PFAS Annihilator® destruction solution

Lessons Learned from Commercial Deployment in Michigan for AFFF and Landfill Leachate

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Thank you for having us

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Revive Environmental: Snapshot

- Water Technology company created in December 2022
- Structure: Founded by Battelle and Viking Global Investors
- Technology: Global Patents on PFAS Annihilator® and GAC Renew™
- Headquarters: Columbus, OH / CEO: David Trueba
- https://revive-environmental.com/

Target Markets and Applications

Drinking Water

Soil Remediation

Landfill Leachate

AFFF

What we will cover today…

- PFAS path from Contaminant of Concern to Long-Term Liability
- Development and Comparison of PFAS Destruction technologies
- Overview of Supercritical Water Oxidation (SCWO)
- Lessons Learned using SCWO to destroy AFFF and Landfill Leachate

Timeline: PFAS Regulations + Actions

1998

Robert Billot helps the Tennants

Chemical Waste Disposal Linked to Health Effects

US EPA Begins Involvement

2000-2008

Medical Monitoring

Largest Illness Cluster Study

Health Effects of PFAS Identified

C8 Manufacture Phaseout Begins

2018

Building Momentum

US DoD Identifies 126 sites exceed safety guidelines

Litigations Gain Traction

C6 (GenX) Replacement Begins

PFAS Management Industry is Born

2021

Holistic Approach

US EPA Announces "Whole Agency Approach"

