | Val S. Frenkel[9] | Viraj deSilva[10] | W. Shane Walker[11] | Andrew K. Safulko[6] | David A. Ladner[12]

[1]F. W. Olin College of Engineering, Needham, Massachusetts, USA
[2]School of Sustainable Engineering and the Built Environment, Nanosystems Engineering Research Center for Nanotechnology Enabled Water Treatment (NEWT), Arizona State University, Tempe, Arizona, USA
[3]David L. Hirschfeld Department of Engineering, Angelo State University, San Angelo, Texas, USA
[4]Office of Research and Development, Center for Environmental Solutions and Emergency Response, U.S. Environmental Protection Agency, Cincinnati, Ohio, USA
[5]Hazen and Sawyer, Clearwater, Florida, USA
[6]Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, Colorado, USA
[7]Office of Research and Development, Center for Environmental Solutions and Emergency Response, U.S. Environmental Protection Agency, Durham, North Carolina, USA
[8]Jacobs, Atlanta, Georgia, USA
[9]Greeley and Hansen, San Francisco, California, USA
[10]Freese and Nichols, Inc., Tampa, Florida, USA
[11]Department of Civil Engineering, Center for Inland Desalination Systems (CIDS), Nanosystems Engineering Research Center for Nanotechnology-Enabled Water Treatment (NEWT), University of Texas at El Paso, El Paso, Texas, USA
[12]Department of Environmental Engineering and Earth Sciences, Clemson University, Clemson, South Carolina, USA

Correspondence
David A. Ladner, Department of Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC, USA.
Email: ladner@clemson.edu

Funding information
National Science Foundation: EEC-1449500

Guest Editor: Michelle Crimi
Guest Associate Editor: Zaid Chowdhury

Abstract
Per- and polyfluoroalkyl substances (PFAS), which are present in many waters, have detrimental impacts on human health and the environment. Reverse osmosis (RO) and nanofiltration (NF) have shown excellent PFAS separation performance in water treatment; however, these membrane systems do not destroy PFAS but produce concentrated residual streams that need to be managed. Complete destruction of PFAS in RO and NF concentrate streams is ideal, but long-term sequestration strategies are also employed. Because no single technology is adequate for all situations, a range of processes are reviewed here that hold promise as components of treatment schemes for PFAS-laden membrane system concentrates. Attention is also given to relevant

Treating Membrane Concentrates

Issues

- Fairly high flow rate (20-30% of feed)
- Higher PFAS concentrations
- Higher salt concentrations
- Higher background levels (e.g., DOC)
- Higher concentrations of other contaminants

Check for updates
Received: 16 April 2021 | Revised: 15 June 2021 | Accepted: 5 July 2021
DOI: 10.1002/aws2.1233
AWWA WATER SCIENCE
REVIEW
TOPICAL COLLECTION ON PFAS ANALYTICS AND TREATMENT

Managing and treating per- and polyfluoroalkyl substances (PFAS) in membrane concentrates

Emily W. Tow[1] | Mahmut Selim Ersan[2] | Soyoon Kum[3] | Tae Lee[4] | Thomas F. Speth[4] | Christine Owen[5] | Christopher Bellona[6] | Mallikarjuna N. Nadagouda[4] | Anne M. Mikelonis[7] | Paul Westerhoff[2] | Chandra Mysore[8] | Val S. Frenkel[9] | Viraj deSilva[10] | W. Shane Walker[11] | Andrew K. Safulko[6] | David A. Ladner[12]

[1]F. W. Olin College of Engineering, Needham, Massachusetts, USA
[2]School of Sustainable Engineering and the Built Environment, Nanosystems Engineering Research Center for Nanotechnology Enabled Water Treatment (NEWT), Arizona State University, Tempe, Arizona, USA
[3]David L. Hirschfeld Department of Engineering, Angelo State University, San Angelo, Texas, USA
[4]Office of Research and Development, Center for Environmental Solutions and Emergency Response, U.S. Environmental Protection Agency, Cincinnati, Ohio, USA
[5]Hazen and Sawyer, Clearwater, Florida, USA
[6]Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, Colorado, USA
[7]Office of Research and Development, Center for Environmental Solutions and Emergency Response, U.S. Environmental Protection Agency, Durham, North Carolina, USA
[8]Jacobs, Atlanta, Georgia, USA
[9]Greeley and Hansen, San Francisco, California, USA
[10]Freese and Nichols, Inc., Tampa, Florida, USA
[11]Department of Civil Engineering, Center for Inland Desalination Systems (CIDS), Nanosystems Engineering Research Center for Nanotechnology-Enabled Water Treatment (NEWT), University of Texas at El Paso, El Paso, Texas, USA
[12]Department of Environmental Engineering and Earth Sciences, Clemson University, Clemson, South Carolina, USA

Correspondence
David A. Ladner, Department of Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC, USA.
Email: ladner@clemson.edu

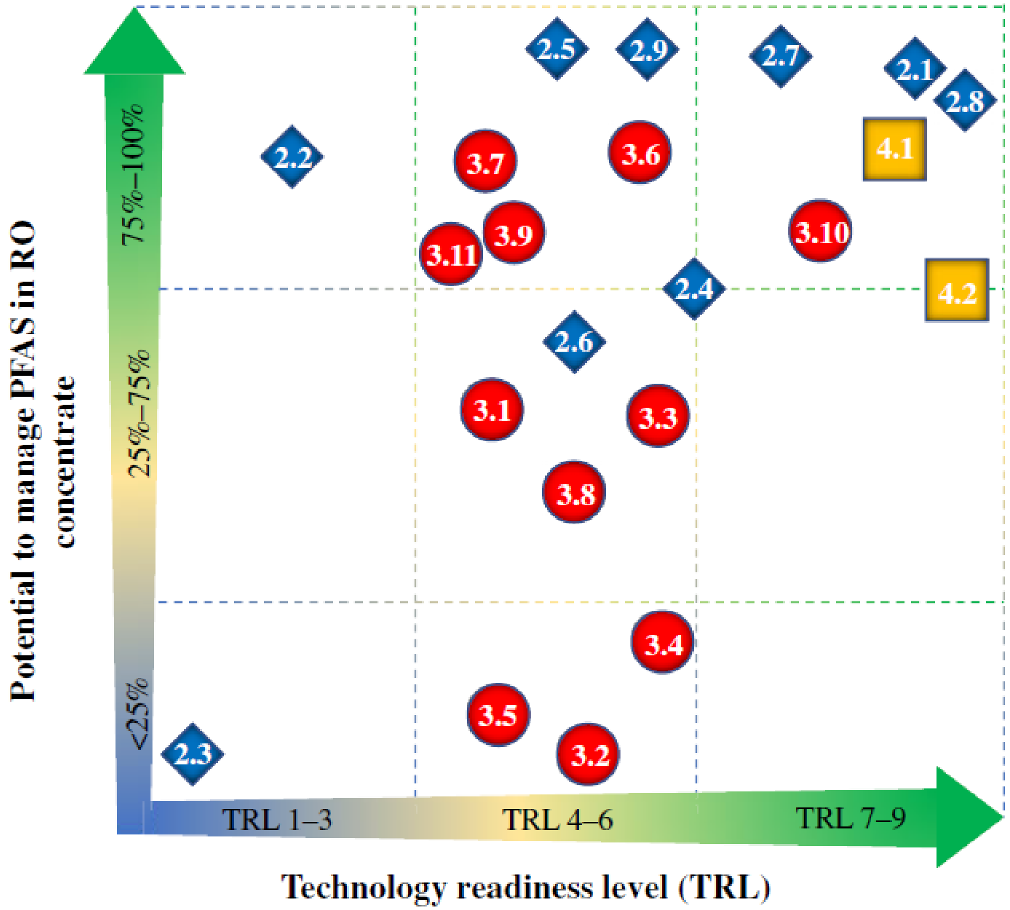
Funding information
National Science Foundation: EEC-1449500

