



Air Force Civil Engineer Center

Restoration Technology Transfer Speakers Series January 2025

Predicting PFAS Leaching in Source Zones and Mass Discharge to Groundwater

PFAS-LEACH is an advanced, comprehensive decision support platform for predicting PFAS leaching in source zones and mass discharge to groundwater. It is comprised of four tiers of simulators spanning from a full-process 3D numerical simulator to analytical solutions implemented in Excel to simple dilution-attenuation calculations. This presentation will describe the specific processes represented in each of the model Tiers and will discuss how the different model Tiers can be used to answer practical questions such as characterizing source strengths and risks of groundwater contamination, and derivation of soil screening levels.

PFAS-LEACH – A Comprehensive Decision Support Platform for Predicting PFAS Leaching in Source Zones

Four models spanning a wide range of complexity
Comprehensive parameter selection module
Documentation and user manual

Tier 1 – PFAS-LEACH-COMP-GW
Features: Full-process model in 3D
Anticipated application: Sites with sufficient data, complex spatial heterogeneity and/or source conditions
(Guo et al. 2020; Zeng & Guo 2021, 2023)

Tier 2 – PFAS-LEACH-HYDRUS-GW
Features: Implemented in HYDRUS-1D GUI
Anticipated application: Insignificant lateral heterogeneity; uncertainty quantification
(Zeng et al. 2021)

Tier 3 – PFAS-LEACH-Analytical-GW
Features: Implemented in Excel
Anticipated application: Limited data; early stage of site management; order-of-magnitude estimate
(Guo et al. 2022; Smith et al. 2018)

Tier 4 – PFAS-LEACH-DAF
Features: Revised EPA dilution-attenuation model
Simplified mass-balance calculations
Anticipated application: Initial screening of sites
(Brusseau & Guo 2023)

Computational Cost & Input Parameters (Y-axis)
Model Complexity (X-axis)

Dr. Bo Guo describing the PFAS-LEACH support platform.

This event and future events are updated and posted on the AFIT website at: <https://www.afit.edu/CE/index.cfm>.

POCs:

Joseph Dimisa, AFIT (joseph.dimisa@us.af.mil)

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Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)



Webinar Structure



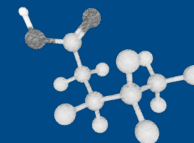
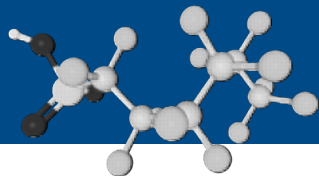
	https://www.milsuite.mil/book/docs/DOC-1352420
5 min	Welcome and Administrative Business
45 min	<i>PFAS-LEACH — A Comprehensive Decision Support Platform for Predicting PFAS Leaching in Source Zones</i> – Bo Guo, Ph.D., University of Arizona
10 min	Questions and Answers
5 min	Final Thoughts

Air Force Civil Engineer Center



PFAS-LEACH: A Comprehensive Decision Support Platform for Predicting PFAS Leaching in Source Zones

Bo Guo, Ph.D.
University of Arizona
January 2025



PFAS-LEACH—A Comprehensive Decision Support Platform for Predicting PFAS Leaching in Source Zones

Bo Guo

Dept. of Hydrology and Atmospheric Sciences
University of Arizona



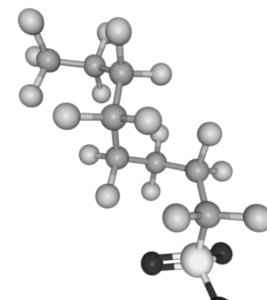
Acknowledgment:

Guo research group:

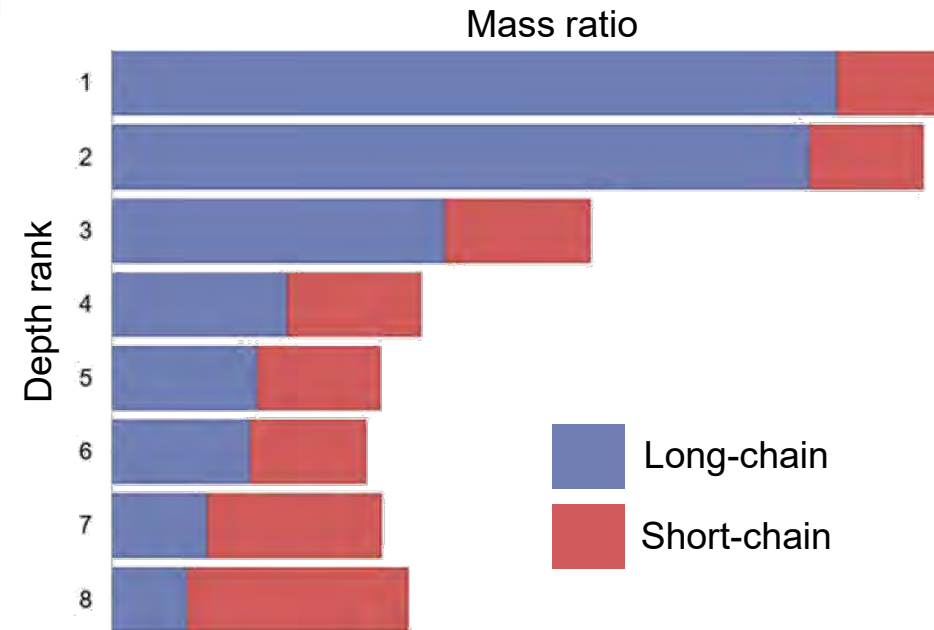
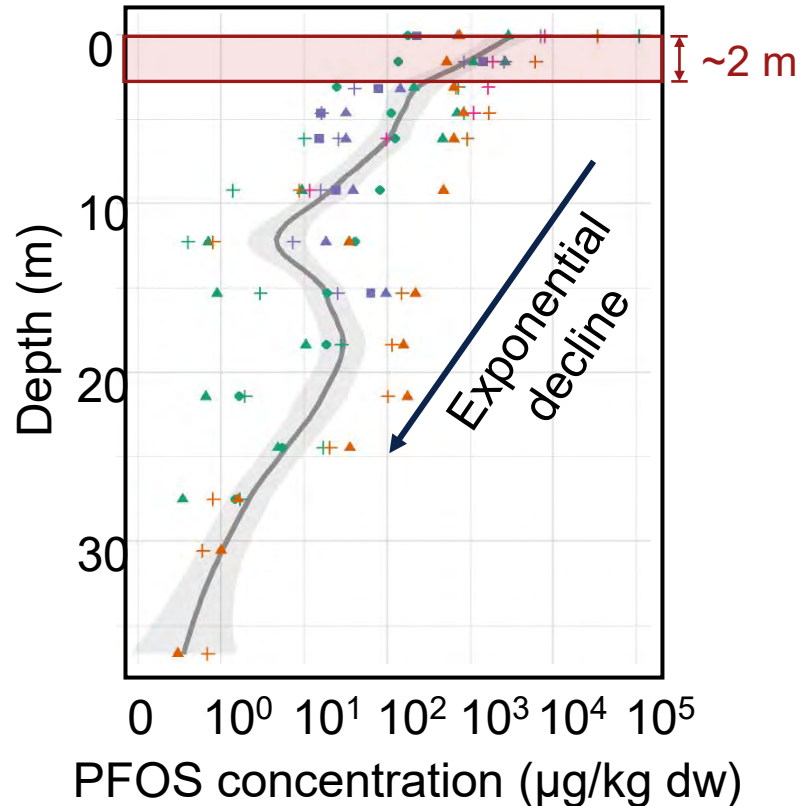
Jicai Zeng, Sidian Chen (now postdoc at Stanford University)

Hassan Saleem, Wenqian Zhang, Jake Smith, Min Ma, Ryan Russell

Mark L. Brusseau (ENVS, University of Arizona)



Spatial Profiles of PFAS Concentrations in Vadose Zones



Brusseau, Anderson, Guo. 2020 SoTE
Anderson et al. 2019. JCH

- Soils appear to act as significant source zones of PFAS.
- Longer-chain PFAS tend to retain in shallow soil, while shorter-chain PFAS migrate to deeper depth.

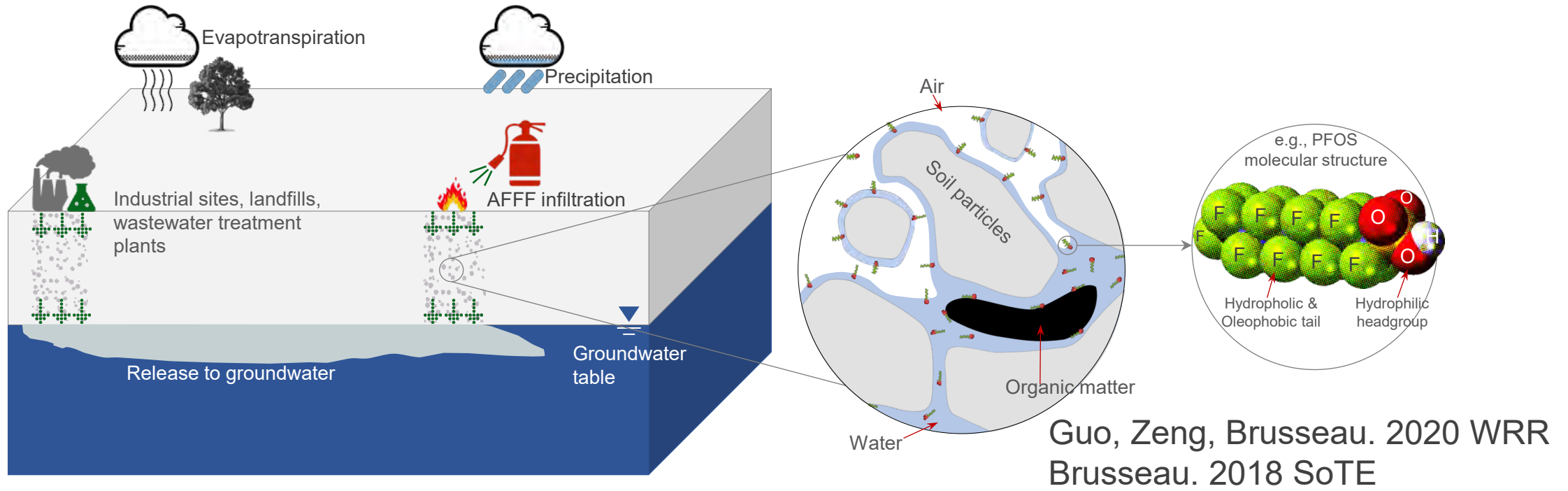
Overarching Questions

What are the primary processes controlling PFAS leaching in soils?

What are the long-term mass discharge rates to groundwater?

PFAS Transport in the Vadose Zone

Physical and Chemical Processes



- PFAS accumulate at solid surfaces and air-water interfaces in soils.
- PFAS present in porewater can modify surface tension and contact angle, which may enhance drainage.

PFAS Transport in the Vadose Zone

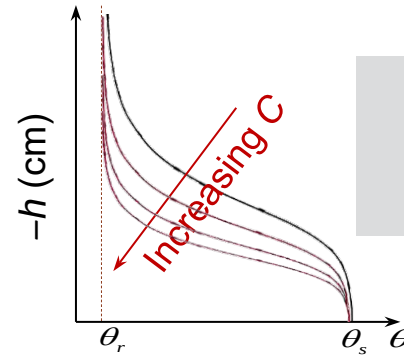
Mathematical Formulation

- Soil water flow:

$$\frac{\partial \theta}{\partial t} - \nabla \cdot [K(\theta) \nabla (h - z)] = 0$$

- PFAS transport:

$$\frac{\partial (\theta C)}{\partial t} + \boxed{\rho_b \frac{\partial C_s}{\partial t}} + \boxed{\frac{\partial C_{aw}}{\partial t}} + \underbrace{\nabla \cdot (\theta \mathbf{v} C)}_{\text{Advection}} - \underbrace{\nabla \cdot (\theta \mathbf{D} \nabla C)}_{\text{Dispersion}} = 0$$



Surfactant-induced flow

$$h = \frac{\sigma(C) \cos \gamma(C)}{\sigma_0 \cos \gamma_0} h_0$$

(Leverett J scaling)

Nonlinear and rate-limited solid-phase adsorption

$$C_{s,1} = F_s K_f C^N$$

Instantaneous

$$\frac{dC_{s,2}}{dt} = \alpha_s [(1 - F_s) K_f C^N - C_{s,2}]$$

Kinetic

Nonlinear and rate-limited air-water interfacial adsorption

$$C_{aw,1} = F_{aw} A_{aw} K_{aw} C$$

Instantaneous

$$\frac{dC_{aw,2}}{dt} = \alpha_{aw} [(1 - F_{aw}) A_{aw} K_{aw} C - C_{aw,2}]$$

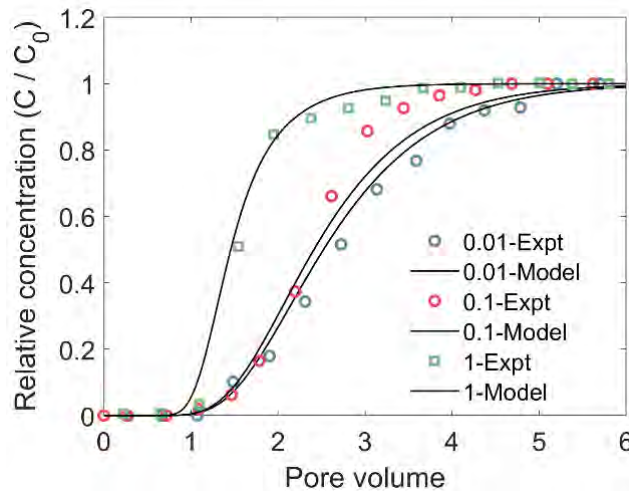
Kinetic

Guo, Zeng, Brusseau. 2020 WRR
Zeng & Guo. 2021 AWR

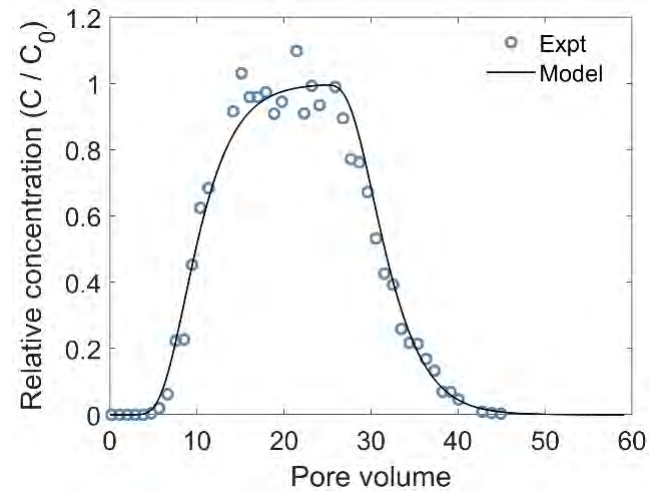
Model validation: *vs. Miscible-displacement Experiments*



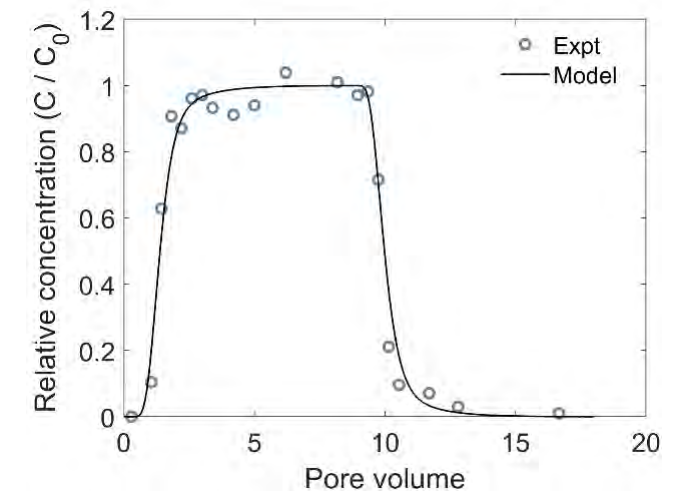
Experimental data set #1
PFOA (1 mg/L, 0.1 mg/L, 0.01 mg/L)
Measured data: Lyu et al., 2018



Experimental data set #2
PFOS (0.1 mg/L)
Measured data: Brusseau et al., 2021



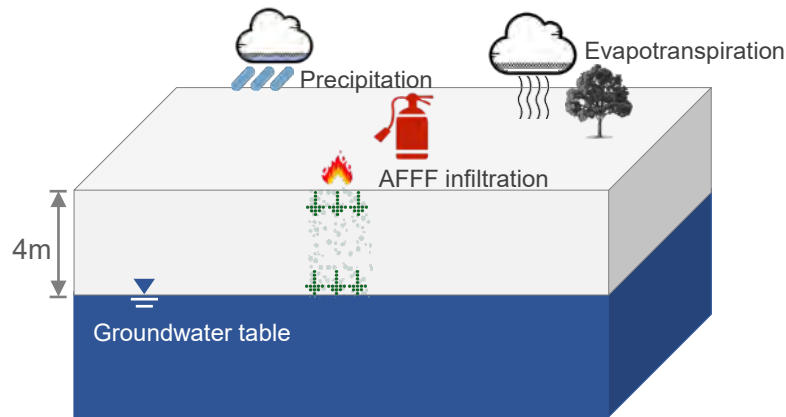
Experimental data set #3
GenX (10 mg/L)
Measured data: Yan et al., 2021



- Independent model predictions match well with experimental data.

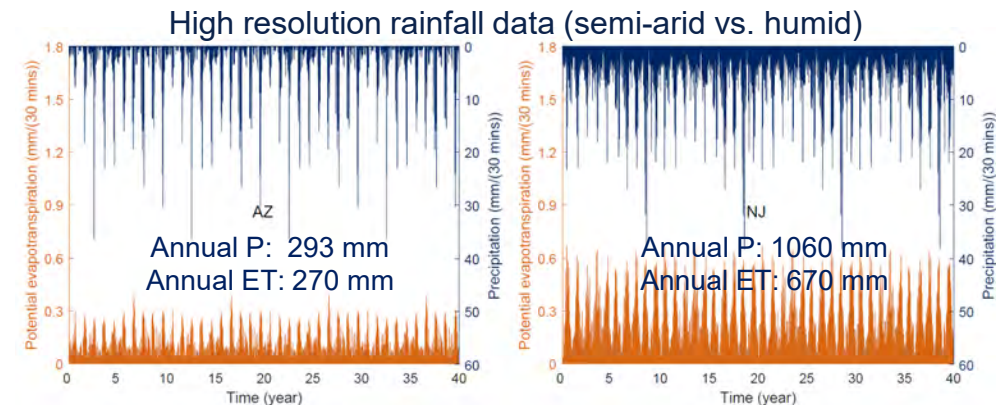
Numerical Simulation: *PFAS Migration at a Fire Training Area*

✓ PFAS contamination scenario at an AFFF-impacted fire training area site

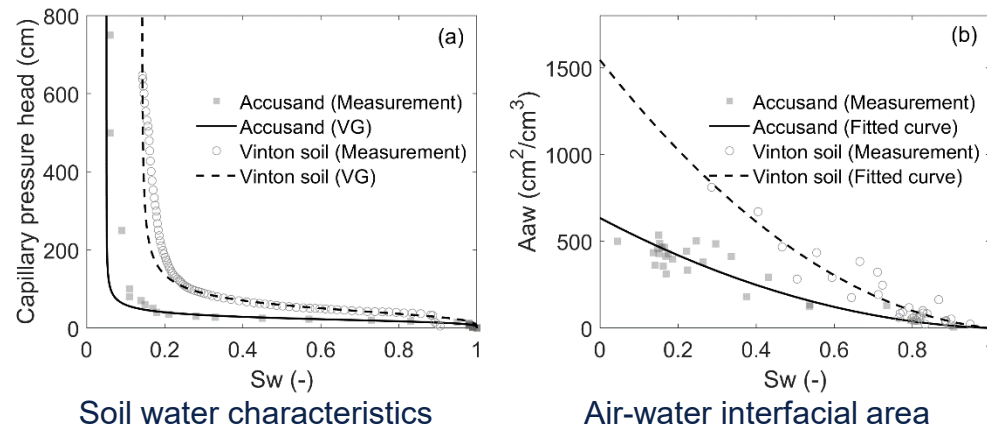


✓ Fire training: one session every 10 days lasting for 30 years

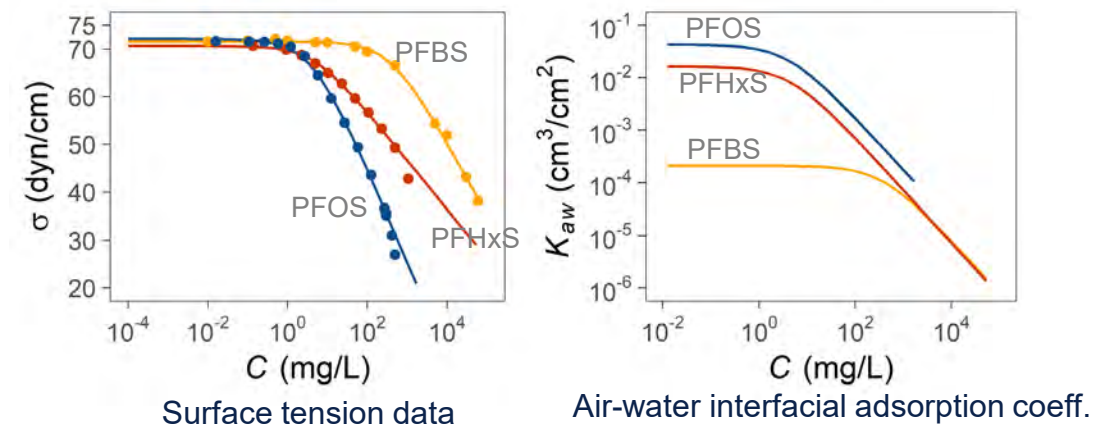
✓ Representative PFAS mixture in 1% diluted AFFF solution
PFOS: 100 mg/L, PFHxS: 7.1 mg/L, PFBS: 1.4 mg/L



Two soil types (Accusand vs. Vinton)



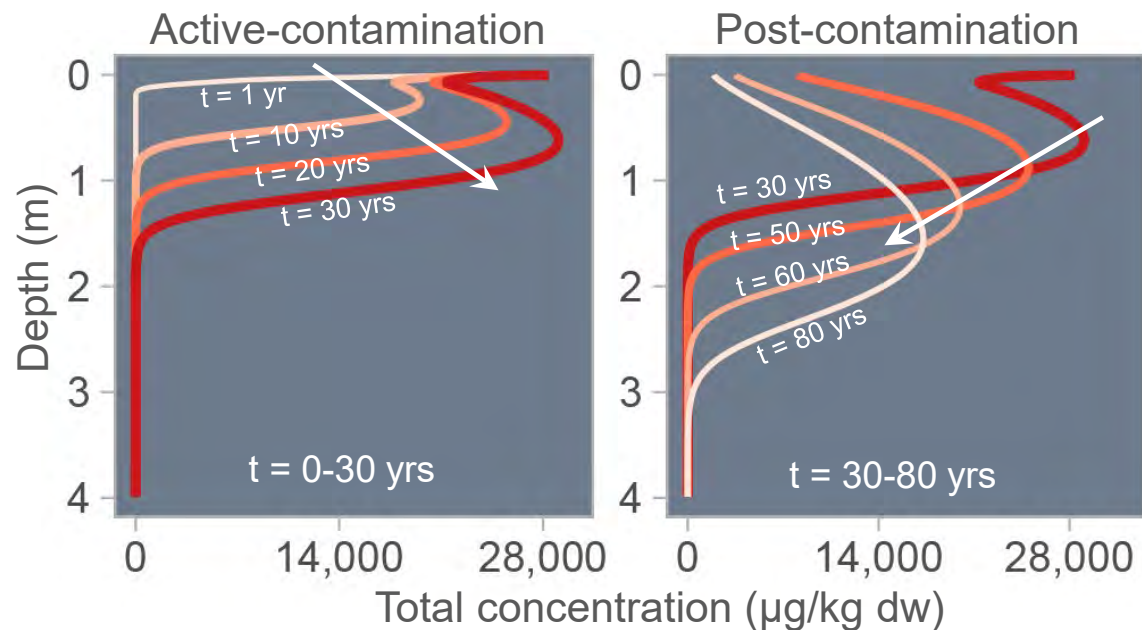
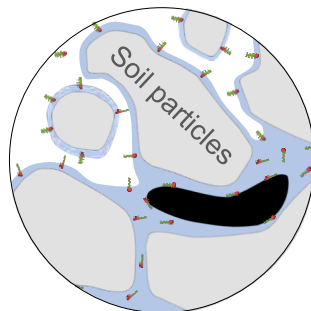
Three representative PFAS



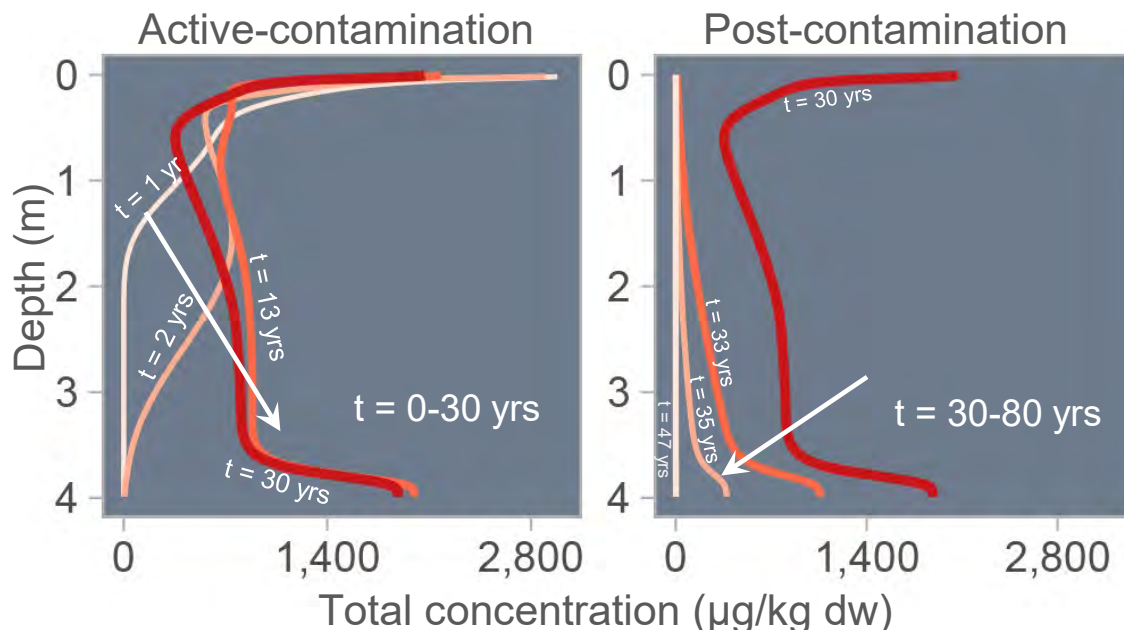
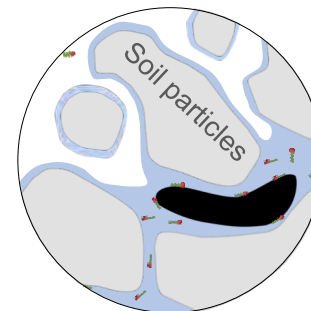
Numerical Simulation: *PFAS Migration at a Fire Training Area*

- ✓ Retention and leaching of PFOS: temporal evolution of spatial profiles

w/ AWI adsorption



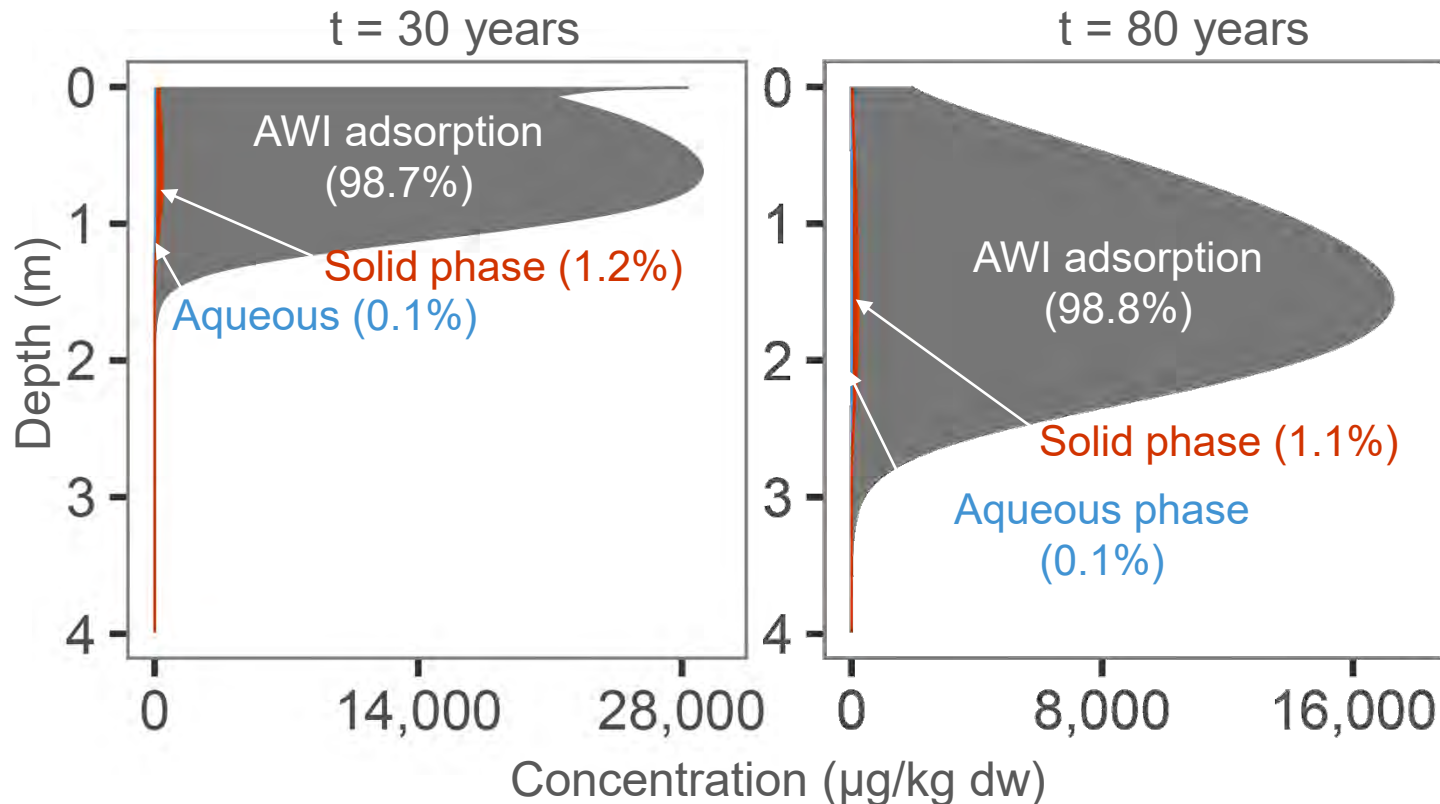
w/o AWI adsorption



- Air-water interfacial adsorption significantly reduces the PFOS leaching in soils.

Numerical Simulation: *PFAS Migration at a Fire Training Area*

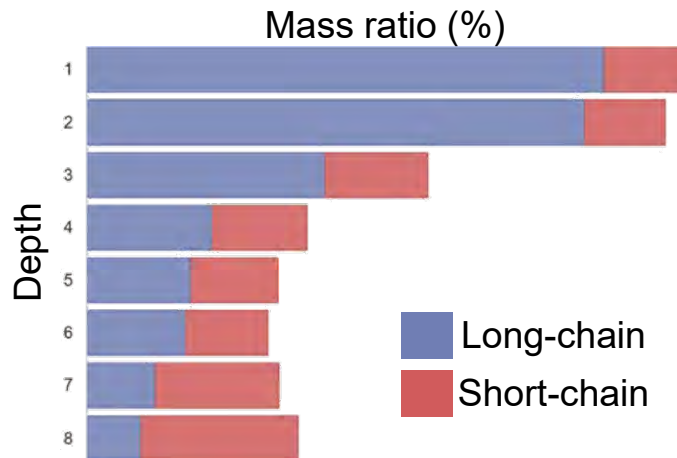
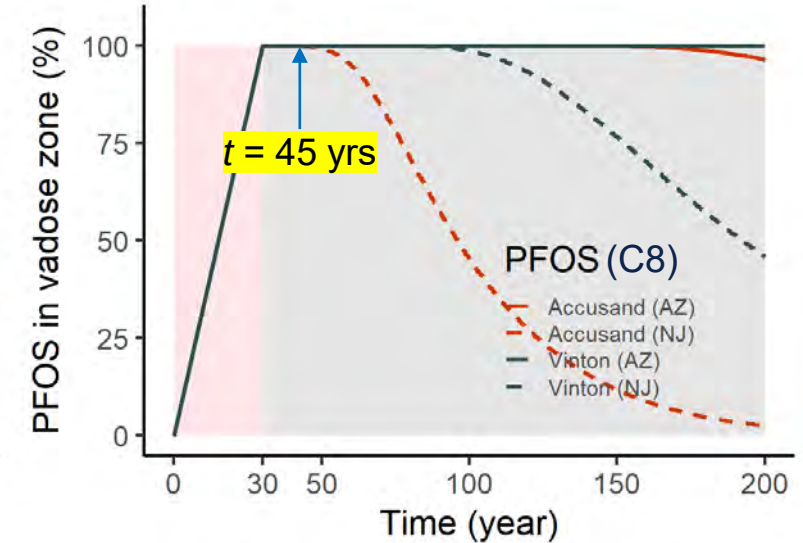
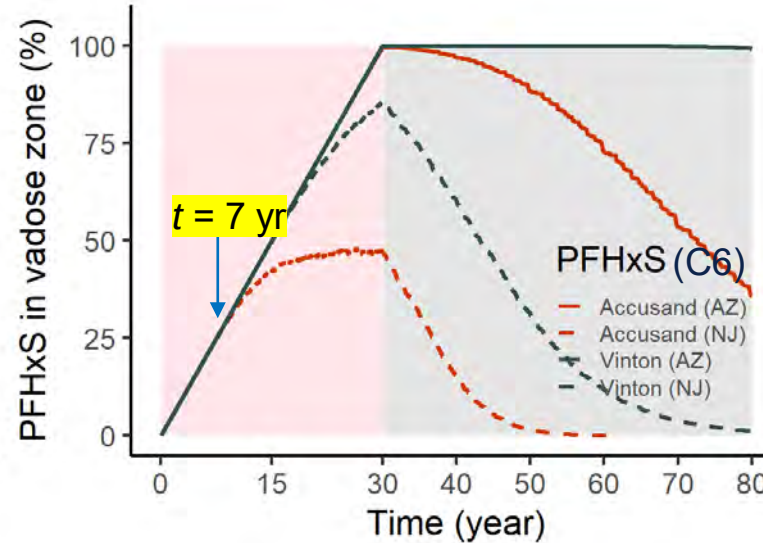
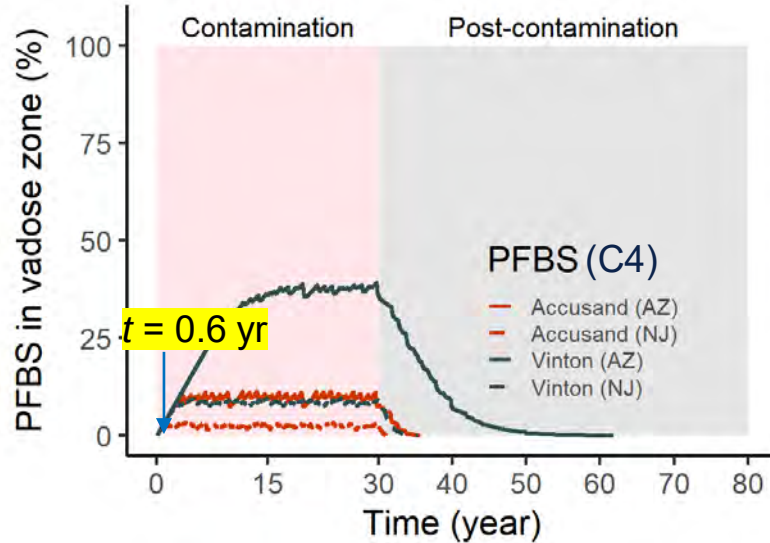
- ✓ Retention and leaching of PFOS: mass distribution in soils



- The majority (>98%) of PFOS in the soil is adsorbed at the air-water interfaces.
- Only 0.1% and ~1% of PFOS in aqueous and solid phase.
- C in soils >> C in groundwater.

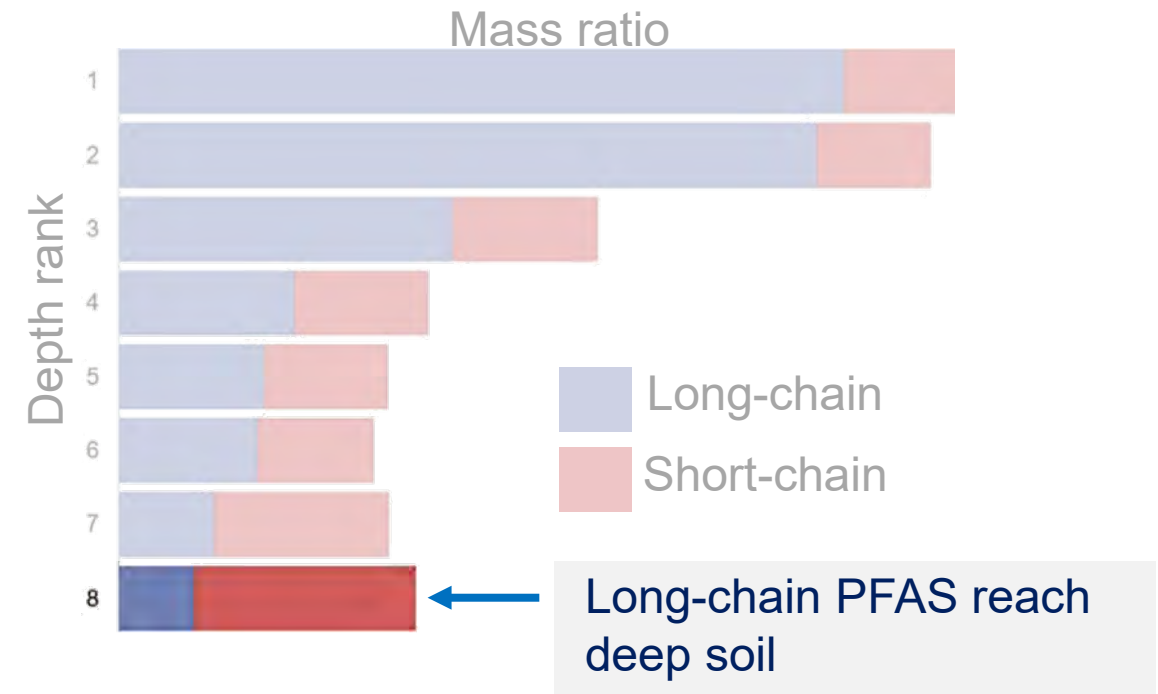
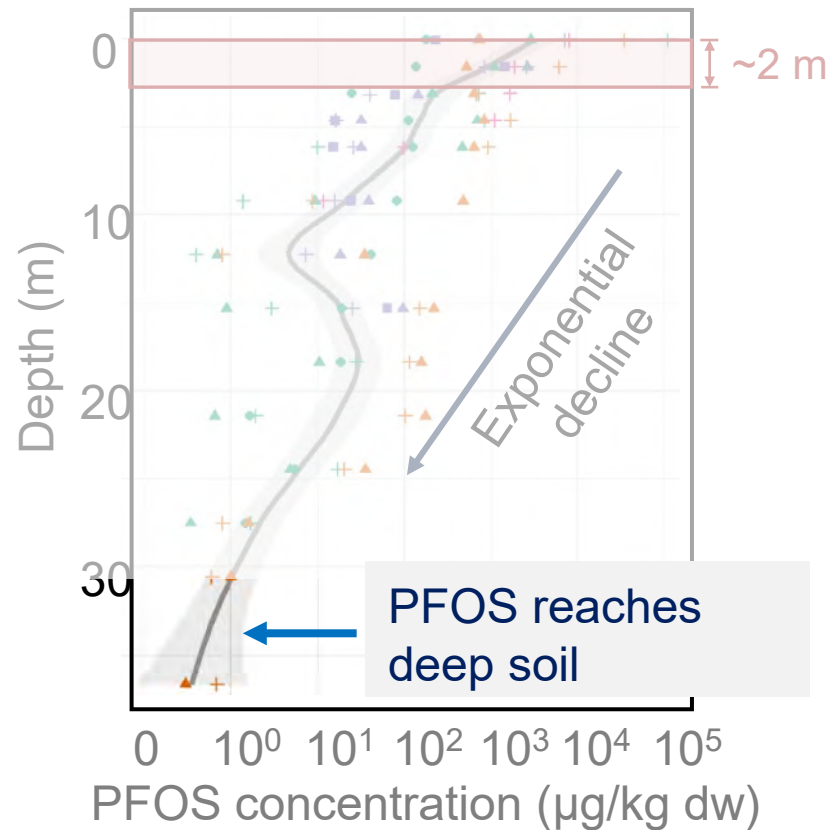
Numerical Simulation: *PFAS Migration at a Fire Training Area*

■ Short-chain vs. long-chain



- PFBS, PFHxS, and PFOS reach groundwater table at $t = 0.6$ yrs, 7 yrs, and 45 yrs.
- PFOS is much more strongly retained in the soil than PFBS and PFHxS.

Spatial Profiles of PFAS Concentrations in Vadose Zones

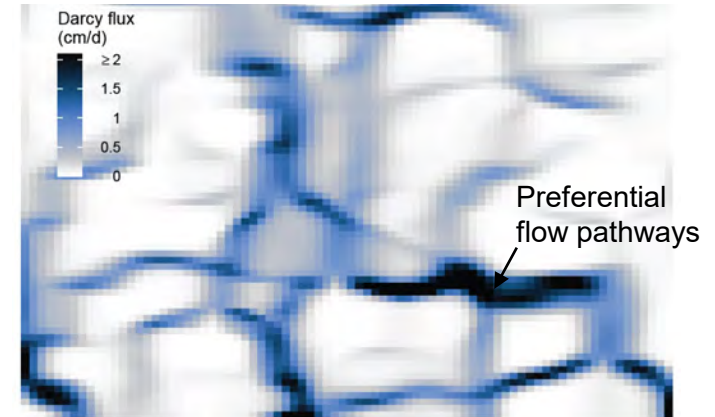


Brusseau, Anderson, Guo. 2020 SoTE
Anderson et al. 2019 JCH

- What drives the leaching of longer-chain PFAS to deep soil and early arrival to groundwater at many sites?

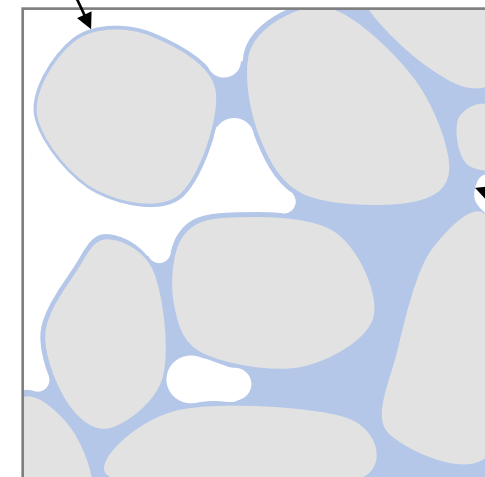
Hypotheses

- Heterogeneity-generated **preferential flow** leads to long-chain PFAS leaching to deep soil.



- Air-water interfacial area may **not** be fully **accessible** at the pore-scale.

Air–water interfaces
in **thin water films**



Air–water interfaces
in **bulk water**

PFAS-LEACH – A Comprehensive Decision Support Platform for Predicting PFAS Leaching in Source Zones

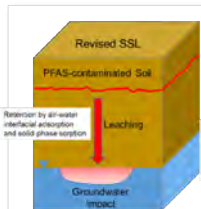
Computational Cost & Input Parameters

- Four models spanning a wide range of complexity
- Comprehensive parameter selection module
- Documentation and user manual

Parameter Selection Module

A1	K_{oc}	f_{oc}	f_{oc}
1	Parameter	Method 1	Method 2
2	K_{oc}	Measured	Advanced estimation
3	K_{oc}	Measured	Advanced estimation
4	K_{oc}	Measured	Advanced estimation

[Brusseau et al. 2019]

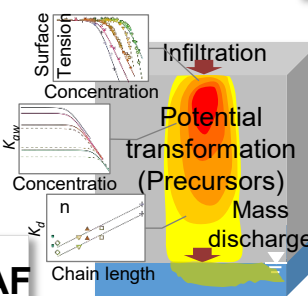


Tier 4 – PFAS-LEACH-DAF

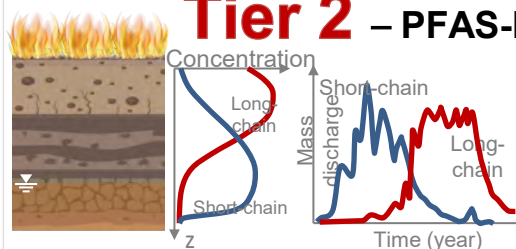
Features: Revised EPA dilution-attenuation model

- Simplified mass-balance calculations

Anticipated application: Initial screening of sites
[Brusseau & Guo, 2023]



Tier 2 – PFAS-LEACH-HYDRUS-GW HYDRUS-1D GUI



Features: Implemented in HYDRUS-1D GUI

Anticipated application: Insignificant lateral heterogeneity; uncertainty quantification

[Zeng et al. 2021]

Tier 3 – PFAS-LEACH-Analytical-GW



Features: Implemented in Excel

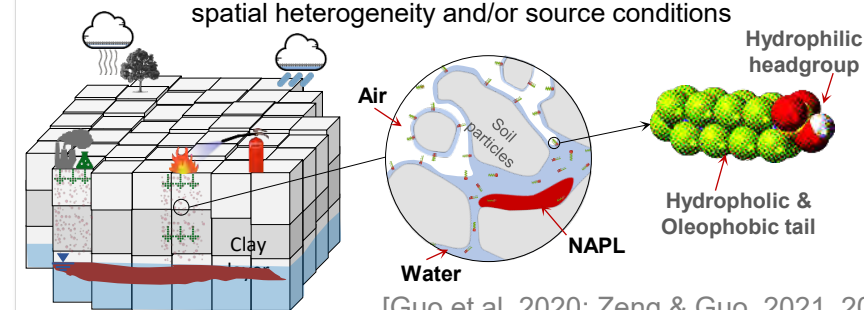
Anticipated application: Limited data; early stage of site management; order-of-magnitude estimate.

[Guo et al. 2022; Smith et al., 2024]

Tier 1 – PFAS-LEACH-COMP-GW

Features: Full-process model in 3D

- Anticipated application: Sites with sufficient data; complex spatial heterogeneity and/or source conditions



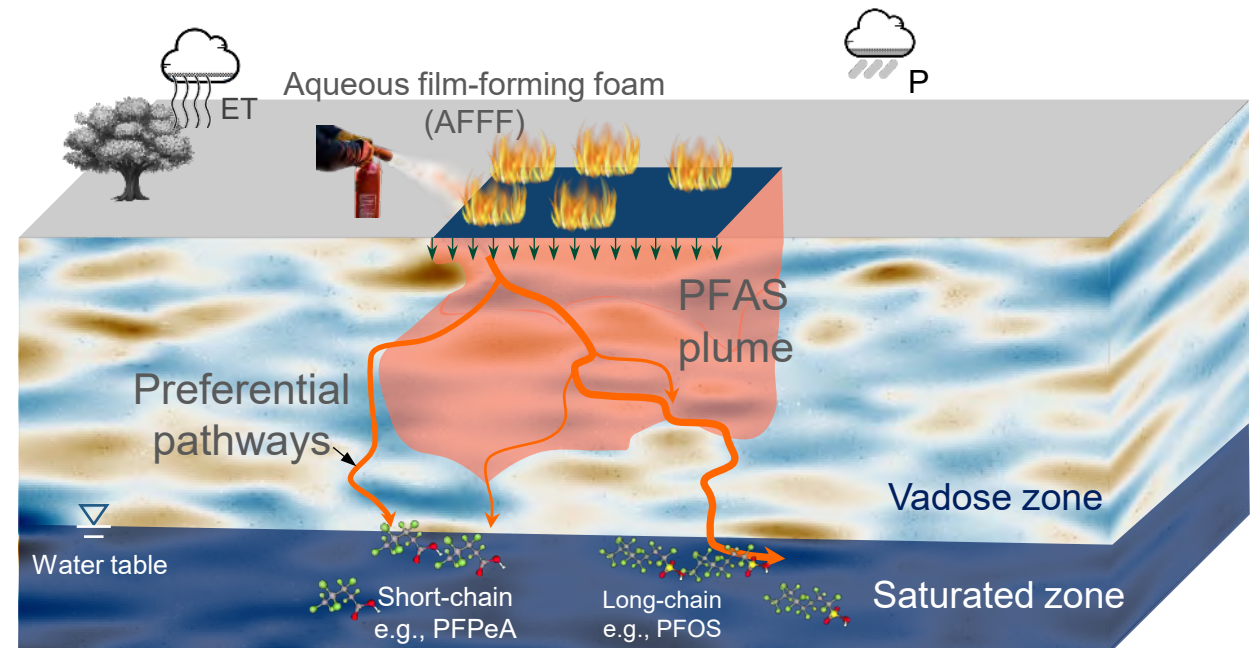
[Guo et al. 2020; Zeng & Guo, 2021, 2023]

Model Complexity

PFAS Contamination at a Fire-training Area

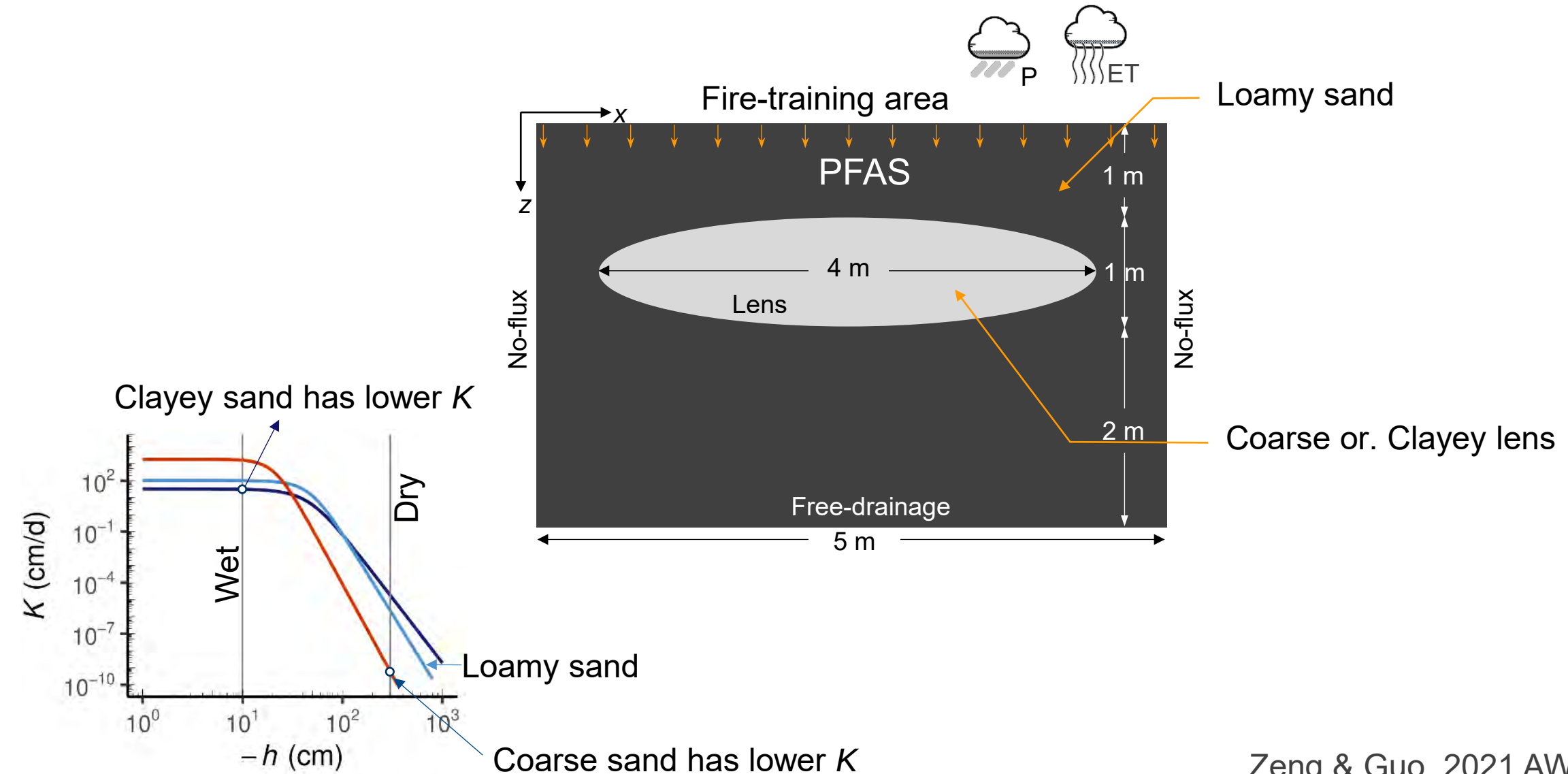
Tier 1: PFAS-LEACH-COMP-GW

- o Area: 30 m × 30 m.
- o 1% diluted AFFF.
- o Fire training: 30 min per 10 days for 30 yrs.
- o Water table is deeper than 4 m.



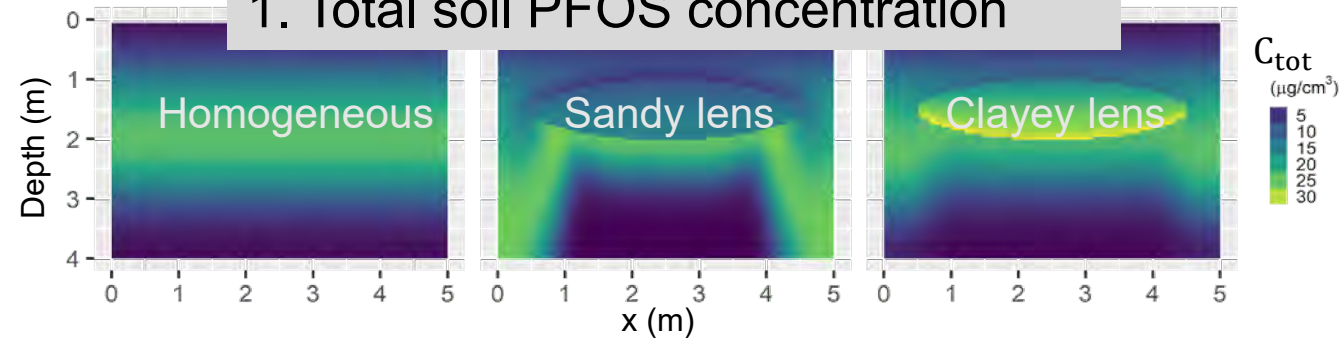
(Zeng, Guo, 2021; Guo, Zeng, Brusseau, 2020)

Soil Lenses

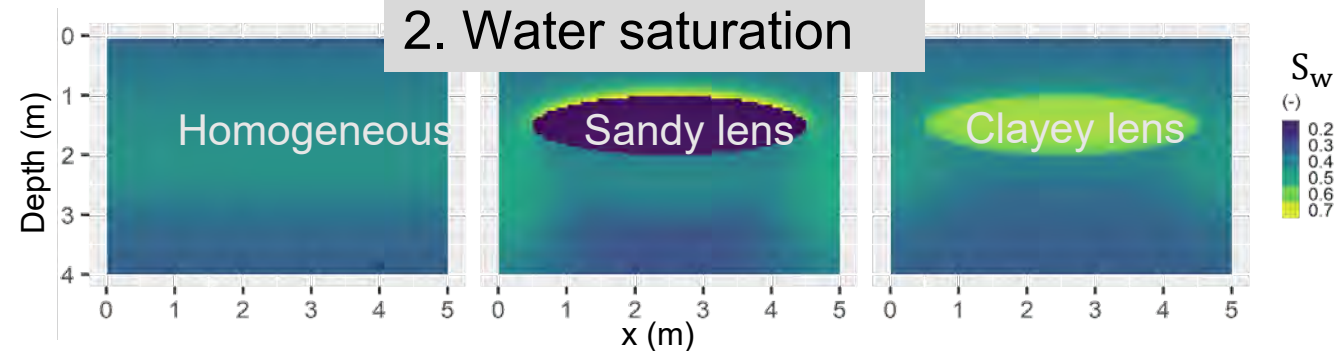


Preferential Flow Accelerates Leaching

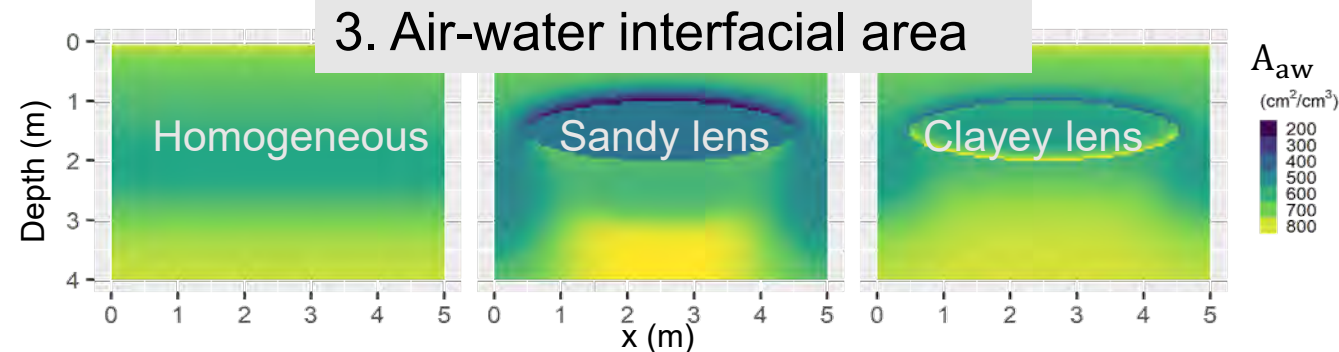
1. Total soil PFOS concentration



2. Water saturation

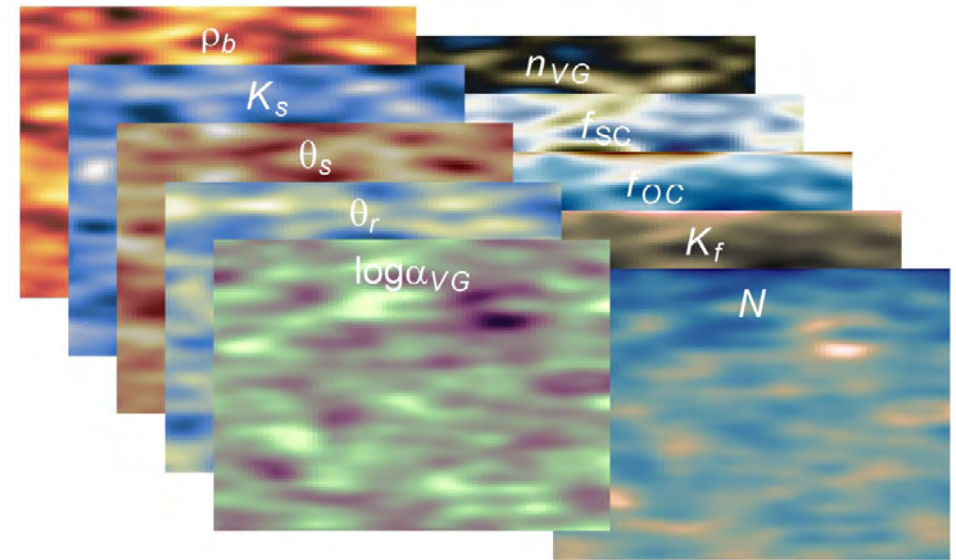
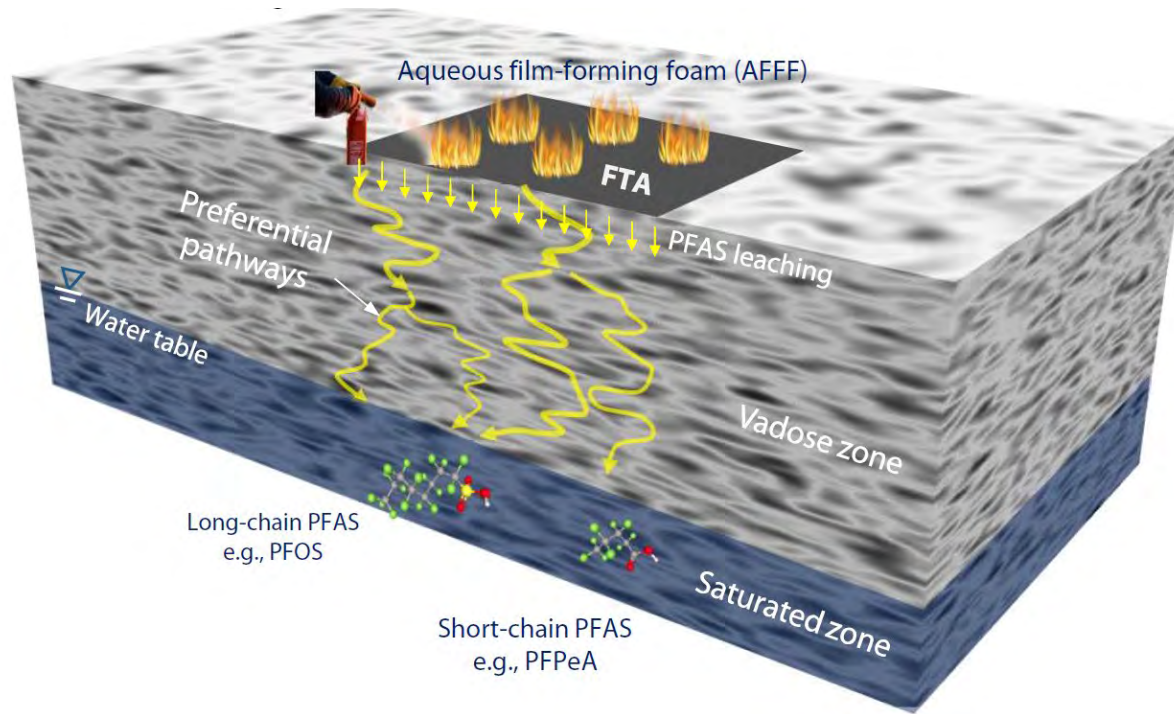


3. Air-water interfacial area



- PFAS leaching is accelerated in the presence of the preferential flow pathways.
- Air-water interfaces collapse along these flow pathways, which further accelerates PFAS migration.
- A phenomenon **unique** for PFAS, especially those longer-chain compounds.

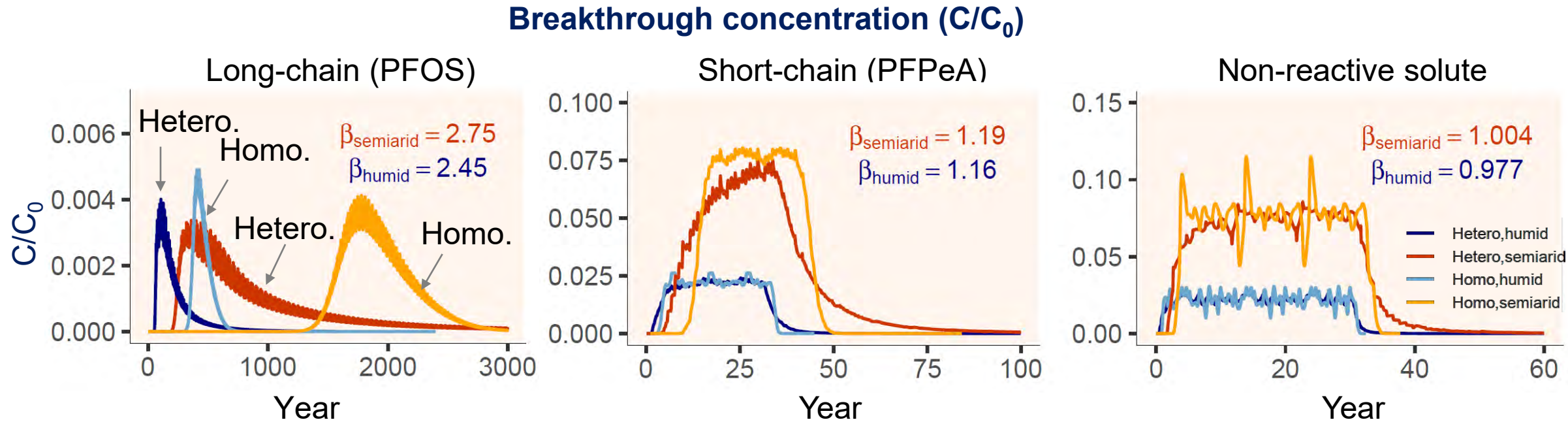
More Complex Heterogeneities



Field-representative heterogeneous fields

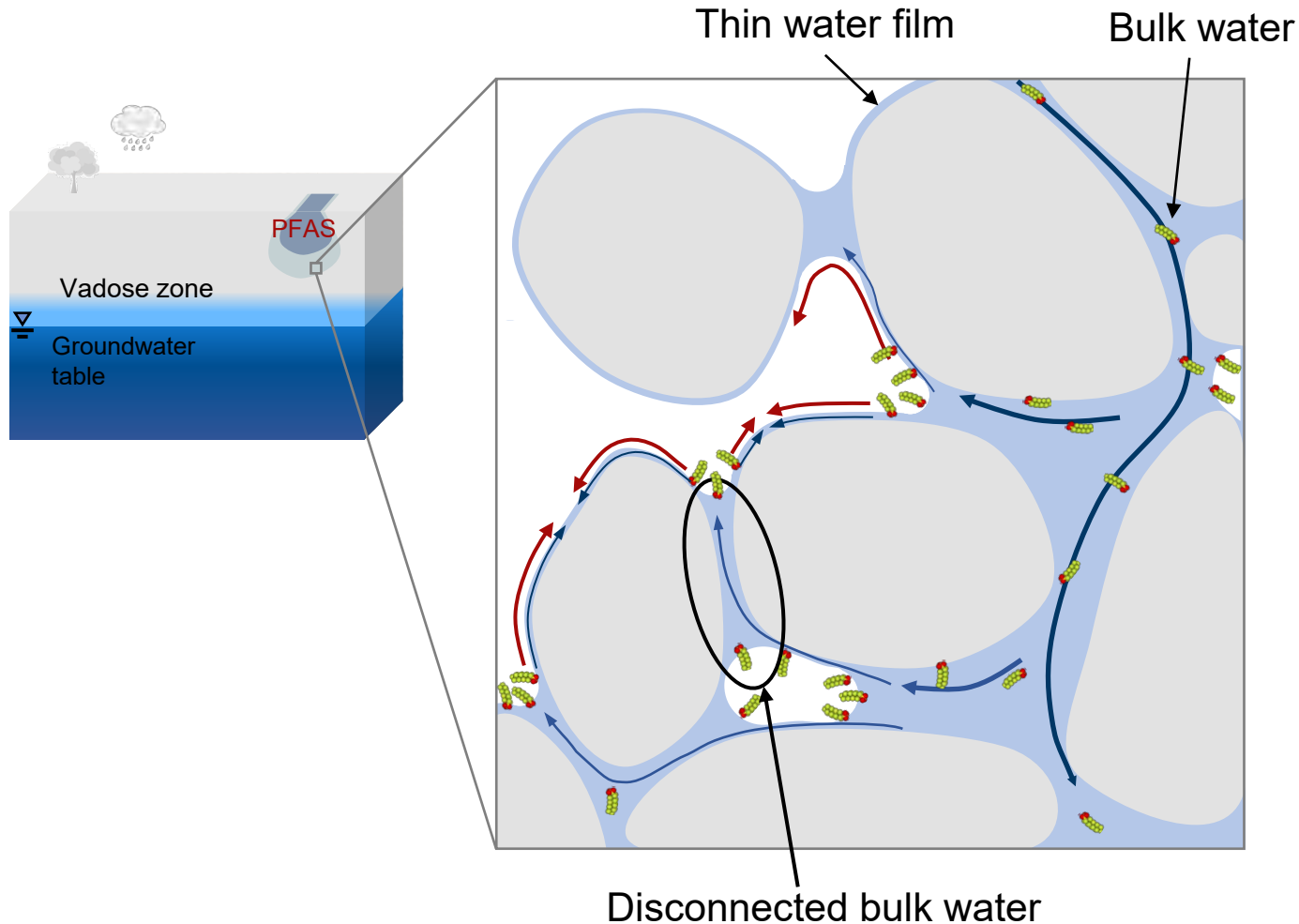
- Stochastically generated heterogeneous parameter fields based on field measurements.
- Geochemical properties correlate with hydraulic parameters.