US EPA Initial Drinking Water Regulation Roadmap

2023

Remediation Scale-Up

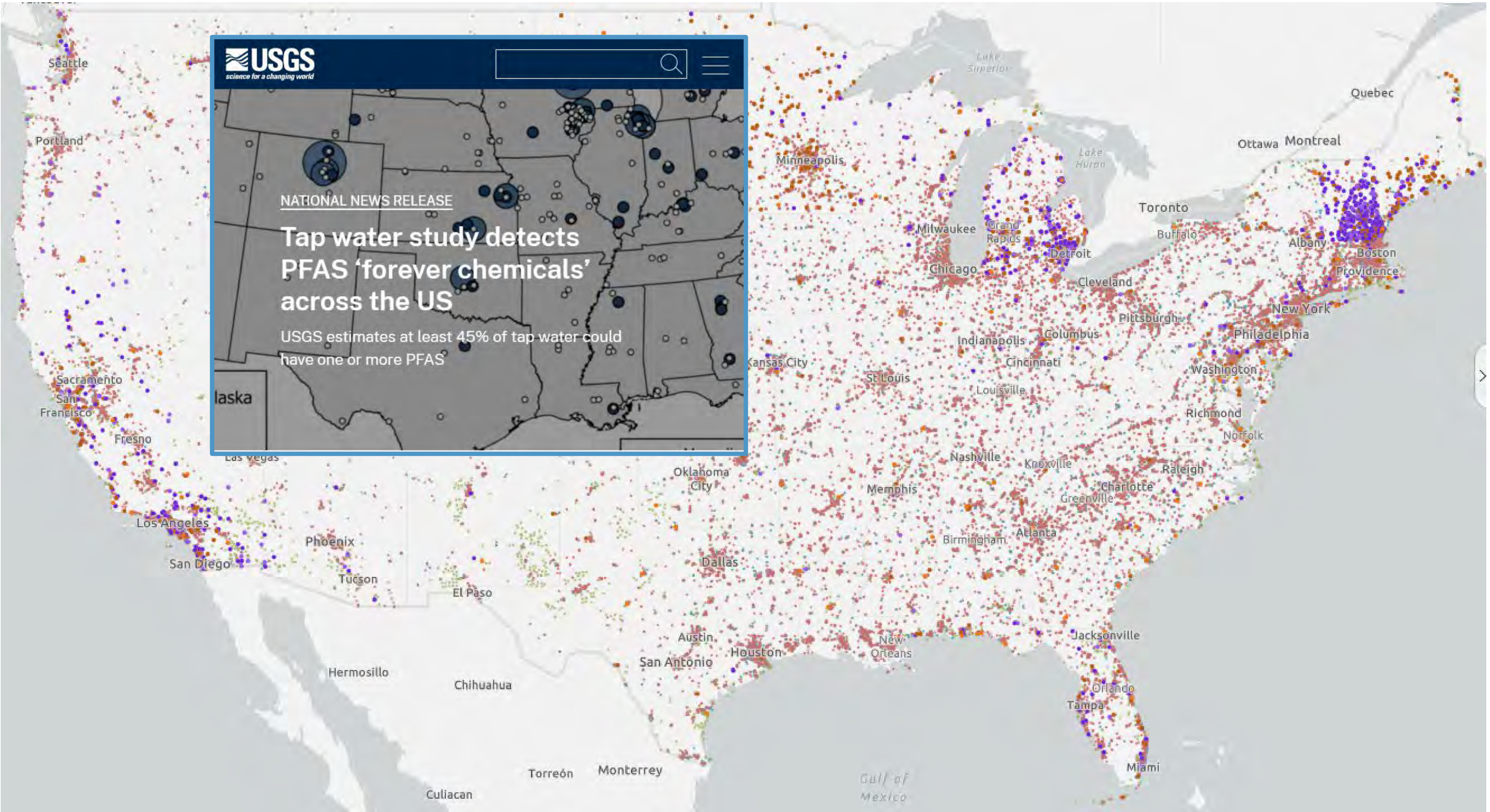
3M $10.3Bn Settlement

~1000 Drinking Water Sites Established

ESTCP/USACE Projects Accelerating

Sources: https://journals.sagepub.com/doi/full/10.1177/0731121420964827; https://pfas-1.itrcweb.org/wp-content/uploads/2020/10/history_and_use_508_2020Aug_Final.pdf

Not just 'forever' but 'everywhere' chemicals



Source: Presumptive Contamination Sites from [PFAS Sites and Community Resources map]

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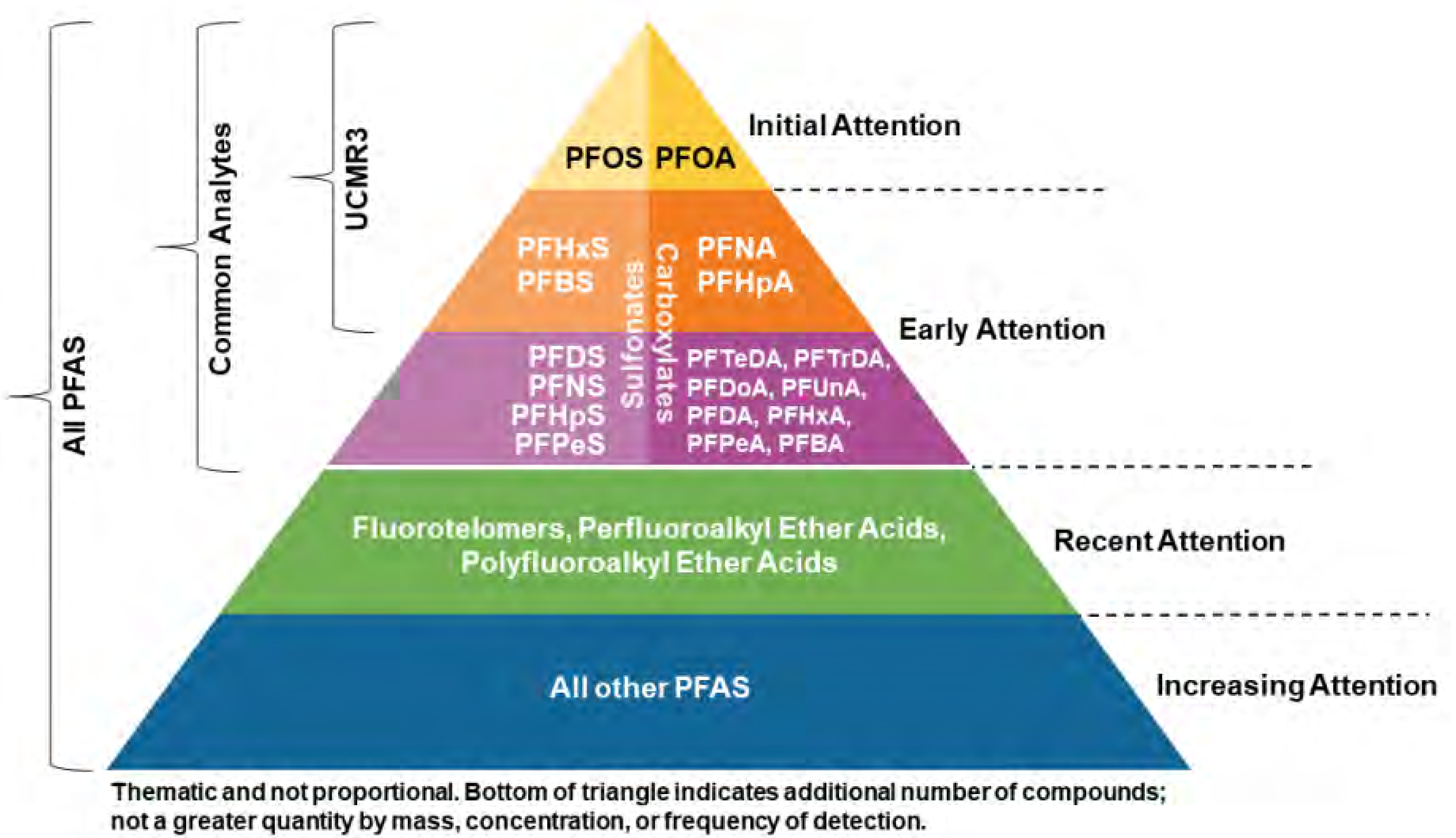
Spectrum of Concerning PFAS Contaminants