Guest Editor: Michelle Crimi
Guest Associate Editor: Zaid Chowdhury

Abstract
Per- and polyfluoroalkyl substances (PFAS), which are present in many waters, have detrimental impacts on human health and the environment. Reverse osmosis (RO) and nanofiltration (NF) have shown excellent PFAS separation performance in water treatment; however, these membrane systems do not destroy PFAS but produce concentrated residual streams that need to be managed. Complete destruction of PFAS in RO and NF concentrate streams is ideal, but long-term sequestration strategies are also employed. Because no single technology is adequate for all situations, a range of processes are reviewed here that hold promise as components of treatment schemes for PFAS-laden membrane system concentrates. Attention is also given to relevant

Tow et al., AWWA Water Science, 2021
https://doi.org/10.1002/aws2.1233

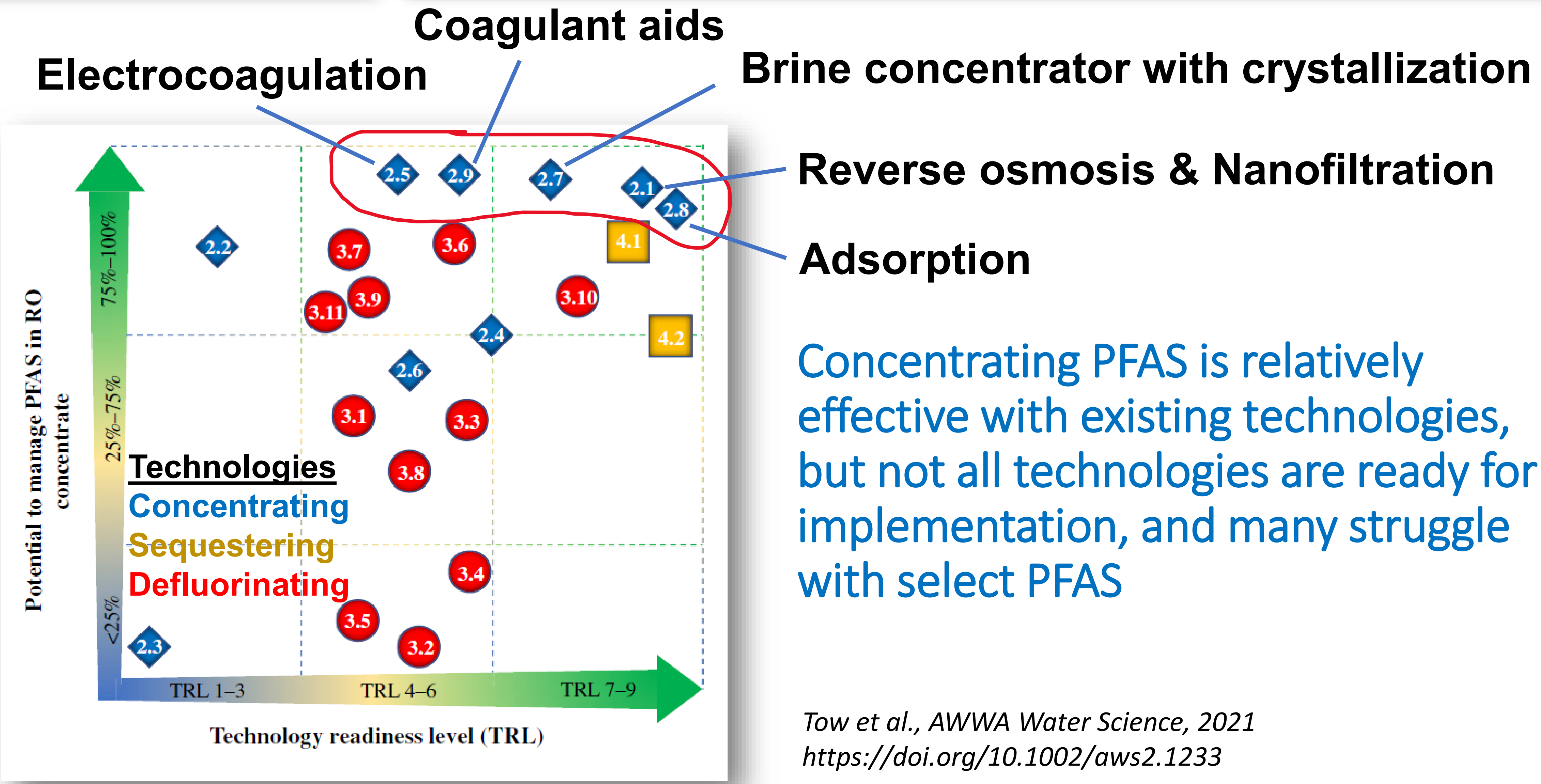
Concentrating, Defluorinating, and Sequestering PFAS



2.1. Reverse osmosis and nanofiltration
2.2. Emerging membrane processes
2.3. ED–RO hybrid systems
2.4. Foam fractionation
2.5. Electrocoagulation
2.6. Evaporation ponds
2.7. Brine concentrator with crystallization
2.8. Adsorption
2.9. Coagulant aids
3.1. Biological treatment
3.2. Ultraviolet irradiation
3.3. Photocatalysis
3.4. Advanced oxidation
3.5. Solvated electrons
3.6. Plasma-based treatment
3.7. Electron beam
3.8. Zero-valent iron
3.9. Sonochemical treatment
3.10. Incineration
3.11. Supercritical water oxidation
4.1. Deep well injection
4.2. Landfill

