Naval Facilities Engineering Systems Command

EXWC Engineering and Expeditionary Warfare Center

Groundwater Treatment Technologies for Per- and Polyfluoroalkyl Substances (PFAS): Sorption, Separation, and Destruction

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NAVFAC EXWC

RITS 2026

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Information in this presentation is current as of 24 April 2026.

EXWC: Engineering and Expeditionary Warfare Center
NAVFAC: Naval Facilities Engineering Systems Command

Speaker Introductions

Tony Danko, PhD, PE
NAVFAC EXWC

- Environmental Engineer
- 15+ years experience
- Natural attenuation, bioremediation, and environmental molecular diagnostic tools
- PFAS SME

John Kornuc, PhD
NAVFAC EXWC

- Physical Scientist
- 40 years experience
- Site characterization, remediation, treatment wetlands
- PFAS SME

PE: Professional Engineer
PhD: Doctor of Philosophy
SME: subject matter expert

Presentation Overview

- **Introduction**
- PFAS in the Subsurface: Properties and Treatment Challenges
- Regulatory Drivers, Guidance, and Policy
- Treatment
- Case Studies
- Guidelines for Selecting Water Treatment Technologies
- Summary/Key Takeaways

Purpose of Presentation

1. Understand the **chemical/physical properties of PFAS** and their **occurrence** in groundwater, and how these factors **impact treatment choices**
2. Evaluate **treatment technologies for PFAS in groundwater,** including technologies in current use and those in development at higher TRLs, for both ***ex situ* and *in situ* application**
3. Understand the general approach of **Separation/Concentration** followed by **Destruction**
4. Understand **technical and economic factors** influencing the selection of cost- effective treatments

TRL: technology readiness level

Past PFAS RITS

2015	• Emerging Information on Emerging Chemicals
2016	• Managing PFAS at Navy Sites
2017	• Risk Communication for PFAS Sites
2018	• PFAS Remediation: Technologies, Guidance, and Application
2019	• Managing Emerging Chemicals at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Sites • PFAS Site Characterization
2021	• Best Practices for Conducting PFAS Remedial Investigations
2022	• Navigating the 2021 EPA PFAS Strategic Roadmap • Emerging Technologies for PFAS Treatment
2023	• Best Practices for PFAS Sampling and Data Interpretation
2024	• Considerations for Conducting Ecological Risk Assessments (ERAs) at PFAS sites • Considerations for Human Health Risk Assessments (HHRAs) During Remedial Investigations at PFAS Sites
2025	• Remediation of PFAS-Impacted Solids
2026	• **We are HERE: Groundwater Treatment Technologies for PFAS: Sorption, Separation, and Destruction**

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What Makes PFAS Unique

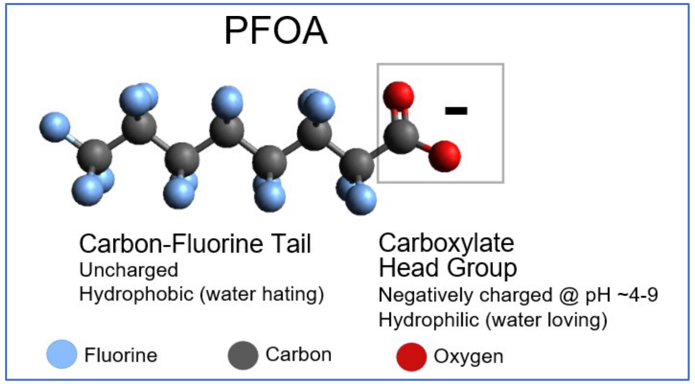
- PFAS are a large group of man-made chemicals (~15,000) characterized by carbon-fluorine bonds
- Degradation resistant—**persistent**
- Water soluble—**mobile**
- Some are **bioaccumulative** and linked to adverse health effects
- Used in many products and processes, in addition to AFFF—**ubiquitous**
- Low-level detections may reflect **background** ubiquity rather than a CERCLA/RCRA release
- FFTAs can have complex site histories using varied AFFF formulations; hundreds of PFAS typically present
- Plumes may have developed without detection for decades
- Challenging for traditional in situ destructive approaches: bioremediation, chemical oxidation/reduction, SVE, etc.

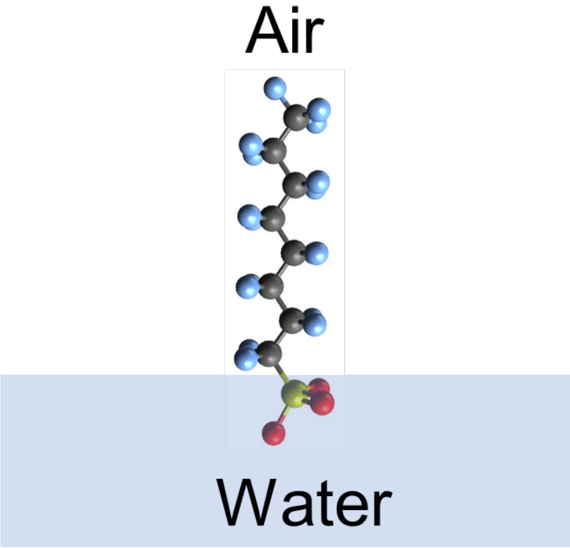
Firefighter Training, Camp Lemonnier, Djibouti Africa
(Denton 2011)

AFFF: aqueous film-forming foam
RCRA: Resource Conservation and Recovery Act
FFTA: firefighter training area
SVE: soil vapor extraction
PFAA: perfluoroalkyl acid

Chemistry

- **C-F bond** is one of organic chemistry's shortest and **strongest single bonds—**difficult to break
- PFAS are inherently both **hydrophobic and oleophobic**
- Most PFAS of current concern in water are **anions** at environmentally-relevant pH's
- **Cationic** and many **zwitterionic** PFAS have net positive charge and included in AFFF formulations; often **sorb** to negatively charged soil minerals
- Transport rates: **anions > zwitterions > cations**
- **Extreme Persistence:** little to no biodegradation or abiotic degradation, though precursor PFAS can transform to "dead end" PFAAs



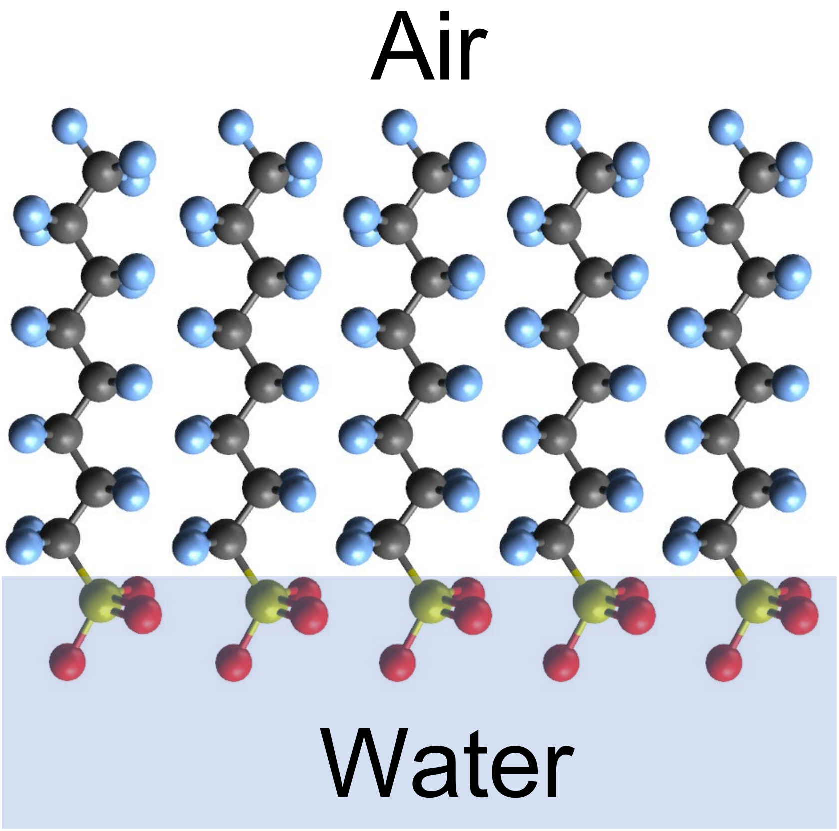


PFOS (***<u>per</u>***fluorooctane sulfonate)

(Kornuc 2024)

Air-Water Interface Sorption

- **Air-water interface** can account for 50%–75% of retention (Lyu et al. 2018)
- Hydrophilic polar head group seeks water; hydrophobic C-F tail avoids water by extending into air
  - **Influencing Factors**
    - Carbon chain length (longer means stronger air-water interface sorption)
    - Ionic strength
    - NAPL Significantly increases PFAS retention (McKenzie et al. 2016)
    - Groundwater composition dictates adsorption magnitudes (Brusseau and Glubt 2019)



(Kornuc 2024)

NAPL: nonaqueous phase liquid

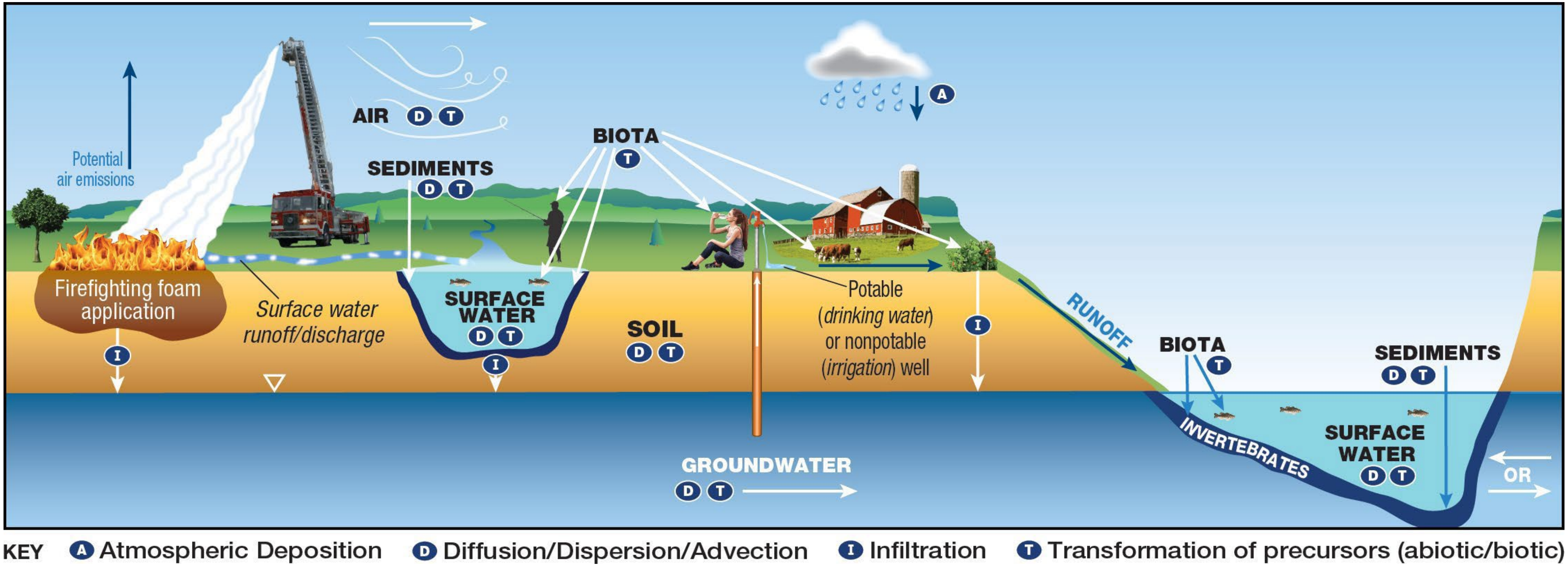
Low Vapor Pressure and Henry's Constant

PFAS have low vapor pressure and low Henry's Law constants; therefore **cannot be air-stripped**

Chemical Property	PCB (Arochlor 1260)	PFOA	PFOS	TCE	Benzene
Molecular Weight g/mol	357.7	414.07	538	131.5	78.11
Solubility mg/L ~20 °C	0.0027	3400-9500	519	1100	1780
Vapor Pressure mm Hg (25 °C)	4.05×10^{-5}	0.03	2.48×10^{-6}	77.5	97
Henry's Constant atm-m^3/mol	4.6×10^{-3}	3.57×10^{-6}	3.05×10^{-6}	0.0103	0.0056
Organic Carbon Part. Coeff. (log K_{oc})	4.8-6.8	2.06	2.57	2.42	2.15

(Adapted from AECOM 2015)

Fire Fighting Site CSM



"Environmental Fate and Transport for Per- and Polyfluoroalkyl Substances (PFAS)", ITRC, 2023.

Key: An accurate CSM is essential in developing treatment strategies

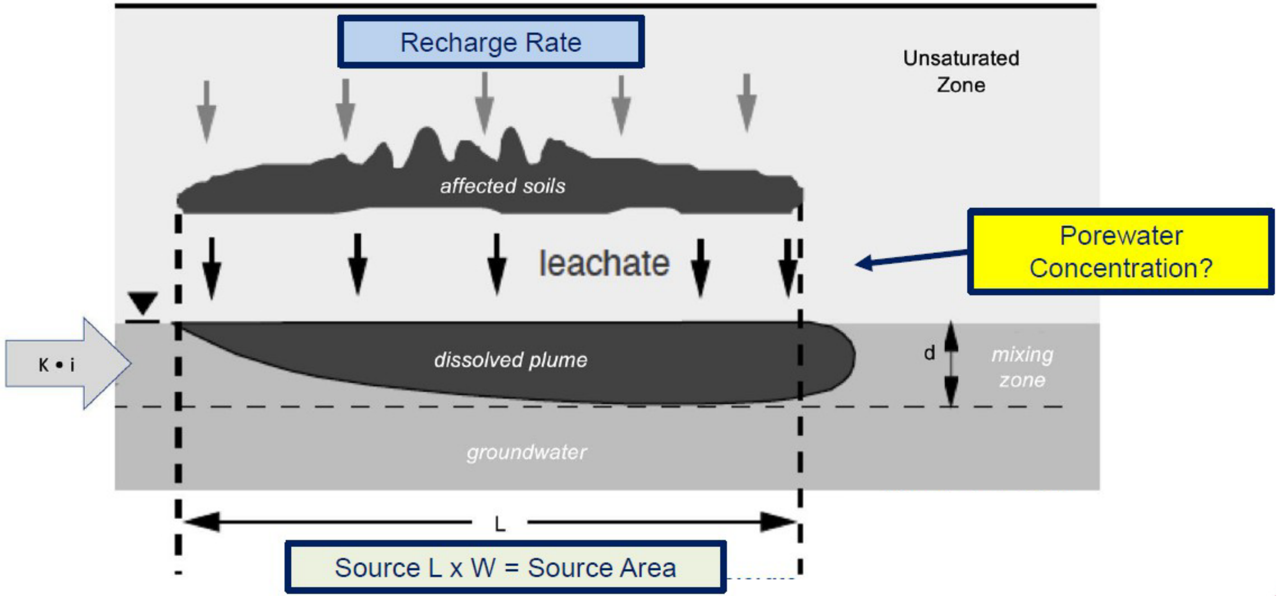
CSM: conceptual site model

Plume Characteristics

- Large dilute plumes
- Plumes long/wide of low concentration (outside of source area)
  - low analytical detection levels (< 1 ng/L) "increases" plume size
  - bulk of plume often <100 ng/L
- PFOS and PFOA typically among highest concentrations
  - PFHxS, 6:2 FTS also high
  - AFFF sites have highest levels in DoW

Recharge x *PFAS Leachate Concentration* = **PFAS Mass Flux**

PFAS *Mass Flux* x *Area* = **PFAS Mass Discharge (mass/time)**



(Schaefer and Newell 2025)

DoW: Department of War
PFOA: perfluorooctanoic acid

FTS: fluorotelomer sulfonic acid
PFOS: perfluorooctansulfonic acid

ng/L: nanograms per liter
PFHxS: perfluorohexanesulfonic acid

Take Aways: PFAS Characteristics

- PFAS are highly resistant to degradation
  - Precursors can transform into intermediates or persistent, terminal PFAAs
  - Recalcitrance makes conventional treatments largely ineffective
- Air-water interfacial sorption is a major retention mechanism in unsaturated media, responsible for 50%–75% of retardation
- Low vapor pressure and low Henry's Law constants means PFAS cannot be air-stripped
- Transport rates depend on PFAS ionic charge (anions > zwitterions > cations) and carbon chain length (shorter = faster)
  - Transport of carboxylates (PFCAs) > sulfonates (PFSAs) of same C-F chain lengths

PFCA: perfluoroalkyl carboxylic acid
PFSA: perfluorosulfonic acid

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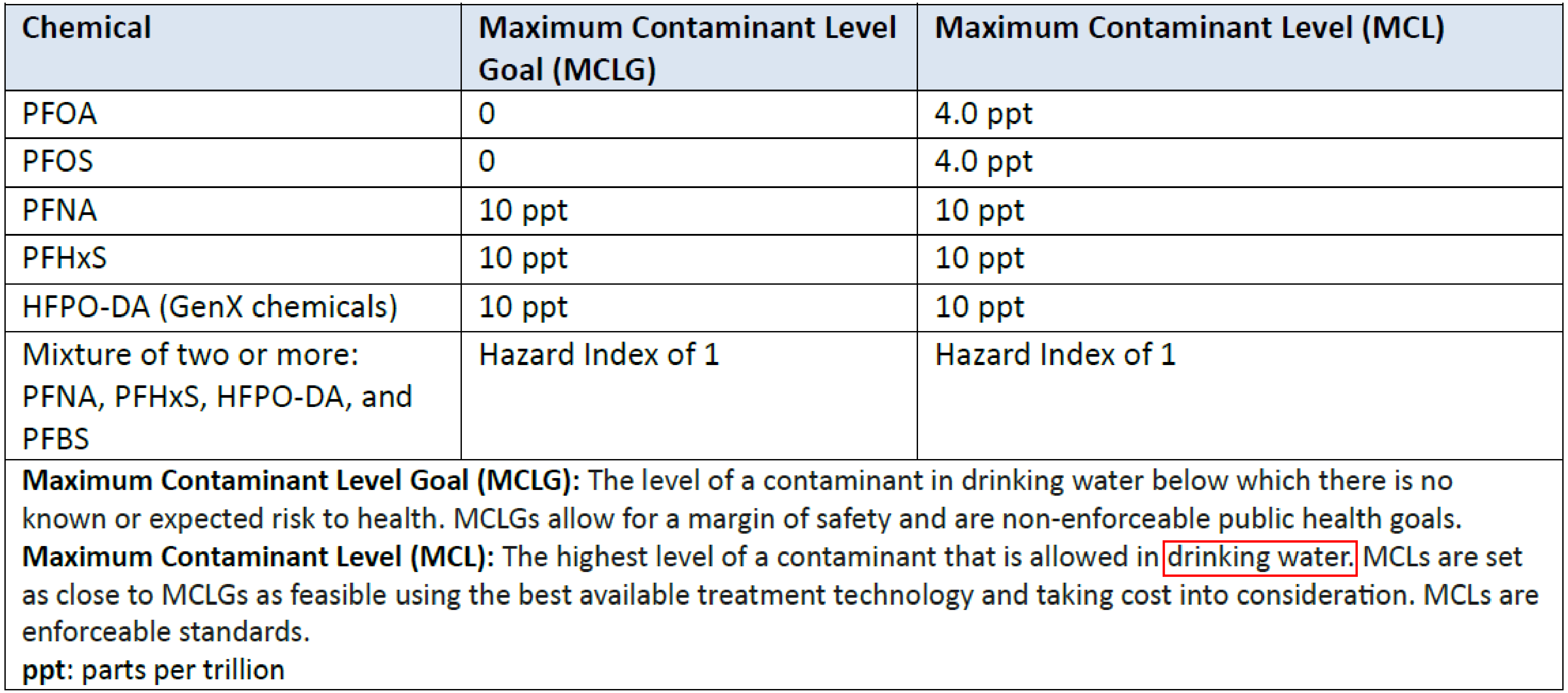
Regulatory Drivers, Guidance and Policy

- US EPA MCLs April 10, 2024 – Maximum Contaminant Levels for 5 PFAS and a Hazard Index (HI) for 2 or more of 4 PFAS (including PFBS, but not PFOS or PFOA)
- MCLs are NOT cleanup levels for groundwater; PFAS not included in RCRA, CAA or CWA

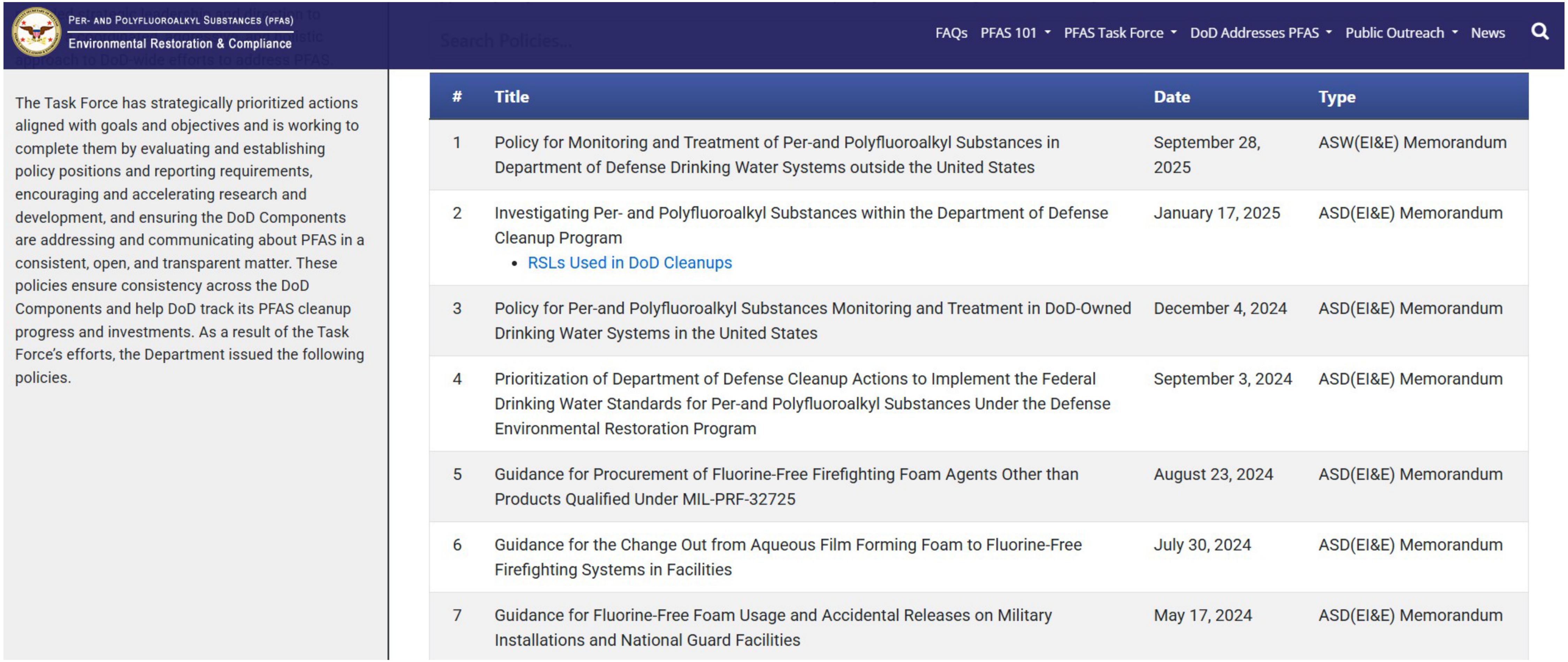


Chemical	**Maximum Contaminant Level Goal (MCLG)**	**Maximum Contaminant Level (MCL)**
PFOA	0	4.0 ppt
PFOS	0	4.0 ppt
PFNA	10 ppt	10 ppt
PFHxS	10 ppt	10 ppt
HFPO-DA (GenX chemicals)	10 ppt	10 ppt
Mixture of two or more: PFNA, PFHxS, HFPO-DA, and PFBS	Hazard Index of 1	Hazard Index of 1

Maximum Contaminant Level Goal (MCLG): The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals.
Maximum Contaminant Level (MCL): The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards.
ppt: parts per trillion

https://www.epa.gov/sdwa/and-polyfluoroalkyl-substances-pfas (EPA 2024)

Regulatory Drivers, Guidance and Policy



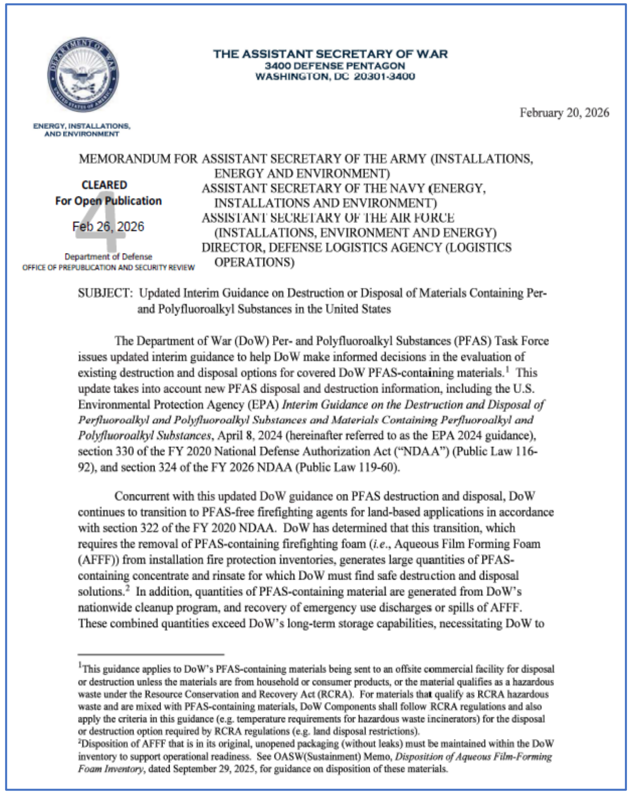
The Task Force has strategically prioritized actions aligned with goals and objectives and is working to complete them by evaluating and establishing policy positions and reporting requirements, encouraging and accelerating research and development, and ensuring the DoD Components are addressing and communicating about PFAS in a consistent, open, and transparent matter. These policies ensure consistency across the DoD Components and help DoD track its PFAS cleanup progress and investments. As a result of the Task Force's efforts, the Department issued the following policies.

#	Title	Date	Type
1	Policy for Monitoring and Treatment of Per-and Polyfluoroalkyl Substances in Department of Defense Drinking Water Systems outside the United States	September 28, 2025	ASW(EI&E) Memorandum
2	Investigating Per- and Polyfluoroalkyl Substances within the Department of Defense Cleanup Program • RSLs Used in DoD Cleanups	January 17, 2025	ASD(EI&E) Memorandum
3	Policy for Per-and Polyfluoroalkyl Substances Monitoring and Treatment in DoD-Owned Drinking Water Systems in the United States	December 4, 2024	ASD(EI&E) Memorandum
4	Prioritization of Department of Defense Cleanup Actions to Implement the Federal Drinking Water Standards for Per-and Polyfluoroalkyl Substances Under the Defense Environmental Restoration Program	September 3, 2024	ASD(EI&E) Memorandum
5	Guidance for Procurement of Fluorine-Free Firefighting Foam Agents Other than Products Qualified Under MIL-PRF-32725	August 23, 2024	ASD(EI&E) Memorandum
6	Guidance for the Change Out from Aqueous Film Forming Foam to Fluorine-Free Firefighting Systems in Facilities	July 30, 2024	ASD(EI&E) Memorandum
7	Guidance for Fluorine-Free Foam Usage and Accidental Releases on Military Installations and National Guard Facilities	May 17, 2024	ASD(EI&E) Memorandum

https://www.acq.osd.mil/eie/eer/ecc/pfas/tf/policies.html

(OSD 2026)

Updated Interim Guidance on Destruction or Disposal



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ENERGY, INSTALLATIONS,
AND ENVIRONMENT

February 20, 2026

CLEARED
For Open Publication
Feb 26, 2026
Department of Defense
OFFICE OF PREPUBLICATION AND SECURITY REVIEW

MEMORANDUM FOR ASSISTANT SECRETARY OF THE ARMY (INSTALLATIONS, ENERGY AND ENVIRONMENT)
ASSISTANT SECRETARY OF THE NAVY (ENERGY, INSTALLATIONS AND ENVIRONMENT)
ASSISTANT SECRETARY OF THE AIR FORCE (INSTALLATIONS, ENVIRONMENT AND ENERGY)
DIRECTOR, DEFENSE LOGISTICS AGENCY (LOGISTICS OPERATIONS)

SUBJECT: Updated Interim Guidance on Destruction or Disposal of Materials Containing Per- and Polyfluoroalkyl Substances in the United States

The Department of War (DoW) Per- and Polyfluoroalkyl Substances (PFAS) Task Force issues updated interim guidance to help DoW make informed decisions in the evaluation of existing destruction and disposal options for covered DoW PFAS-containing materials.[1] This update takes into account new PFAS disposal and destruction information, including the U.S. Environmental Protection Agency (EPA) *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances*, April 8, 2024 (hereinafter referred to as the EPA 2024 guidance), section 330 of the FY 2020 National Defense Authorization Act ("NDAA") (Public Law 116-92), and section 324 of the FY 2026 NDAA (Public Law 119-60).