Source: J. Hale, Kleinfelder. Used with permission.

Proposed MCLs could require 99.9999% removal

Compound	Proposed MCLG	Proposed MCL (enforceable levels)
PFOA	Zero	4.0 parts per trillion (also expressed as ng/L)
PFOS	Zero	4.0 ppt
PFNA	1.0 (unitless) Hazard Index	1.0 (unitless) Hazard Index
PFHxS		
PFBS		
HFPO-DA (commonly referred to as GenX Chemicals)		

Source: EPA, Proposed PFAS National Primary Drinking Water Regulation
https://www.epa.gov/sdwa/and-polyfluoroalkyl-substances-pfas

Using PFOA as example…

If source contains 3,000 ppb
(or 3,000,000 ppt)

Achieving discharge of 4 ppt
(or 0.004 ppb)

Requires 99.9999% removal
(4/3,000,000 = 0.0001%)

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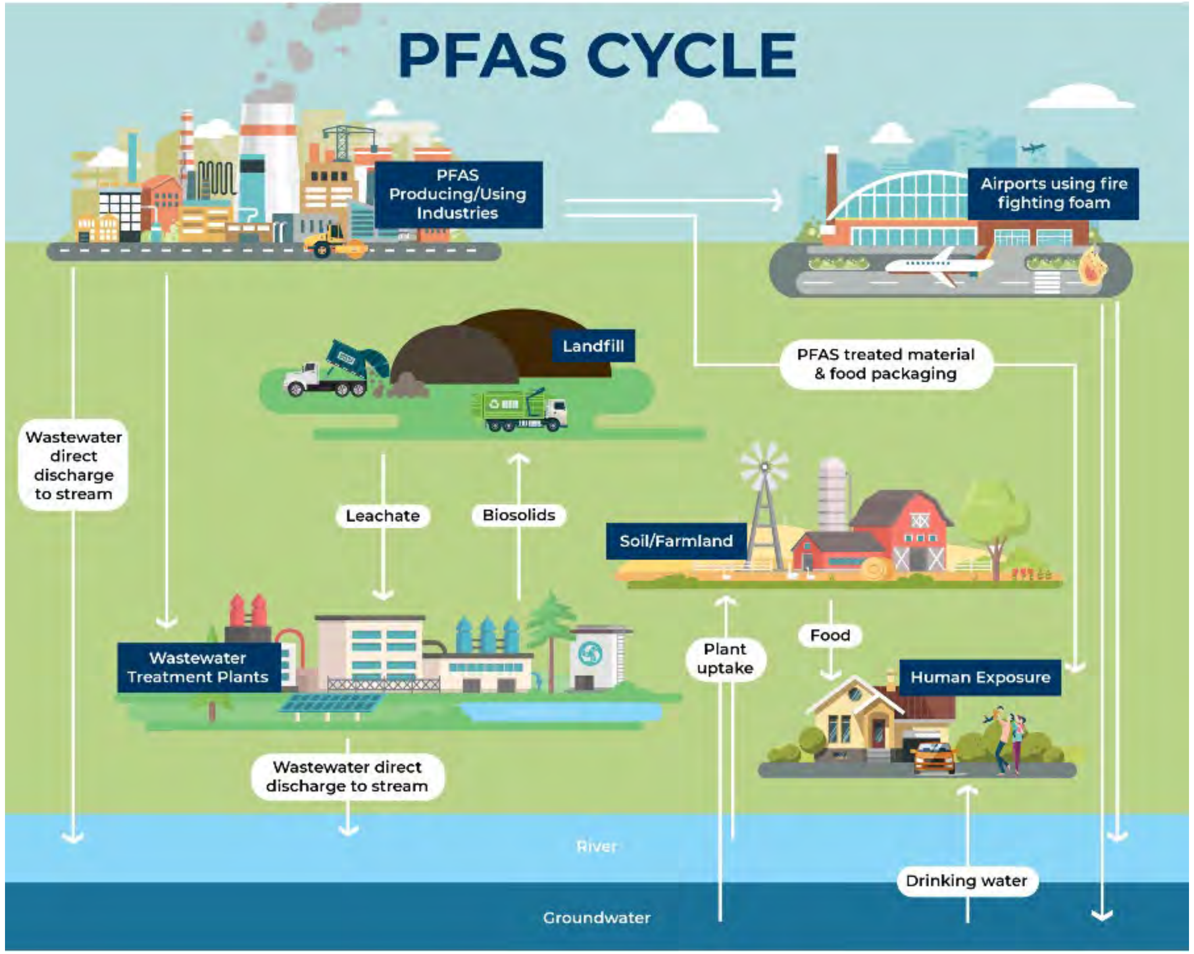
Challenges will differ by application/source



