DESTRUCTIVE TECHNOLOGIES FOR PER- AND POLYFLUOROALKYL SUBSTANCES (PFAS) IMPACTED SOIL

Ramona Iery*, Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) | Poonam Kulkarni, Yue (Beatrice) Li*, Hassan Javed*, John Cook, Charles Newell, GSI Environmental Inc. | Danny Suits, Steve McKnight, Marc Deshusses, Howard Teicher, 374Water Inc. | Kavitha Dasu, Battelle Memorial Institute | Timothy Strathmann, Colorado School of Mines

* presenters

PROBLEM STATEMENT

Remediation of per- and polyfluoroalkyl substances (PFAS)-impacted soils is a significant challenge for long term site management. Soil treatments are currently limited to sorption and stabilization, and excavation and disposal (ITRC, 2022). However, several high-pressure thermal treatment technologies, while still emerging, are promising for PFAS-impacted soils.

TECHNICAL OBJECTIVES

NAVFAC funded this work to address the following key technical objectives:

- ***Task 1:*** Provide status on technology development and effectiveness of destructive technologies currently available for treating PFAS-impacted soils.
- ***Task 2:*** Conduct Bench-Scale testing of a subset of technologies.
- ***Task 3:*** Based on results of Task 2, conduct field demonstration of 1-2 destructive technologies.

TECHNOLOGIES EVALUATED

Technologies Selected for Bench-Scale Testing:

> Supercritical Water Oxidation (SCWO), 374Water
> Supercritical Water Oxidation (SCWO), Battelle
> Hydrothermal Alkaline Treatment (HALT), Colorado School of Mines (CSM)

PROJECT TEAM

Ramona Iery, Ph.D.

Poonam Kulkarni, P.E.
Yue (Beatrice) Li, Ph.D., P.E.
Hassan Javed, Ph.D.
John Cook
Charles Newell, Ph.D., P.E.

Danny Suits
Steve McKnight
Marc Deshusses, Ph.D.
Howard Teicher

Kavitha Dasu, Ph.D.

Timothy Strathmann, Ph.D.

Contact: Ramona Iery, ramona.iery.civ@us.navy.mil

Technology Description

SCWO: 374Water

How does it Work?

Supercritical Water Oxidation (SCWO) is rapidly emerging as the technology of choice for PFAS destruction. SCWO is an advanced oxidation conducted at elevated pressure and temperature. 374Water's AirSCWO™ is a continuous process designed to treat and completely mineralize PFAS in a variety of matrices (IDW, AFFF, concentrates, IX and GAC slurries). It uses air as the oxidant, and combined with efficient energy recovery systems, it provides efficient and sustainable PFAS mineralization.

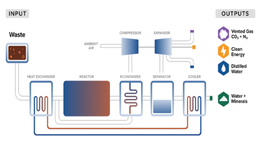


Figure 1. Process diagram of the 374Water AirSCWO™ (Technology SC-1) (374Water, 2023).

Technology Development Status

> Commercially Available: 1,500 – 52,000 gallons per day capacity
> Media Tested: Liquids and Slurries (IDW, AFFF, concentrates, IX and GAC slurries)
> Key Results:
- >99.9% destruction of PFOA and PFOS; ~99.9% destruction of short-chain PFAS
- Generates energy through oxidation reactions, with high energy recovery (produces 240 kWh/day more than it uses
- 6-8 second reactor residence time
- Demonstrated complete mineralization of organofluorine to inorganic fluoride, and absence of significant emission of volatile PFAS (including short chain)

SCWO: Battelle

How Does it Work?

The PFAS Annihilator™ is a "closed-loop, destruction" technology developed by Battelle Memorial Institute applying SCWO. It utilizes the unique properties of supercritical water (temperature > 374 °C; pressure > 221.1 Bar) to enable the destruction of PFAS (Figure 2).