Concurrent with this updated DoW guidance on PFAS destruction and disposal, DoW continues to transition to PFAS-free firefighting agents for land-based applications in accordance with section 322 of the FY 2020 NDAA. DoW has determined that this transition, which requires the removal of PFAS-containing firefighting foam (*i.e.*, Aqueous Film Forming Foam (AFFF)) from installation fire protection inventories, generates large quantities of PFAS-containing concentrate and rinsate for which DoW must find safe destruction and disposal solutions.[2] In addition, quantities of PFAS-containing material are generated from DoW's nationwide cleanup program, and recovery of emergency use discharges or spills of AFFF. These combined quantities exceed DoW's long-term storage capabilities, necessitating DoW to

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[1] This guidance applies to DoW's PFAS-containing materials being sent to an offsite commercial facility for disposal or destruction unless the materials are from household or consumer products, or the material qualifies as a hazardous waste under the Resource Conservation and Recovery Act (RCRA). For materials that qualify as RCRA hazardous waste and are mixed with PFAS-containing materials, DoW Components shall follow RCRA regulations and also apply the criteria in this guidance (e.g. temperature requirements for hazardous waste incinerators) for the disposal or destruction option required by RCRA regulations (e.g. land disposal restrictions).

[2] Disposition of AFFF that is in its original, unopened packaging (without leaks) must be maintained within the DoW inventory to support operational readiness. See OASW(Sustainment) Memo, *Disposition of Aqueous Film-Forming Foam Inventory*, dated September 29, 2025, for guidance on disposition of these materials.

(DoW 2026b)

NDAA moratorium on Incineration: Incineration now permitted for RCRA waste that also contains PFAS materials (See Footnote 1 of Guidance). Also need to reach destruction temperature of 1,100°C and have proper permits.

Destruction/Disposal Options Identified: DoW has identified the following commercially available options to be used by the DoW Components (with environmental permits)

- Carbon reactivation units (for used GAC only)
- Hazardous waste landfills
- Solid waste landfills that have composite liners, and gas and leachate collection and treatment systems (not an option for AFFF concentrate)
- Hazardous waste incinerators
- Underground injection control wells
- Thermal desorption units that use off-gas collection and thermal oxidation with environmental permits (for soils)
- Other PFAS destruction options, with pre-notification to OASW(EI&E)
    - E.g., mechanochemical degradation, electrochemical oxidation, gasification and pyrolysis, and SCWO, but only SCWO is currently permitted.

Details provided at https://www.acq.osd.mil/eie/eer/ecc/pfas/index.html

GAC: granular activated carbon
EPA: United States Environmental Protection Agency
NDAA: National Defense Authorization Act

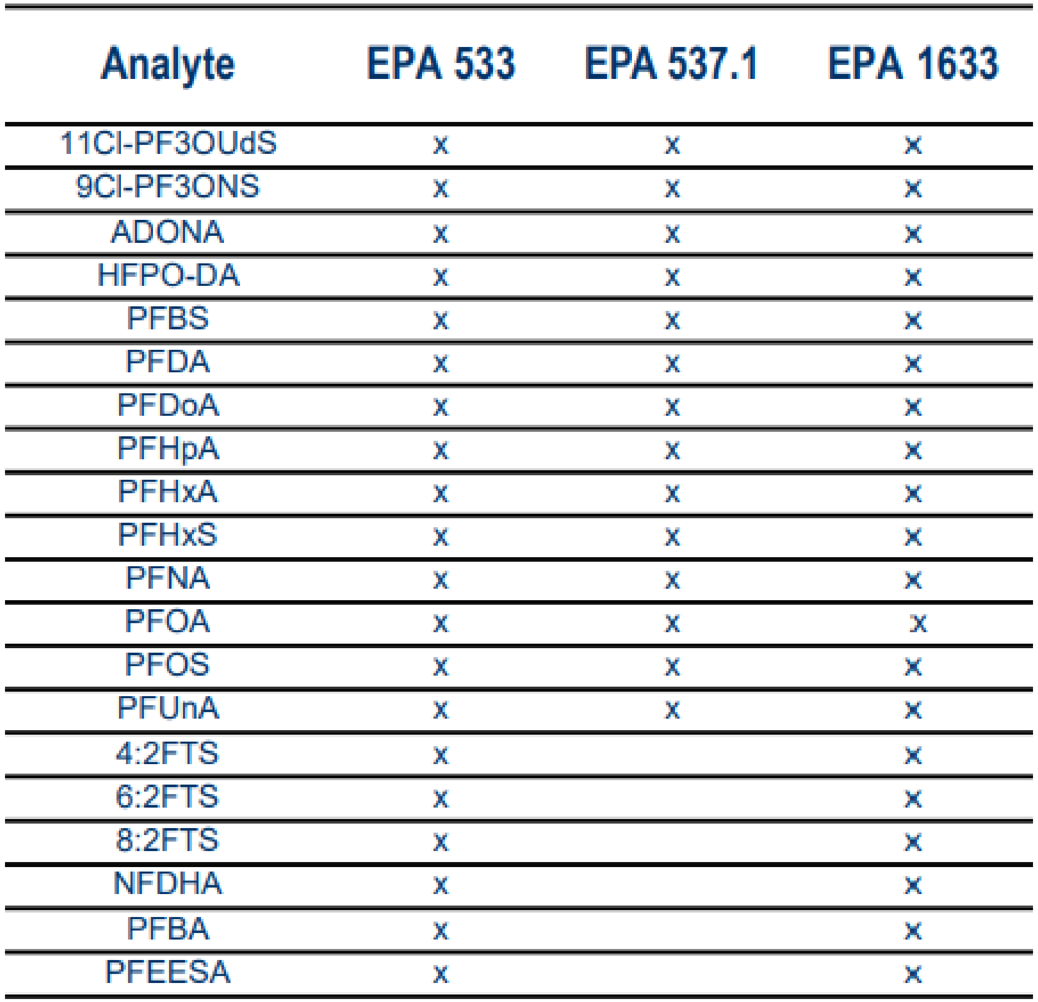
OASW(EI&E):Office of the Assistant Secretary of War for Energy, Installations, and Environment
SCWO: supercritical water oxidation

Analytical Method for Groundwater

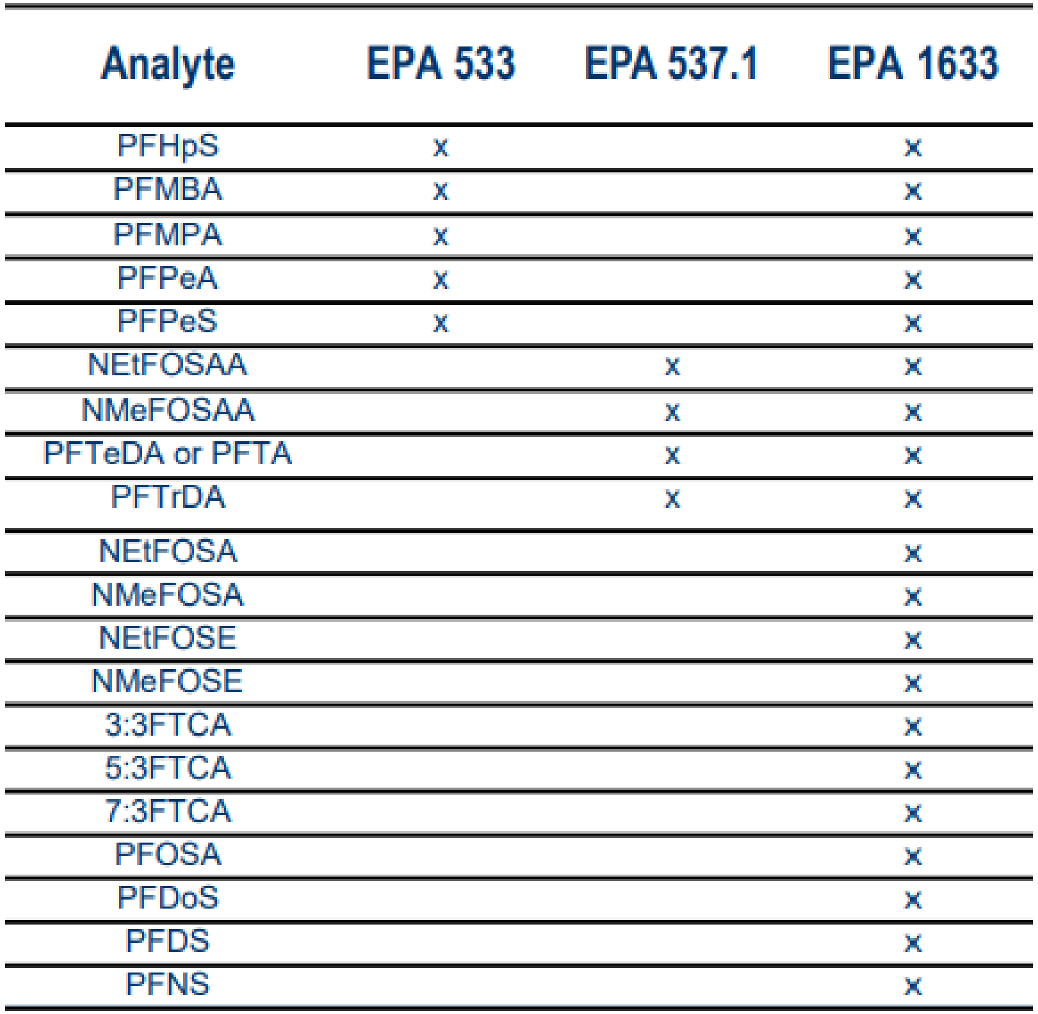
- **EPA 1633** is the required method for **nondrinking water matrices including groundwater**
- **EPA 1633 ~40** compounds in aqueous, solid, tissue, and landfill media
- Method 533 is now the recommended method for drinking water (537.1 includes 4 additional PFAS which are low occurrence for DoW)
- Prior PFAS Analytical Methods listed as few as 3 analytes, so early reporting may not have included some PFAS (did not mean they were "nondetect")
- Some accredited labs that offer 533 also include some of the 4 additional PFAS in 537.1 as part of 533
- Ensure current lab accreditation for all analytes and matrices

  https://www.denix.osd.mil/edqw/accreditation/accreditedlabs/

EPA Methods 537.1, 533, and1633 Analyte Comparison



Analyte	EPA 533	EPA 537.1	EPA 1633
11Cl-PF3OUdS	x	x	x
9Cl-PF3ONS	x	x	x
ADONA	x	x	x
HFPO-DA	x	x	x
PFBS	x	x	x
PFDA	x	x	x
PFDoA	x	x	x
PFHpA	x	x	x
PFHxA	x	x	x
PFHxS	x	x	x
PFNA	x	x	x
PFOA	x	x	x
PFOS	x	x	x
PFUnA	x	x	x
4:2FTS	x		x
6:2FTS	x		x
8:2FTS	x		x
NFDHA	x		x
PFBA	x		x
PFEESA	x		x



Analyte	EPA 533	EPA 537.1	EPA 1633
PFHpS	x		x
PFMBA	x		x
PFMPA	x		x
PFPeA	x		x
PFPeS	x		x
NEtFOSAA		x	x
NMeFOSAA		x	x
PFTeDA or PFTA		x	x
PFTrDA		x	x
NEtFOSA			x
NMeFOSA			x
NEtFOSE			x
NMeFOSE			x
3:3FTCA			x
5:3FTCA			x
7:3FTCA			x
PFOSA			x
PFDoS			x
PFDS			x
PFNS			x

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Treatment: The Two General Categories

1. **Separate and concentrate**
   - Includes both in situ and ex situ processes
2. Destroy/Mineralize (Concentrates)

Separation and Concentration from Water

Technology Category	Technology	Maturity/Availability (May 2026)
Sorption	Activated Carbon*	Commercialized, can be purchased from vendors
	Anion Exchange Resin*	
	Zeolites/Modified clays	
	Cyclodextrin	
Concentration	Foam Fractionation	
Membrane Filtration	Reverse Osmosis/Nanofiltration	
Coagulation	Specialty Coagulants	Full Scale application being conducted by researchers

Separation and Concentration: Proven Technologies

Sorption

- Granular Activated Carbon (GAC)
- Ion exchange (IX) resin

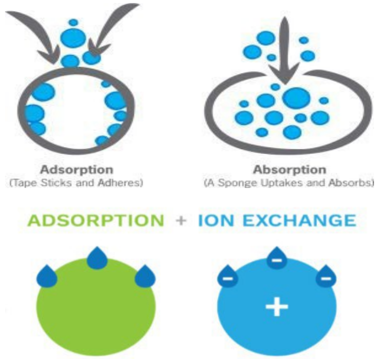
Membrane

- Separation based on size

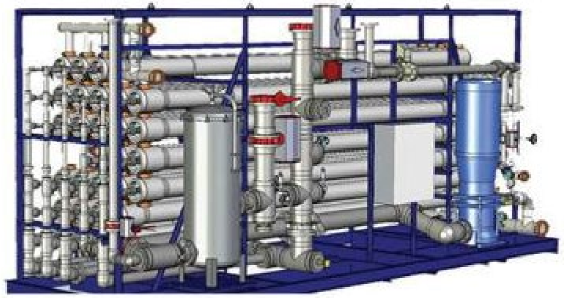
Foam Fractionation

- Air/Water Interfacial Concentration

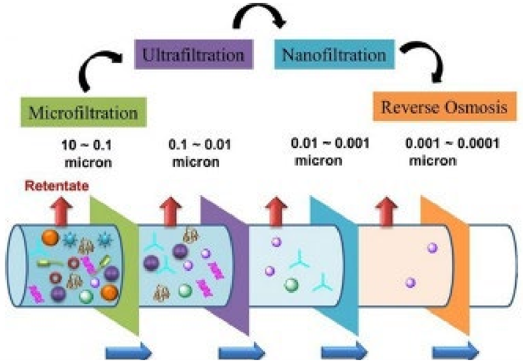
(Pelton Environmental 2025)



(Calgon Carbon 2026)



(Brownlee-Morrow 2025)



(Elsevier 2024)

(Allonnia 2026)

- **More recently proven**
- **Wider performance variability**

Pump-and-Treat – Granular Activated Carbon

- **Granular activated carbon (GAC)**
  - **Adsorbs PFAS** primarily by hydrophobic interactions (van der Waals forces)
    - Long C-F chain = more hydrophobic, greater affinity
    - Short chain = lower affinity
  - Typically used for **groundwater in pump-and-treat** systems (also in situ applications)
  - **Lead/lag** configuration
  - Is **widely available**; bituminous GACs (e.g. F400) more effective, simple to operate, established for remediation and drinking water production

- Can be used for **high TDS** (salinity) water
- **Limitations:** Early breakthrough of short-chain PFAS; natural organic matter competes w/ PFAS binding; media replacement generates PFAS-laden solid needing disposal/reactivation

(Todd 2026)

TDS: total dissolved solids

Pump-and-Treat – GAC

- **GAC**
  - Standard vessel sizes available on short notice, though increasing demand for PFAS treatment may require longer lead times
  - As lead vessel loads up with PFAS, short chain PFAS (esp. PFCAs) break through in effluent; lag vessel then sorbs these PFAS
  - Valves switched so lag vessel becomes new lead vessel


(Calgon Carbon 2022)

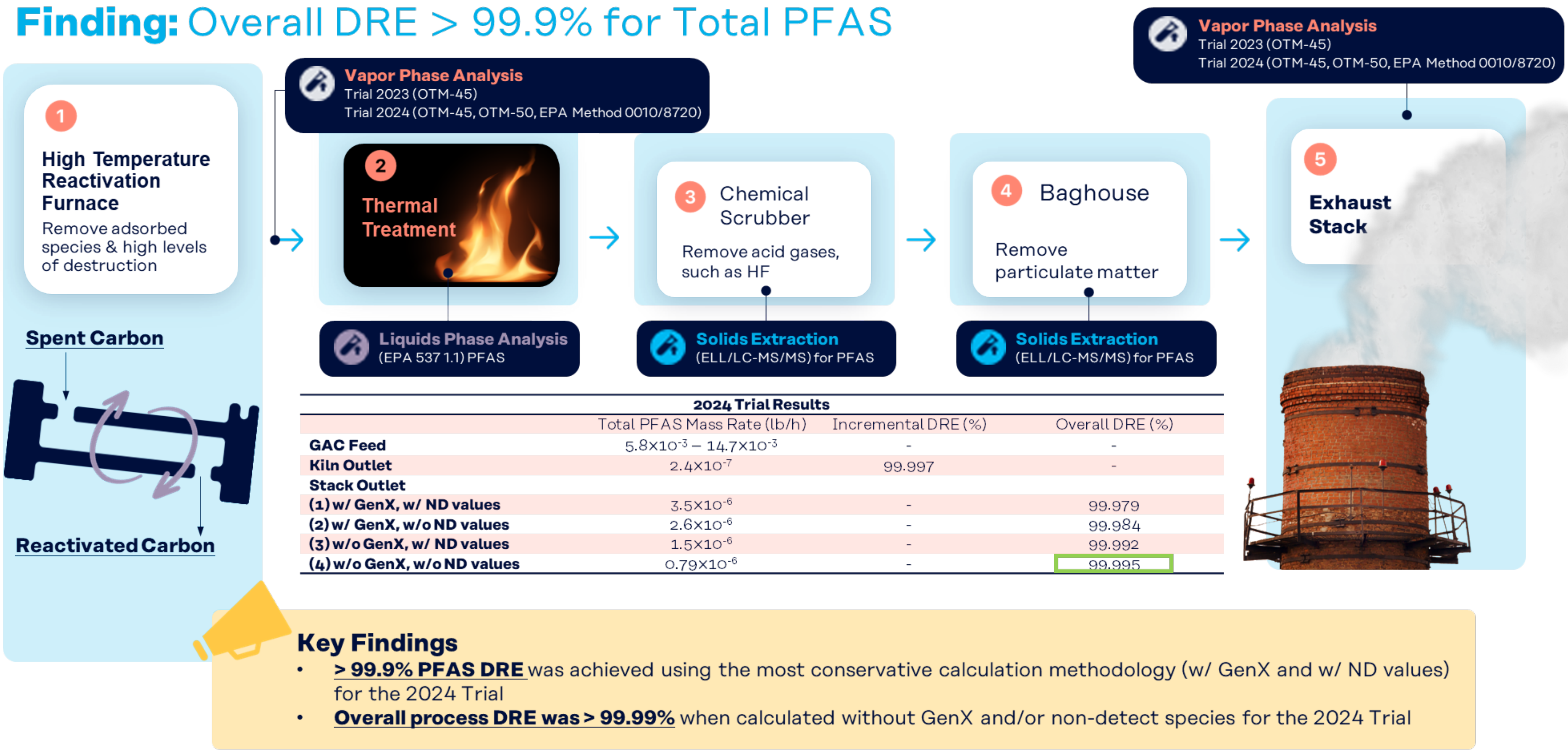
- Spent GAC exchanged out for new (which becomes new lag vessel)
  - Spent GAC can be disposed or **reactivated** (*regeneration* is a different process, carried out in the vessel on-site at lower temperatures using steam, but inappropriate for GAC with PFAS)

Pump-and-Treat, GAC Reactivation

- GAC Reactivation (Calgon) takes place in one of six United States furnaces (Norit also performs reactivation in Oklahoma)
    - Three for potable water—New York, Ohio, and Arizona (a fourth location planned for South Carolina); also Italy and Belgium
    - GAC heated (to 1,000°C) in a rotary kiln to high temperature with limited oxygen and the PFAS destroyed
    - Batches of GAC are kept separate during treatment so they are returned to the same customer as reactivated GAC (which decreases costs ~30%+)
    - Three for nonpotable water—Pennsylvania, Kentucky, Texas— GAC from various customers is mixed during reactivation in Herreshoff furnace (difficult to segregate batches)
    - Carbon profiling (description of use, laboratory analyses) required for reactivation and must conform to limits for certain constituents (e.g. Hg, Pb, Cl, F)

(Calgon Carbon 2025)

Pump-and-Treat, GAC Reactivation



Finding: Overall DRE > 99.9% for Total PFAS

Vapor Phase Analysis
Trial 2023 (OTM-45)
Trial 2024 (OTM-45, OTM-50, EPA Method 0010/8720)

1 **High Temperature Reactivation Furnace**
Remove adsorbed species & high levels of destruction

2 **Thermal Treatment**

3 Chemical Scrubber
Remove acid gases, such as HF

4 Baghouse
Remove particulate matter

5 **Exhaust Stack**

Liquids Phase Analysis
(EPA 537 1.1) PFAS

Solids Extraction
(ELL/LC-MS/MS) for PFAS

Solids Extraction
(ELL/LC-MS/MS) for PFAS

Spent Carbon

Reactivated Carbon

2024 Trial Results

	Total PFAS Mass Rate (lb/h)	Incremental DRE (%)	Overall DRE (%)
GAC Feed	$5.8\times10^{-3} – 14.7\times10^{-3}$	-	-
Kiln Outlet	2.4×10^{-7}	99.997	-
Stack Outlet			
(1) w/ GenX, w/ ND values	3.5×10^{-6}	-	99.979
(2) w/ GenX, w/o ND values	2.6×10^{-6}	-	99.984
(3) w/o GenX, w/ ND values	1.5×10^{-6}	-	99.992
(4) w/o GenX, w/o ND values	0.79×10^{-6}	-	99.995

Key Findings

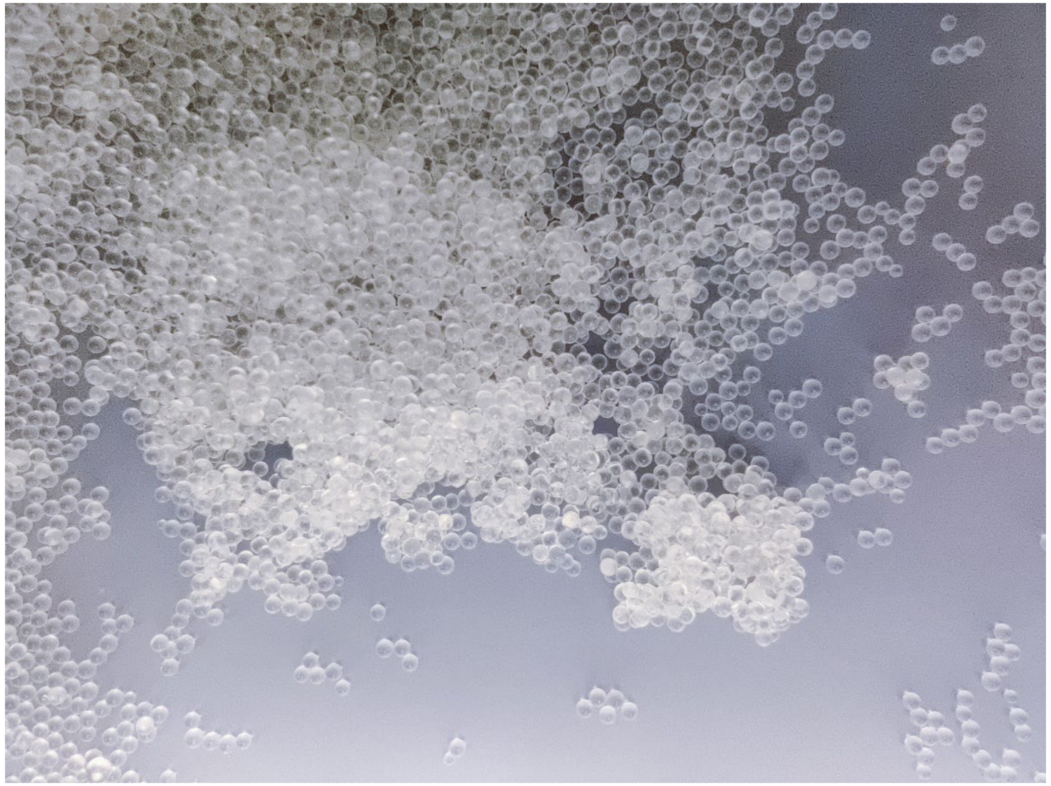
- **> 99.9% PFAS DRE** was achieved using the most conservative calculation methodology (w/ GenX and w/ ND values) for the 2024 Trial
- **Overall process DRE was > 99.99%** when calculated without GenX and/or non-detect species for the 2024 Trial

DRE: destruction and removal efficiency

(Calgon Carbon 2025)

Ion Exchange Resin

- **Adsorbs PFAS** primarily by ionic interactions
- Higher capacity per unit volume compared to GAC and shorter EBCTs (1–2 minutes vs 10–15 minutes) result in **smaller reactors**
- Single use resin most common use; may perform better than GAC for short chain and other PFAS
- Regenerable resins available but perform less well than single use and requires infrastructure to regenerate
- Cost per mass PFAS removed similar to GAC
- **Cannot** be used for **high TDS** (salinity) water
- Limitations: Early breakthrough of short-chain PFAS; natural organic matter competes w/ PFAS binding (but less than GAC); media replacement generates PFAS-laden solid needing disposal



IX resin: Purolite PFA694E, single use resin. Styrene beads 0.6-0.75 mm diameter, coated with a quaternary amine and exchangeable cation.
(Kornuc 2026)

mm: millimeter(s)
EBCT: empty bed contact time

Other Sorbents

- Cyclodextrin (Dexsorb): a D-glucose polymer (starch) chemically modified by cross-linking
  - Cup-shaped with a 0.78 nm open end, only allowing small molecules such as PFAS to enter
  - Molecular exclusion limits large organic molecules such as NOM (e.g., humic acids) from entering and depleting binding capacity, reserving binding capacity for PFAS and other small molecules which can fit into the opening
  - High capacity similar to IX
  - Regenerable using base and alcohol (by returning to manufacturer, Cyclopure)
- Other types of GAC (e.g. coconut shell): these less costly forms of GAC can be used to remove NOM to reserve binding capacity of more costly bituminous GAC to bind PFAS
- Modified clays (Fluorosorb): less costly than GAC, can also be effective, also good for up-front treatment to remove NOM in series with F400 GAC

KEY POINT

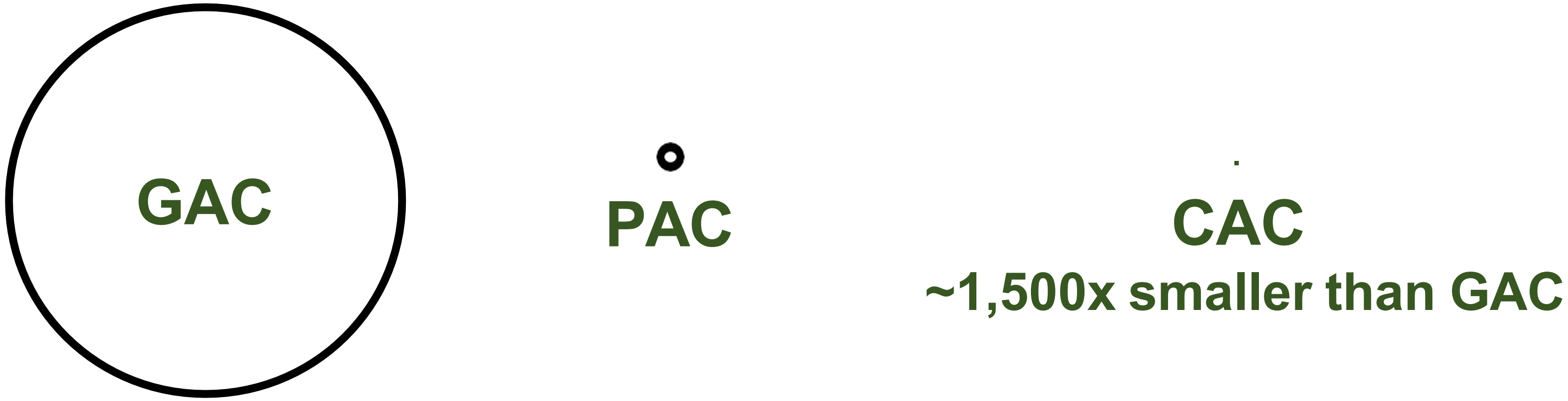
Treatability testing should be conducted where large amounts of sorbent are anticipated to be purchased; even small differences in cost of materials/ performance can translate to large costs over the life of a project.

nm: nanometer

NOM: natural organic matter

In Situ Sorption: Enhanced Retention

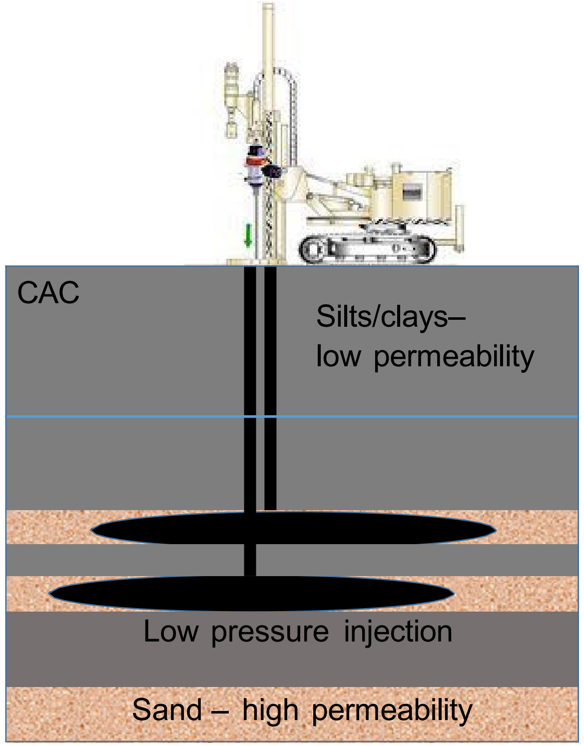
- Binding mechanisms same as ex situ sorption
  - Sorbents can include activated carbon, IX, cationic polymers, modified clays
- Most applications have used activated carbon
- GAC → CAC with a particle size in the lower µm range
  - GAC generally 0.4–1.2 mm; PAC ~ 0.075 mm; CAC 0.1–3 micron (0.003 mm)
  - CAC can be suspended for better aquifer injection, mobility/flow in porous media, and deposition onto soils and sediment