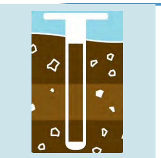
Source: Walnut Valley Water District, https://walnutvalleywater.gov/your-water/your-drinking-water/water-quality/

Drinking Water

- Very High Volume
- Recurring - Continuous
- Low PFAS Concentrations
- Removal via Media, RO

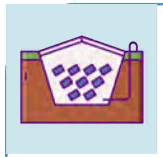
AFFF

- Lower Volume
- One-Time - Remediation
- Very High PFAS Concentrations
- Concentrate vs Rinsewater vs Contaminated Groundwater/Soil



Soil Remediation

- High Volume
- One-Time - Remediation
- Lower PFAS Concentrations
- In-Situ vs Ex-Situ
- Treatment of Soil vs Rinsate



Landfill Leachate

- High Volume
- Recurring - Continuous
- Differing PFAS Concentrations
- High amount of co-contaminants

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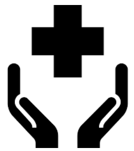
Customers have shared…



Health + Toxicity concerns are growing – more PFAS analytes

Sources and areas for treatment increasing in number and complexity

Need flexibility in deployment – onsite + off-site options

CERCLA, RCRA changes may expose Generator of Record to major liability

Need proof of destruction to eliminate liability – eg, batch material balance

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PFAS Destruction Technologies

Technology overview – focus on SCWO

PFAS Destruction Technologies

	SCWO (Supercritical Water Oxidation)	HALT (Hydrothermal Alkaline Treatment)	ECO (Electrochemical Oxidation)	Plasma
Readiness	• Commercial, Permitted • > 20 years Operational Success	• Pilot + Designing scaled-up system for testing	• Pilot	• Design + Initial field pilot
Strengths	• Most comprehensive depth and breadth of PFAS destruction • Can handle wide variety of contaminated aqueous matrices • Short residence time	• Very effective on long chain PFAS • Lower corrosion vs SCWO given lower temperatures • Short residence time	• Highly mobile unit • Low energy consumption for PFAS destruction	• Highly mobile, low-cost unit • Low energy consumption for PFAS destruction • Can handle PFAS-containing air streams
Consider-ations	• Susceptible to salt plugging • Susceptible to corrosion given high temperatures • Readiness being established for solid matrices	• Susceptible to salt plugging • Optimization for short chain PFAS	• Difficulty handling foam fractionated / concentrated waste streams • Effectiveness on short chain PFAS not yet proven • Long residence time	• Limited breadth and depth of PFAS destruction • Impacted by water quality • Long residence time • Potential for air emissions