Preferential Flow Uniquely Accelerated PFAS Leaching in the Vadose Zone



- Accelerated movement of the center of mass through the vadose zone.
- The acceleration (β) increases for
 - longer-chain PFAS
 - vadose zone with stronger heterogeneities

Air–water Interfaces in Thin Water Films vs. Bulk Water

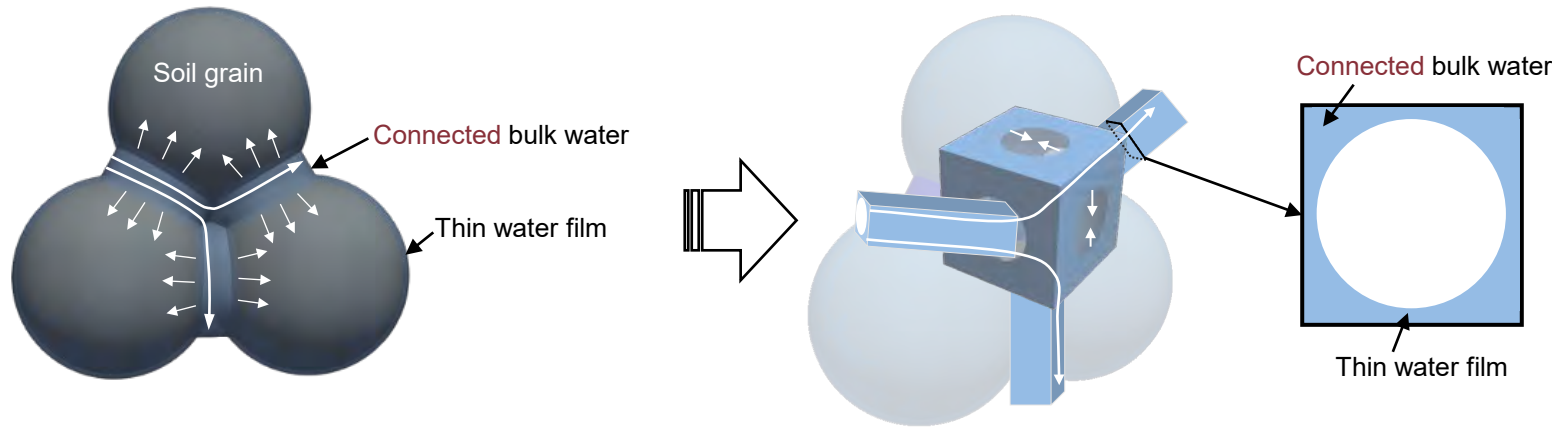


Are air–water interfaces in thin water films accessible?

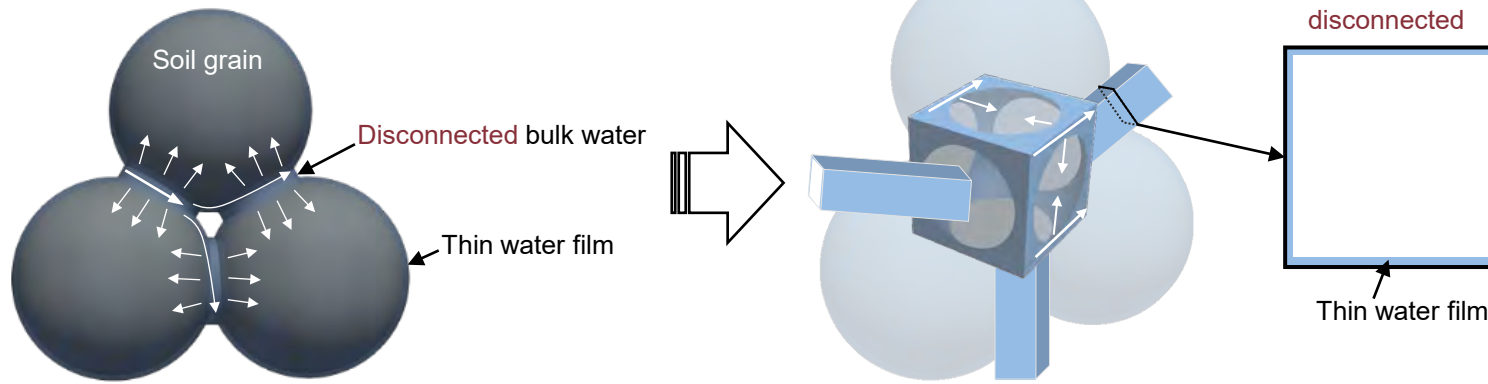
- Connected bulk water
Access bulk air–water interfaces via **advection & diffusion in bulk water**
- Disconnected bulk water
Access air–water interfaces via **diffusion in thin water films** (*decreases with film thickness*)
- Diffusion along air–water interfaces
Access air–water interfaces via **surface diffusion** (*independent of film thickness*)

Pore-network Modeling: *Water Configuration, Flow, & PFAS Transport*

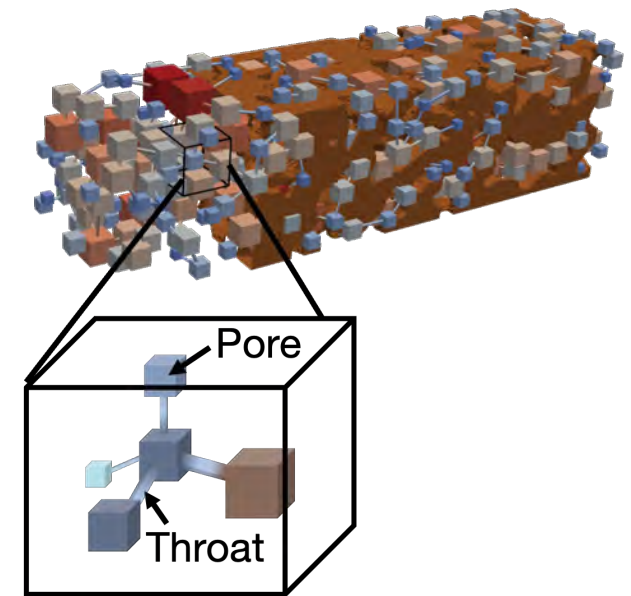
- Wetter soil (higher water saturation)



- Drier soil (lower water saturation)

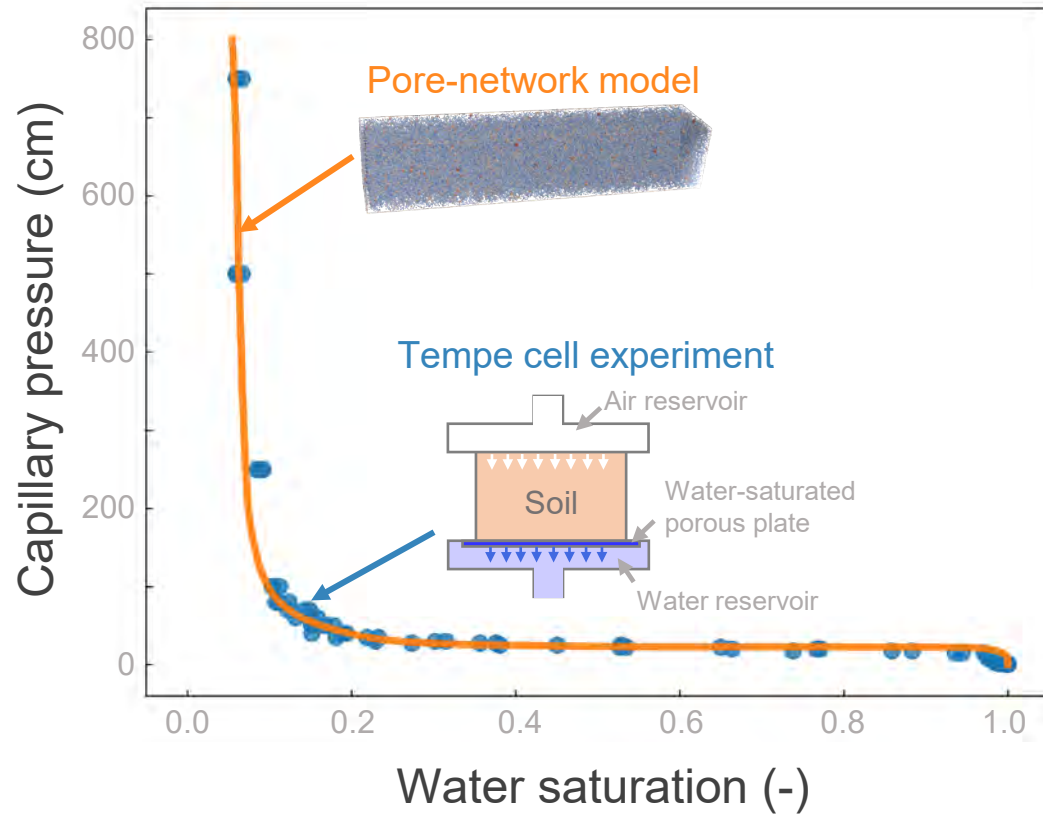


Represent water flow and PFAS transport in soil pore networks

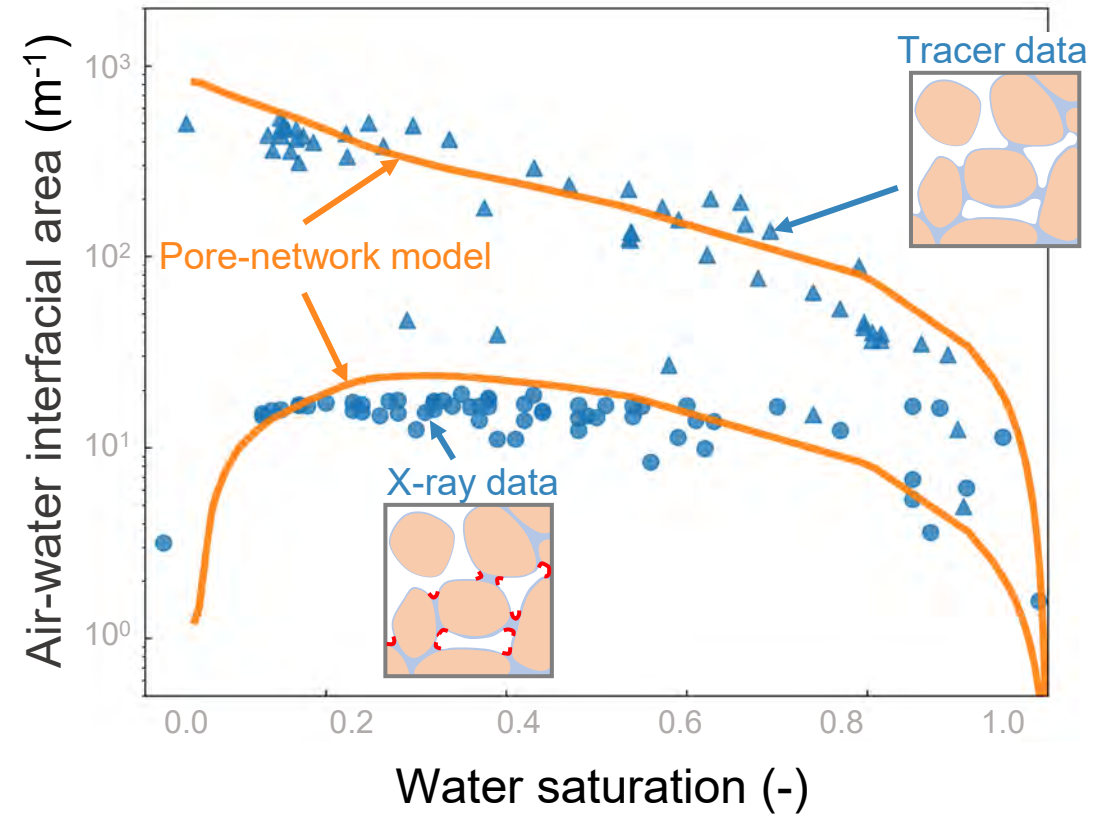


Constraining the Pore-network Model with Datasets for a Sandy Soil

Soil water characteristic curve

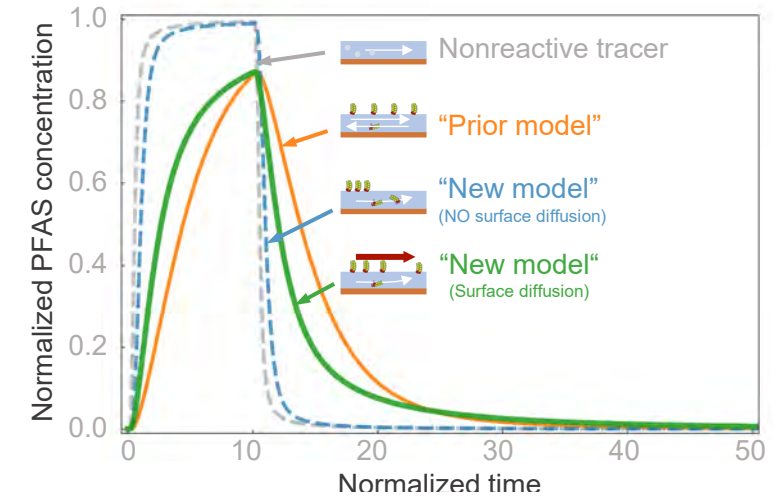
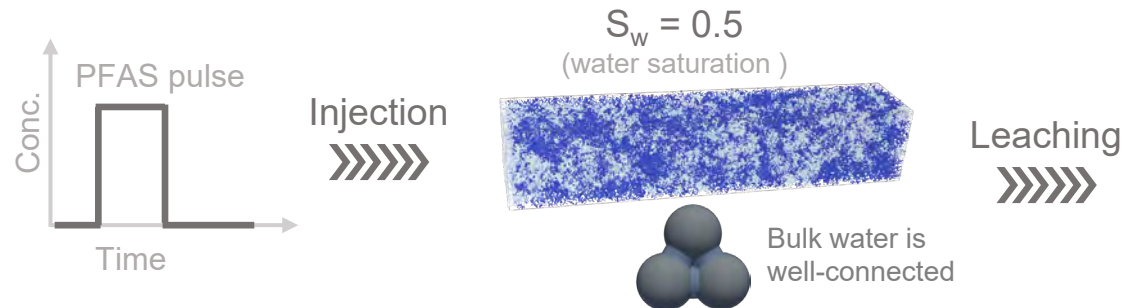


Air-water interfacial area vs water saturation

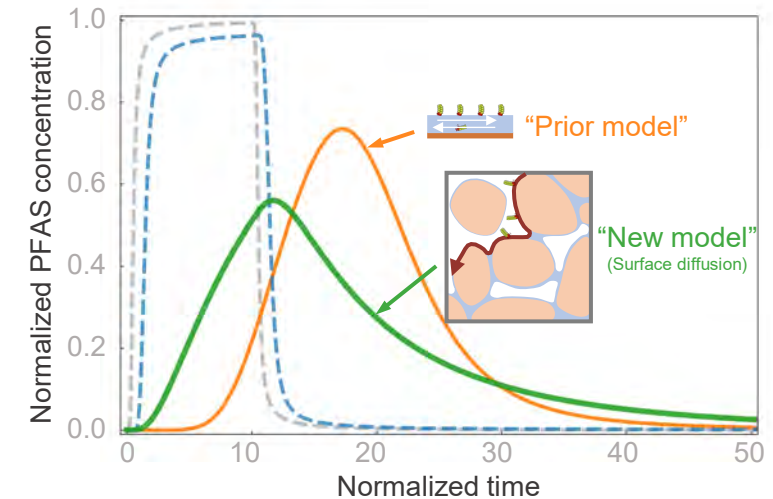
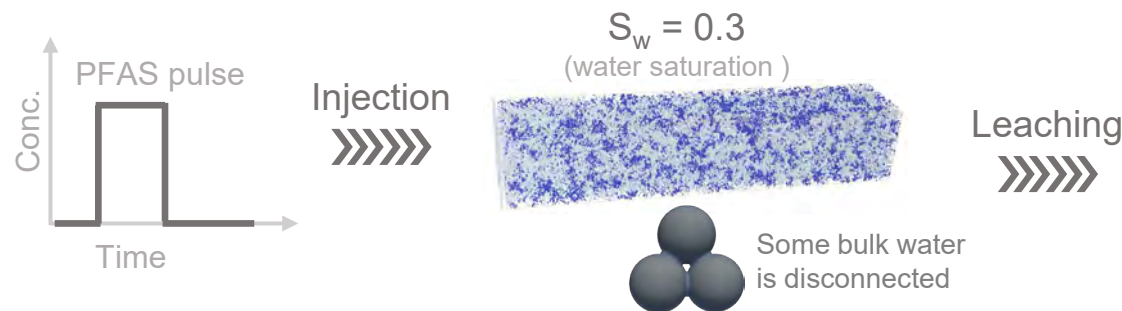


Modeling PFAS Transport under Wetter vs. Drier Conditions

Wetter condition

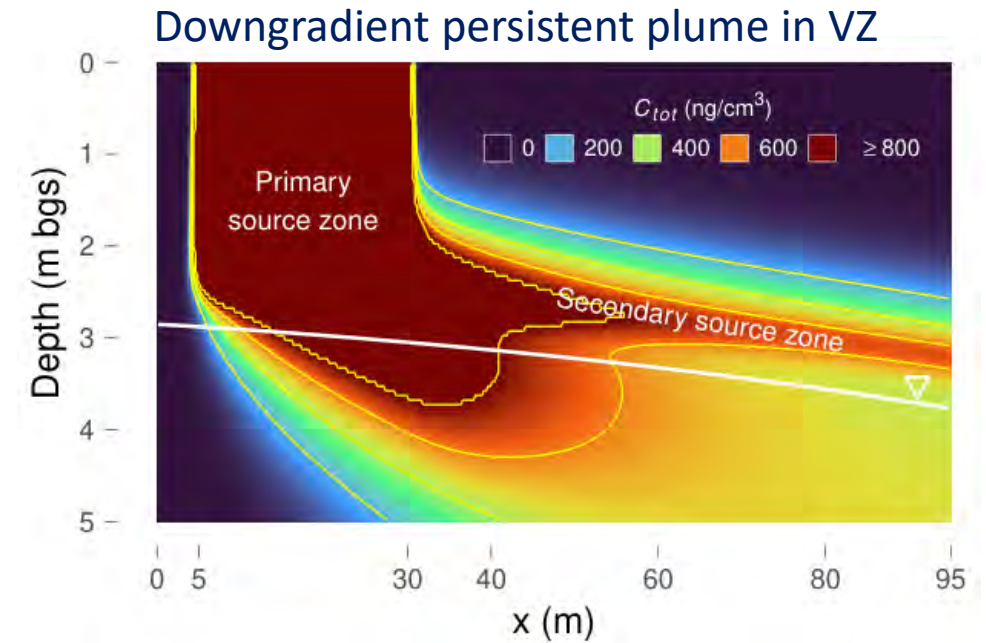
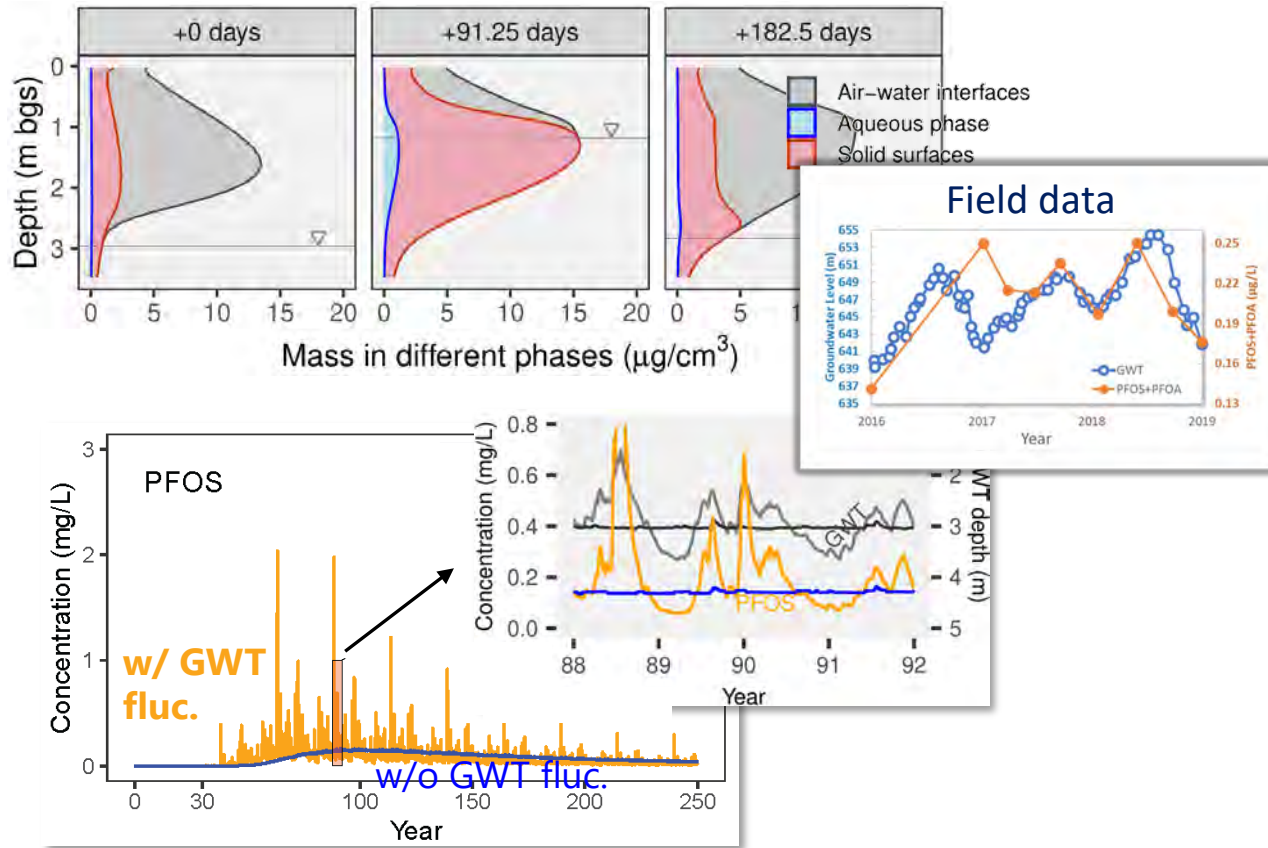


Drier condition



- Surface diffusion needs to be incorporated.
- Mass transfer limitation may occur under drier conditions.

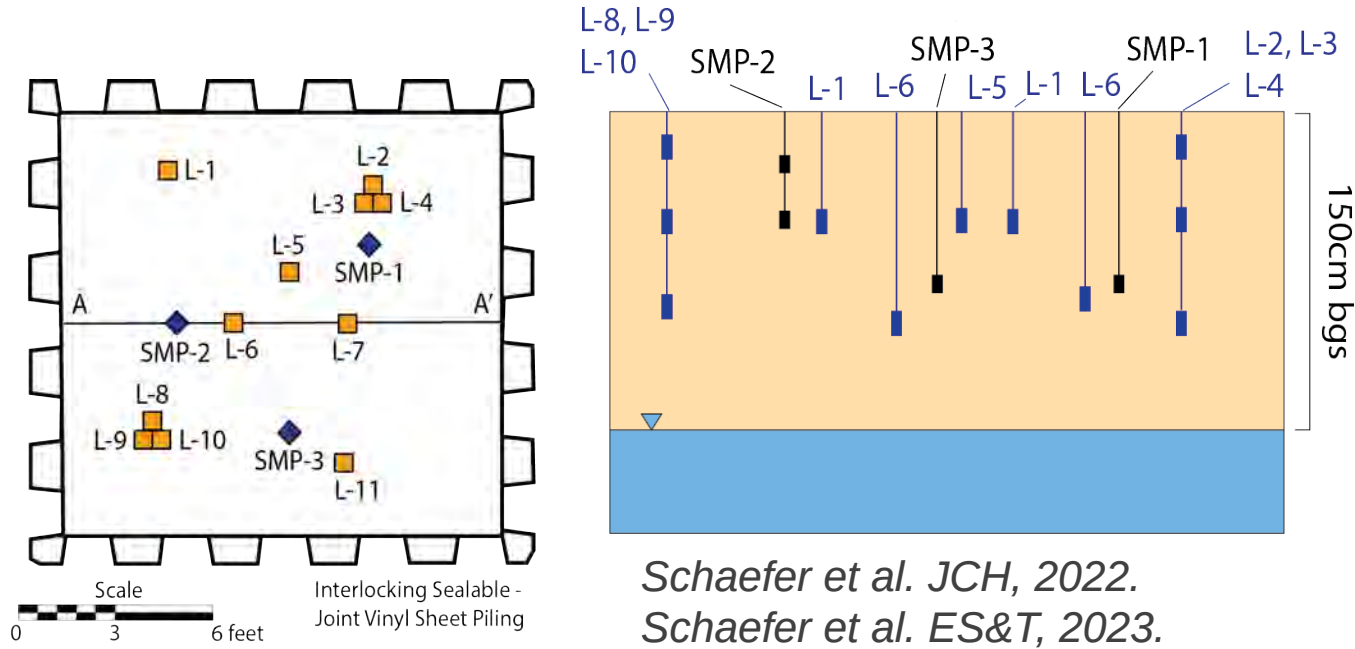
Groundwater Table Fluctuation Enhances Source-zone Leaching and Causes Temporal Variation in GW Concentration



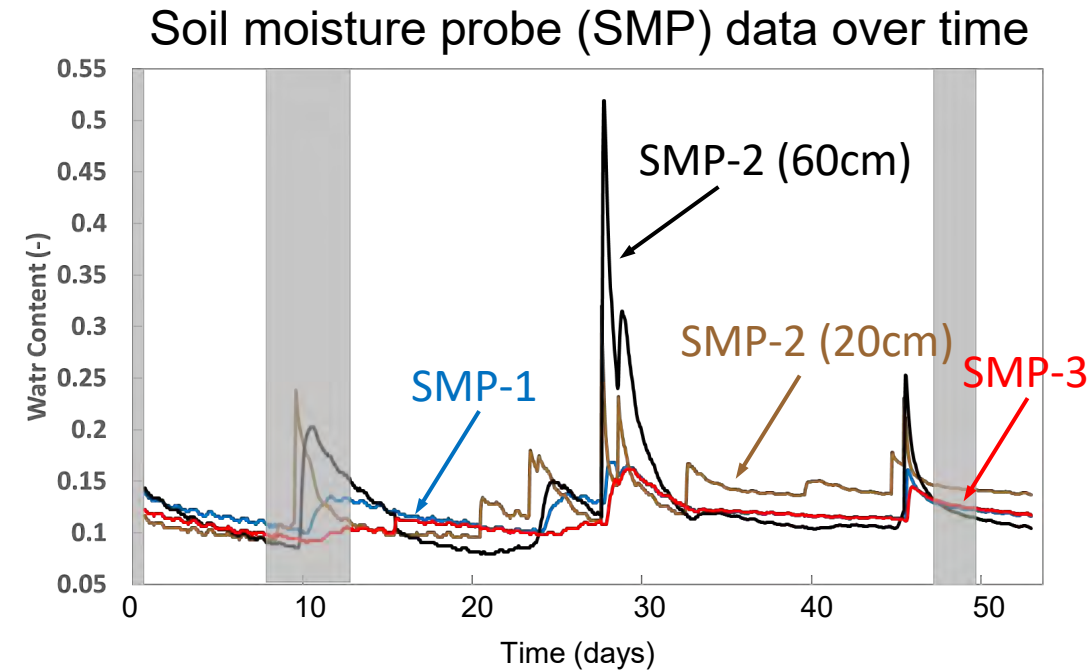
- Enhanced source-zone leaching; Strong temporal variation of GW concentration.
- A persistent plume in the downgradient vadose zone.

Modeling Lysimeter Porewater Data at an AFFF-impacted Site

Tier 2: PFAS-LEACH-HYDRUS-GW



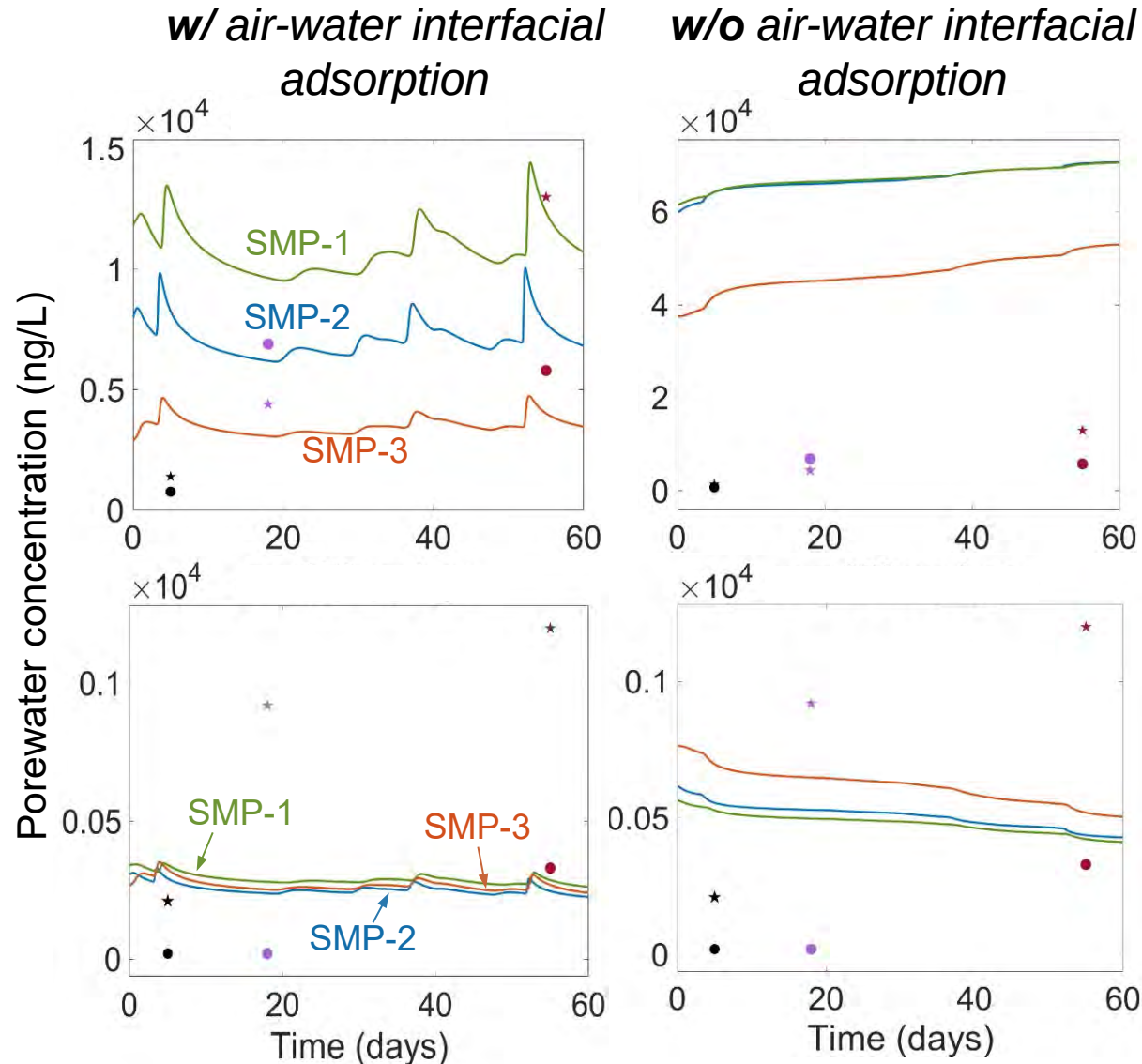
Field test cell at a PFAS-contamination site.
SERDP ER-1204; PI: Charles Schaefer



Lysimeter sampling intervals represented by grey boxes

- 4.3 m by 4.3 m instrumented test cell at an AFFF-impacted FTA site.
- Soil moisture data was collected continuously under regular rainfall infiltration.
- Lysimeter porewater concentration was measured for multiple sampling events.

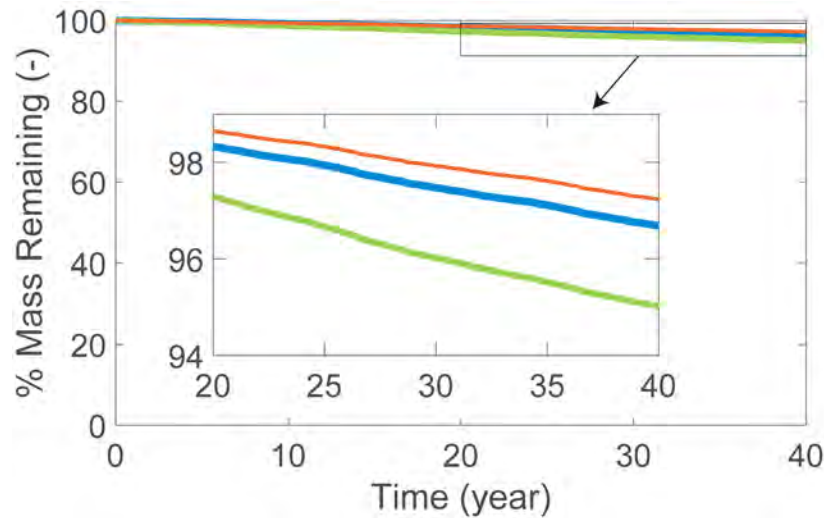
Predicted vs. Measured Lysimeter Porewater Data



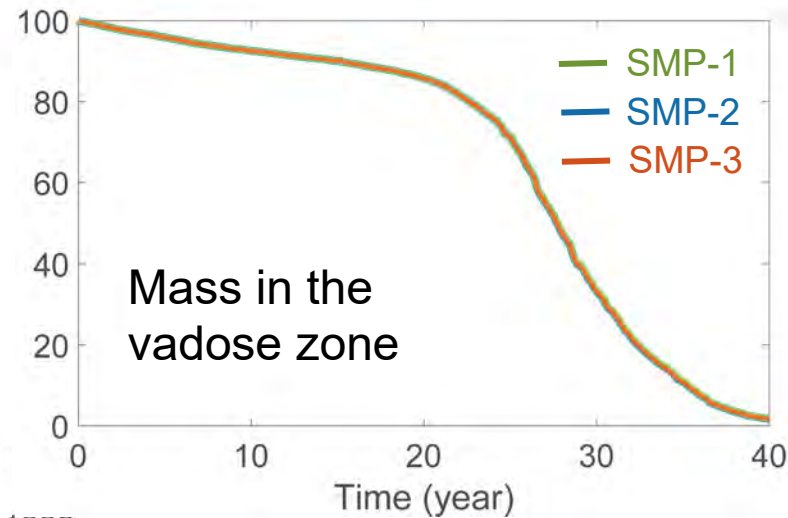
- No parameter tuning, thus agreement between model and data represents a field validation of PFAS-LEACH.
- Accounting for air-water interfacial adsorption and solid-phase rate-limited desorption improves the model prediction.

Simulating Cumulative Mass Discharge to Groundwater

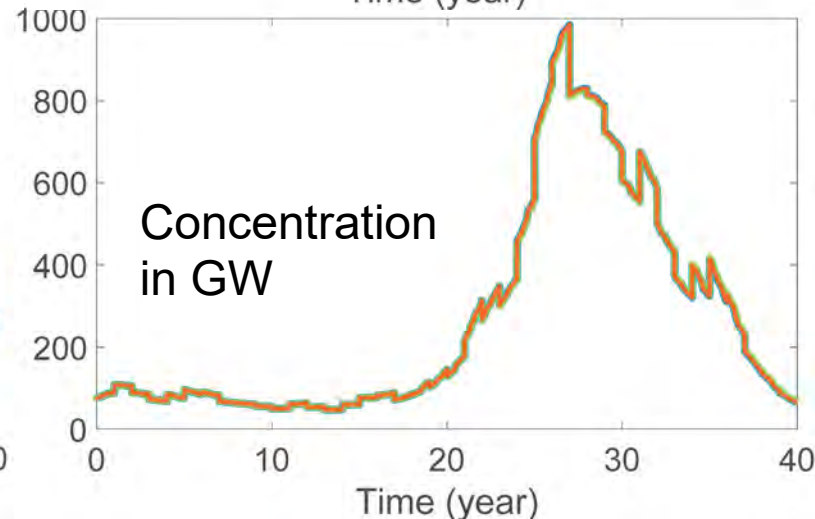
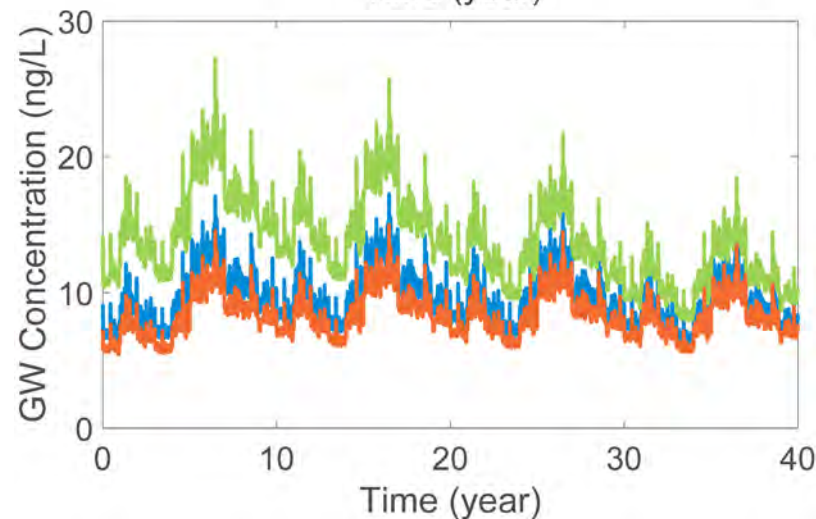
*w/ air-water interfacial
adsorption*



*w/o air-water interfacial
adsorption*



- Air-water interfacial adsorption significantly delays PFOS mass discharge to groundwater.



Leverage Porewater C for Practical Applications?

- Air-water interfacial area is one of the parameters with greatest uncertainties.
- Measured porewater C may be used to constrain the air-water interfacial area.

Total PFAS
in soil

$$C_{\text{soil}} = \theta C_{aq} + \rho_b K_d C_{aq} + A_{aw} K_{aw} C_{aq}$$

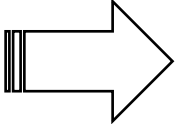
↑
Porewater

↑
Solid-phase
adsorption

↑
Air-water
interfacial
adsorption

$$\Rightarrow A_{aw} = \frac{C_{\text{soil}} - \theta C_{aq} - \rho_b K_d C_{aq}}{K_{aw} C_{aq}}$$

Can we develop simplified models for practical screening-type analysis?

 *Tier 3: PFAS-LEACH-Analytical-GW*

PFAS Transport in the Vadose Zone

Simplified Mathematical Model

- Steady-state unsaturated flow:

$$q = K$$

- PFAS transport:

$$\frac{\partial (\theta C)}{\partial t} + \boxed{\rho_b \frac{\partial C_s}{\partial t}} + \boxed{\frac{\partial C_{aw}}{\partial t}} + \underbrace{\nabla \cdot (\theta \mathbf{v} C)}_{\text{Advection}} - \underbrace{\nabla \cdot (\theta \mathbf{D} \nabla C)}_{\text{Dispersion}} = 0$$

Linear and rate-limited solid-phase adsorption

$$C_{s,1} = F_s K_d C \quad \frac{dC_{s,2}}{dt} = \alpha_s [(1 - F_s) K_d C - C_{s,2}]$$

Instantaneous Kinetic

Linear and equilibrium air-water interfacial adsorption

$$C_{aw} = A_{aw} K_{aw} C$$

Instantaneous

Guo, Zeng, Brusseau, Zhang. 2022 AWR

Model Validation

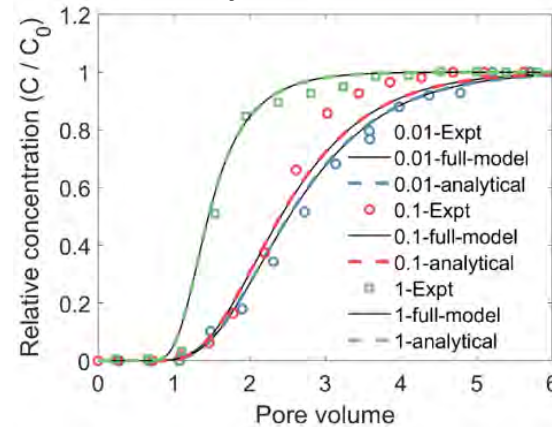
vs. Miscible-displacement Experiment

- ✓ PFAS retention in the vadose zone and mass discharge to groundwater



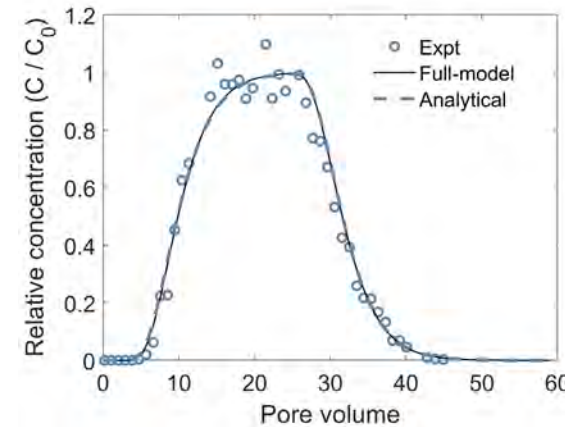
Experimental data set #1
PFOA (1 mg/L, 0.1 mg/L, 0.01 mg/L)

Measured data: Lyu et al., 2018



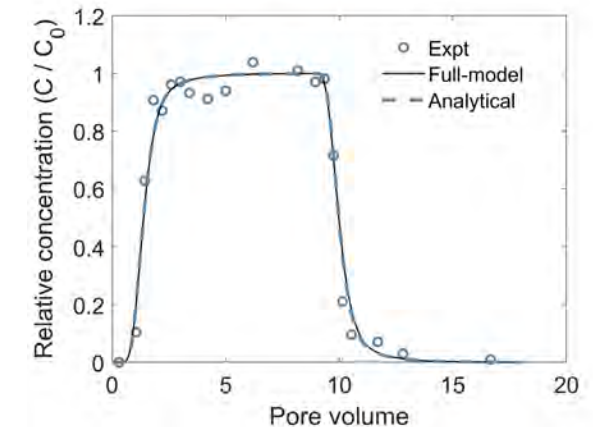
Experimental data set #2
PFOS (0.1 mg/L)

Measured data: Brusseau et al., 2021



Experimental data set #3
GenX (10 mg/L)

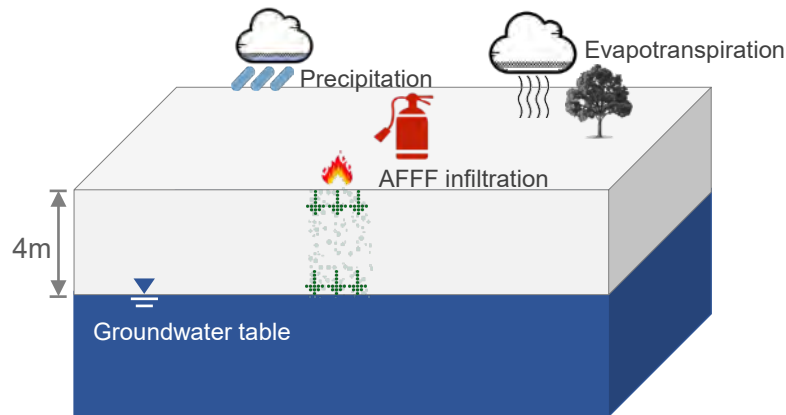
Measured data: Yan et al., 2021



- Analytical solutions are identical to the numerical solutions of the full-process model.
- Independent model predictions match well with experimental data.

Model Validation *vs. Full Process Model*

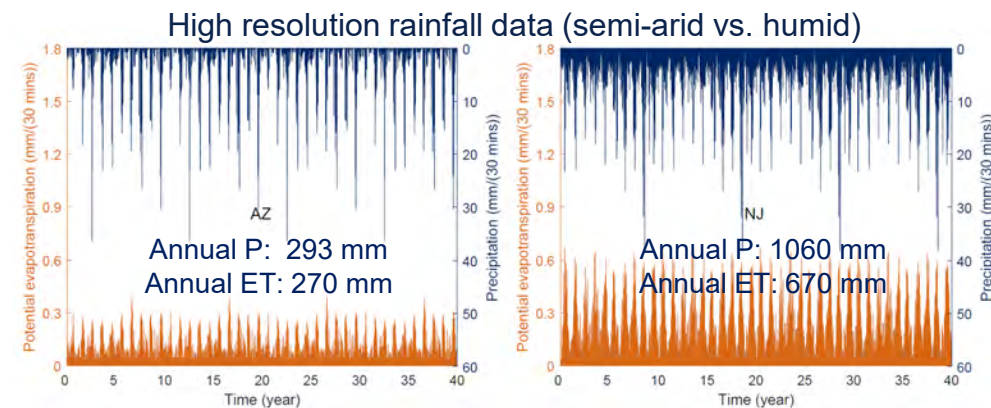
✓ PFAS contamination scenario at an AFFF-impacted fire training area site



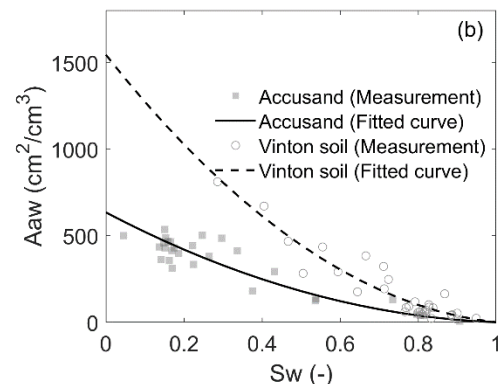
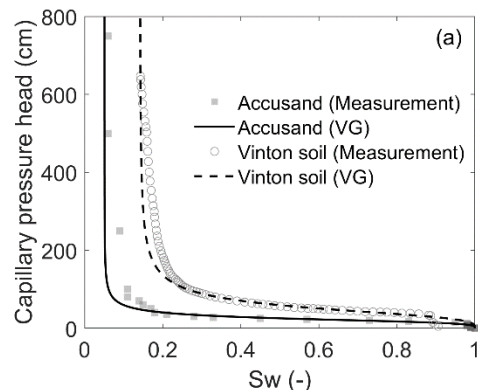
✓ Fire training: one session every 10 days lasting for 30 years

✓ Representative PFAS mixture in 1% diluted AFFF solution

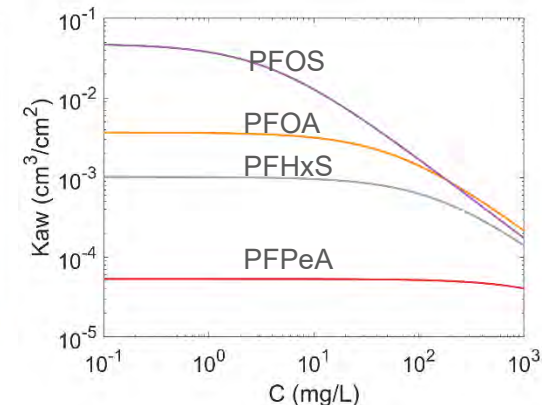
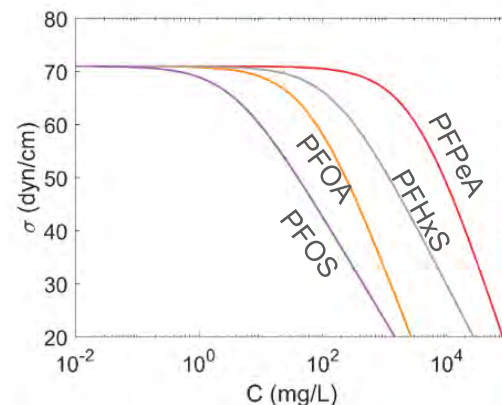
PFPeA: 0.23 mg/L, PFOA: 0.9 mg/L, PFHxS: 7.1 mg/L, PFOS: 100 mg/L



Two soil types (Accusand vs. Vinton)

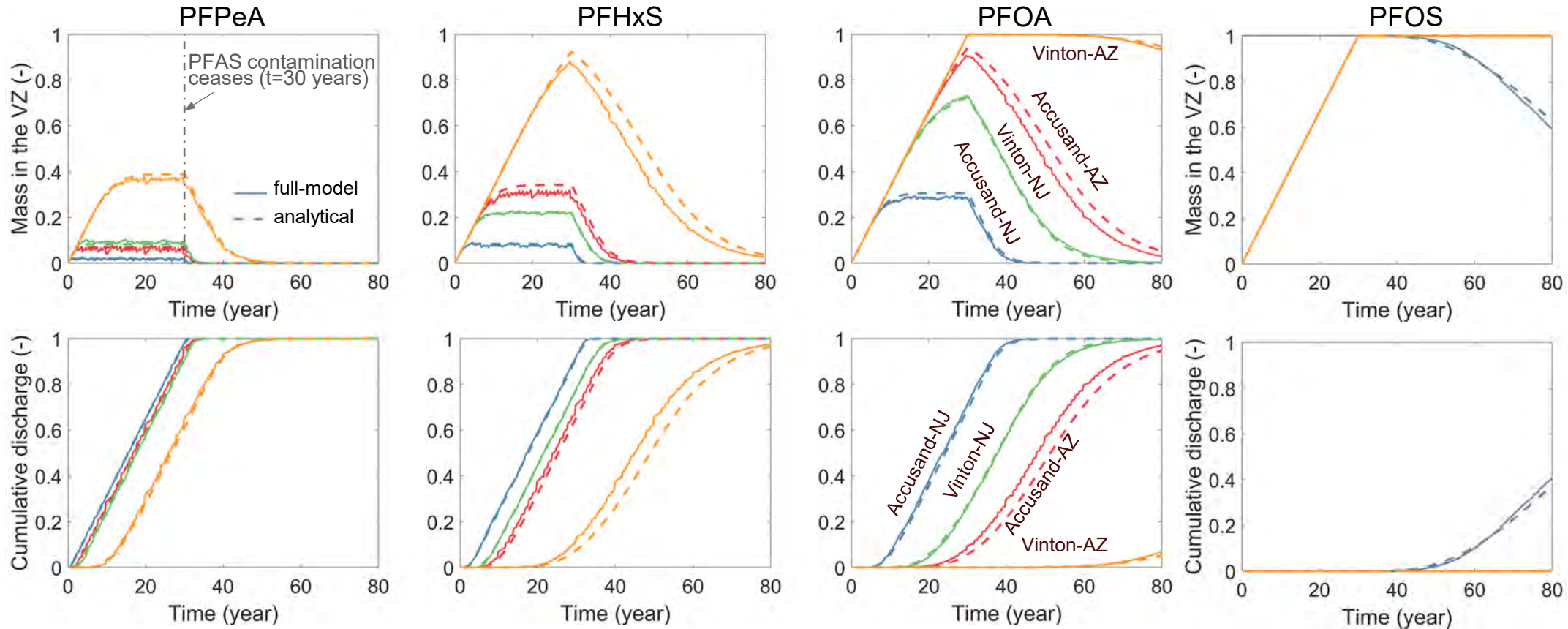


Four representative PFAS



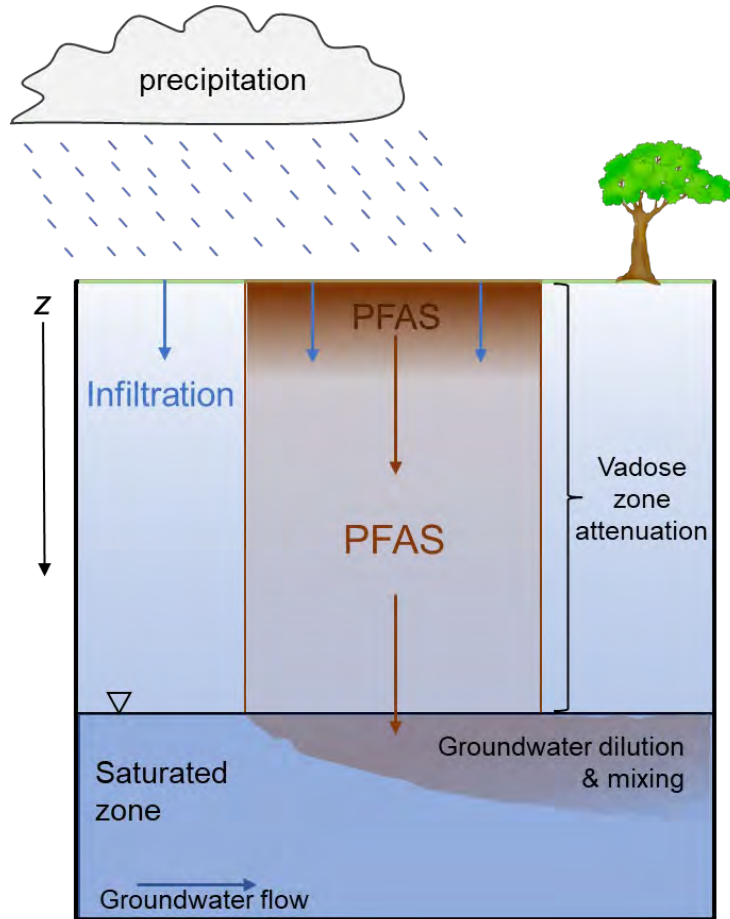
Simulated Long-term PFAS Leaching in the Vadose Zone

- ✓ PFAS retention in the vadose zone and mass discharge to groundwater



- Analytical model matches remarkably well with the full-process model for all four PFAS.

Derive Site-specific Soil Screening Levels (SSLs) for PFAS



Conceptual Model

Vadose zone (analytical **process-based** model, Guo et al. 2022)

- Assuming steady-state infiltration
- Transient transport
 - advection-dispersion
 - **kinetic** linear solid-phase adsorption
 - linear air-water interfacial adsorption

Representing VZ
attenuation directly

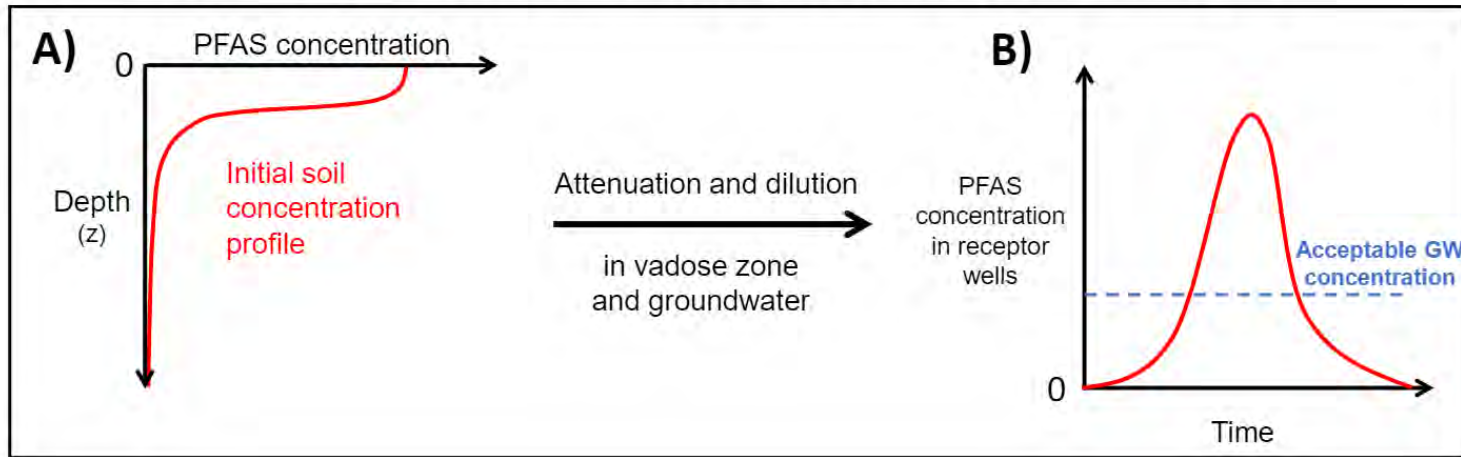
Transient mass
discharge rates

Groundwater (GW mixing model, EPA 1996)

- Well-mixed between source zone and receptor point.
- Only accounts for dilution, not attenuation in groundwater.

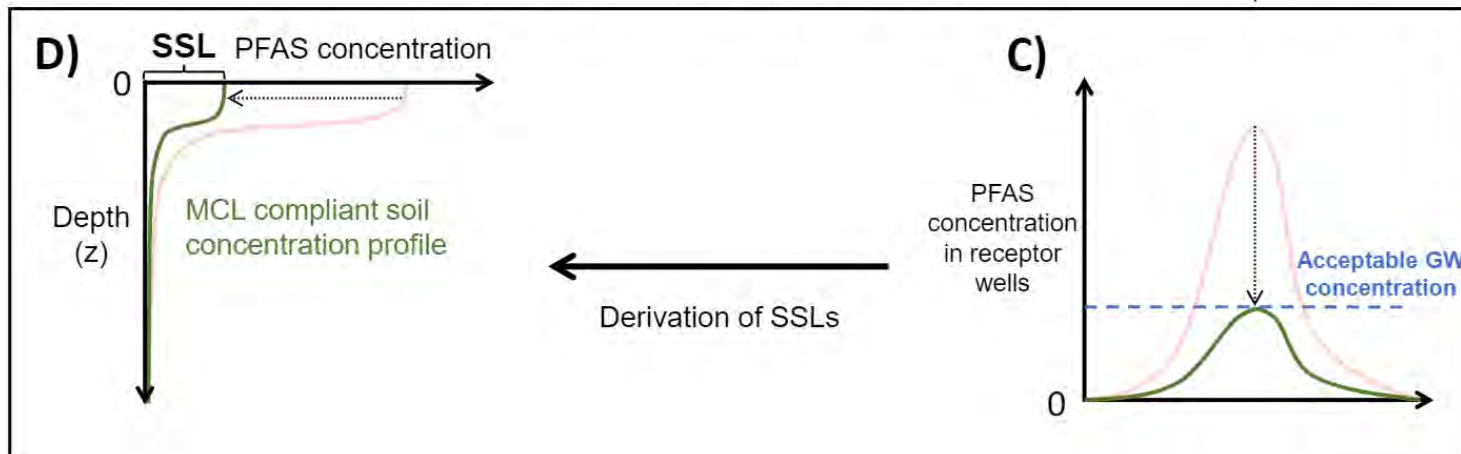
Derive Site-specific Soil Screening Levels (SSLs) for PFAS

Forward mode – characterization of groundwater contamination risk



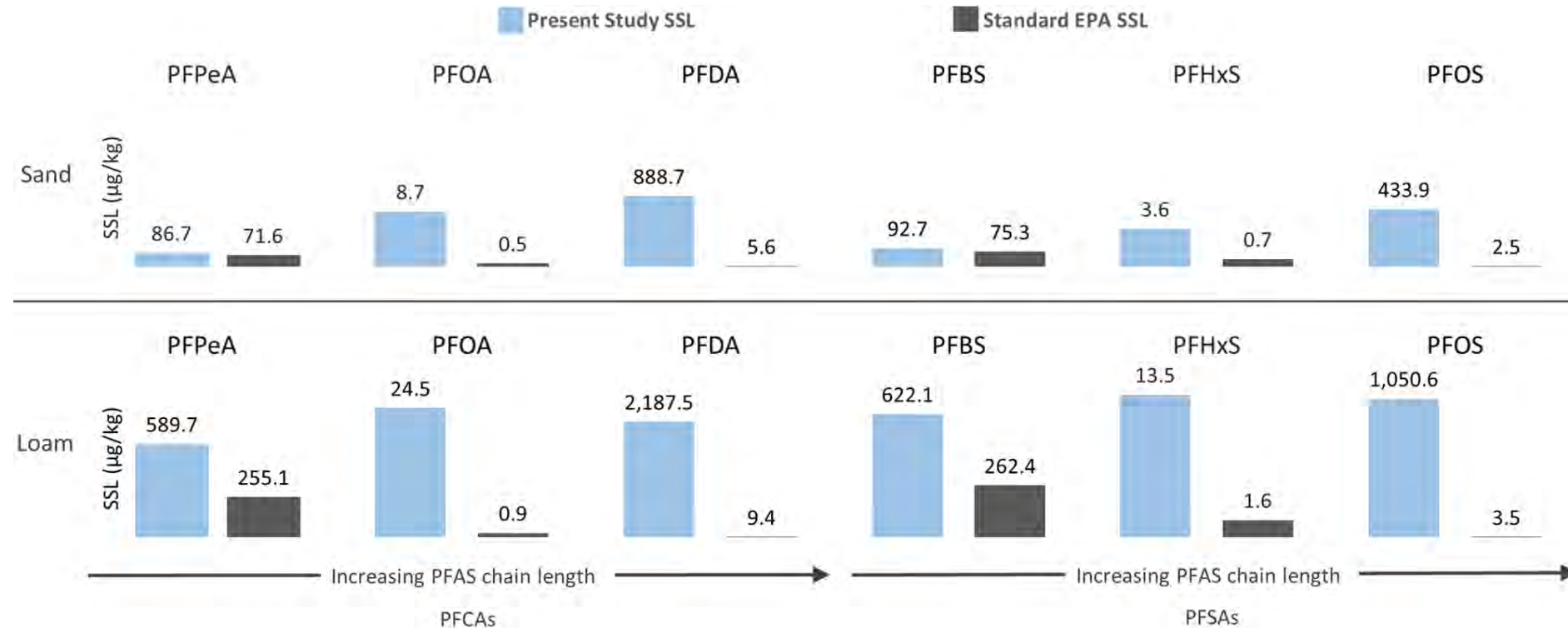
- **Forward** mode evaluates groundwater contamination risk for a receptor point at a given contamination site.

Inverse mode – derivation of SSLs



- **Inverse** mode derives an SSL for a specific site that is protective of groundwater.

Derived SSLs for Example Soils and PFAS



- New SSL framework accounting for air-water interfacial adsorption leads to much greater SSLs, especially for longer-chain PFAS.
- Derived SSLs are highly site-specific.

Revising EPA Dilution-Attenuation Factor SSL for PFAS

Tier 4: PFAS-LEACH-DAF-GW

- EPA DAF Soil Screening Level (SSL) model

$$SSL = C_{soil} = C_{gw} DAF \left[K_d + (\theta_w + \theta_a H) \frac{1}{\rho_b} \right]$$

Solid-phase adsorption
Partitioning to the air phase

- Our revised EPA DAF SSL model

$$SSL^{Rev} = C_{soil} = C_{gw} DAF \frac{\theta_w}{\rho_b} R_d$$

Distribution of PFAS between porewater & soil concentrations

$$1 + \underbrace{K_{d*} \frac{\rho_b}{\theta_w} + H \frac{\theta_a}{\theta_w}}_{\text{Considered in original EPA SSL model}} + \underbrace{K_{aw*} \frac{a_{aw}}{\theta_w}}_{\text{Air-water interfacial adsorption}} + \underbrace{K_n \frac{\theta_n}{\theta_w} + K_{nw*} \frac{a_{nw}}{\theta_w} + K_{an*} \frac{a_{an}}{\theta_w} + K_{c*} X_c}_{\text{Other additional retention processes}}$$

Assuming air-water interfacial adsorption is the only additional retention

$$\Rightarrow SSL^{Rev} = C_{soil} = C_{gw} DAF \left[K_d + (K_{aw} a_{aw} + \theta_w + \theta_a H) \frac{1}{\rho_b} \right]$$

Revising EPA Dilution-Attenuation Factor SSL for PFAS

Example Parameters and Calculated SSLs for PFOS and PFOA.

Parameter	PFOS		PFOA	
	Standard Model	Revised Model	Standard Model	Revised Model
Soil Screening Level (SSL, $\mu\text{g}/\text{kg}$)	<u>4.3</u>	75.6	<u>2.3</u>	7.0

- This revised EPA DAF soil screening model represents the simplest SSL model.
- The estimated SSLs can be more than 1 order of magnitude greater under certain conditions.
- The ONLY additional mechanism included in the example is the revised mass distribution in the vadose zone due to air-water interfacial adsorption.
- NO attenuation in the vadose zone is included.



Conclusions

- PFAS-LEACH provides a suite of models across different levels of complexities for quantifying PFAS transport in the subsurface.
- The models account for the primary processes influencing PFAS migration and retention in the vadose zone.
- PFAS-LEACH models have been partly validated by field observations and demonstrated to be effective tools for various site management purposes.

*Beta version of **PFAS-LEACH Tier 3 and 4** to be released on GitHub in January 2025. Check guolab.arizona.edu for updates.