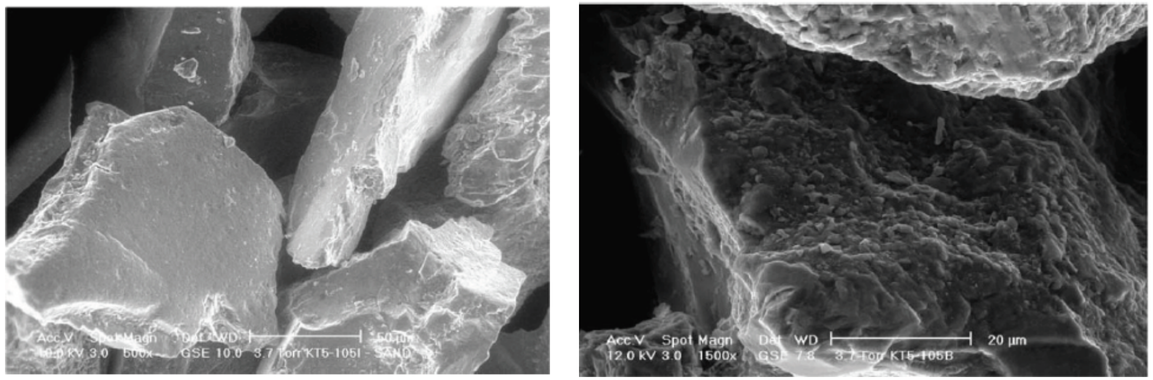
CAC: colloidal activated carbon

In Situ Sorption: Enhanced Retention

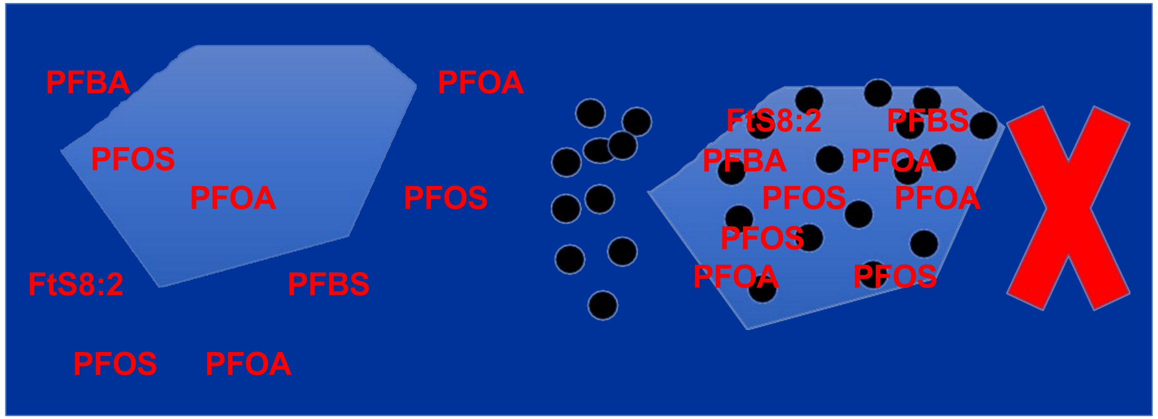
CAC is now being marketed and applied as an in situ adsorbent and sequestrant for **PFAS**



(Hatzinger 2020)



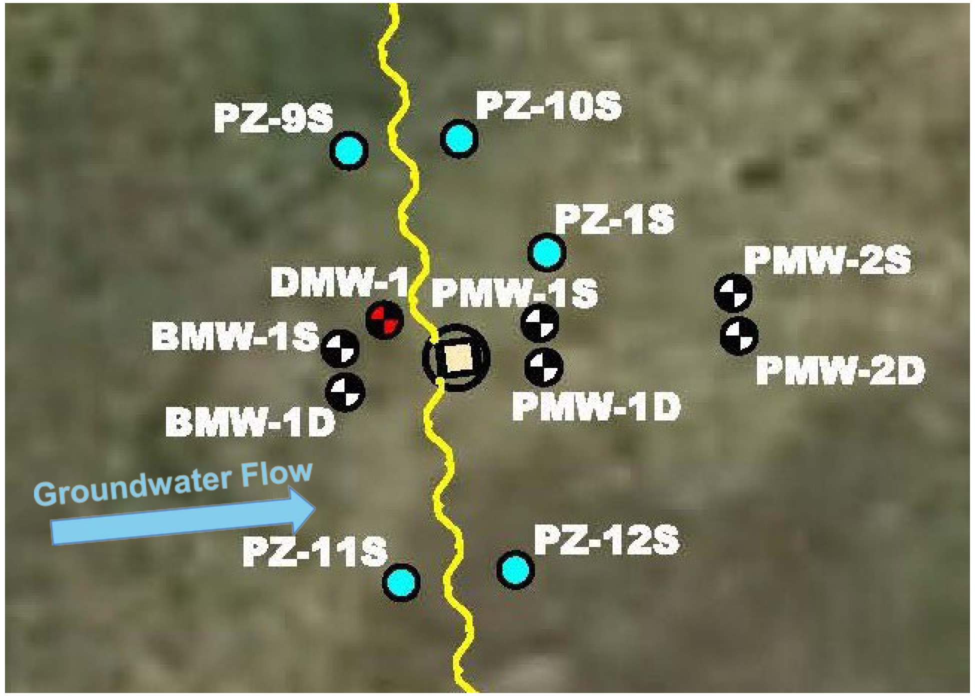
(Birnstingl et al. 2014)



(Hatzinger 2020)

In Situ Sorption: Funnel and Gate

Most applications have focused on injections of the sorbent, but teams are exploring funnel and gate applications



ESTCP ER20-5252

Sheet Pile Installation

Completed Funnel & Gate

- Protective vault in cement pad
- High visibility cones & chain

(Lippincott 2024)

In Situ Sorption Considerations (1)

- Column testing was a useful tool in assisting dosing requirements and answering questions from the agencies
- Some surfacing of CAC should be expected
  - Causes: Misunderstood aquifer characteristics, oversized pumps, or short-circuiting via poorly constructed wells
  - Important to evaluate avenues for migration of CAC prior to injection
- Photographic logs and a CAC distribution assessment are recommended
- Downgradient well performance variability increases with distance from treatment zone
- Barrier longevity (i.e. sorption capacity
  - More rapid breakthrough of shorter chains and carboxylates

In Situ Sorption Considerations (2)

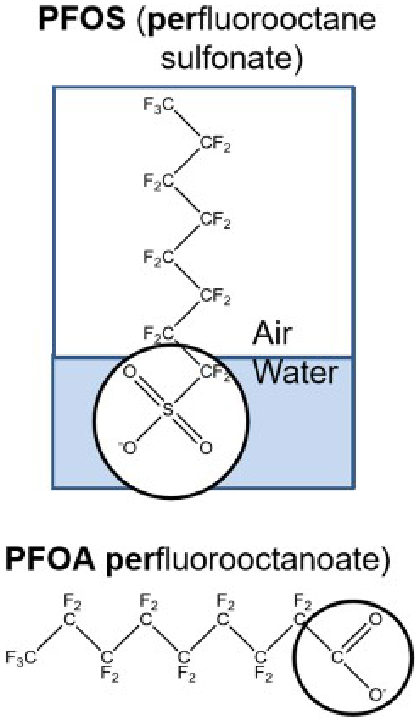
- Water levels should be used to determine if flow is going around the barrier (piezometers, transducers, etc.)
- CSM and the site itself plays a significant role in the design and implementation of CAC injection locations, etc.
- Well inspection (especially in barrier wells) and rehabilitation should be included due to CAC migration during and after injection
- Geologic considerations
  - High permeability zones, low pressure injection
- Unlikely to be a standalone remedy
- Can be part of a treatment train
- Can be useful as an interim action to help mitigate migration to sensitive receptors

In Situ Sorption Considerations (3)

- If a CAC barrier is being considered, additional site investigation may be needed to assist in barrier design and performance assessments
  - Obtain sorption parameters (co-located soil and GW PFAS concentrations)
  - Fraction of organic carbon
- Importance of water table fluctuations in interpreting results, as well as the height of these barriers (tidal and seasonal rainfalls)
- Coastal sites may have challenges that are not present at freshwater sites
  - Tides, impact of geochemistry, etc.
- Note that not all amendments have been thoroughly demonstrated.
- **Please check with your SME!**

Foam Fractionation

- Exploits air/water interface sorption of PFAS using bubbles
- PFAS concentrate in foam layer; foam can be skimmed off
- Excellent mass separation for high strength liquid matrices
  - GW, IDW, Wastewater, Landfill Leachate
- Both in situ and ex situ approaches
  - Allonnia (SAFF®), E2METRIX^{TM} (Olift^{TM}), Onterris (FOAM-X^{TM}), etc.
  - Approaches vary



(Reynolds 2022)

(Nelson 2021)

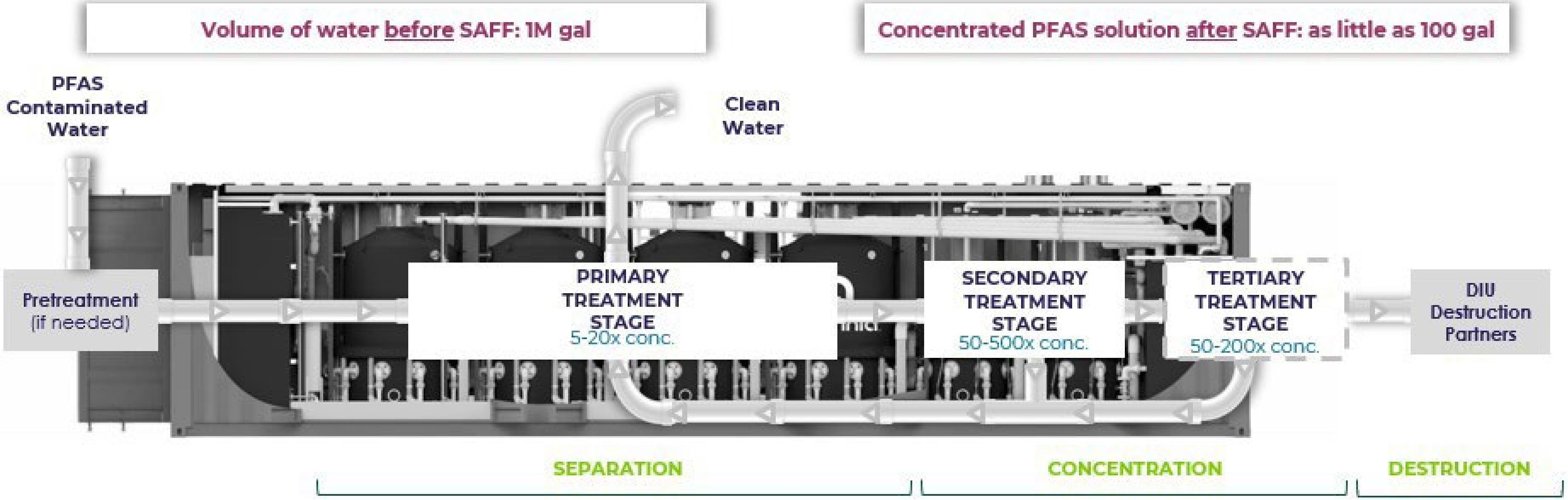
GW: groundwater; IDW: investigation-derived waste

Foam Fractionation

- Short chain PFAS removed less efficiently (like almost all other approaches); can add surfactants to enhance removal
- For these foam enhancers, consider the following
  - Toxicity, effectiveness, availability, and cost
  - Proprietary
  - Regulatory approval might be needed
  - Most of the added foam enhancers may end up in the foam

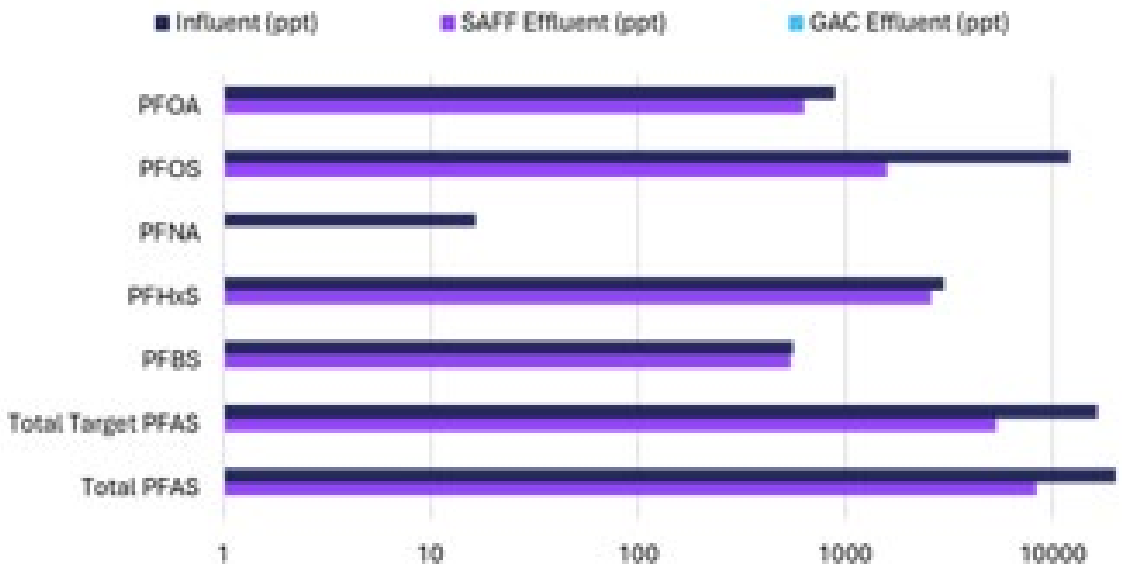
(Nelson 2021)

Example of an Ex Situ Foam Fractionation System



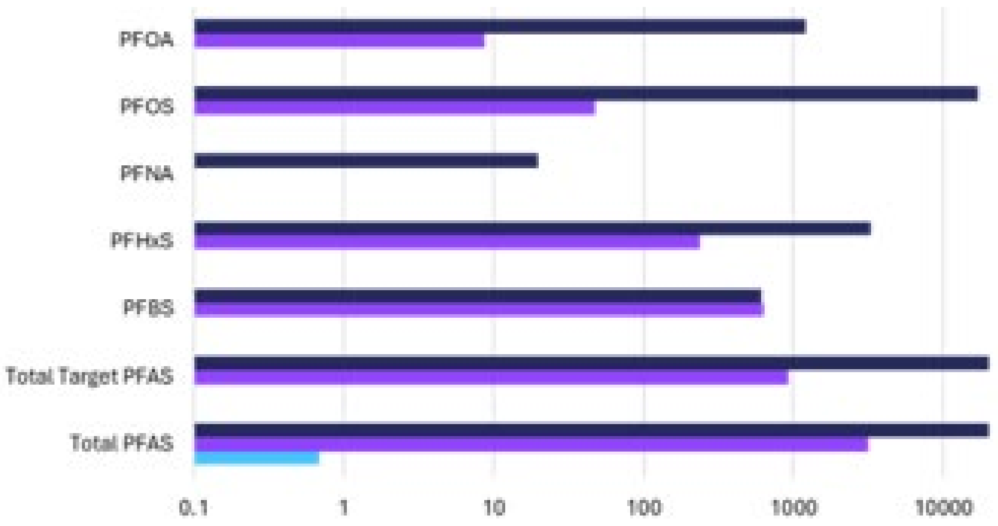
(Allonnia 2025)

SAFF 40® Performance at Biddle Air National Guard (Pennsylvania)



No Additive

68% Total Target PFAS removal



With Additive (Saponin (plant derived surfactant))

96% Total Target PFAS Removal

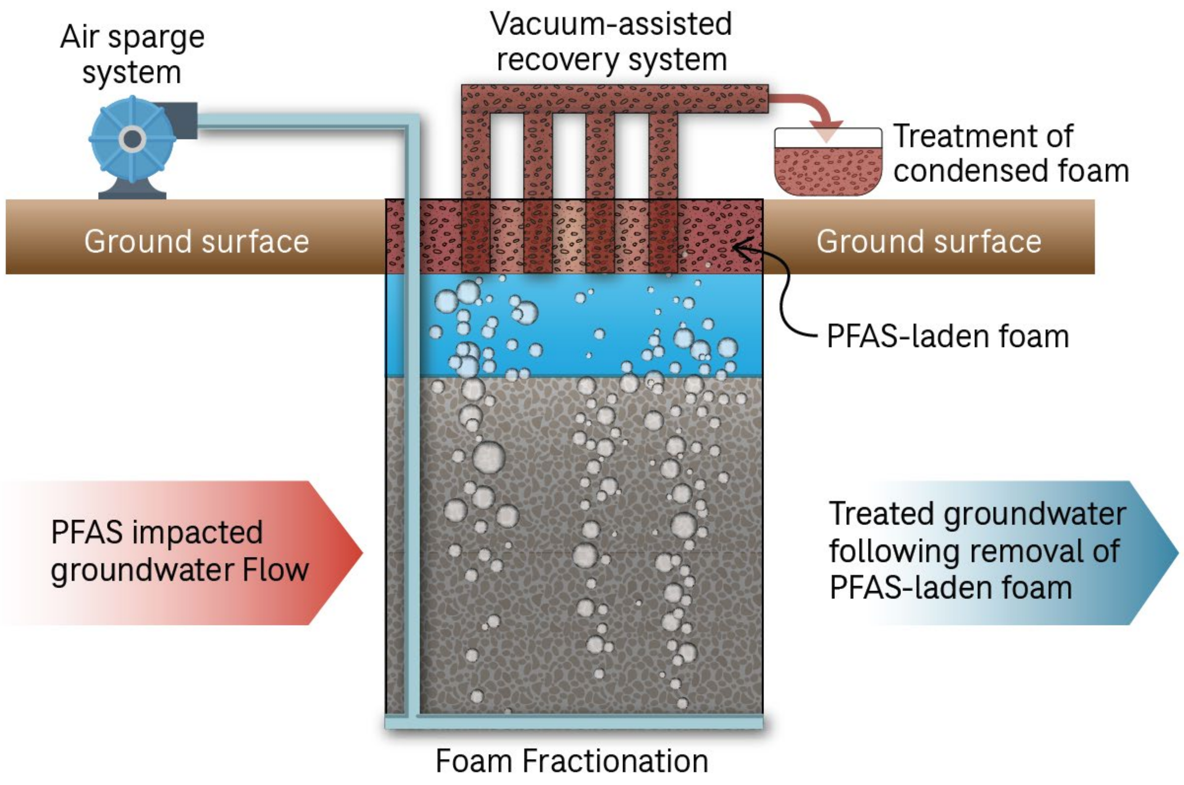
Note: Treatment performance at your site may vary

ESTCP ER23-8381
(Allonnia 2025)

ESTCP: Environmental Security Technology Certification Program

In Situ Foam Fractionation Example

- ESTCP ER21-5124
  - Title: Low-Cost, Passive In Situ Treatment of PFAS-Impacted Groundwater Using Foam Fractionation in an Air Sparge Trench
- Project Objective
  - Demonstrate and validate the use of a novel treatment approach for PFAS-impacted groundwater from AFFF source areas



(Smith 2025)

In Situ Foam Fractionation Example

ESTCP ER21-5124

System Installation: Spring 2026

Startup/Optimization: Summer 2026

Operation: 6 Months

Key parameters

- PFAS reduction within treatment zone
- Volume of foam production
- PFAS destruction in collected foam
- Assess ease of operation

(CDM Smith 2026)

Foam Fractionation Considerations (1)

- Significant concentration factors can be achieved, but be wary of these claimed factors at every site
- Bench scale testing is important to determine if site GW naturally foams or whether a foam enhancer is needed
- A sorption unit will likely be needed to treat the effluent
  - PFAS and foam enhancer
- Please check with your SME!
- There is such a thing as too much foam
- Consideration of air emissions (VGAC)
- What to do with the foam?
  - How much do you expect to produce?
  - On-site versus off-site
  - Spills and containment (potential reporting requirements!)
- What is the application?
  - Different sizes and throughput

VGAC: vapor-phase granular activated carbon

Foam Fractionation Considerations (2)

- Regional/Installation considerations
  - Winterization
  - Can the trailer get to the location (length and height)?
- Analysis of foam may be challenging
- In situ foam fractionation is a mass removal technology and by itself is unlikely to achieve remedial action levels
  - Rebound of PFAS from lower permeability units
  - Flushing from PFAS in the vadose zone
  - PFAS coming from upgradient/outside of the treatment zone
- The permeability of a site is important because air is introduced into subsurface
- Impacts of groundwater geochemistry (for example, dissolved iron and manganese)
- Water table fluctuations can create challenges for in situ foam removal efforts
- Many foam fractionation systems are designed to be contained within a CONEX box which can lead to some difficulty with O&M and component replacement

Knowledge Check

If a site groundwater has high concentrations of total dissolved solids and low natural organic matter (NOM), which sorbent(s) would be appropriate?

A. GAC

B. Ion Exchange

C. Cyclodextrin

D. Polypropylene

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A. GAC

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D. Polypropylene

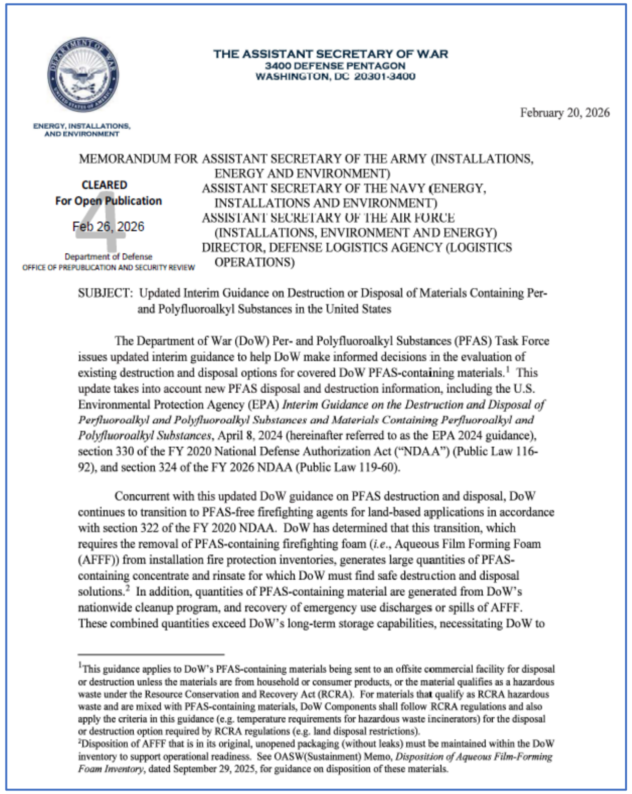
Treatment: The Two General Categories

1. Separate and concentrate
   - Includes both in situ and ex situ processes
2. **Destroy/Mineralize (Concentrates)**

PFAS Destruction Technologies

- Technologies should be considered for low volume/high concentration waste streams
  - "Separation" and "Concentration" PFAS streams
- Variety of PFAS destruction technologies have been tested with different destruction mechanisms
- Status among technologies varies with commercial status
- Most are focusing on liquids
- Treatment of effluent may be required

Reminder: Updated Interim Guidance



THE ASSISTANT SECRETARY OF WAR
3400 DEFENSE PENTAGON
WASHINGTON, DC 20301-3400

ENERGY, INSTALLATIONS,
AND ENVIRONMENT

February 20, 2026

CLEARED
For Open Publication
Feb 26, 2026
Department of Defense
OFFICE OF PREPUBLICATION AND SECURITY REVIEW

MEMORANDUM FOR ASSISTANT SECRETARY OF THE ARMY (INSTALLATIONS, ENERGY AND ENVIRONMENT)
ASSISTANT SECRETARY OF THE NAVY (ENERGY, INSTALLATIONS AND ENVIRONMENT)
ASSISTANT SECRETARY OF THE AIR FORCE (INSTALLATIONS, ENVIRONMENT AND ENERGY)
DIRECTOR, DEFENSE LOGISTICS AGENCY (LOGISTICS OPERATIONS)

SUBJECT: Updated Interim Guidance on Destruction or Disposal of Materials Containing Per- and Polyfluoroalkyl Substances in the United States

The Department of War (DoW) Per- and Polyfluoroalkyl Substances (PFAS) Task Force issues updated interim guidance to help DoW make informed decisions in the evaluation of existing destruction and disposal options for covered DoW PFAS-containing materials.[1] This update takes into account new PFAS disposal and destruction information, including the U.S. Environmental Protection Agency (EPA) *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances*, April 8, 2024 (hereinafter referred to as the EPA 2024 guidance), section 330 of the FY 2020 National Defense Authorization Act ("NDAA") (Public Law 116-92), and section 324 of the FY 2026 NDAA (Public Law 119-60).

Concurrent with this updated DoW guidance on PFAS destruction and disposal, DoW continues to transition to PFAS-free firefighting agents for land-based applications in accordance with section 322 of the FY 2020 NDAA. DoW has determined that this transition, which requires the removal of PFAS-containing firefighting foam (*i.e.*, Aqueous Film Forming Foam (AFFF)) from installation fire protection inventories, generates large quantities of PFAS-containing concentrate and rinsate for which DoW must find safe destruction and disposal solutions.[2] In addition, quantities of PFAS-containing material are generated from DoW's nationwide cleanup program, and recovery of emergency use discharges or spills of AFFF. These combined quantities exceed DoW's long-term storage capabilities, necessitating DoW to

---

[1] This guidance applies to DoW's PFAS-containing materials being sent to an offsite commercial facility for disposal or destruction unless the materials are from household or consumer products, or the material qualifies as a hazardous waste under the Resource Conservation and Recovery Act (RCRA). For materials that qualify as RCRA hazardous waste and are mixed with PFAS-containing materials, DoW Components shall follow RCRA regulations and also apply the criteria in this guidance (e.g. temperature requirements for hazardous waste incinerators) for the disposal or destruction option required by RCRA regulations (e.g. land disposal restrictions).

[2] Disposition of AFFF that is in its original, unopened packaging (without leaks) must be maintained within the DoW inventory to support operational readiness. See OASW(Sustainment) Memo, *Disposition of Aqueous Film-Forming Foam Inventory*, dated September 29, 2025, for guidance on disposition of these materials.

(DoW 2026b)

NDAA moratorium on Incineration: Incineration now permitted for RCRA waste that also contains PFAS materials (See Footnote 1 of Guidance). Also need to reach destruction temperature of 1,100°C and have proper permits.

Destruction/Disposal Options Identified: DoW has identified the following commercially available options to be used by the DoW Components (with environmental permits)

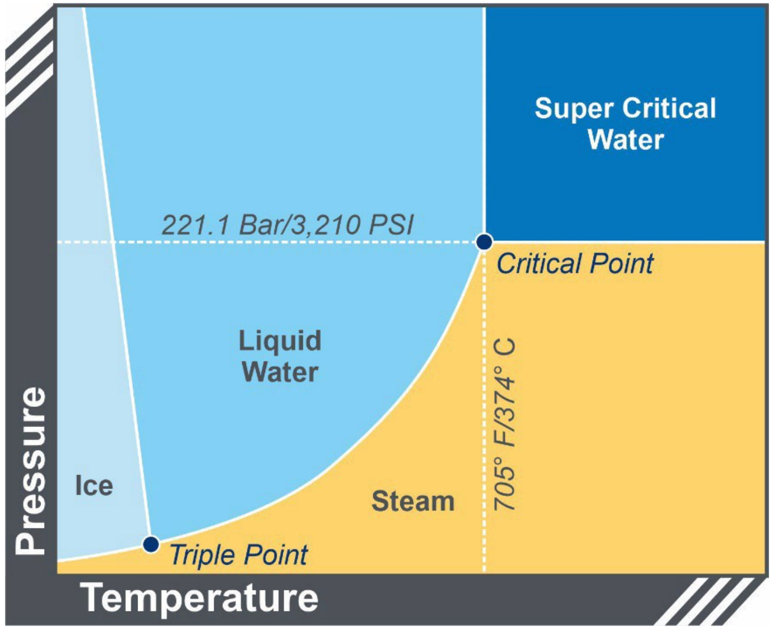
- Carbon reactivation units (for used GAC only)
- Hazardous waste landfills
- Solid waste landfills that have composite liners, and gas and leachate collection and treatment systems (not an option for AFFF concentrate)
- Hazardous waste incinerators
- Underground injection control wells
- Thermal desorption units that use off-gas collection and thermal oxidation with environmental permits (for soils)
- Other PFAS destruction options, with prenotification to OASW(EI&E)
    - E.g., mechanochemical degradation, electrochemical oxidation, gasification and pyrolysis, and SCWO, but only SCWO is currently permitted.

Details provided at https://www.acq.osd.mil/eie/eer/ecc/pfas/index.html

Supercritical Water Oxidation (SCWO)

- Leverages unique properties of supercritical water
- High temperature and pressure
    - Gas and liquid phases become indistinguishable
    - Density is about 10% of water above the supercritical point
    - Water no longer behaves as a polar solvent
    - Oxygen is fully soluble
- High temperature in an oxidizing environment overcomes activation energy to break C-F bond

- SCWO has been used since the 1980s to treat recalcitrant compounds, but only recently to treat PFAS



(Battelle 2022)

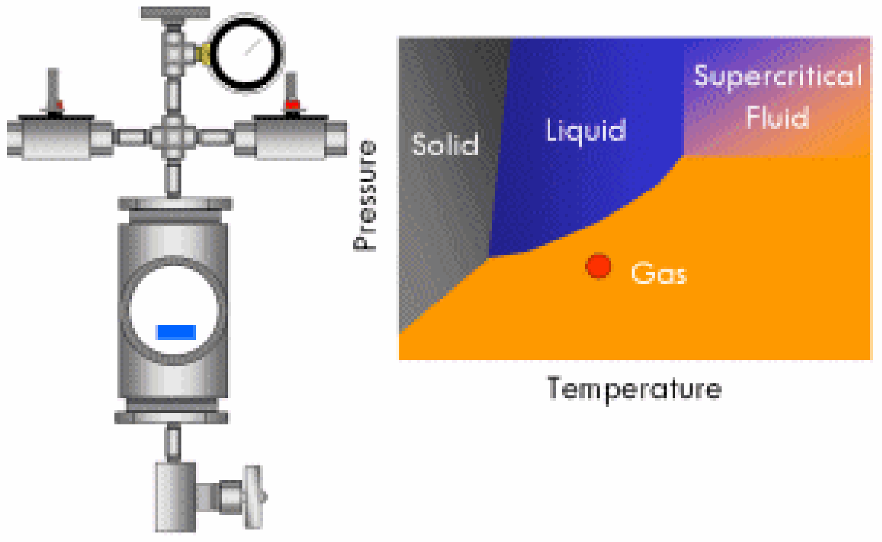
SCWO Considerations

Capabilities and Deployment

- Effective oxidative process for liquids and solids
- Capable of treating solids like spent GAC and resins (not all vendors accept solids for treatment)
- Allowable solids percentage varies depending on vendor
- Often better suited for shipping material offsite to a vendor
- Vendors are actively iterating on process designs and equipment

Technical and Commercial Constraints

- High energy use; extreme pressure/temp (zero tolerance for failure)
- Sensitive to salts (IX bottoms); requires costly, specialty alloys
- Limited commercial availability for treating concentrates at permitted TSDFs
- Effluent polishing likely required

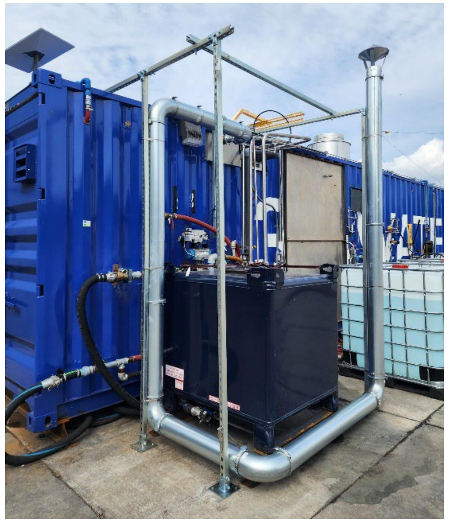


(CCYYSA n.d.)