Sources: TME: The Military Engineer, Society of American Military Engineers (July • August • Vol 115 • No 46), https://online.fliphtml5.com/fedq/opti/#p=55; Revive internal analysis

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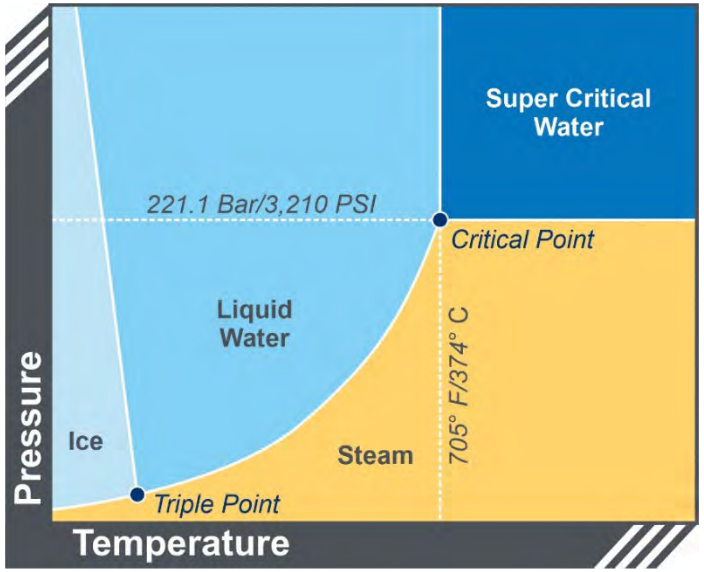
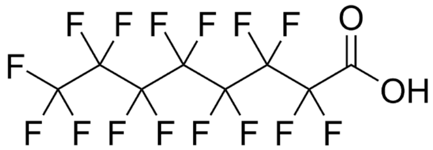
What is Supercritical Water Oxidation?

- Supercritical water exhibits unique properties
  - 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

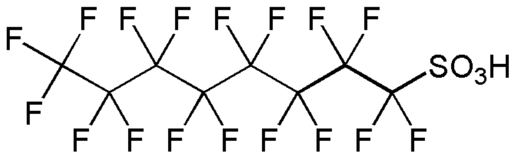


- High temperature in an oxidizing environment overcomes activation energy to break C-F bond

PFOA

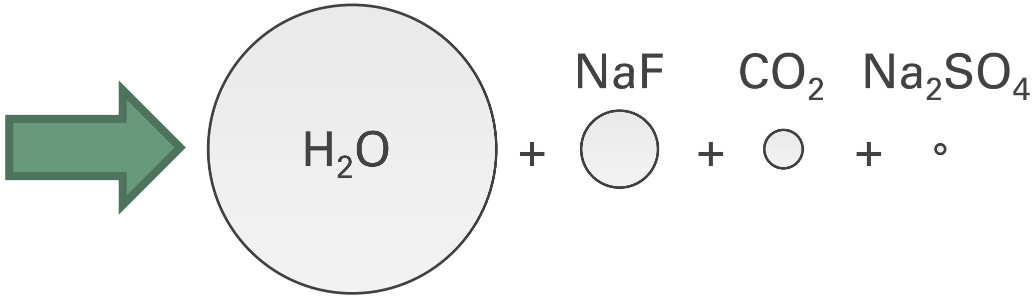


PFOS



+ H_2O_2 (oxygen source)

+ NaOH (Neutralization)



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SCWO: Batch tracking, treatment and annihilation