Publications

- Guo, B., Zeng, J. and Brusseau, M.L., 2020. A mathematical model for the release, transport, and retention of per-and polyfluoroalkyl substances (PFAS) in the vadose zone. *Water Resources Research*, 56(2), p.e2019WR026667.
- Zeng, J. and Guo, B., 2021. Multidimensional simulation of PFAS transport and leaching in the vadose zone: Impact of surfactant-induced flow and subsurface heterogeneities. *Advances in Water Resources*, 155, p.104015.
- Zeng, J., Brusseau, M.L. and Guo, B., 2021. Model validation and analyses of parameter sensitivity and uncertainty for modeling long-term retention and leaching of PFAS in the vadose zone. *Journal of Hydrology*, 603, p.127172.
- Guo, B., Zeng, J., Brusseau, M.L. and Zhang, Y., 2022. A screening model for quantifying PFAS leaching in the vadose zone and mass discharge to groundwater. *Advances in Water Resources*, 160, p.104102.
- Guo, B., Saleem, H. and Brusseau, M.L., 2023. Predicting Interfacial Tension and Adsorption at Fluid–Fluid Interfaces for Mixtures of PFAS and/or Hydrocarbon Surfactants. *Environmental Science & Technology*. 57, 21, 8044-8052.
- Brusseau, M.L. and Guo, B., 2023. Revising the EPA dilution-attenuation soil screening model for PFAS. *Journal of Hazardous Materials Letters*, 4, p.100077.
- Zeng, J. and Guo, B., 2023. Reduced accessible air–water interfacial area accelerates PFAS leaching in heterogeneous vadose zones. *Geophysical Research Letters*, 50(8), p.e2022GL102655.
- Chen, S. and Guo, B., 2023. Pore-Scale Modeling of PFAS Transport in Water-Unsaturated Porous Media: Air–Water Interfacial Adsorption and Mass-Transfer Processes in Thin Water Films. *Water Resources Research*, 59(8), p.e2023WR034664.
- Zeng, J., Brusseau, M.L. and Guo, B., 2024. Modeling PFAS subsurface transport in the presence of groundwater table fluctuations: The impact on source-zone leaching and exploration of model simplifications. *Water Resources Research*, 60(11), p.e2024WR037707.
- Smith, J., Brusseau, M.L. and Guo, B., 2024. An integrated analytical modeling framework for determining site-specific soil screening levels for PFAS. *Water Research*, 252, p.121236.



Thank You



Questions?



Your Success is Our Mission!



Air Force Civil Engineer Center

Restoration Technology Transfer Speakers Series February 2025

PFAS Remediation Using In Situ Foam Fractionation and Follow Up Destruction Using EradiFluor

This webinar included two parts. The first part focused on field demonstration of in situ groundwater remediation of PFAS using an in situ foam fractionation technology (D-FAS). Successful field demonstration was completed under the ESTCP program at a DoD facility located on the East Coast. A follow-up contract was awarded to further apply the technology for in situ PFAS remediation at the site. The second part focused on PFAS destruction using an innovative destruction technology (EradiFluor) that is based on ultraviolet (UV)/sulfite reactions. Field demonstration for PFAS destruction in the foam fractionate concentrate produced in the D-FAS process was recently completed under the ESTCP program at the same DoD facility located on the East Coast. Results of field demonstrations of both D-FAS and EradiFluor technologies were discussed.

Treatment of waste concentrate: in situ foam fractionation

- Foamate produced from an in situ foam fraction remediation system from a Navy site
 - Tens of ppm level of PFAS
 - PFOS and 6:2 FTS dominant
 - Low level of TOC and nitrate/nitrite

In situ foam fractionation system for groundwater remediation

PFAS concentrate produced from an in situ foam fractionation system for groundwater remediation (Source: Nelson 2022)

HALEY ALDRICH

John Xiong and Christopher Nelson present details of their field demonstration setup.

This event and future events are updated and posted on the AFIT website at: <https://www.afit.edu/CE/index.cfm>.

POCs:

Joseph Dimisa, AFIT (joseph.dimisa@us.af.mil)

C.J. Garcia, CTR, Booz Allen Hamilton (carlos.garcia.56.ctr@us.af.mil)

Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)



Webinar Structure



<https://www.milsuite.mil/book/docs/DOC-1354669>

5 min

Welcome and Administrative Business

20 min

In-Situ Treatment of PFAS Using D-FAS Technology – Christopher Nelson, P.E, eMinus LLC

20 min

EradiFluor™ - An innovative PFAS destruction technology – John Xiong, Ph.D., P.E., Haley Aldrich

10 min

Questions and Answers

5 min

Final Thoughts

Air Force Civil Engineer Center



In-Situ Treatment of PFAS Using D-FAS Technology

SERDP-ESTCP
ER19-5075

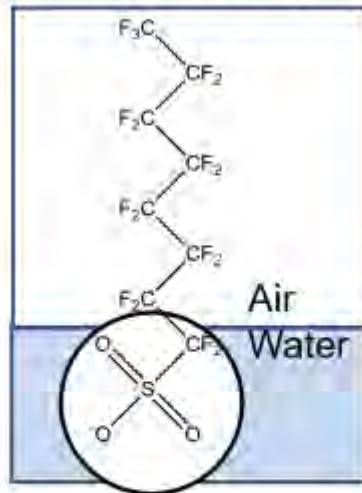
Christopher Nelson, P.E
eMinus LLC
February 2025

The Team

- | | |
|------------------|--------------|
| ■ David Reynolds | Geosyntec |
| ■ Rich Spehar | BLDI Inc. |
| ■ Tony Danko | NAVFAC |
| ■ Jason Speicher | NAVFAC |
| ■ Amelia DaCruz | Avanti Corp. |

Remove and Destroy

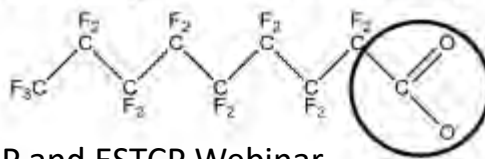
PFOS (perfluorooctane sulfonate)



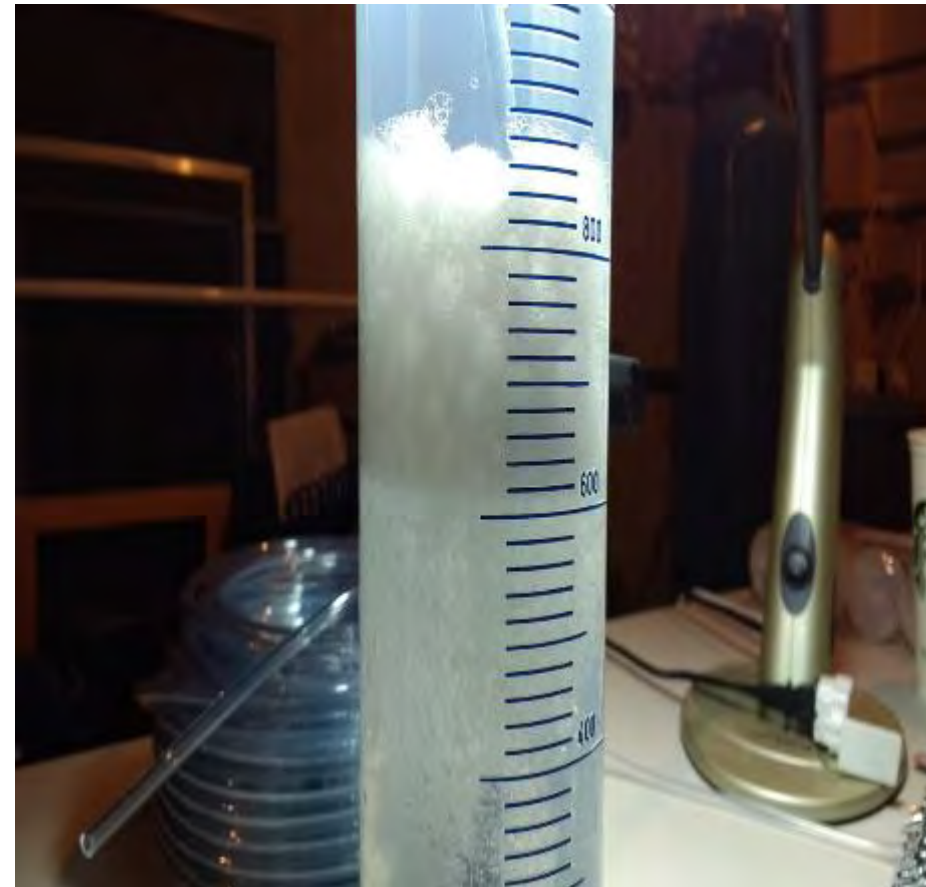
Hydrophobic

Hydrophilic

PFOA (perfluorooctanoate)



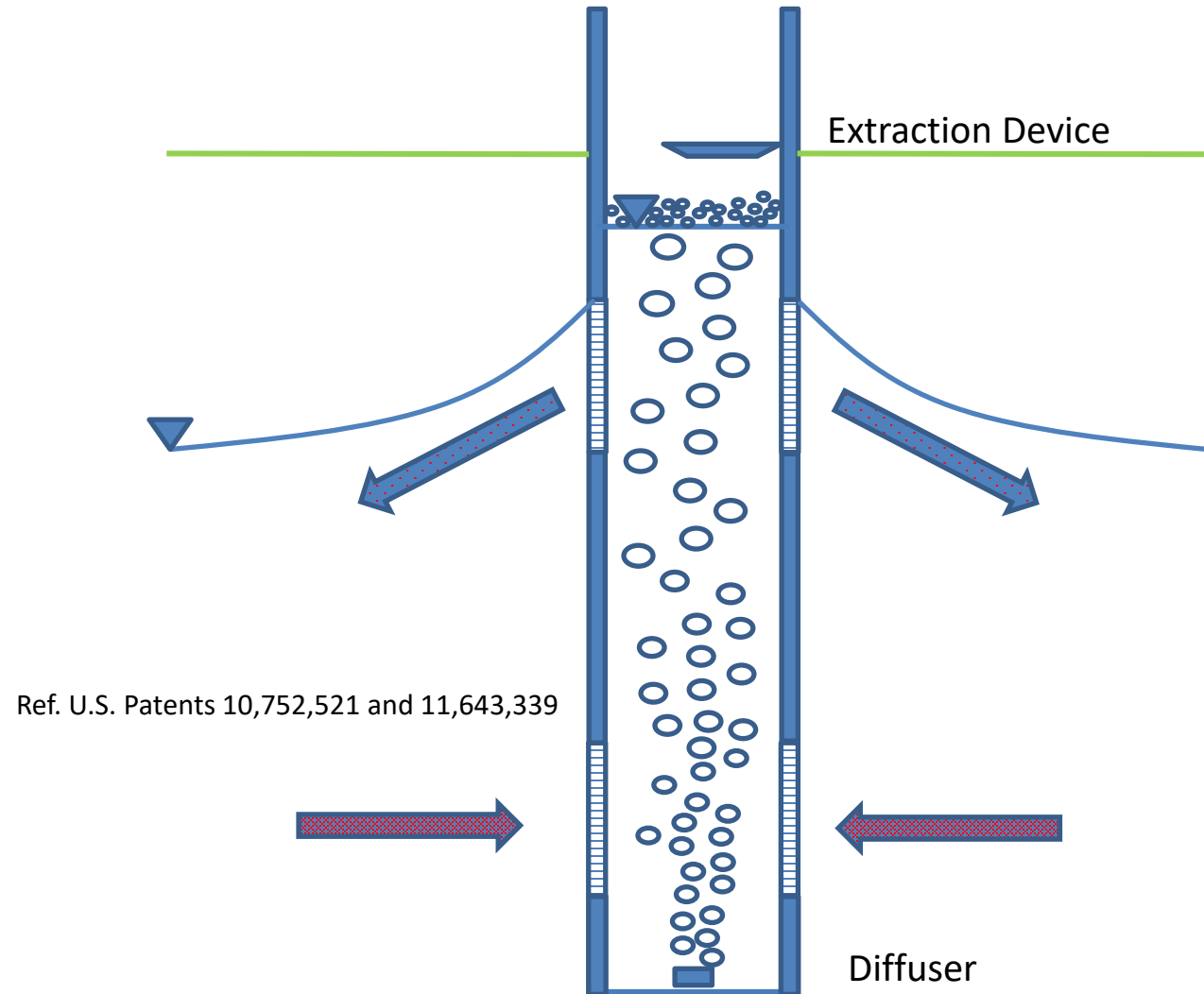
SERDP and ESTCP Webinar Series (#26)



PFAS partitions to air/water interface

D-FAS Conceptual Approach

No Groundwater Extraction!



What is D-FAS?

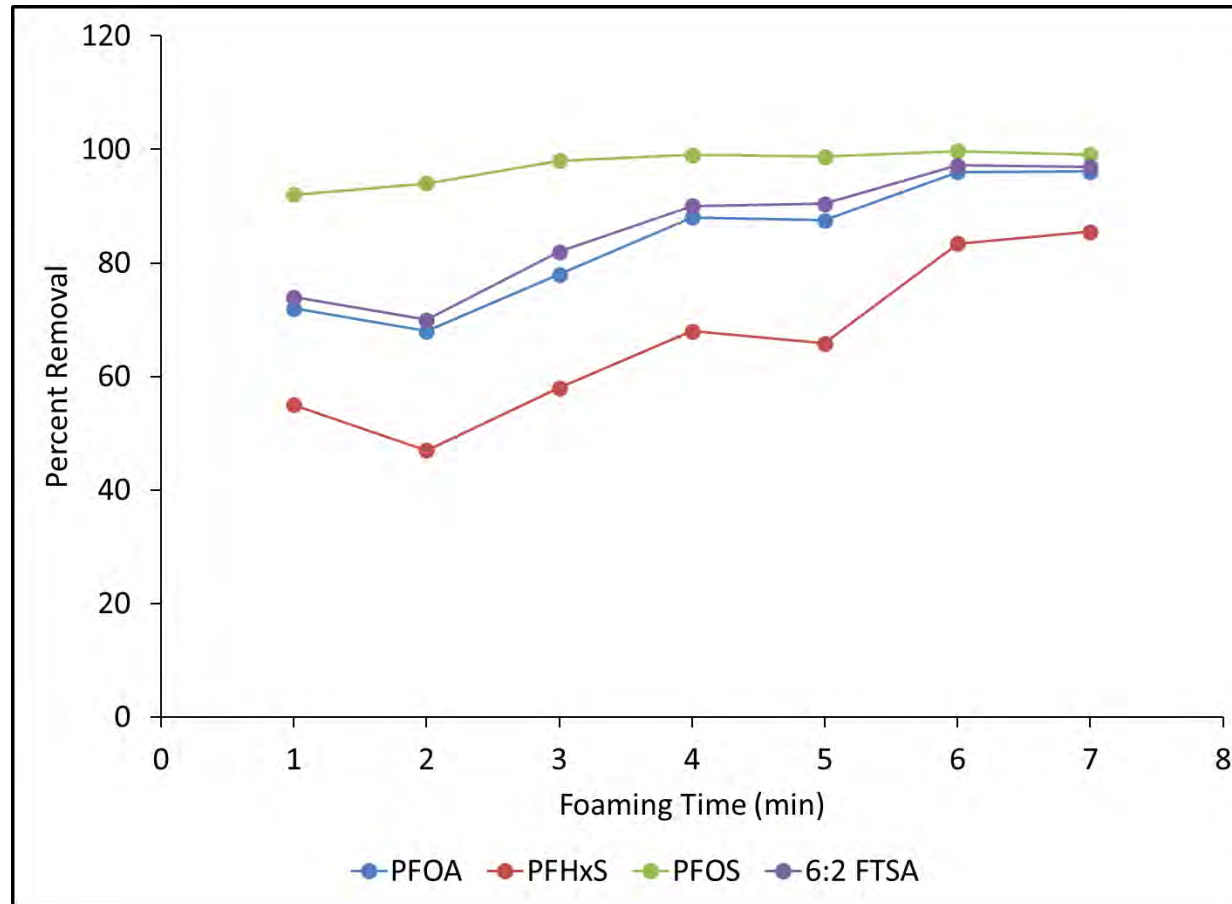
- In-situ remediation platform that includes:

- ◆ Foam fractionation
- ◆ Redox/geochemical manipulation
- ◆ Groundwater recirculation

And can include:

- ◆ Bioremediation enhancement
- ◆ ISCO (for precursor conversion)
- ◆ VOC removal

Phase 1 – Treatability Testing



Site Groundwater

Analyte	Concentration (ug/L)
PFOA	120
PFHxS	380
PFOS	450
6:2 FTS	460

Mass Balance

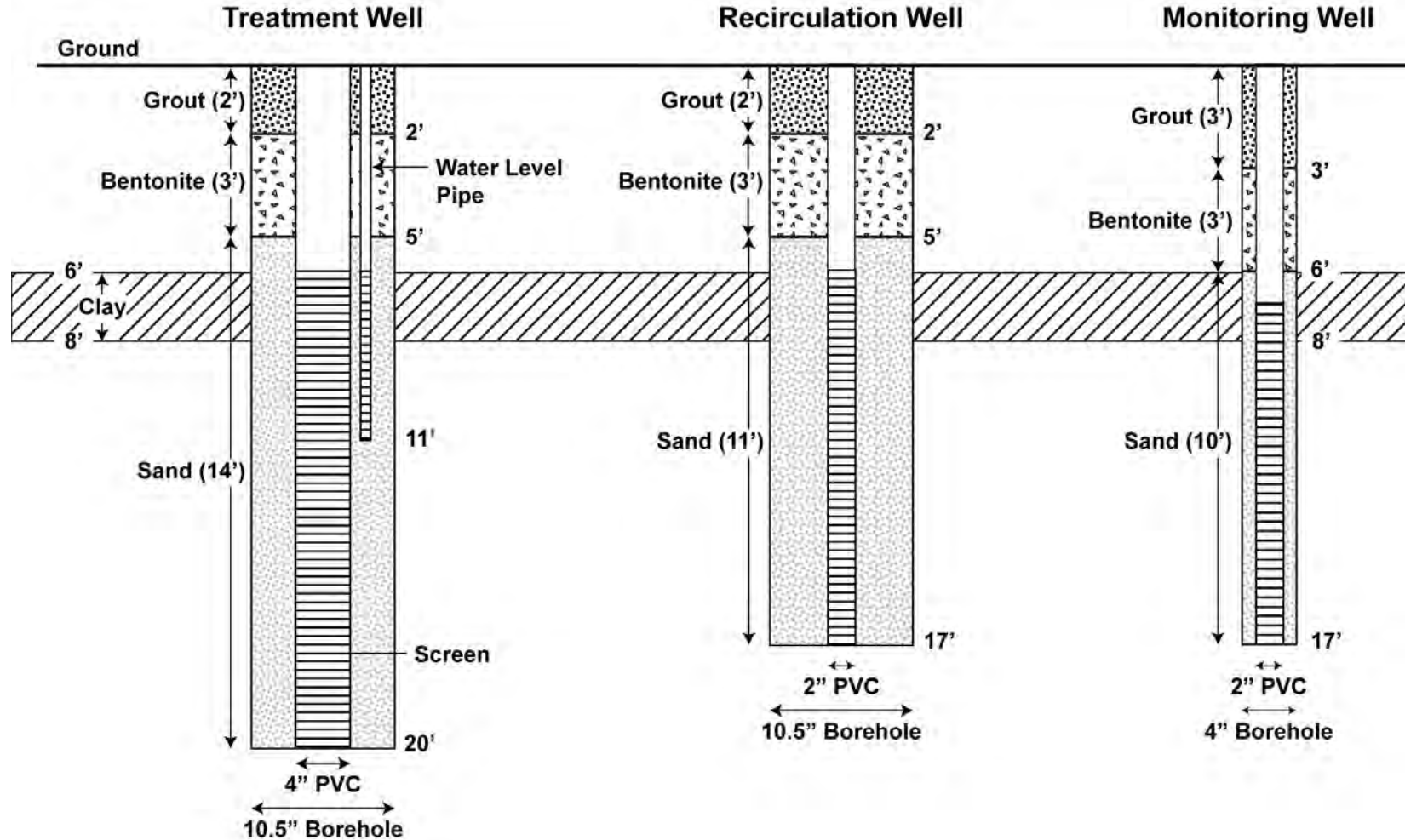
PFAS Analyte	Site Water (Before)	Foam (After)
	Mass (ug)	Mass (ug)
PFOA	72	83
PFHxS	228	233
PFOS	270	323
6:2 FTSA	276	338
Total	846	977

Phase 2 – Pilot Test

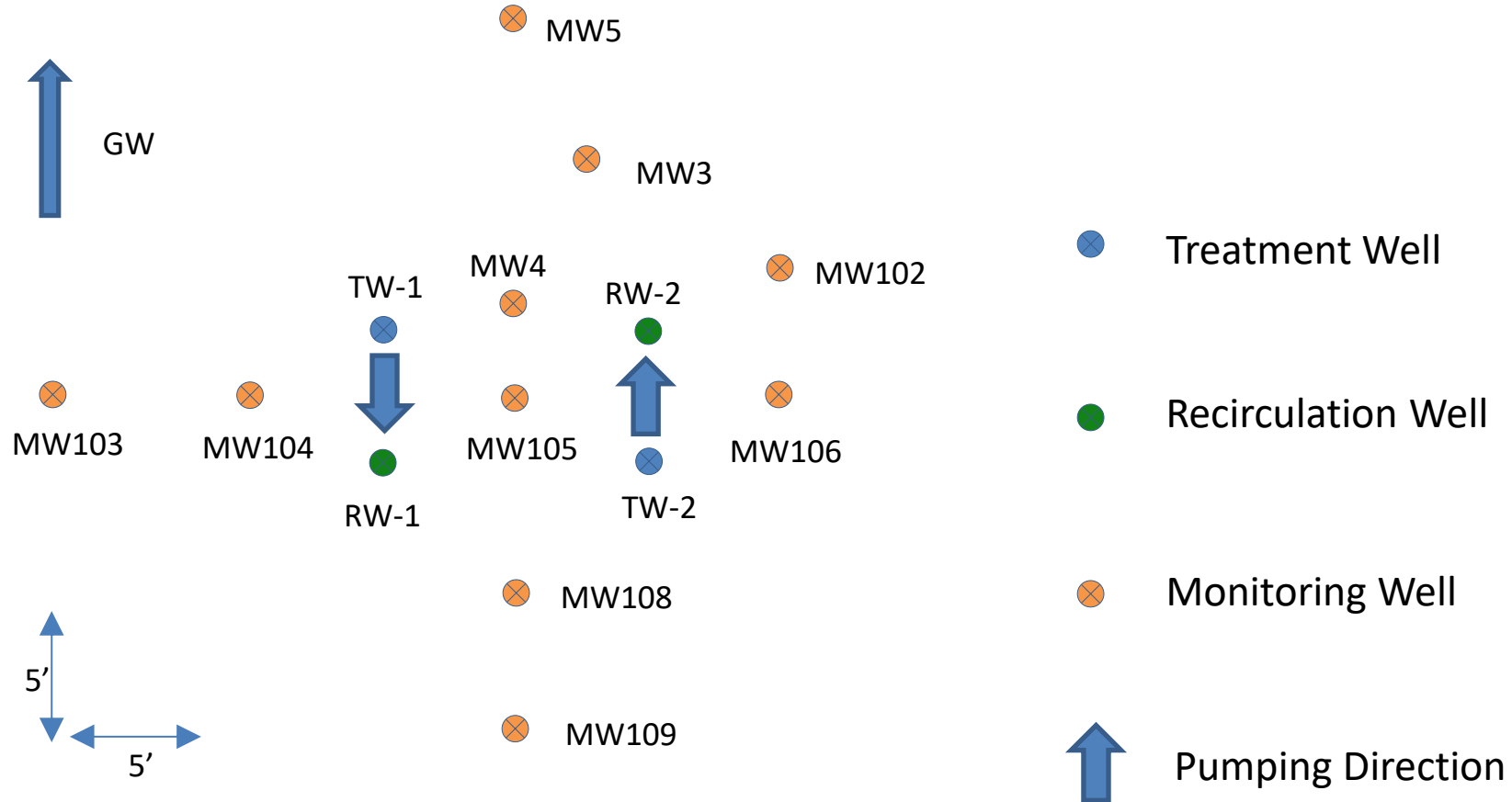
- Shallow clays found in preliminary drilling
- Likely to prevent upper screen discharge



Well Diagrams



System Well Layout



System Layout

Treatment, Recirculation, and Monitoring Wells



Product Tank and Treatment Trailer



D-FAS In Action

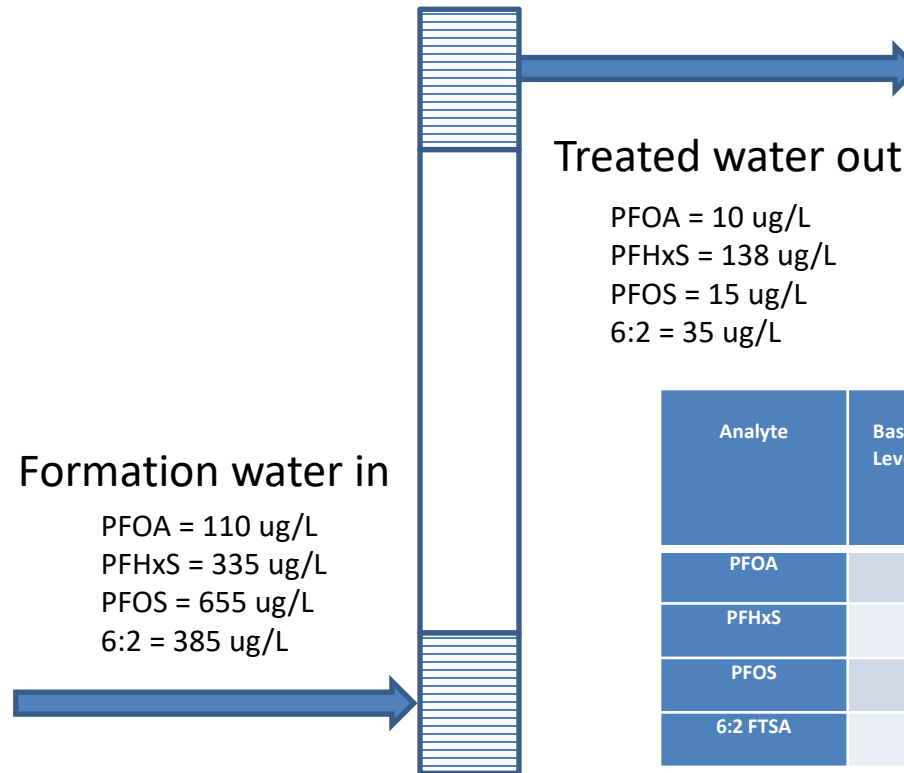


During Extraction



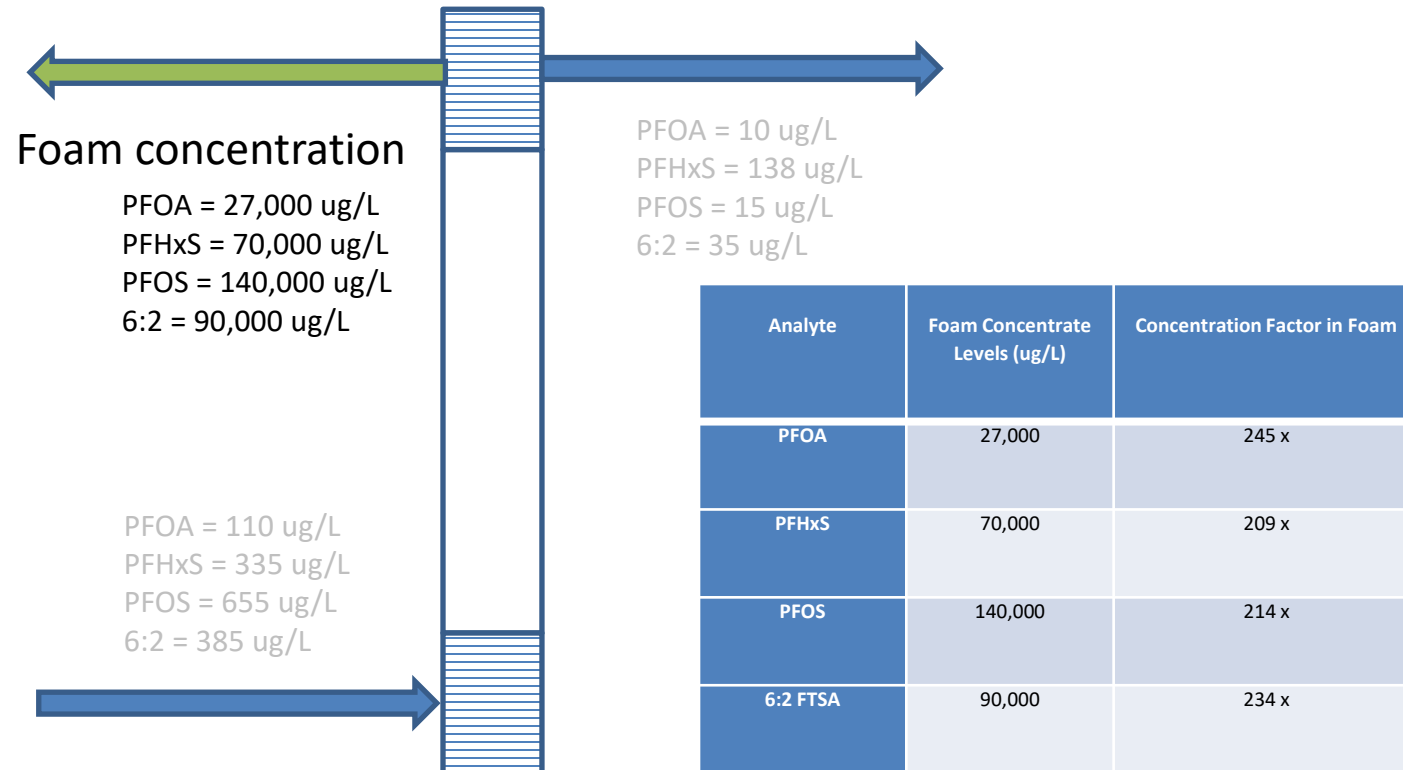
After Condensation

Concentration Reductions In a Single Pass-Through TW

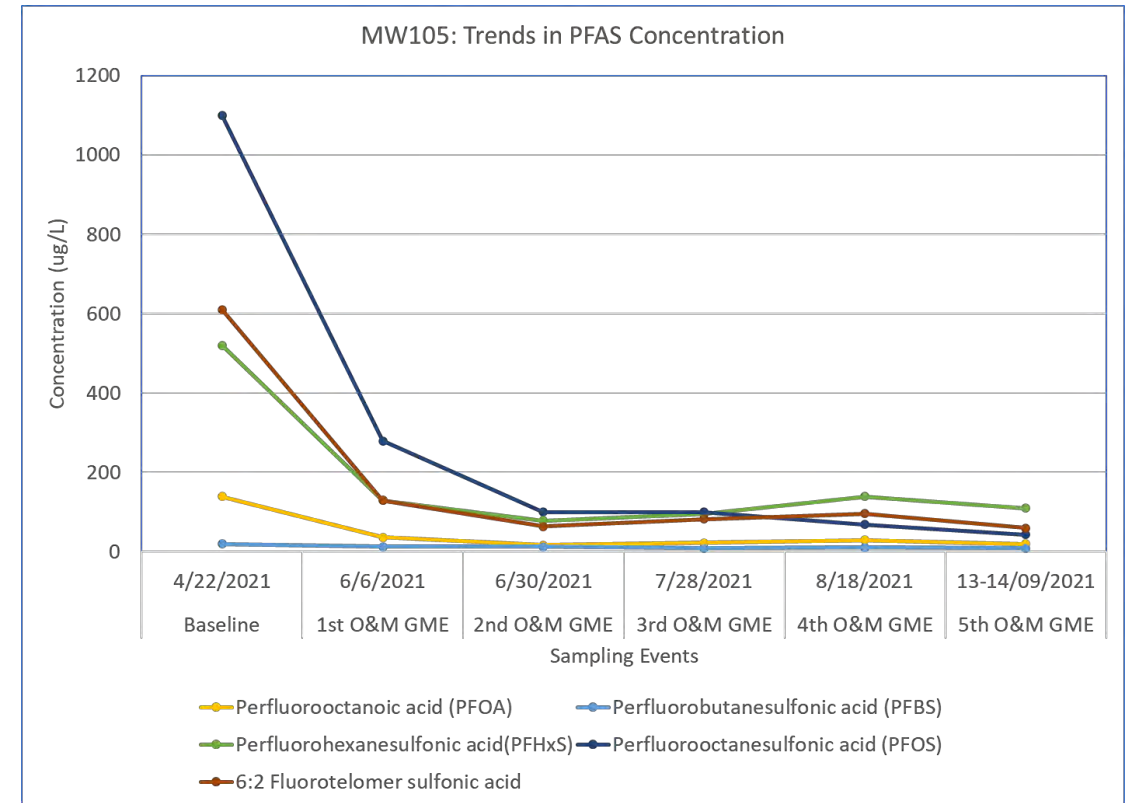
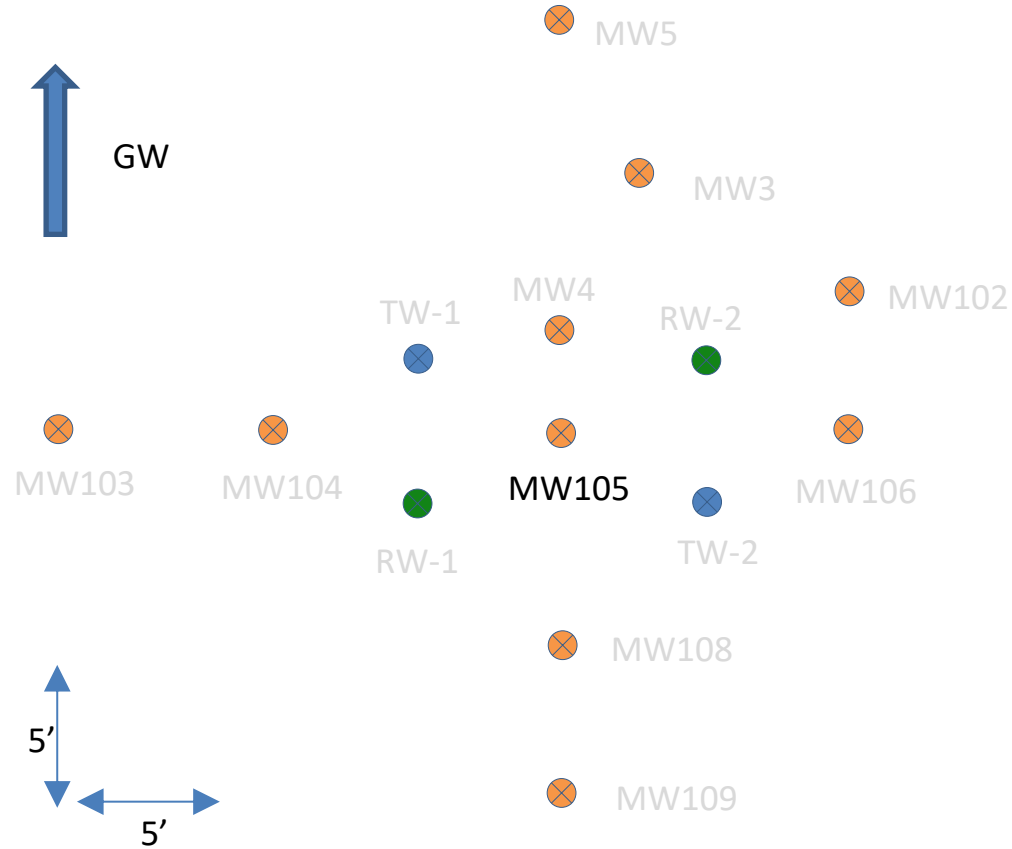


Analyte	Baseline GW Levels (ug/L)	GW Post System Treatment (ug/L)	Percent Reduction in GW
PFOA	110	10	91%
PFHxS	335	138	59%
PFOS	655	15	98%
6:2 FTSA	385	35	91%

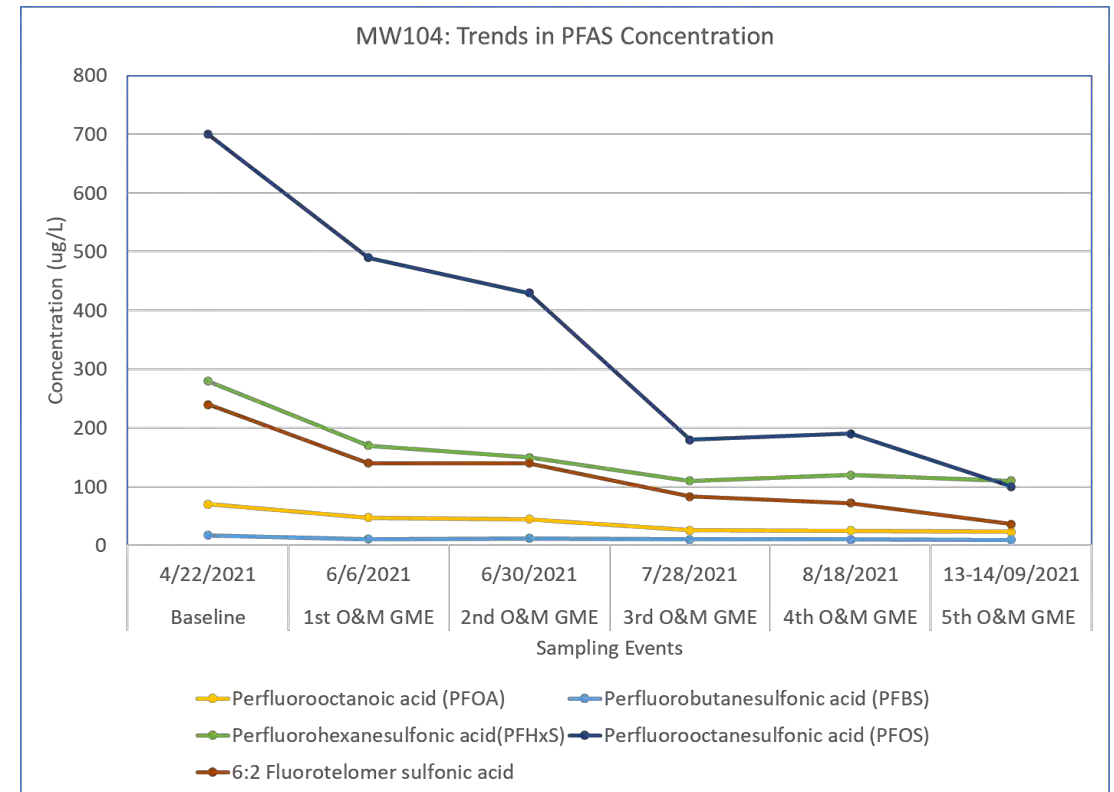
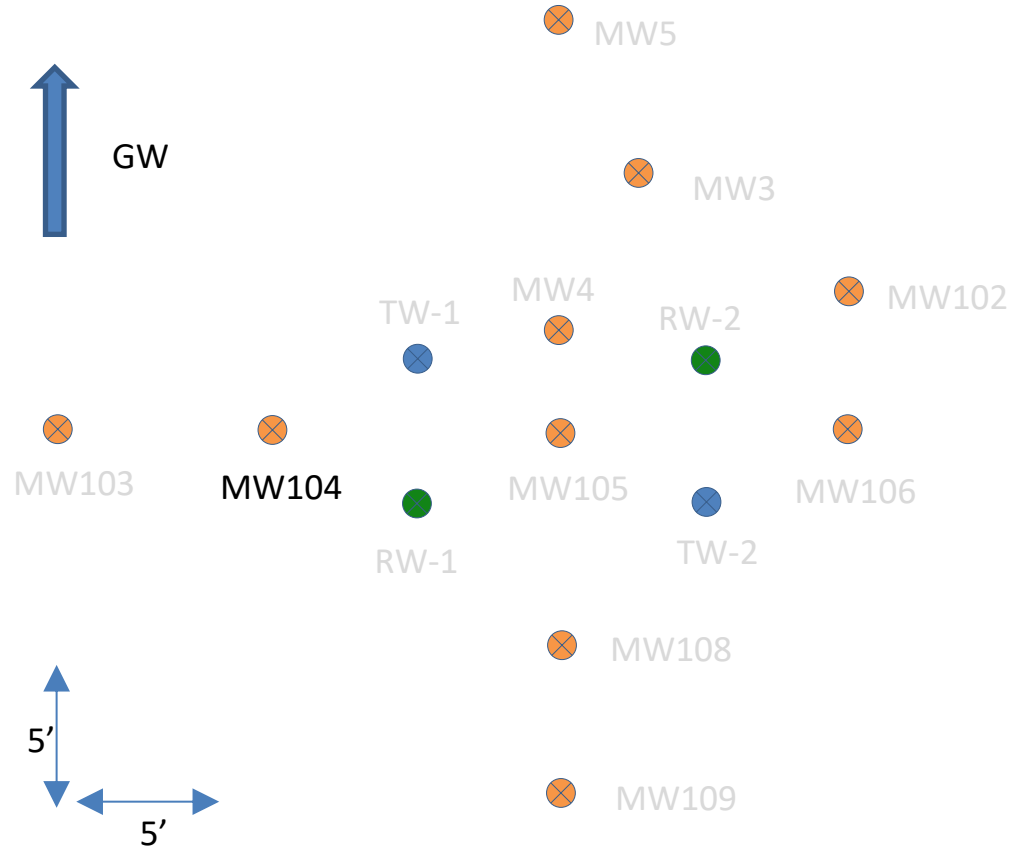
Foam Concentrations Removed from TW



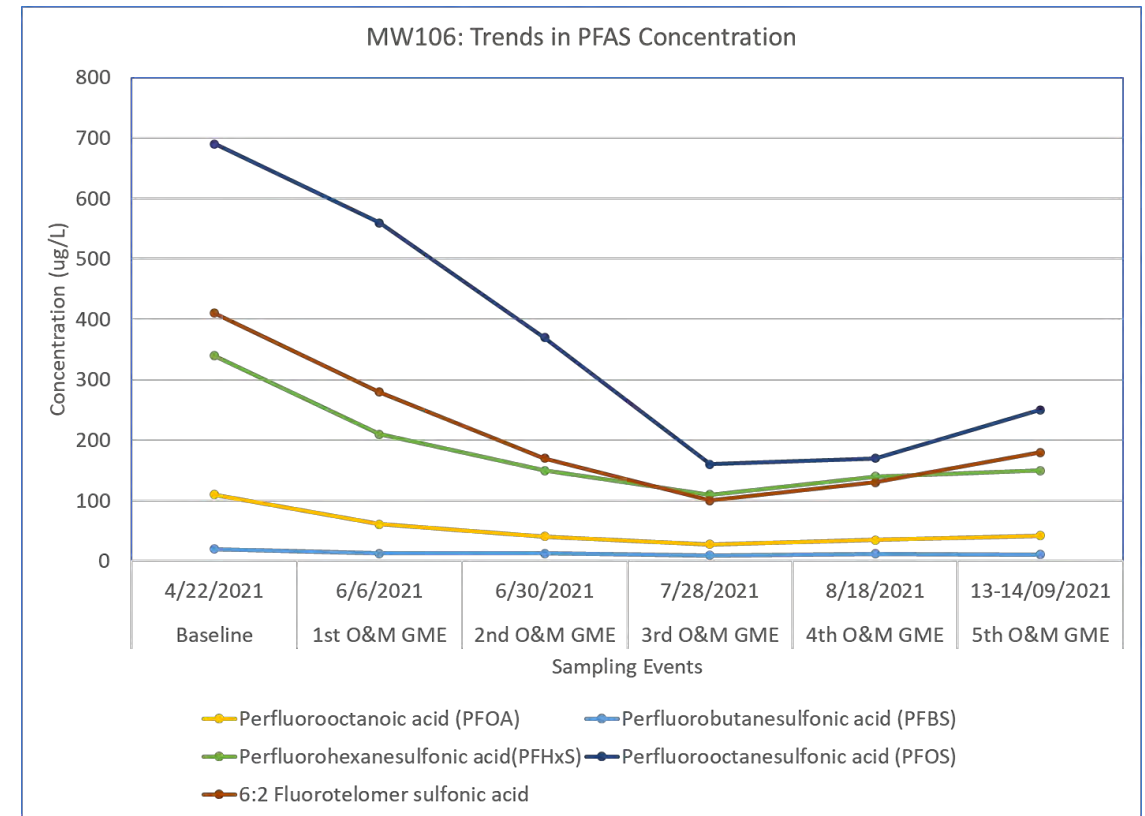
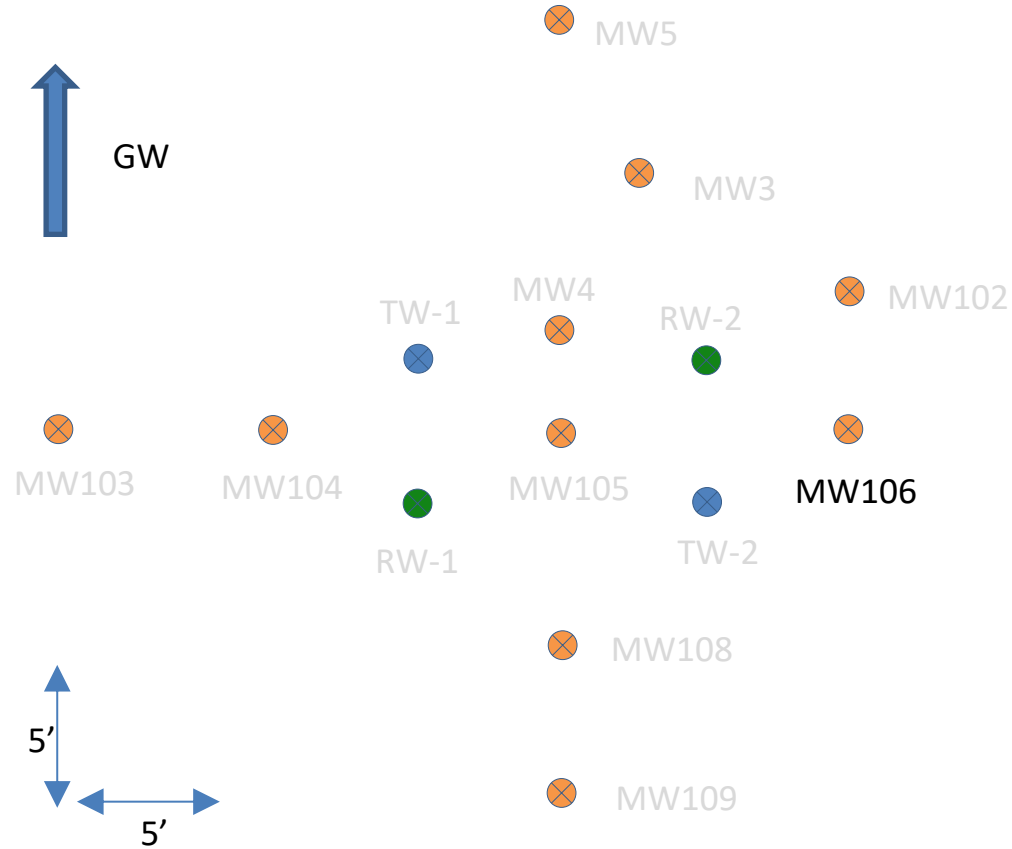
Results in Monitoring Wells



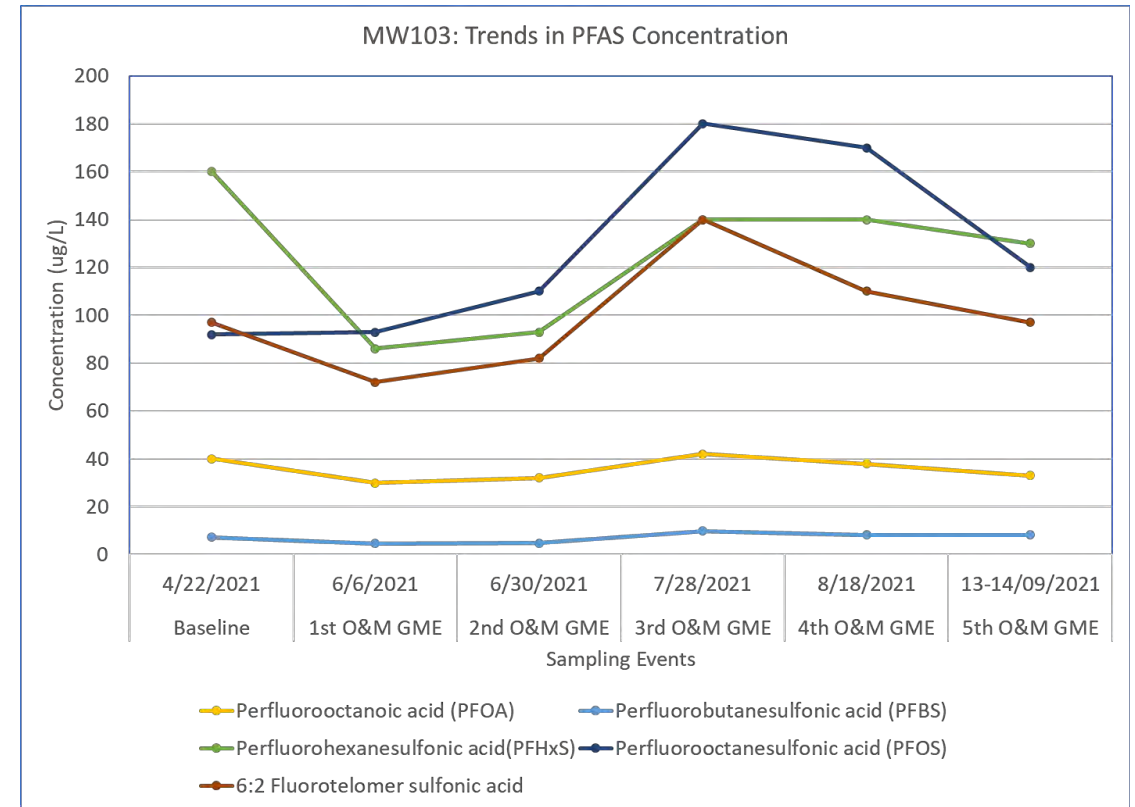
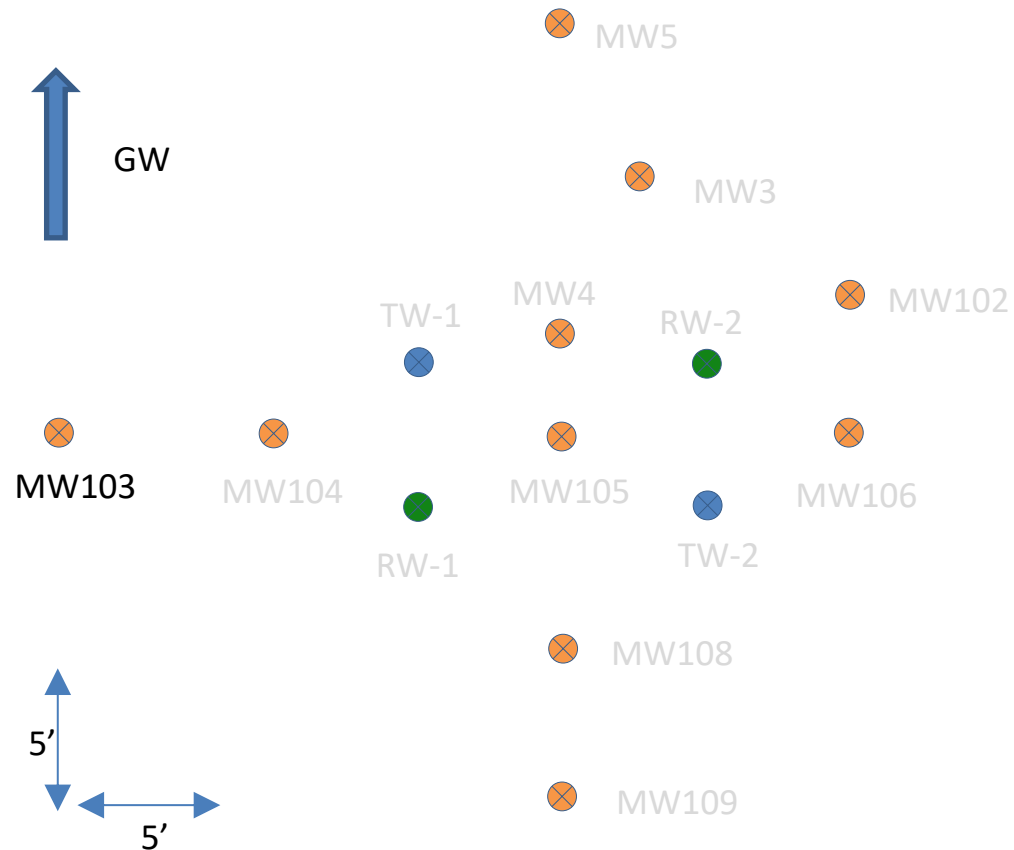
Results in Monitoring Wells



Results in Monitoring Wells



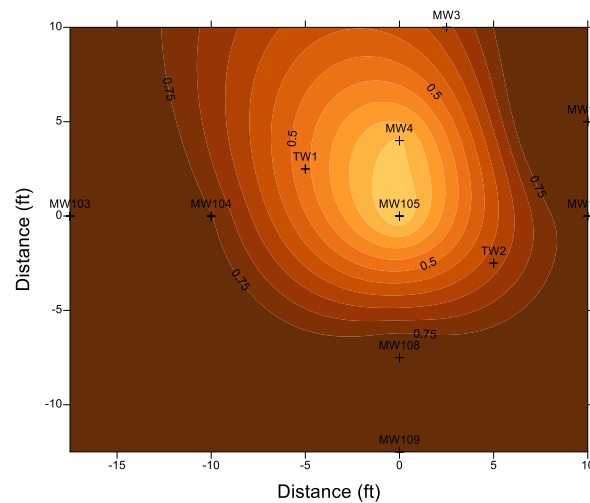
Results in Monitoring Wells



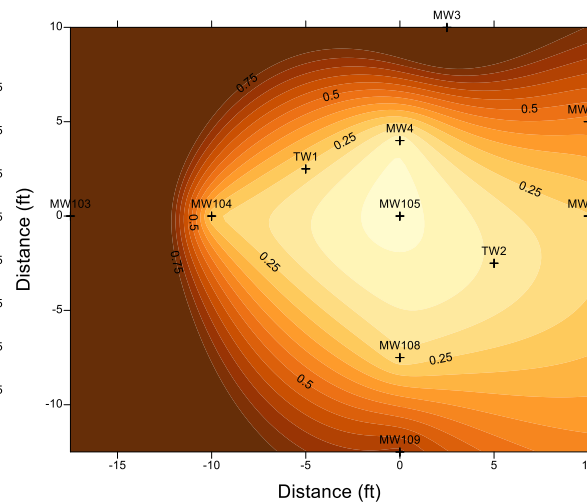
PFOS/PFOSo GME1, 3 and 5

[GMEx] / [Baseline]

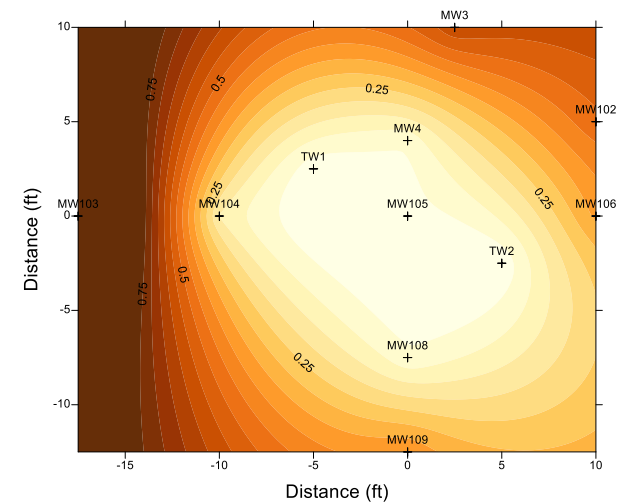
0.1 = 90% Reduction



GME 1



GME 3

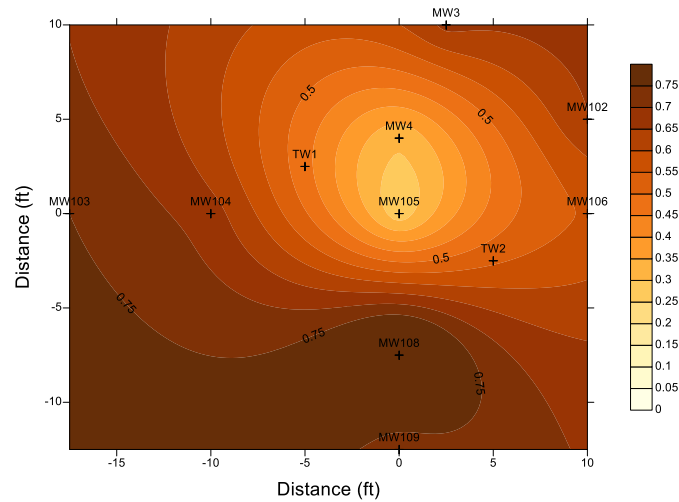


GME 5

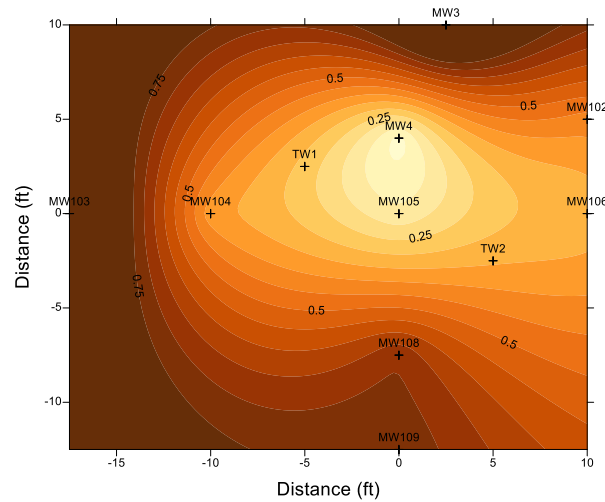
PFOA/PFOA_o GME 1, 3 and 5

[GMEx] / [Baseline]

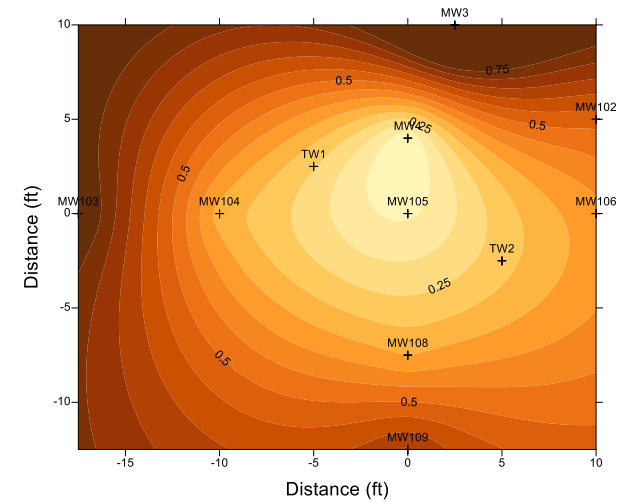
0.1 = 90% Reduction



GME 1

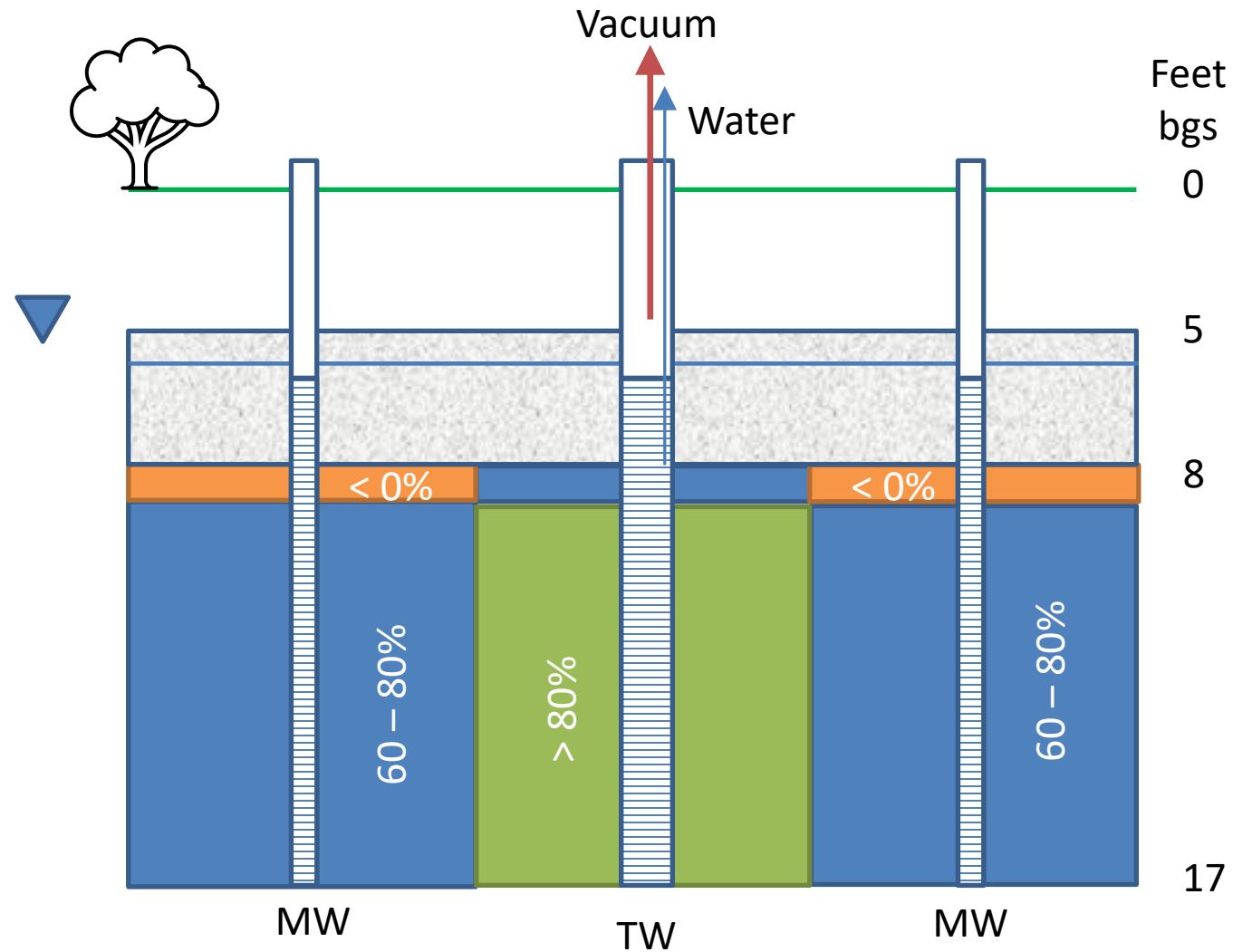


GME 3



GME 5

PFOS Reductions in Soil



PFAS Mass Removal

- Total PFAS mass removed (in product tank after 3 months of operation) = 107 g
- Total PFOS mass removed = 47 g
- Total PFOS mass (estimated from saturated soil and gw samples) from pilot test area = 54 g
- PFOS estimates indicate significant mass removal!

Conclusions

- PFAS reductions in groundwater ranged from 79 to 96%
- PFAS reductions in soil ranged from no change to 94%
- System was operating > 95% uptime by GME4
- Removed 107 g of total PFAS in 12 weeks with 2 treatment wells

Benefits to DoD

- D-FAS is a promising technology for in-situ PFAS removal
- Flexible technology to accommodate site-specific conditions
- Highly effective for PFAS source areas
- Not likely to get to drinking water levels
- Low impact, robust, cost-effective technology
- Easily scalable

Condensate Treatment Options

- Plasma arc
- Supercritical water oxidation (SCWO, Annihilator)
- Hydrothermal alkaline treatment technology (HALT). Subcritical temperature and pressure
- Electrochemical Oxidation (EO, DE-FLUORO)
- Photoactivated Reductive Defluorination PFAS Destruction (Inspired Solutions)

Recent Improvements

Laboratory Tests

	Units	Initial	Air	% Reduction	Nitrogen	% Reduction
Perfluorooctanoic acid (PFOA)	ug/L	1.30	0.88	32%	0.870	33%
Perfluorononanoic acid (PFNA)	ug/L	0.029	0.011	62%	0.015	48%
Perfluorooctanesulfonic acid (PFOS)	ug/L	0.26	0.080	69%	0.140	46%

	Units	Initial	Foaming Agent	% Reduction	Surfactant	% Reduction
Perfluorooctanoic acid (PFOA)	ug/L	1.30	0.076	94%	0.031	98%
Perfluorononanoic acid (PFNA)	ug/L	0.029	0.0021 U	99%	0.0021 U	99%
Perfluorooctanesulfonic acid (PFOS)	ug/L	0.26	0.0035 U	99%	0.0081	97%
U = Below detection limits						



Thank You



For additional information, please visit

[https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER19-5075/ER19-5075/\(language\)/eng-US](https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER19-5075/ER19-5075/(language)/eng-US)

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Air Force Civil Engineer Center



EradiFluor™ **An Innovative PFAS** **Destruction Technology**

John Xiong, Ph.D., P.E.
Haley Aldrich
February 2025

Acknowledgements



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Darrin Costantini
Rochester, NY



Prachi Jain, P.E.
Rochester, NY



Co-PI: Jinyong Liu, Ph.D.