TSDF: treatment, storage, and disposal facility

SCWO: 374Water AirSCWO^{TM} Field Deployment

- ESTCP ER23-8398
- Demonstration at a Clean Earth facility (TSDF) in Detroit
  - CWT Plant
- Shipped in a CONEX Box (AS6)
  - Unloaded with a crane
- Operated using a generator
- Tested various PFAS-impacted materials
  - Foam fractionate, spent sorbent media, AFFF



(Arcadis 2025)

CWT: centralized water treatment

SCWO: 374Water AirSCWO^{TM} Field Deployment

- Operation
  - Feedstock: 1,200 gallons foam fractionate
  - Airflow rate = 240 kg/hr
  - Cofuel = 0.35 L/hr
  - Feedstock flowrate = 1.3 L/min
  - Reactor > 595 °C
- Results
  - Preliminary DRE greater than at least 99.9% total PFAS for all media tested
    - Carryover possible
  - HF was nondetect via 26A
  - OTM (45, 50, and 55) showed hits of PFAS plus some other compounds, but overall < 0.001%

Allonnia foamate

Total PFAS Influent Concentration (1633) (ng/L)	Total PFAS Effluent Concentration (1633) (ng/L)	Total PFAS DRE
33,668,000	0	**100%**

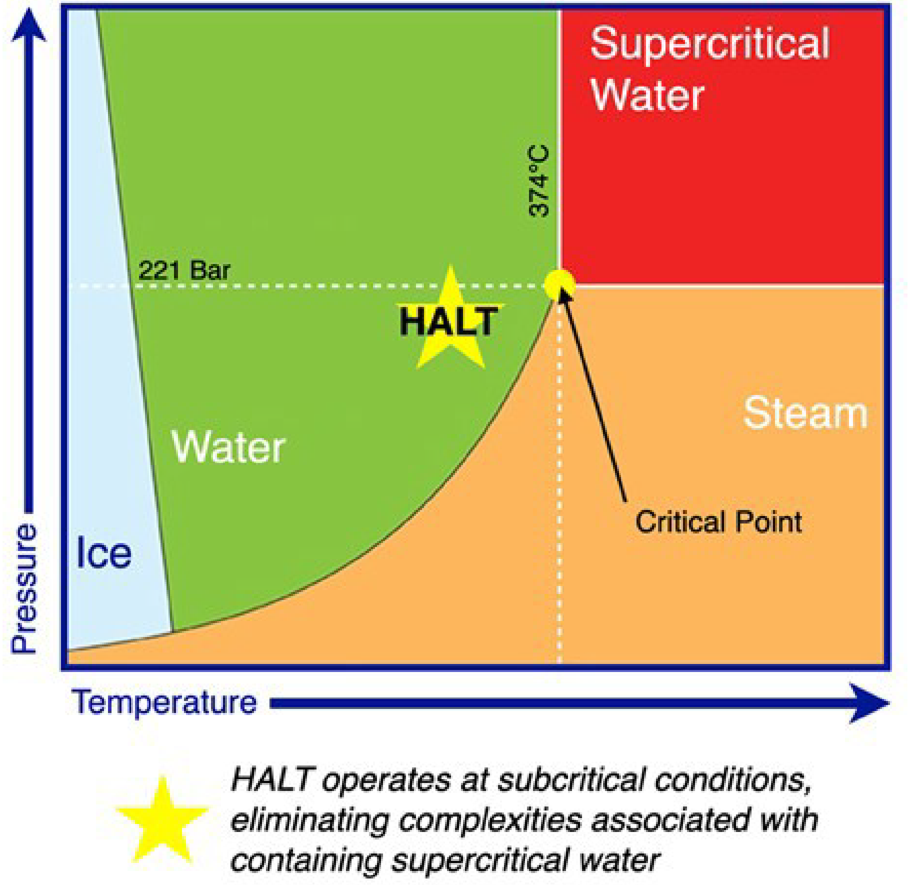
Sample Type	PFOS (ng/L)	PFOA (ng/L)	PFHxS (ng/L)	PFHxA (ng/L)	6:2 FTS (ng/L)	PFHpS (ng/L)	PFPeA (ng/L)
FEED	23,000,000	2,500,000	3,400,000	310,000	3,000,000	680,000	150,000
EFF	**<1.6**	0.9	**<1.6**	**<1.6**	2.4 J	**<1.6**	**<1.6**
DRE	**99.999997%**	**99.99996%**	**99.99998%**	**99.9997%**	**99.99992%**	**99.99988%**	**99.9995%**

(Arcadis 2025)

HF: hydrofluoric acid
kg/hr: kilograms per hour
L/hr: liters per hour
L/min: liters per minute
OTM: other test method

Hydroalkaline Thermal (HALT)

- PFAS destruction under subcritical water conditions (300 to 350 °C, ~3,000 psi, pH > 14)
- Sodium hydroxide used for high pH
- Capable of >99% destruction of individual and total PFAS, with complete conversion to inorganic fluoride (mineralization)
- First developed under SERDP project ER18-1501 at Colorado School of Mines (Strathmann et al.)
- Foundational HALT patent exclusively licensed to Aquagga



HALT operates at subcritical conditions, eliminating complexities associated with containing supercritical water

(Aguagga 2025)

psi: pounds per square inch
SERDP: Strategic Environmental Research and Development Program

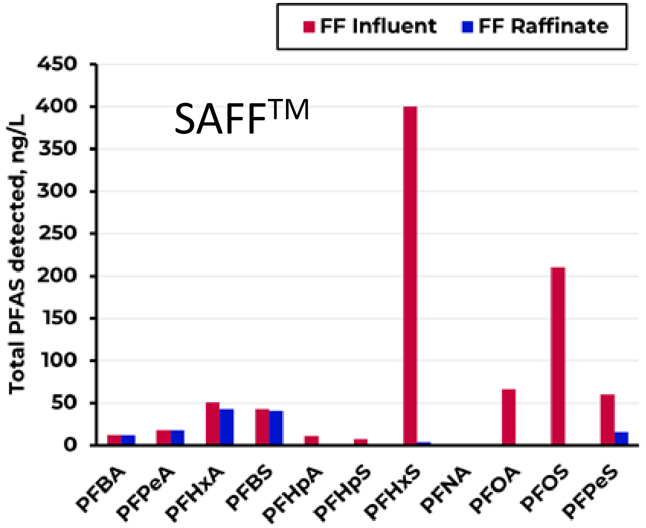
HALT Considerations

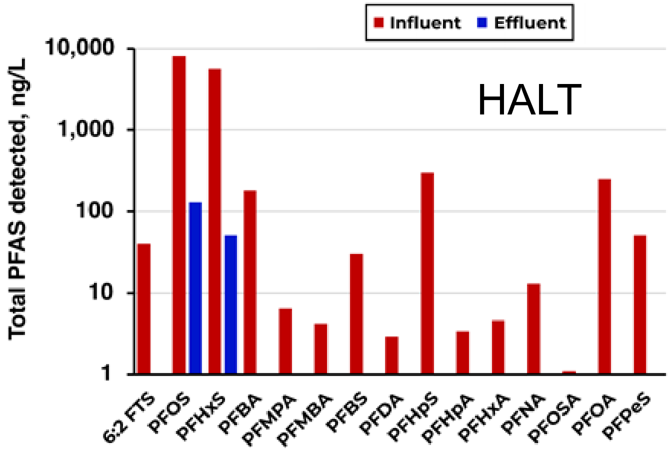
- Less energy than SCWO
- Ability to handle high salt matrices
- Liquids only (not focused on treating solids)
- Effluent has relatively high concentration TDS effluent (neutralize NaOH)
- Does not effectively treat many organics
- Current throughput is 10 gallons per hour
  - New unit planned (Stampede Series) in 2026 with potential for 1 gallon per minute

Steed Series – 8' x 10'
(Aguagga 2025)

HALT Project Example: Groundwater Remediation

- Pump & treat system for AFFF-impacted GW
- Foam fractionation + HALT
- Project goals
  - Reduce PFAS concentrations to the groundwater extraction and treatment system
- Significant reduction in PFAS concentrations
- On-site concentration + destruction
  - No processing challenges with foam fractionation concentrate
  - 24/7 operations with automated sample collection



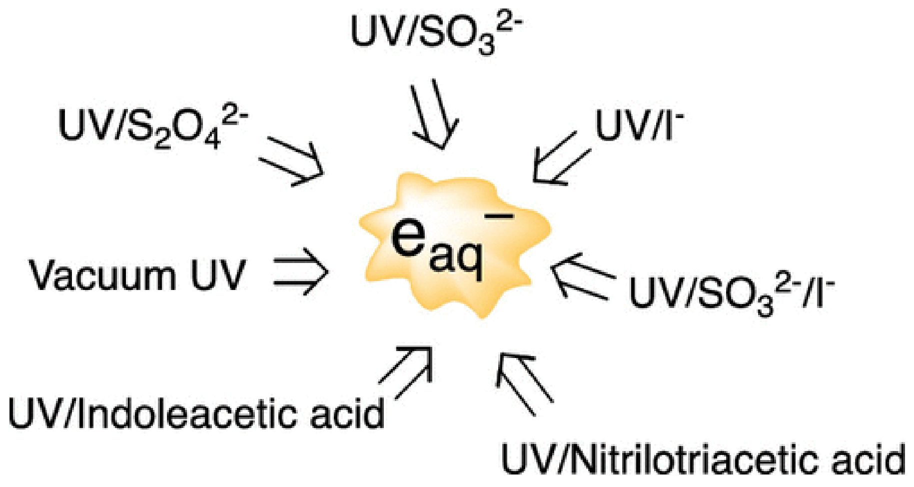


ppt: parts per trillion

(Aquagga 2025)

UV Destruction Technologies

- Chemistries can be different, but these destructive processes are based on the production of oxidative and/or reductive reactants from UV
  - Example reactants
    - e_{aq}^- is a strong reductant (standard potential = −2.9 V)
    - OH• is a strong oxidant (standard potential = + 2.9 V)



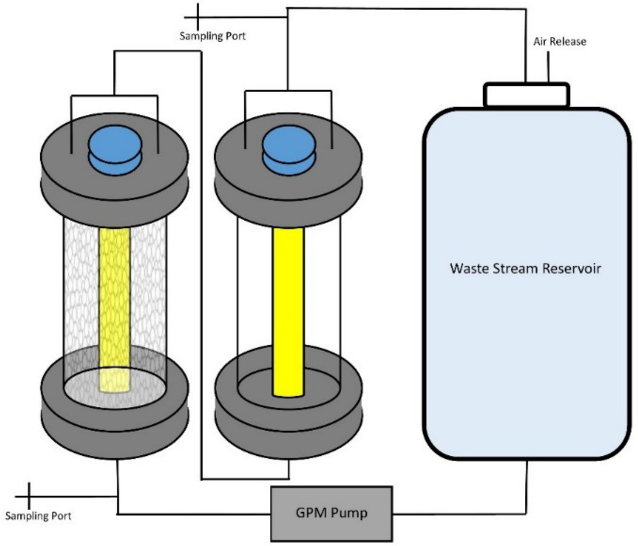
Several ways to produce e_{aq}^- as shown here

(Haley & Aldrich 2025)

OH•: hydroxide radical
UV: ultraviolet
V: volts

UV Destruction Technologies: Considerations

- Several different technologies and vendors at various stages of development, testing, and commercialization
  - EradiFluor™, PFASigator™, UV/SGM, etc.
- Destruction can be from oxidation, reduction, or a combination from highly reactive species
- Currently focused on batch operation
- Treatment of effluent from these systems may be required
- Potential to take effluent to influent of foam fractionation system



(Geosyntec 2025)

UV Destruction Technologies: Considerations

- Some systems are trailerable and can be operated onsite at ambient or slightly elevated temperatures
- Applications so far are focused on highly concentrated, low volume liquids (common element among all PFAS destructive technologies)
- Due to the need for UV for reaction, some matrices are challenging to treat (color absorbs UV light)
- Uncertainties with O&M due to limited deployment times

(Enspired Solutions 2025)

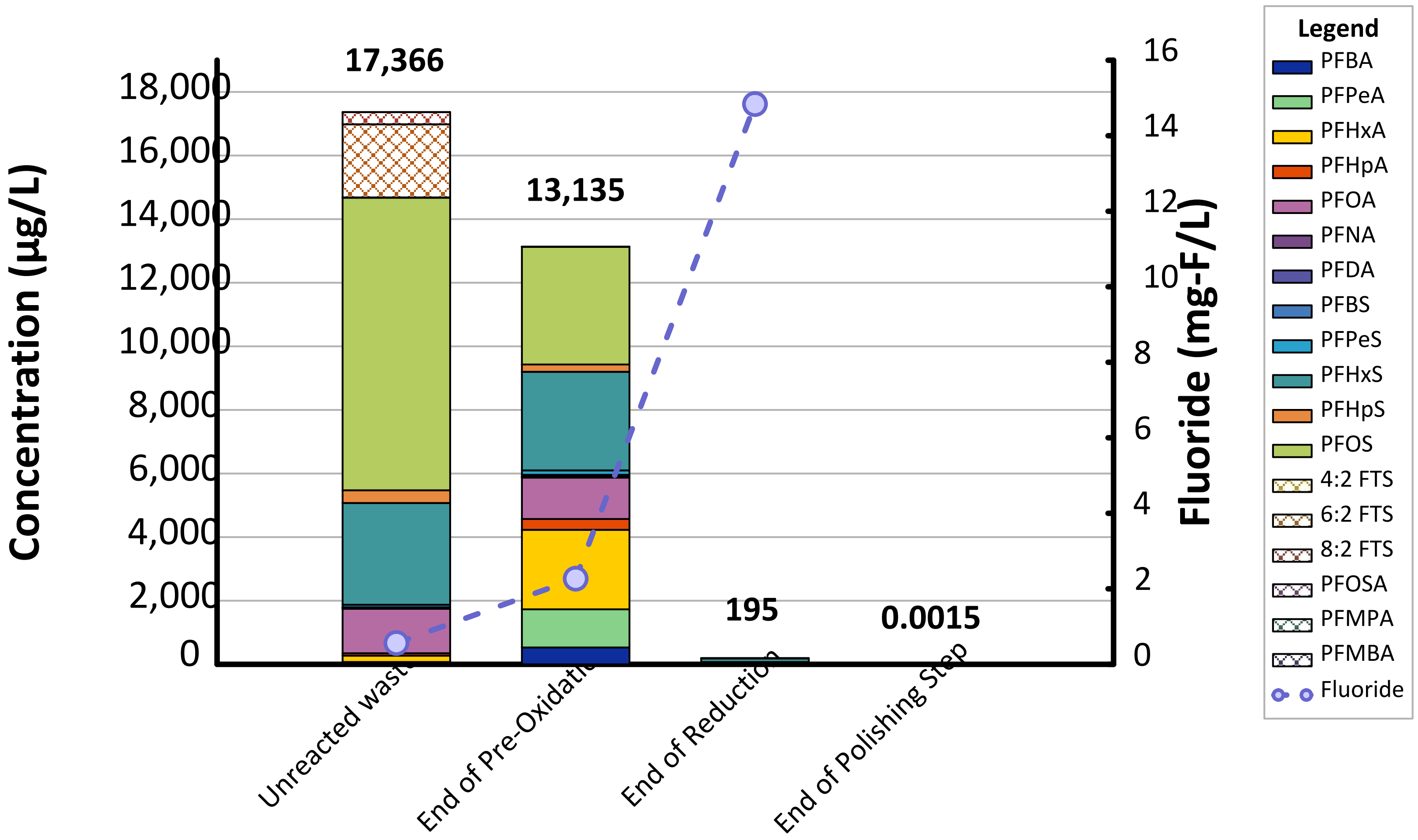
UV Technologies: EradiFluor^{TM}

- Haley & Aldrich designed and constructed this PFAS treatment system
  - UV/sulfite-based treatment process
  - Mobile, on-site treatment unit
  - Ambient reaction conditions
  - Control/monitoring components
- System deployed at an East Coast NAS for ISFF destruction testing

(Haley & Aldrich 2025)

ISFF: in situ foam fractionation
NAS: Naval Air Station

UV Technologies: EradiFluor™



(Haley&Aldrich 2025)

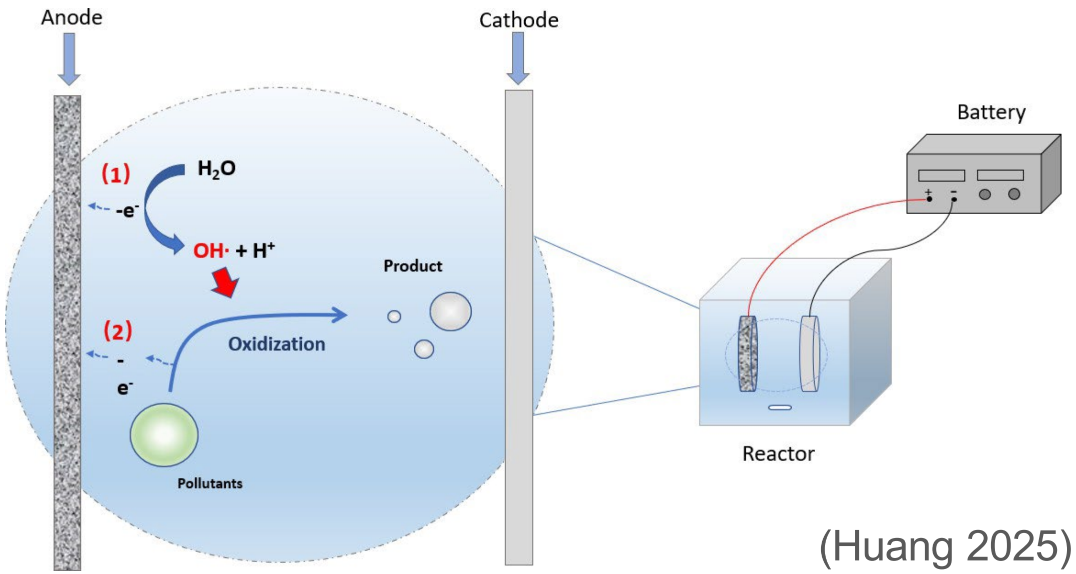
About 99% of PFAS were destroyed at end of reduction step

After polishing step, all residual PFAS were removed to the nondetect level, except one compound PFOS reported as 1.5 ng/L

(Haley & Aldrich 2025)

Electrochemical Oxidation

- Electrochemical oxidation (EO) involves applying a direct current to electrodes (anode and cathode) which then drives oxidation reactions through (1) reactive oxygen species that are generated (e.g., OH•) and (2) direct electron transfer on surface of anode
- EO defluorinates and mineralizes PFAS by breaking C-F bonds; PFAS compounds are sequentially defluorinated and ultimately mineralized to CO_2 and fluoride
- Two most common types of electrodes
  - Magnéli phase titanium suboxide (Ti_nO_{2n-1})
    - Lower cost
    - Can be manufactured as plates, porous ceramic membrane, porous monolith
    - More scalable
  - Boron doped diamond (BDD)
    - Faster treatment kinetics
    - Manufactured as plates

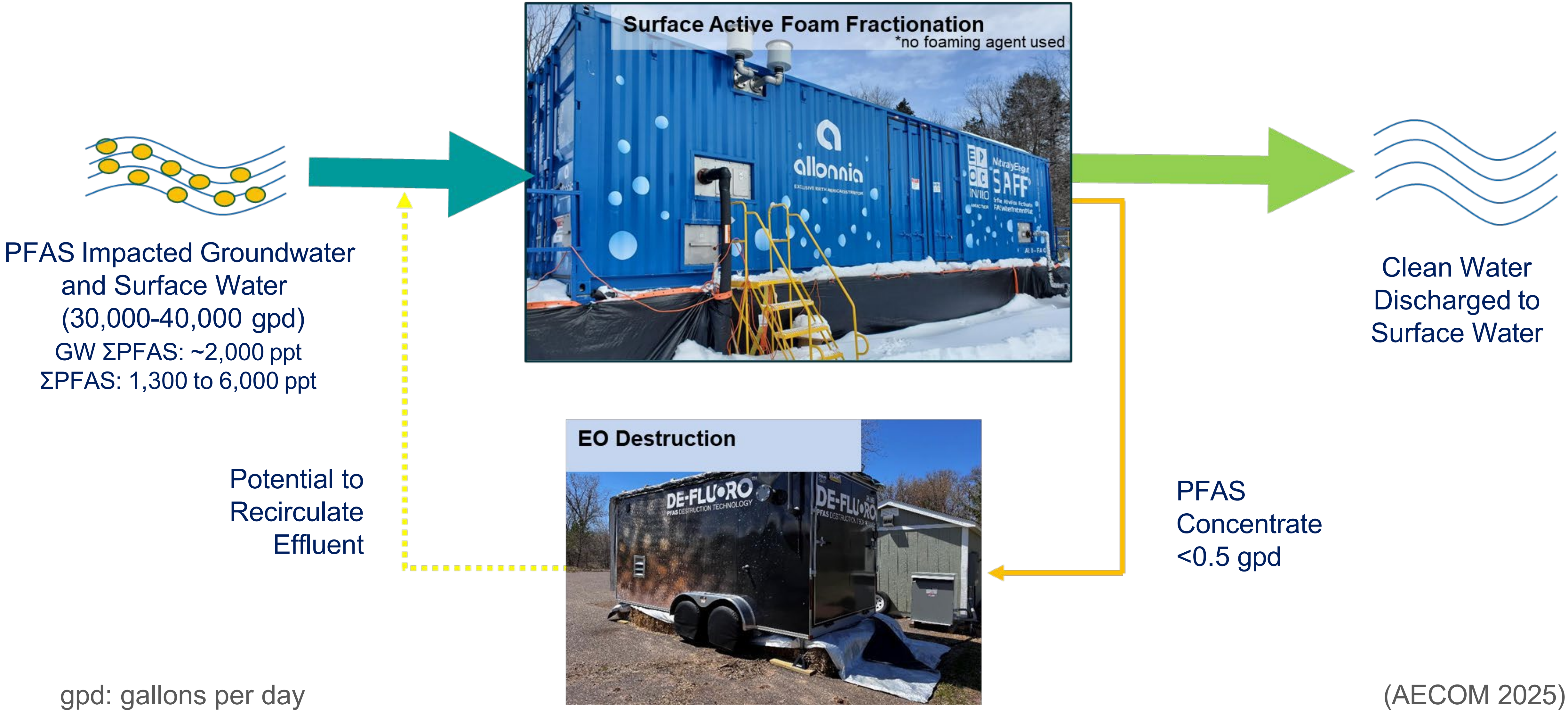


(Huang 2025)

Electrochemical Oxidation Considerations

- Operates and ambient temperature and pressure
- Kinetics generally slower than more aggressive technologies
- Focus is on liquids (foamate, soil washing wastewater, etc.)
- Perchlorate generation
  - Continuing efforts to address
- Potential for mineral buildup on electrodes
  - Continuing efforts to address

EO Field Deployment: DE-FLUORO™



Surface Active Foam Fractionation
*no foaming agent used

PFAS Impacted Groundwater and Surface Water (30,000-40,000 gpd)
GW ΣPFAS: ~2,000 ppt
ΣPFAS: 1,300 to 6,000 ppt

Clean Water Discharged to Surface Water

EO Destruction

PFAS Concentrate <0.5 gpd

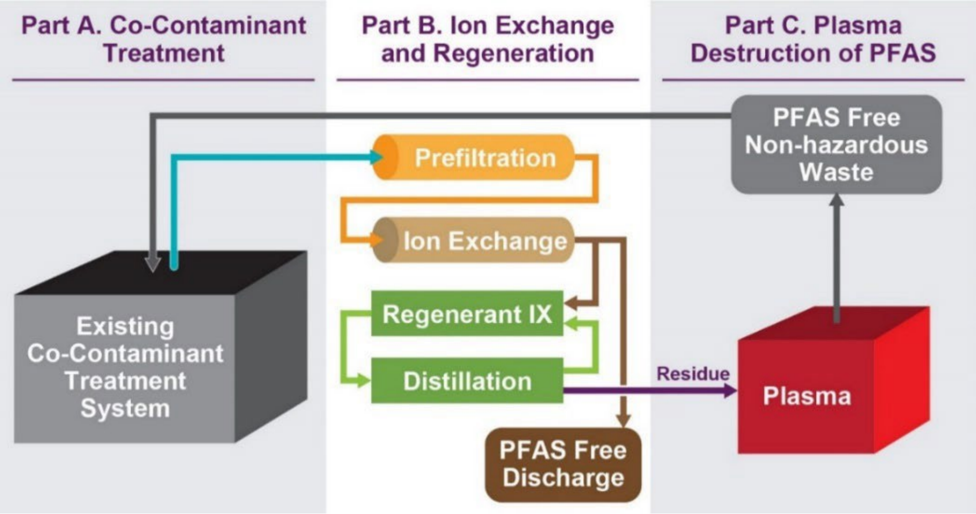
Potential to Recirculate Effluent

gpd: gallons per day

(AECOM 2025)

Plasma Destruction

- **Plasma (nonthermal/cold plasma)**
  - **Generate highly reactive species** that attack PFAS, mainly used on concentrated streams
  - **Potentially complete destruction** with recirculation
  - Can pair with foam fractionation concentrate
  - **Considerations**
    - Plasma destruction occurs in narrow layer
    - May experience plasma instability and system overflow with certain applications
    - Requires argon gas and (typically) multiple modular reactors



Part A. Co-Contaminant Treatment

Part B. Ion Exchange and Regeneration

Part C. Plasma Destruction of PFAS

PFAS Free Non-hazardous Waste

Prefiltration

Ion Exchange

Regenerant IX

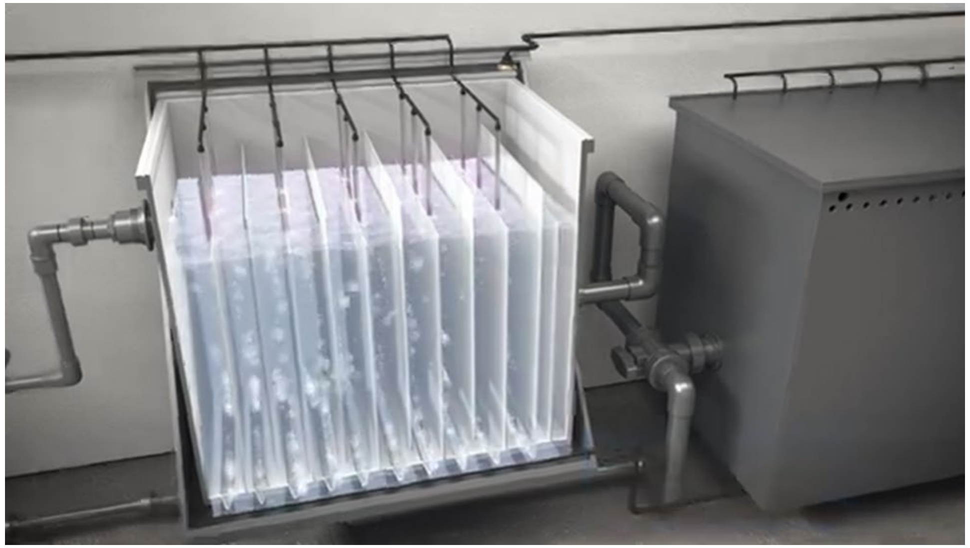
Distillation

Existing Co-Contaminant Treatment System

Residue

Plasma

PFAS Free Discharge



(DMAX Plasma 2025)

Knowledge Check

What Temperature and Pressure does SCWO need to achieve for PFAS destruction?

A. 374 C and 221.1 Bar

B. 225 C and 100.3 Bar

C. 125 C and 350.6 Bar

D. 0.01 C and 0.006 Bar

Knowledge Check

What Temperature and Pressure does SCWO need to achieve for PFAS destruction?