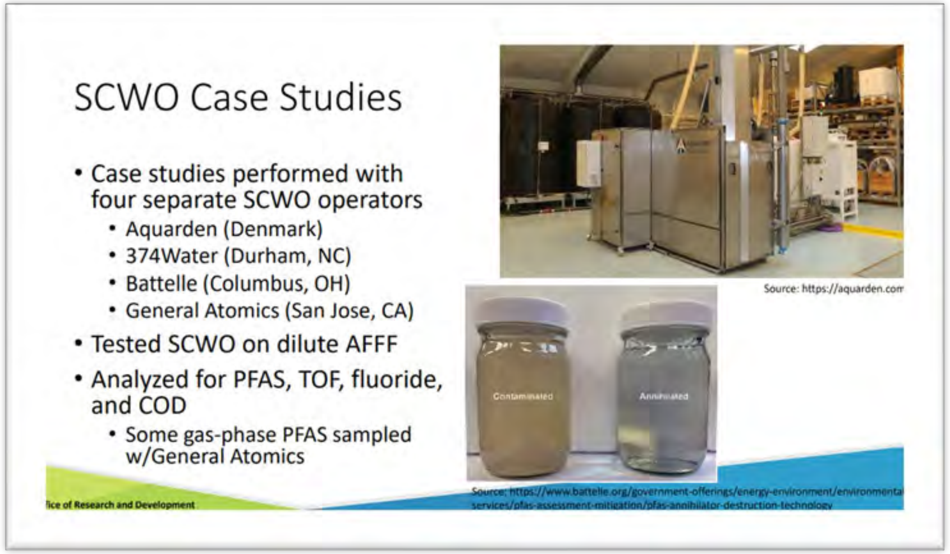
Chain of Custody
Batch receipt tied to analytical data and operating parameters

PFAS destruction
Full combustion of all organic compounds incl. all PFAS analytes

Influent, Effluent Testing
Regular sampling of all aqueous and vapor streams to ensure full destruction

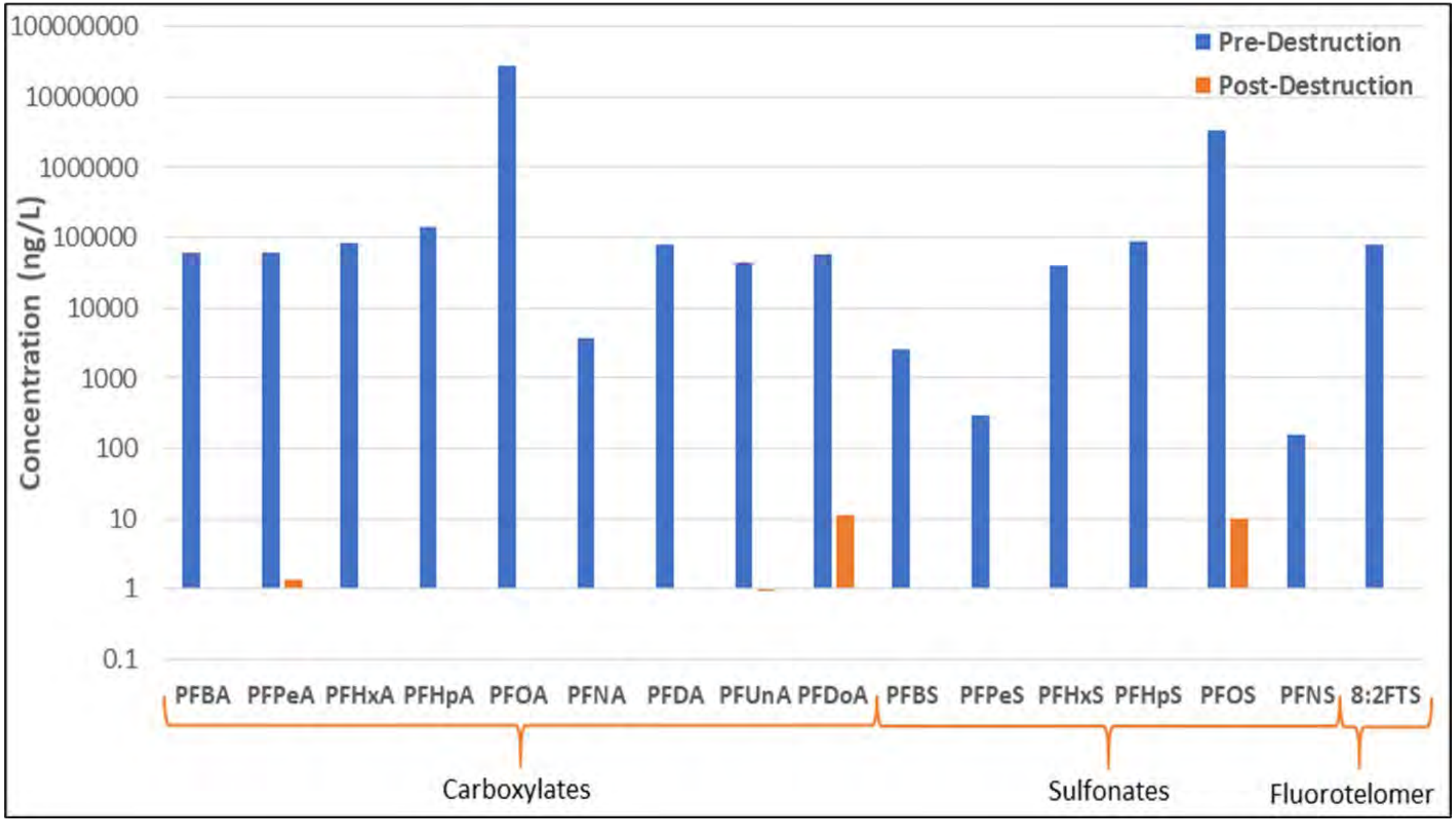
No Harmful Byproducts
SCWO reaction results in clean water, nominal CO_2, and inert salts (e.g., NaF)