Sarah Mass, P.E.
Denver, CO



Mike Calhoun, P.G., CHG
New York, NY



Elie Haddad, P.E.
San Jose, CA



Existing separation technologies leave behind concentrated waste

Conventional technology



Granular activated carbon

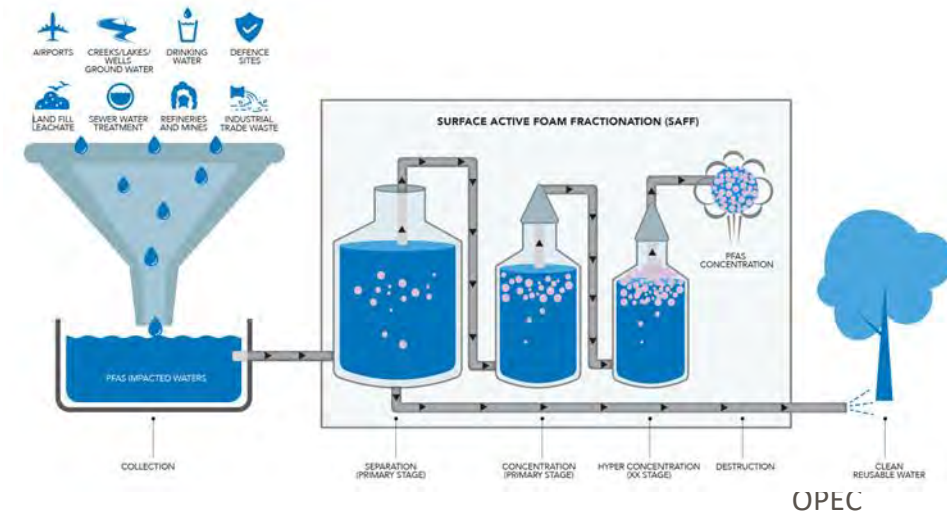


Membrane filtration



Ion exchange resin

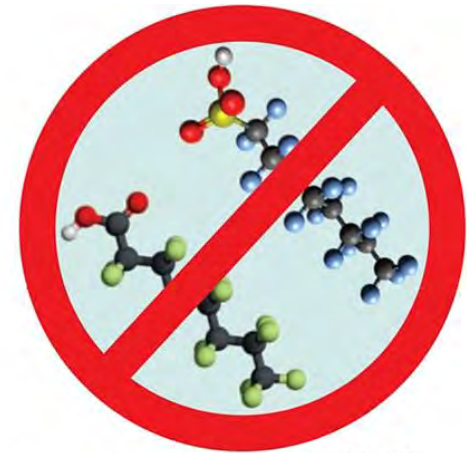
Recent developments



Foam fractionation

There is a growing need for destructive technologies

- Regulations on PFAS are evolving
- Several destructive technologies are under development, and some have moved to commercial application:
 - Supercritical water oxidation
 - Hydrothermal alkaline treatment
 - Electrochemical oxidation
 - Plasma technology
 - Electron beam



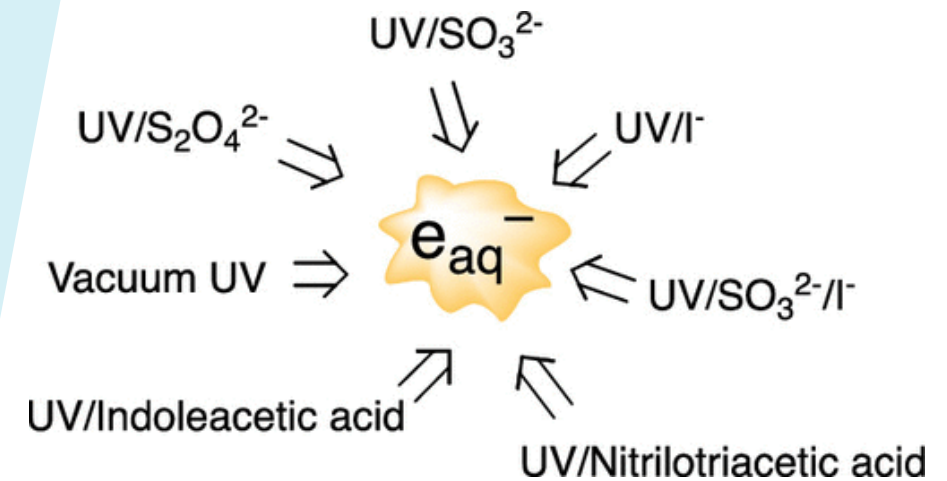
Innovative Ways to Destroy PFAS

PER- AND POLYFLUOROALKYL SUBSTANCES

EPA launched a technical challenge
for innovative ways to destroy PFAS in 2020

A new approach: UV-based advanced reduction process

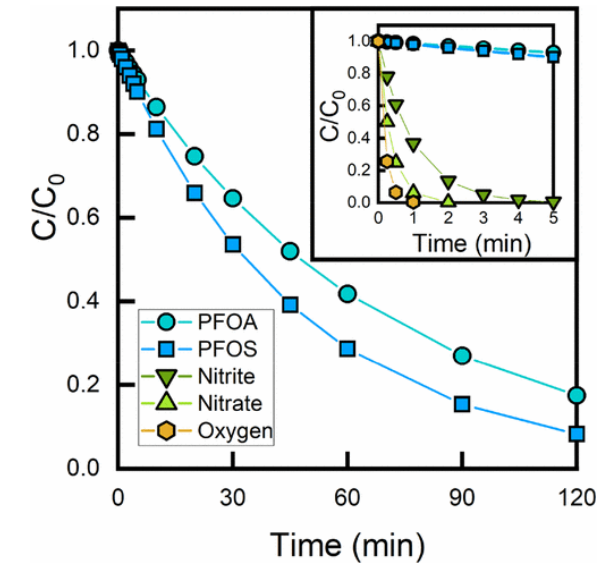
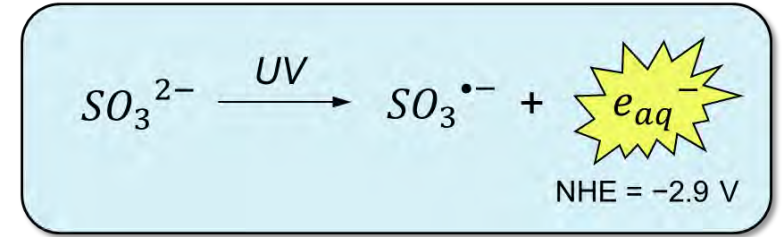
- This process is based on the production of highly reducing hydrated electrons, e_{aq}^-
 - Different from UV/H₂O₂ used in water treatment
 - e_{aq}^- is a strong reductant (standard potential = -2.9 V)
 - Key reactant for PFAS destruction by non-thermal plasma and electron beam
- e_{aq}^- can be generated under UV irradiation
 - Several ways to produce e_{aq}^-
 - As shown in the figure on the right



Source: Fennell et al., 2022

A new approach: UV-based advanced reduction process

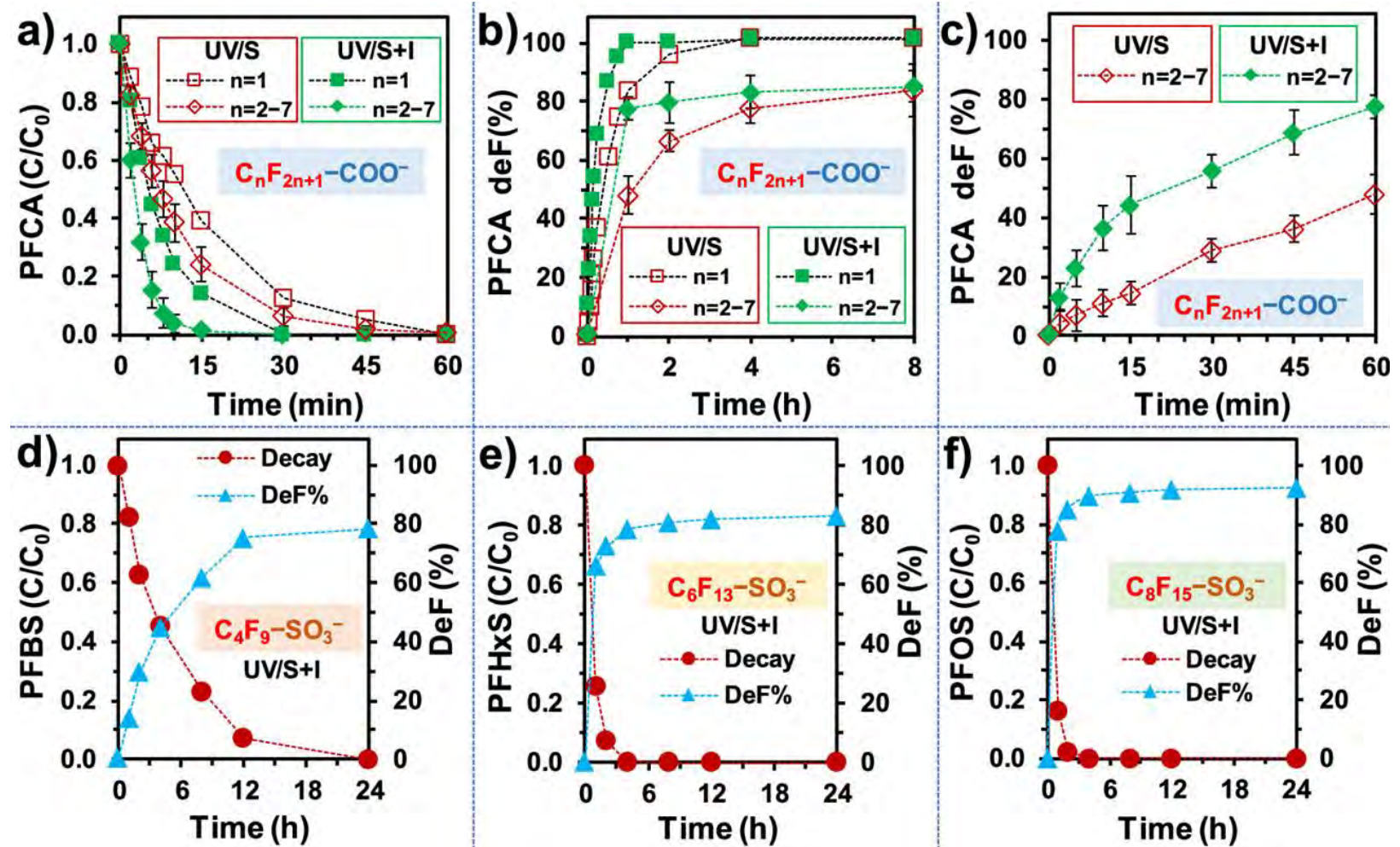
- e_{aq}^- break C-F bond and degrade PFAS compounds
 - Highly effective in PFAS destruction
- e_{aq}^- highly effective for treatment
 - Chlorinated solvents, perchlorate, bromate, nitrate, chromium (VI)
- Certain water constituents may scavenge e_{aq}^-
 - Oxygen
 - Nitrate/nitrite



Source: Fennell et al., 2022

Laboratory study results showed effective destruction of various PFAS

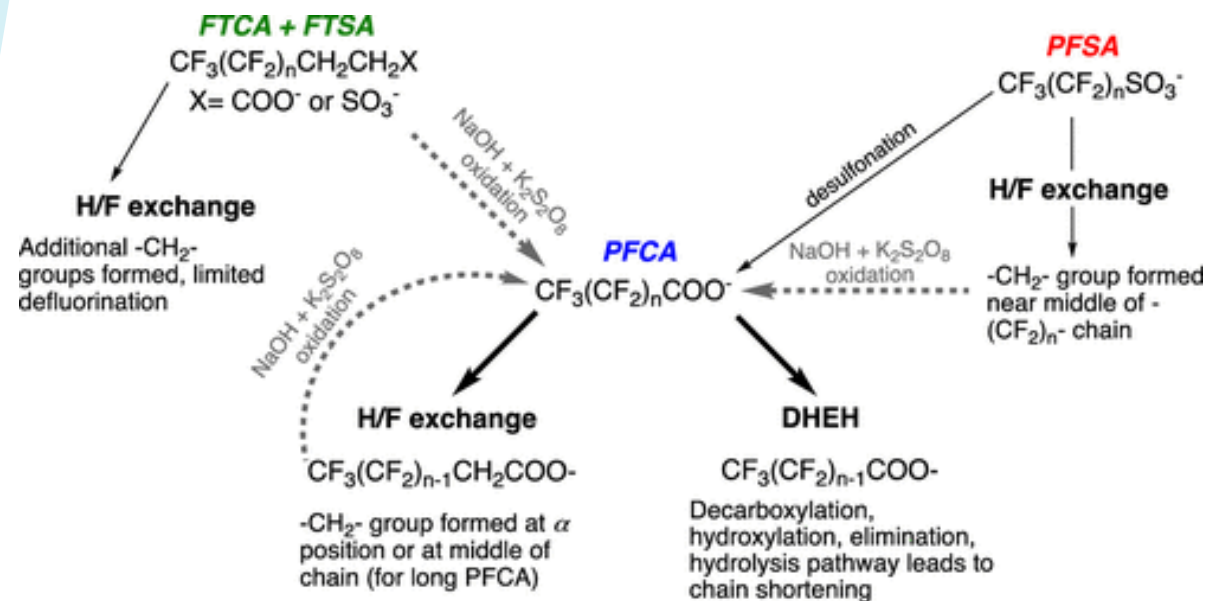
Source: Liu et al., 2022



Mechanism of PFAS destruction by hydrated electrons

- Two PFAS defluorination pathways are identified:
 - H/F atom exchange
 - CF₂- group to -CH₂- group
 - Produces polyfluorinated products
 - DHEH
 - Shorten one -CF₂- group each step
 - Deeper defluorination
 - Mostly occur to PFCAs

DHEH = Decarboxylation, hydroxylation, elimination, hydrolysis



Source: Fennell et al., 2022

EradiFluor - PFAS destruction system

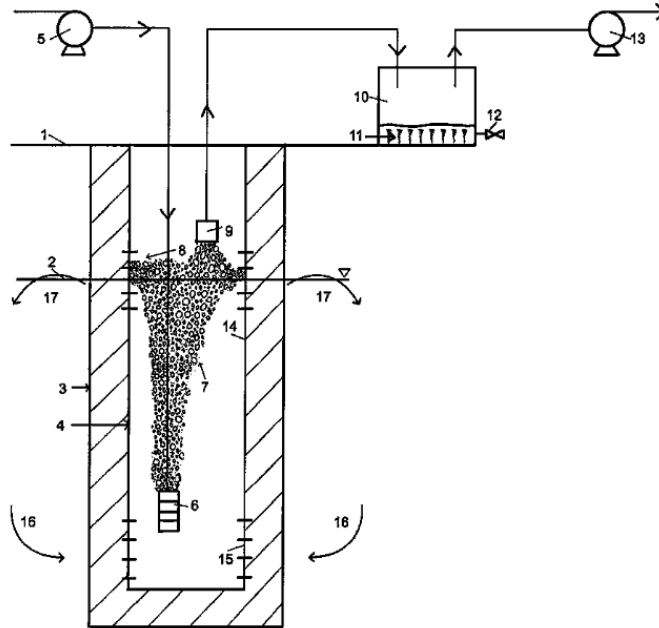
- A PFAS treatment system has recently been designed and constructed
 - UV/sulfite-based treatment process
 - Mobile, on-site treatment unit
 - Ambient reaction conditions
 - Control/monitoring components
- Concentrated PFAS streams to be treated under DoD field conditions



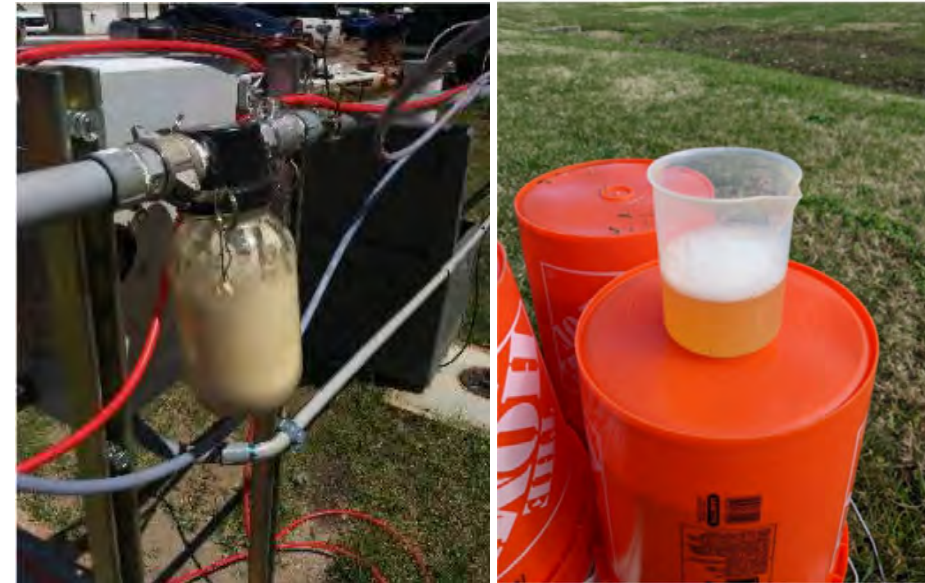
View from the rear of the trailer

Treatment of waste concentrate: in situ foam fractionation

- Foamate produced from an in situ foam fraction groundwater remediation system from a Navy site
 - Tens of ppm level of PFAS
 - PFOS and 6:2 FTS dominant
 - Low level of TOC and nitrate/nitrite

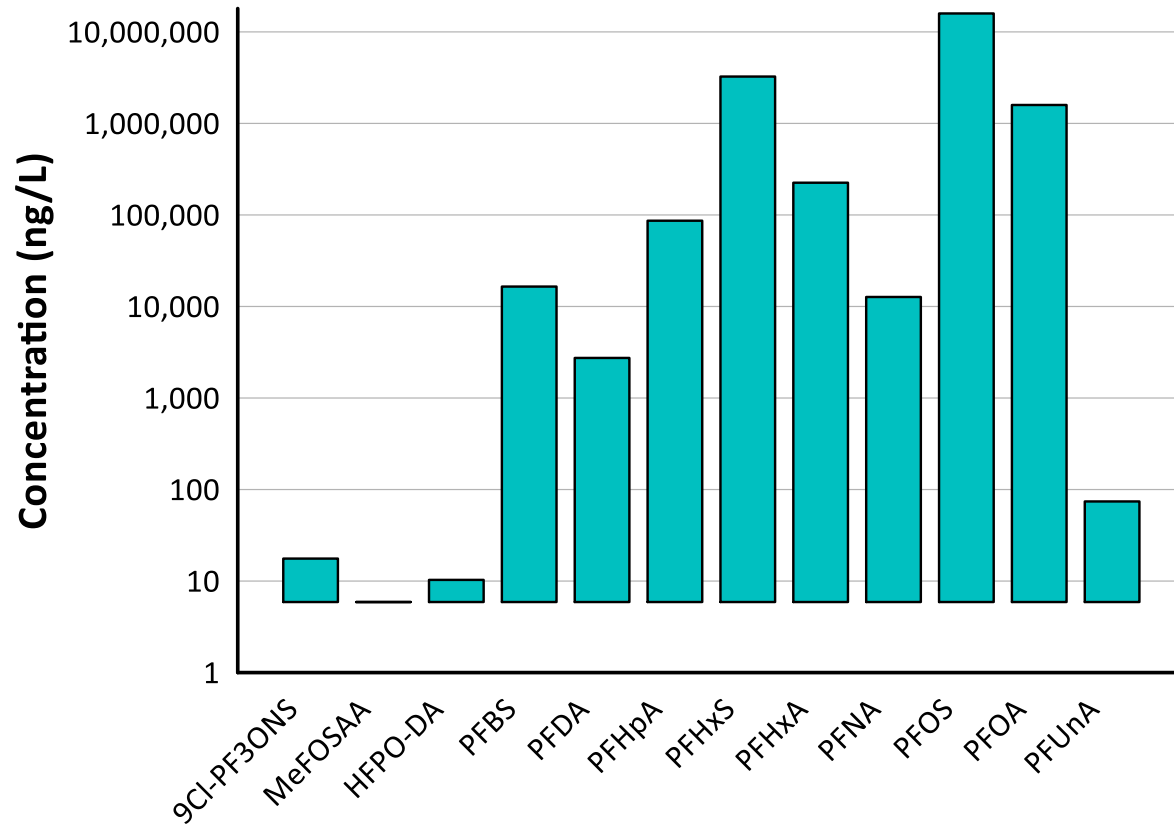


In situ foam fractionation system for groundwater remediation



PFAS concentrate produced from an in situ foam fractionation system for groundwater remediation (Source: Nelson 2022)

Constituents of the foam fractionate



Parameter	Concentration	Unit
Alkalinity	28.4	mg CaCO ₃ /L
Total Dissolved Solids	92	mg/L
Nitrogen, Nitrite	ND	mg/L
Nitrogen, Nitrate	ND	mg/L
Total Organic Carbon	16	mg/L
Sulfate	34.3	mg/L

Field demonstration at a Navy site

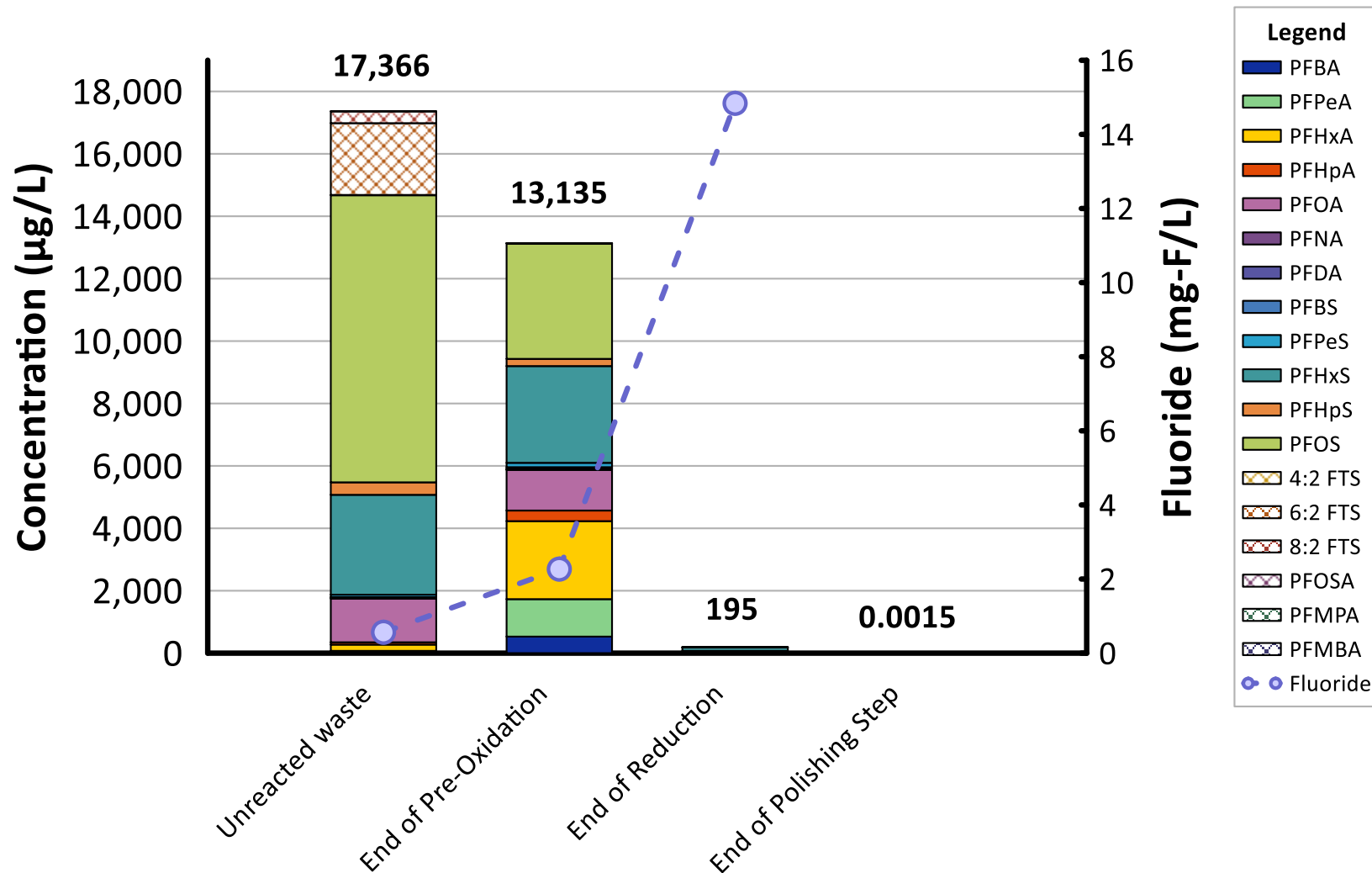
- Treatment system was mobilized to the site in summer 2024.
 - Simple setup
 - 24/7 operation
 - Ambient conditions
 - Near complete PFAS destruction



EradiFluor trailer was transported to the Navy site in the East Coast with a pickup truck.

EradiFluor system and a temporary tent was set up for the field demonstration

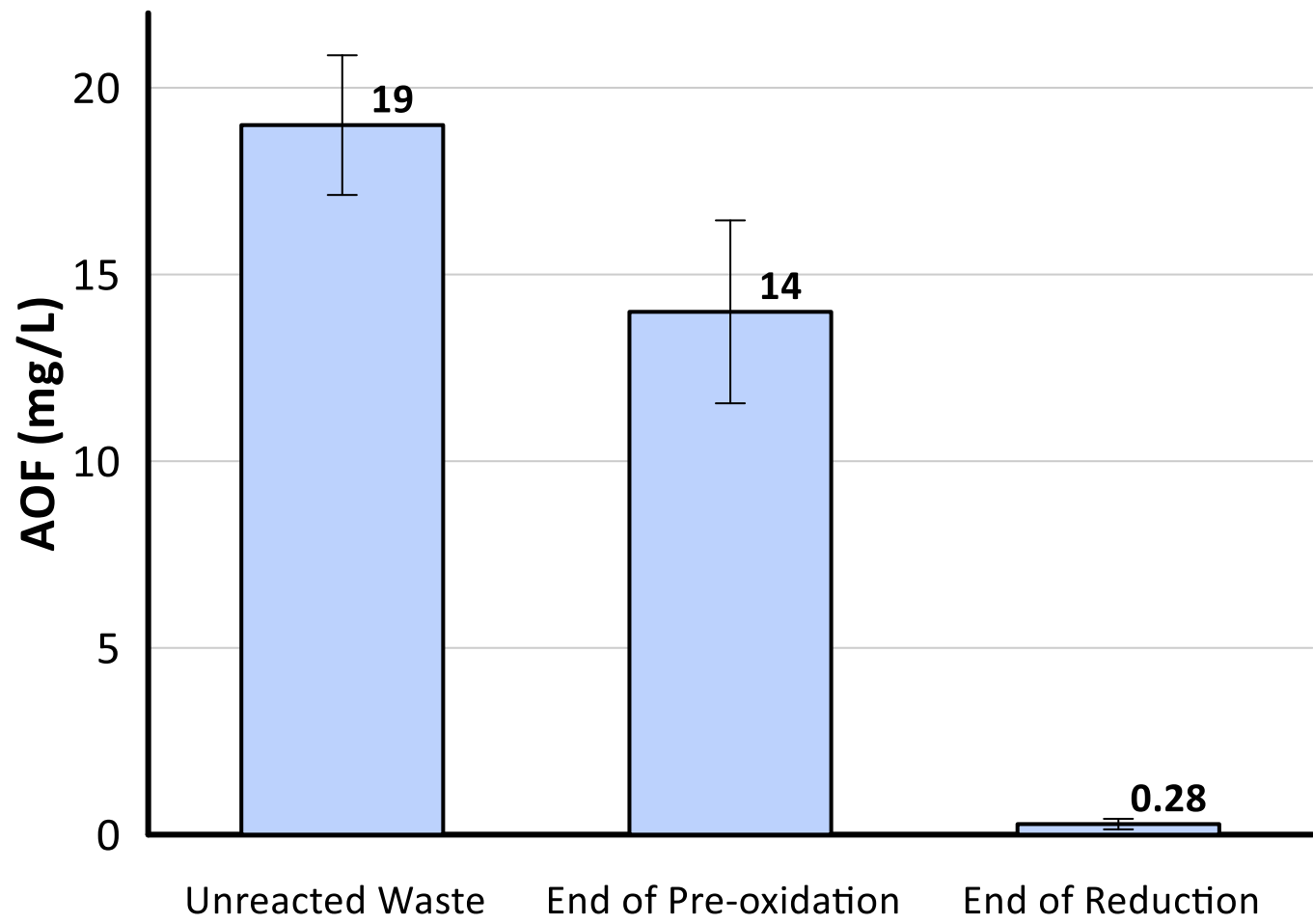
Field results show near-complete destruction of PFAS and removal of all PFAS



About 99 percent of PFAS were destroyed at the end of the reduction step.

After the polishing step, all residual PFAS were removed to the Not-Detect level, except one compound PFOS reported as 1.5 ng/L (below MCL of 4 ng/L).

Adsorbable organic fluorine results provided another proof of PFAS destruction



Average of multiple batches shows 98.5 percent of adsorbable organic fluorine (AOF) was destroyed after EradiFluor treatment. AOF combusts and measures carbon-sorbed PFAS and is an estimate of PFAS-associated fluorine mass.

Effective destruction of long- and short-chain PFAS

- Average of multiple batches shows > 99% destruction of most PFAS (short- and long-chain)
- PFBS showed slightly less destruction, but still effectively degraded

Destruction (%) (end of reduction)

Batch	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFBS	PFPeS	PFHxS	PFHpS	PFOS	4:2 FTS	6:2 FTS	8:2 FTS
1	> 99.8	> 99.99	99.96	> 99	> 99.98	> 98	> 99.7	> 99.98	> 99.4	> 99.99	> 97.2	> 99.98	> 99.9
2	99.9	99.8	99.8	> 99.9	99.8	94	99.8	99.8	99.7	99.7	99.6	99.9	99.9
3	99.98	99.96	99.99	> 99.6	> 99.998	95	> 99.98	99.99	99.98	99.97	99.7	99.99	99.97
4	99.98	99.9	99.99	> 99.99	> 99.997	92	> 99.98	99.996	99.98	99.97	99.5	99.997	> 99.99
5	99.9	99.95	99.96	> 99.96	99.99	66	98.7	99.96	99.98	99.9	98	99.99	99.1

Notes:

Destruction (%) = $100 \times [(C_{\max} - C_{\text{end of reduction}}) / C_{\max}]$

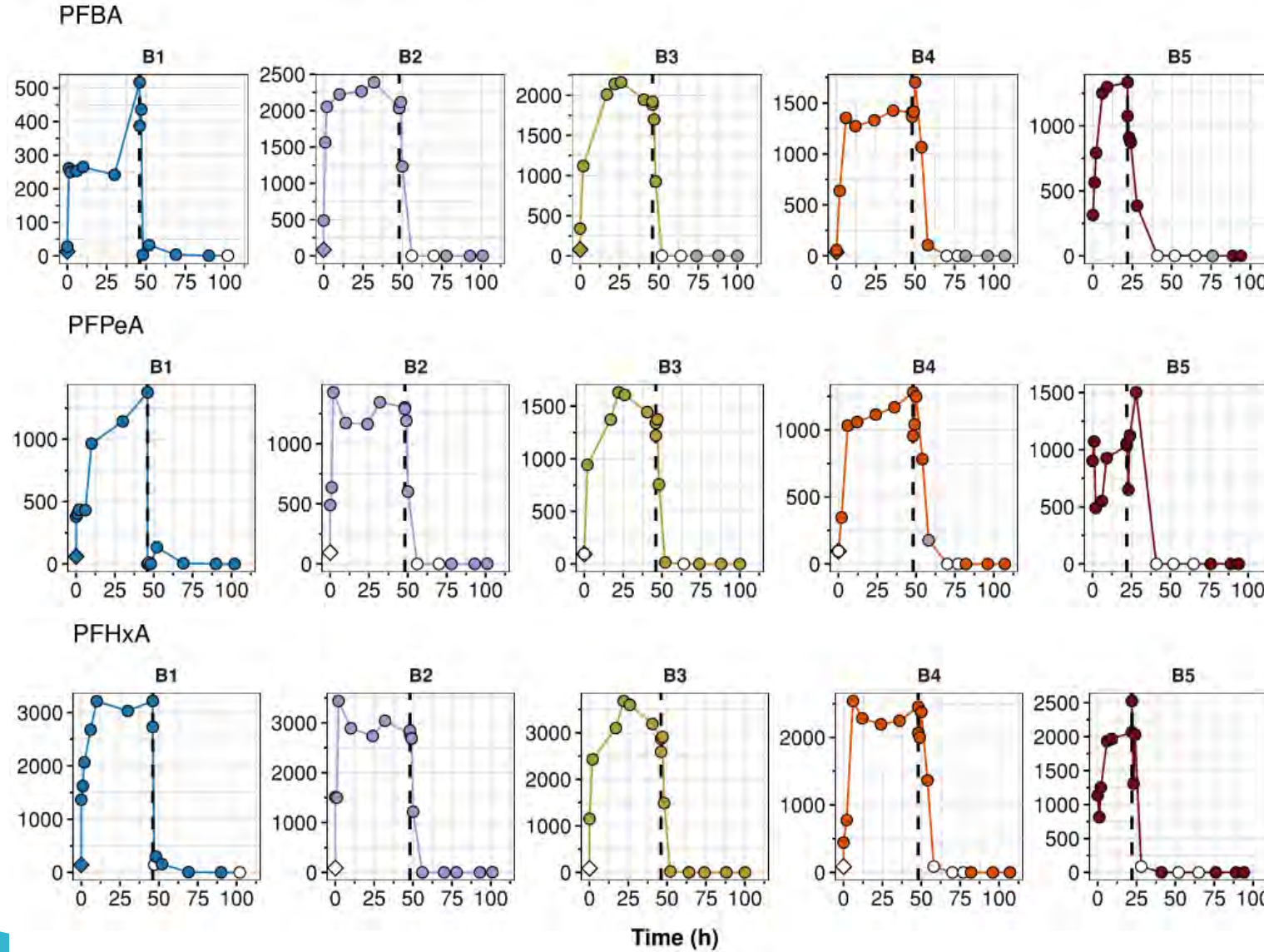
Calculation uses $C_{\max}$ (and not C_{initial}) since certain PFAS were generated during pre-oxidation step

Blue = $C_{\text{end of reduction}}$ was above the method detection limit, but below the reporting limit (i.e., J-flag estimated)

Purple = Outlier. Possibly due to operational adjustments in batch 5.

Effective destruction of short-chain PFAS

Concentration ($\mu\text{g/L}$)



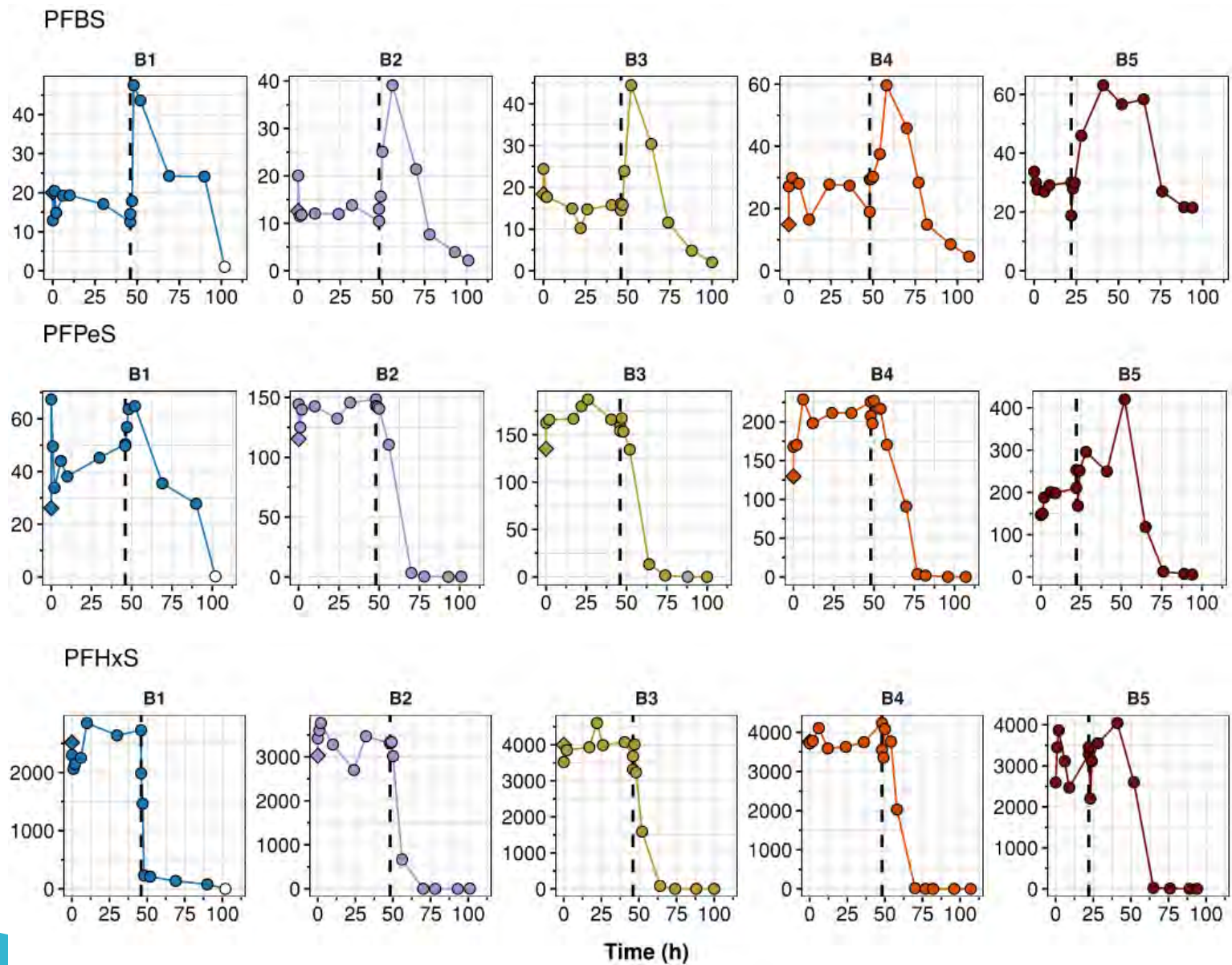
Detection

- B1 Detect
- B2 Detect
- B3 Detect
- B4 Detect
- B5 Detect
- Estimated
- Non-Detect

Sample Type

- ◆ Foamate
- Reaction

Effective destruction of short-chain PFAS (cont.)



Detection

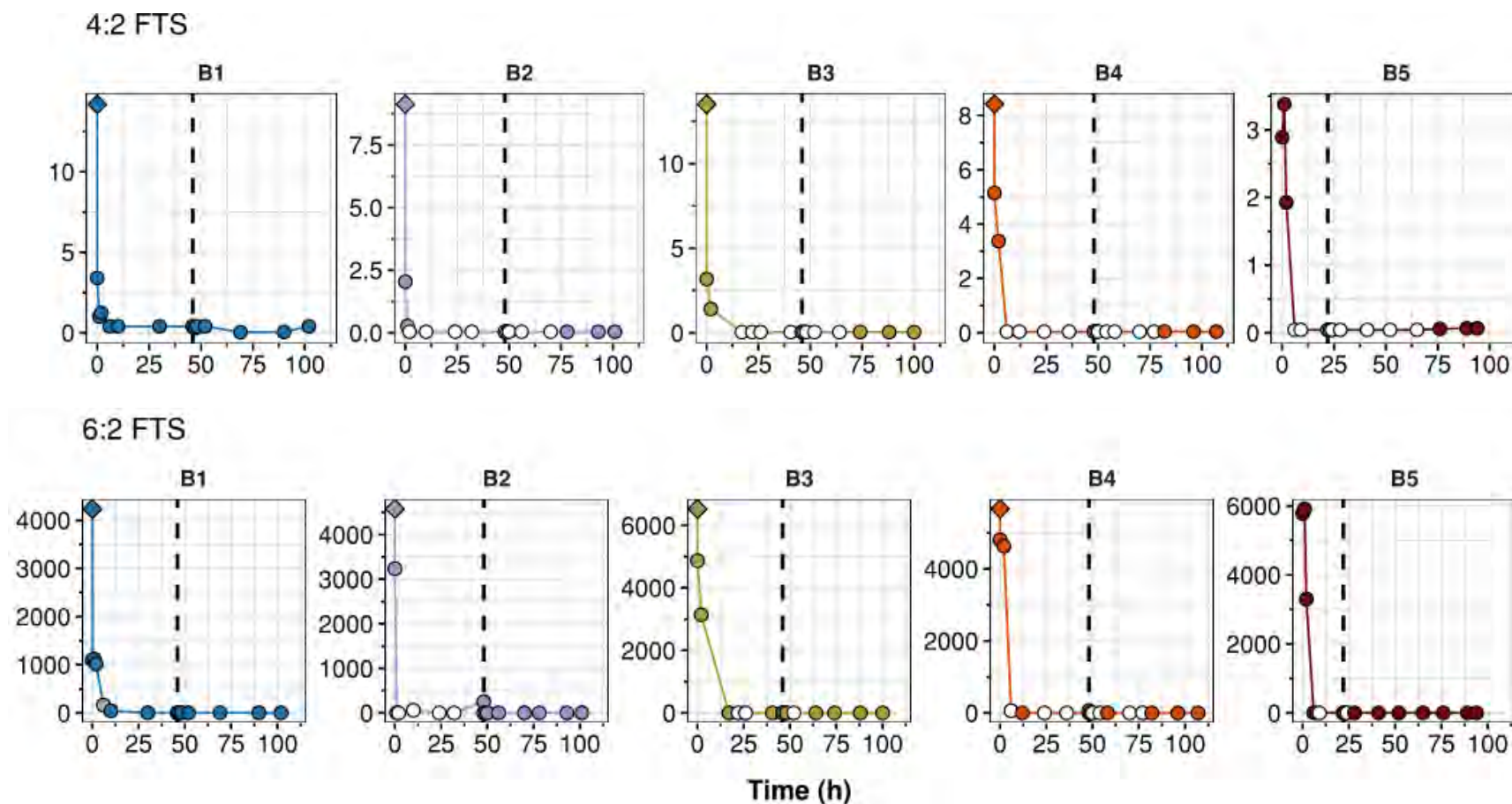
-  B1 Detect
 B2 Detect
 B3 Detect
 B4 Detect
 B5 Detect
 Estimated
 Non-Detect

Sample Type

- ◆ Foamate
● Reaction

Effective destruction of short-chain PFAS (cont.)

Concentration ($\mu\text{g/L}$)



Detection

- B1 Detect
- B2 Detect
- B3 Detect
- B4 Detect
- B5 Detect
- Estimated
- Non-Detect

Sample Type

- Foamate
- Reaction

Potential Byproducts Analysis

- EradiFluor **influent** and **effluent** samples were collected and analyzed for:
 - Total Arsenic (As), Arsenite (III, AsO_3^{3-}), Total Selenium (Se), Selenite (IV, SeO_3^{2-}), Nitrate (NO_3^-), and Nitrite (NO_2^-)
- Results suggest that no harmful byproducts was produced during PFAS destruction

	Metals Speciation				Nitrate/Nitrite	
Sample/Value	Arsenite (As(III)) ($\mu\text{g/L}$)	Selenite (Se) ($\mu\text{g/L}$)	As (total) ($\mu\text{g/L}$)	Se (total) ($\mu\text{g/L}$)	Nitrate (N) (mg/L)	Nitrite (N) (mg/L)
EPA MCL	10	50	10	50	10	1
Untreated Foamate (Destruction influent)	< 0.5	< 0.2	4.7	0.23	< 0.1	< 0.05
End of Reduction (Destruction effluent)	< 0.5	< 0.2	0.13	0.54	< 0.1	< 0.05

Methods

Total As, Se - EPA 1638

Arsenite – laboratory-specific method (EPA 1632 reference)

Selenite – laboratory-specific method

Nitrate/nitrite – EPA 353.2

Key Points

- A PFAS destruction system (EradiFluor) is constructed. PFAS destruction tests were conducted on simulated waste and real waste samples with effective destruction of various PFAS.
- Field demonstration was successfully conducted
 - 24/7 continuous operation
 - Ambient conditions
 - Effective destruction of long- and short-chain PFAS
 - Near-complete destruction was achieved based on
 - Target PFAS analysis
 - Fluoride generation
 - AOF analytical results
 - Polishing step (ion exchange) further removed residual PFAS

Comparison with other destructive technologies

Strength:

- Does not need special parts
- Low capital cost
- Operate under ambient pressure and temperature (and high pH)
- Low energy use and cost
- Safer operation
- High uptime (rarely shuts down)
- Performance not affected by salt

Limitation:

- Reaction time (to be applied along with concentration technologies)
- Color of liquid waste affects performance (pretreatment is required)

Questions?



John Xiong, Ph.D., P.E.

Principal

jxiong@haleyaldrich.com

Haley & Aldrich, Inc. | Costa Mesa, CA

Take-home messages

- Existing technologies produce concentrated PFAS waste
- **EradiFluor** effectively and reliably destroys PFAS



Find out more at:



<https://serdp-estcp.mil/projects/details/4c073623-e73e-4f07-a36d-e35c7acc75b6/er21-5152-project-overview>



<https://info.haleyaldrich.com/eradifluor>



Thank You



Questions?

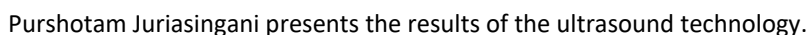


Your Success is Our Mission!



Ultrasound Technology for the Mineralization of PFAS

A field demonstration was conducted at Offutt Air Force Base where PFAS-impacted groundwater was pumped into a mobile ultrasound treatment trailer. Extracted groundwater was treated in the high frequency sonolysis reactors.



Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)



Webinar Structure



	<u>https://www.milsuite.mil/book/docs/DOC-1359625</u>
5 min	Welcome and Administrative Business
45 min	<i>Ultrasound Technology for Mineralization of PFAS</i> Purshotam Juriasingani – Tetra Tech
10 min	Questions and Answers
5 min	Final Thoughts

Air Force Civil Engineer Center



Ultrasound Technology for Mineralization of PFAS

BAA 2103

Purshotam Juriasingani, PE

Vice President, Technology Development-Emerging
Contaminants

Tetra Tech, Inc

March 2025



- Objectives
- Mechanism of Sonochemical Degradation of PFAS
- Laboratory Testing
- Pilot Testing
- Site Demonstration
- Remedy Performance and Optimization



Objectives



Objectives



Objectives



- Characterize the contaminated groundwater for PFAS, organics, and inorganics content and investigate the impact of these co-occurring species on sonolysis treatment efficiency.
- Fabricate the field treatment trailer and demonstrate the ultrasound technology at an Air Force site.
- Quantify the degradation efficiency.
- Quantify the fluorine mass balance to determine if PFAS has been mineralized.
- Evaluate and optimize critical technical parameters such as power density (Watts per Liter [W/L]) and residence time to achieve maximum degradation efficiency of PFAS.

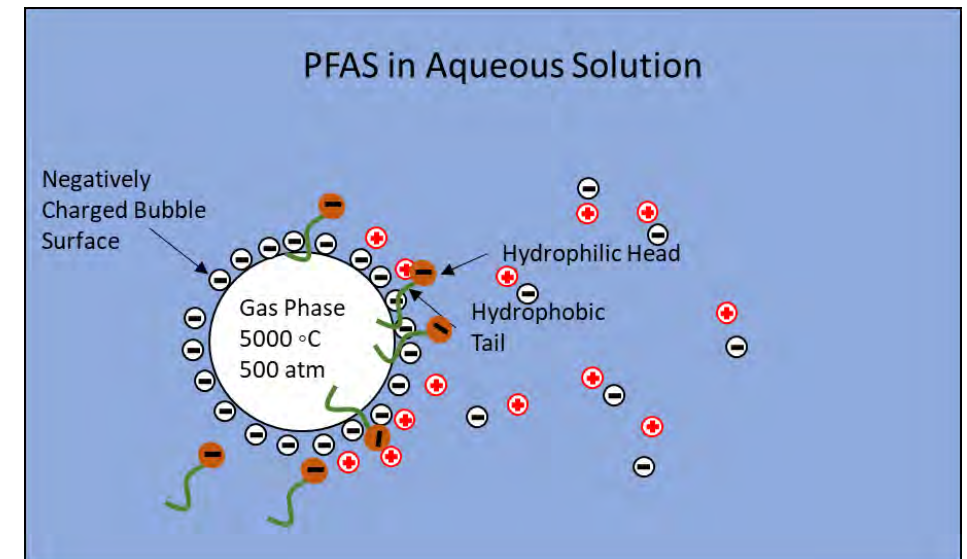
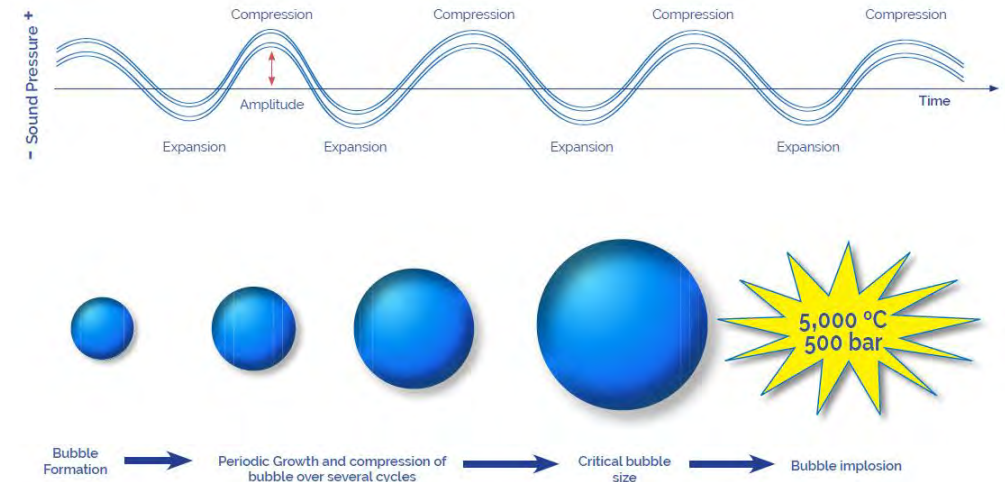


Mechanism of Sonochemical Degradation



Mechanism of Sonochemical Degradation

- PFAS are known to accumulate at interfaces and concentrate at the gas bubble–liquid interfacial region.
- Sound waves >19 kHz create cavities in liquids
- Cavities collapse at maximum radius creating extreme localized conditions
 - High heat
 - High pressure
- Cavity collapses
 - Cleaves bond between hydrophobic and hydrophilic portions of molecules
- PFAS destruction potentially attributed to high-temperature during bubble collapse.





Parameters Affecting Sonochemical Efficiency



Factors	Affecting Factors
Ultrasonic Factors	Applied frequency
	Input power/ Intensity
	Continuous and pulse irradiation
Transducer	Type of transducer (plate/horn)
	Transducer location/array
	Arrangement Method
Geometric factors	Reactor shape/ material
	Volume
	Mixing/aeration/internal structure
Experimental factors	Dissolve gases and ions
	Temperature, pressure, and pH
	Solution type
Contaminant Factors	Volatility/ hydrophobicity
	Molecular structures/ Weight
	Initial concentration
	Presence of multiple contaminants



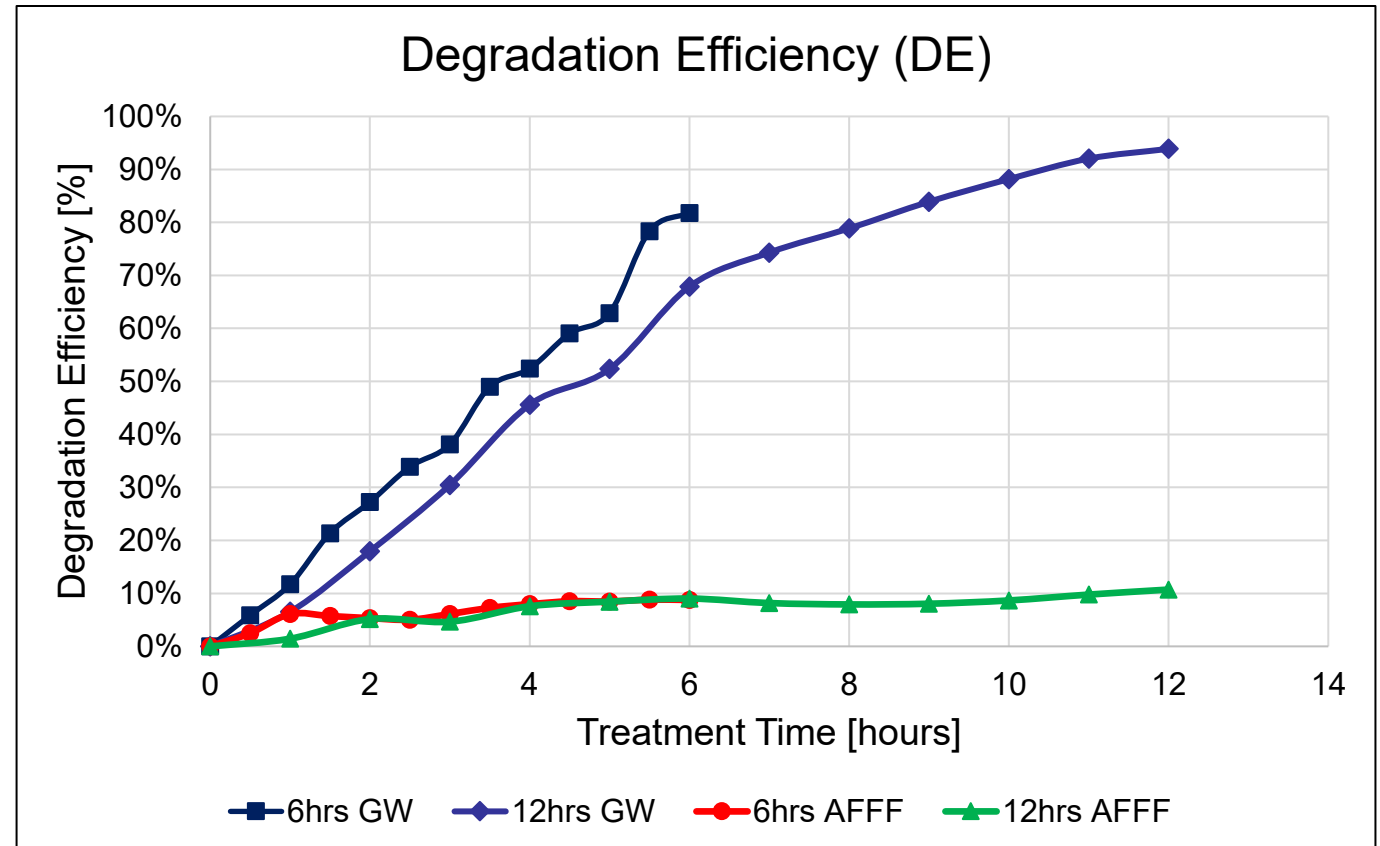
Laboratory Testing



Laboratory Testing (10 L Reactor)

PFAS Degradation Efficiency

- A 10 L multi-frequency ultrasonic reactor was designed, fabricated, and used to treat PFAS-impacted waste-streams.
- The PFAS degradation efficiency for GW was 82% in the 6-hour test and 94% in the 12-hour test.
- The PFAS degradation efficiency for AFFF was 9% in the 6-hour test and 11% in the 12-hour test.
- AFFF had the highest initial concentration of PFAS at 42 parts per million (ppm) compared to between 0.5 to 1 ppm for groundwater.
- Original sample concentration
 - GW - 0.5 to 1 ppm
 - AFFF - 8,700 ppm

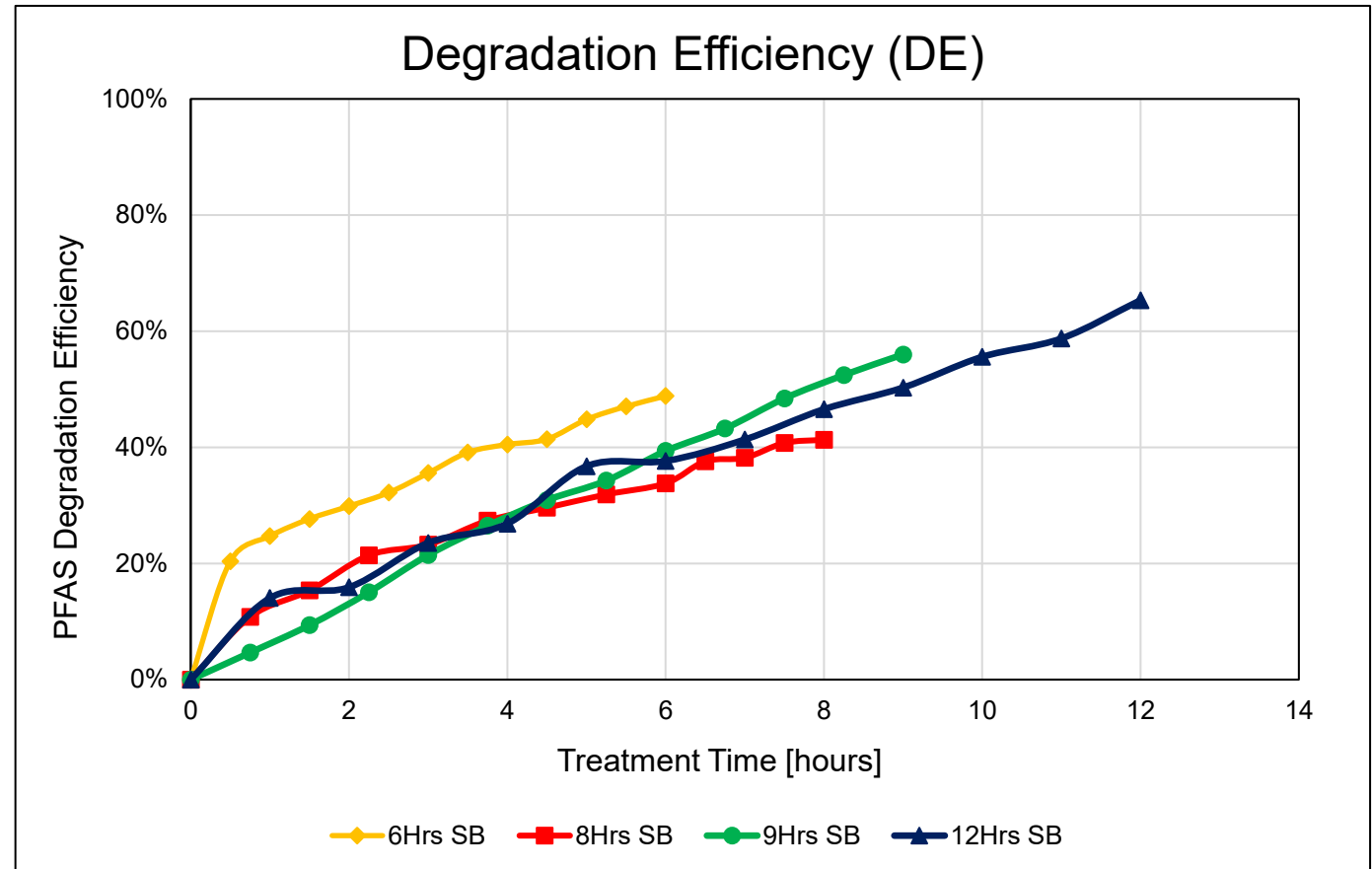


GW – Groundwater

AFFF – Aqueous Film Forming Foam

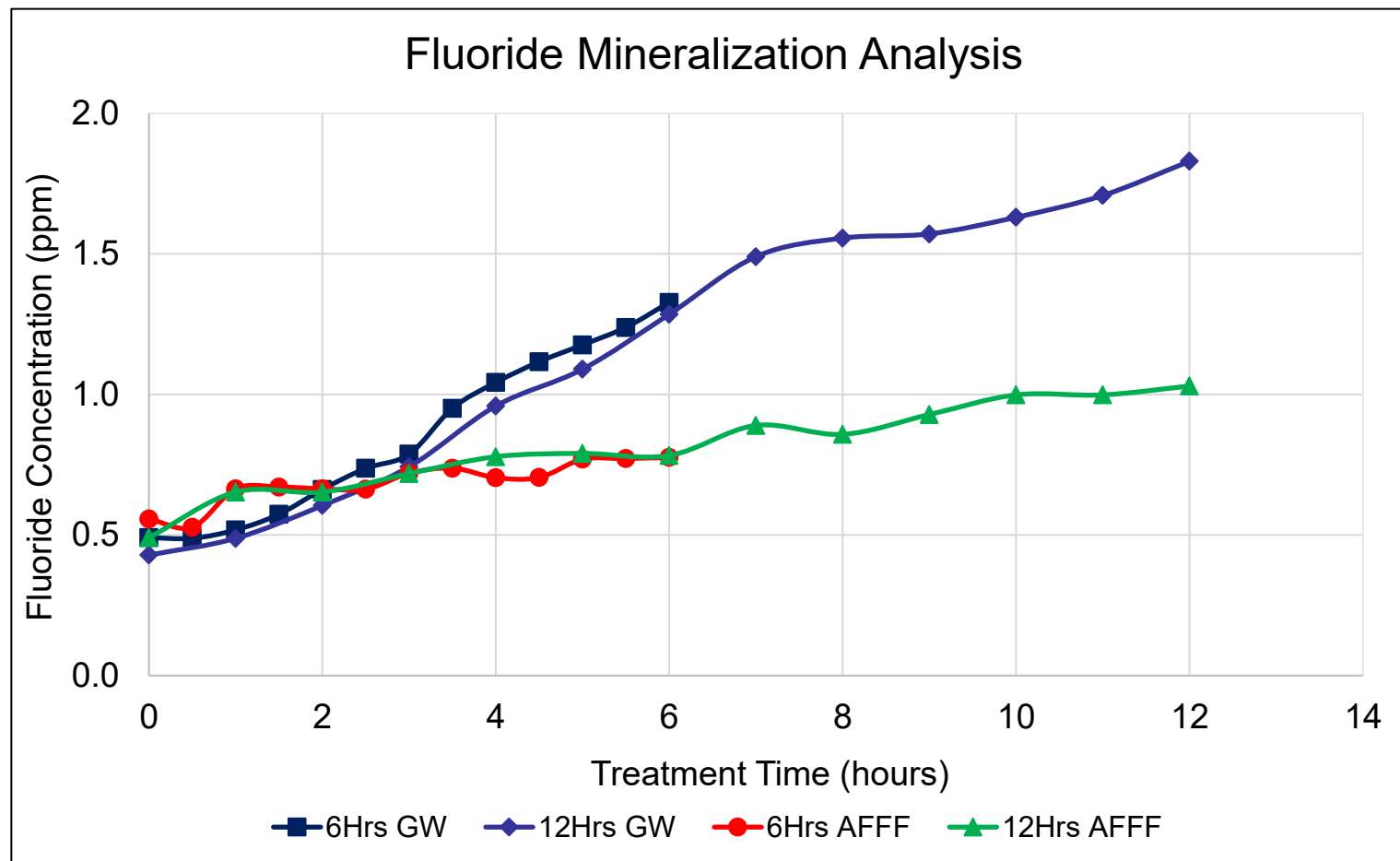
PFAS Degradation Efficiency

- The PFAS degradation efficiency for SB was 49% in the 6-hour test, 41% in the 8-hour test, 56% in the 9-hour test, and 65% in the 12-hour test.
- Original sample concentration
 - SB-600 ppm
- The initial concentration of the SB sample was diluted to 18 ppm for 6 and 8 hours of treatment and 12 ppm for 9 and 12 hours of treatment.



SB – Still bottoms

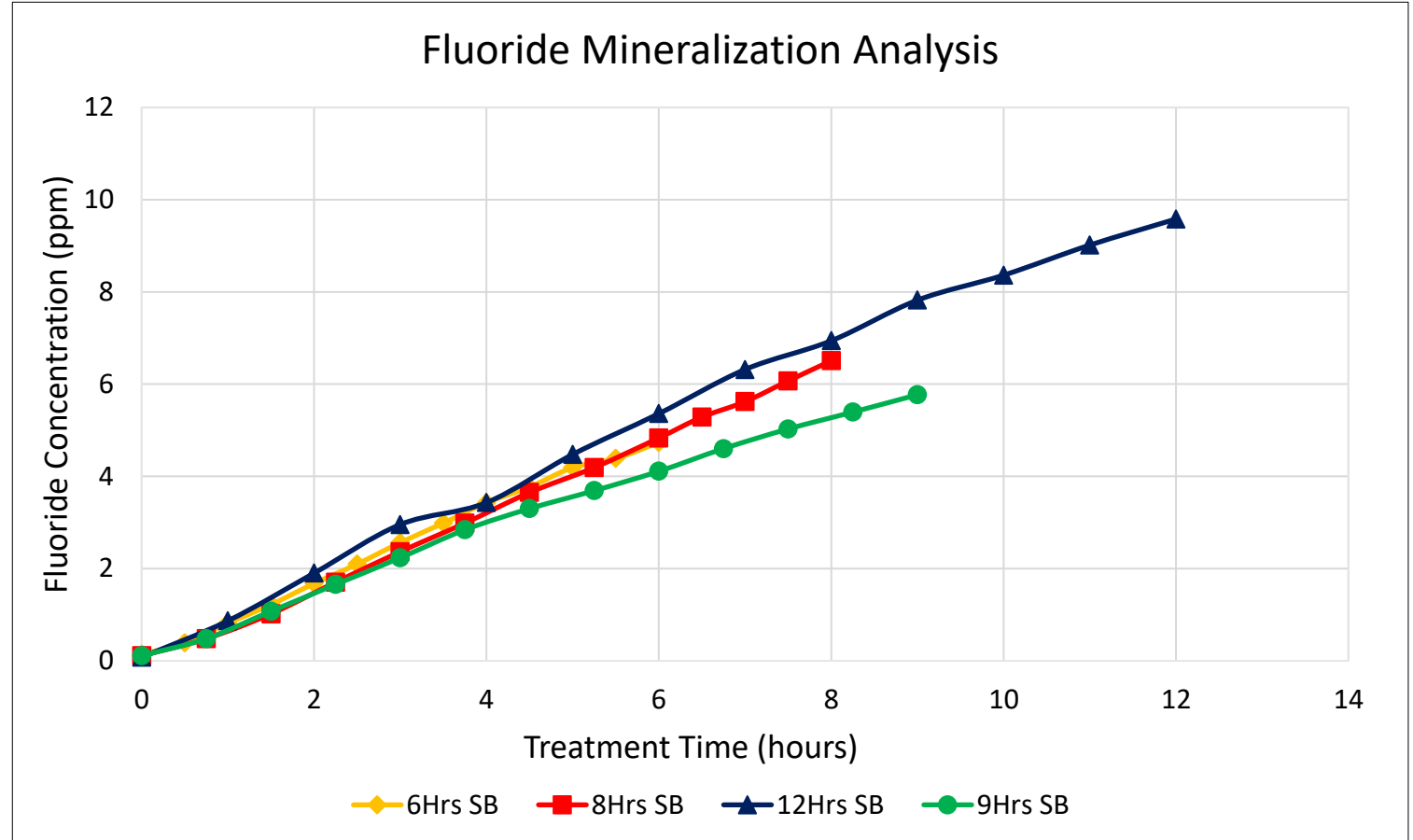
- The purpose of fluoride analysis was to gather evidence that the PFAS destroyed was completely mineralized without the formation of byproducts.
- In GW, lower initial concentrations could result in low fluoride increases during mineralization. For AFFF, the lower degradation efficiency and matrix complexity could explain the low fluoride concentrations compared to the high initial PFAS concentrations.



GW – Groundwater

AFFF – Aqueous Film Forming Foam

- Each test demonstrated similar rates of PFAS mineralization for Still Bottoms.