FIGURE 6 Graphical summary of technology readiness levels (ITRC, 2020) and nominal reported potential to manage (separate, defluorinate, or sequester) PFAS from reverse osmosis concentrate. The relative placement of processes in the plot does not consider capital and operating costs, in part because these are challenging to estimate for early-stage technologies. Numbers correspond to the sections of this article where each technology is discussed

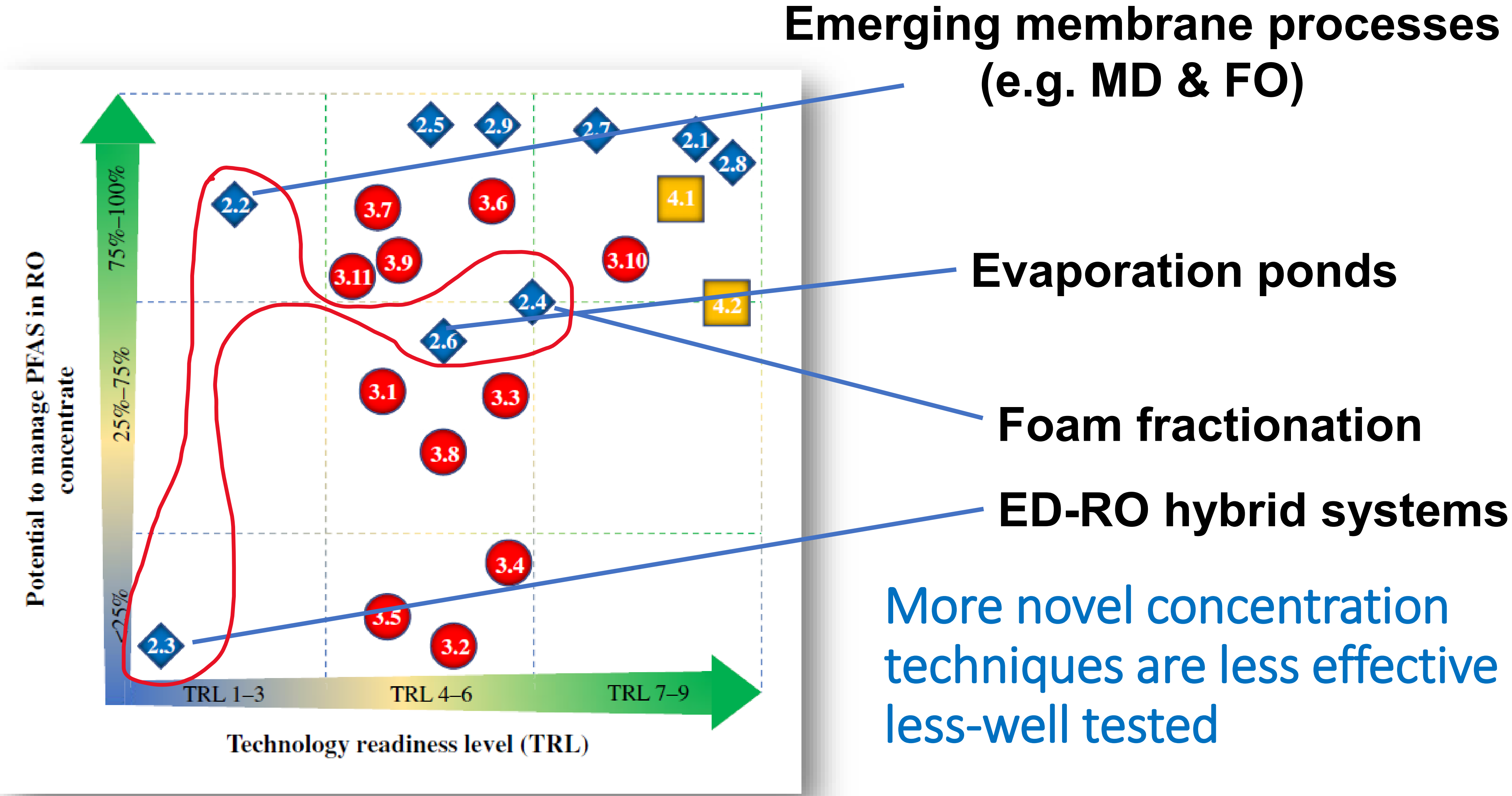
Concentrating PFAS (existing technologies)



Concentrating PFAS is relatively effective with existing technologies, but not all technologies are ready for implementation, and many struggle with select PFAS

Tow et al., AWWA Water Science, 2021
https://doi.org/10.1002/aws2.1233

Concentrating PFAS (novel technologies)