EPA Case Studies on SCWO



The tests achieved 99.99% destruction and removal efficacies of targeted PFAS and total organic carbon. The tests show that hydrothermal flame as an internal heat source reduces residence time, with minimum corrosion, by controlling the wall temperature and construction materials. SCWO process shows limited partial and incomplete oxidation products that are entrained in the solution, and no fluorinated compounds were detected in the stack gas emission. The effluent from SCWO is easily collected, analyzed, and can be recycled. Gaseous effluents from SCWO were carbon dioxide and oxygen with traces of carbon monoxide and trace quantities of hydrothermal heat source oxidized products. The hydrogen fluoride formed within the reactor was neutralized, precipitated from the SCWO reactor water solution, and removed from the SCWO reaction vessel. The study provided additional data on the effectiveness of SCWO as an alternative technology for treating high PFAS-concentrated aqueous waste.

Destroys PFAS Regardless of Chain Length or Functional Groups



Effectively Treats a Range of PFAS-Impacted Media

		∑PFAS (µg/L)		
Feed Type	TOC (mg/L)	Pre-Destruction	Post-Destruction	% Removal
Investigation Derived Waste	62.1	960	0.027	>99.9
AFFF – Legacy PFOS (Lightwater)	23,900	2,150,000	0.667	>99.9
AFFF – Legacy Fluorotelomer	26,500	13.3	0.171	>99.9
AFFF Modern Fluorotelomer	126,000	13.6	3.08	>99.9
Landfill Leachate	804	41.0	0.0135	99.9
GAC Regenerant (alcohol-based)	NA	23.9	0.0157	99.9
Soil Wash Rinsate	582	0.709	0.0422	92.8
Reverse Osmosis Concentrate	15.8	14.7	0.0578	99.6
Surface Activated Foam Fractionate	11.9	16,644	31.1	99.8

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PFAS Annihilator® is being used for PFAS-impacted media directly and in combination with non-destructive treatment technologies

Scenario		Relative PFAS Concentrations	In-situ or Ex-situ	PFAS Treatment / Pre-Treatment Options
Liquid Wastes	Stockpile	Dilute to High Concentrations	Ex-situ	
Contaminated Groundwater	High Flow	Dilute to Moderate Concentrations	Ex-situ	• Reverse osmosis • Granular activated carbon
			In-situ	• Foam fractionation
Contaminated Soil	< 10,000 yd^3	Dilute to Moderate Concentrations	Ex-situ	
	> 10,000 yd^3			• Soil Washing, granular activated carbon, regeneration
			In-Situ	• Thermal Treatment, Condensation, electro-osmosis

PFAS Annihilator® Total Destruction Solution

- AFFF, IDW, concentrated waste
- Reverse osmosis reject/concentrate
- Carbon/resin regen concentrate
- Contaminated groundwater and/or wastewater

BENEFITS

- Quick, low energy input; inexpensive oxygenation and neutralization chemicals
- No additional cost to incinerate or dispose
- Risk mitigation due to complete destruction of PFAS:
  - ✓ Destroys All PFAS at any level
  - ✓ Eliminates long-term exposure risk from landfilling and new potential exposure pathways
  - ✓ Reduces risk of breakthrough, eliminates need for off-site reactivation and/or disposal; increased carbon/resin life - up to 4 regen cycles