SB – Still bottoms



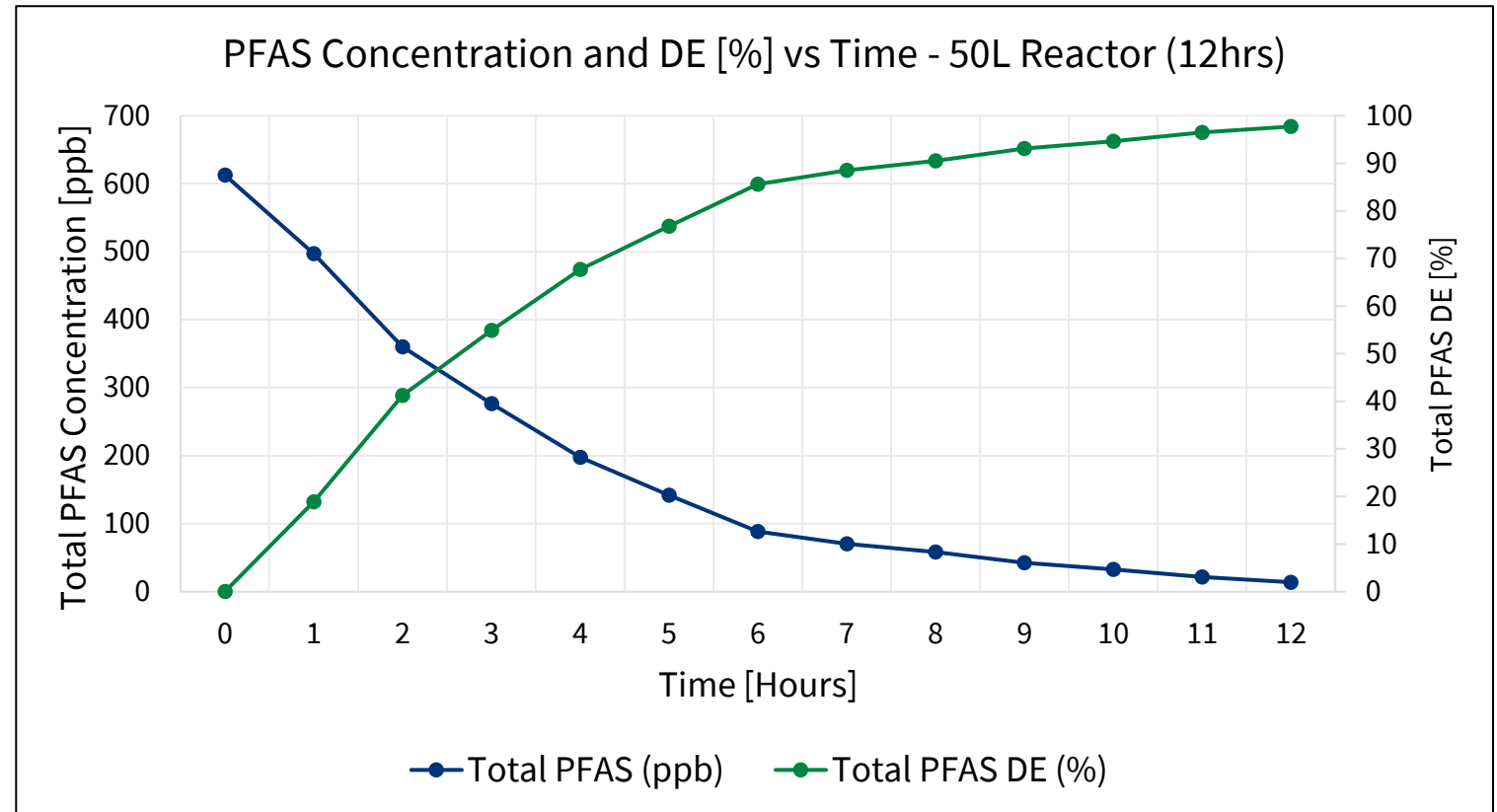
Pilot Testing (50 L Reactor)



PFAS Degradation Efficiency 50 L Reactor



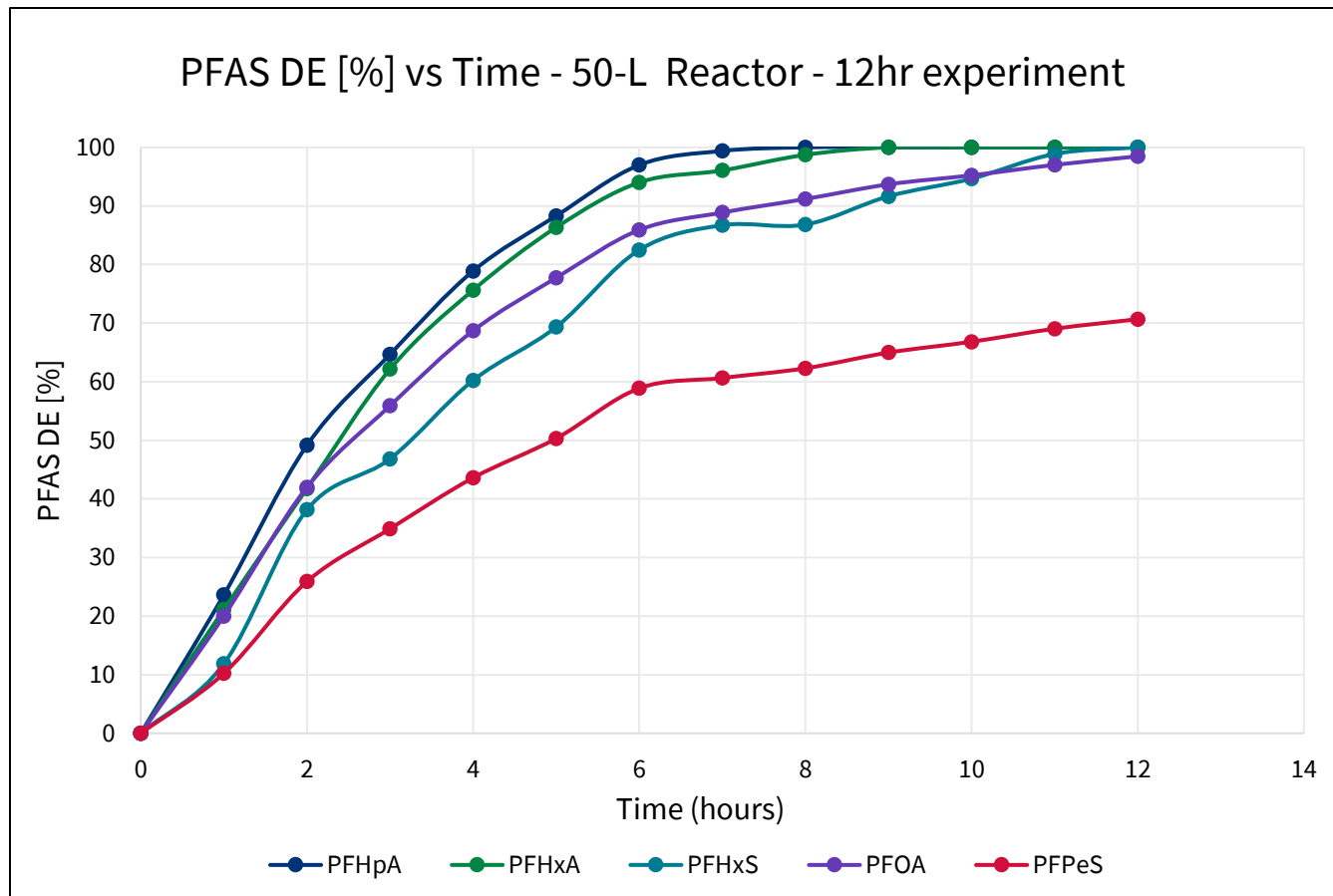
- Initial testing of a 50 L reactor was conducted on the mineralization of PFAS on GW.
- A 97.7% reduction in PFAS was achieved.
- Initial PFAS concentrations was approximately 0.6 ppm.



GW – Groundwater

PFAS Degradation Efficiency 50 L Reactor

- It was observed that shorter-chain PFAS such as PFPeS had a lower degradation efficiency when compared to longer-chain PFAS.
- Based on the results of the treatability study, the 50-L reactor system was optimized, and a treatment trailer was constructed.



GW – Groundwater



Site Demonstration

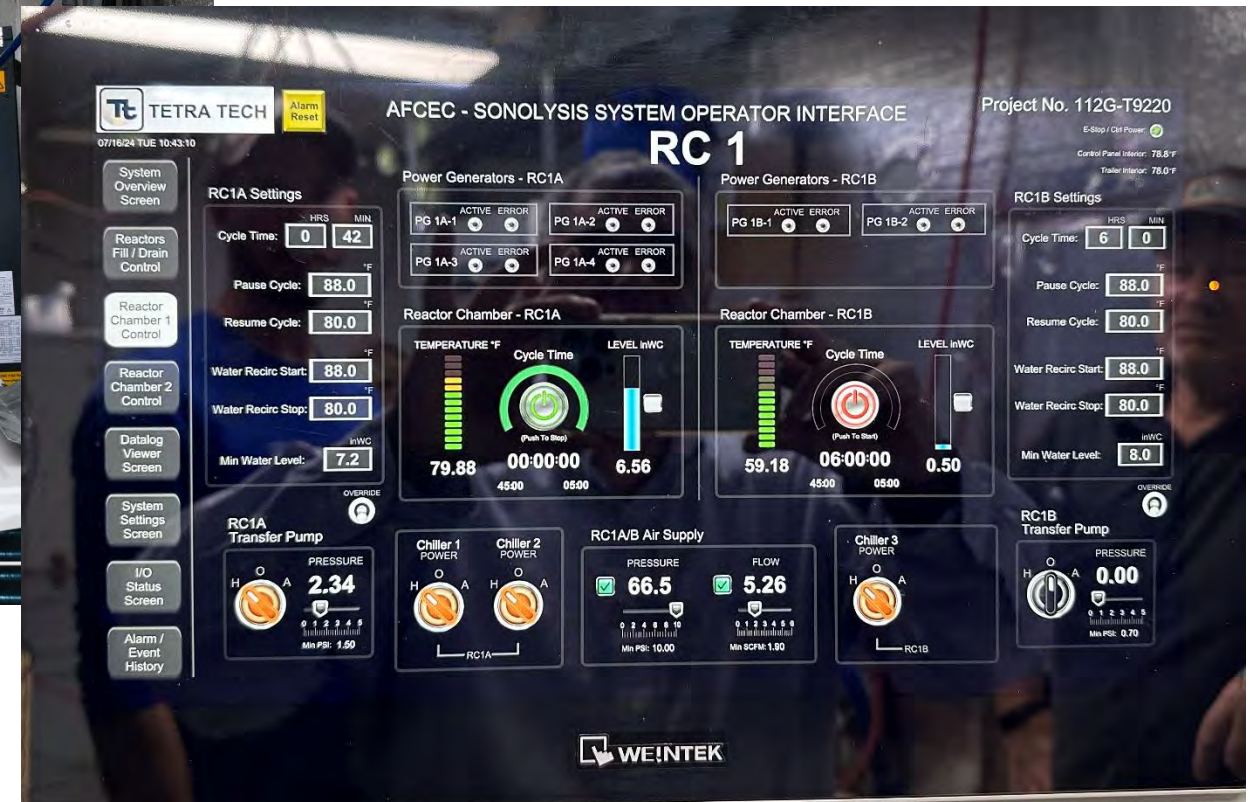


Site Demonstration



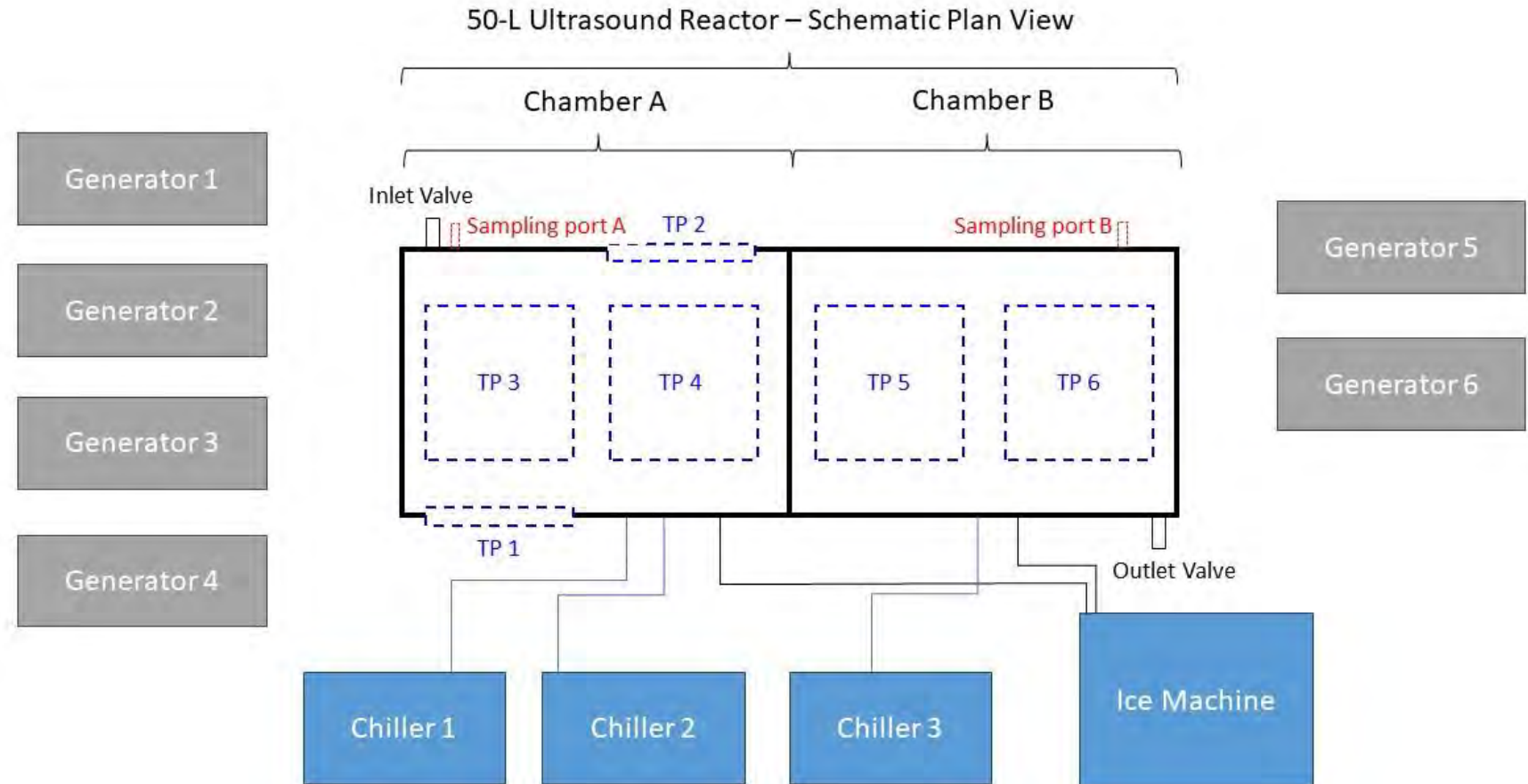
Offutt Air Force Base



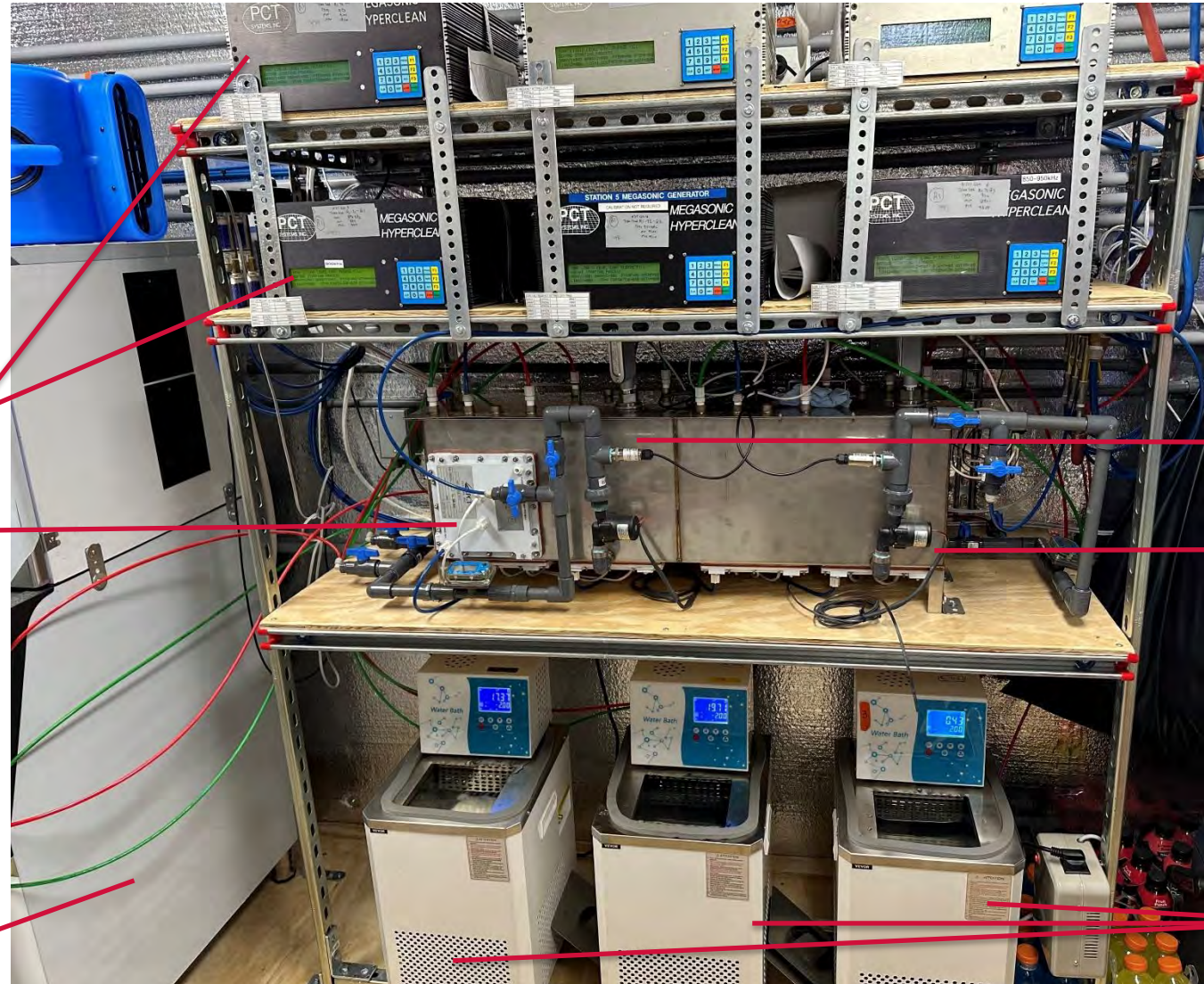


Intermediate scale (50-L) Multi-Frequency Ultrasonic Reactor

- Influent was treated for 12 hours total
- Influent was first treated in Chamber A for six hours (4 transducers)
- Water was pumped to Chamber B and treated for six hours (2 transducers)



Intermediate scale (50 L) Multi-Frequency Ultrasonic Reactor



Generators

Transducer Plate

Ice Machine

Reactor Chamber A

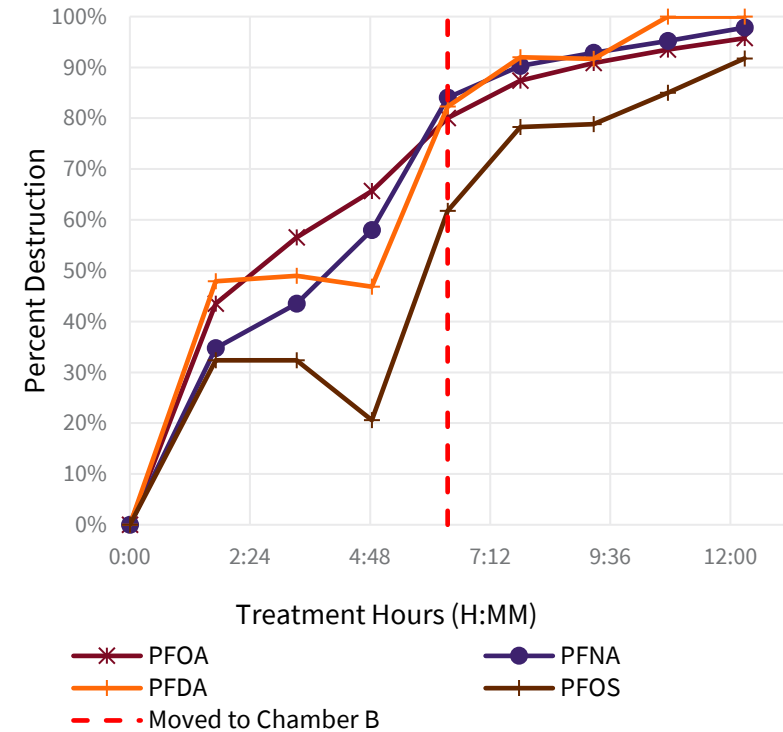
Reactor Chamber B

Chillers

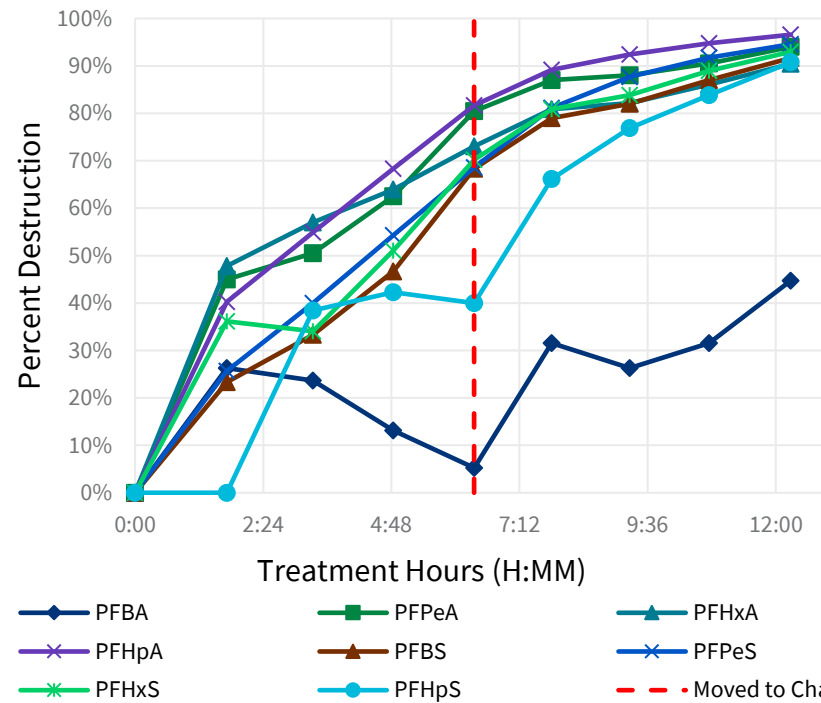


PFAS Maximum Percent Destruction

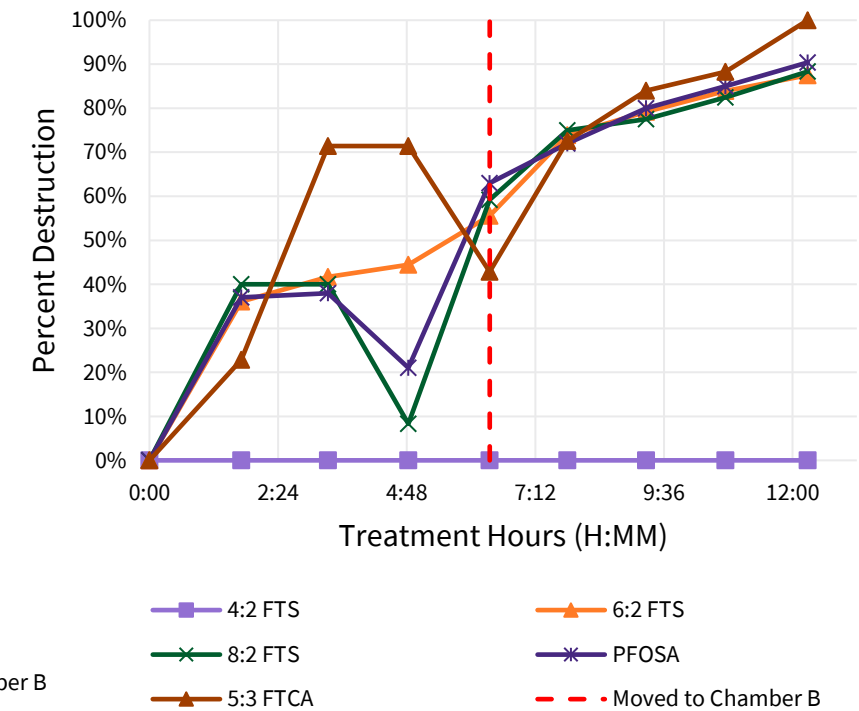
Percent Destruction of Long-Chain PFAS



Percent Destruction of Short-Chain PFAS



Percent Destruction of PFAS Pre-cursors



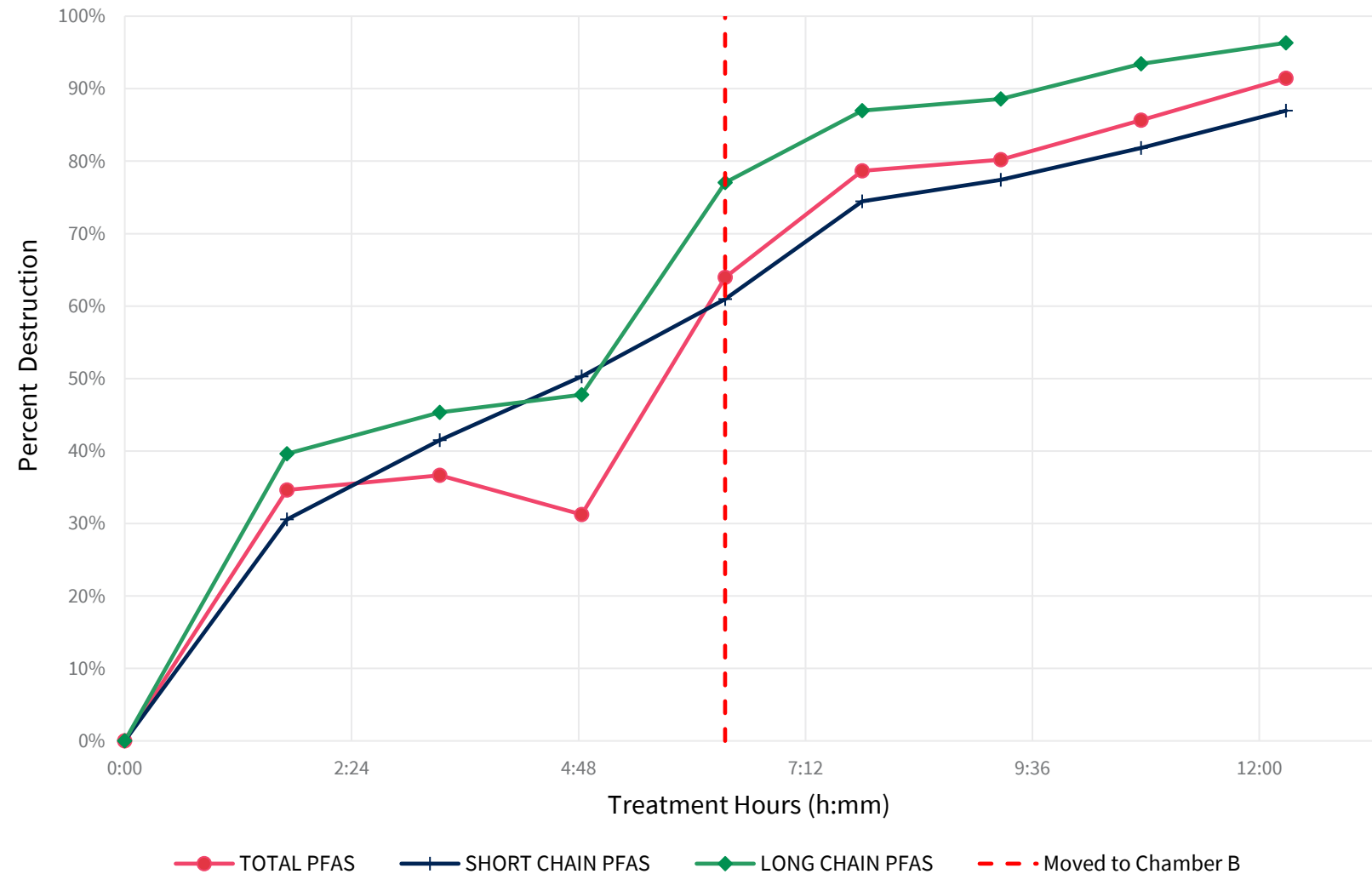
- Long-chain PFAS decrease in concentration faster than short-chain PFAAs
- PFDA presented the highest removal rate of the PFAS detected
- PFBA presented the lowest removal rate of the PFAS detected



PFAS Maximum Percent Destruction Summary

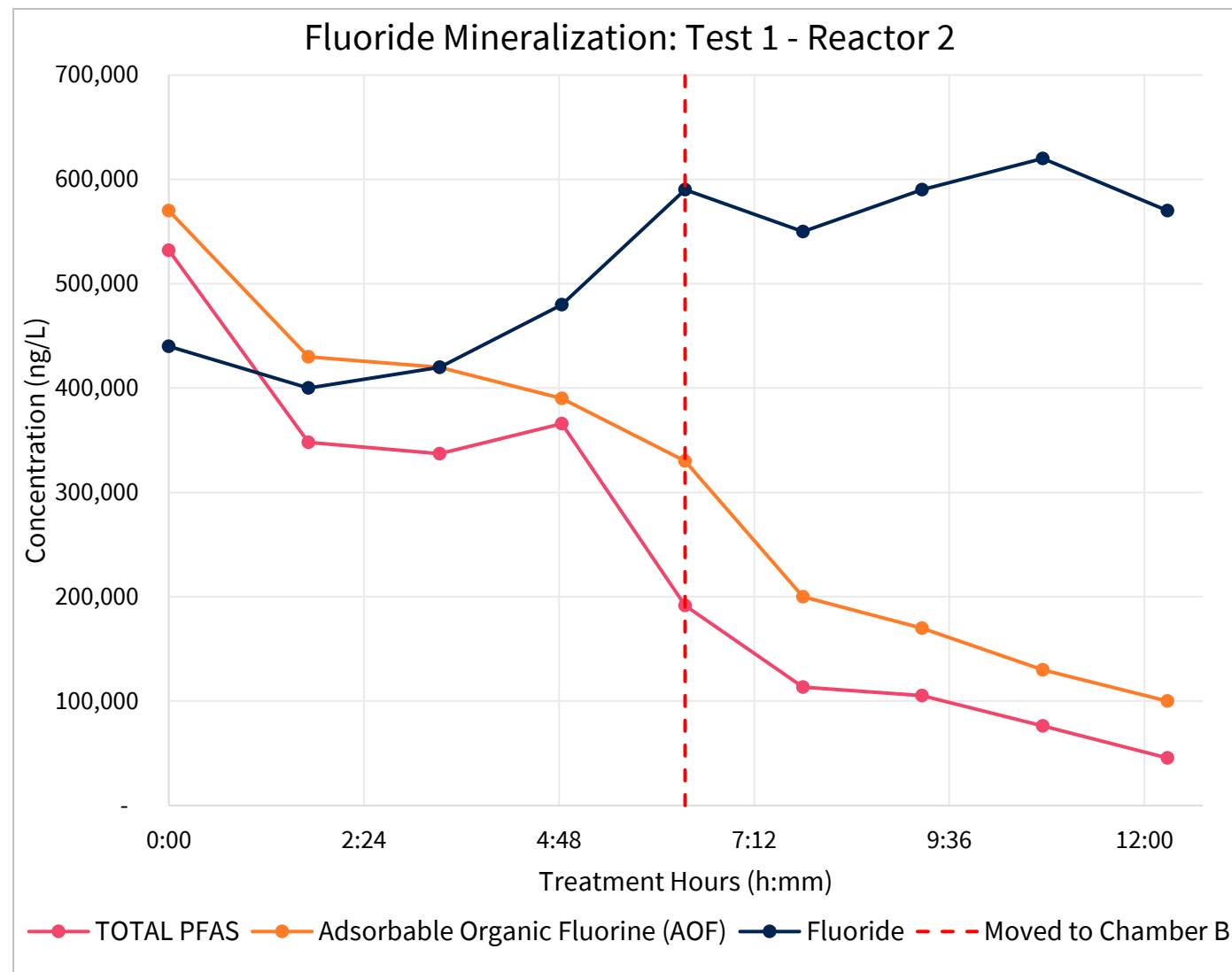
- The total PFAS destruction percentage was 91%.
- The short-chain PFAS destruction percentage was 87%.
- The long-chain PFAS destruction percentage was 96%.

Summary of Maximum Percent Destruction of PFAS



Fluoride Mineralization

- A fluorine mass balance was conducted to determine whether PFAS has been fully degraded without the formation of harmful byproducts.
- AOF measures all organic fluorine including PFAS and any PFAS precursors or other compounds not analyzed by EPA 1633.
- Decreased concentrations of AOF is an indicator of mineralization because it includes degradation of all PFAS including any precursors. AOF and total PFAS decreased at the same rate.
- Fluoride increased as total PFAS and AOF decreased indicating that the compounds were fully mineralized.
- Fluoride was mineralized by 91% which mirrors the 91% total PFAS degradation rate for this test.





Remedy Performance and Optimization



Remedy Performance and Optimization



Remedy Performance and Optimization



- The total power for the trailer for one 12-hour treatment cycle was 317 kWh.
- The power cost for the treatment system only, without considering miscellaneous power consumption such as lights or air conditioning, was \$1.57 per gallon (\$0.41 per L), assuming a power cost of \$0.15/kWh.
- Groundwater influent had extremely high concentrations of iron which is believed to interfere with the PFAS degradation.
- In Chamber A, the percent destruction is roughly 10% per hour of treatment as compared to Chamber B where the percent destruction is roughly 3% per hour of treatment.
- If the average rates of destruction were extrapolated, at 10 hours of treatment in Chamber A, the contaminated groundwater would reach near 100% PFAS destruction. Further testing is recommended to confirm this estimation.



Remedy Performance and Optimization



- Ultrasound technology provides a cost-effective, highly-efficient, mobile PFAS destructive treatment for high-concentration groundwater.
- The demonstration found that ultrasound treatment was effective in fully mineralizing PFAS without the formation of harmful byproducts.
- Further testing is recommended to increase total capacity above 100-L.
- Iron removal prior to treatment is recommended as part of future tests to increase the PFAS destruction efficiency.
- Future studies should consider removing the low-power chamber and increasing residence time in the high-power chamber to optimize treatment duration required.



Acknowledgements



- Jeffrey Davis, PhD (Air Force Civil Engineer Center (AFCEC));
- Jay Meegoda, PhD (New Jersey Institute of Technology)
- Rick Arnseth, PhD, Paul Jobmann, Daniel Forester, Hayley Heyser (Tetra Tech, Inc)



Thank You



Questions?



Your Success is Our Mission!

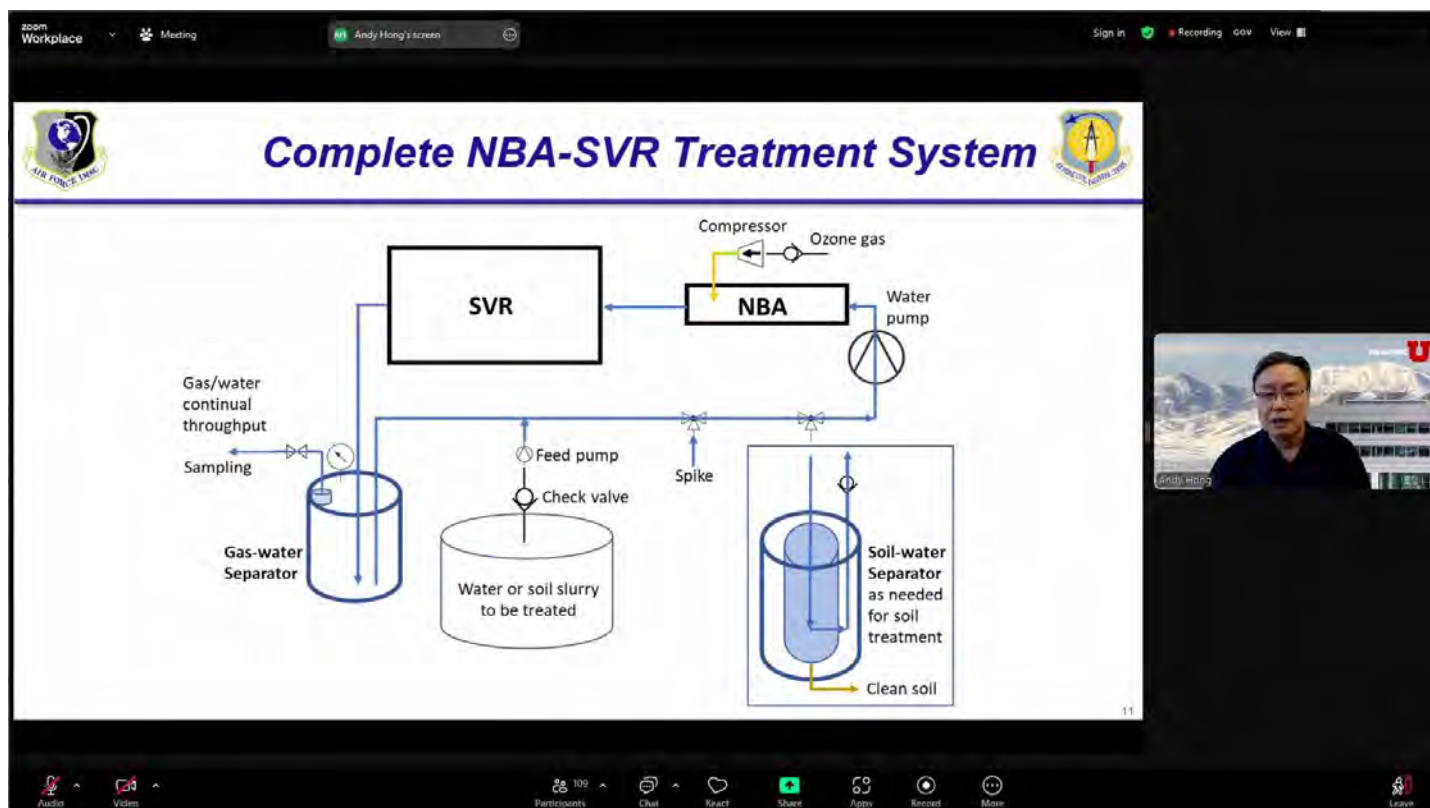


Air Force Civil Engineer Center

Restoration Technology Transfer Speakers Series April 2025

The Destruction of PFAS by Ozone Nanobubbles

This webinar covered the treatment of per- and polyfluoroalkyl substances (PFAS) using ozone nanobubbles (ONB). The process involves a newly invented nanobubble aerator (NBA) that generates ONB from an ozone stream. PFAS-laden groundwater is treated by circulating it through the NBA and a serial venturi reactor (SVR). The NBA-SVR system produces ample ONB with extensive interfacial area, attracting PFAS contaminants. Reductive superoxide and oxidative hydroxyl radicals are created at the bubble interface, leading to PFAS degradation through repeated reductive attacks. The webinar presented pilot test results, discussed laboratory challenges, and provided evidence of consecutive chain breakage.



Dr. Andy Hong presents the details of the ONB technology.

This event and future events are updated and posted on the AFIT website at: <https://www.afit.edu/CE/index.cfm>.

POCs:

Joseph Dimisa, AFIT (joseph.dimisa@us.af.mil)

C.J. Garcia, CTR, Booz Allen Hamilton (carlos.garcia.56.ctr@us.af.mil)

Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)



Webinar Structure



	https://usaf.dps.mil/teams/eDASH/WPP/Speaker%20Series/Speaker%20Series.aspx
5 min	Welcome and Administrative Business
45 min	<i>Destruction of PFAS by Ozone Nanobubbles</i> Andy Hong, Ph.D. – University of Utah
10 min	Questions and Answers
5 min	Final Thoughts

Air Force Civil Engineer Center



Destruction of PFAS by Ozone Nanobubbles

BAA2123

Andy Hong, PhD

Civil & Environmental Engineering

University of Utah

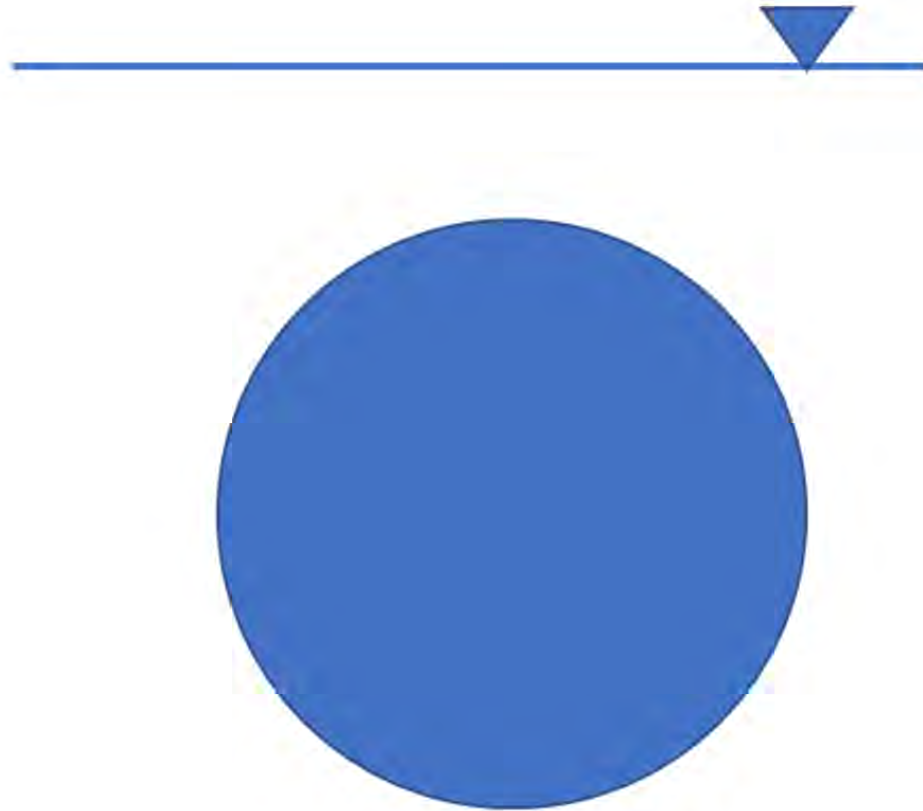
April 2025



Project Objective and Approach



- Objective: Destruct to remove PFAS from impacted groundwater
- Needs: Current approaches are either not technically or economically effective
- New Approach: Create a new treatment technology using ozone nanobubbles to destruct PFAS via both reduction and oxidation processes



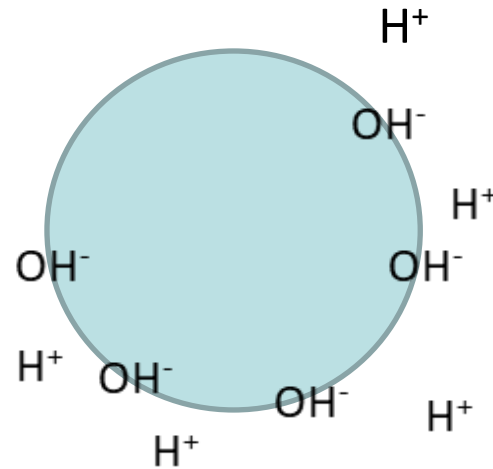
- $> 65 \mu\text{m}$, rise and expand (Stoke's equation) ($>14 \text{ cm/min}$)
- $< 10 \mu\text{m}$, rise very slowly ($<0.33 \text{ cm/min}$), allowing gas transfer and shrinkage to nano sizes
- Young-Laplace equation for P
 - $P = 4 \sigma / d$
 - $P = 2.9 \text{ atm at } 1 \mu\text{m}$
 - $P = 2,900 \text{ atm at } 1 \text{ nm}$
 - $P \sim 60 \text{ atm at } 50 \text{ nm}$

- $dC/dt = K_{La}(C^* - C)$

Where C^* = equil. Conc. wrt P and P is huge!

So, gas transfer should be over quickly and bubbles completely dissolve and disappear

- Yet NB is long-lasting



Negatively charged nanobubbles

Solvation energies

H^+ : -1052 to -1064 kJ/mol

OH^- : -380 to -462 kJ/mol

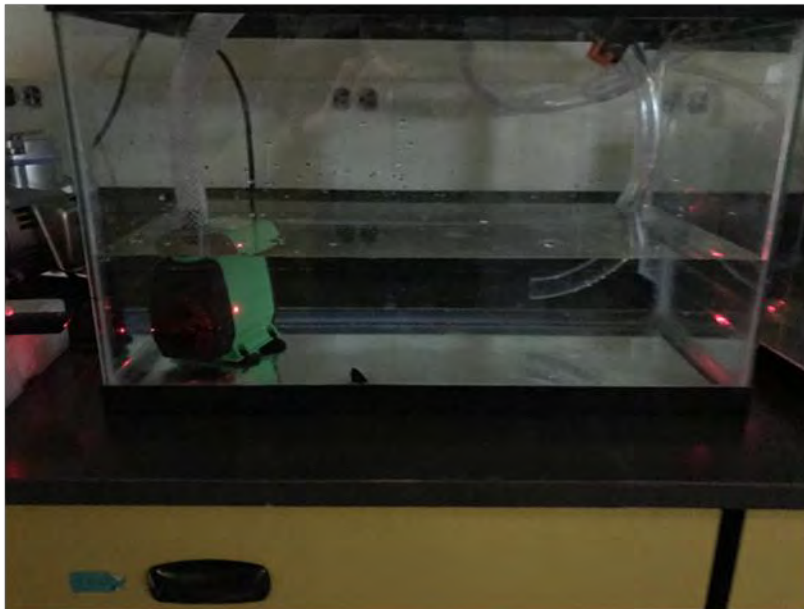


NB Applications (Literature)

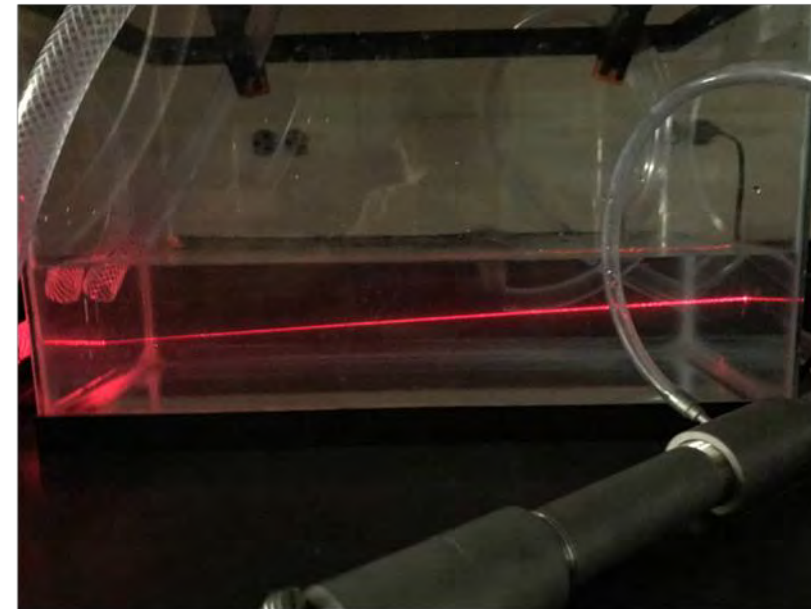


- **PFAS destruction (Today's focus)**
- **Wastewater treatment**
- **Carbon capture, storage, transport, utilization**
- **Surface cleaning**
- **Froth flotation**
- **Ultrasound contrast agent**
- **Drug delivery**
- **Drag reduction**
- **Sterilization of bacteria**
- **Enhance seed germination rates**
- **Improve blood oxygenation**
- **Improve engine efficiency by hydrogen NB**
- **Promotion of physiological activities of living organisms**

Light scattering before and after aeration



Before



After



Equipment and Methods



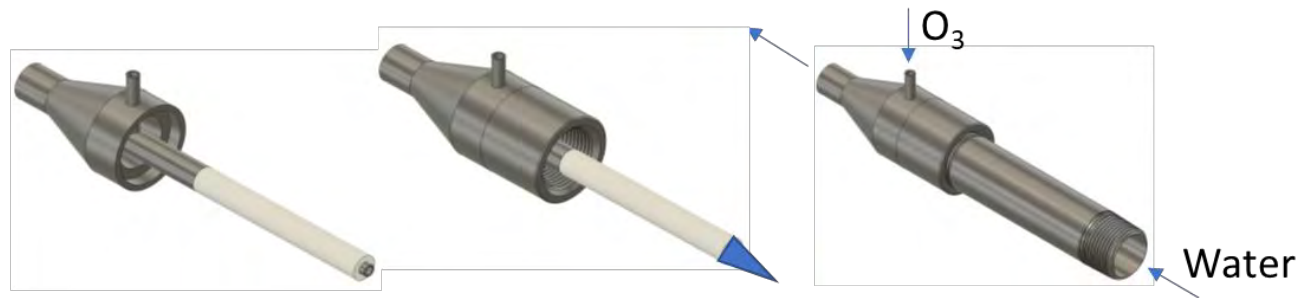
- Ozone compressor – Oxidation Technologies; OC-P1 with FMSS-4 ozone resistant 0-4 LPM stainless steel flowmeter
- Ozone resistant water pump – Oxidation Technologies; WP1 Model 5036ES1BJPRW56J-S
- Ozone Generator – Ozone Solutions; TS-40
- Oxygen Generator – Philips Respironics EverFlow with OPI – SKU 1020001
- Aerator & SVR - custom built
- Turbidity meter – LaMotte 2020we (Code 1970-EPA)
- Dynamic Light Scattering (DLS) – Anton Parr Litesizer 500
- Atomic Force Microscopy (AFM) Bruker Dimension Icon

PFAS Reference Standard Chemicals from Wellington Laboratories:

- A: Method 1633 Native PFAS mix – Product EPA-1633 STK
- B: Labeled PFC Internal Standard – Product MPFAC-HIF-IS
- C: Labeled PFC Extraction Standard – Product MPFAC-HIF-ES

Other supplies used in PFAS analysis is as per EPA 1633A. U.S. Environmental Protection Agency. (2024, December). Method 1633A: Analysis of per- and polyfluoroalkyl substances (PFAS) in aqueous, solid, biosolids, and tissue samples by LC-MS/MS (EPA 820-R-24-007). Office of Water, www.epa.gov

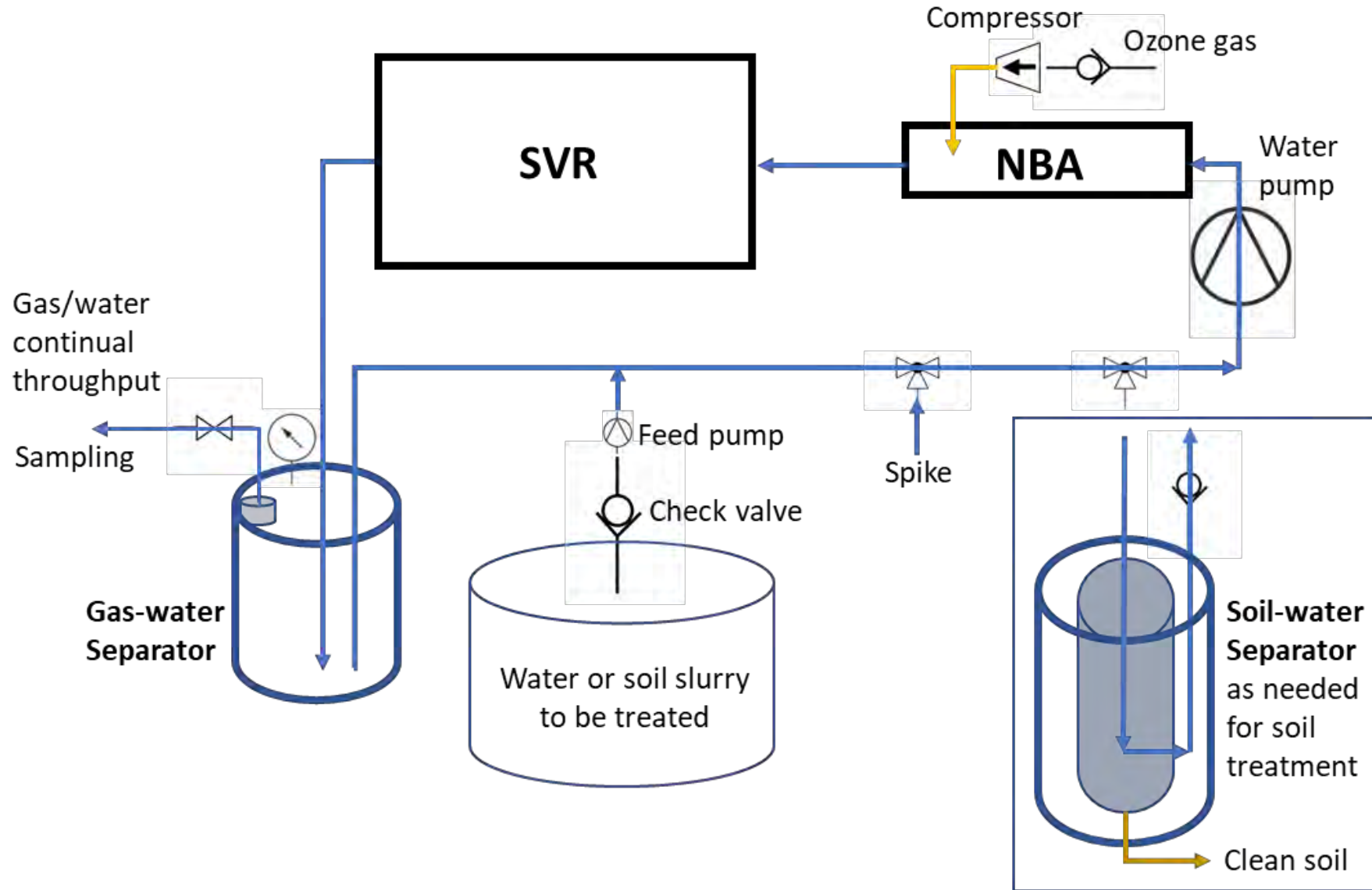
■ Nanobubble Aerator (NBA)



■ Serial Venturi Reactor (SVR)

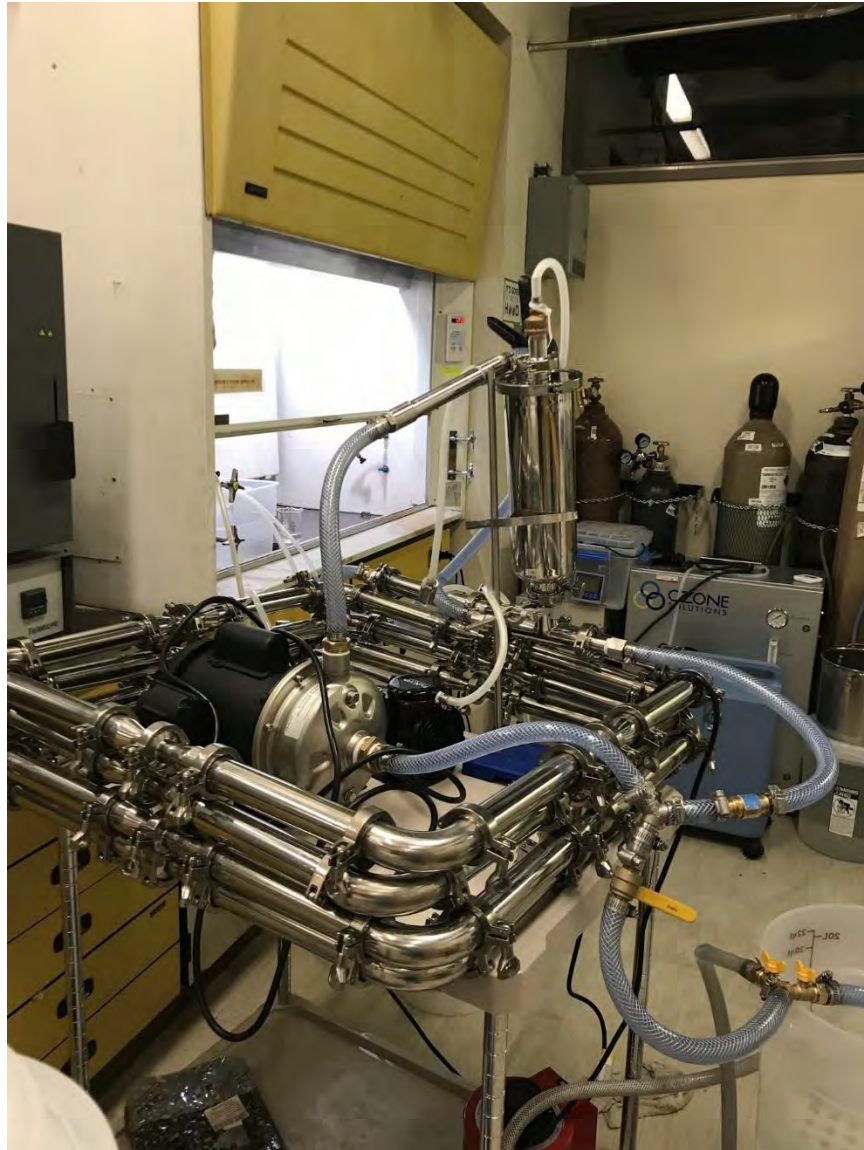


Complete NBA-SVR Treatment System





NBA-SVR Treatment System – Lab & Field

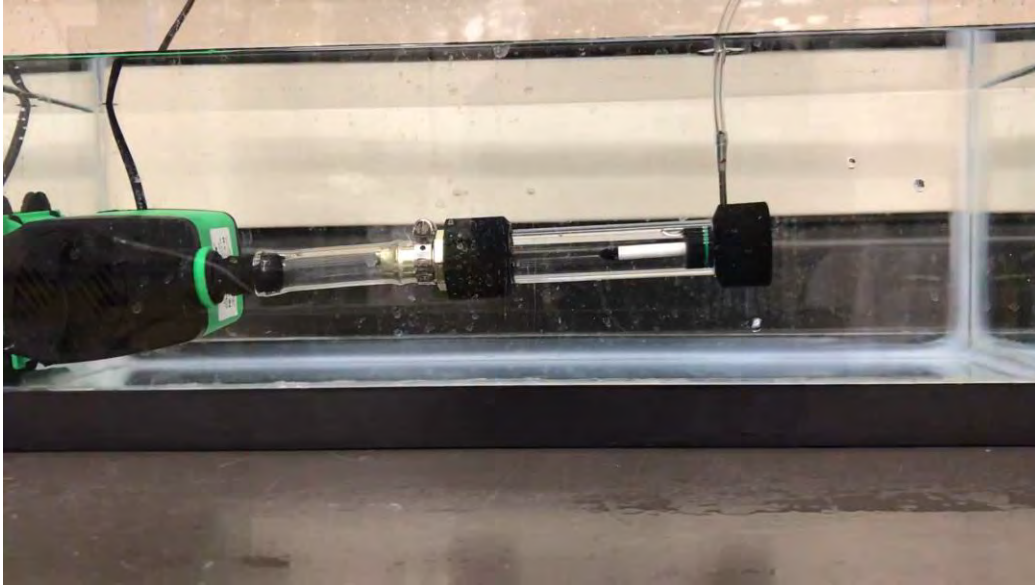




Groundwater Access & Pilot System Setup

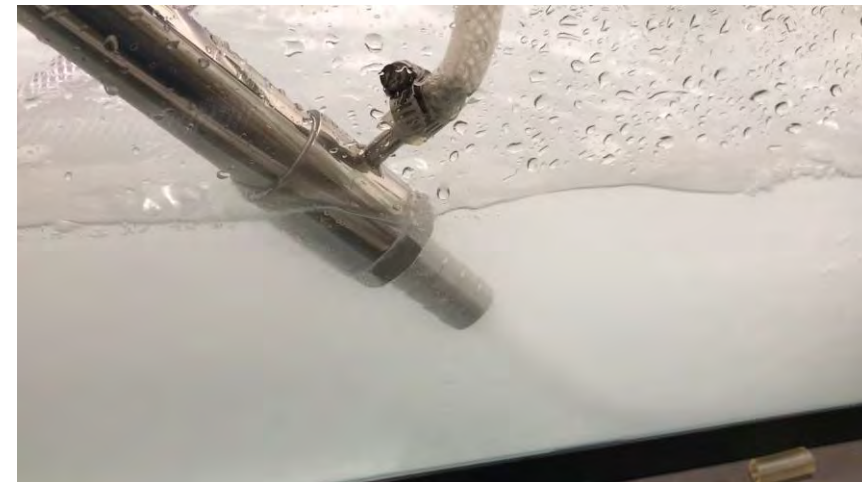
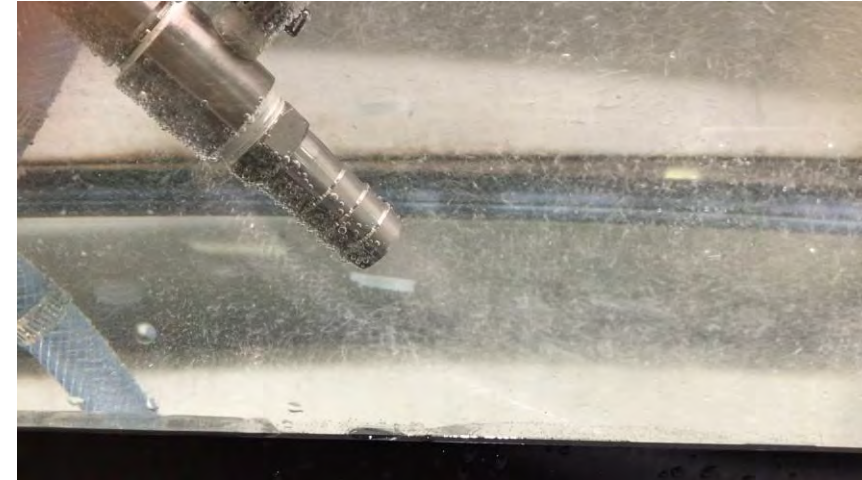


Ozone Nanobubbles Production



Watch in action:

<https://youtu.be/D4GCz9Hin6c>



Evidence of Nanobubble Generation

Nanobubbles scattering a laser pointer beam

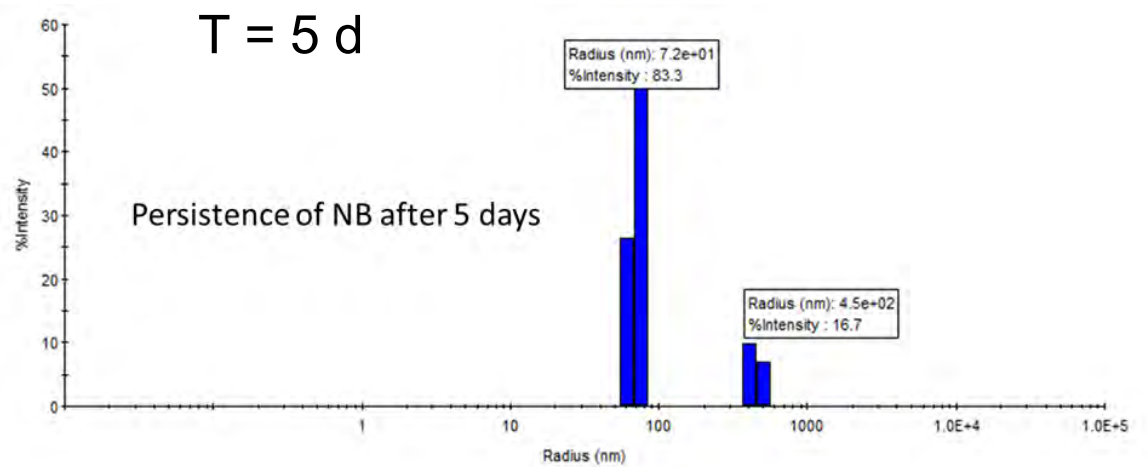
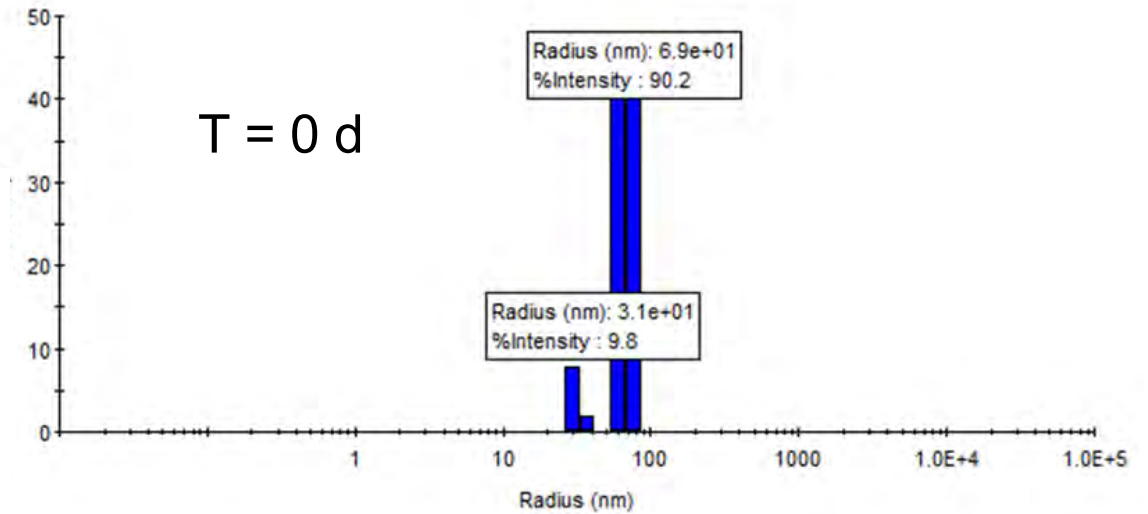
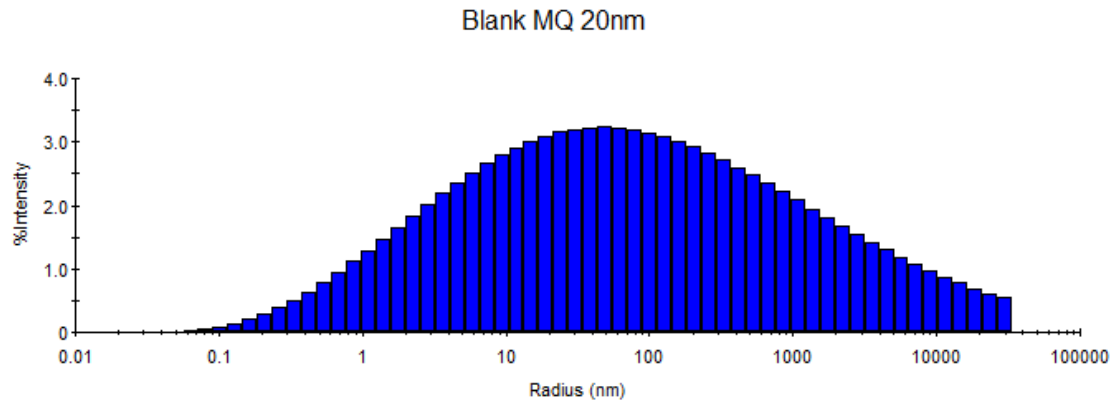


Water samples under subdued light after aeration by MNBA (left) and before aeration (right), showing no differences in appearance.