More novel concentration techniques are less effective or less-well tested

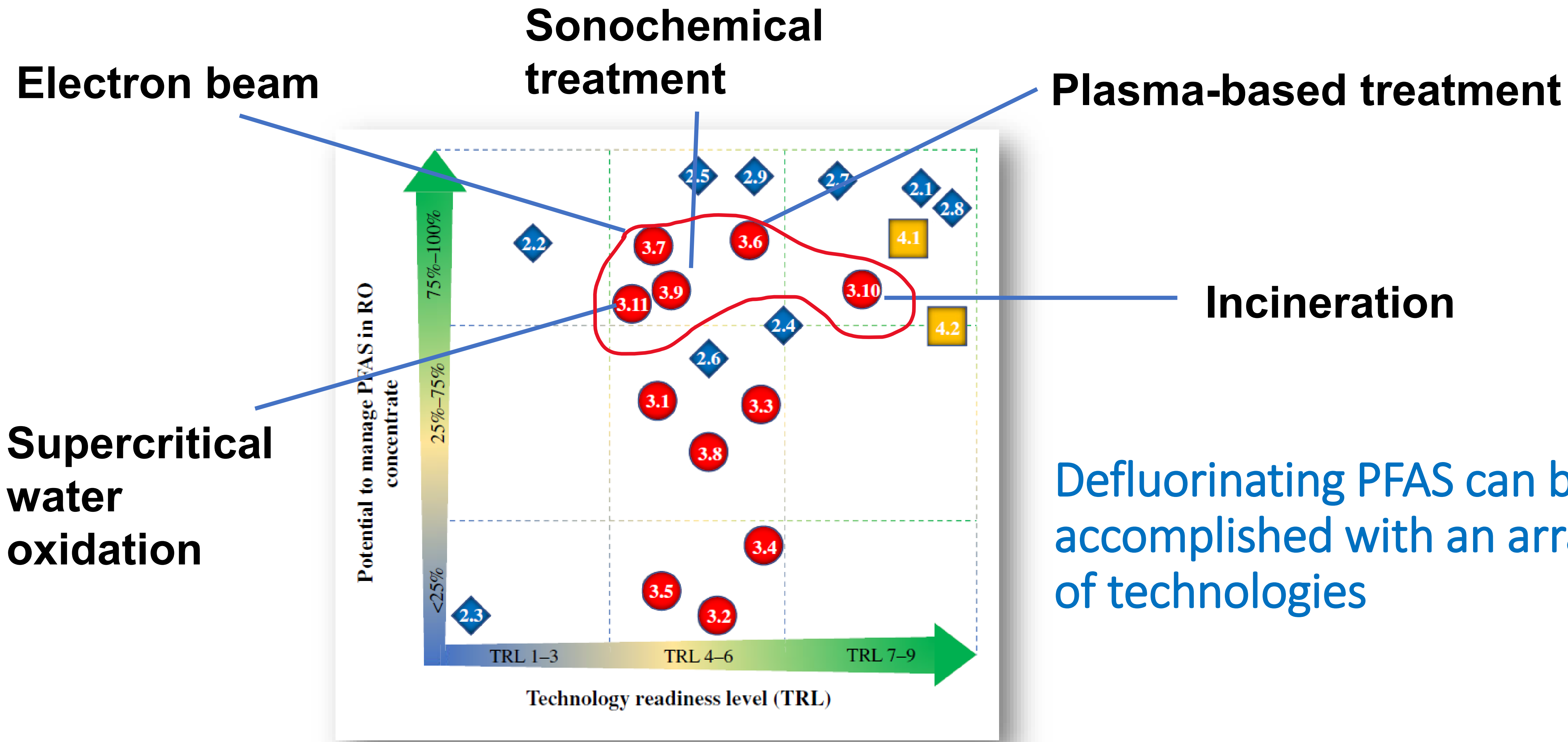
Foam Fractionation

Foam fractionation takes advantage of PFAS' surfactant properties

- Bubble air and increase interfacial surface area
- Less effective for short-chain PFAS

FIGURE 3 (a) Foam fractionation column treating PFAS-laden water (photo courtesy of Evocra Pty Ltd). (b) Foam fractionation system (photo courtesy of OPEC systems and Dora Chiang, CDM Smith)

Defluorinating PFAS



Defluorinating PFAS can be accomplished with an array of technologies

E-beam technology

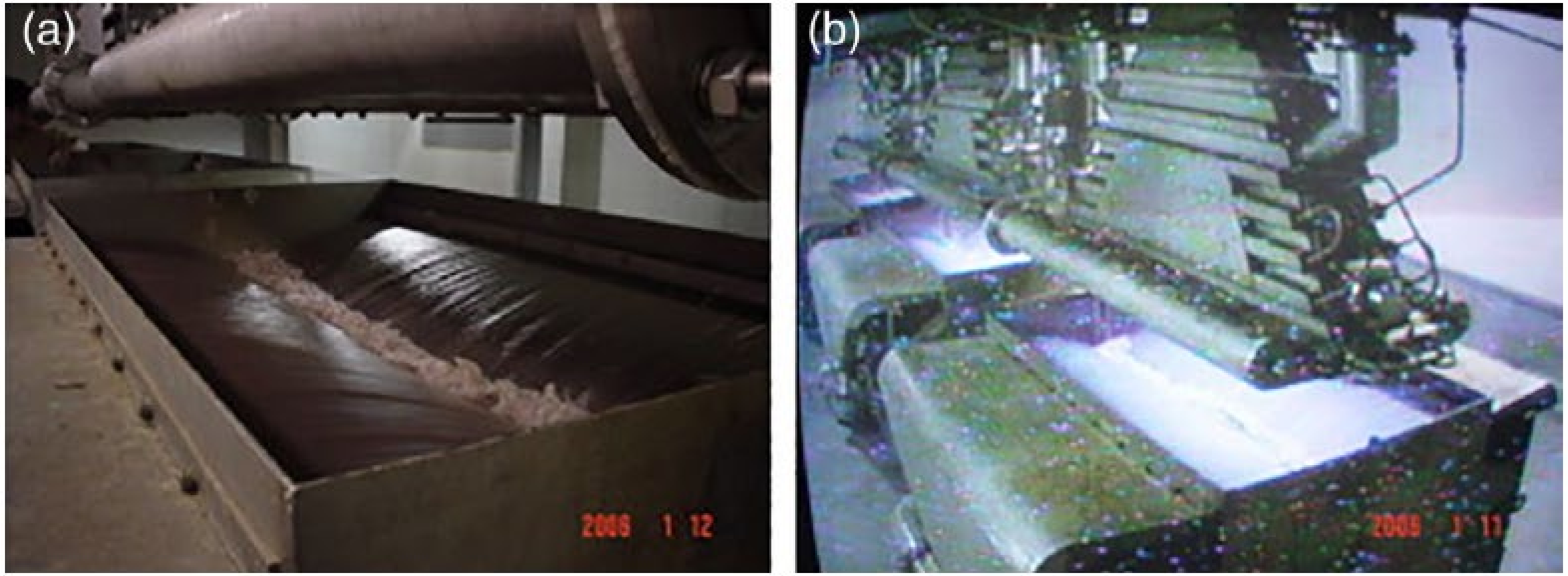
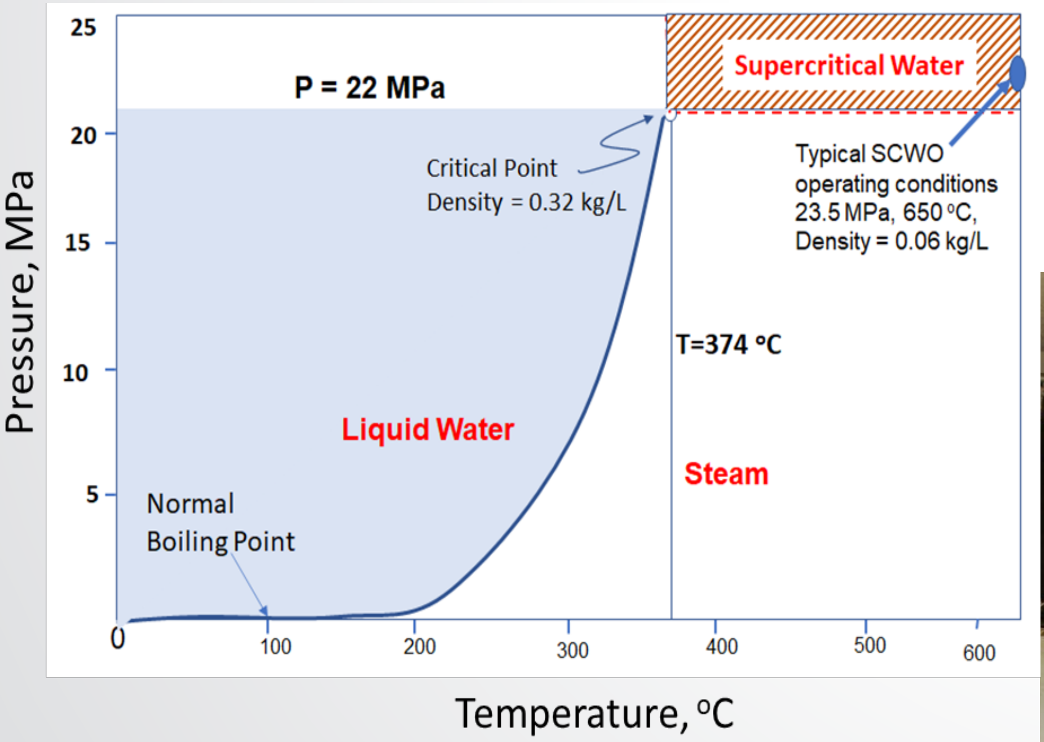