A. 374 C and 221.1 Bar

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C. 125 C and 350.6 Bar

D. 0.01 C and 0.006 Bar

Presentation Overview

- Introduction
- PFAS in the Subsurface: Properties and Treatment Challenges
- Regulatory Drivers, Guidance, and Policy
- Treatment
- **Case Studies**
- Guidelines for Selecting Water Treatment Technologies
- Summary/Key Takeaways

Case Study 1: Sorption of PFAS from Water

- MCAS Iwakuni needed to treat ~350,000 gallons PFAS-impacted water collected from various locations:
  - 110,000+ gallons ARFF Training Facility pond
  - Water runoff and infiltration at hangars (including PFAS-impacted concrete) in cisterns
  - Fire water supply tanks

(Kornuc 2024)

ARFF: Aircraft Rescue and Fire Fighting
MCAS: Marine Corps Air Station

MCAS Iwakuni: PFAS Mobile Treatment System

Trailer, F400 GAC drums and effluent tank

(Kornuc 2024)

Influent ballast tank at Site 1

(Kornuc 2024)

MCAS Iwakuni: PFAS Mobile Treatment System

- **Designed for simplicity, ease of O&M**
  - Cartridge filter for solids separation
  - F400 GAC sorbent
  - Modular to accommodate site constraints
  - 5 gpm
- Treated water held in 20k gallon bladders pending analysis
- Successfully treated water to below discharge requirements
  - Used 8 drums of F400 GAC, ~20 filter cartridges

Change-out of GAC to cyclodextrin sorbent (Dexsorb canisters)

(Kornuc 2025)

SCADA and sorbent vessel valves

(Kornuc 2024)

SCADA: Supervisory Control and Data Acquisition

Case Study 2: NAF Atsugi PFAS Sorbent Selection Study

- NAF Atsugi supplies **drinking water and irrigation water** to installation by pumping **on-site groundwater**
- Groundwater impacted by low levels of **PFAS**
- Current treatment includes air-stripping for intermittent, low levels of **CVOCs**

- EXWC is assessing performance of **sorbents** for removal of PFAS from groundwater from production wells
  - Collected ~400 gallons of water prior to air stripping tower
    - Shipped to EXWC for testing
    - Rapid Small Scale Column Testing (RSSCT)
    - Laboratory-scale pilot column test
- Provide estimates of various sorbent performance in full-scale (2.4 MGD) system

CVOC(s): chlorinated volatile organic compound(s)
MGD: million gallons per day
NAF: Naval Air Facility

NAF Atsugi PFAS Treatability Study

- Available space is limited
- Air stripping tower is nearing end of life, sorbent may treat both low levels of PFAS and CVOCs
- Small space favors use of IX resin
  - Short EBCT, higher capacity means smaller footprint
- Low PFAS, DOC, and TDS (“uncomplicated” chemistry) favors simple sorbent treatment

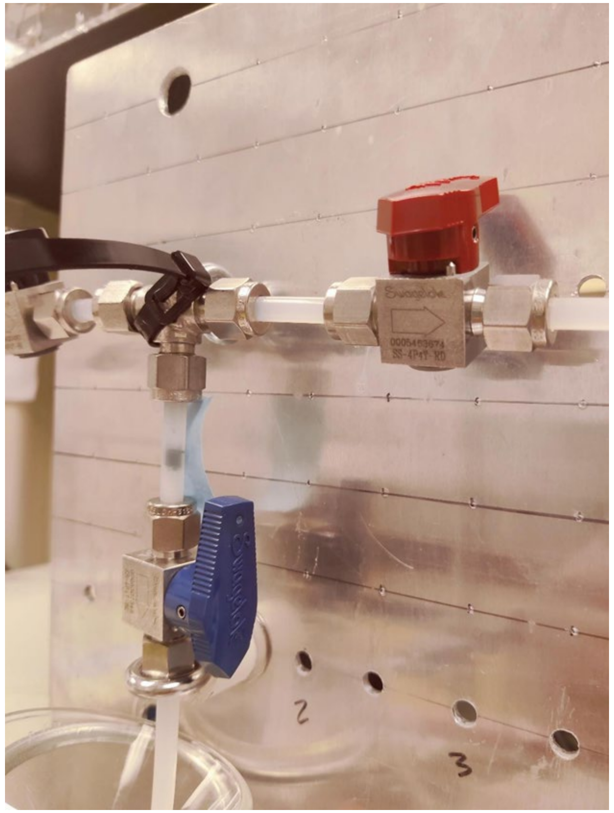
(Kornuc 2025)

DOC: dissolved organic carbon

NAF Atsugi PFAS Treatability Study: RSSCT

- Rapid Small Scale Column Tests (RSSCT) predicts full scale treatment
- Runs require only days rather than years
- Water volumes much reduced -2-5 gallons (small bed volumes, BVs)
- Particle size of media proportionally smaller (grind media, 200-230 mesh)

(Kornuc 2026)



(Kornuc 2026)

BV: bed volume

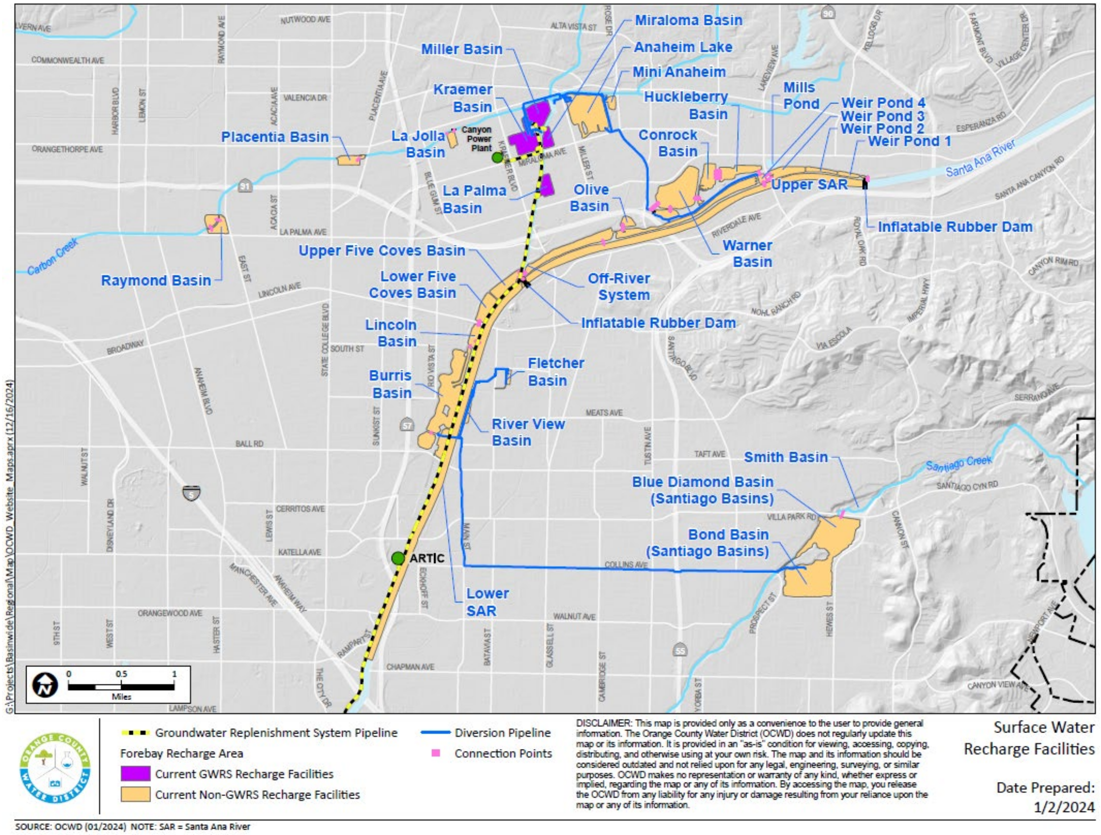
NAF Atsugi PFAS Treatability Study

- Testing GAC (three types), IX (two types) and cyclodextrin
- Samples collected at up to 1,000,000 BVs
- Analytical range finding or “bookending” to preserve analytical budget

(Kornuc 2026)

Case Study 3:
Orange County Water District PFAS Treatment

- OCWD manages groundwater basin serving 2.5M residents
- Manage the largest indirect potable water reuse system—GWRS—1,600 acres of recharge basins that also helped mobilize PFAS
- 400 wells managed, 106 exceed 80% of California Reporting Limit for PFOS or PFOA (2019)
- $1.8B projected cost for construction and O&M over 30 years
- OCWD ran a detailed treatability study using 10 representative wells



(OCWD 2021)

GWRS: groundwater replenishment system
OCWD: Orange County Water District

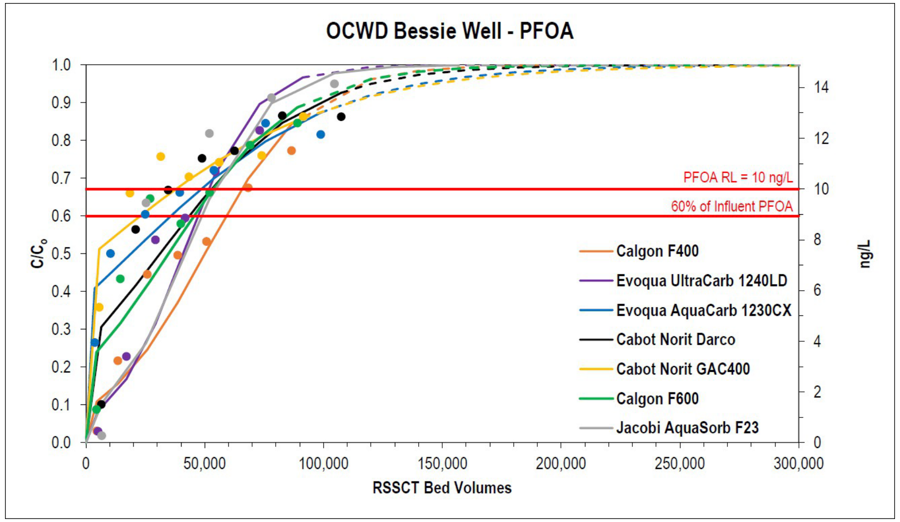
OCWD Treatability RSSCT and Pilot Columns

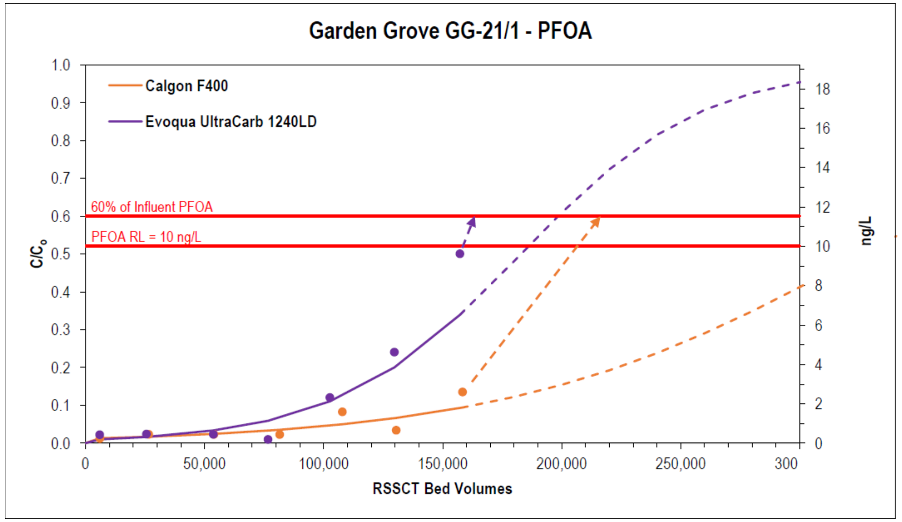
- Ran RSSCTs and Pilot Columns (pictured to the right)
  - Performed tests on-site, near wells, so nearly unlimited water sources
  - Not always the case for Navy, especially OCONUS
  - RSSCTs require relatively little water
- Tested eight GACs, four IX, and two alternative sorbents
- Tested different source waters from different plants in watershed
  - Representative range of PFAS concentrations low to high
  - Range of TOC/DOC

(OCWD 2022)

OCONUS: Outside the Continental United States
TOC: total organic carbon

OCWD Treatability RSSCT and Pilot Column Results



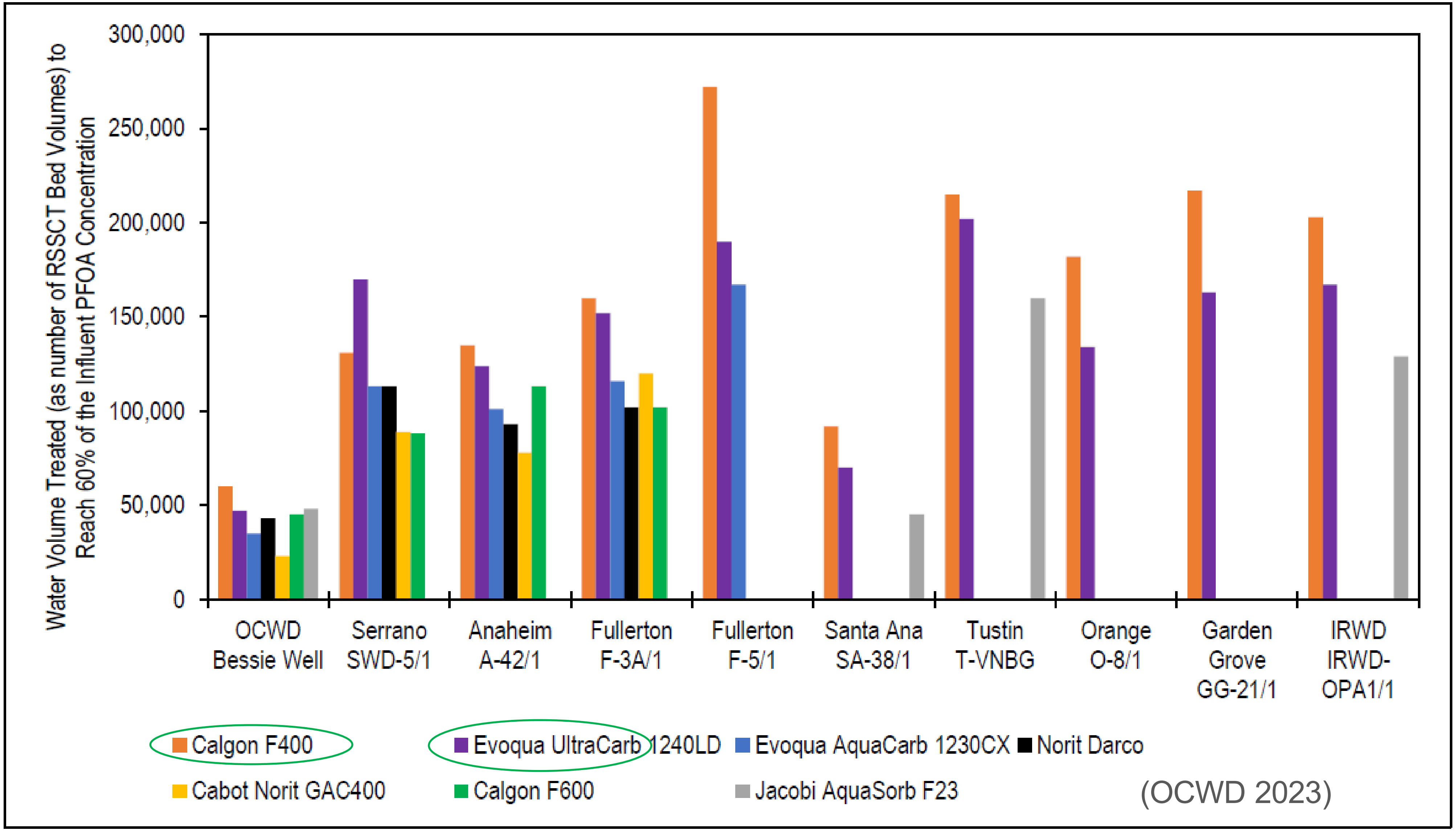


(OCWD 2023)

Adsorbent Media	Time (Months) to Reach PFOA Breakthrough	
	Initial Breakthrough Above Detection Limit	Effluent Concentration at ~60% of Influent Concentration(a)
Granular Activated Carbon		
Calgon F400 (Virgin and Reactivated)	5.7 (V), 5.2 (R)	> 13
Calgon F600	2.7	> 13
Cabot Norit GAC 400	3.1	> 13
Evoqua AquaCarb 1230CX	2.7	12.8
Cabot Norit HYDRODARCO 4000	4.3	9.0
Jacobi AquaSorb F23	5.2	8.9
Evoqua UltraCarb 1240LD	3.8	8.7
Ion Exchange (IX) Resins		
Evoqua PSR2+	7.1	> 13
Calgon CalRes 2301	4.3	7.9
Purolite Purofine PFA694E	4.3	7.9
ECT2 Sorbix LC4	3.9	7.1
Alternative (Novel) Adsorbents		
CETCO FLUORO-SORB® 200	8.7	> 11
Cyclopure DEXSORB+®	2.7	5.6

(OCWD 2023)

OCWD Treatability RSSCT Results Varied by Source Water



(OCWD 2023)

OCWD Treatability Study: Key Takeaways

- IX (Amberlite PSR2+) was determined to be best performer overall for most water sources, F400 performed best for some sources
- IX performs best for PFOA, which was driver for most sources
- IX also performed better for short chains (PFBS)
- Performance was **different** for **same media** compared to test results using water from other source locations and projects

KEY POINT

Performance is very site-specific for sorbents. Small differences can add up to large life cycle cost variances.

OCWD Treatment Systems

- 53 of 106 impacted production wells have been brought back online
- Treatment plants range from a single pair of lead/lag sorbent vessels to 11 pairs of vessels, and sediment filtration bag or cartridge filters
- Sorbent vessels are mainly 1220 or 1240 (12-foot diameter x 20,000 or 40,000 pounds of media)
- Average 1220 vessel pair cost is ~$600k, media ~$200k each, so ~$1M total/pair
- Mix of systems: Amberlite PSR2+ IX resin and Calgon GAC F400

Issues/Lessons Learned

- SCADA controls – add to existing PLC or is upgrade/replacement required
- Non chlorinated water source for flushing – IX Media incompatible with chlorine
- Sanding in wells – wastes prefiltration media

Ryan Bouley

Issues/Lessons Learned

- Co-contaminate clogging and “skimming” – Remove surface Manganese and Iron buildup

Clean Media

Media with Iron and Manganese

(OCWD 2023)

OCWD Treatment Systems: Largest Plant

(OCWD 2023)

Case Study 4: In Situ Sorption

- NESDI 569
- Project Objective
- Evaluate effectiveness of CAC for in situ enhanced retention
- Environmental Questions
  - Does CAC distribute well in aquifers—influence of lithology?
  - What is the general in situ treatment effectiveness on different PFAS?
  - What is the long-term adsorption capacity and potential for rerelease of PFAS?
  - Are there any significant aquifer effects (CAC in monitoring wells or hydraulic conductivity impacts)

NESDI: Navy Environmental Sustainability Development to Integration

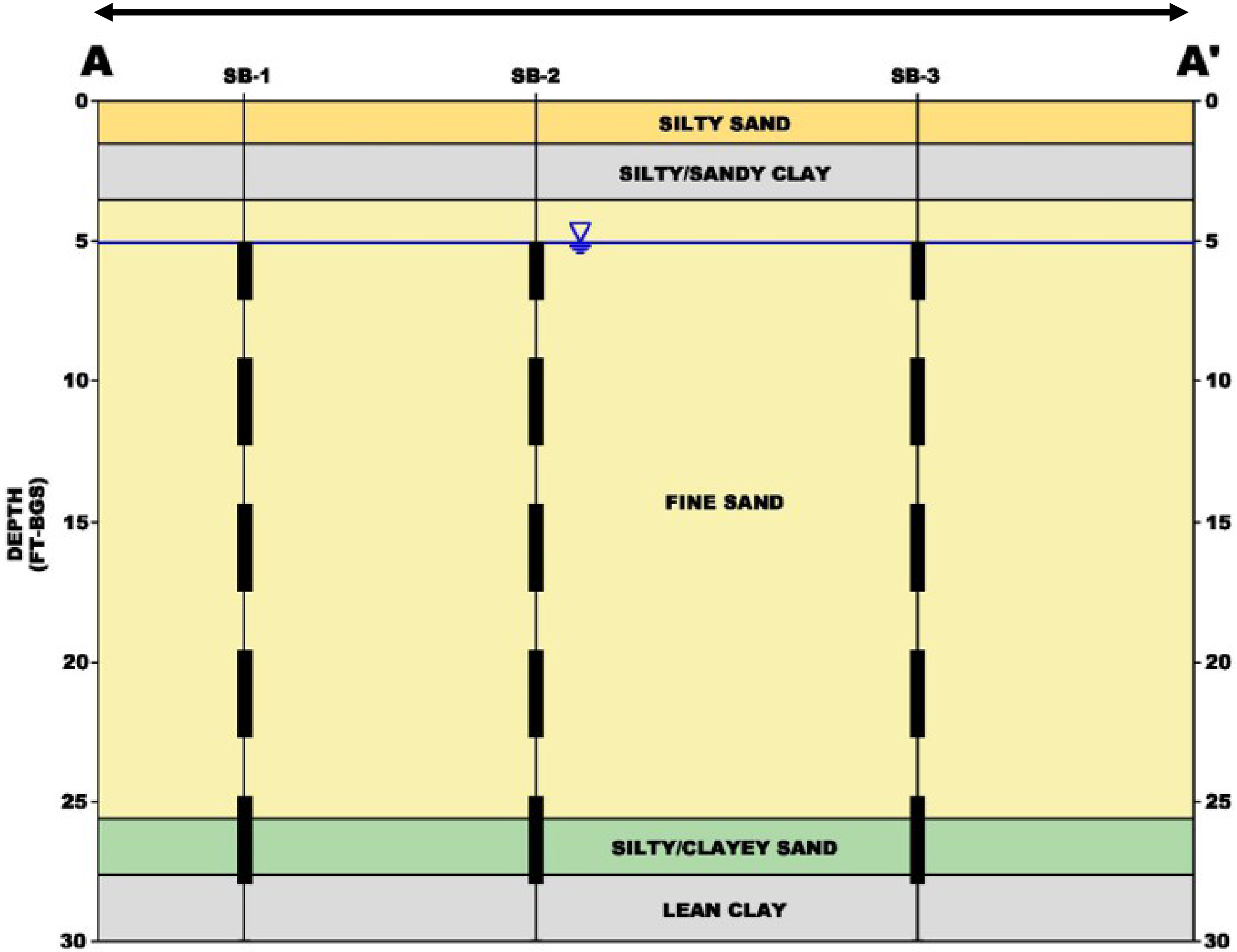
Conceptual Site Model

- Field carrier landing practice and helicopter training operations
- High permeability (medium sand or better)
- Water table close to the surface (5–6 feet bgs)
- Homogeneous
- Relatively high concentrations of PFAS

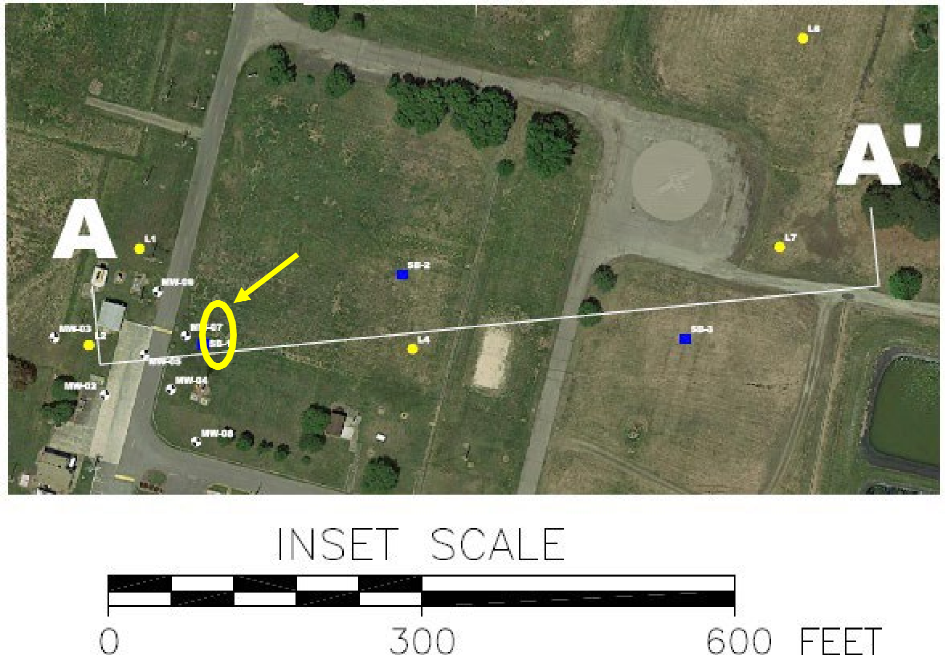
(CH2M 2021)

bgs: below ground surface

Site Characterization Activities



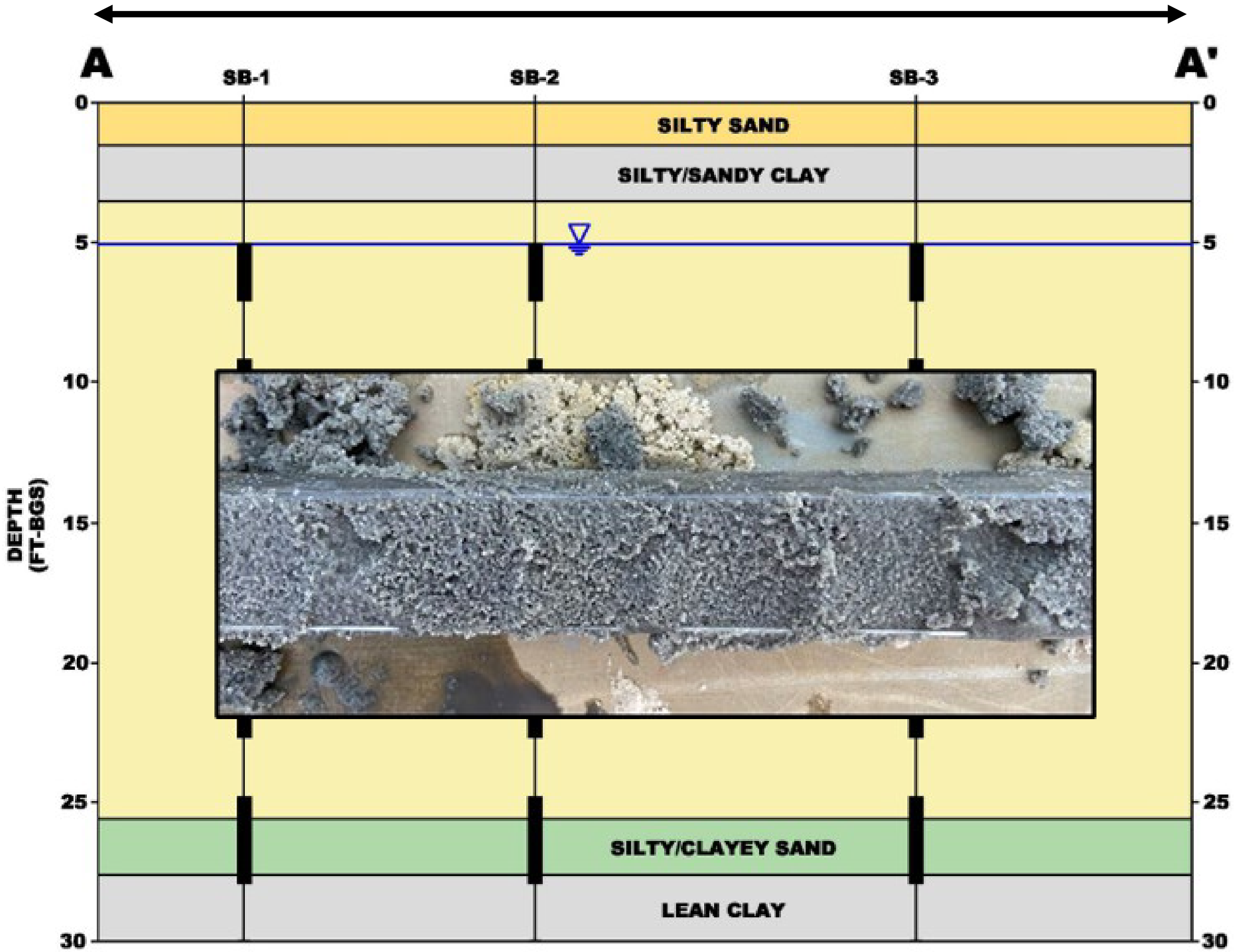
(Danko 2024)