Water samples illuminated by a laser pointer after aeration (left) and before aeration (right), showing strong scattering of the laser beam by nanobubbles created by aeration.

DLS Measurements of bubbles

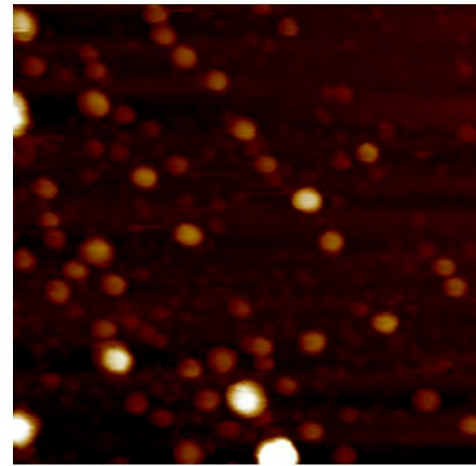


Measurements – Turbidity, Sizes, at pHs

Ph	Time (mins)	Turbidity (NTU)	Sample	Laser beam for the samples	Radius(nm) and %intensity
4.01	0	0.00	*		
	20	0.02			
	30	0.08	*		88 (100%)
	50	0.10			
	60	0.11	*		75 (100%)
7.02	0	0.00	*		
	10	0.07			
	20	0.09	*		74 (100%)
	30	0.12			
	50	0.15	*		67 (100%)
	60	0.18	*		62 (100%)
10.21	0	0.00	*		
	20	0.10	*		71 (100%)
	40	0.28	*		60 (100%)
	60	0.38	*		52 (83.1%) and 59 (16.9%)

3-D Images of Nanobubbles by Atomic Force Microscopy (AFM)

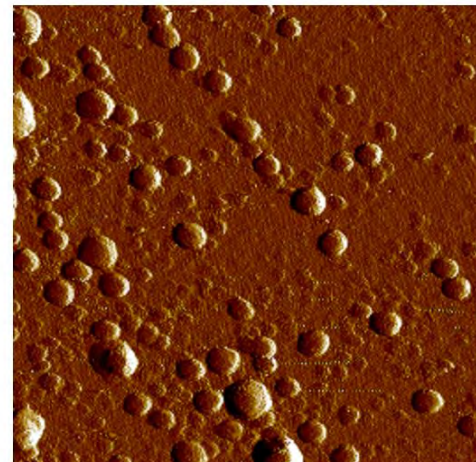
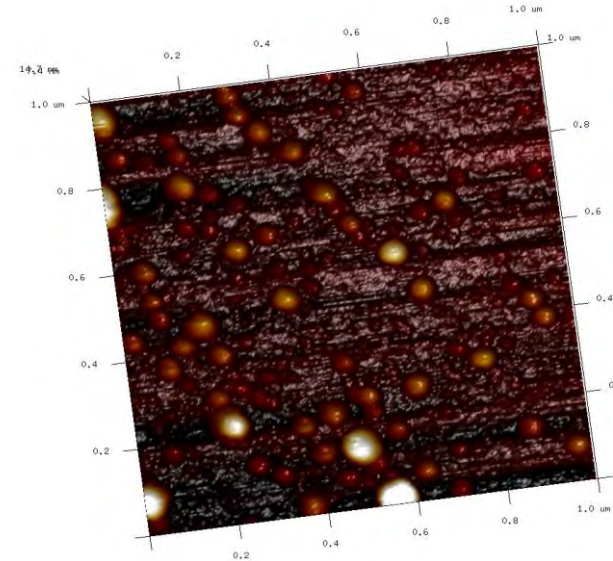
ROI – 1 μm



Height Sensor

200.0 nm

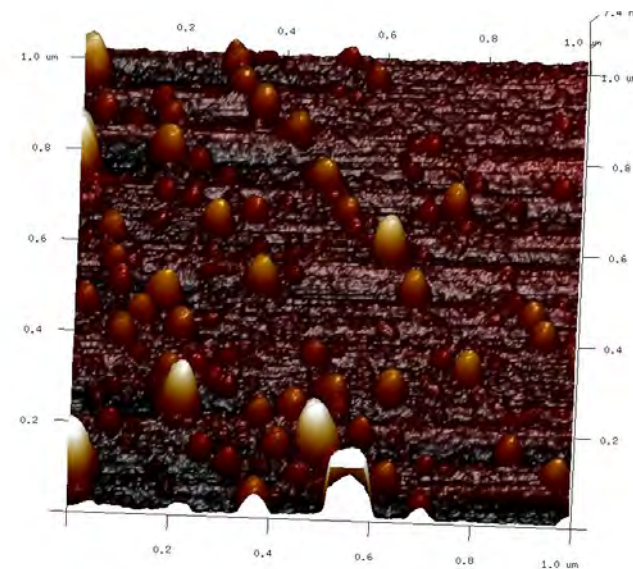
14.7



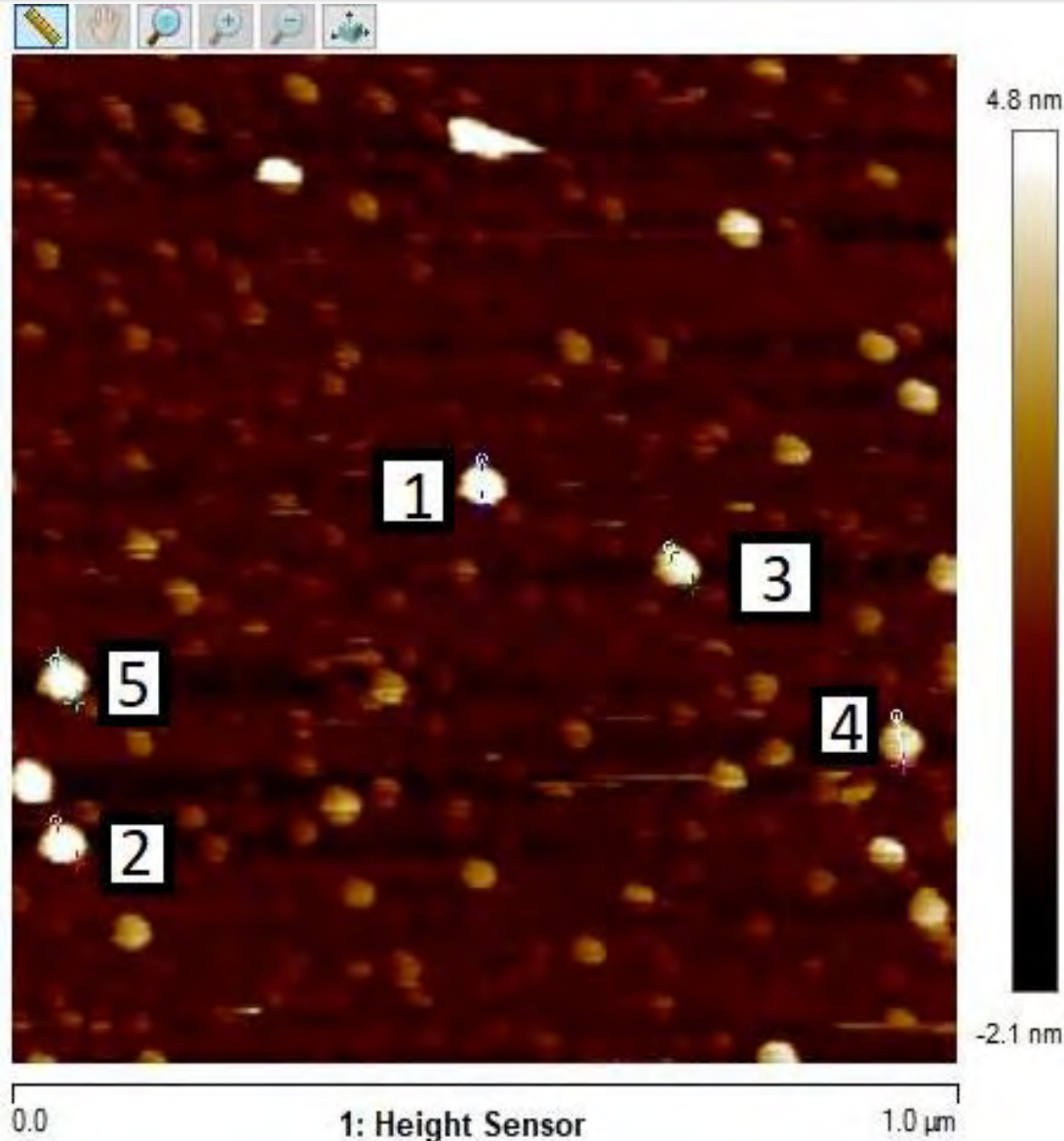
Peak Force Error

200.0 nm

208.5



NB on n-type Silicon Substrate

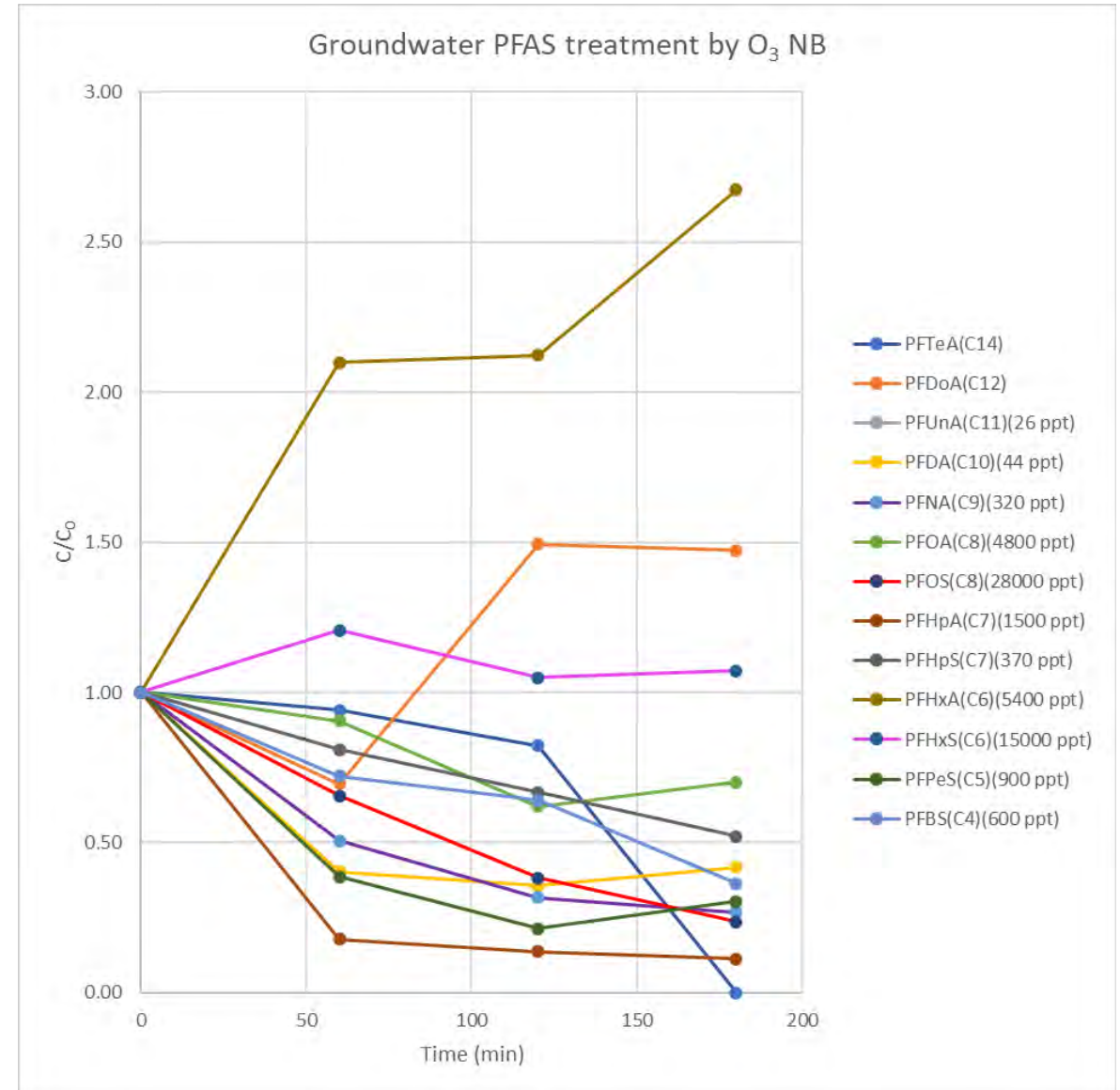
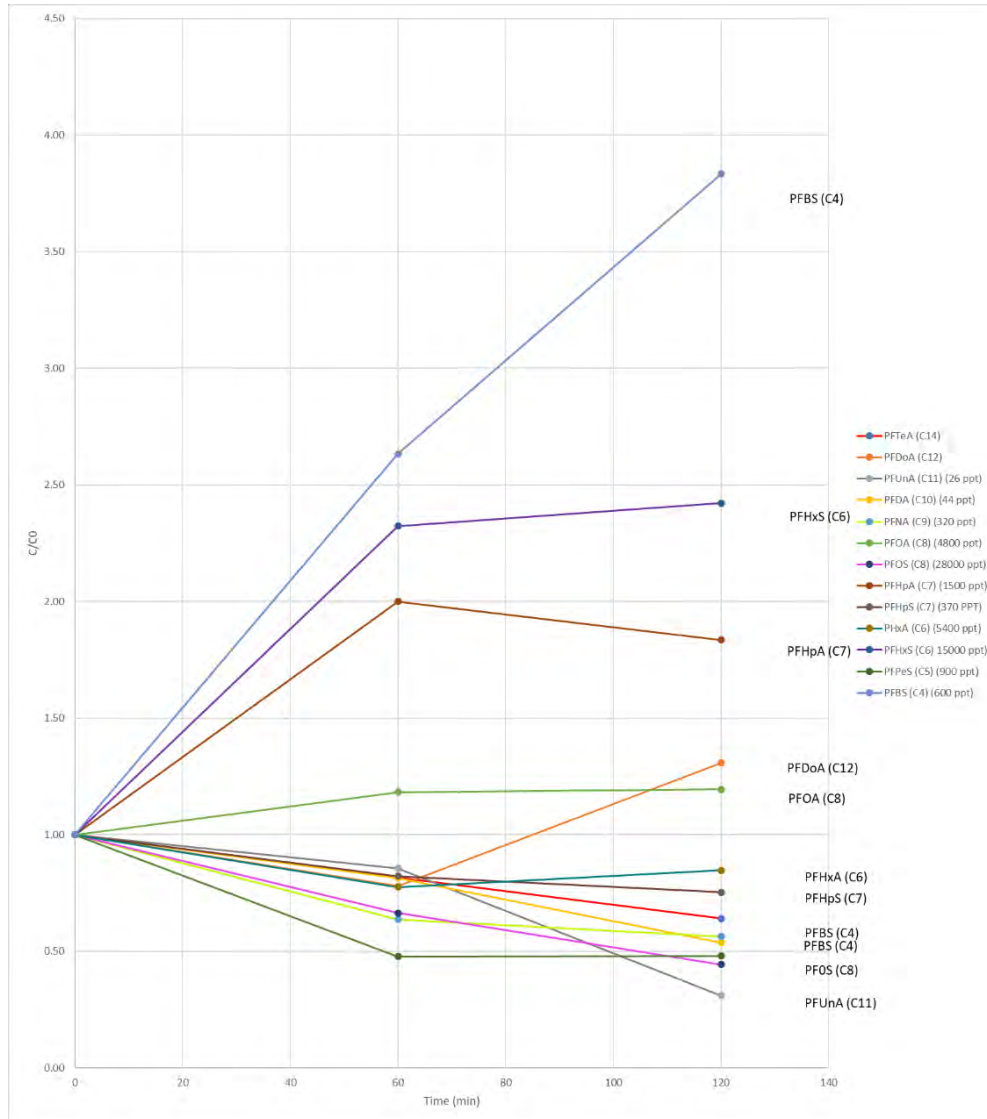


#Bubble	Diameter (nm)
1	43.137
2	41.16
3	39.745
4	43.645
5	39.46
Mean	41.394
STD	1.709

Nanobubble concentration
 2.5×10^{11} #/mL



Treatment of PFAS in Groundwater by O_3 NB





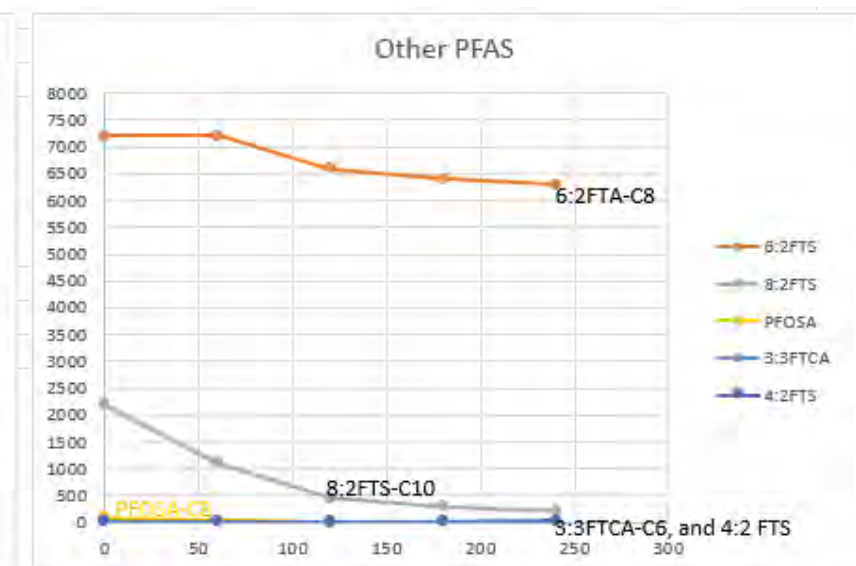
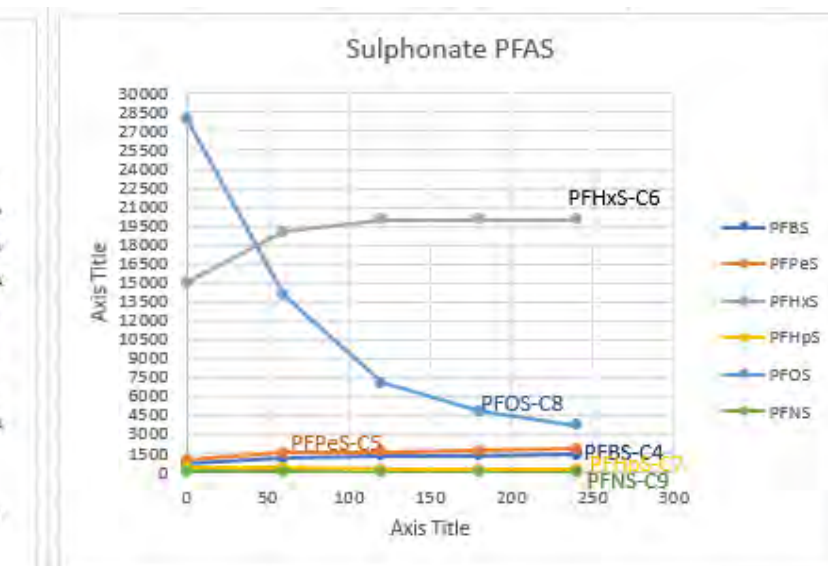
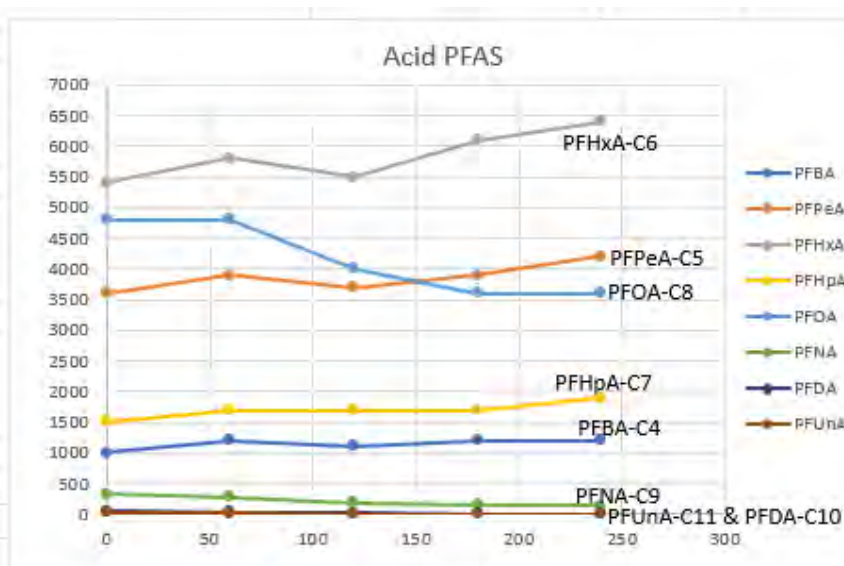
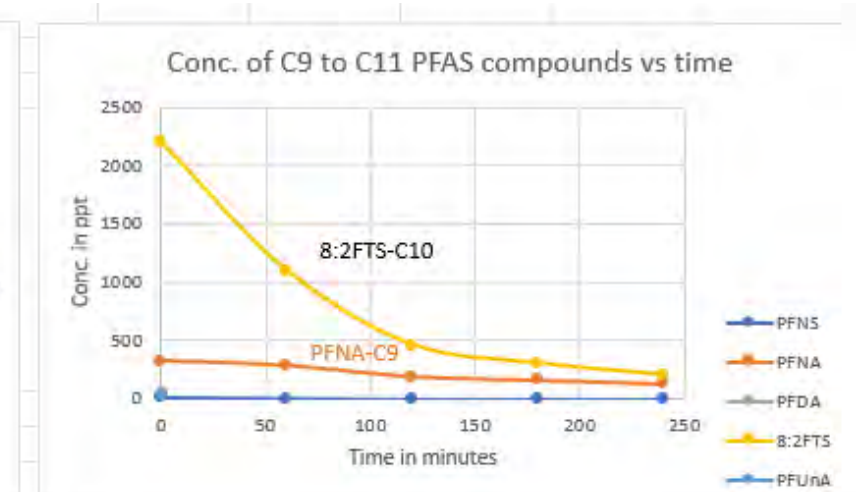
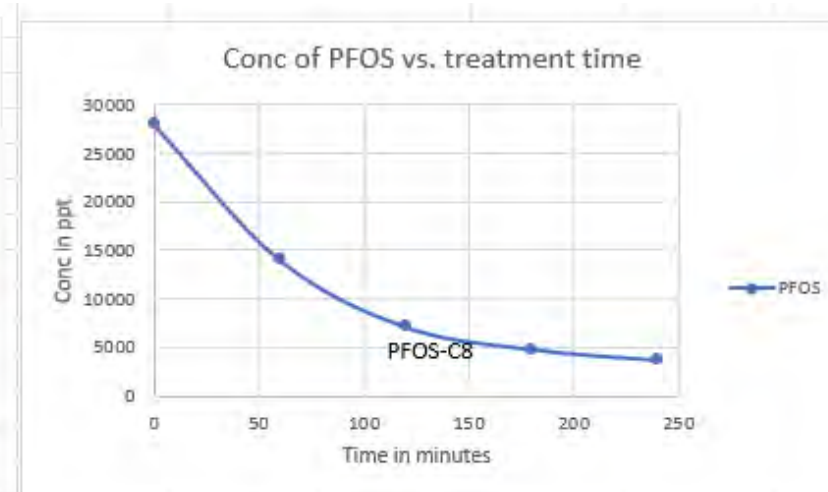
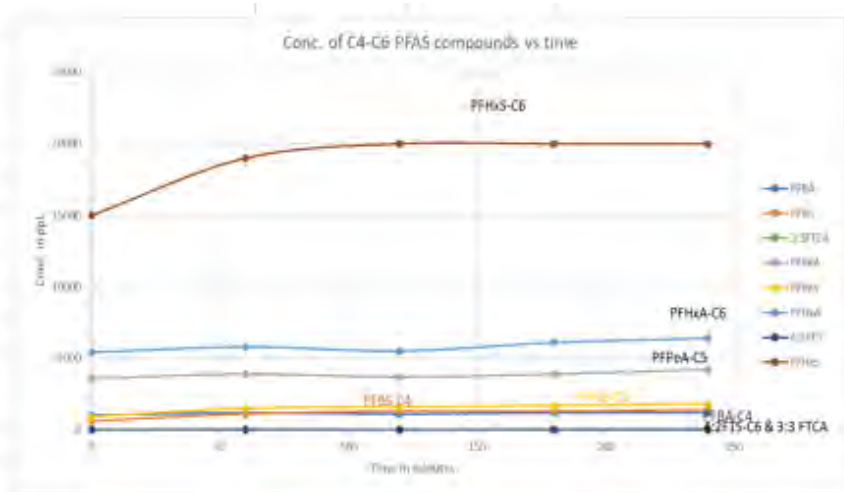
Results of Pilot Treatment in the Field



■ Field pilot test results (analyzed by Eurofins Sacramento)

# Carbon	4	4	5	5	6	6	6	6	7	7	8	8	8	8	9	9	10	10	11	Total
MW	212.8	298.7	263	349.1	313	241	327.1	398.7	363.1	449	413	498.9	498.1	427.1	548.8	463	512.9	527.1	563.1	
Time	PFBA	PFBS	PFPeA	PFPeS	PFHxA	3:3FTCA	4:2FTS	PFHxS	PFHpA	PFHpS	PFOA	PFOS	PFOSA	6:2FTS	PFNS	PFNA	PFDA	8:2FTS	PFUnA	
(min)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	(ppt)	
0	1000	600	3600	900	5400	14	10	15000	1500	370	4800	28000	77	7200	9.6	320	44	2200	26	71070.6
60	1200	1100	3900	1500	5800	15	22	19000	1700	320	4800	14000	35	7200	4.4	280	23	1100	12	62011.4
120	1100	1300	3700	1600	5500	0	22	20000	1700	220	4000	7100	19	6600	0	190	9.6	460	3.6	53524.2
180	1200	1300	3900	1700	6100	13	22	20000	1700	180	3600	4800	15	6400	0	160	6.3	300	0	51396.3
240	1200	1400	4200	1800	6400	13	27	20000	1900	180	3600	3700	17	6300	0	130	3.5	200	0	51070.5
% Removal	-20	-133	-17	-100	-19	7	-170	-33	-27	51	25	87	78	13	100	59	92	91	100	28

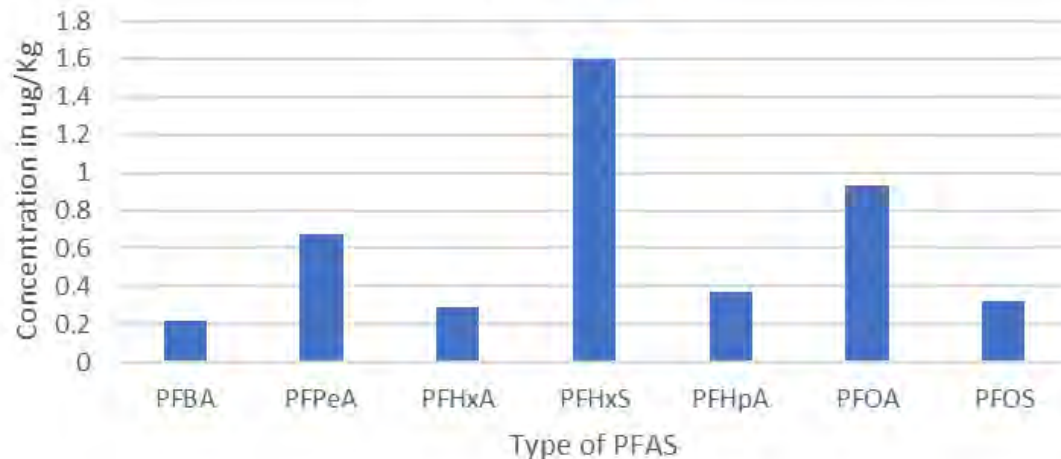
Concentration Changes of Various PFAS



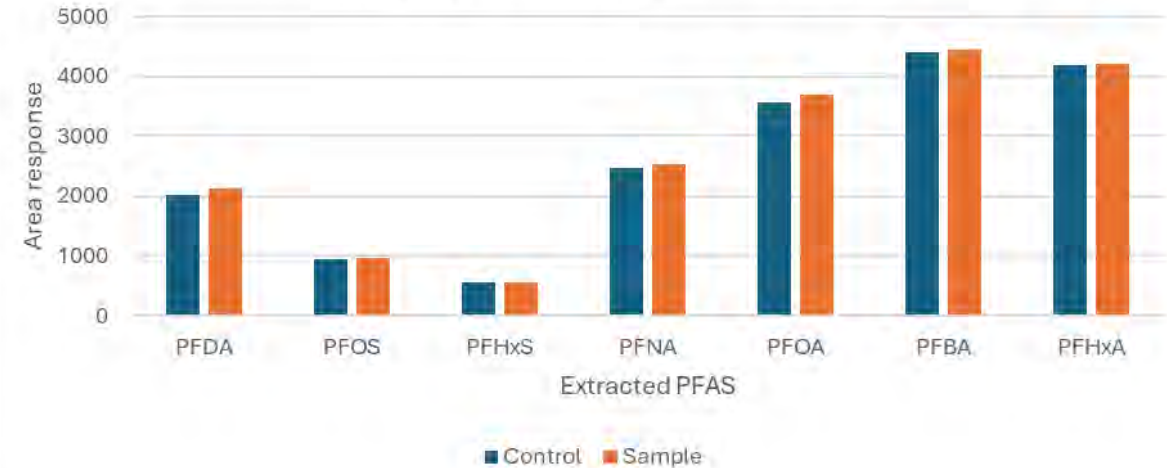
Remediation Plan

- Soil washing to get PFAS in solution
- Destruction of PFAS in aqueous phase by O_3 NB in NBA-SVR
- Results: Adequate washing with water with or without nanobubbles

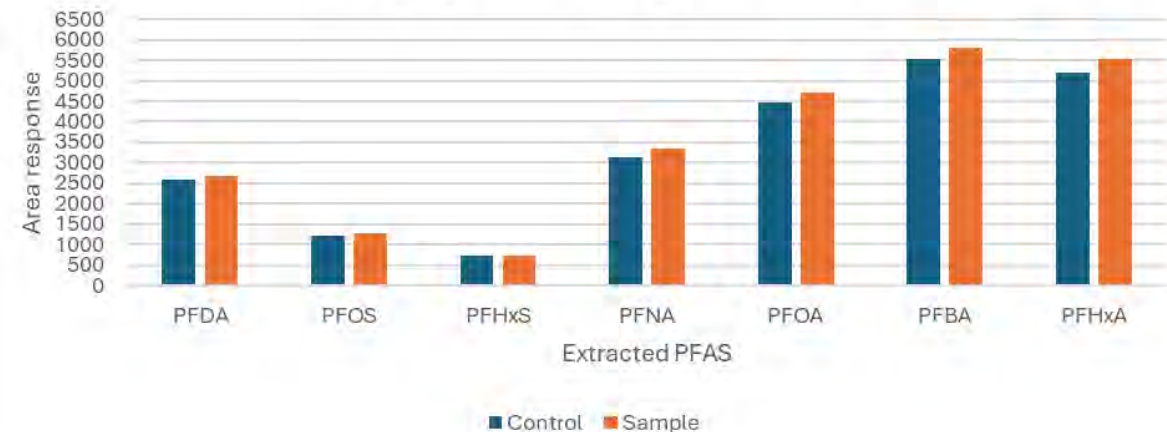
Concentration of PFAS in untreated soil (ug/Kg)



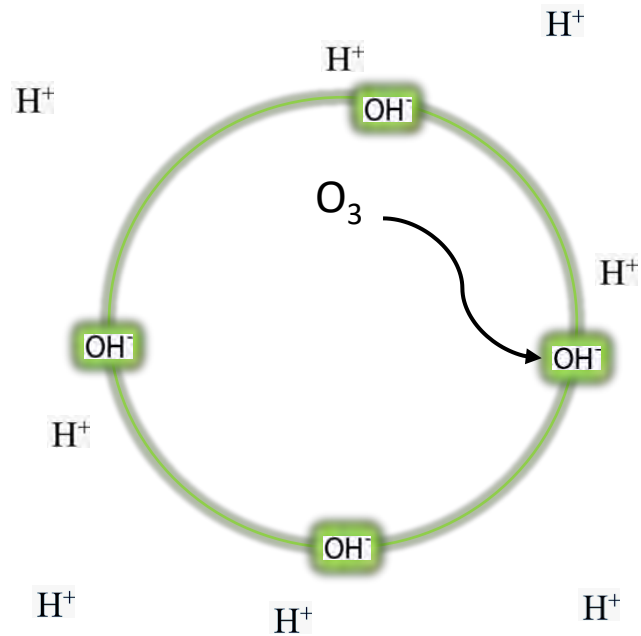
Extraction using O_2 NB with 50 g soil with 500 ml water



Extraction using O_2 NB with 200 g of soil in 500 ml water



How Ozone Nanobubbles work?



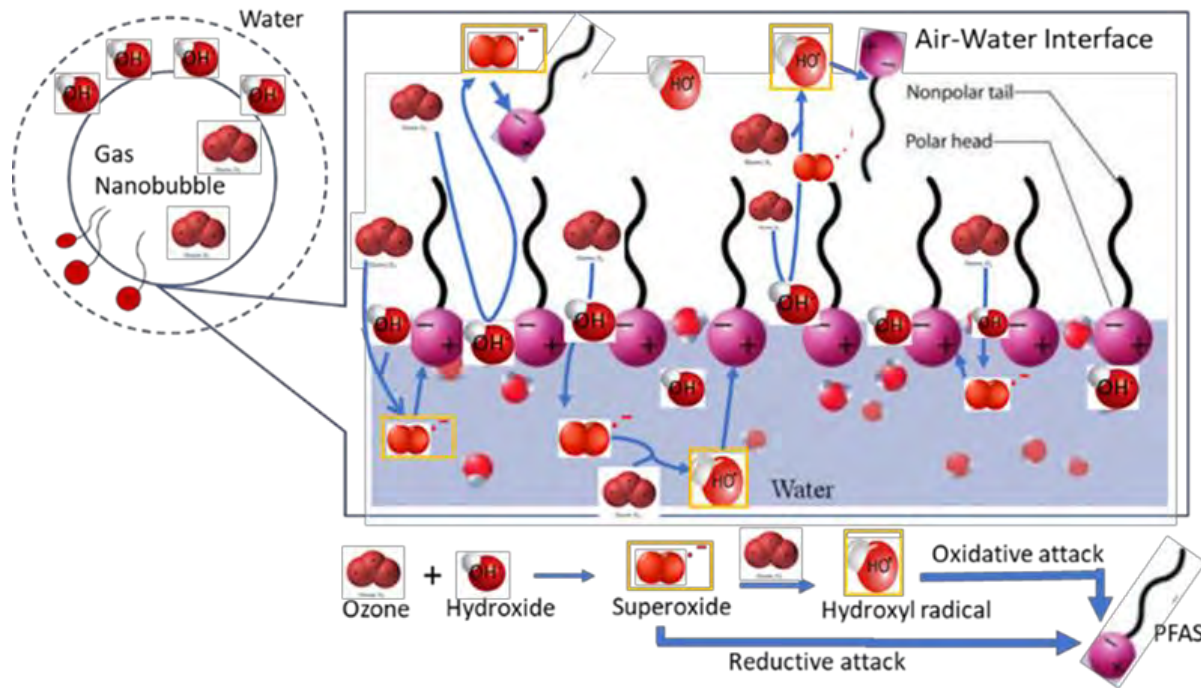
Negatively charged nanobubbles

Solvation energies

H^+ : -1052 to -1064 kJ/mol

OH^- : -380 to -462 kJ/mol

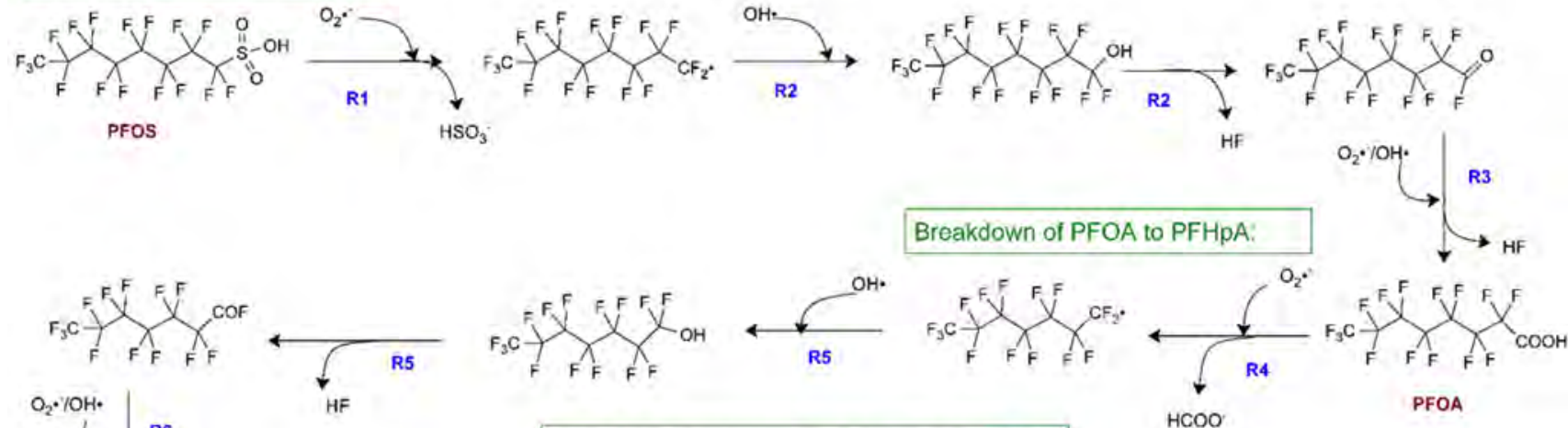
How are Reactive Oxygen Species Created



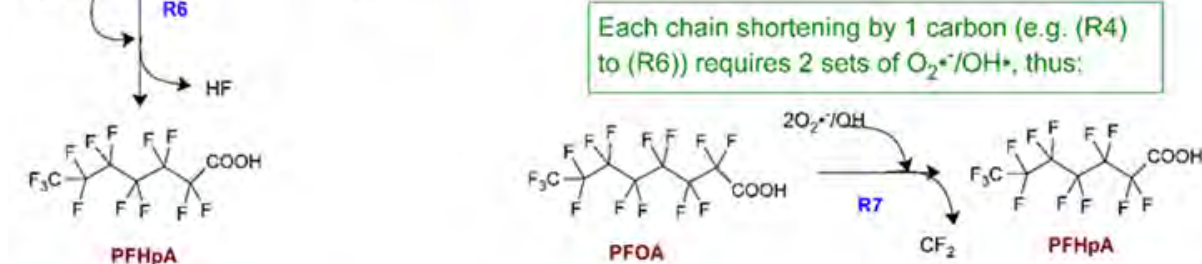
- Negatively charged nanobubbles with hydroxide ions at the interface
- Stable nanobubbles
- Reaction of ozone with hydroxide at the interface to form superoxide
- Further reaction of ozone with superoxide to form hydroxyl radical
- Presence of both reductant and oxidant at the interface where PFAS are concentrated

Mineralization Mechanism

Conversion of PFOS to PFOA:

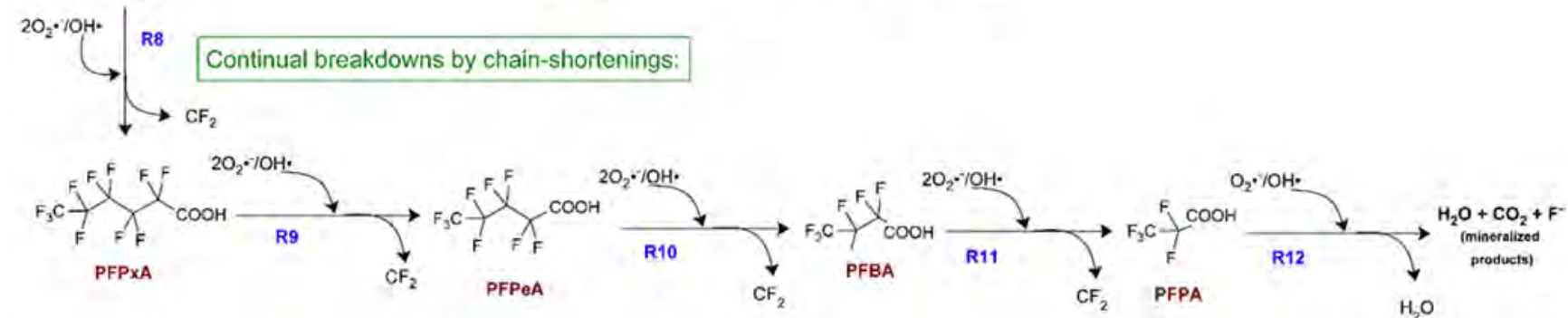


Breakdown of PFOA to PFHpA:



Each chain shortening by 1 carbon (e.g. (R4) to (R6)) requires 2 sets of $O_2^{\bullet-}/OH^{\bullet}$, thus:

Continual breakdowns by chain-shortenings:





Summary and Conclusions



- **100% removal of major contaminant PFOS**
- **Incomplete removal of all PFAS**
- **Sequential chain shortening during degradation**
- **Destruction requires concurrent reduction and oxidation steps**

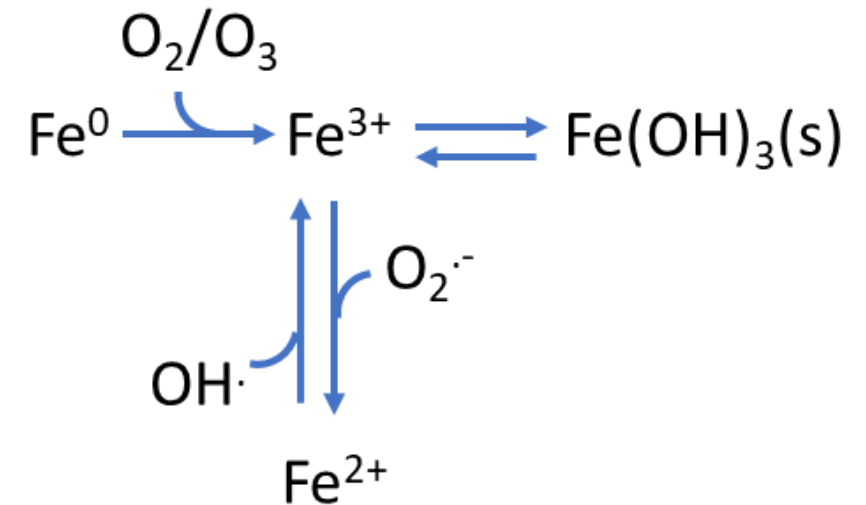


Challenges and Lesson Learned



- **Membrane pores closure**
- **Separation of gas and water with continual gas intake**

- Most operation challenges overcome
- Optimize contact time and number of serial venturi segments
- Interferences of groundwater species
- Heat dissipation of the gas compressor





Optimization via Flowrate of O_3 and Geometry of Venturis



Time (hr)	PFOS	PFNA	PFHpS	PFOA	PFHxS	PFHpA	PFPeS	PFHxA	PFBS	PFPeA	PFBA
Ini. conc (ppt)	969	20	18	850	1005	243	63	456	55	625	190
0	0	0	0	0	0	0	0	0	0	0	0
1	96	100	100	62	39	22	9	-25	-8	-48	-60
2	100	100	100	87	60	48	25	-6	3	-33	-103
3	100	100	100	96	71	56	30	2	3	-25	-113
4	100	100	100	98	71	55	15	-9	-22	-40	-151

01.0 LPM O_3

Time (hr)	PFOS	PFNA	PFHpS	PFOA	PFHxS	PFHpA	PFPeS	PFHxA	PFBS	PFPeA	PFBA
ini conc (ppt)	1052	21	19	881	1056	256	70	490	58	684	209
0	0	0	0	0	0	0	0	0	0	0	0
1	97	100	100	62	39	25	21	6	16	4	0
2	100	100	100	89	66	45	37	10	24	4	-1
3	100	100	100	97	79	54	46	8	21	-1	-6
4	100	100	100	100	89	67	53	13	29	-1	-7

0.4 LPM O_3



University of Utah – Patent Pending Technology Licensing & Collaboration



Contact:

Ainsley Lloyd
Associate Director

Energy Accelerator
The University of Utah
ainsley.lloyd@utah.edu

Pronouns: She/Her/Hers



Thank You



Questions?



Your Success is Our Mission!



Air Force Civil Engineer Center

Restoration Technology Transfer Speakers Series May 2025

Near-Surface and Borehole Geophysics Techniques Available for High-Resolution Site Characterization Part 1 of 2

Presenters: Jaime Hincapie, Ph.D. – Noblis

Near surface geophysical (NSG) methods are minimally invasive, non-destructive technologies that use the physical properties subsurface materials to aid in understanding complex geologic and hydrogeologic settings. The methods include:

- Transmission of mechanical vibrations – seismic methods
- Detection of atomic-level particle physics – quantum physics methods
- Resistance to the flow of electricity– electrical methods
- Transmission of electromagnetic signals – EM and ground-penetrating radar methods
- Variations of Earth's magnetic field - magnetometry
- Variations of Earth's gravitational pull – gravimetry

While NSG can be implemented as standalone technologies, they are often used in tandem with other ancillary methods. These geophysical methods help identify optimal locations for drilling to confirm and further extrapolate the initial findings. They are decision-making tools widely used in geotechnical engineering and environmental investigations among others. NSG covers large areas quickly and provides valuable information at a fraction of the cost of invasive exploration techniques. Preliminary results from some methods are available in the field and provide timely information that can be used to optimize available resources and reduce costs and time in the field.

The screenshot shows a Zoom meeting interface. The main window displays a presentation slide titled "Ground Penetrating Radar" with the Air Force Civil Engineer Center logo. The slide content includes:

- Ground penetrating radar (GPR)**
Uses radar pulses to image the subsurface.
- Environmental Applications**
 - Locating pipes, tanks, and other utilities
 - Locating the groundwater surface
 - Identifying and mapping the extent of groundwater contamination
 - Identifying karst features, voids, and burrows
 - Mapping bedrock configuration, structure and depth
 - Detecting unexploded ordnance and unmarked graves
 - Delineating soil horizons and soil stratigraphy
 - Determining ice thickness (e.g., permafrost)
 - Determining water depth in lakes

To the right of the text is a 3D diagram of a subsurface model. It shows a rectangular prism with dimensions 35 m (length), 15 m (width), and 7 m (height). Inside the prism, various layers and features are labeled: B30, B31, B32, B33, B41, B42, B43, B44, B45, B46, B47, B48, B49, B50, B51, B52, B53, B54, B55, B56, B57, B58, B59, B60, B61, B62, B63, B64, B65, B66, B67, B68, B69, B70, B71, B72, B73, B74, B75, B76, B77, B78, B79, B80, B81, B82, B83, B84, B85, B86, B87, B88, B89, B90, B91, B92, B93, B94, B95, B96, B97, B98, B99, B100. A legend on the right indicates: Sand (yellow), Gravel (orange), and Sandy gravel (light blue). A red line labeled "Traverse" is shown within the prism. The source is cited as "Source: EGS".

At the bottom of the Zoom window, there is a video feed of Dr. Hincapie, a man with short dark hair, wearing a dark shirt, sitting at a desk. The Zoom interface includes a top bar with "zoom Workplace", "Meeting", "M32047's screen", "Sign in", "Recording", "GOV", "View", and a bottom bar with "Audio", "Video", "Participants", "Chat", "React", "Share", "Apps", "Record", "More", and "Leave".

Dr. Hincapie describing GPR technology environmental applications.

This event and future events are updated and posted on the AFIT website at: <https://www.afit.edu/CE/index.cfm>.

POCs:

Joseph Dimisa, AFIT (joseph.dimisa@us.af.mil)

C.J. Garcia, CTR, Booz Allen Hamilton (carlos.garcia.56.ctr@us.af.mil)

Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)



Webinar Structure



	<u>Restoration Technology Transfer Webinar Series – eDASH Archive</u>
5 min	Welcome and Administrative Business
45 min	<i>Geophysics Techniques Available for High-Resolution Site Characterization, Part 1 – Near-Surface Geophysics, Noblis</i>
10 min	Questions and Answers
5 min	Final Thoughts

Air Force Civil Engineer Center



Geophysics Techniques Available for High-Resolution Site Characterization (HRSC)

Part 1 – Near-Surface Geophysics

Jaime Hincapie
Geophysicist

Noblis

May 2025



Today's Presenter



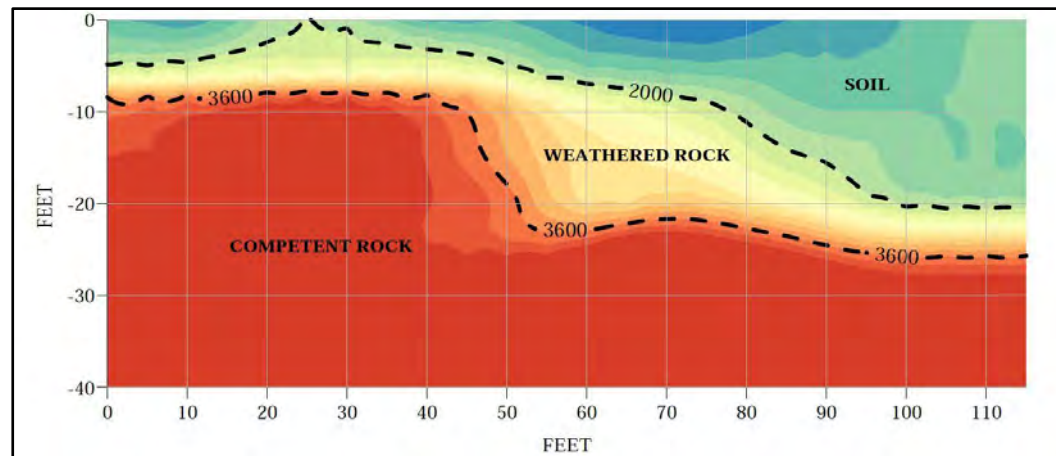
Jaime Hincapie, PhD, PG, CDA

Earth Systems / Data Scientist (25 years)

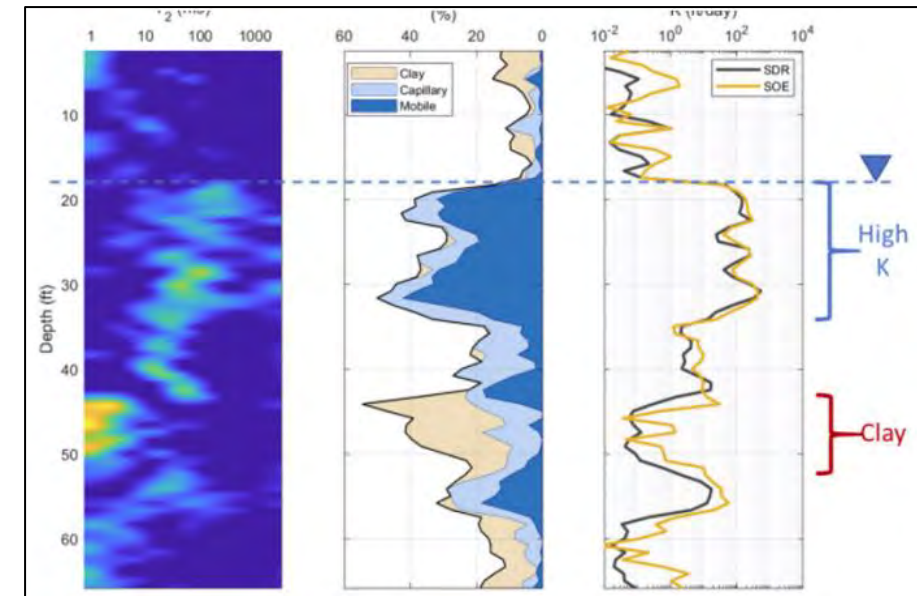
San Antonio, TX

Jaime.Hincapie@noblis.org

Part 1 – Near Surface Geophysics



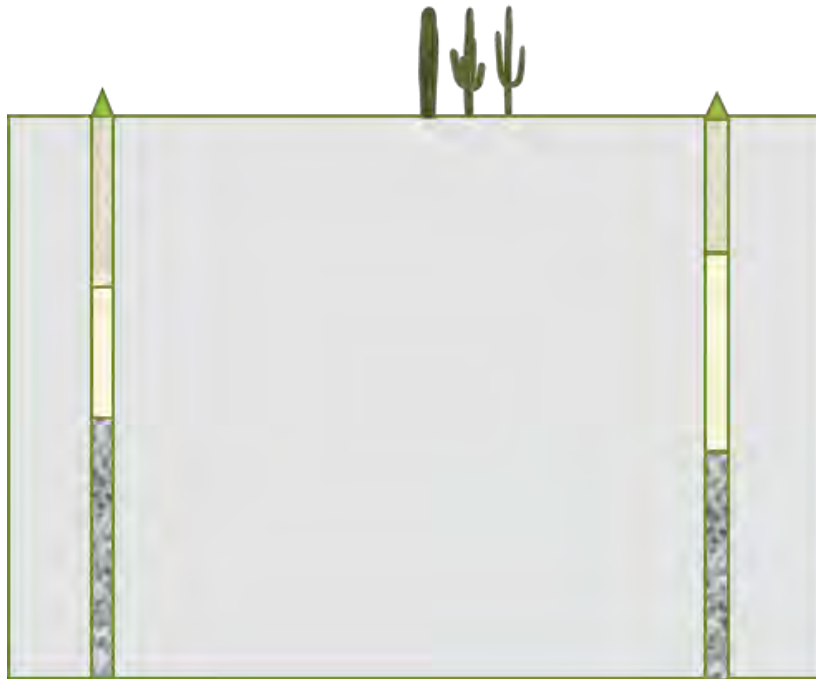
Part 2 – Borehole Geophysics



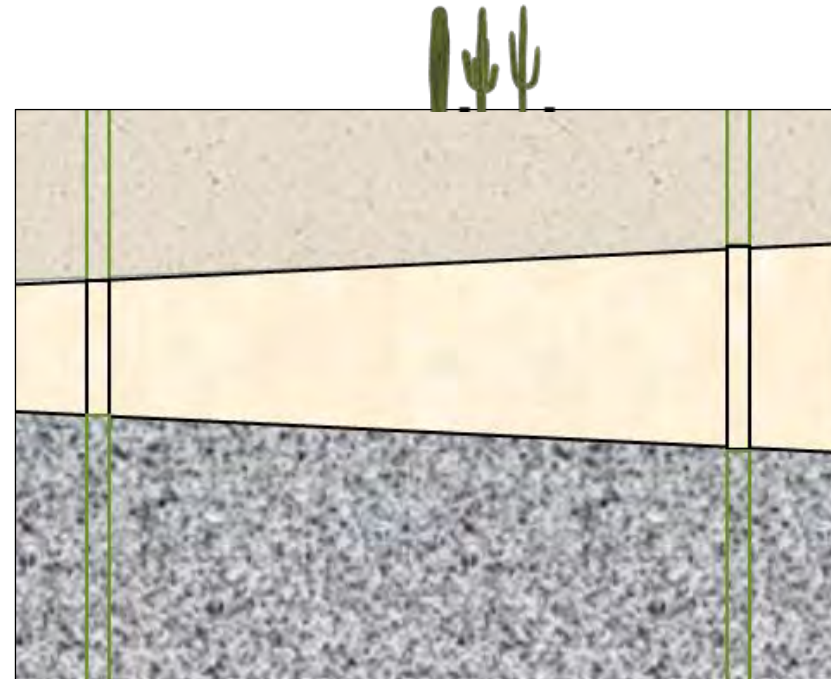


- **Training Webinar Part 1**
 - **Learning Objectives**
 - **Near-Surface Geophysics Techniques**
 - **Scope and Cost Considerations**
 - **Takeaways**

Geophysical investigations can enhance knowledge of sitewide conditions, reduce uncertainties and ultimately provide a more informed and efficient HRSC* scope design



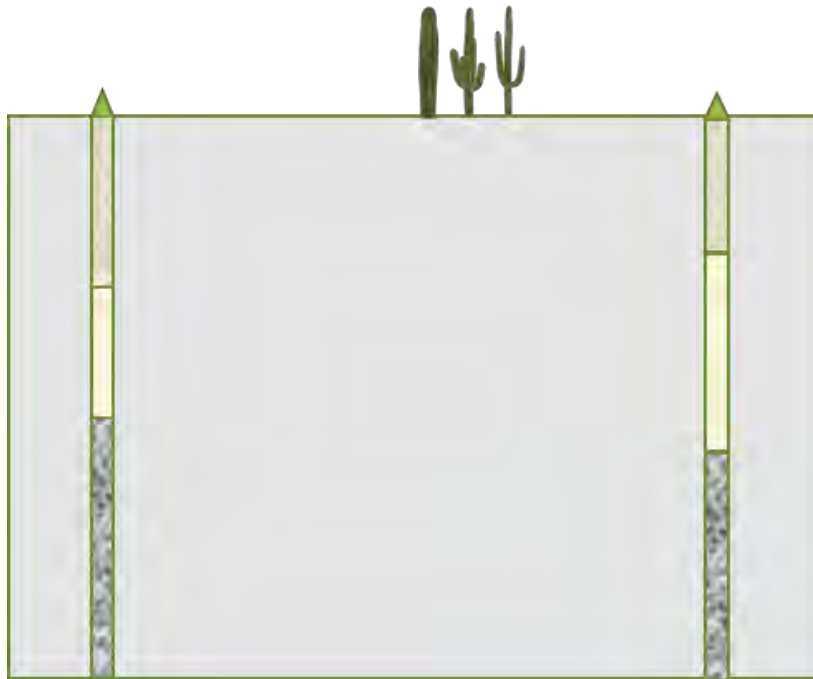
Point information from boreholes



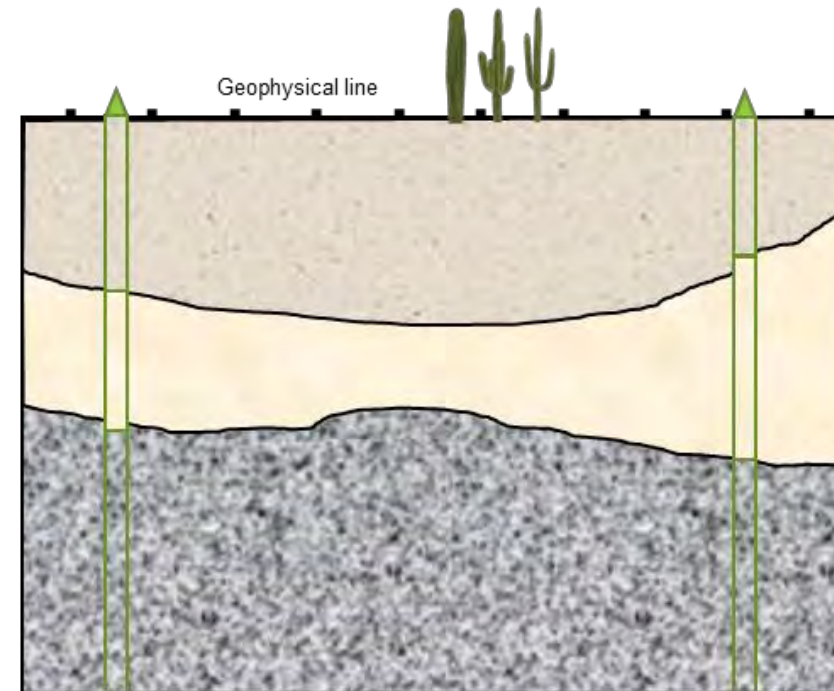
An interpretation of point data

* HRSC: High Resolution Site Characterization

Geophysical investigations can enhance knowledge of sitewide conditions, reduce uncertainties and ultimately provide a more informed and efficient HRSC* scope design



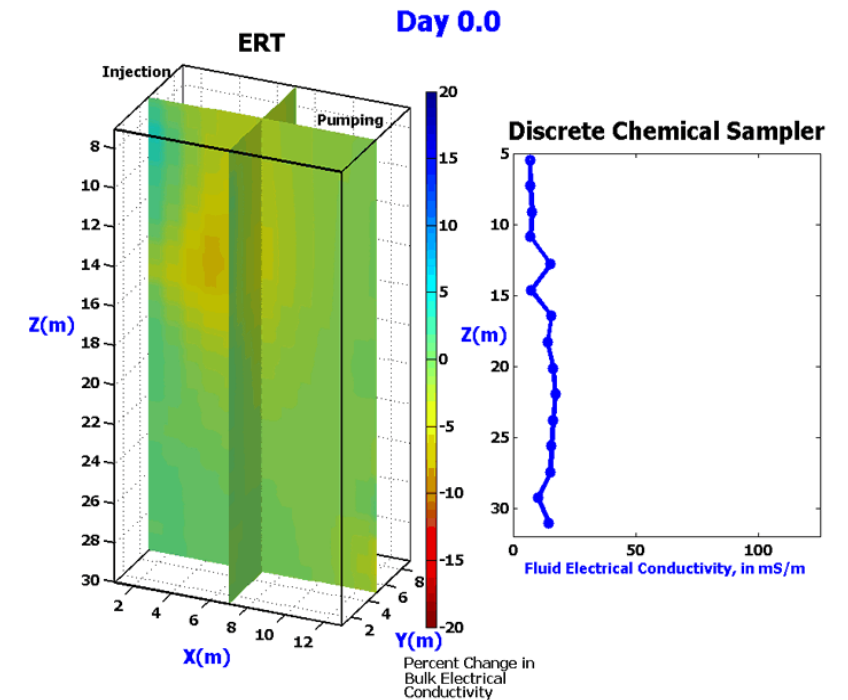
Point information from boreholes



Point data integrated with geophysics and knowledge of the local geology.

* HRSC: High Resolution Site Characterization

- **Purpose:** Provide an overview of environmentally-focused geophysics tools
- Environmental geophysics measures the physical properties of the Earth to aid in understanding complex geologic and hydrogeologic settings, which can include:
 - Lithologic mapping
 - Structural mapping (fractures, joints, bedding)
 - Aquifer property characterization
 - Distribution of water content and mobility
 - Contaminant plume mapping
 - Well integrity testing
 - Remedial system monitoring and/or design
 - Fluid migration over time (e.g., tracer testing)
- Non-invasive techniques (surface or in-well or in-borehole)
- Requires and informs the conceptual site model (CSM)
- Specific method(s) selection depends on the problem at hand



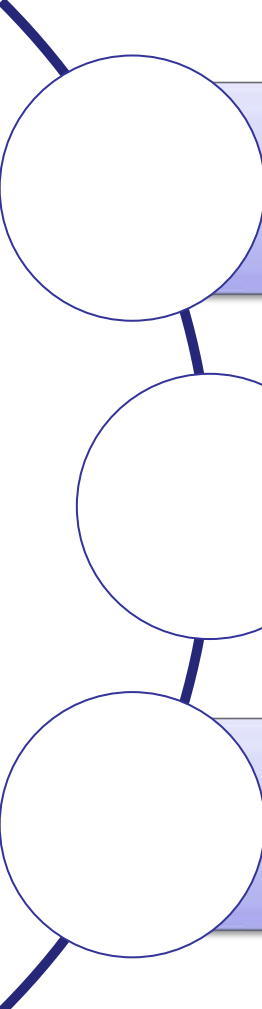
Source: [USGS](#)



Near-Surface Geophysics



Learning Objectives

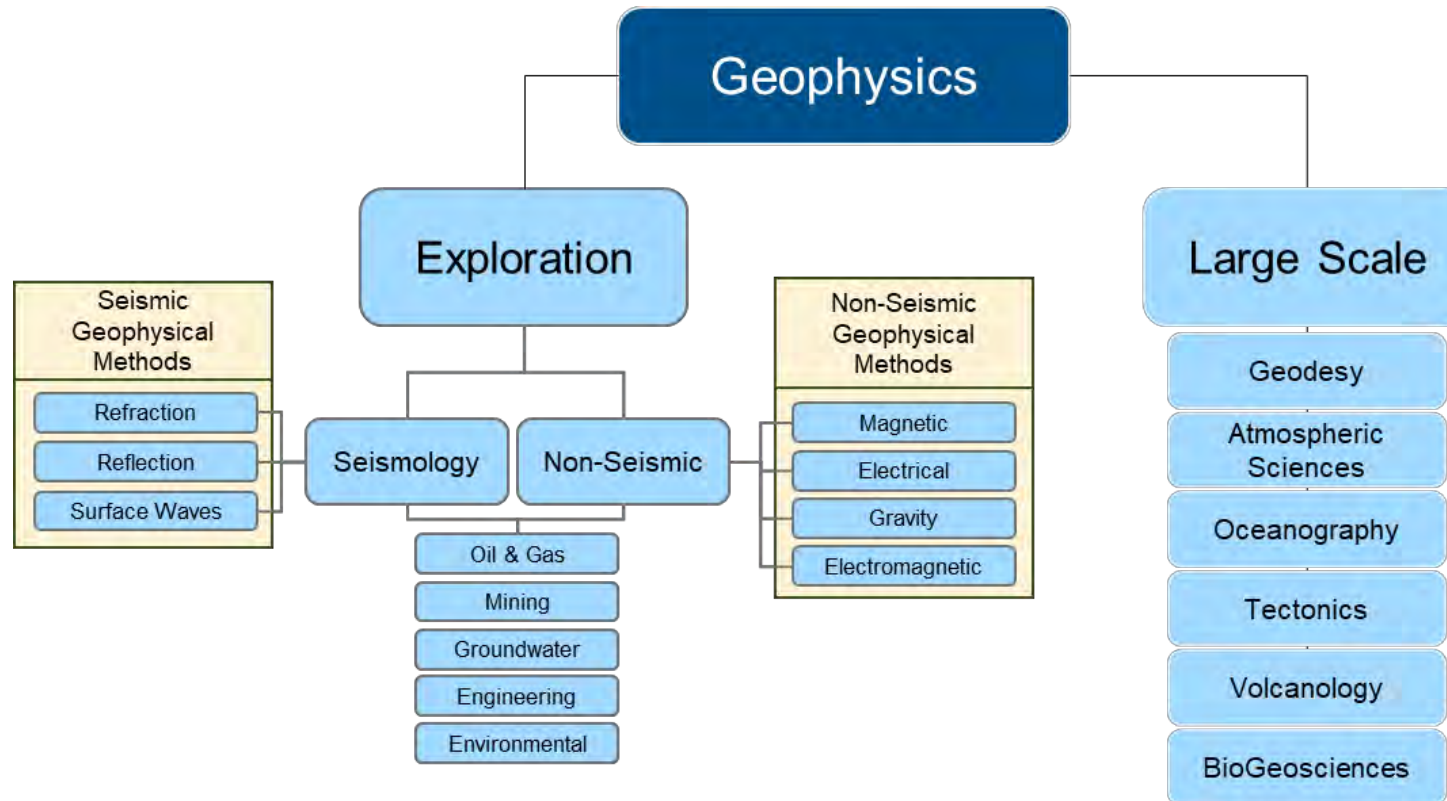
A diagram on the left side of the slide consists of three white circles connected by a dark blue line. The line starts at the top circle, goes down to the middle circle, and then goes down to the bottom circle. The circles are positioned to the left of the learning objective text boxes.