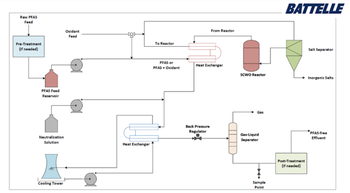


Figure 2. PFAS Annihilator™ Conceptual Diagram†

Technology Development Status

> Commercially Available: 40 – 500 gallons per day capacity
> Media Tested: Liquids (groundwater, landfill leachate, IDW, AFFF, GAC regenerant)
> Key Results:
- >99.9% destruction of PFOA with <10 second reactor residence time.
- Generation of highly corrosive byproducts (hydrofluoric acid, sulfuric acid), and fluoride salts that precipitate and cause system blockages.

† Diagram for liquid for illustrative purposes

HALT

How Does it Work?

Hydrothermal processing heats liquid water in a sealed vessel to temperatures over the boiling point most often between 200 and 350 °C and transitions it to a reactive medium that has altered solvent properties and catalyzes many reactions. Hydrothermal alkaline treatment (HALT), utilizing a strong base as the catalyst, has shown PFAS destruction in liquid and solid in both batch and continuous settings (Hao et al., 2022; Pinkard et al., 2023).

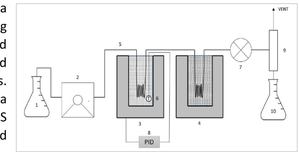


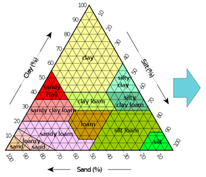
Figure 3. Process flow diagram of the continuous HALT reactor used in the destruction of PFAS in AFFF-impacted water (Technology HA-1) (Pinkard et al., 2023).

Technology Development Status

> Commercially Available: 48 – >10,000 gallons per day capacity
> Media Tested: Liquids (groundwater, AFFF); Soil (lab-scale)
> Key Results:
- >99% removal of PFCAs, >99% removal of PFSAs, >99% removal of sulfonamides and fluorotelomers in groundwater
- >99% removal of PFCAs, >93% removal of PFSAs, >99.3% removal of sulfonamides in soils
- Reaction time = 90 minutes
- Generation of highly alkaline solutions (pH=12-14) containing residual NaOH and fluoride
- Energy for order of magnitude reduction (EE/O) ~ 110-127 kWh/m^3

Bench-Scale Testing

SCWO: 374Water



5 Clean Soils

- Analysis of soil characteristics to optimize pumpability and treatment
- Evaluate options for liquid additives, and co-fuel

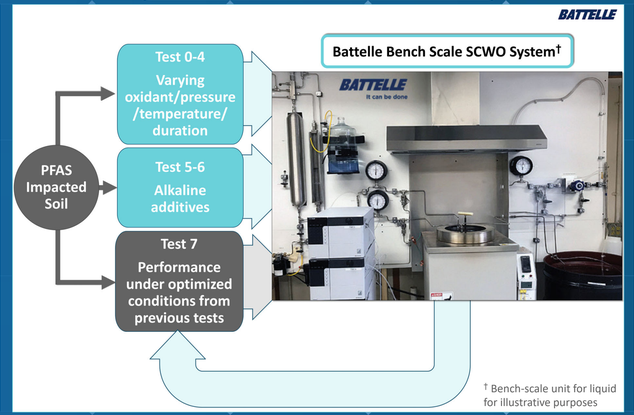
Solid Treatability matrix

- Identify 3 soil types suitable for system
- Specify pre-treatment processes

PFAS-Impacted Soils compatible with AirSCWO

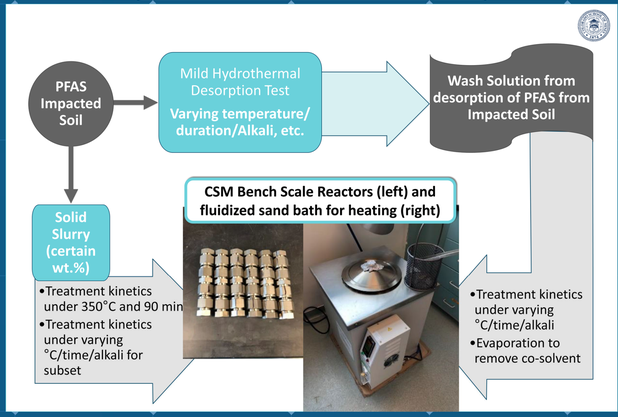
- Test runs in bench-scale AirSCWO System
- Evaluate runs with and without pretreatment
- Analyze solid and liquid effluents
- Potential pilot runs in commercial units depending on bench results

SCWO: Battelle



† Bench-scale unit for liquid for illustrative purposes

HALT



Summary

Goals and Performance Metrics

> Operating conditions to achieve maximum percent removal of PFAS concentrations.
> Treatment kinetics in units of residence time required for treatment in the reactor.
> Transformation products, particularly other PFAS.
> Generation of harmful by-products.
> Physical state of influent solids required (e.g., pre-treatment steps needed).