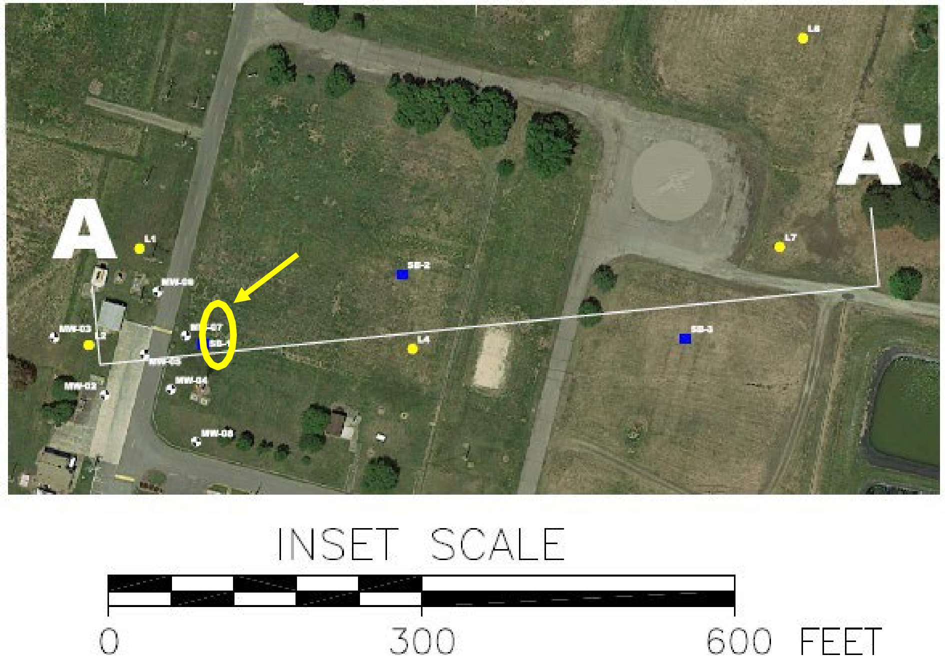
Site Characterization

- Soil cores for lithology
- Discrete groundwater sampling

Site Characterization Activities



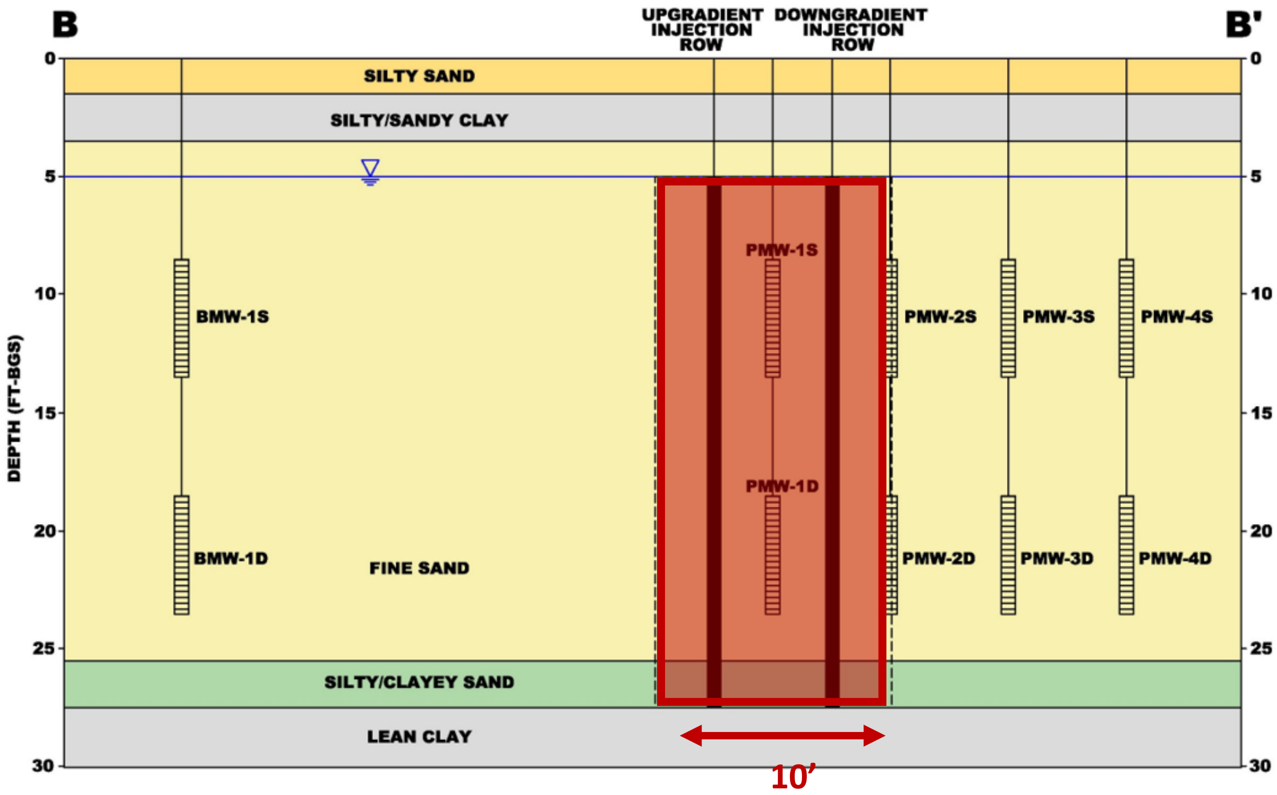
(Danko 2024)



Site Characterization

- Soil cores for lithology
- Discrete groundwater sampling

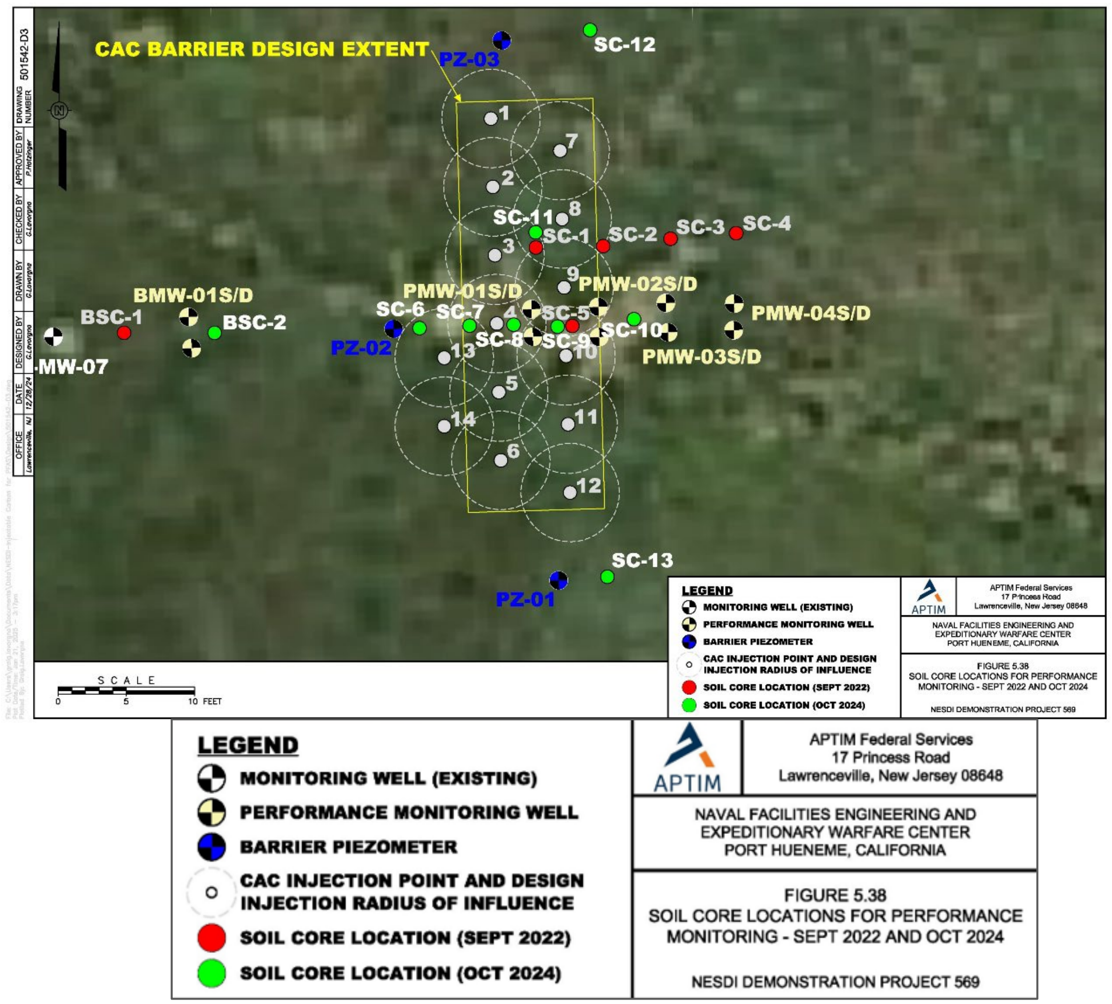
In Situ Sorption: Design



30-foot long x 10-foot wide barrier
2 injection rows/12 points

(Danko 2024)

DEMONSTRATION WELL AND INJECTION POINT LAYOUT



(NESDI 2025)

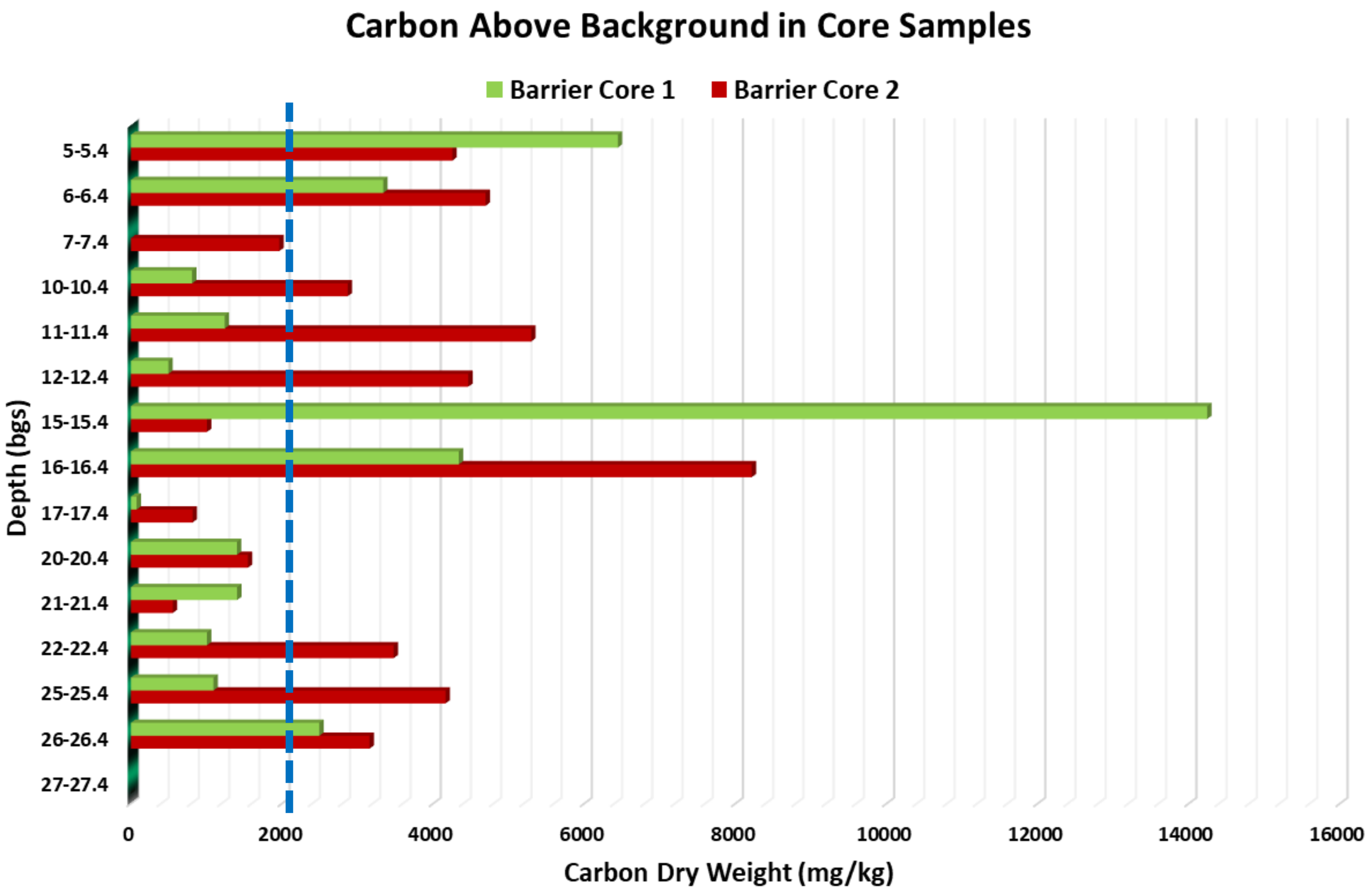
In Situ Sorption: CAC Injection

9,600 lbs/1,065 gal of CAC and 10,456 gal mix water
Target concentration = 2,000 mg carbon per kg soil

gal: gallons mg: milligrams lbs: pounds

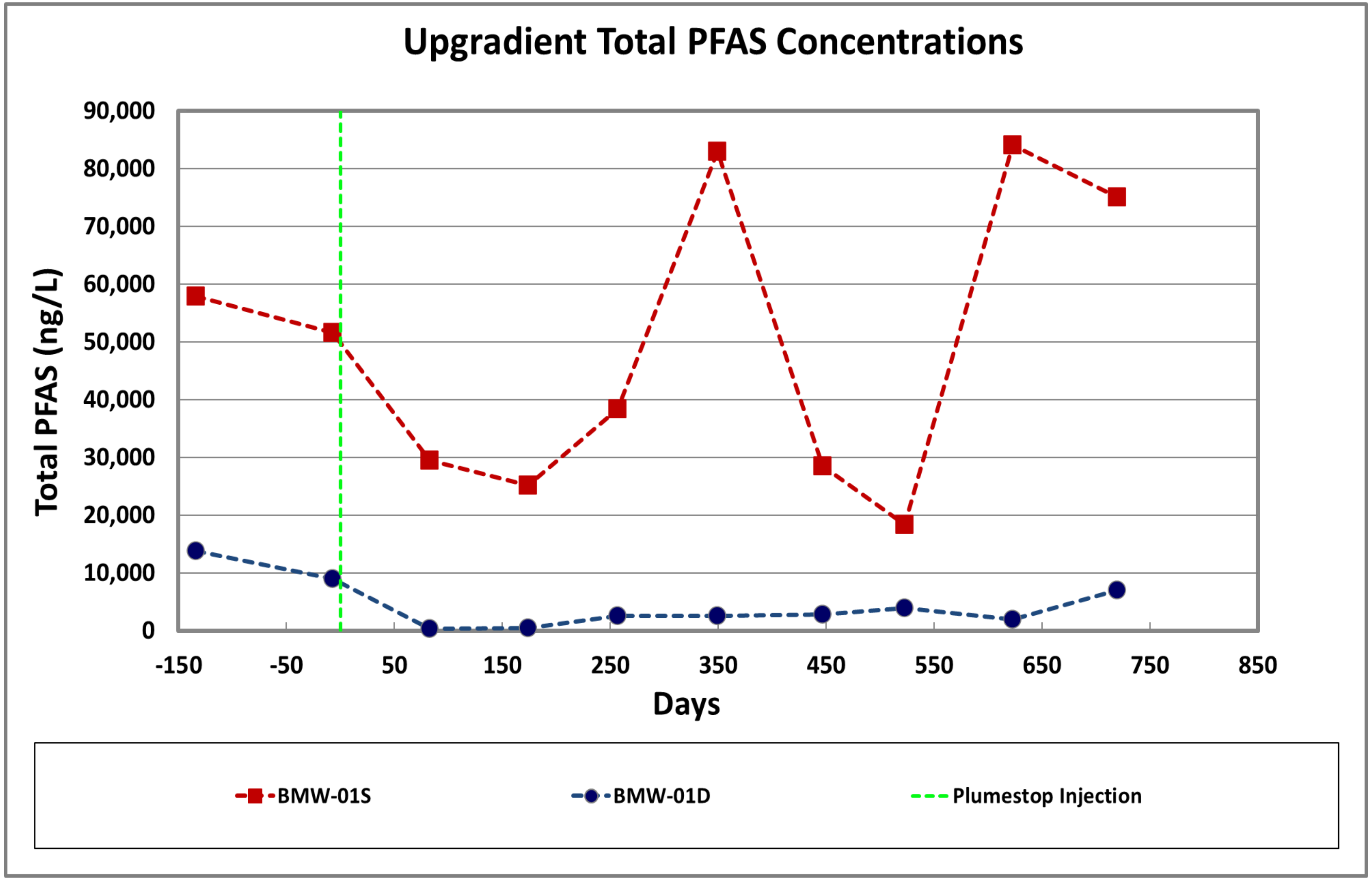
(Danko 2024)

In Situ Sorption: CAC Distribution Assessment



(Danko 2024)

In Situ Sorption



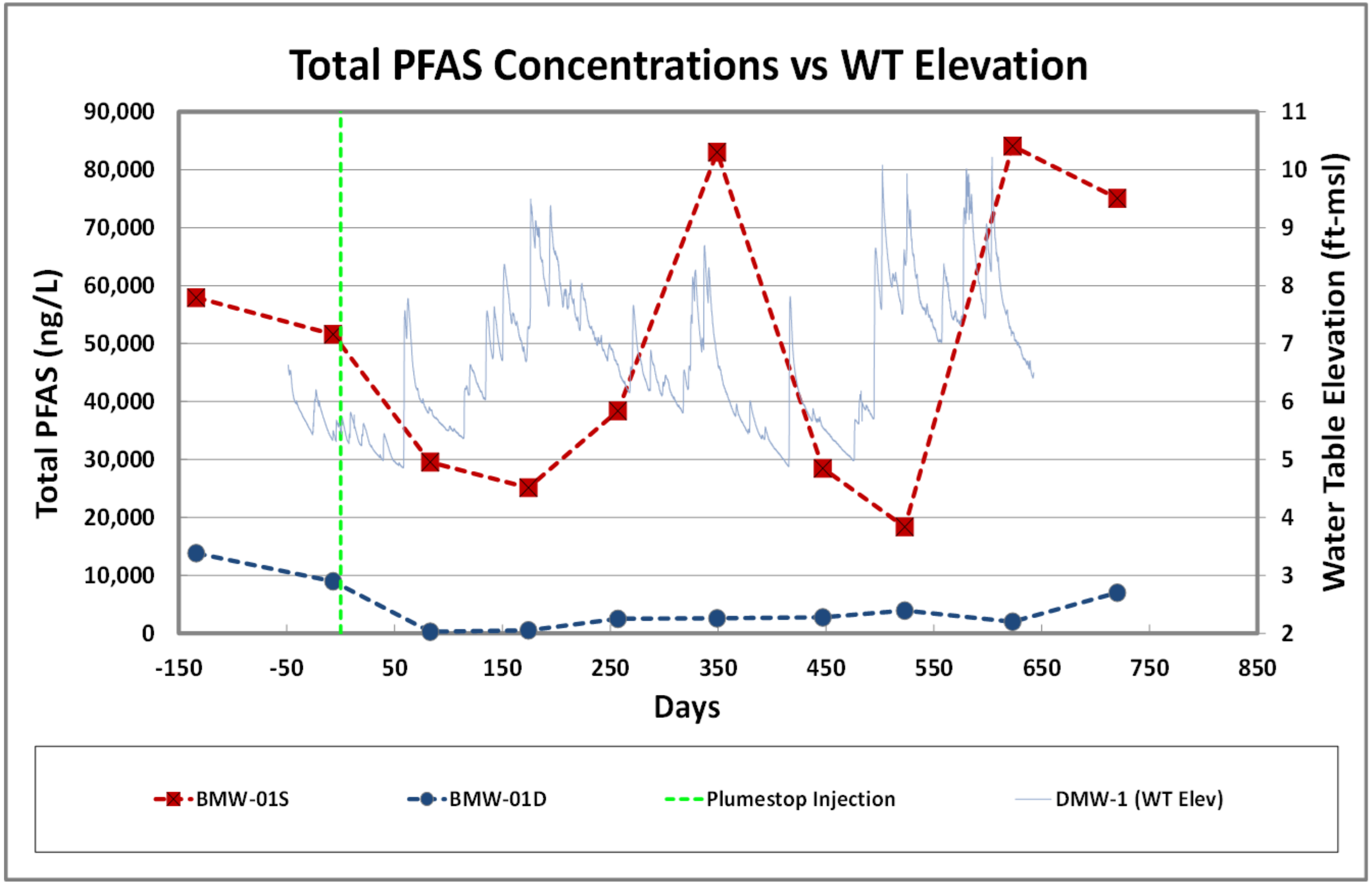
Upgradient– 2 YRS

- Pre-injection baseline
  - Shallow: 52–58 µg/L
  - Deep: 9–14 µg/L
- Less variability in Deep Zone
- Why more variability in Shallow Zone?

µg/L: micrograms per liter

(Danko 2024)

In Situ Sorption: Impact of Water Table Fluctuations



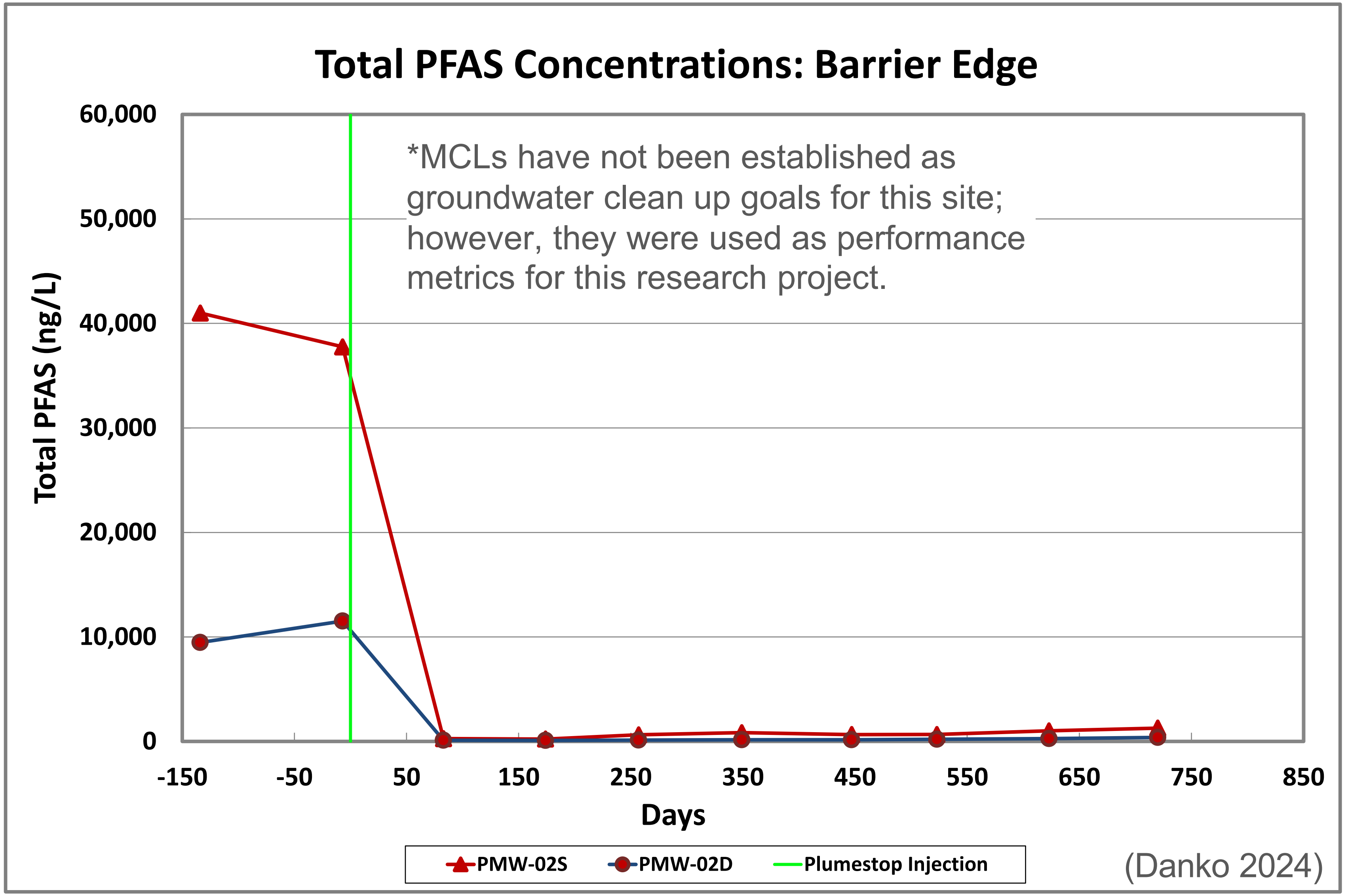
Upgradient– 2 YRS

- Pre-injection baseline
  - Shallow: 52–58 µg/L
  - Deep: 9–14 µg/L
- Over time variability in shallow GW suggests vadose zone impacts - groundwater elevation
- Less variability in Deep Zone

µg/L: micrograms per liter

(Danko 2024)

PFAS Data (Total): Downgradient Barrier Edge



*MCLs have not been established as groundwater clean up goals for this site; however, they were used as performance metrics for this research project.

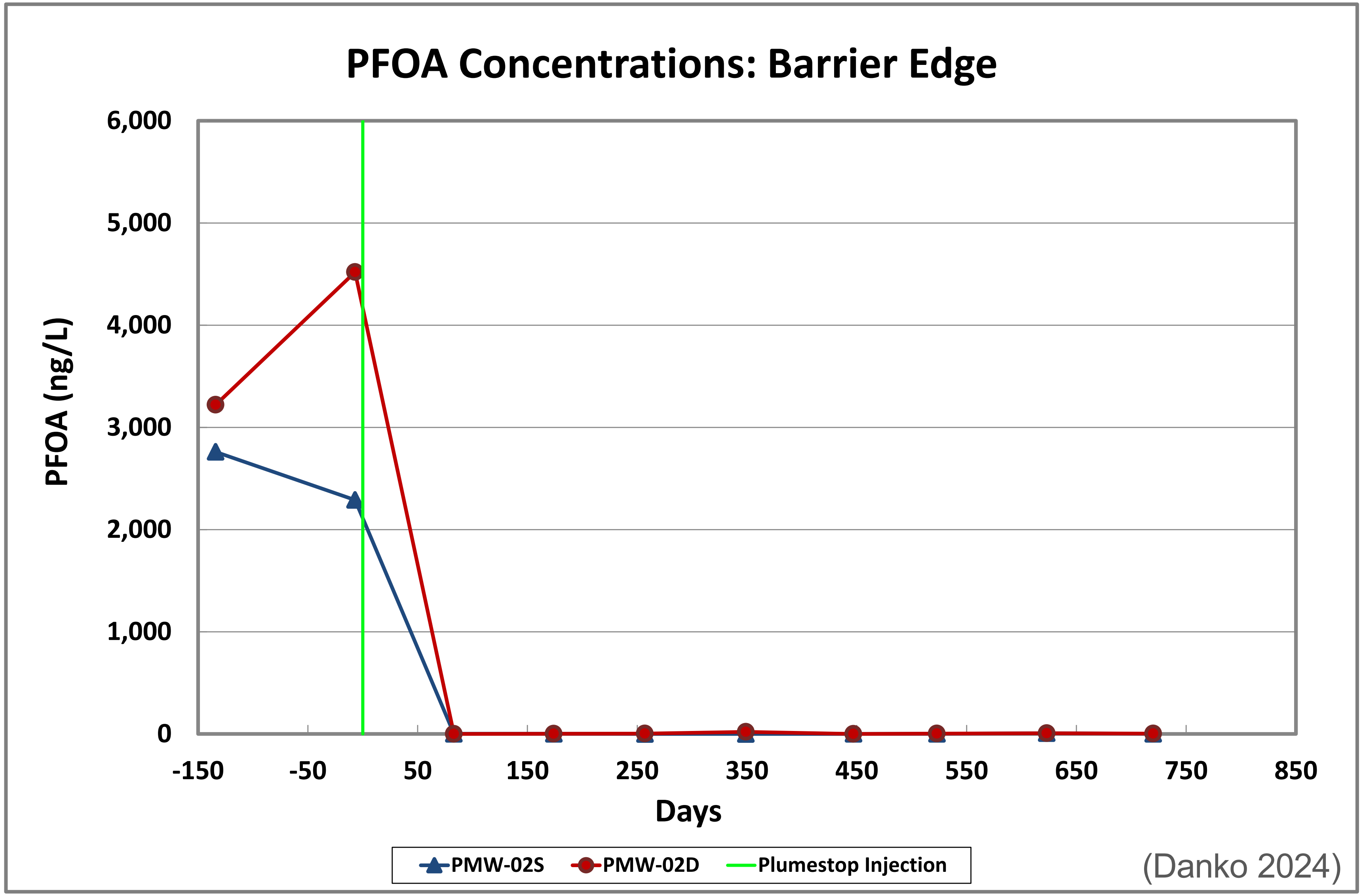
(Danko 2024)

2 years after injection

- 96.8% reduction in shallow zone
- 96.3% reduction in deep zone
- EPA MCLs met*
- Complete breakthrough of PFBA
- PFPeA, PFHxA also increasing gradually with time
- Excluding PFBA, 99.85% removal at downgradient edge

MCL: maximum contaminant level

PFAS Data (PFOA): Downgradient Barrier Edge



(Danko 2024)

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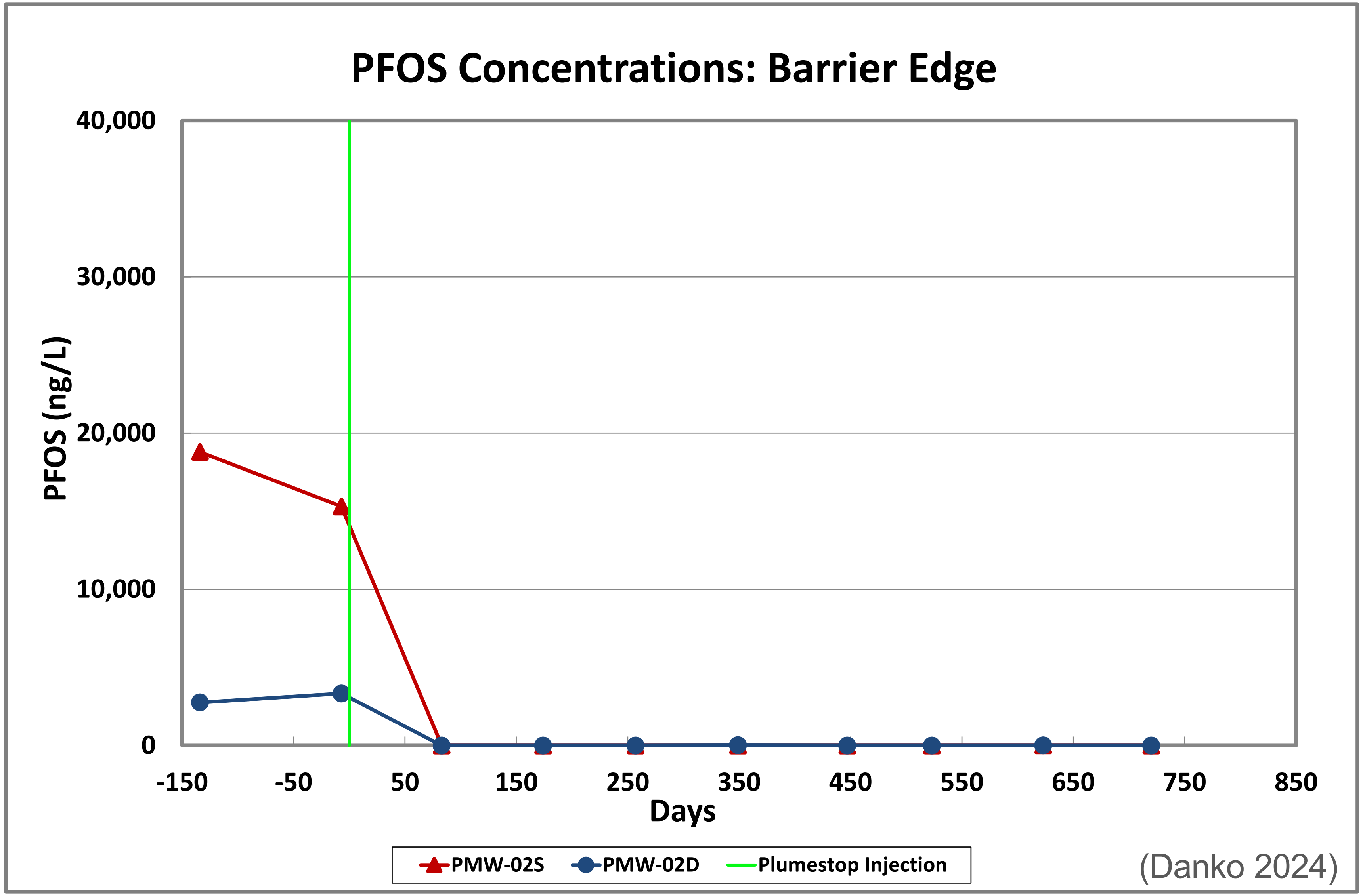
- EPA MCLs met*
- Complete breakthrough of PFBA
- PFPeA, PFHxA also increasing gradually with time
- Excluding PFBA, 99.85% removal at downgradient edge