Understand how near-surface geophysical methods can be used in environmental applications.

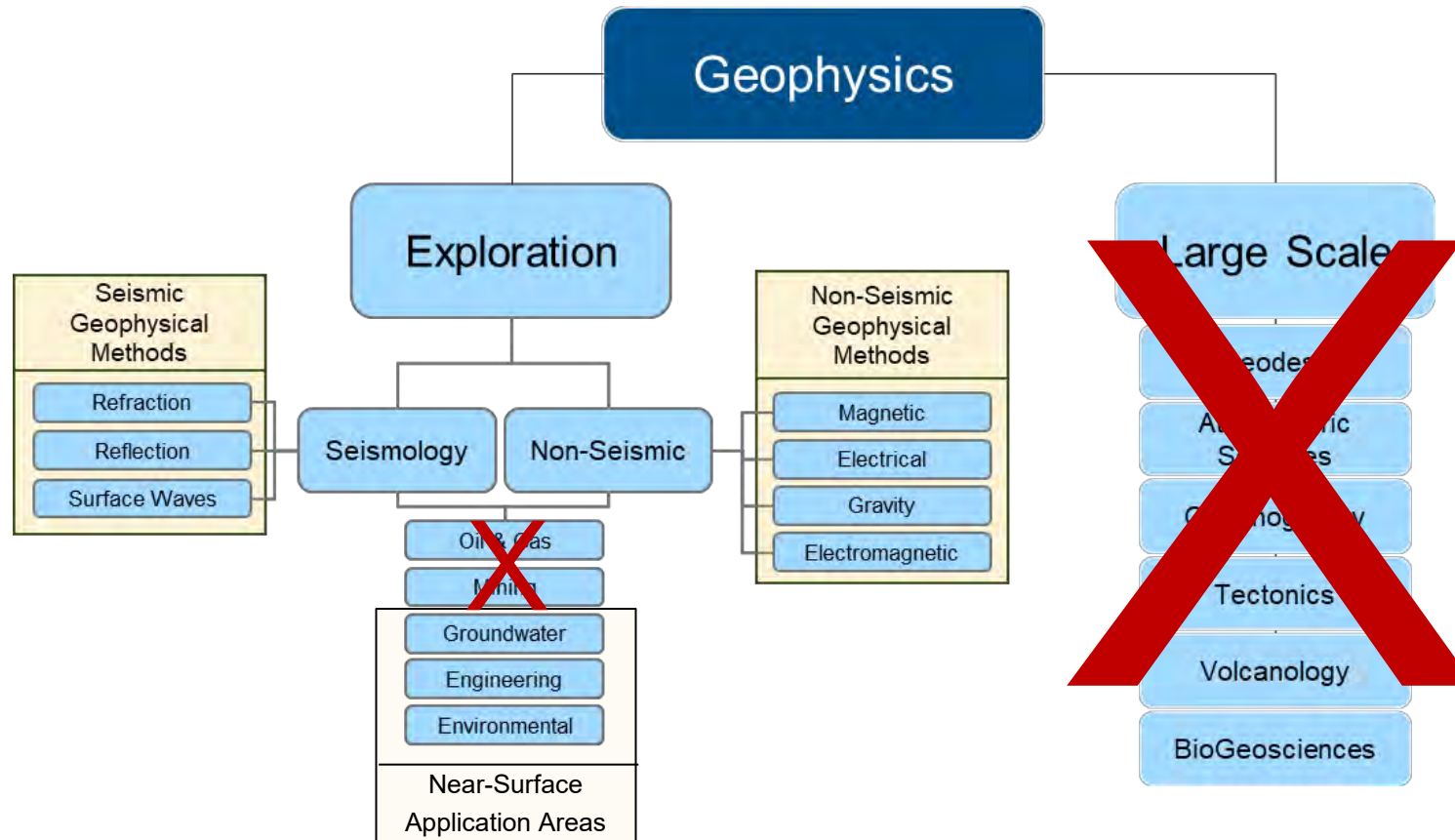
Learn that near-surface geophysical methods can probe large areas quickly, accurately, economically, and can extrapolate findings from direct exploration methods (boreholes).

Learn that near-surface geophysical methods selection depends on the problem at hand and can be used as standalone, but they complement each other effectively.

- Non-invasive/non-destructive approach
- Near-Surface Geophysics within approximately 100 meters below ground surface
- Environmental studies are mostly in the *near-surface* depth range
- Any Geophysical Exploration Method can be *near-surface*



- Non-invasive/non-destructive approach
- Near-Surface Geophysics within approximately 100 meters below ground surface
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- Any Geophysical Exploration Method can be *near-surface*

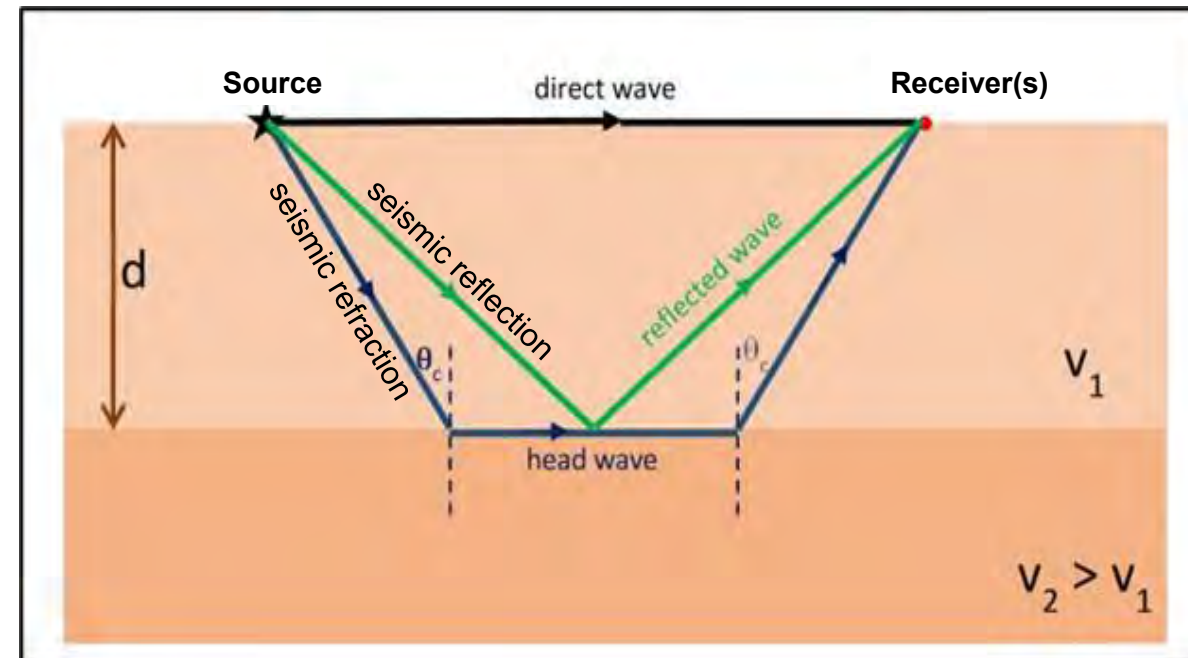


Seismic Methods Measure Time

- Distance (along the surface) between source and receivers is known,
- Source produces waves that travel into the ground,
- Waves can reflect (bounce off) the top of layers (reflection) or
- They can travel along the layers' interface (refraction) and
- They go back to the surface where they are detected and recorded

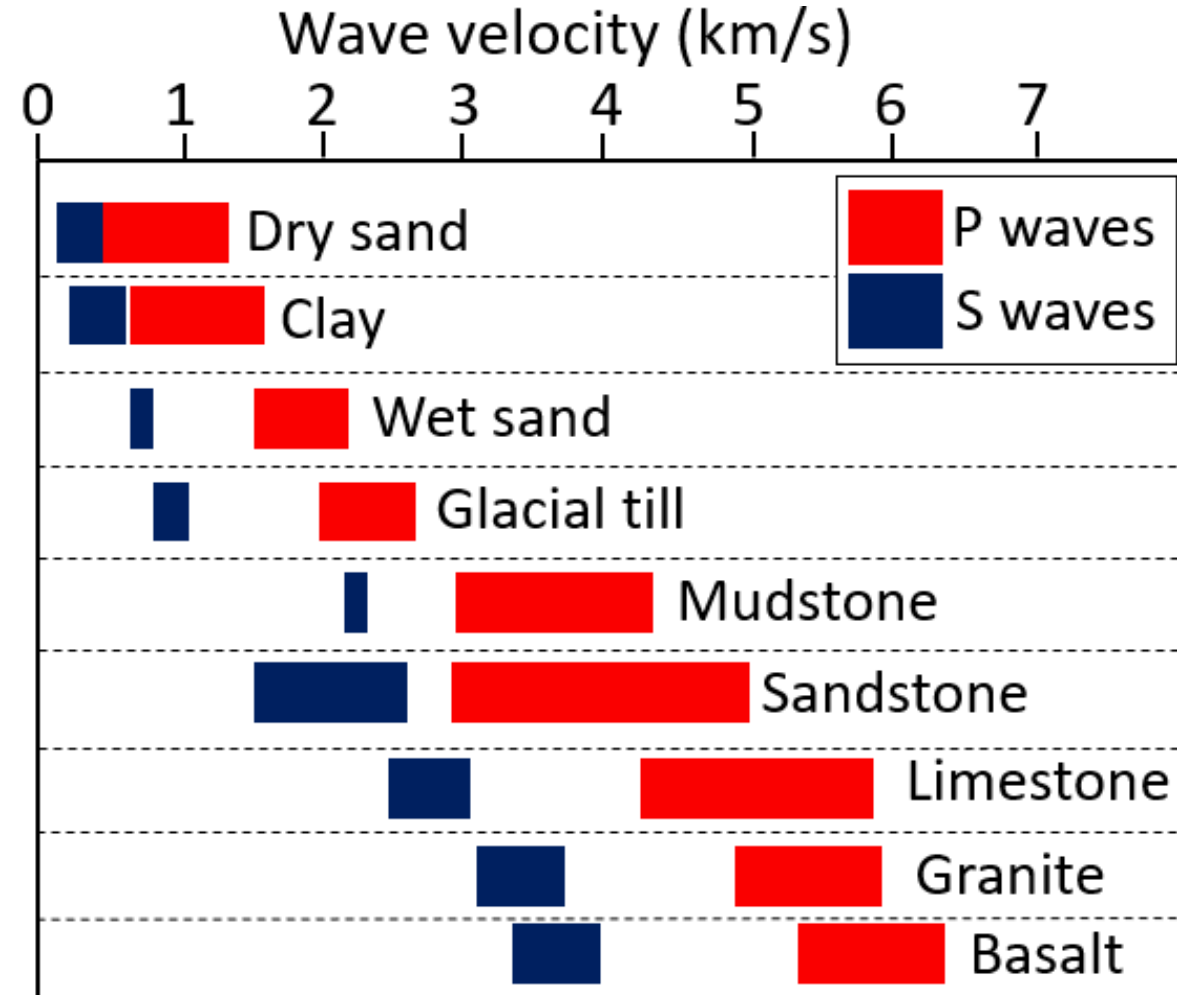
By measuring the time it takes for the waves to travel from the source to the receivers you can calculate

- How fast the waves move through the layers (proxy for the material type)
- Layer geometry: depth, thickness, inclination, shape, etc.



Velocities of Some Earth Materials

- P-waves always faster than S-waves
- S-waves do not travel through fluids



Source: Understanding Earth Through Seismology – Physical Geology – 2nd Edition (opentextbc.ca)

Seismic Reflection

How It works

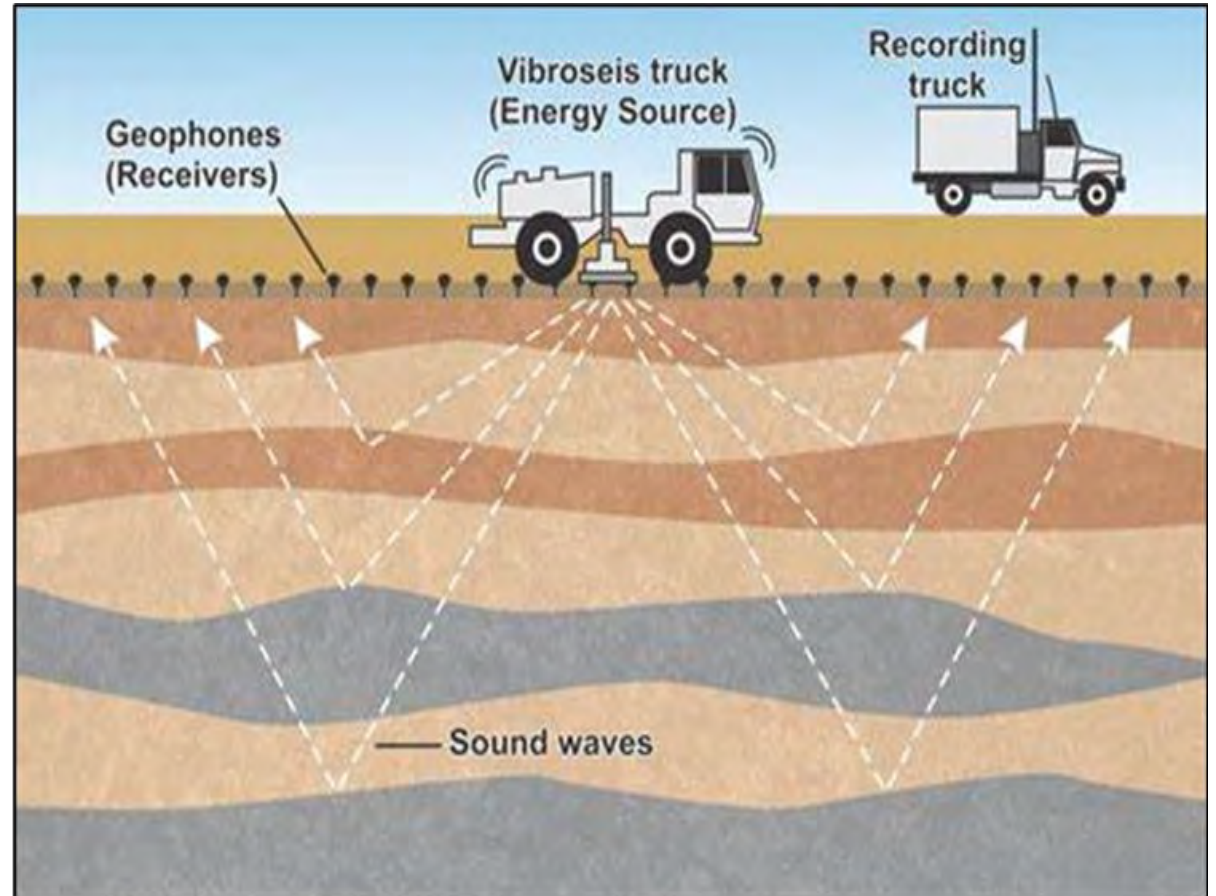
- Active source sends waves into subsurface
- Waves reflect at layer interfaces (reflectors)
- Reflections are recorded with sensors (geophones) on the surface
- Source-reflector-sensor time is measured
- Data processing leads to depth and shape of reflectors

Applications

- Mostly Oil & Gas exploration
- Limited environmental application
- Almost none in near-surface depths

Challenges

- Lengthy data processing
- Cost-prohibitive

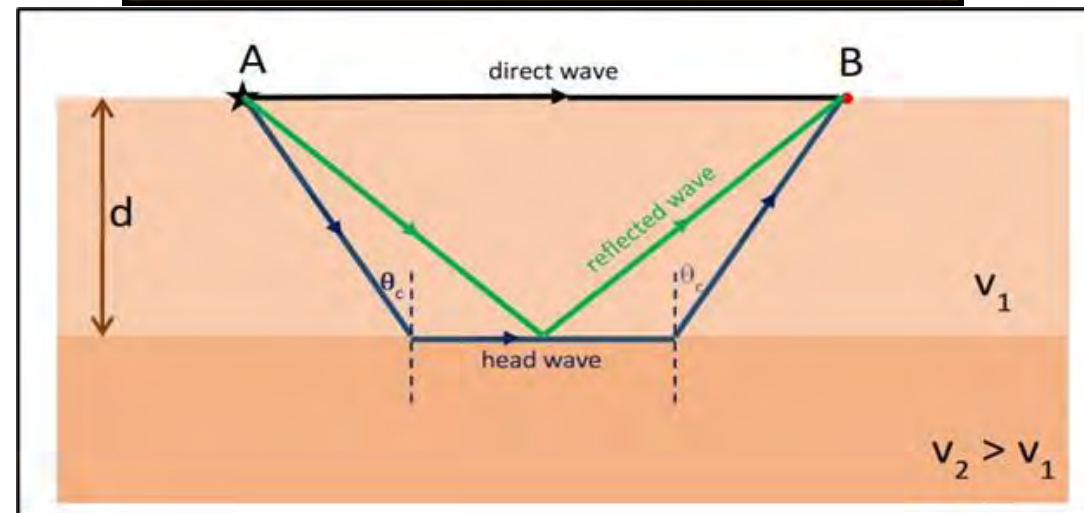
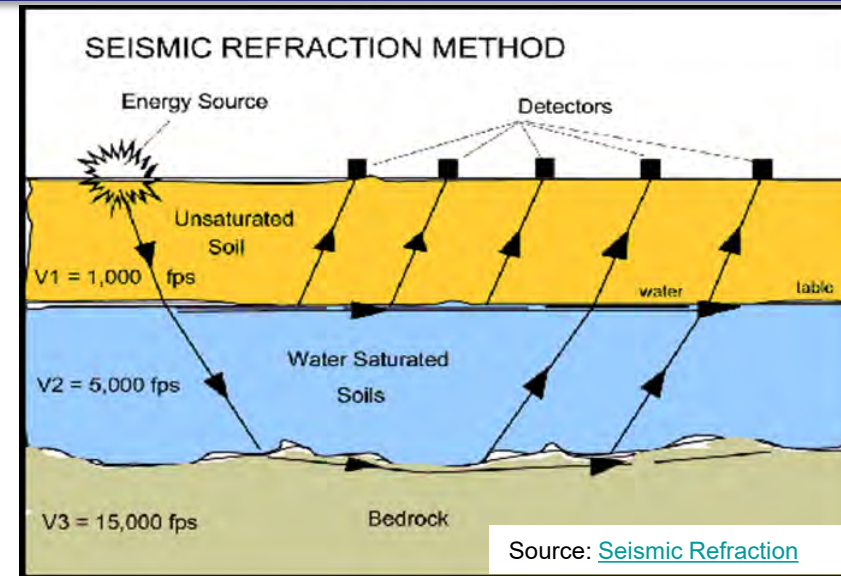


Source: [Seismic Reflection](#)

Seismic Refraction

Environmental Applications

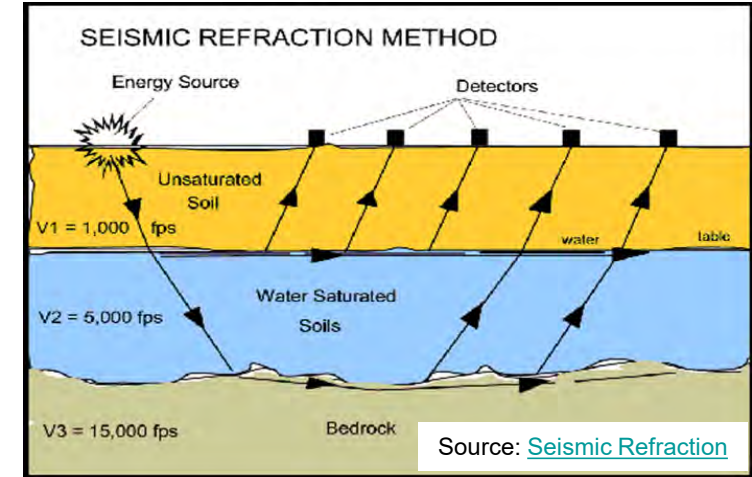
- Depth to bedrock
- Layer thickness and geometry
- Rock type estimation
- Proxy for fracturing patterns
- Depth to water table
- Cavity detection



P-waves Refraction

How It works

- Active source sends waves into subsurface
- Waves refract at layer interfaces (refractors) (Snell's Law, Huygen's Principle)
- Reflections are recorded with sensors (geophones) on the surface
- Source-refractor-sensor time is measured
- Data processing leads to depth and shape of refractors

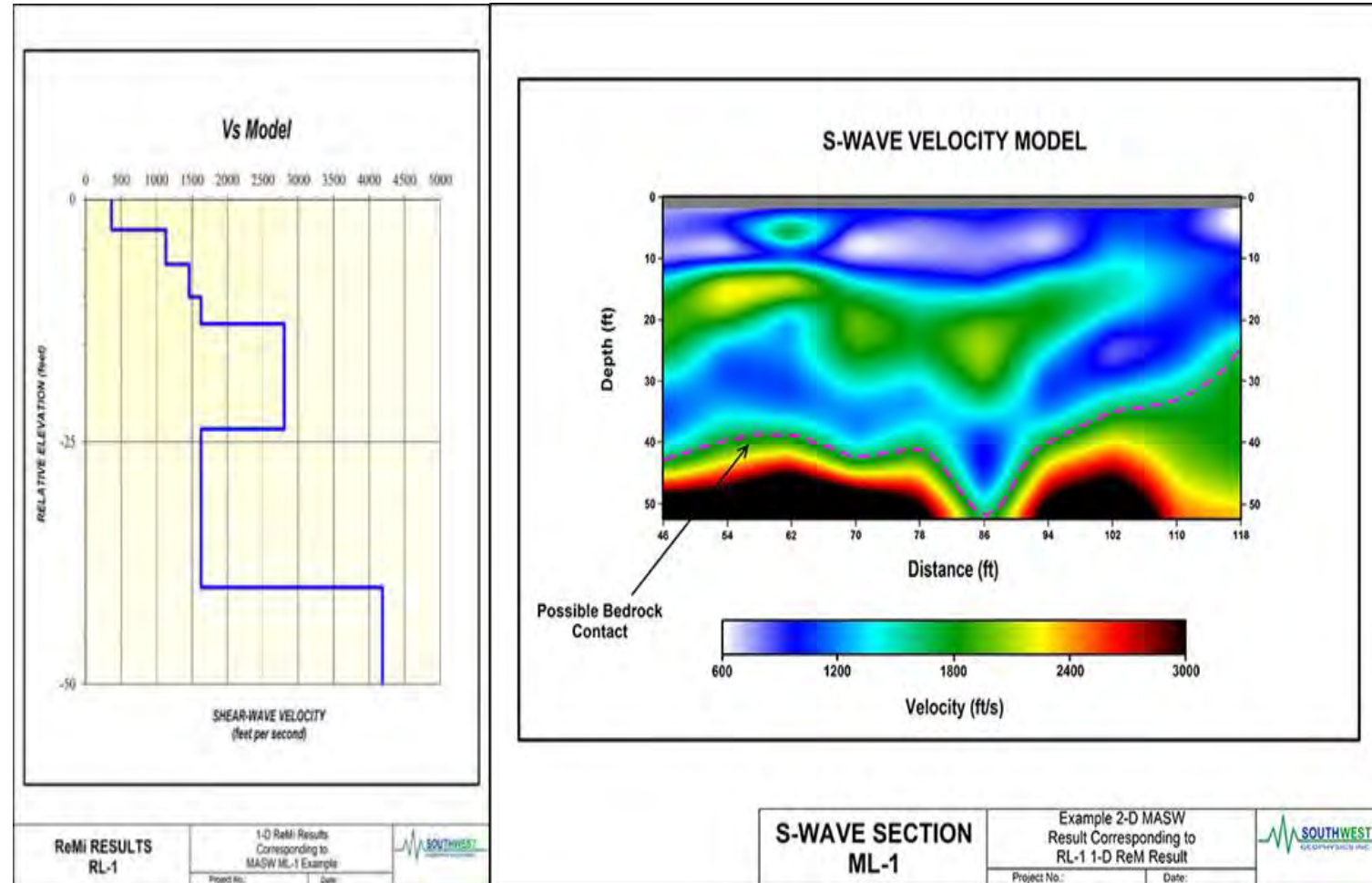


Three Main survey types

- Multichannel Analysis of Surface Waves (MASW)
- Spectral Analysis of Surface Waves (SASW)
- Refraction Microtremor (ReMi)

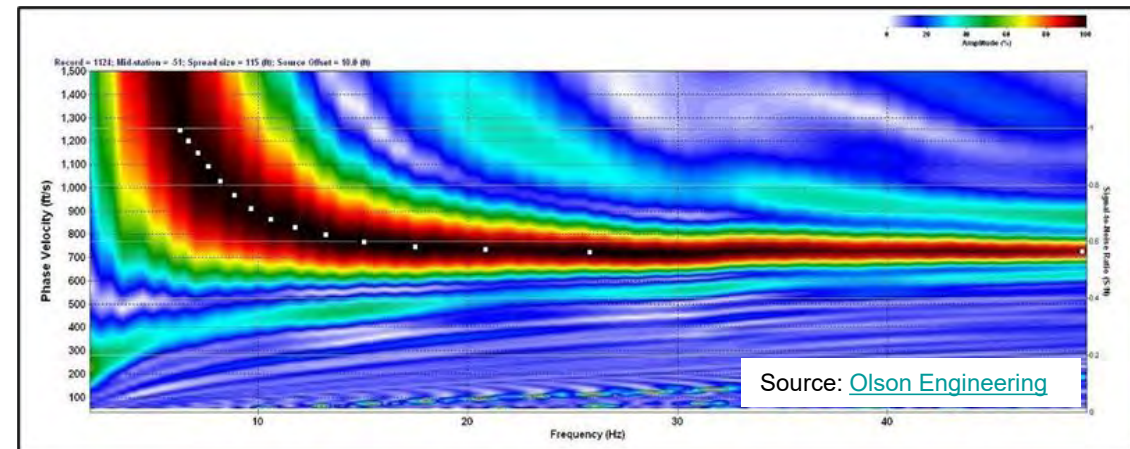
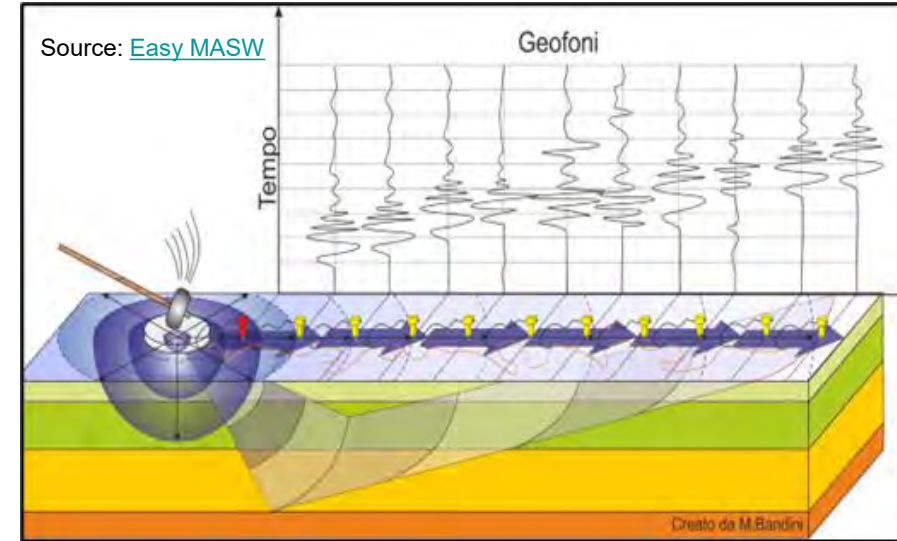
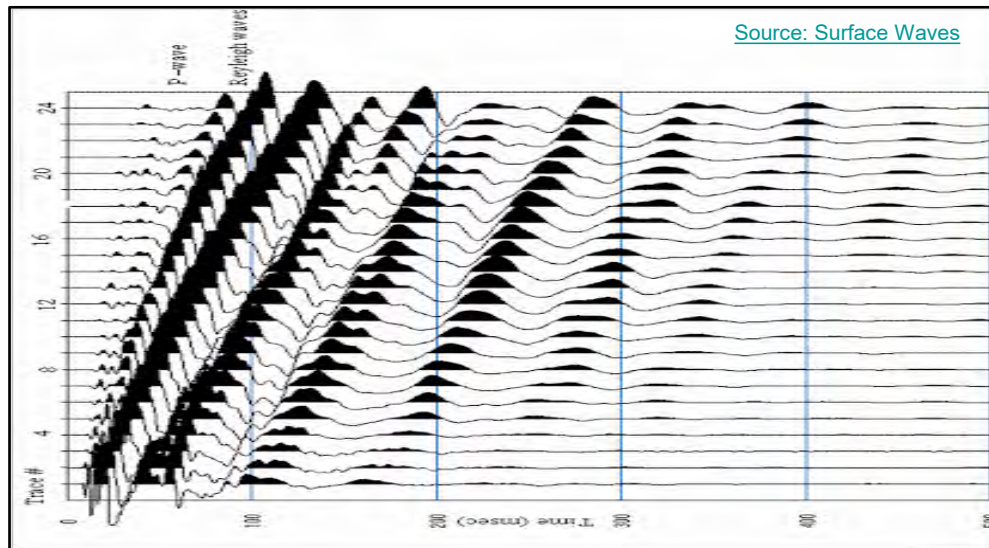
Applications

- ReMi and SASW mostly in Geotechnical Engineering to get shear moduli for soil bearing capacity and response to dynamic loads
- Environmental Surveys: proxy for rock compactness (fracturing, permeability) as potential contaminant paths
- Identification of velocity reversals and/or rock/soil containing fluids
- Depth to water table
- Cavity detection
- Subsurface layers mapping



How They Work

- MASW data can be collected with refraction data (geophone array)
- Source-geophones times are collected, wave dispersion and spectrograms are created
- Times and dispersion curves are processed to produce depth to layers and their geometries

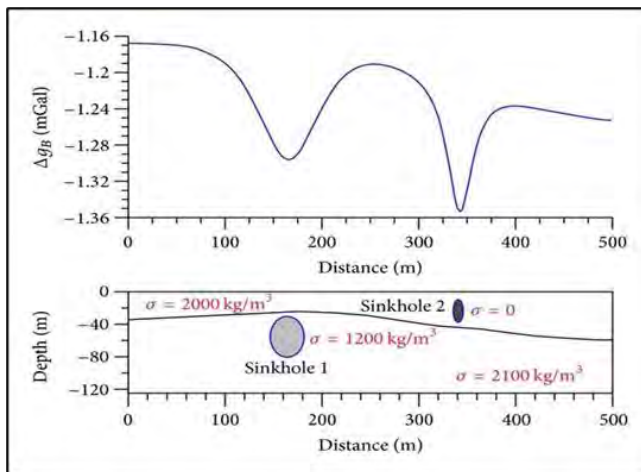


Gravimetry

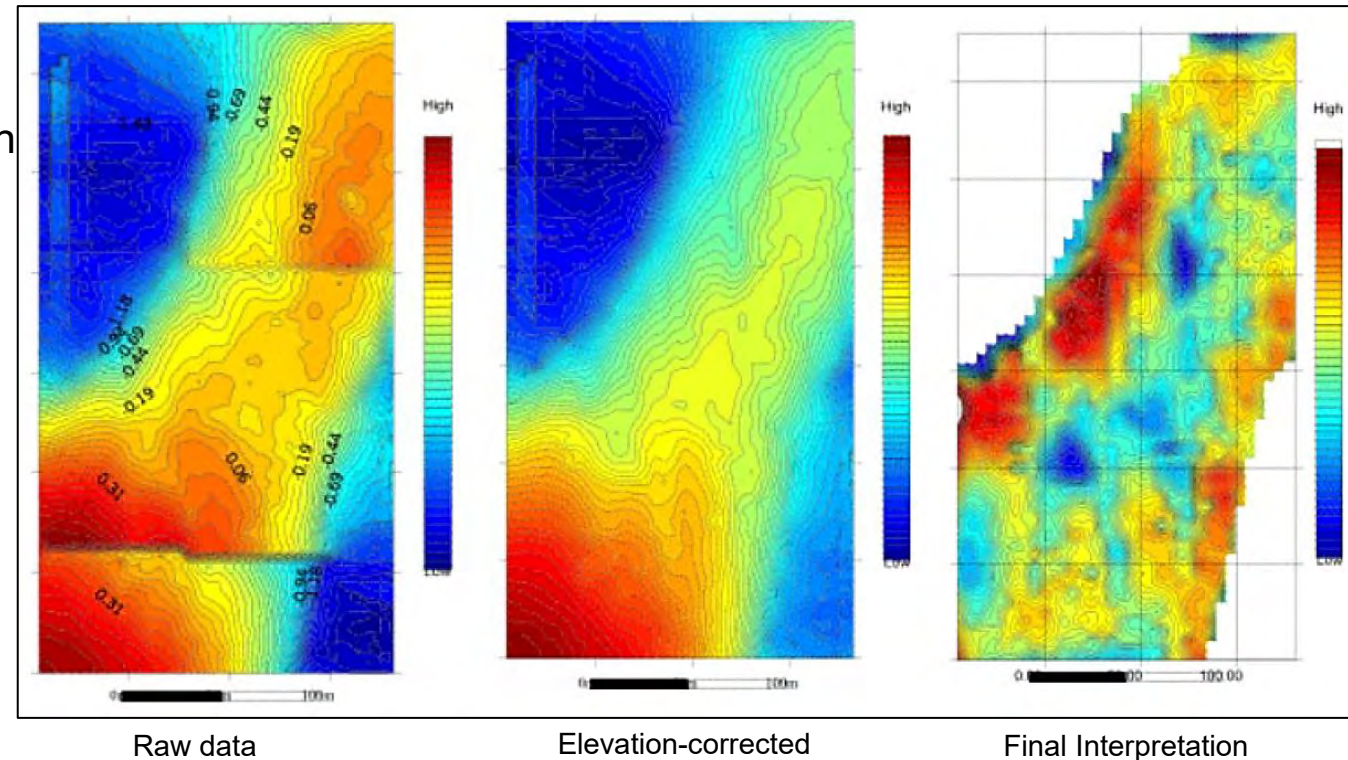
Detection and location of features of interest by recording the very small local variations of Earth's gravitational field

Environmental Applications

- Regional bedrock mapping (due to its low spatial resolution)
- Very good for void detection and estimation of changes in material density due to fracturing and porosity (microgravimetry)



Source: ResearchGate



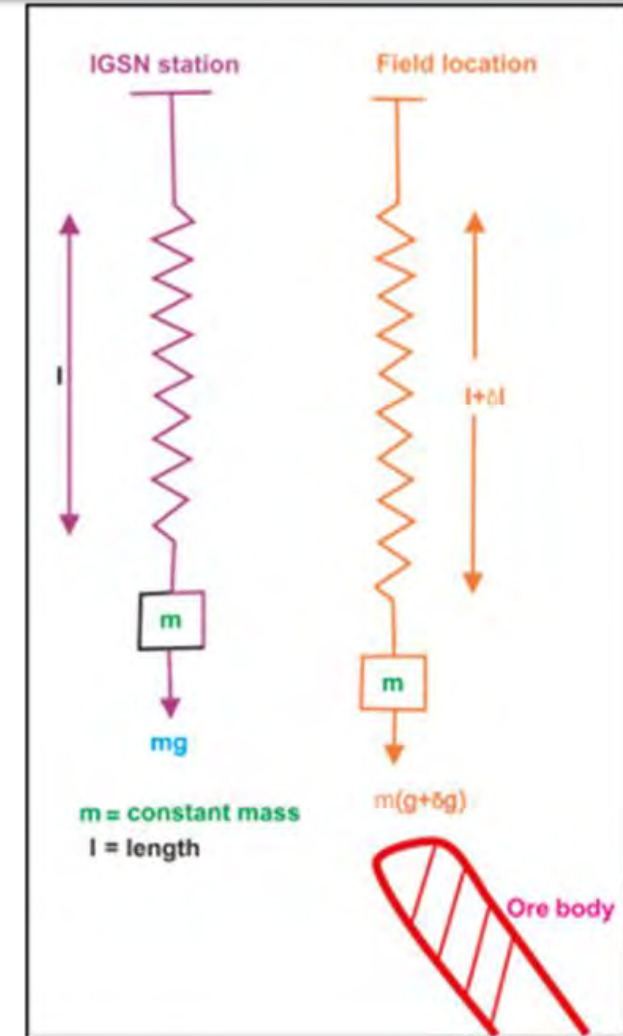
Source: HRSC Guidance for Groundwater Restoration Sites

Gravimetry

Detection and location of features of interest by recording the very small local variations produced on Earth's gravitational field

How It works

- Since gravity is a function of density, changes in subsurface materials' density will cause local alterations of gravity field
- Measures extension/contraction of a spring -attached to a known mass - as a result of change in the local gravitational pull
- Spring stiffness is very well known
- Calculations produce the density of the material causing the change in the gravity field.



Source: [Geology Science](#)

Magnetometry

Detection and location of features of interest by recording the very small variations they produce on Earth's magnetic field

Applications

- UXO
- UST
- Buried Pipes
- Landfills surveys
- "Lost" septic tanks

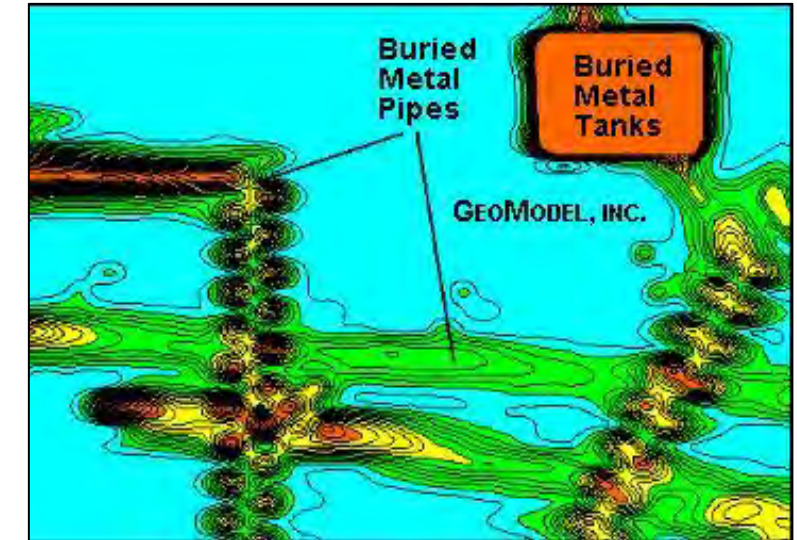
Tools

- Gradiometer
- Magnetometric resistivity (MMR)



Source: [Edwards AFB](#)

MMR Survey



Source: [Geomodel](#)

Magnetometry

Detection and location of features of interest by recording the very small variations produced on Earth's magnetic field

How It works

- Measures hydrogen atoms' precession as a response to an induced magnetic field
- Precession helps calculate strength and direction of local magnetic field
- Calculations lead to location (depth) and size of the cause of the magnetic anomaly



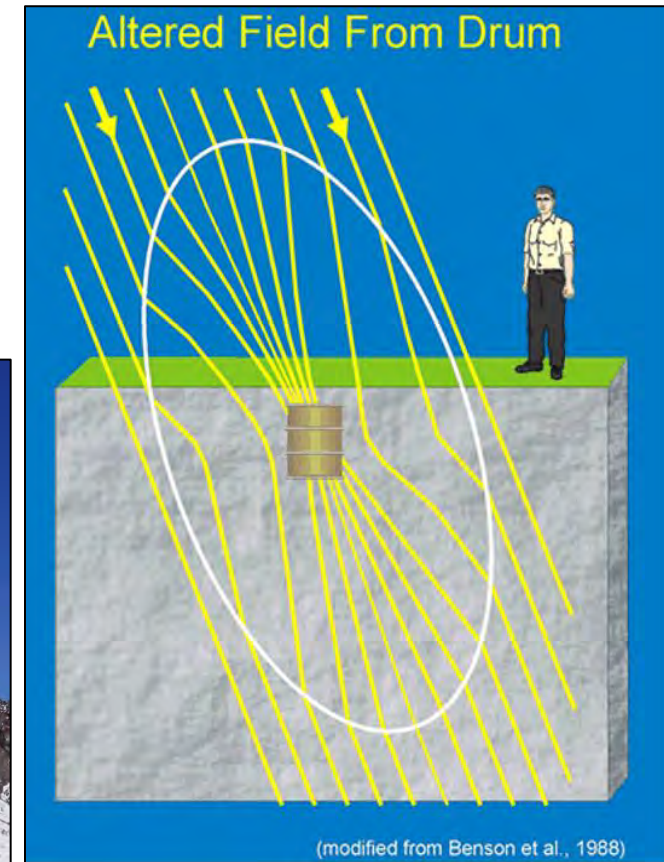
Source: [Gemsys California](https://www.gemsys.com)



Source: www.ageophysics.com



Source: [Commons Wikimedia](https://commons.wikimedia.org)



Source: [CLU-IN Technologies](https://www.clu-in.com)

Electrical Methods

Measure material's resistance to electric flow

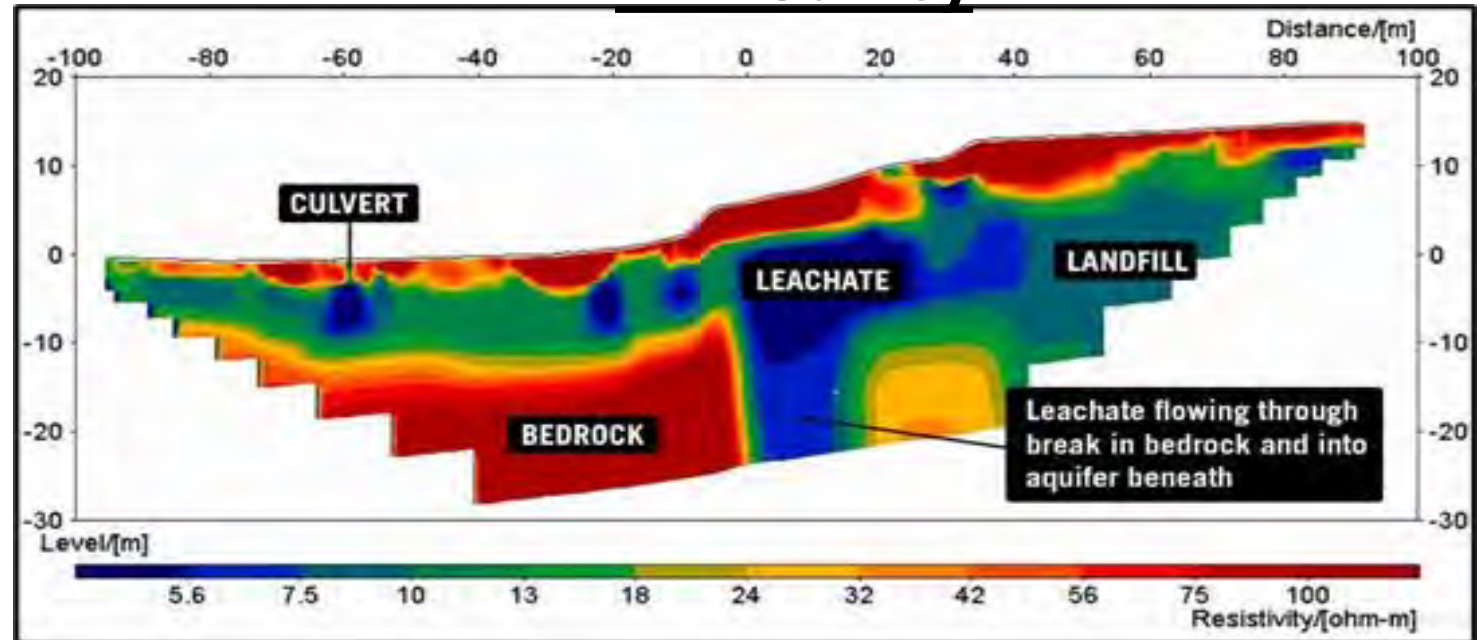
Applications

- Depth to water table
- Depth and geometry of layers
- Fluids presence/absence in groundwater
- Pore space water volume
- Cavity detection
- UST leakage
- Landfill characterization

Tools

- Vertical Electric Sounding (VES)
- Electrical Resistivity Tomography (ERT)

ERT Survey



Source: www.guidelinegeo.com: resistivity and induced polarization

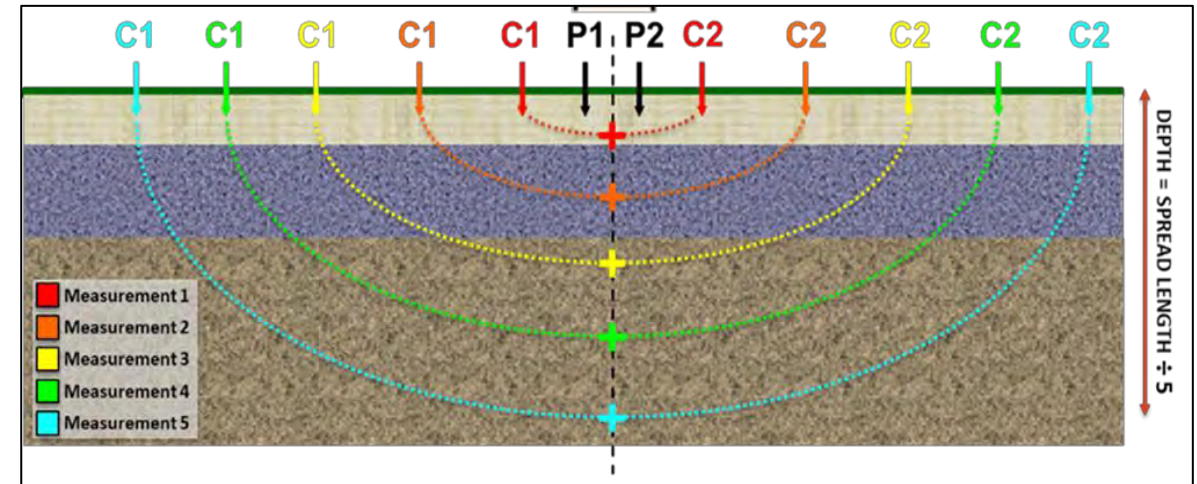
Electrical Methods

Measure earth materials' resistance to electric flow

How They Work

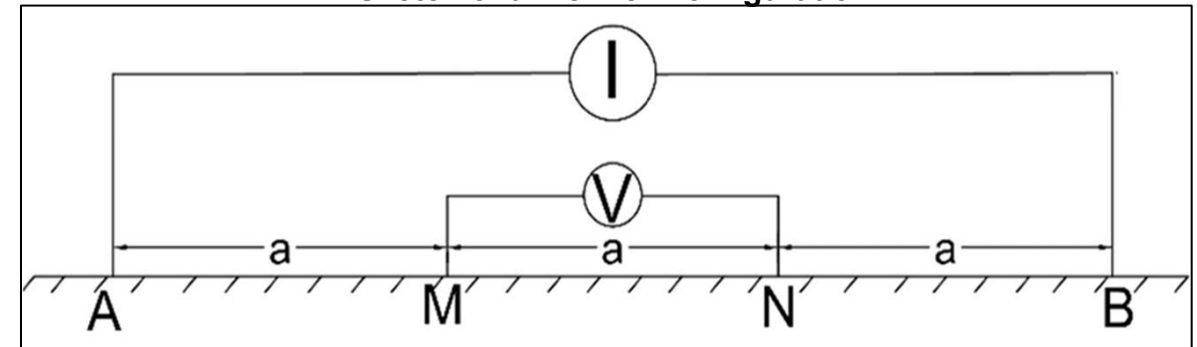
- Electrical current is sent into the ground through electrode pairs ("current" electrodes)
- Current interacts with materials
- Interaction with earth materials is measured by electrode pair ("potential" electrodes) as voltage
- Using electrode distances, current intensity and voltage measurements; depth, layer thickness and geometry can be calculated.
- There are many array configurations (selected for site-specific application)
 - Most common: VES, Wenner
 - Grid configurations for 3D mapping of subsurface (ERT)

Sketch of a VES Configuration



Source: [Terrameter VES](#)

Sketch of a Wenner Configuration



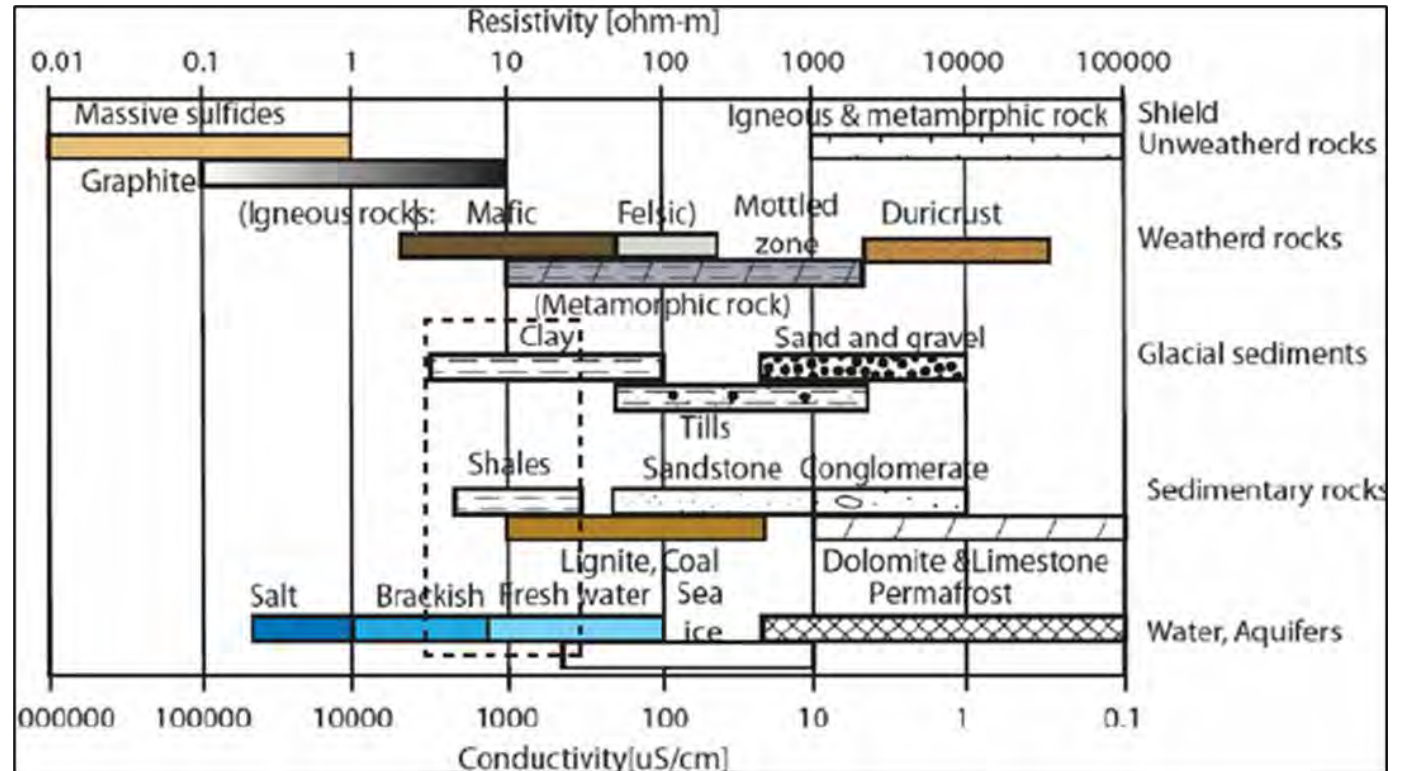
Source: [ResearchGate](#)

Electrical Methods

Measure material's resistance to electric flow

Resistivities of Some Earth Materials

- Water content has a strong influence
- Due to their mineral structure, clays and shales are often more conductive
- Rocks, sediments with metallic minerals are often more conductive



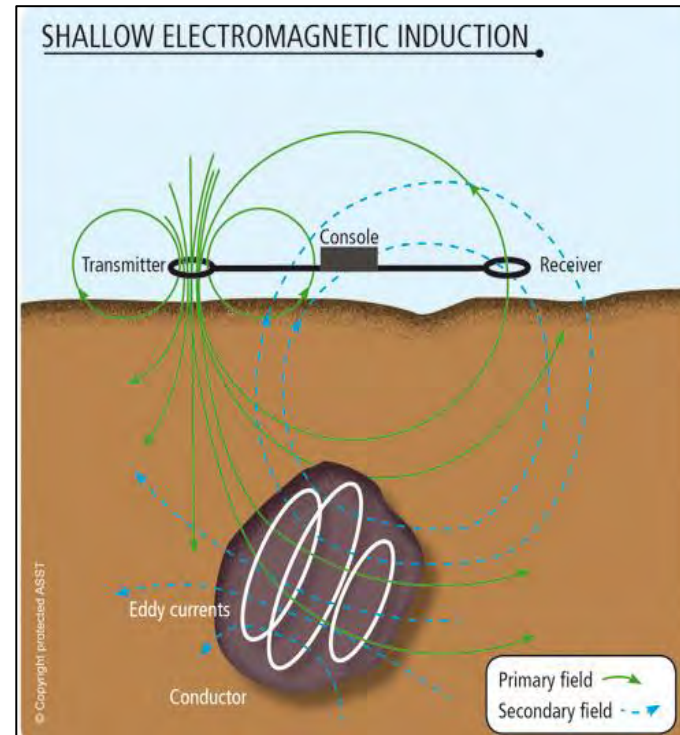
Source: [Research Gate](#)

Electromagnetic conductivity (EM)

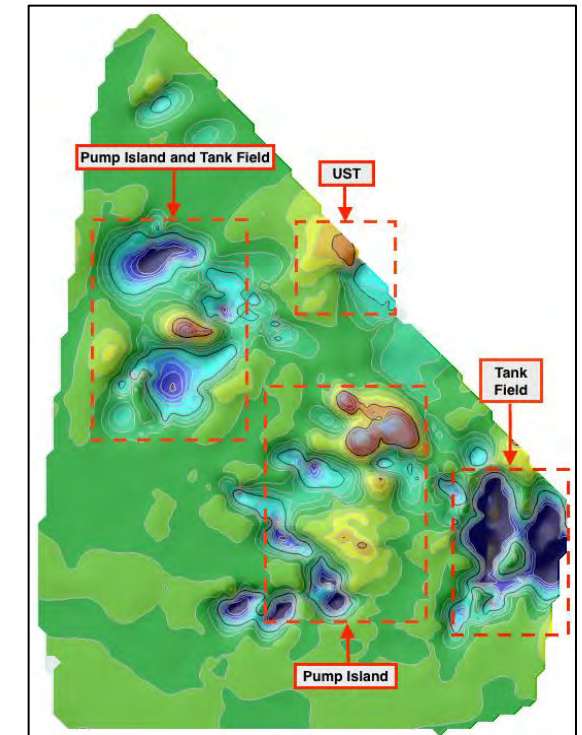
Measure electromagnetic and magnetic properties of materials

Environmental Applications

- Mapping soil moisture/porosity/structure
- Mapping soil/groundwater salinity
- Identifying tunnels, unexploded ordinance (UXO), utilities, drums, tanks, etc.
- Mapping groundwater contamination, plume locations, and/or groundwater discharge
- Monitoring changes in fluid conductivity or salt-water intrusion over time
- Mapping bedrock structure and/or permafrost



Source: [ASST Group](#)



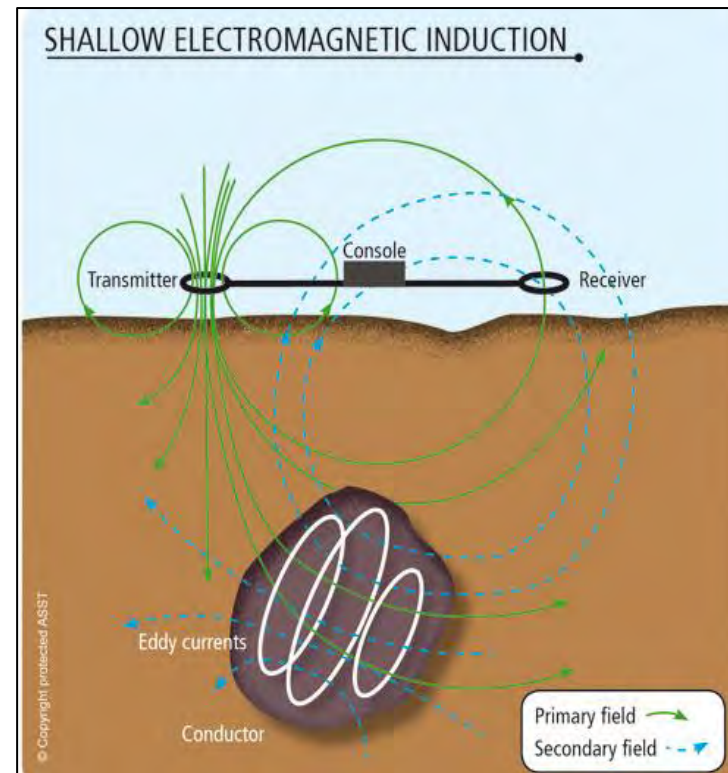
Source: [American Geophysics](#)

How it Works

- Time-varying electromagnetic signals are sent into the ground by a transmitter antenna (Tx).
- Materials create time-varying magnetic fields that are recorded by the instrument's receiver antenna (Rx).

Tools

- Depending on depth of exploration and resolution.
- Most common:
 - EM31 and EM38 (groundwater, layering, UST)
 - GEM3 (UXO)



Source: [ASST Group](#)

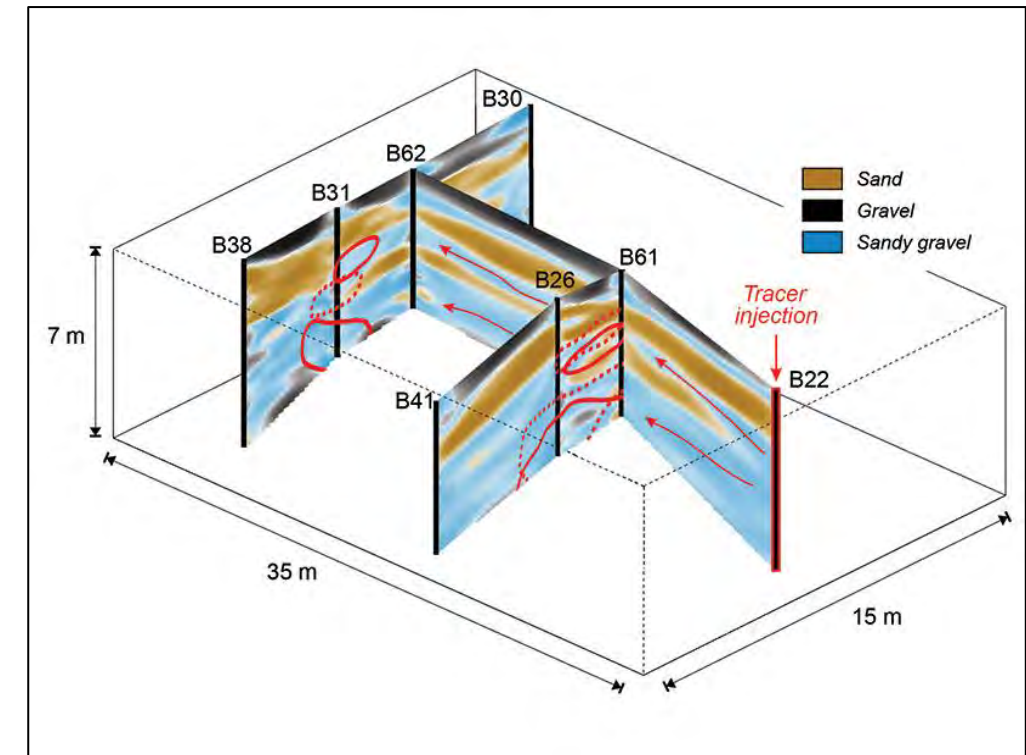


Ground penetrating radar (GPR)

Uses radar pulses to image the subsurface.

Environmental Applications

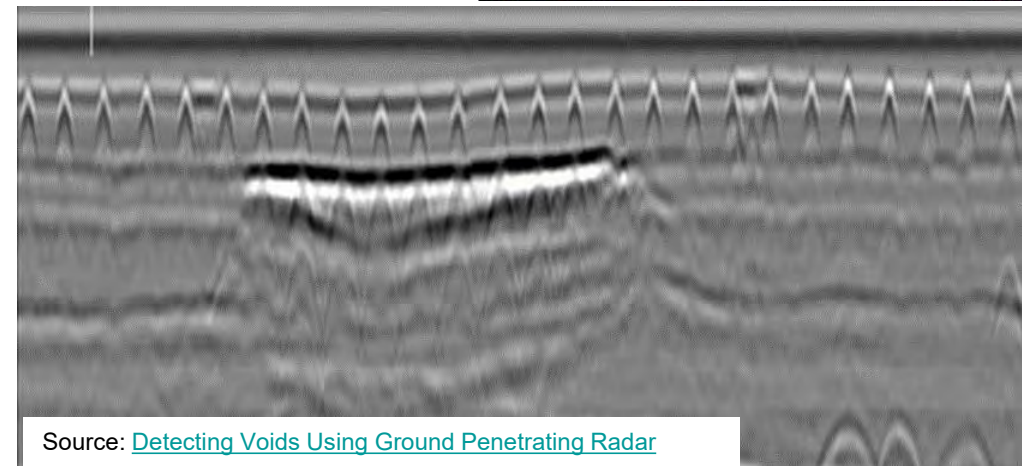
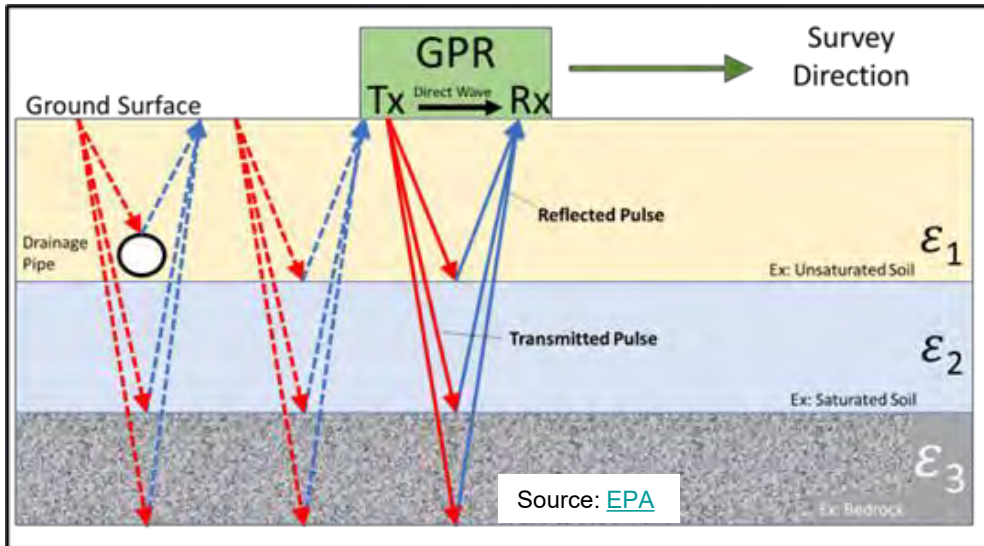
- Locating pipes, tanks, and other utilities
- Locating the groundwater surface
- Identifying and mapping the extent of groundwater contamination
- Identifying karst features, voids, and burrows
- Mapping bedrock configuration, structure and depth
- Detecting unexploded ordinance and unmarked graves
- Delineating soil horizons and soil stratigraphy
- Determining ice thickness (e.g., permafrost)
- Determining water depth in lakes



Source: [EOS](#)

How It Works

- Signal is transmitted into the subsurface where it reflects off the dielectric interfaces
- Continuous survey produces cross section or 3D image
- Electromagnetic signals' velocities are used to calculate depth to targets





Scope and Cost Considerations

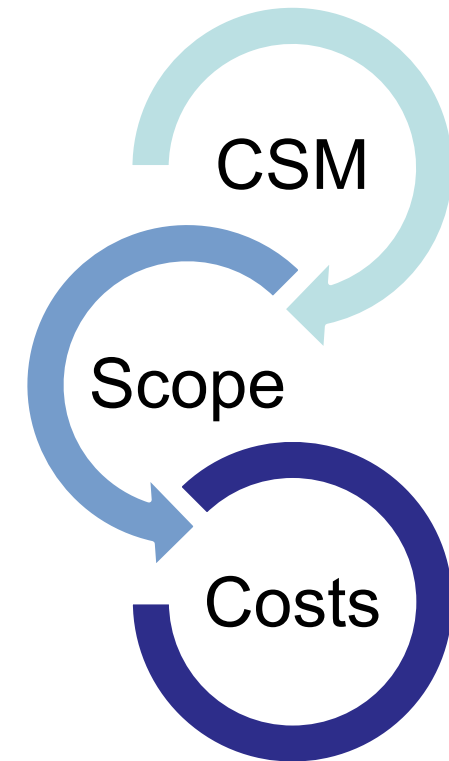


■ Scope Considerations

- Evaluate responses of geophysical methods to environmental issues before deciding an alternative course of action.
- Make appropriate judgments and decisions for the remediation, protection and improvement of the affected areas
- Enable the understanding of the causes and consequences of the issues and measures to minimize their effects.

■ Costs are usually dependent on

- Technology or technologies (methods) to be used
- Size of the survey (e.g., single line vs. 3D survey)
- Presence/absence of hazardous materials/objects
 - Slope
 - Loose rocks
 - Utility corridor (subsurface power lines, conduits, etc.)
 - Flammable materials
 - Wildlife





Takeaways



- The selection of geophysical method(s) depends on the challenge or problem that is being addressed (e.g., water table: seismic; UST/UXO: magnetics)
- These methods can be used as standalone or as complementary technologies
- These methods can provide 2D and 3D information of the subsurface, quickly, economically, and accurately
- When used with borehole information, they can extrapolate and provide a very accurate picture of the subsurface between boreholes



Understand how near-surface geophysical methods can be used in environmental applications.



Learn that near-surface geophysical methods can probe large areas quickly, accurately, economically, and can extrapolate findings from direct exploration methods (boreholes).