PFAS Annihilator® Systems Operational Today

Bench/Lab Unit

- 2019 to present
- ~2 to 6 gallons per test
- Technology development
- Validate destruction of field samples
- Prepare for field deployment
  - Characterization
  - Optimization

Pilot Mobile Unit

- Jan 2020 to present
- 30 to 50 gpd
- Longer-term operation than bench-scale
- Technology development (longer-duration tests, salt removal)
- Field demonstrations/validation

Commercial Mobile Units

- March 2023 to present
- 300 to 500 gpd
- Continuous operation
- Fully permitted for operations today
- Field demonstrations
- Destruction of stockpiled waste
- Six additional units will be in service in 2023

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Lessons Learned

SCWO destruction of AFFF, Leachate

Commercial Operations in Wyoming, MI

Permit Establishment: EGLE and City of Wyoming, MI

- Regulatory Review: Paper, Physical Audit, Ongoing Monitoring/Transparency
- Permitting Result: Permit by Exemption for Air, Water

Commercial Operations: March ‘23 commissioning, May ‘23 operation

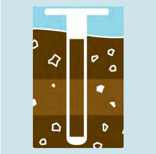
- Receiving 85K-150K gallons per day of raw leachate from 3 landfills, then running through Foam Fractionation with resulting concentrate destroyed via SCWO
- Additionally processing concentrated streams from other sources and applications

Landfill Leachate

- Foam Fractionation concentrates (1,000x, 10,000x)
- Reverse Osmosis reject

AFFF

- Concentrate stockpiles
- Rinse/Cleanout waters
- Contaminated groundwater



Soil Remediation

- Investigation Derived Waste (IDW)
- Contaminated groundwater
- Soil wash water

Drinking Water

- GAC Renew™ rinse water

Energy Usage for Startup vs Operation depends on organic content of waste stream – higher content increases energy generation and reduces electrical requirements

Leachate: Regulatory Compliance

EFFLUENT ANALYSIS	PFOA (3,200 ng/L) Limit	PFBS (12 ng/L) Limit	PFOS (12 ng/L) Limit
SAMPLE 1	4.58 ng/L	0.65 ng/L	4.01 ng/L
SAMPLE 2	5.70 ng/L	0.70 ng/L	6.98 ng/L
SAMPLE 3	2.09 ng/L	0.71 ng/L	2.09 ng/L
SAMPLE 4	1.14 ng/L	0.70 ng/L	0.98 ng/L
SAMPLE 5	1.16 ng/L	0.71 ng/L	0.99 ng/L
SAMPLE 6	1.07 ng/L	0.65 ng/L	0.91 ng/L

AFFF: Field-Scale Destruction

AFFF Type	Foam Concentration (%)	Avg. PFAS Concentration (ng/L)	Total PFAS Removal (%)
Buckeye AR	6	93,931	99.91
Buckeye AR	6	5,121,619	99.99
Buckeye AR	6	5,308,470	99.99
Buckeye AR	6	10,955,951	99.99
Buckeye AR	8	13,857,691	99.99
Buckeye AR	10	5,309,200	99.98
Buckeye AR	12	8,362,470	99.96
Buckeye AR	14	9,081,876	99.99
Buckeye AR	16	19,675,497	99.99
Thunderstorm AR	12	1,235,186	99.40
Thunderstorm AR	12	1,534,273	99.79
Universal Gold AR	12	55,245,305	99.99

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Lessons Learned from Scaling Technology…

Lead with Safety

- Coordination critical with onsite partners
- Safe handling / Chain of custody

Quality Processes / Scale

- Batch tracking
- Local regulations compliance
- 500 GPD operational capability

Regulatory Transparency

- Pre-deployment coordination
- Physical audit
- Ongoing sampling
- Water discharge limits

Infrastructure

- People
- Supply Chain / Manufacturing
- Analytical Support Ecosystem

What we covered today…

- PFAS path from Contaminant of Concern to Long-Term Liability
- Development and Comparison of PFAS Destruction technologies
- Overview of Supercritical Water Oxidation (SCWO)
- Lessons Learned using SCWO to destroy AFFF and Landfill Leachate

RENEW. RESTORE.

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