MCL: maximum contaminant level

PFAS Data (PFOS): Downgradient Barrier Edge



(Danko 2024)

2 years after injection

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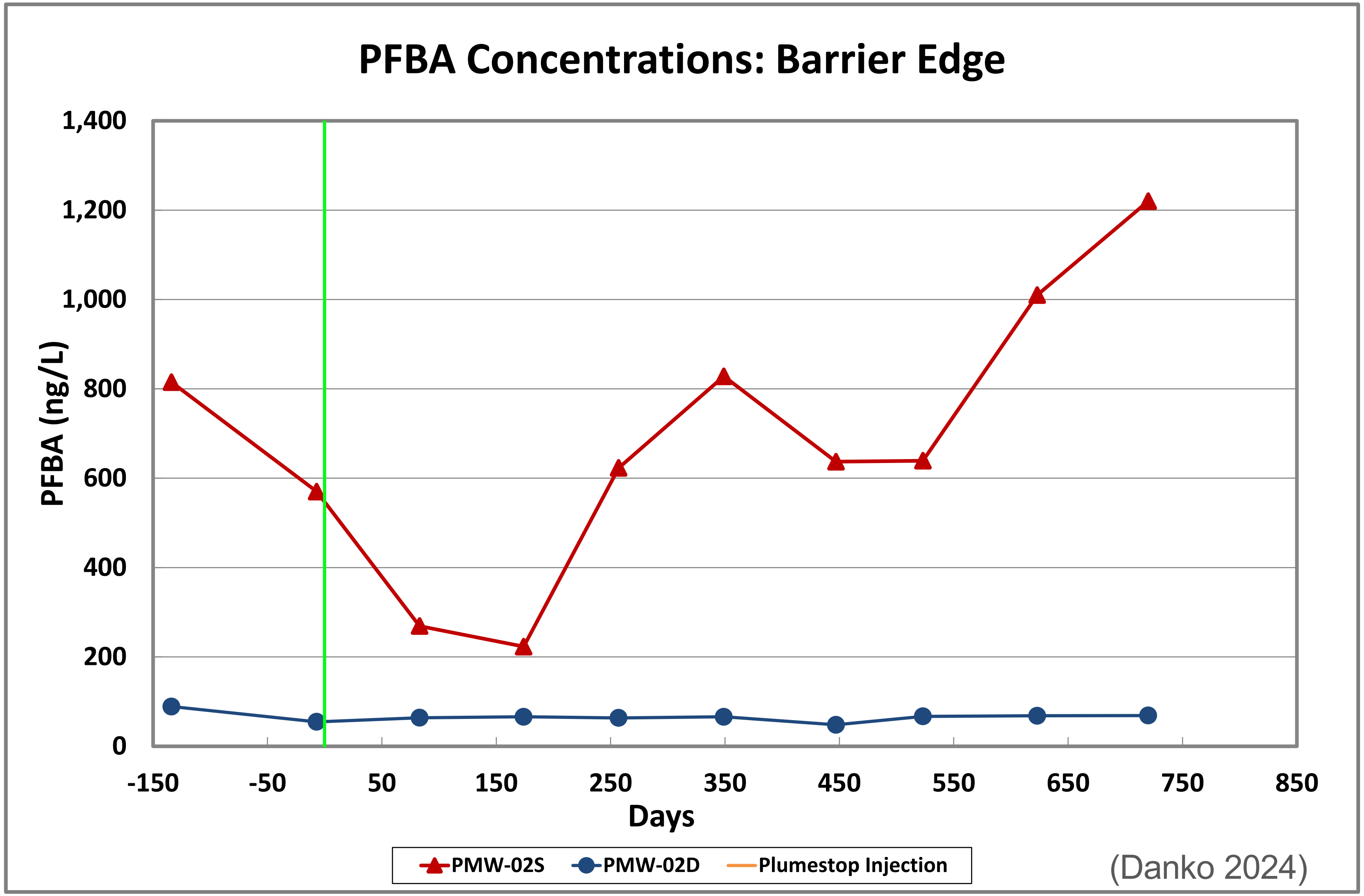
MCL: maximum contaminant level

PFAS Data (PFBA): Downgradient Barrier Edge



(Danko 2024)

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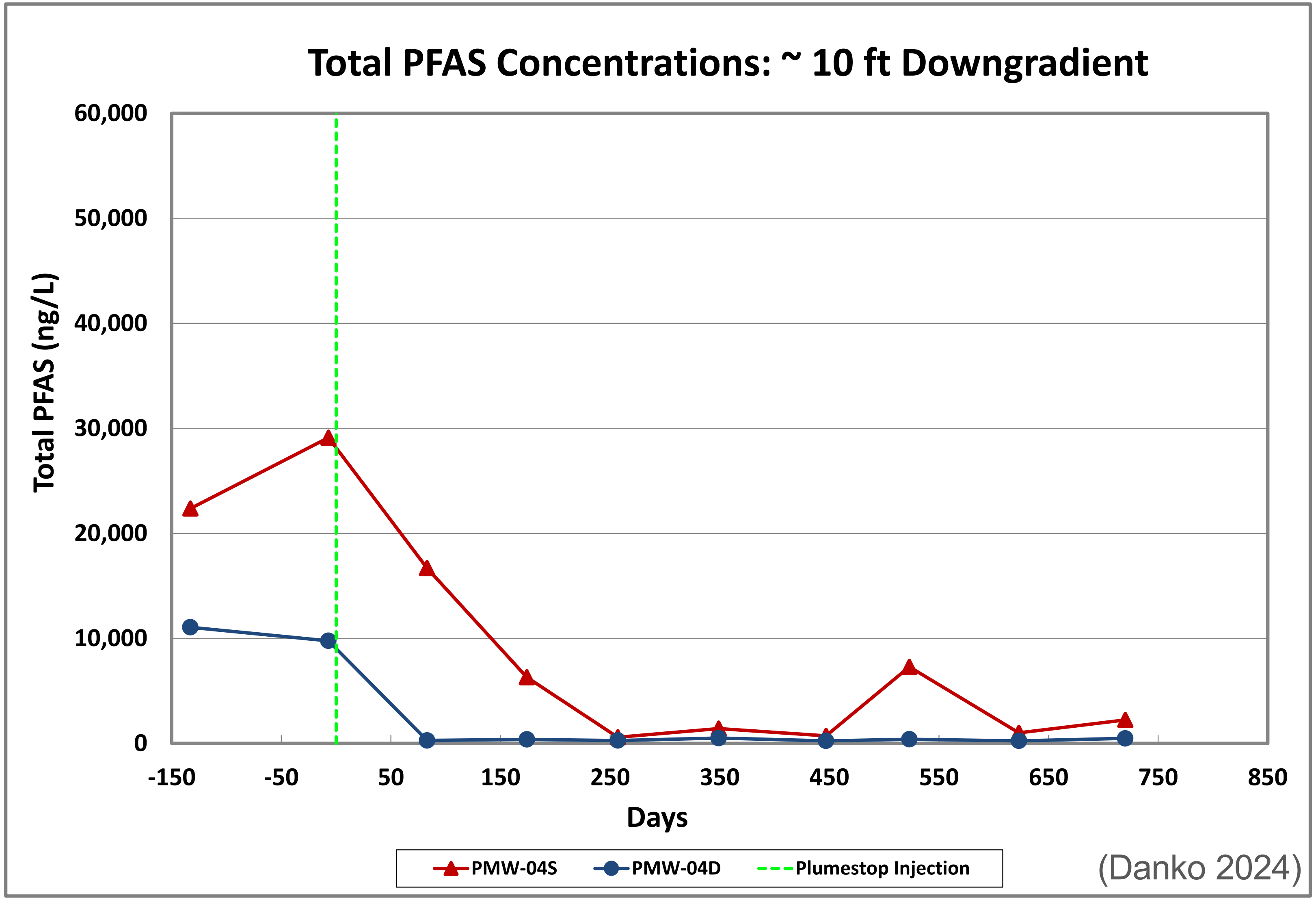
- Complete breakthrough of PFBA
- PFPeA, PFHxA also increasing gradually with time
- Excluding PFBA, 99.85% removal at downgradient edge

MCL: maximum contaminant level

PFAS Data (Total): 10-Foot Downgradient

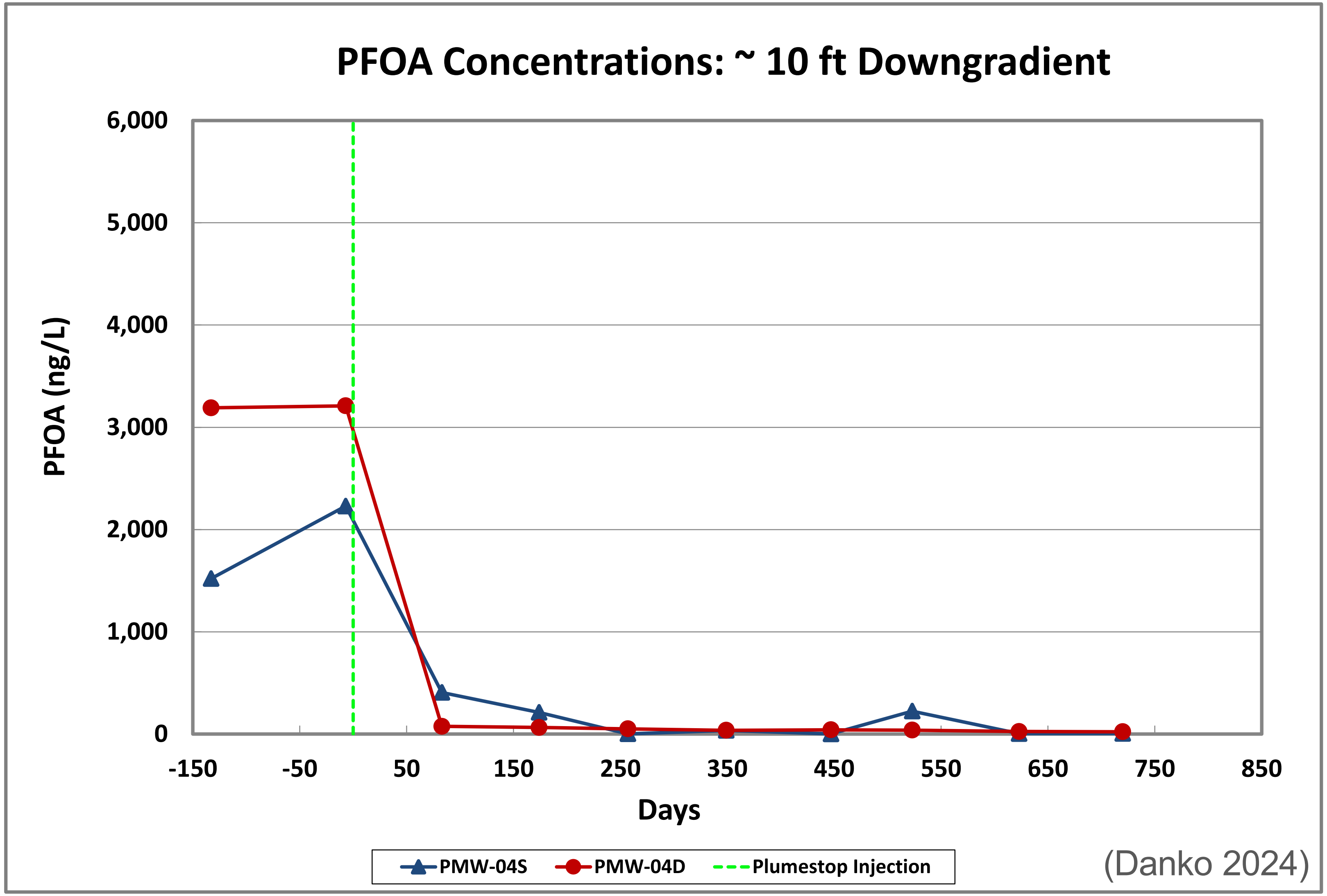


(Danko 2024)

2 years after injection

- 91.2% reduction in shallow zone
- 95.3% reduction in deep zone
- EPA MCLs not met*
- Complete breakthrough of PFBA
- Rate-limited and back-diffusion downgradient of barrier + new vadose zone addition

PFAS Data (PFOA): 10-Foot Downgradient

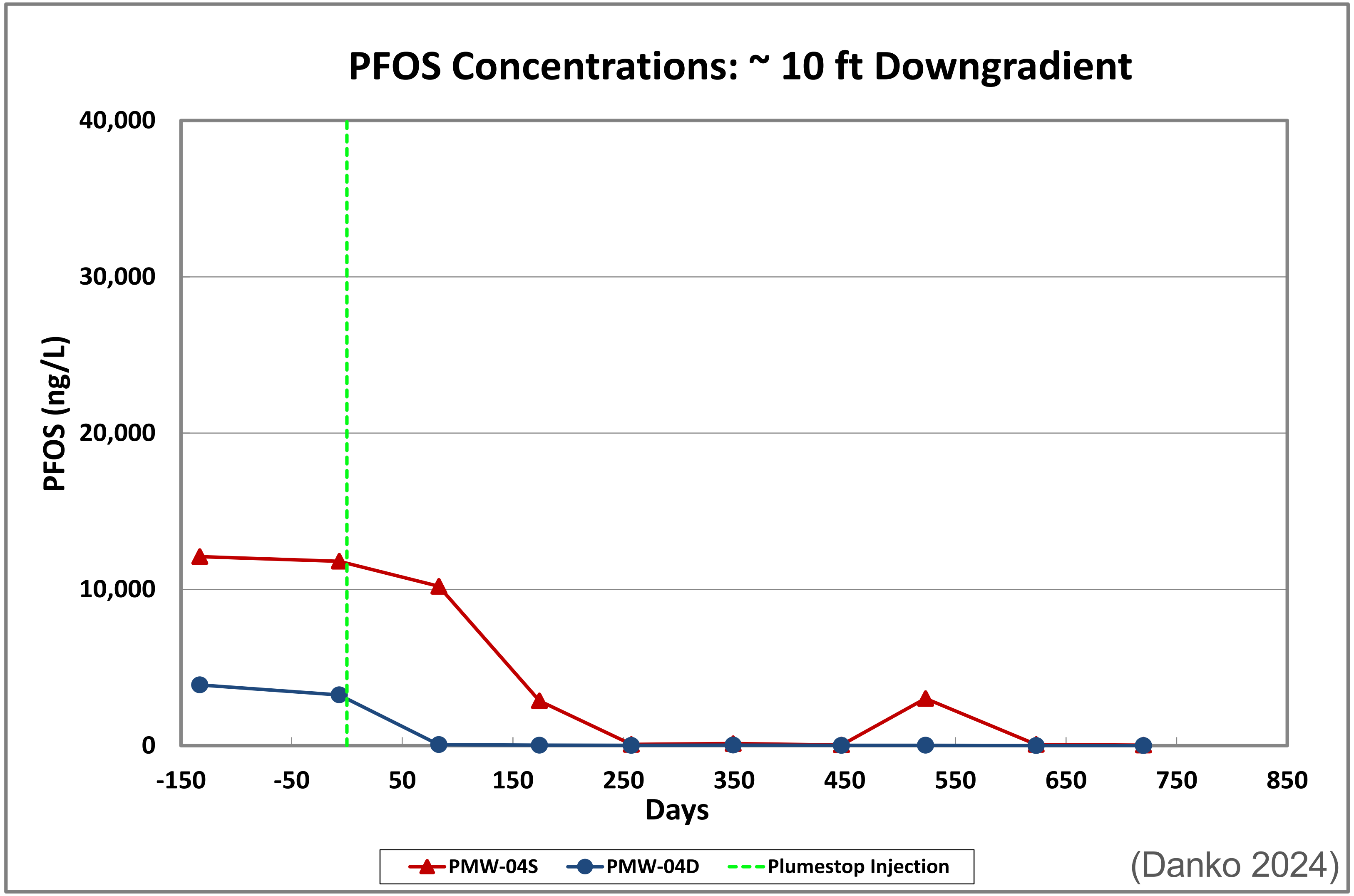


(Danko 2024)

2 years after injection

- 91.2% reduction in shallow zone
- 95.3% reduction in deep zone
- EPA MCLs not met*
- Complete breakthrough of PFBA
- Rate-limited and back-diffusion downgradient of barrier + new vadose zone addition

PFAS Data (PFOS): 10-Foot Downgradient



(Danko 2024)

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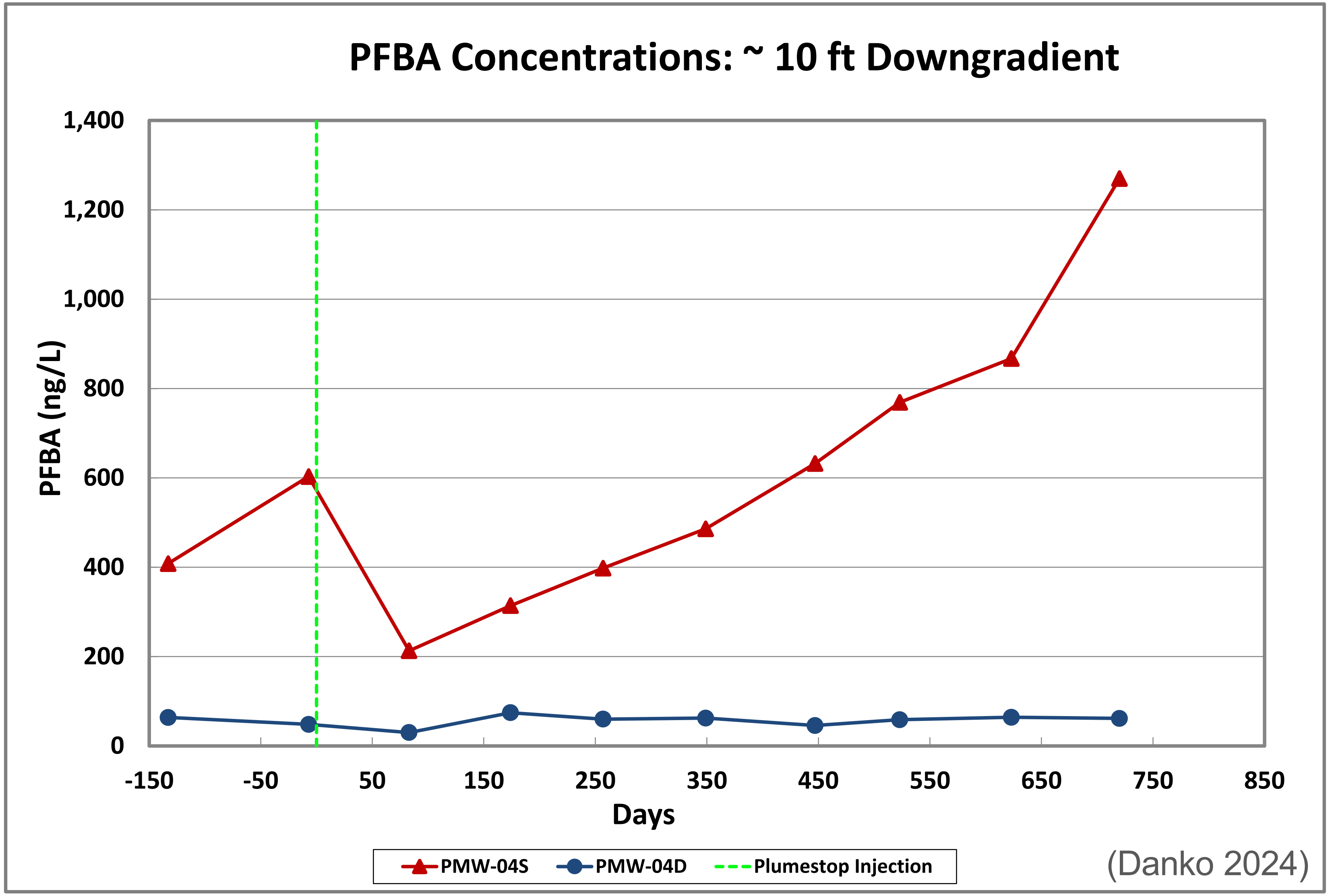
PFAS Data (PFBA): 10-Foot Downgradient



(Danko 2024)

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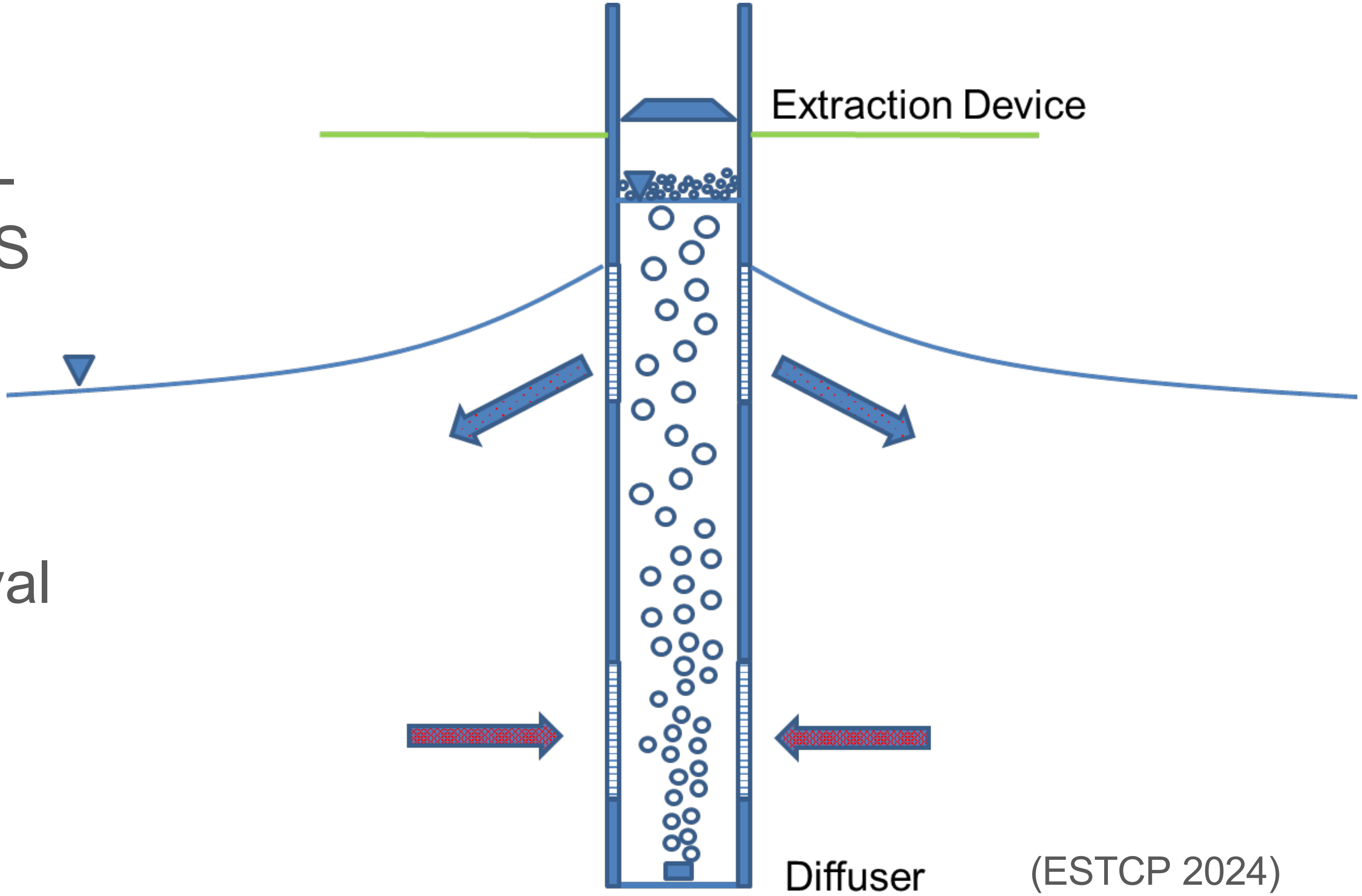
- 91.2% reduction in shallow zone
- 95.3% reduction in deep zone
- EPA MCLs not met*
- Complete breakthrough of PFBA
- Rate-limited and back-diffusion downgradient of barrier + new vadose zone addition

In Situ Sorption: Key Takeaways

- Injected CAC barriers can sequester PFAS and reduce downgradient migration in groundwater
- Breakthrough of short chain PFAS like PFBA can occur
- If source mass still remains downgradient of treatment, achieving cleanup goals may be challenging due to vadose zone leaching and matrix diffusion/desorption
- A reminder to please check with a SME!