FIGURE 4 Operation of industrial wastewater plant with electron beam. (a) Injection of wastewater through nozzles. (b) Wastewater under treatment (reprinted from [Han et al., 2012] with permission from Elsevier)

E-beam technology is a radiation-based method where electrons are accelerated and delivered to produce radicals

Supercritical Water Oxidation (SCWO)

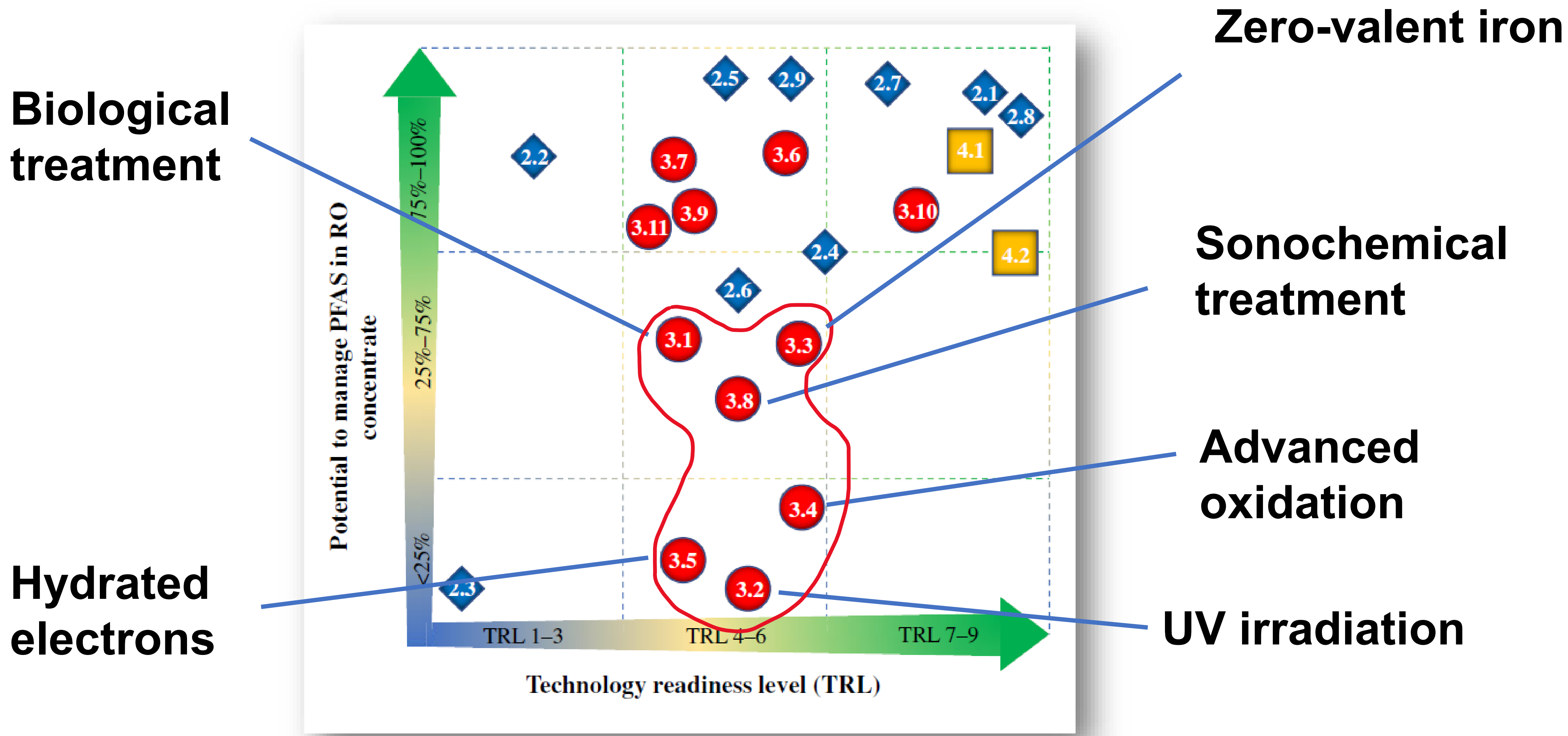
- Short residence time (< 10 sec)
- Can handle high feed concentrations and organic co-contaminates
- Relatively low operating temperatures
- Generates little waste



- Case studies performed with four separate SCWO suppliers
  - Aquarden (Denmark)
  - 374Water (Durham, NC)
  - Battelle (Columbus, OH)
  - General Atomics (San Jose, CA)
- Tested SCWO on dilute AFFF
- Results showed greater than 99% reduction of the targeted PFAS Krause et al., 2022