Bench-Scale Testing Summary

Parameter	Units	Supercritical Water Oxidation, 374Water (SC-1)	Supercritical Water Oxidation, Battelle (SC-2)	Hydrothermal Alkaline Treatment, CSM (HA-1)
Soil Types	--	Range of clean soil types	PFAS-impacted site soils	PFAS-impacted site soils
Key Goals	--	Determine soil types that can be turned into slurries for a continuous flow reactor (Task 1).	• Reactor temp., pressure, oxidant and residence times needed to achieve PFAS target levels. • Effect of $Ca(OH)_2$ and NaOH on PFAS destruction efficiency.	• PFAS destruction efficiency of various soils without dissolving soil minerals. • Evaluate 2-step desorption/destruction treatment method and soil slurries.
Number of Soils	#	5	2	4
Volume per Soil	L	3-5	19 (5 gal)	0.35
Test Conditions				
Reactor Vessel Capacity	L	Continuous flow bench-scale system	0.5 (Batch)	0.005 (Batch)
Temperature Conditions	°C	400 – 600	450	350
Pressure Conditions	psi	~3400	~3500	No added external pressure
Treatment Time	hrs	0.002 – 0.01	0.5-2	0.25 - 1

Other Emerging Technologies: State of Science

Technology	Technical Maturity	Key Results
High Energy Electron Beam (E-Beam)	Lab-Scale	• >99.99% of PFOS and 98.6% of PFOA
Infrared Thermal Treatment	Small Mobile Treatment Unit	• High PFAS removal (>99.6%) for soils contaminated with low PFAS concentrations • Produces PFAS vapor stream that needs to be managed
Smoldering	Lab-Scale	• Reduces long-chain and short-chain PFAS concentrations by >98.9% • Has not yet been able to provide full defluorination of PFAS
Mechanochemical Destruction (Ball Milling)	Lab-Scale	• ~90% to 99.99% destruction of PFAS • Long milling time needed to treat PFAS to low levels (~hours) • Low capacity (25 L) pilot trial attempted

REFERENCES

374Water. (2023. PFAS Treatment Study in Maine Municipal Sludge. 374Water°. https://374water.com/wp-content/uploads/2022/06/374Water-Maine-PFAS-Case-Study.pdf. Accessed 24 April 2023.

Chiang, D. S-Y.; Saba, M.; Leighton, M.; Ballenghien, D.; Hatler, D.; Gal, J.; Deshusses, M. A., Supercritical water oxidation for the destruction of spent media wastes generated from PFAS treatment. J. of Hazardous Materials, 2022

ITRC (2022). Per- and Polyfluoroalkyl Substances (PFAS) Fact Sheet – 12 Treatment Technologies. https://pfas-1.itrcweb.org/12-treatment-technologies/#12_3. Accessed 24 April 2023.

Hao, S., Choi, Y. J., Deeb, R. A., Strathmann, T. J., & Higgins, C. P. (2022). Application of Hydrothermal Alkaline Treatment for Destruction of Per- and Polyfluoroalkyl Substances in Impacted Groundwater and Soil. Environmental Science & Technology, 56(10), 6647–6657.

Li, J., Pinkard, B. R., Wang, S., & Novosselov, I. V. (2022). Review: Hydrothermal treatment of per- and polyfluoroalkyl substances (PFAS). Chemosphere, 307, 135888.

Pinkard, B. R., Austin, C., Purohit, A. L., Li, J., Novosselov, I. V., Destruction of PFAS in AFFF-impacted fire training pit water, with a continuous hydrothermal alkaline treatment reactor, Chemosphere, Volume 314, 2023, 137681, ISSN 0045-6535,