Case Study 5: In Situ Foam Fractionation

- ESTCP ER19-5075
- Demonstrate capability of D-FAS system to remove PFAS mass from source zones
- Determine return on investment of system
- Estimate PFAS mass removal
- Estimate treatment cost efficiency
- Assess ease of operation



(ESTCP 2024)

U.S. Patent 10,752,521

Conceptual Site Model

- East Coast Master Jet Base
- High permeability (medium sand or better)
- Water table close to the surface (5–6 feet bgs)
- Homogeneous
- Relatively high concentrations of PFAS
- TTA close to fire station burn pit (SWMU 26) and fire station

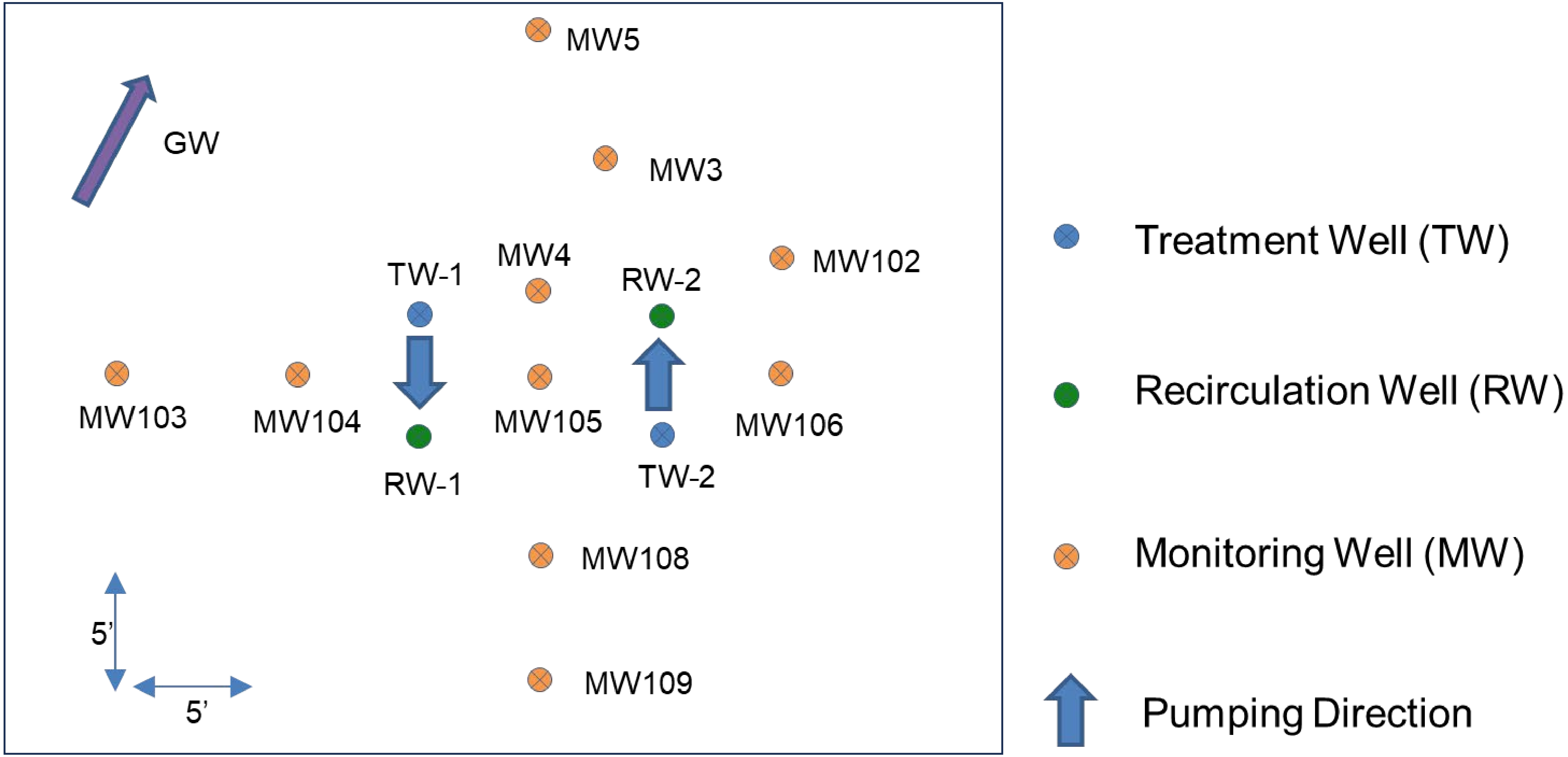
TTA, Adapted from ER19-5075 Final Report

PFOA = 22,600 ng/L
PFOS = 493,600 ng/L

(CH2M Hill 2018)

SWMU: solid waste management unit
TTA: target treatment area

System Infrastructure Layout



(Reynolds 2022)

System Infrastructure Layout


(Nelson 2021)


(Nelson 2021)

Example of an In Situ Foam Fractionation System

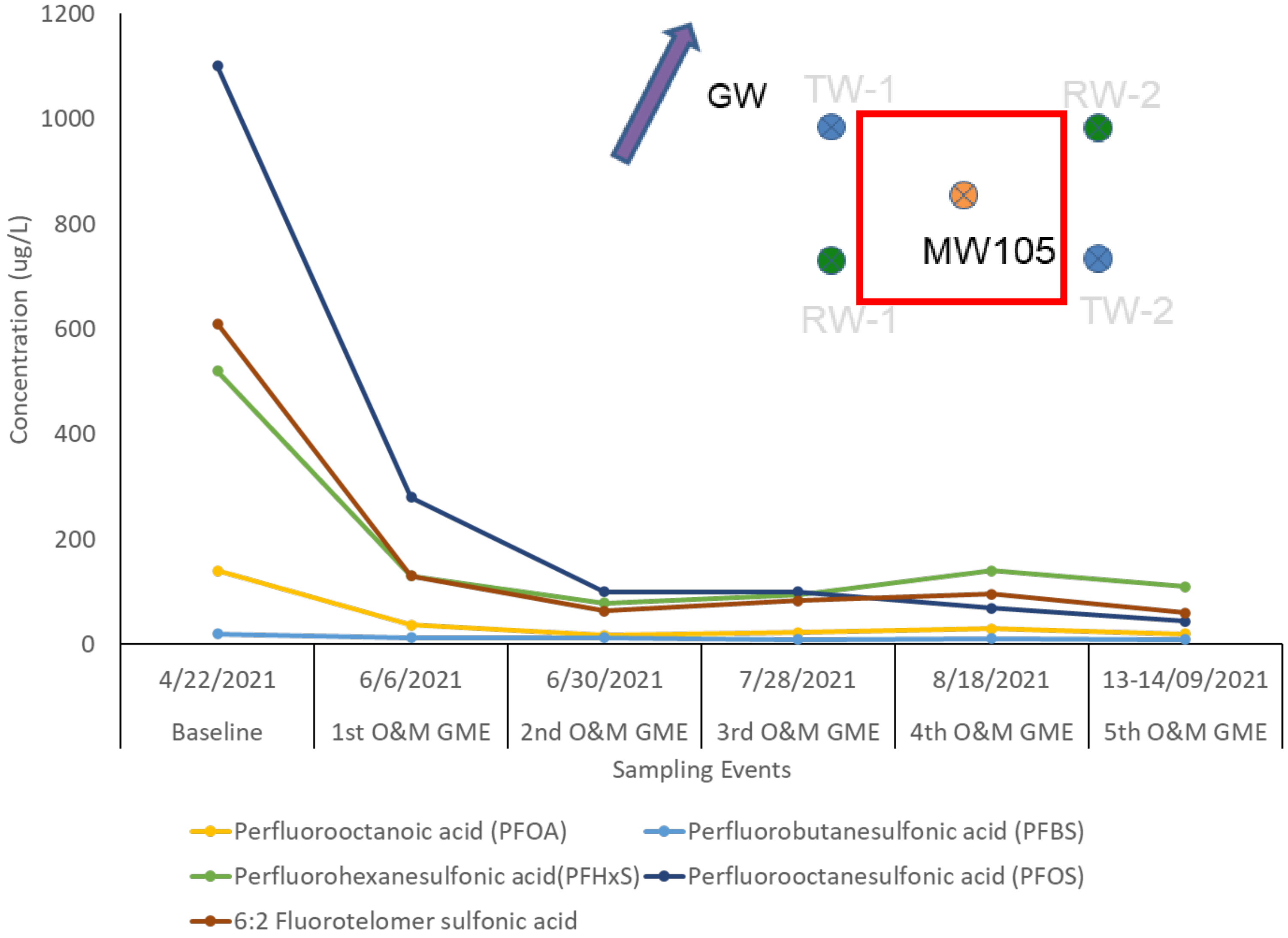
During Extraction

After Settling

Note: Foam collection tank should be in secondary containment and contents clearly labeled.

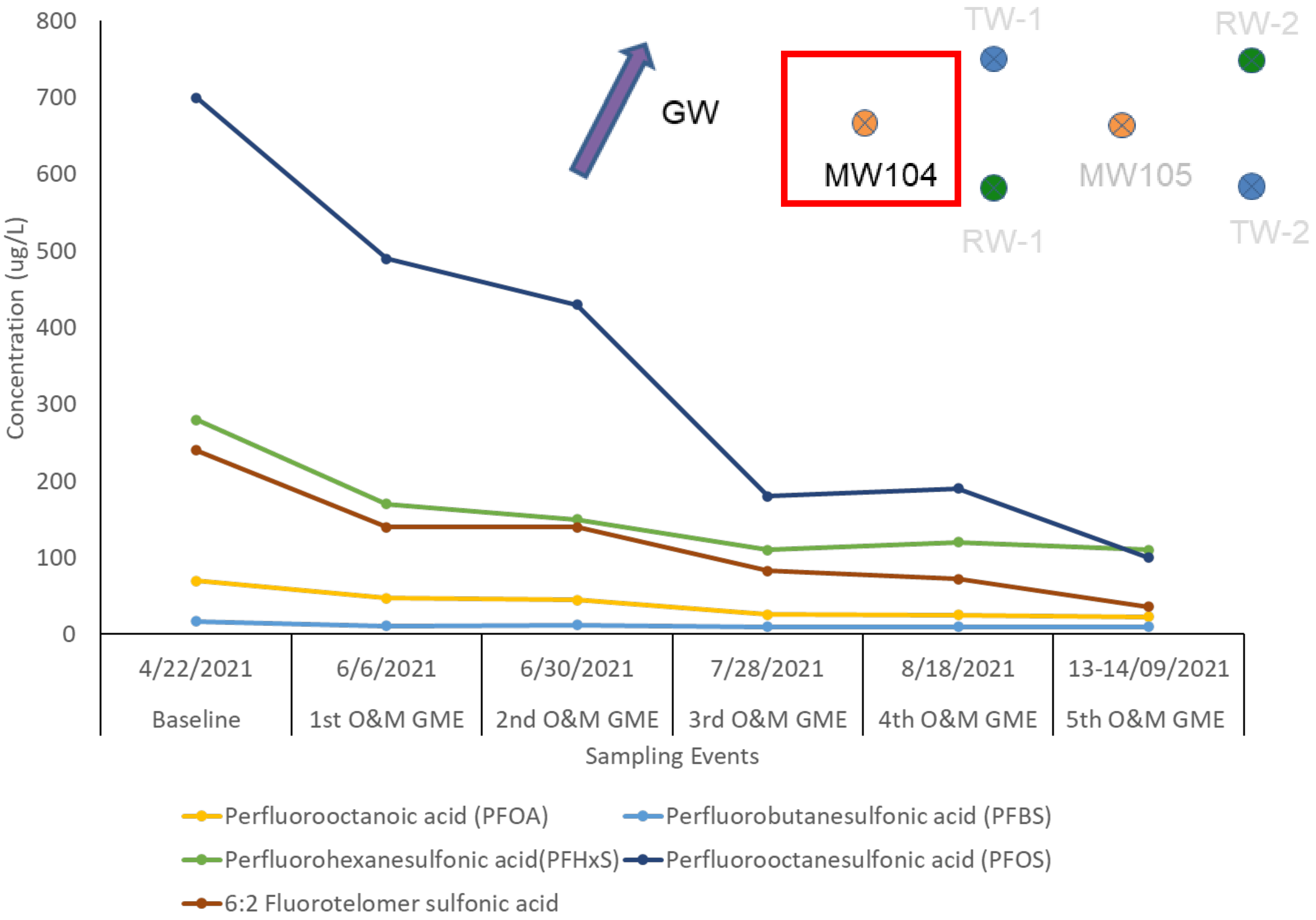
(Nelson 2021)

Results in Monitoring Wells Inside Target Treatment Zone



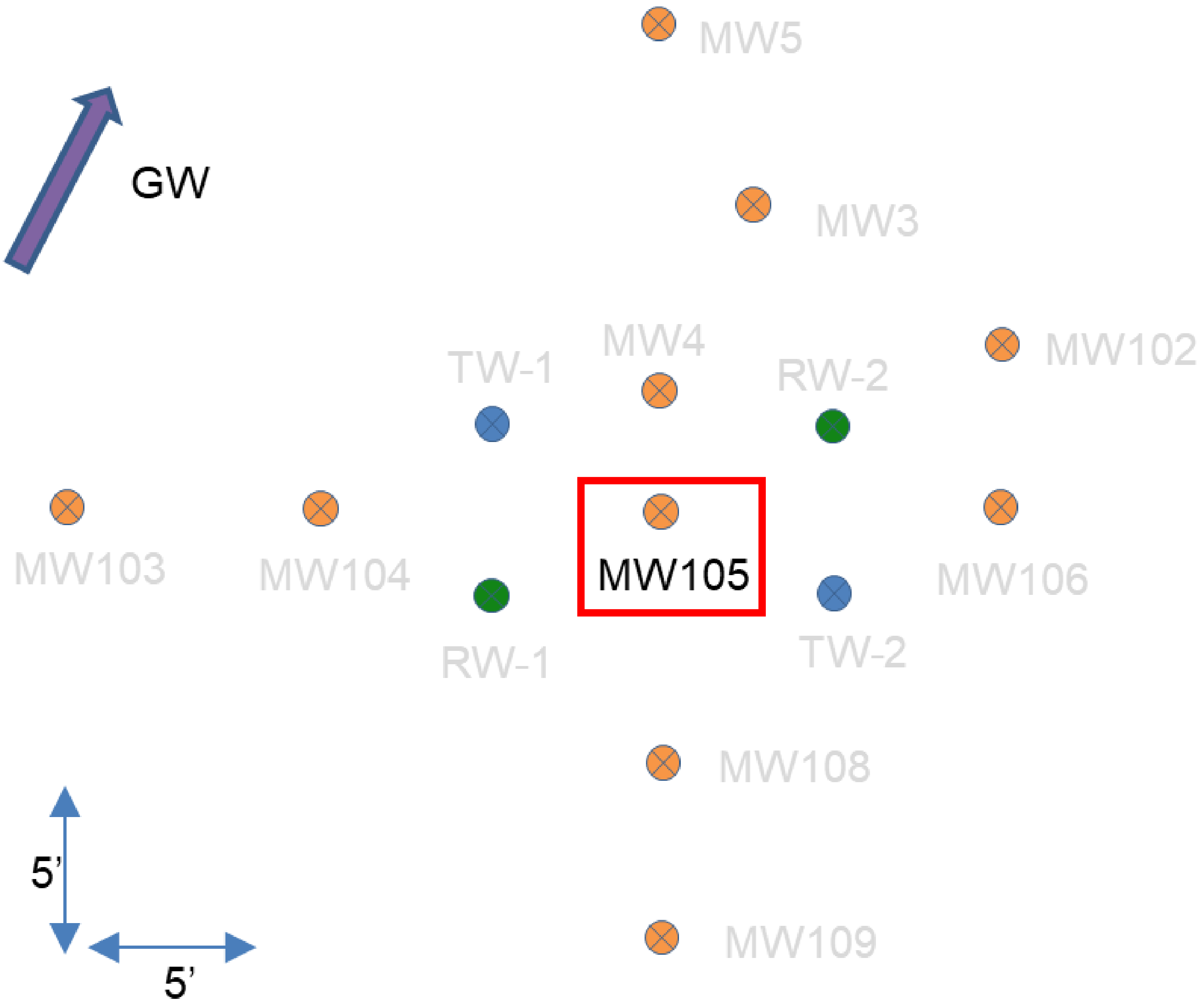
(Reynolds 2022)

Results in Monitoring Wells Outside of Target Treatment Zone



(Reynolds 2022)

Soil Results (Percent Reduction)

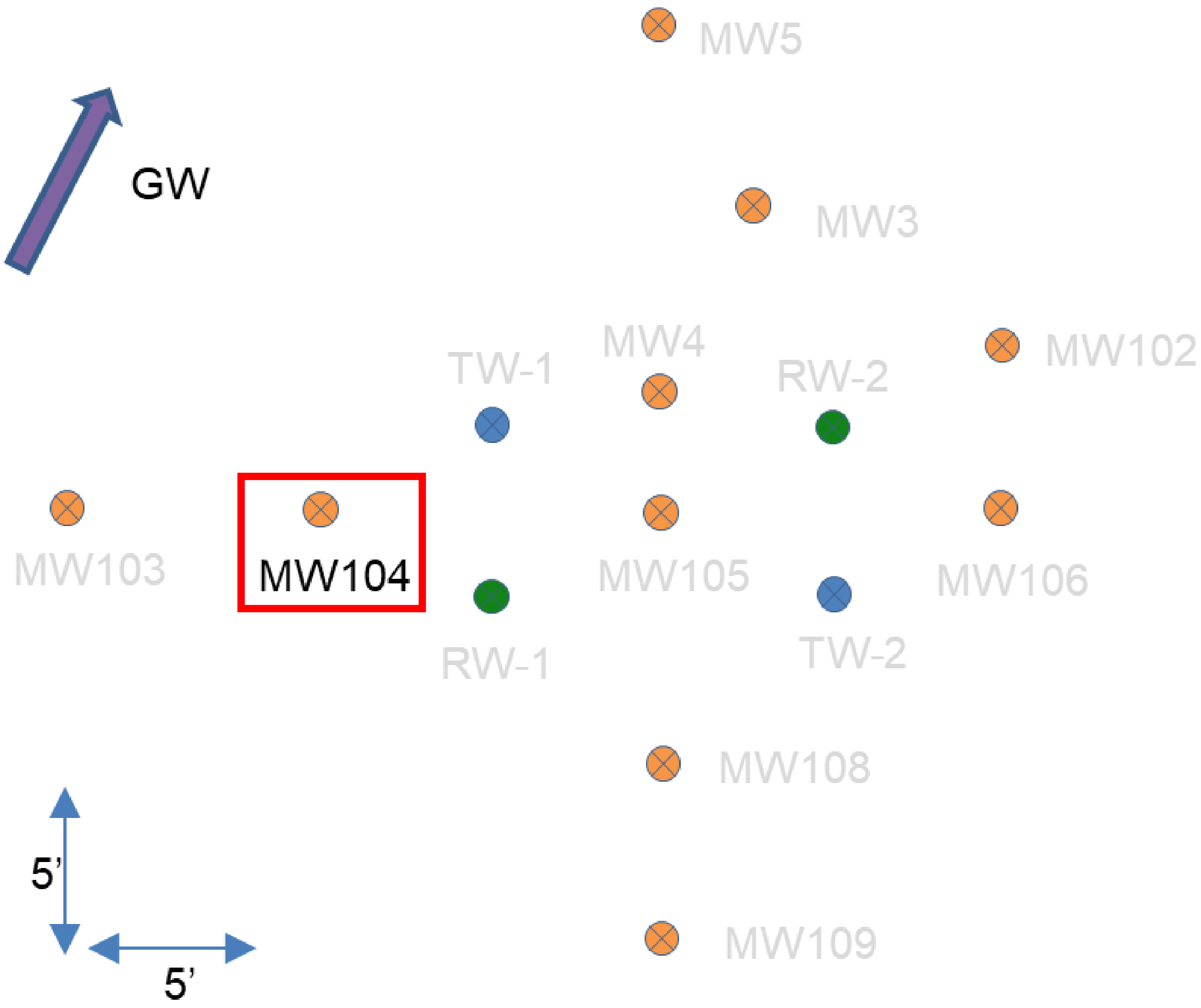


Depth (feet)	PFOS	PFOA	Sum PFAS
11 - 12	94	85	86
14 - 15	62	55	64
16 - 17	78	43	70

Percent Reduction in Water
PFOS = 96%
PFOA = 86%

(Reynolds 2022)

Soil Results (Percent Reduction)

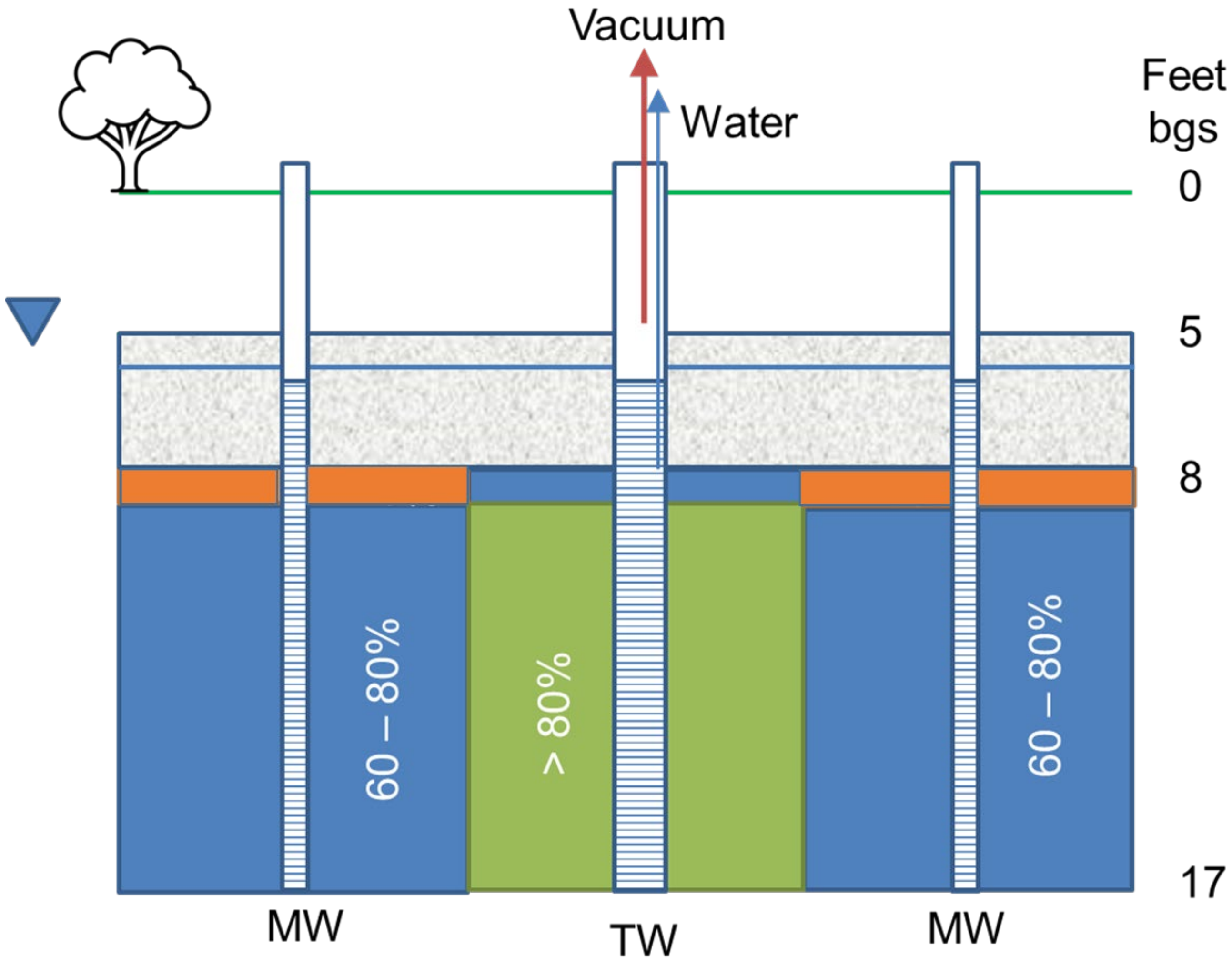


Depth (feet)	PFOS	PFOA	Sum PFAS
11 - 12	74	80	71
14 - 15	82	82	81
16 - 17	78	33	69

Percent Reduction in Water
PFOS = 86%
PFOA = 67%

(Reynolds 2022)

PFOS Reductions in Soil



(Reynolds 2022)

(Reynolds 2022)

ISSF Performance Key Takeaways

- PFAS reductions in groundwater ranged from 79% to 96%
- PFAS reductions in soil decreased up to 94%
- System operating > 95% uptime by GME4
- Removed 107 grams of total PFAS in 12 weeks with 2 wells

- Potential to couple to PFAS condensate destruction technology
- Expanded pilot follow-on expected to start in the spring 2026 timeframe and run for approximately 4–5 months
- A reminder to please check with a SME!

Presentation Overview

- Introduction
- PFAS in the Subsurface: Properties and Treatment Challenges
- Regulatory Drivers, Guidance, and Policy
- Treatment
- Case Studies
- **Guidelines for Selecting Water Treatment Technologies**
- Summary/Key Takeaways

Selecting the Treatment Approach: Key Considerations

- Accurate Conceptual Site Model (PFAS nature and extent, soils, hydrology, etc.)
- Risk (beneficial use/ecological impacts)
  - Potential for **human health drinking water exposure** at levels creating **unacceptable risk** may require more aggressive approach (e.g. pump and treat)
  - In situ methods should be considered
- PFAS Concentration
  - **Low** PFAS concentration: water can be concentrated using **sorbents**, possibly foam fractionation; destructive methods require low volume/high concentration to be economically feasible
  - **High** PFAS concentrations may be appropriate for **foam fractionation** (since direct sorbent treatment could require frequent sorbent change-outs) with **sorbent** used for **polishing** treatment only
- Other Water Chemistry
  - **High TDS** precludes IX, narrowing sorbent choice to GAC, organoclay or cyclodextrin
  - Elevated **TOC/DOC**: pre-treatment, e.g. organoclay, can preserve capacity of main sorbent for PFAS
  - **Metals** such as dissolved iron and manganese can be removed via pre-treatment using aeration/precipitation, flocculation, to prevent clogging of sorbent
  - **High TSS** may require filtration; subsequent disposal of solids

TSS: total suspended solids

Selecting the Treatment Approach (cont'd)

- Destructive Treatment of Concentrates or Spent Sorbents
  - **Refer to DoW memorandum on PFAS Destruction**
  - **Incineration**
  - **GAC Reactivation**
  - On-site destruction vs off-site
  - Destructive methods in various stages of validation, commercialization, and/or permitting
  - Some sorbents can be regenerated (typically off-site) such as Dexsorb, GAC
- Disposal in Appropriate Landfills (Subtitle D, C)
- **Site Constraints/Logistics**
  - OCONUS sites could make sorbent disposal more costly due to lack of disposal options and transportation to and from CONUS
    - e.g. Calgon does not operate GAC reactivation furnaces outside of CONUS, Italy and Belgium, so transportation of spent GAC could be cost-prohibitive; incinerators may not be properly permitted outside of CONUS for destruction of PFAS-containing materials
  - Utilities availability
- Procurement
  - Increasing demand for sorbents; 10-week lead times in some cases
  - Other equipment, such as vessels, may become more difficult to obtain/costly
  - Municipalities and water suppliers may create high demand

Selecting the Treatment Approach: Treated Water Discharge

- Discharge/Reuse of Treated Water
  - Ex situ treatment often requires treated water to be treated as wastewater
  - Sanitary sewer may be acceptable (may need to comply with discharge requirements)
  - Land application (irrigation) requires approvals
  - Uncommon, but other possibilities: soil flushing, evaporation, groundwater recharge, etc.

- Long-term Monitoring
  - Rebound
  - Soil concentrations/desorption
  - Additional/future analytes and regulated compounds
  - Transformation products from non-target precursors that feed plumes

Selecting the Treatment Approach: Vendor Information

Vendors should have:

- Multiple, peer-reviewed case studies with verifiable data
- Case studies treating real-world matrices (e.g., on-site treatment, or site-collected material such as foam fractionate)
- Case studies should be validated by an independent third-party technical body such as ESTCP, DIU, ERDC, EXWC, etc.
- Commercial availability: Systems, including ancillary equipment, should be available from technology vendor with clear pricing/performance criteria
- Relationship between technology and TSDF and/or POTW
- Ability to provide permits for operation and final effluent discharge; payment contingent on successful treatment and disposition of all effluent and generated waste

Adapted from Arcadis 2025

DIU: Defense Innovation Unit

ERDC: Engineer Research and Development Center

POTW: publicly owned treatment

Selecting the Treatment Approach: Vendor Information

Be Cautious

- Claims of “100% destruction”
- Case studies without third-party oversight (e.g., only “gray literature” articles)
- No verifiable third-party analytical
- Fluorine mass balance not provided
- Significant pre- or post-treatment is still required; is this only a “polishing” step, and will further treatment be needed?
- Disposal of waste stream(s) is still required; volume/mass? Subtitle C Landfill?
- Vendor will not divulge general technology employed, obfuscates with “proprietary” language
- No related published literature from universities regarding basic mechanisms (“black box”)

Adapted from Arcadis 2025

Selecting the Treatment Approach: Additional Considerations

- Is pretreatment required, what type? (e.g., sorbent treatment may use a “sacrificial” sorbent up-front to sorb high TOC/NOM, or TSS filtration)
- Is a high DRE (>99%) likely for the target waste stream? Consider performing treatability testing of representative samples
- Is treatment more practical/cost effective on-site or off-site?
- Off-site treatment may be favored for smaller projects (which are more typical)
- On-site treatment requires operators which often are unavailable or not programmed in budgets
- Some technologies may require significant site prep (e.g., power, water, footprint area, subbase)
- In situ treatment should be considered

Adapted from Arcadis 2025

Presentation Overview

- Introduction
- PFAS in the Subsurface: Properties and Treatment Challenges
- Regulatory Drivers, Guidance, and Policy
- Treatment
- Case Studies
- Guidelines for Selecting Water Treatment Technologies
- **Summary/Key Takeaways**

Key Takeaways

- Concentration/separation using sorbents is current “Go-To” approach; foam fractionation is up and coming
  - **GAC** is most common sorbent, especially bituminous F400, but **IX** can be more appropriate and effective for some applications, as can alternative sorbents such as Dexsorb (cyclodextrin) and FluoroSorb (modified clay)
  - Multiple sorbents in a **treatment train** may be appropriate (e.g. to first knock out high TOC/NOM)
  - **Treatability studies** can optimize technology selection, including sorbent type, and should be used when treatment is anticipated over long time periods or large volumes (i.e. where incremental differences in performance translate to large cost savings over time of treatment
- **Foam fractionation** may be appropriate at some sites but a **polishing sorbent** is almost always necessary

Key Takeaways

- **Disposal and Destruction**
  - **See 'Updated Interim Guidance on Destruction or Disposal of Materials Containing Per- and Polyfluoroalkyl Substances'** (https://www.acq.osd.mil/eie/eer/ecc/pfas/docs/policies/DoW_PFAS%20DD%20DetailedAnalysis_clear.pdf)
  - **Effectively rescinds 2022 NDAA moratorium on Incineration:** Incineration permitted for RCRA waste and also contains PFAS materials (See Footnote 1 of Guidance). Also need to reach destruction temperature of 1,100 °C, and with proper permits
- **Destruction/Disposal Options Identified:** DoW has identified commercially available options to be used by the DoW Components (all must be appropriately permitted):
  - Carbon Reactivation Units (for GAC only)
  - Hazardous Waste Landfills
  - Solid Waste Landfills (NOT for AFFF concentrate)
  - Hazardous Waste Incinerators that meet specific temperature requirements
  - Underground injection control wells (liquids only)
  - Thermal desorption units that use off-gas collection and thermal oxidation (for soils)
  - Other PFAS destruction technologies with Environmental permits or regulator acceptance
- Overall, **cost** will be a central factor and a **primary driver**

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Additional Resources: NAVFAC OER2 Webinars

- **Lessons Learned from In Situ Per- and Polyfluoroalkyl Substances (PFAS) Sequestration (May 2026)**
  - This webinar will provide an overview of in situ sequestration approaches for PFAS, including commonly used amendments and application methods. Drawing from case studies, the webinar will highlight key lessons learned from implementing a range of PFAS sequestration strategies.
- **Understanding PFAS Leaching: Key Processes, Decision Frameworks and Management Strategies (May 2025)**
  - This OER2 webinar provides insights into PFAS leaching processes from soil to groundwater, along with practical tools to understand, assess, and manage PFAS leaching. It focuses on key processes, essential data requirements, and modeling techniques.
- **PFAS Remedial Investigation Sampling and Analysis Plan Case Studies (October 2024)**
  - This OER2 webinar provides insights into the development of per- and polyfluoroalkyl substances (PFAS) Remedial Investigation (RI) Sampling and Analysis Plan (SAPs).
- **Revised Interim General Guidelines for PFAS Remedial Investigations (RI) (December 2023)**
  - This OER2 webinar series is a two-part presentation on general guidelines that the Navy has updated for PFAS RIs. Part 1 of this presentation focuses on the document overview and discusses site characterization, analytical methodologies, screening/cleanup levels, risk assessments, and investigative-derived waste (IDW) management for PFAS RIs.

OER2: Open Environmental Restoration Resources

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Questions