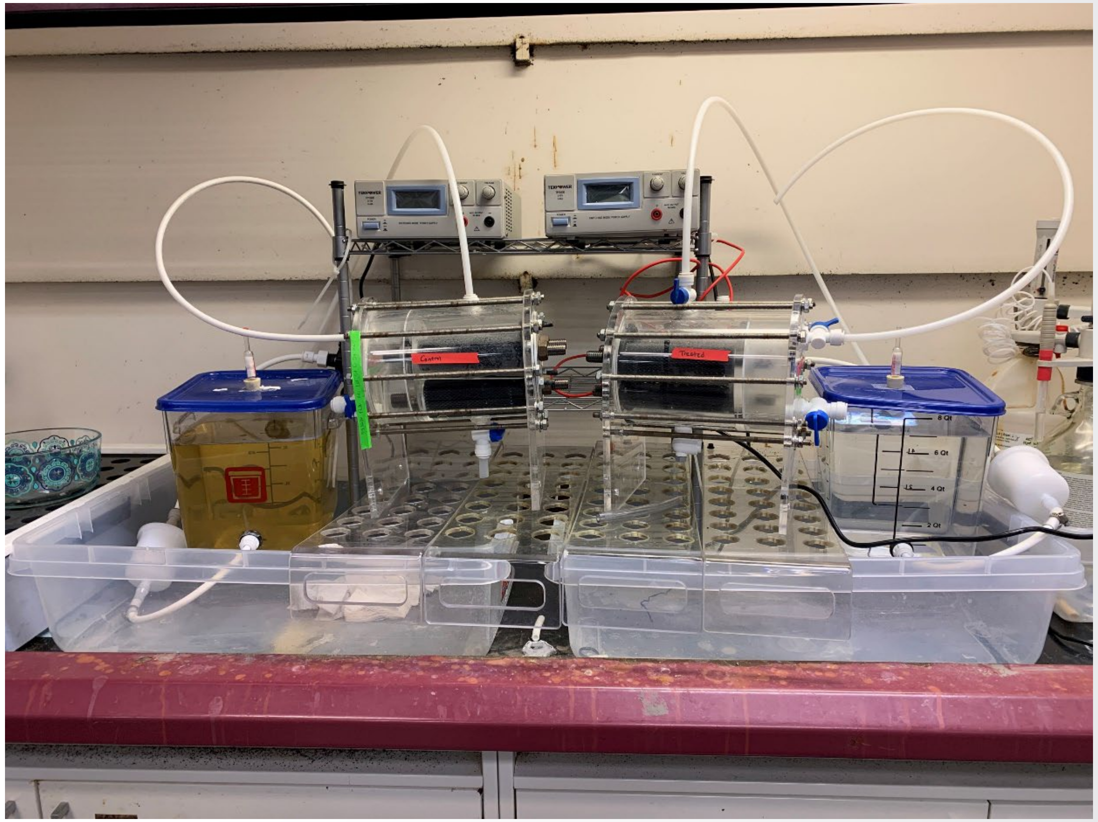
Source: https://aquarden.com

Other Potential Destruction Technologies



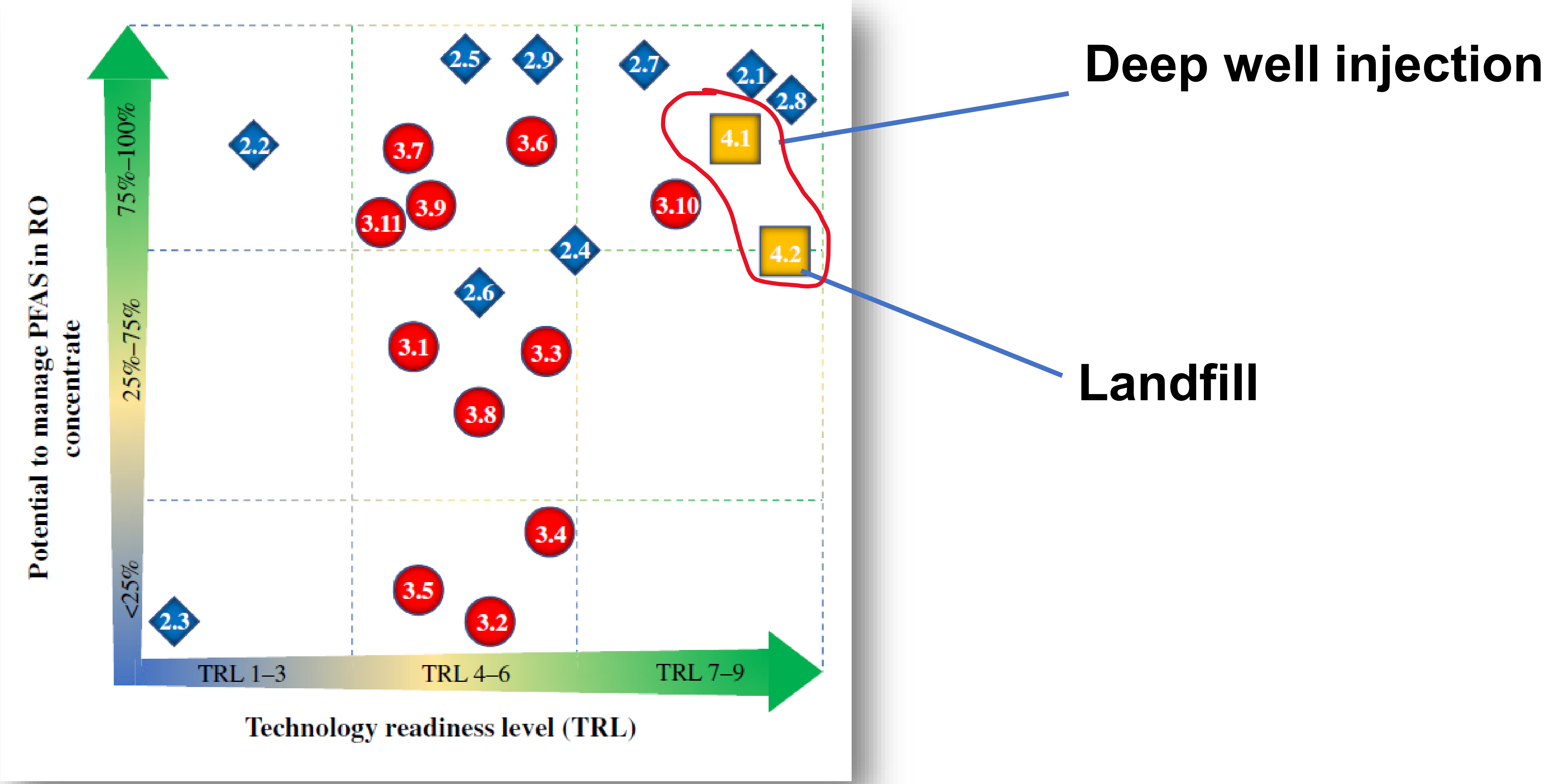
Electrochemical Oxidation

- 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

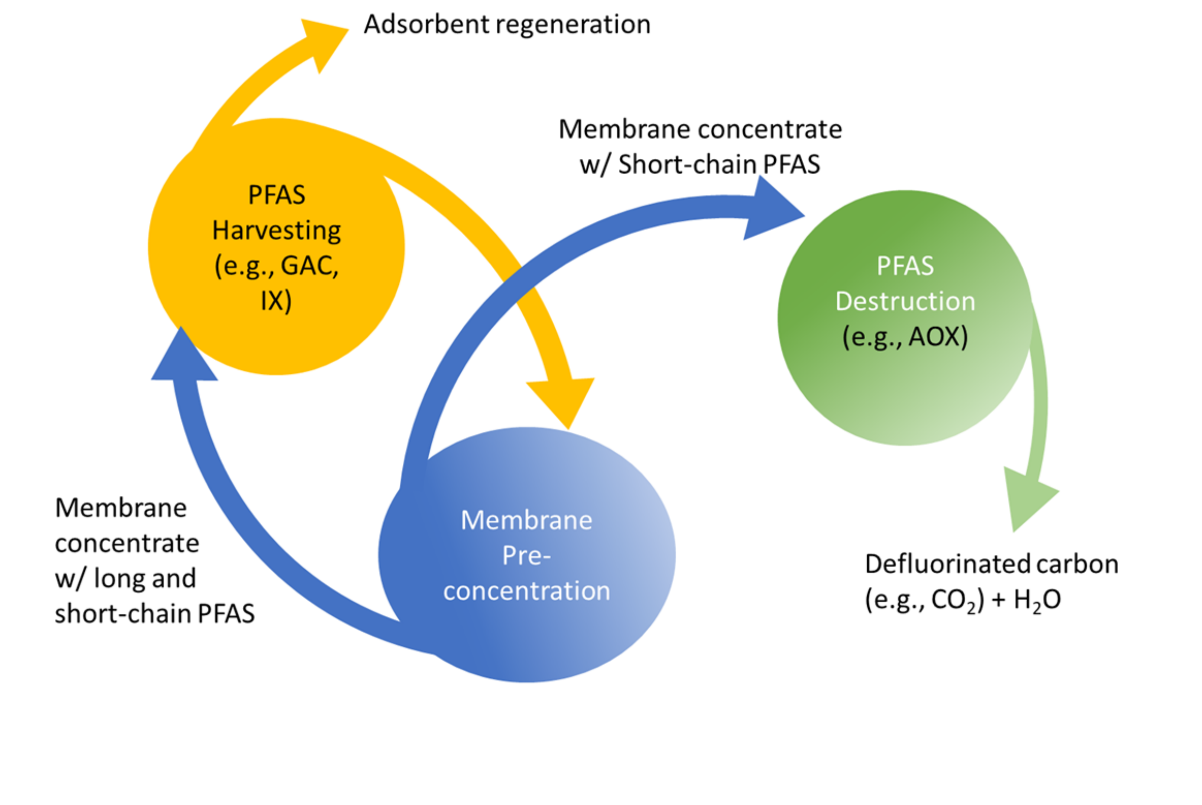


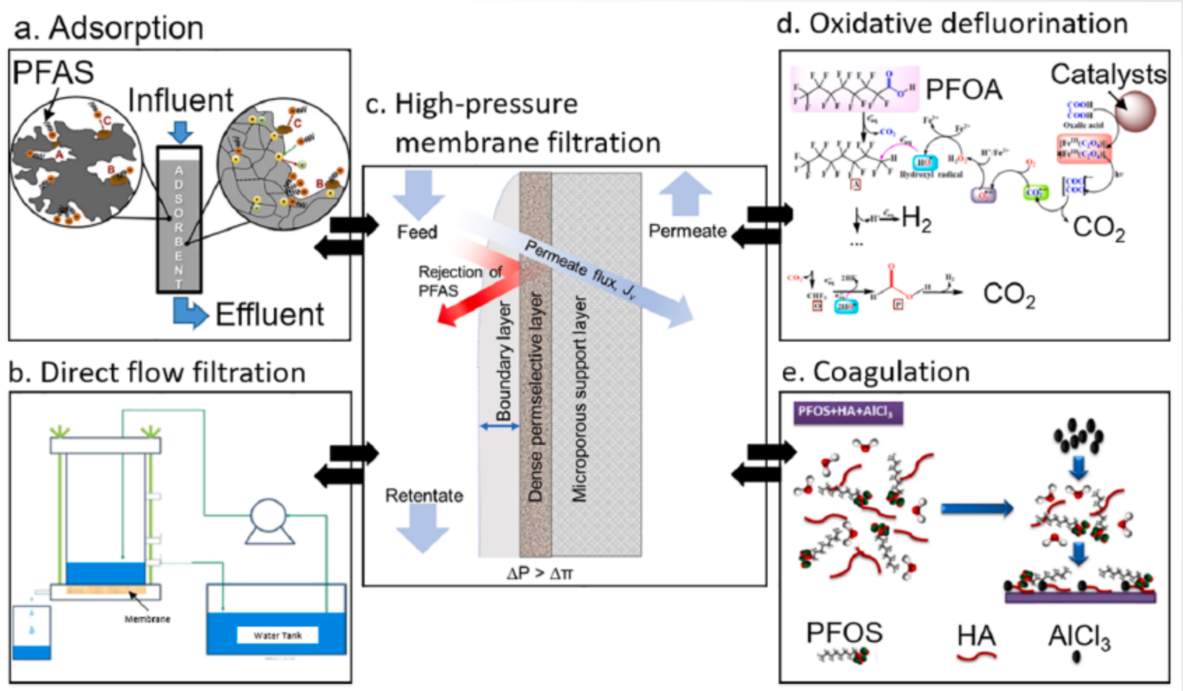
Source: Max Krause (2020)

Sequestering PFAS



RO in combined system (RO/GAC/AOX)





Likely very expensive, but a combined (hybrid) system approach may overcome treatment shortcomings

DWSRF Support: Emerging Contaminants

Background:

There is limited information available on the performance of treatment technologies for removing PFAS and other emerging contaminants (EC)

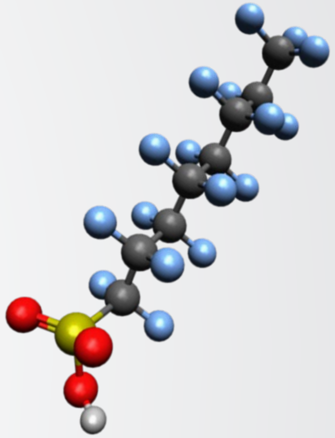
Objectives:

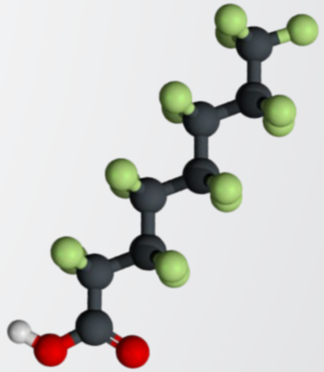
In direct support of BIL directive to address PFAS/EC, the program will:

1) Identify and implement sustainable and cost-effective PFAS/EC treatment technologies, with a particular focus on small and disadvantaged drinking water systems

This program will:

1) Help identify appropriate treatment technology to remove PFAS/EC from various waters and to manage any residual waste stream (solids, liquids, or gases) generated
2) Develop long-term PFAS/EC treatment performance and cost data
3) Develop tools (performance and cost models) and approaches (best practice guides) for determining effective treatment for PFAS/EC across the country





EPA Project Co-authors

- Nicholas Dugan
- Page Jordan
- Max Krause
- Jonathan Krug
- Tae Lee
- Marc Mills
- Mallikarjuna Nadagouda
- Phillip Potter
- William Roberson
- Endalkachew Sahle-Demessie
- Erin Shields

Membrane Concentrate Treatment Coauthors

- **Emily W. Tow**, F. W. Olin College of Engineering, Needham, MA
- **Mahmut Selim Ersan**, School of Sustainable Engineering and The Built Environment, Arizona State University, Tempe, AZ
- **Soyoon Kum**, David L. Hirschfeld Dept of Engineering, Angelo State University, San Angelo, TX
- **Tae Lee**, U.S. Environmental Protection Agency, Cincinnati, OH
- **Thomas F. Speth**, U.S. Environmental Protection Agency, Cincinnati, OH
- **Christine Owen**, Hazen and Sawyer, Clearwater, FL
- **Christopher Bellona**, Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, CO
- **Mallikarjuna N. Nadagouda**, U.S. Environmental Protection Agency, Cincinnati, OH
- **Anne M. Mikelonis**, U.S. Environmental Protection Agency, Durham, NC
- **Paul Westerhoff**, School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ
- **Chandra Mysore**, Jacobs, Atlanta, GA
- **Val S. Frenkel**, Greeley and Hansen, San Francisco, CA
- **Viraj deSilva**, Freese and Nichols, Tampa, FL
- **W. Shane Walker**, Department of Civil Engineering, University of Texas at El Paso, El Paso, TX
- **Andrew K. Safulko**, Brown and Caldwell, Denver, CO
- **David A. Ladner**, Clemson University, Anderson, SC


Check for updates

Received: 16 April 2021 | Revised: 15 June 2021 | Accepted: 5 July 2021
DOI: 10.1002/aws2.1233

REVIEW

AWWA WATER SCIENCE

TOPICAL COLLECTION ON PFAS ANALYTICS AND TREATMENT

Managing and treating per- and polyfluoroalkyl substances (PFAS) in membrane concentrates

Emily W. Tow[1] | Mahmut Selim Ersan[2] | Soyoon Kum[3] | Tae Lee[4] | Thomas F. Speth[4] | Christine Owen[5] | Christopher Bellona[6] | Mallikarjuna N. Nadagouda[4] | Anne M. Mikelonis[7] | Paul Westerhoff[2] | Chandra Mysore[8] | Val S. Frenkel[9] | Viraj deSilva[10] | W. Shane Walker[11] | Andrew K. Safulko[6] | David A. Ladner[12]

[1]F. W. Olin College of Engineering, Needham, Massachusetts, USA
[2]School of Sustainable Engineering and the Built Environment, Nanosystems Engineering Research Center for Nanotechnology Enabled Water Treatment (NEWT), Arizona State University, Tempe, Arizona, USA
[3]David L. Hirschfeld Department of Engineering, Angelo State University, San Angelo, Texas, USA
[4]Office of Research and Development, Center for Environmental Solutions and Emergency Response, U.S. Environmental Protection Agency, Cincinnati, Ohio, USA
[5]Hazen and Sawyer, Clearwater, Florida, USA
[6]Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, Colorado, USA
[7]Office of Research and Development, Center for Environmental Solutions and Emergency Response, U.S. Environmental Protection Agency, Durham, North Carolina, USA
[8]Jacobs, Atlanta, Georgia, USA
[9]Greeley and Hansen, San Francisco, California, USA
[10]Freese and Nichols, Inc., Tampa, Florida, USA
[11]Department of Civil Engineering, Center for Inland Desalination Systems (CIDS), Nanosystems Engineering Research Center for Nanotechnology-Enabled Water Treatment (NEWT), University of Texas at El Paso, El Paso, Texas, USA
[12]Department of Environmental Engineering and Earth Sciences, Clemson University, Clemson, South Carolina, USA

Correspondence
David A. Ladner, Department of Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC, USA.
Email: ladner@clemson.edu

Funding information
National Science Foundation: EEC-1449500

Guest Editor: Michelle Crimi
Guest Associate Editor: Zaid Chowdhury

Abstract
Per- and polyfluoroalkyl substances (PFAS), which are present in many waters, have detrimental impacts on human health and the environment. Reverse osmosis (RO) and nanofiltration (NF) have shown excellent PFAS separation performance in water treatment; however, these membrane systems do not destroy PFAS but produce concentrated residual streams that need to be managed. Complete destruction of PFAS in RO and NF concentrate streams is ideal, but long-term sequestration strategies are also employed. Because no single technology is adequate for all situations, a range of processes are reviewed here that hold promise as components of treatment schemes for PFAS-laden membrane system concentrates. Attention is also given to relevant

Disclaimer

The views expressed in this presentation are those of the individual authors and do not necessarily reflect the views and policies of the US EPA. Mention of trade names or commercial products does not constitute endorsement or recommendation for use

QUESTIONS?

Thomas Speth, Ph.D., P.E.
Senior Science Advisor
Center for Environmental Solutions and Emergency Response
Office of Research and Development
U.S. Environmental Protection Agency

speth.thomas@epa.gov

The views expressed in this presentation are those of the individual author and do not necessarily reflect the views and policies of the US EPA.

EPA PFAS Activities – www.epa.gov/pfas

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