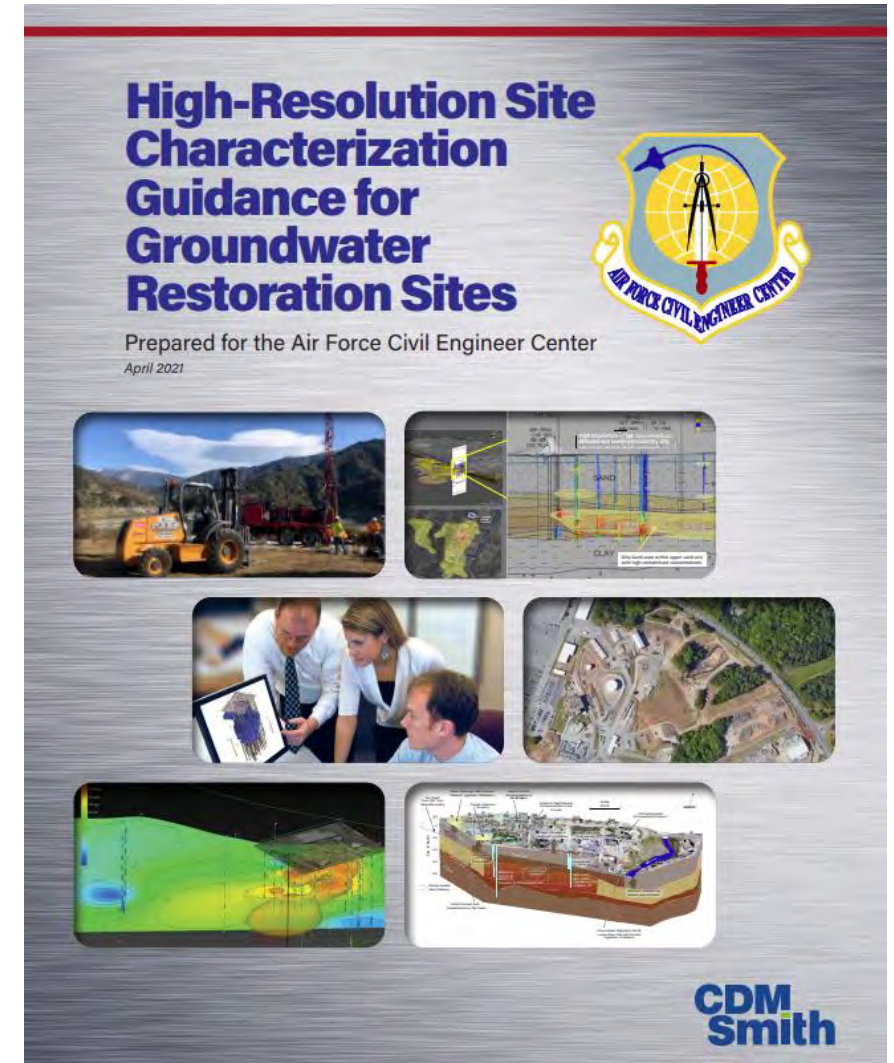
Learn that near-surface geophysical methods selection depends on the problem at hand and can be used as standalone, but they complement each other very effectively.



Supplementary HRSC Guidance



- **HRSC guidance document for groundwater restoration at Air Force sites (April 2021)**
- **Topics covered include:**
 - Building a CSM
 - HRSC tools
 - HR-CSM role in site life cycle
 - Implementing this HRSC guidance
 - HRSC demonstration case study
- **AFCEC/CZTE contacts**
 - Kent Glover (Air Force Subject Matter Specialist, Remedial Engineering Systems, kent.glover@us.af.mil)
 - Kurt Lee (Air Force Subject Matter Specialist, Remedial Engineering Systems, kurt.lee.3@us.af.mil)
 - Jeffrey L. Davis, PhD (Air Force Subject Matter Specialist, Remedial Engineering Systems, jeffrey.davis.90@us.af.mil)





Training Webinar Part 2 – Borehole Geophysics



■ **Borehole Geophysics Techniques**

- Quantum physics methods
- Acoustic methods*
- Electric and electromagnetic methods*
- Combined optical/acoustic methods
- Colloidal borescope
- Mechanical caliper

* same physical principles as near surface methods



Thank you!

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Your Success is Our Mission!



Air Force Civil Engineer Center

Restoration Technology Transfer Speakers Series June 2025

Borehole Geophysics Techniques Available for High-Resolution Site Characterization Part 2 of 2

Presenters: Matthew Spurlin – Noblis

Near surface geophysical (NSG) methods are minimally invasive, non-destructive technologies that use the physical properties subsurface materials to aid in understanding complex geologic and hydrogeologic settings. The methods include:

- Transmission of mechanical vibrations – seismic methods
- Detection of atomic-level particle physics – quantum physics methods
- Resistance to the flow of electricity– electrical methods
- Transmission of electromagnetic signals – EM and ground-penetrating radar methods
- Variations of Earth's magnetic field - magnetometry
- Variations of Earth's gravitational pull – gravimetry

While NSG can be implemented as standalone technologies, they are often used in tandem with other ancillary methods. These geophysical methods help identify optimal locations for drilling to confirm and further extrapolate the initial findings. They are decision-making tools widely used in geotechnical engineering and environmental investigations among others. NSG covers large areas quickly and provides valuable information at a fraction of the cost of invasive exploration techniques. Preliminary results from some methods are available in the field and provide timely information that can be used to optimize available resources and reduce costs and time in the field.

Magnetometric Resistivity (MMR)

- Measures the magnetic field generated by low-frequency direct current (DC) between two electrodes
- Cross-hole imaging technique with electrodes placed in separate boreholes
- Applications
 - Geology (lithology, structure)
 - Hydrogeology (depth to water, preferential flowpaths, seepage detection)
- Borehole can be open or polyvinyl chloride (PVC)-cased
- Provides qualitative 2-D or 3-D map

Groundwater flowpaths at a tailings dam.

Willowstick Technologies, LLC. 2010. "Willowstick Technologies, LLC White Paper: A Patented Non-Invasive Process to Accurately Model Preferential Groundwater Flow in Three Dimensions."

Matthew Spurlin describing MMR technology applications.

This event and future events are updated and posted on the AFIT website at: <https://www.afit.edu/CE/index.cfm>.

POCs:

Joseph Dimisa, AFIT (joseph.dimisa@us.af.mil)

C.J. Garcia, CTR, Booz Allen Hamilton (carlos.garcia.56.ctr@us.af.mil)

Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)



Webinar Structure



	<u>Restoration Technology Transfer Webinar Series – eDASH Archive</u>
5 min	Welcome and Administrative Business
30 min	Main Presentation – <i>Borehole Geophysics Techniques Available for High-Resolution Site Characterization</i>
10-15 min	Questions and Answers
5 min	Final Thoughts

Air Force Civil Engineer Center



Borehole Geophysics Techniques Available for High-Resolution Site Characterization

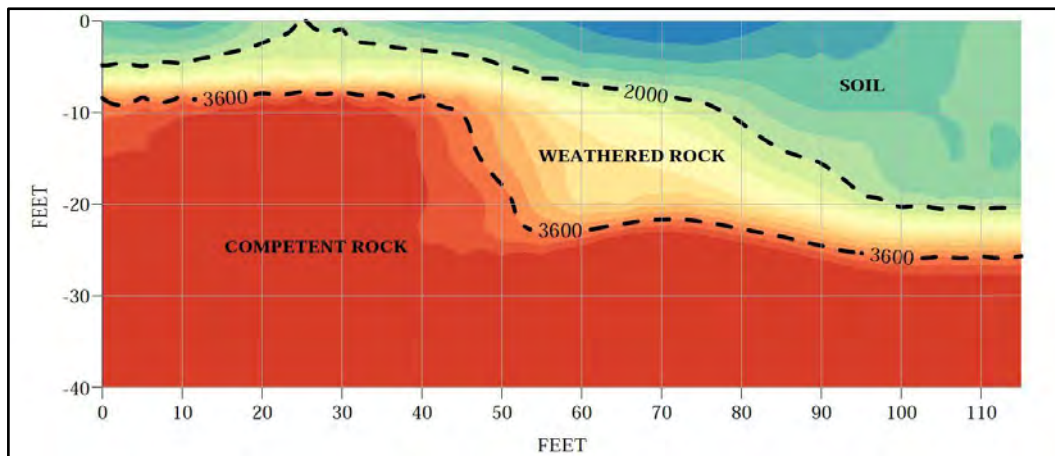
Matthew Spurlin, MS, CPG

Senior Hydrogeologist

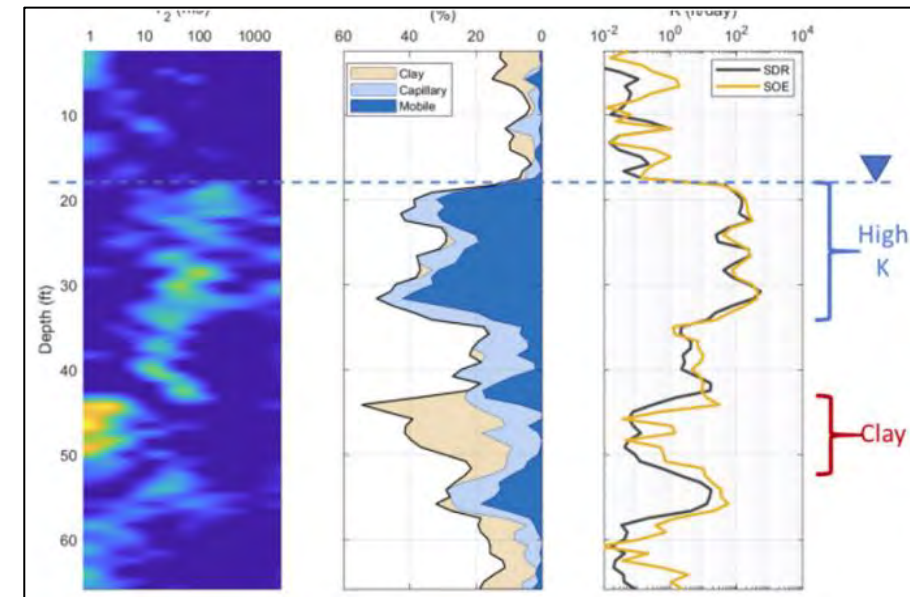
Noblis

June 2025

Part 1 – Near Surface Geophysics



Part 2 – Borehole Geophysics





- **Training Webinar Part 1 (Near-Surface Geophysics) – Review**
- **Training Webinar Part 2 (Borehole Geophysics)**
 - High-Resolution Site Characterization (HRSC) Tools
 - Environmental Geophysics – Recap
 - Borehole Geophysics Techniques
 - Scope and Cost Considerations
 - Takeaways



Training Webinar Part 1 – Review



■ **Near-Surface Geophysics Techniques**

- Seismic
- Microgravity
- Magnetometry
- Electrical
- Electromagnetic
- Ground penetrating radar (GPR)



- **Downhole HRSC strategies and techniques use scale-appropriate measurements and/or sampling density to map contaminant distribution and subsurface conditions that account for site heterogeneity**
- **Conventional methods (scale: tens of meters) vs HRSC (scale: centimeters or less)**

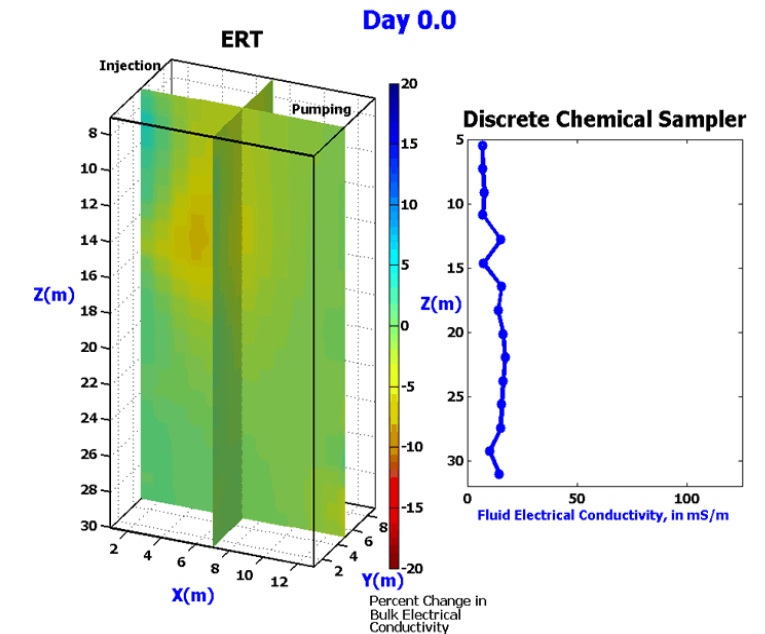
Contaminant mapping tools and strategies:

- Membrane Interface Probe (MIP)
- Laser-Induced Fluorescence (LIF)
- Ultraviolet Optical Screening Tool (UVOST)
- Tar-specific Green Optical Screening Tool (TarGOST)
- Vertical aquifer profiling/sampling (VAP/VAS) along transects
- Passive flux meters (PVMs)
- Passive Samplers

Hydrogeologic mapping tools:

- Hydraulic Profiling Tool (HPT)
- Cone Penetrometer Test (CPT)
- Electrical conductivity (EC)
- Waterloo Advanced Profiling System (APS™)
- FLUTe™ multilevel sampling system
- Point velocity probes (PVPs)
- Flowmeter

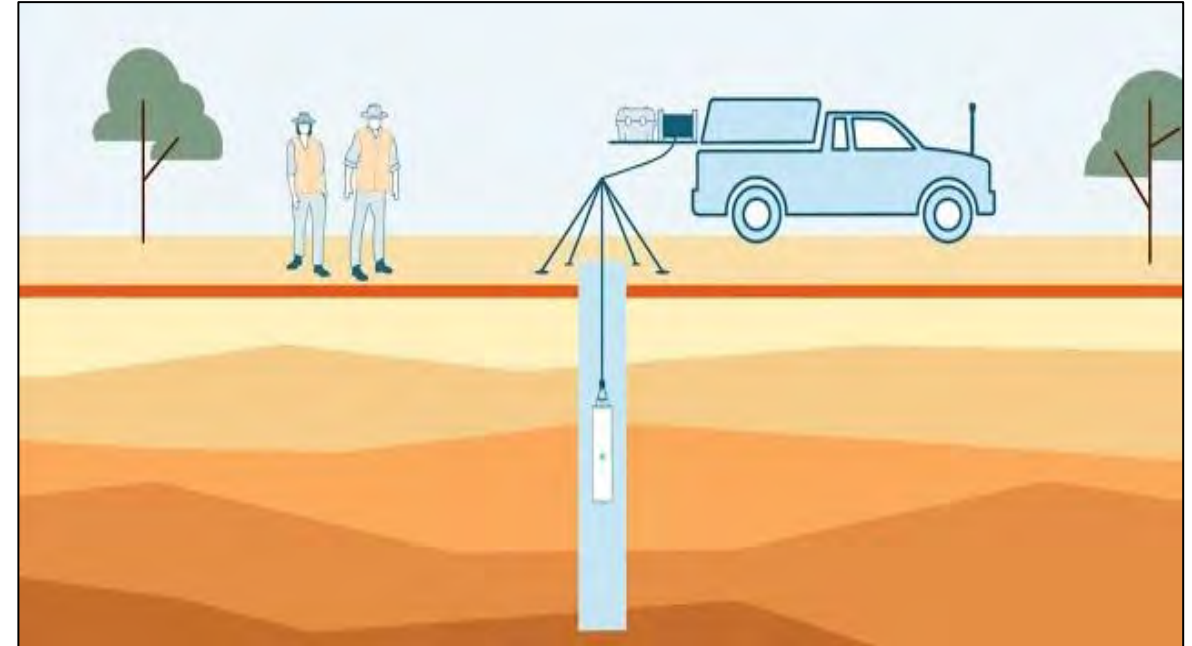
- **Purpose**: Provide an overview of environmentally-focused geophysics tools
- Environmental geophysics measures the physical properties of the Earth to aid in understanding complex geologic and hydrogeologic settings, which can include:
 - Lithologic mapping
 - Structural mapping (fractures, joints, geologic bedding)
 - Aquifer characterization
 - Distribution of water content and mobility
 - Contaminant plume mapping
 - Well integrity testing
 - Remedial system monitoring and/or design
 - Fluid migration over time (e.g., tracer testing)
- Analogous to medical imaging prior surgical procedures
- Non-invasive (ground surface) or minimally techniques (in-well or in-borehole)
- Requires and informs the conceptual site model (CSM)



Source: www.usgs.com

Methods presented today:

- Quantum physics methods
- Acoustic methods
- Electric and electromagnetic methods
- Combined optical/acoustic methods
- Colloidal borescope
- Mechanical caliper



Source: [Geoscience Australia](https://www.geoscienceaustralia.gov.au/)

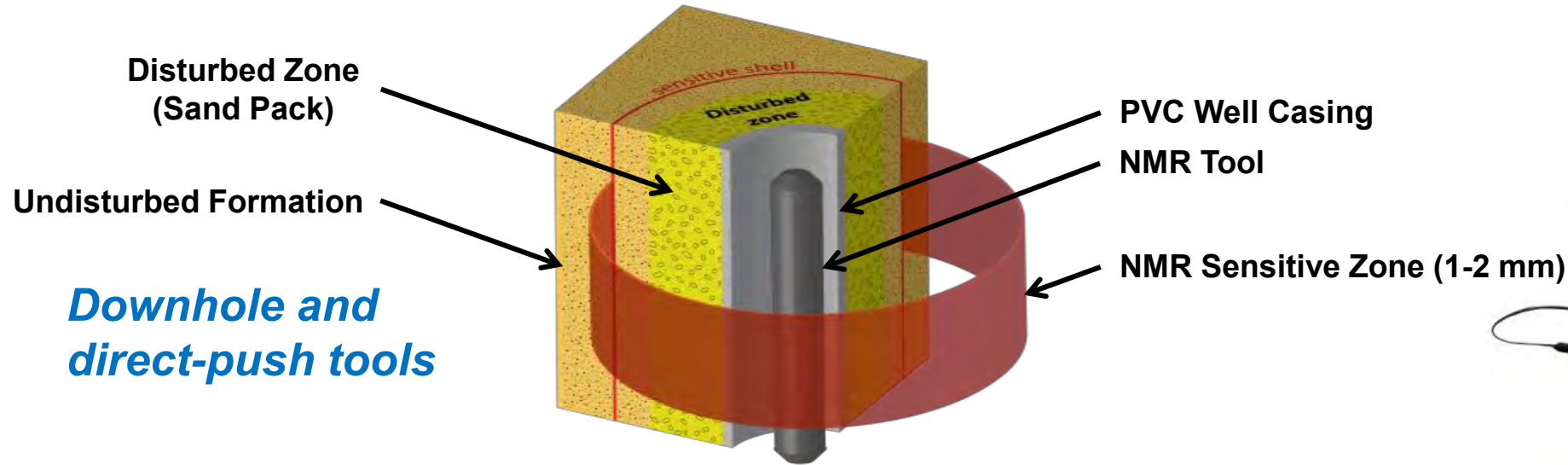


Quantum Physics Methods



- **Quantum physics is the study of the behavior of matter and energy at the smallest scales of nature.**
- **Quantum physics methods for environmental investigations utilize the behavior of atomic-level particles and the laws that govern them.**
- **Logging methods that use quantum physics:**
 - **Nuclear Magnetic Resonance (NMR)**
 - **Neutron**
 - **Natural Gamma**
 - **Spectral Gamma Ray (SGR)**

Nuclear Magnetic Resonance (NMR)



Source: www.vista-clara.com

Directly and Indirectly Measured Parameters

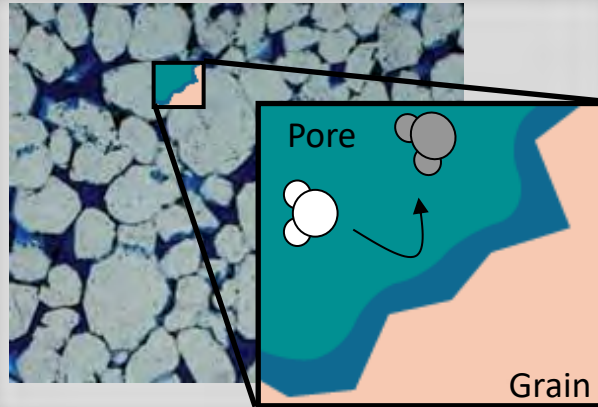
- Water content
- Porosity and pore size distribution
- Bound vs. mobile water
- Permeability
- Light non-aqueous phase liquid (LNAPL) detection

Benefits

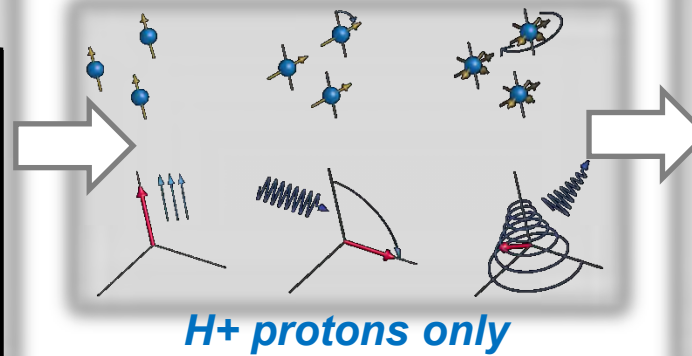
- Improved site characterization and CSM refinement
- Informs well design parameters
- Remedial design optimization

Nuclear Magnetic Resonance (cont.)

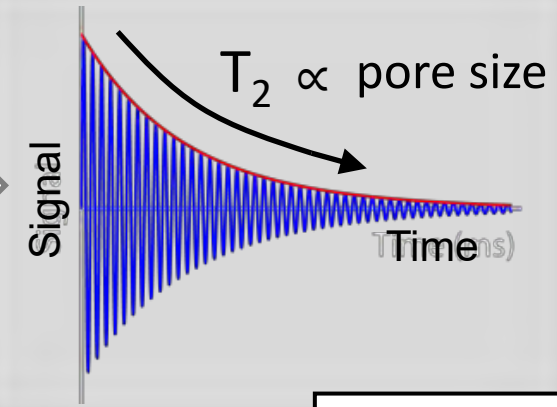
Geologic Material



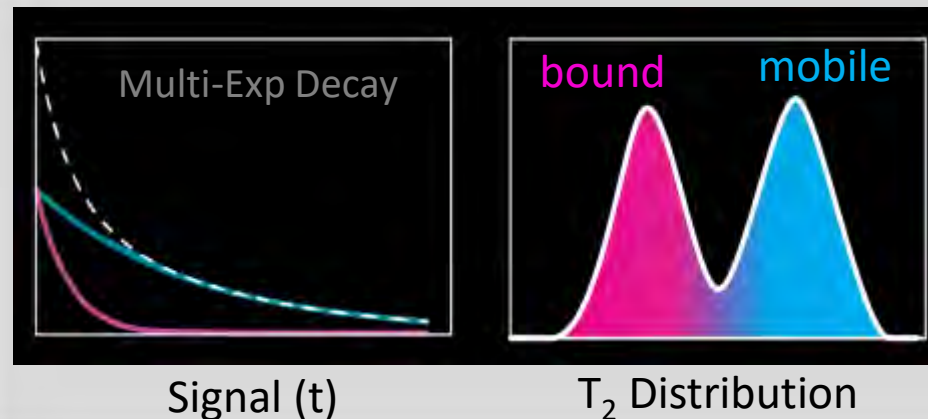
Polarization & Excitation



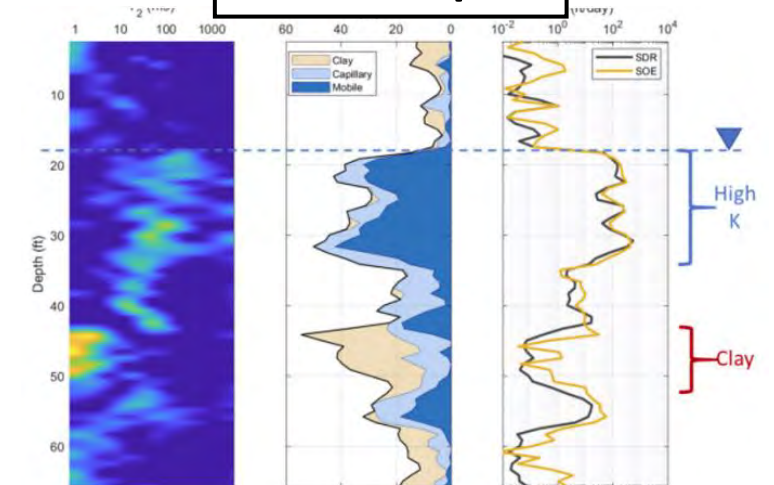
NMR Signal



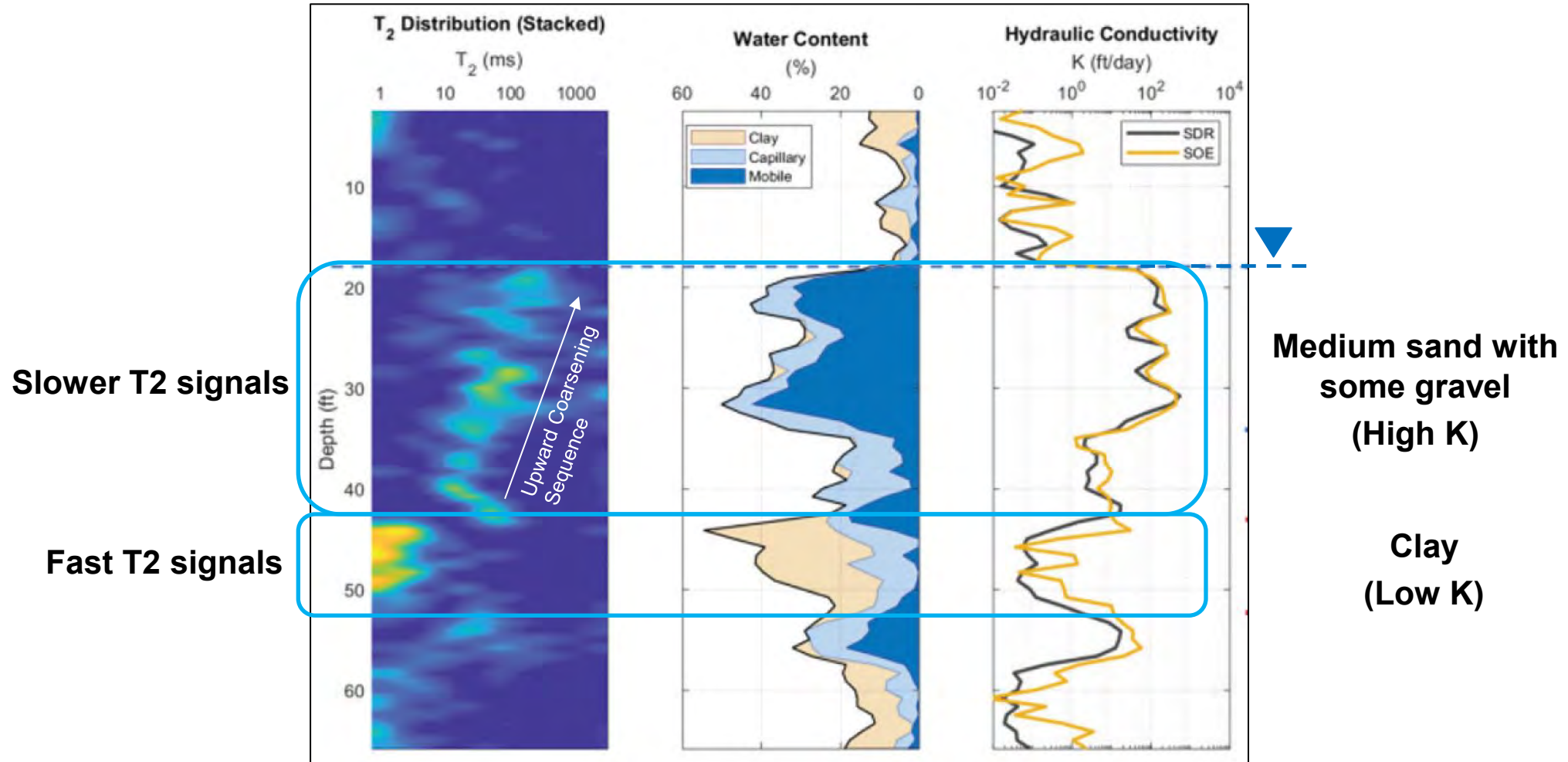
Data Output



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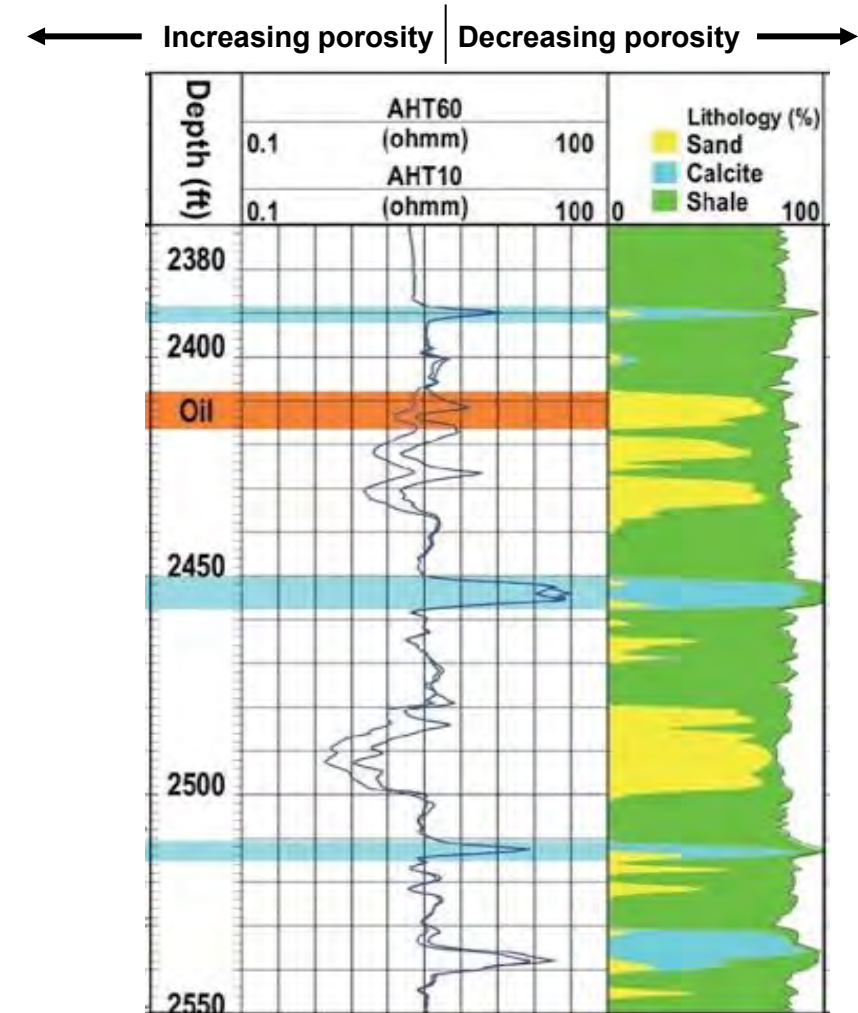


Nuclear Magnetic Resonance (cont.)



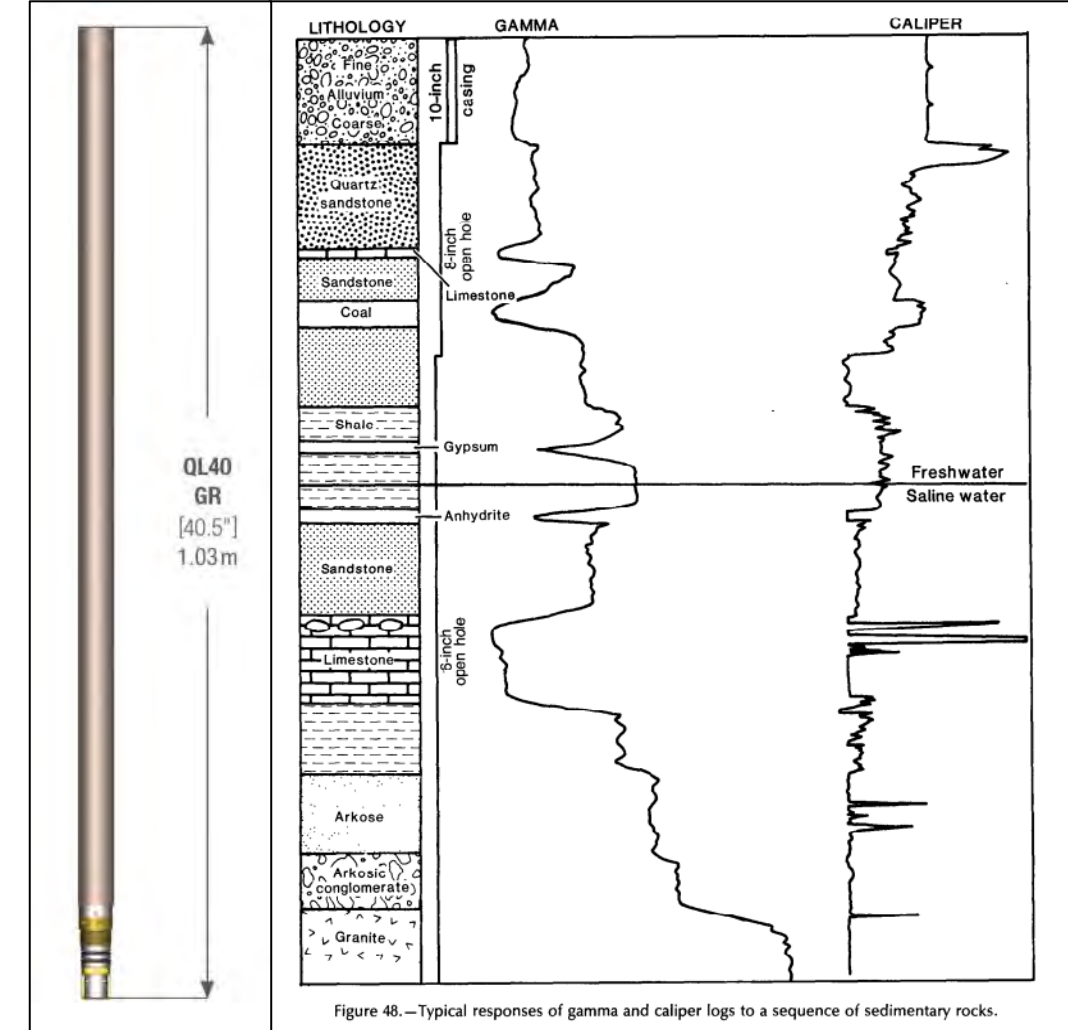
Source: <https://www.vista-clara.com/>

- **Active-source method primarily used to identify formation porosity (saturated or unsaturated)**
 - Only moisture content measured in vadose zone
- **Neutron radiation emitted by controlled source, then slowed, scattered and absorbed**
- **Tool is specifically sensitive to hydrogen content**
 - All hydrogen is assumed to be contained within the pore fluids (e.g., water, hydrocarbons)
 - Neutron counts are inversely proportional to hydrogen content
- **Borehole can be open, filled, cased, or uncased**
- **Radioactive source may be prohibited at some sites (potential limitation)**



Source: [Parra and Hackaert \(2006\)](#)

- Naturally-occurring radioactive elements emit small amounts of gamma radiation
 - Potassium-40 (^{40}K)
 - Thorium (^{232}Th)
 - Uranium (^{238}U)
 - Related daughter products
- Natural gamma tools passively receive radiation and convert measurements into interpreted data logs
- Primarily used to identify:
 - Geologic contacts
 - Coarsening/fining sequences
 - Clay aquitards
 - Aquifer thickness evaluations
- Borehole can be open, filled, cased, or uncased
- Cost-effective and straightforward (often used first)



Source: www.mountsopris.com

[TWRI 2-E2 \(usgs.gov\)](http://TWRI-2-E2.usgs.gov)

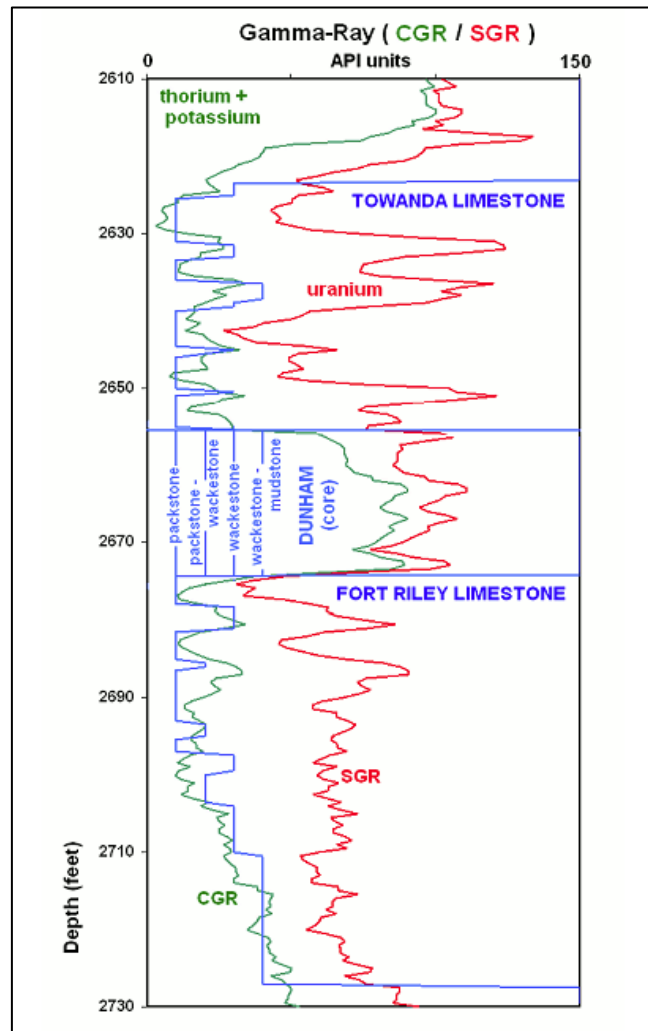
- **SGR is useful for determining:**
 - Clay/shale/sand content
 - Shale percentages
 - Clay mineralogy and depositional environment
 - Correlations of structural/stratigraphic features
 - Water-rock interactions
- **Differentiates targeted radioactive elements:**
 - Potassium-40 (^{40}K)
 - Thorium (^{232}Th)
 - Uranium (^{238}U)
- **Borehole can be open, filled, cased, or uncased**
- **Requires calibration**



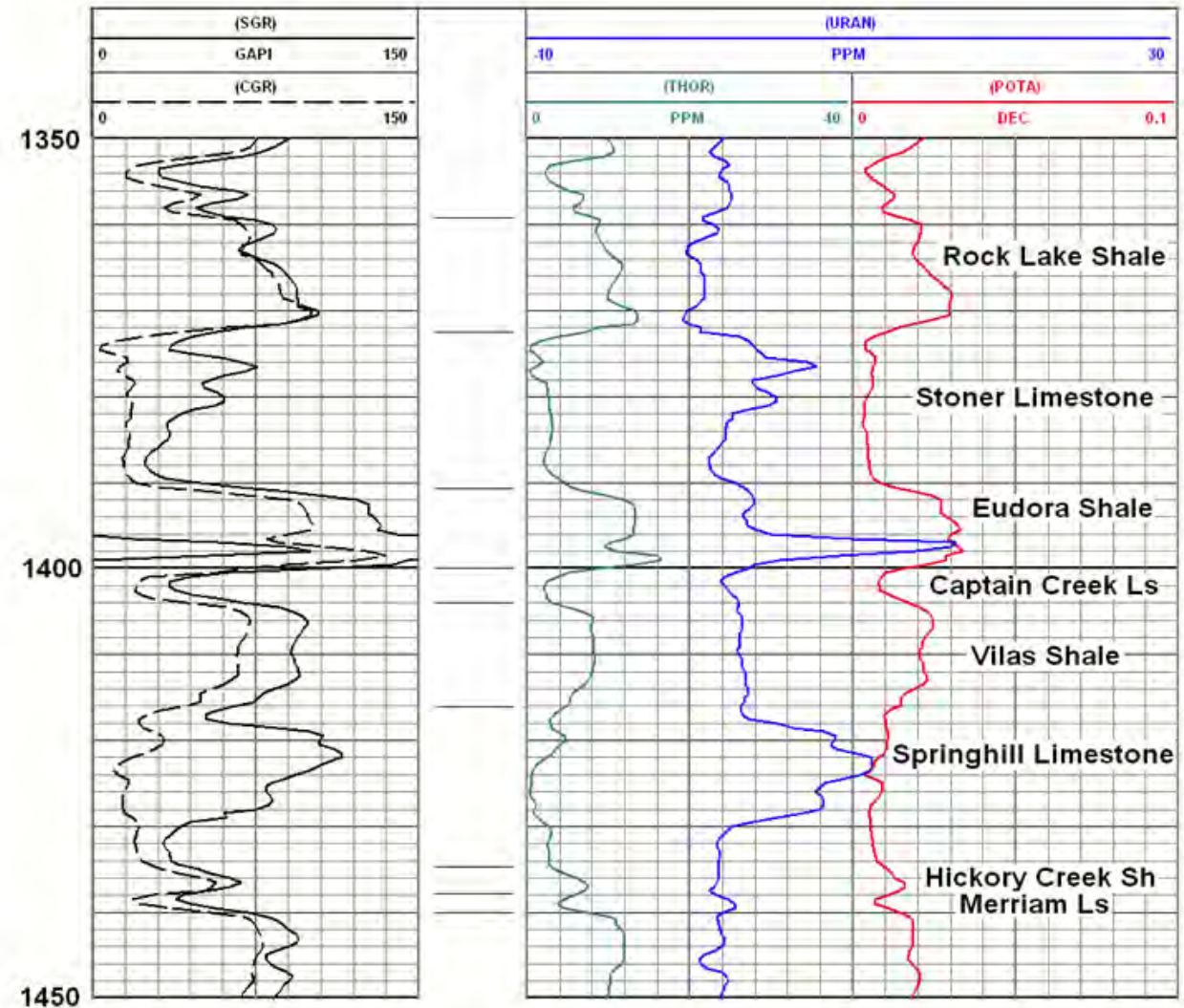
[Spectral Gamma Borehole Logging | U.S. Geological Survey \(usgs.gov\)](https://www.usgs.gov/survey)

Spectral Gamma Ray – KUT Logs

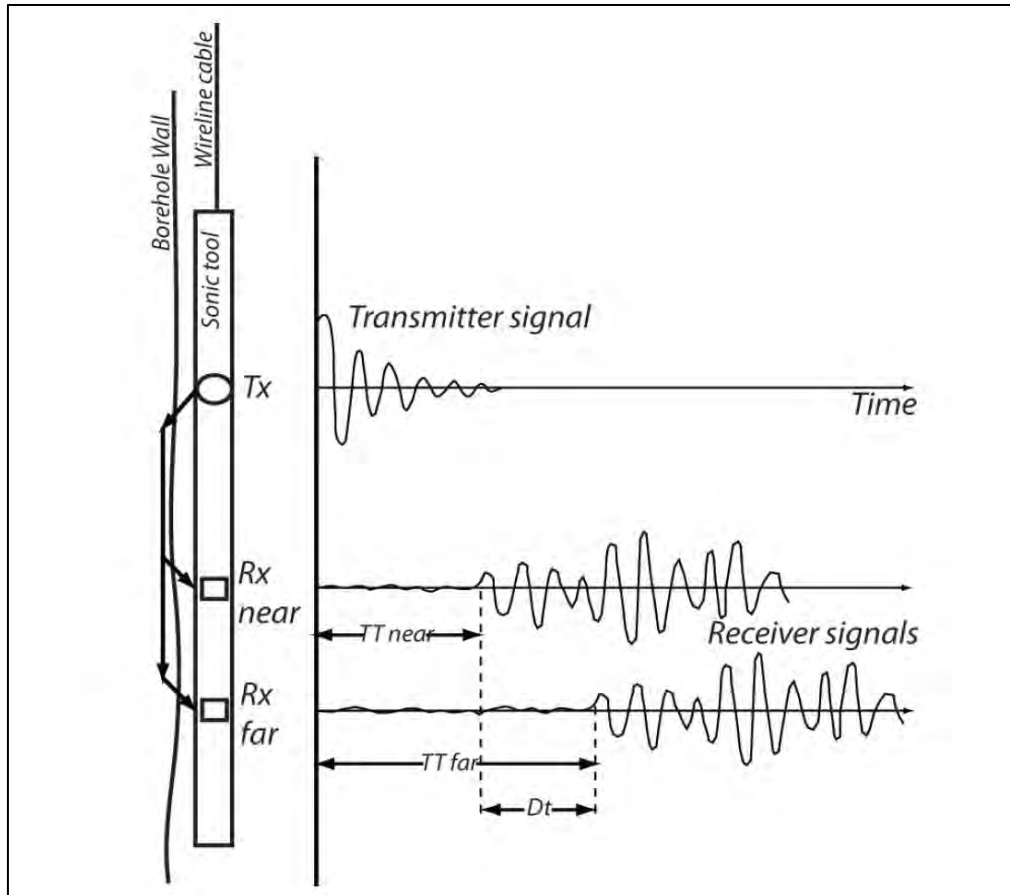
Permian Chase Group (Hugoton gas field)



Gamma-Ray Logs of the Plattsburg and Stanton Cyclothem



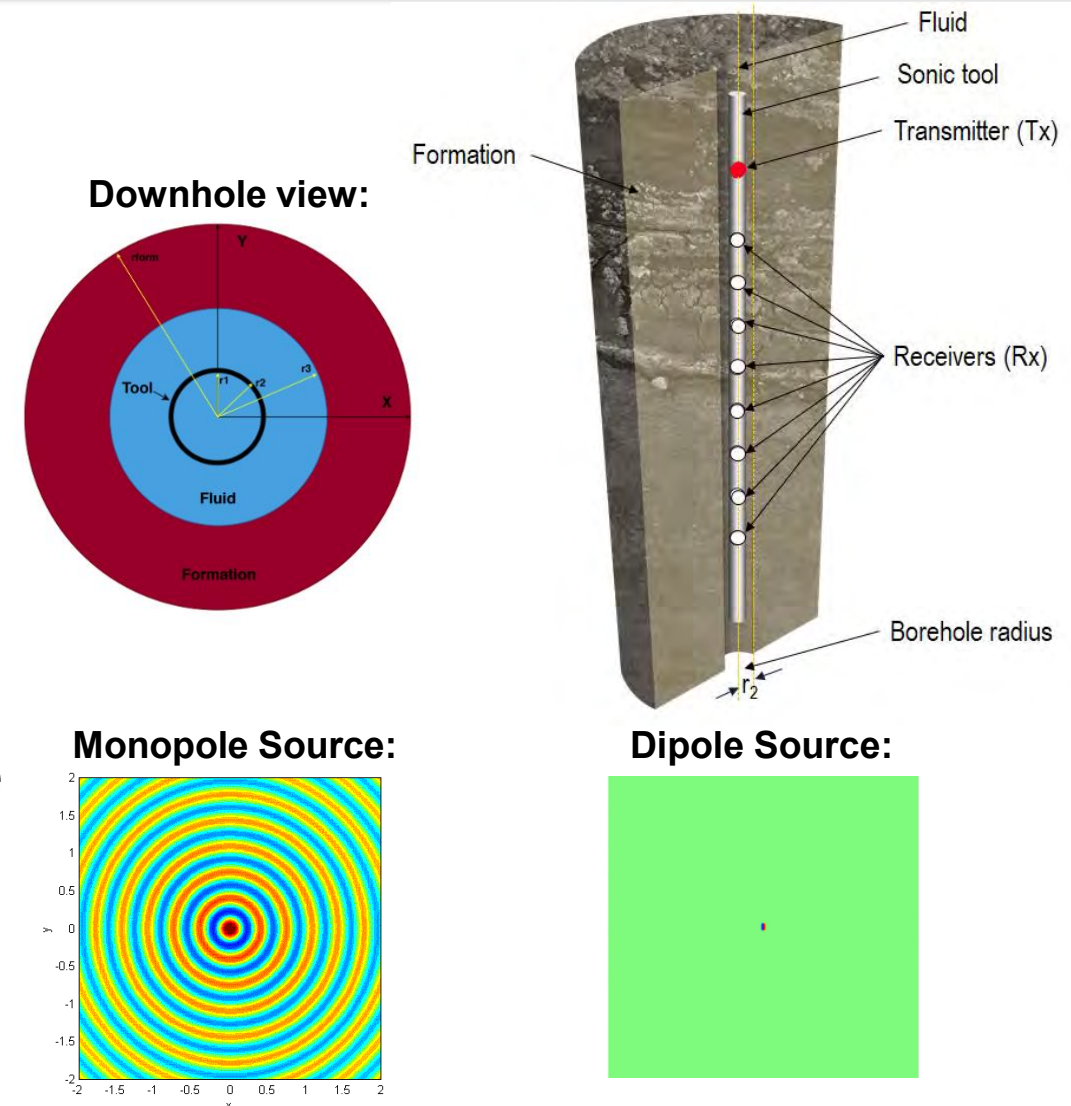
Provide information about materials and the fluids they contain by interpreting the changes in the velocity of mechanical vibrations ("sound" waves) that travel through them.



Sonic (acoustic) logs use sound waves that travel from a source, through the formation, and arrive at a receiver.

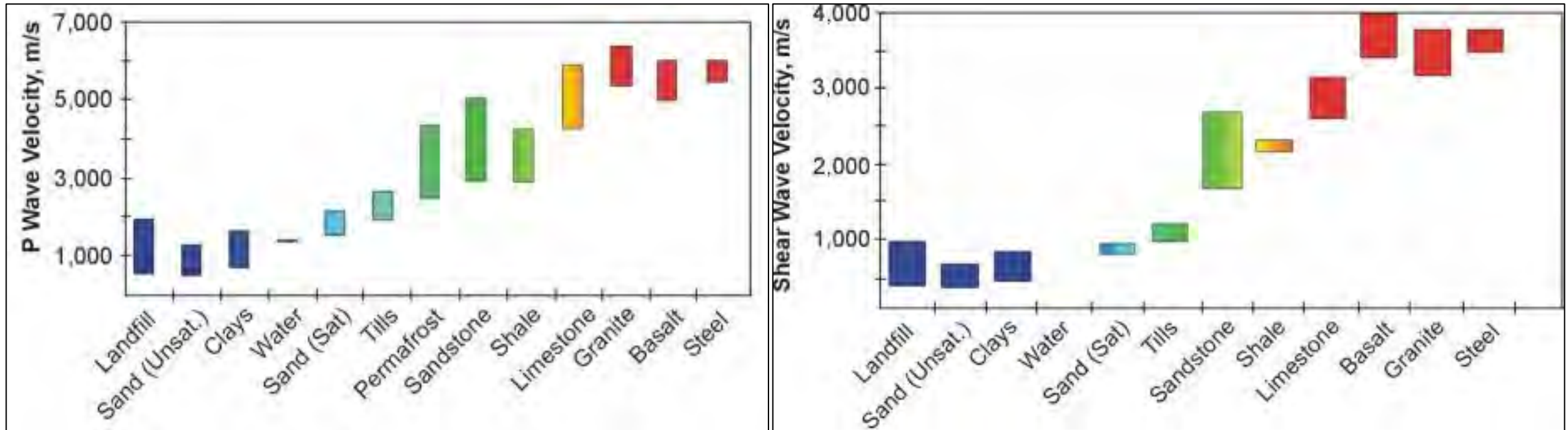
Therefore, sonic logs are great indicators of rock quality and entrained fluids.

- **Source-receiver travel times correlate to specific formation characteristics:**
 - Porosity
 - Permeability
 - Fluid content type and saturation
 - Fracture locations
- **Modern tools can use open or cased boreholes (must be fluid-filled)**
- **Monopole source produces P-waves, dipole source produces P- and S-waves**
- **Sonic log data generally compared to core data**



Source: www.onscale.com

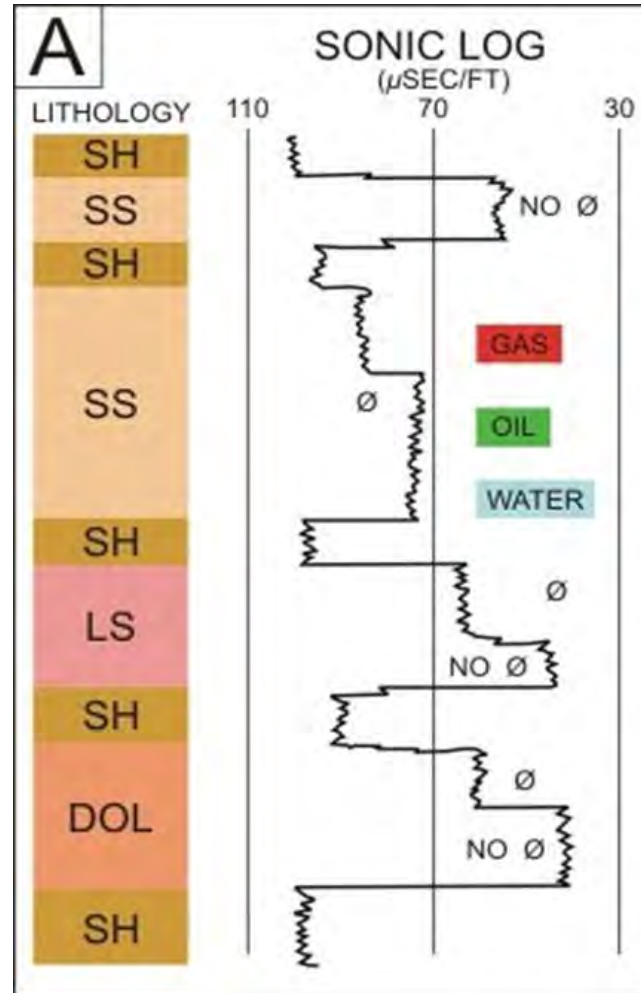
Generalized acoustic velocities (transit times) for selected geologic materials:



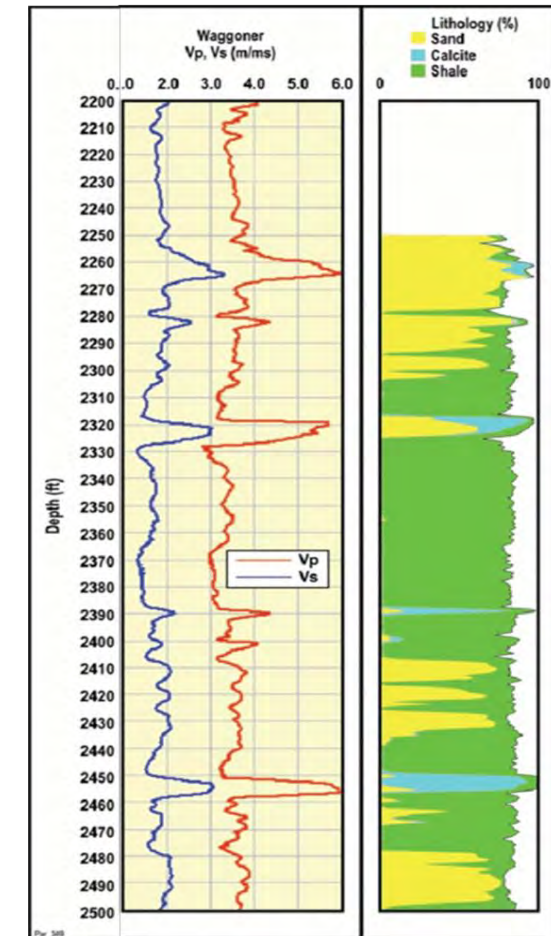
Source: Geomechanical (Engineering) Properties | Environmental Geophysics | US EPA

Applications:

- Lithologic mapping
- Porosity estimates
- Permeability estimates
- Fracture network mapping
- Hydrocarbon resource mapping
- Mechanical property estimates
- Cement bond logging (CBL)



Source: Reservoir Characterization - Chapter 2
(elsevier.com)



Source: Parra Jorge O., Hackert C.L. Attenuation Analysis of Acoustic Waveforms in a Borehole Intercepted by a Sand-Shale Sequence Reservoir. Geophysics 25(2). February 2006.



Electric and Electromagnetic Methods

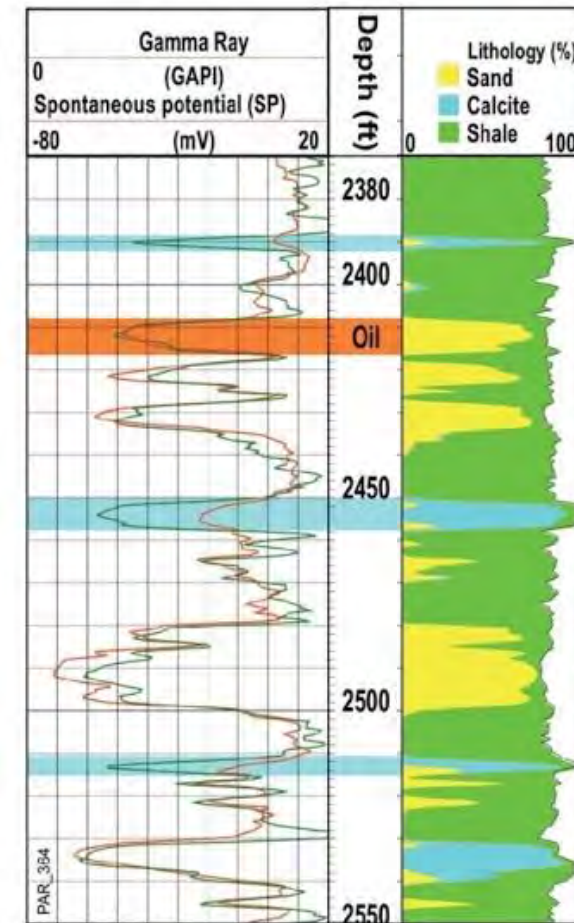


- **Spontaneous Potential (SP)**
- **Resistivity**
- **Magnetometric Resistivity (MMR)**
- **Electromagnetic (EM) Induction**

SP logging passively measures naturally occurring voltage anomalies along the length of an open, fluid-filled borehole that occur at lithologic contacts.

Environmental Applications

- Aquifer identification
- Groundwater flow mapping
- Freshwater-saltwater interface mapping
- Contaminant plume mapping
- Landfill leachate monitoring
- Acid mine drainage detection
- Redox zone delineation
- Geothermal site evaluation

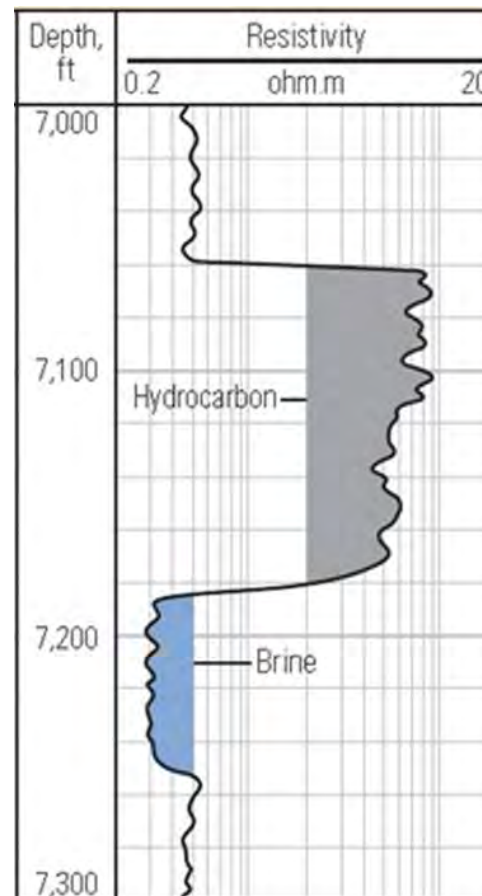


Resistivity is the ability of a material to resist the flow of electricity.



Borehole Logging Geophysical Land Products (geomatrix.co.uk)

Source: How To Easily Read A Well Log in 5 Minutes Using 'Six Ko Ko Rules' - Production Technology (production-technology.org)



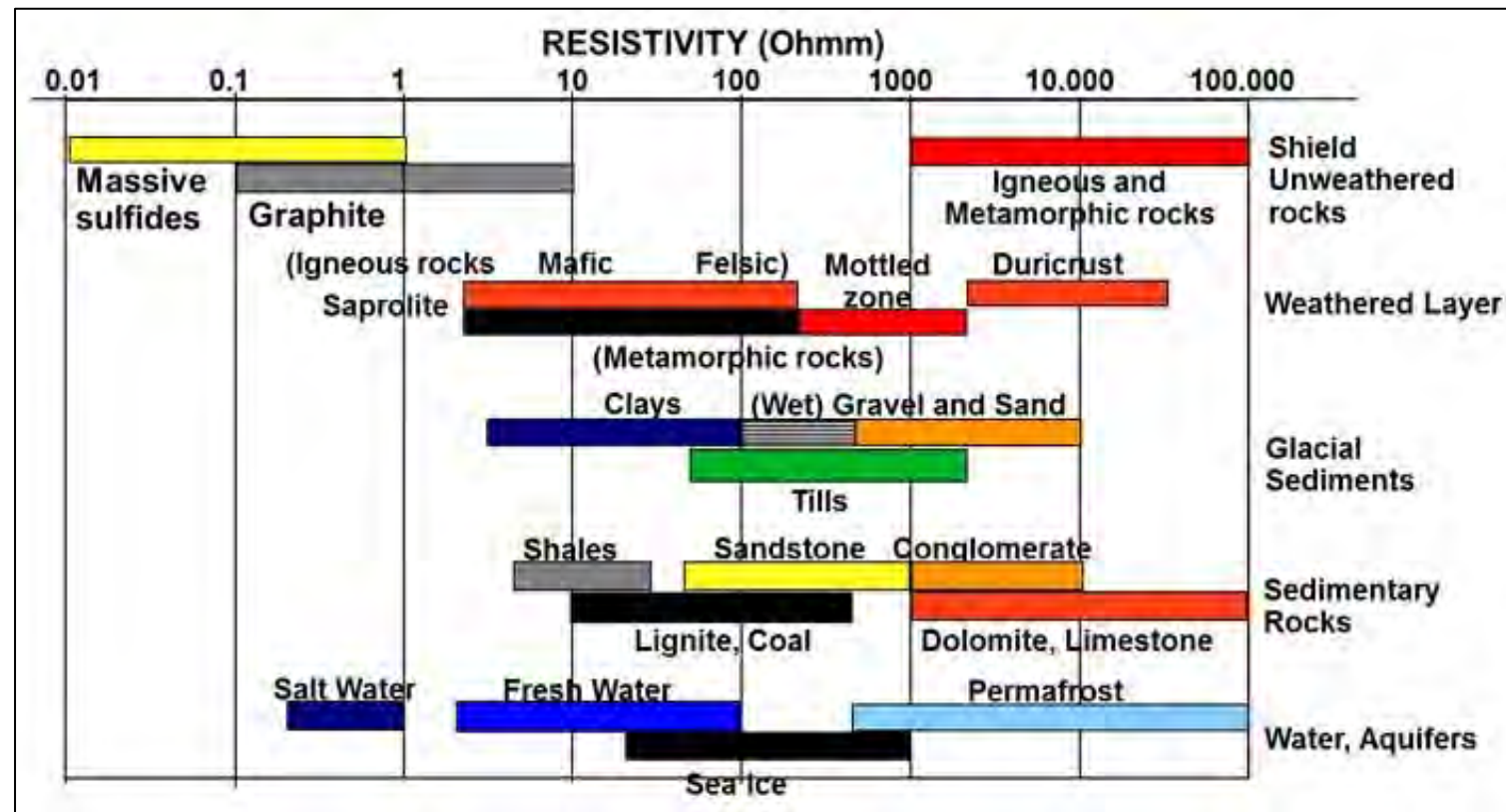
Directly and Indirectly Measured Parameters

- Rock vs. shale vs. sandstone
- Formation porosity
- Water content (fluid saturation)
- Water salinity

Types of Resistivity Tools

- Normal-Resistivity
- Focused Resistivity
- Single-Point Resistivity
- Dipmeter
- Microresistivity

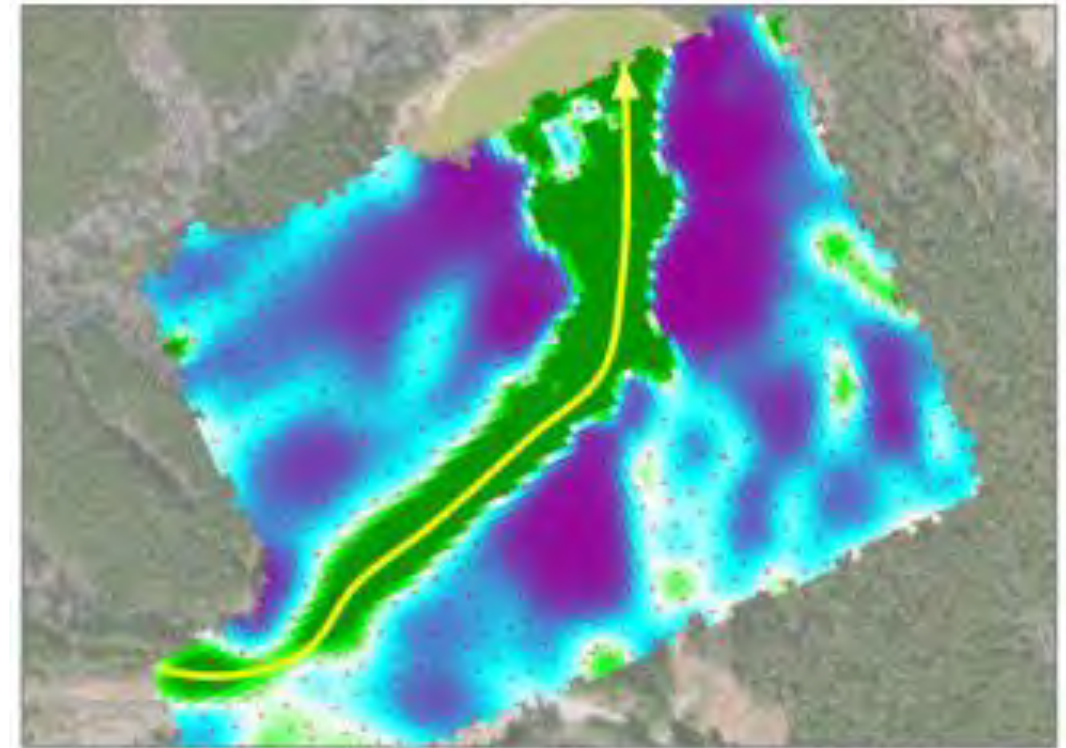
Generalized resistivities for selected geologic materials:



Source: Seis Tech (seis-tech.com)

Magnetometric Resistivity (MMR)

- Measures the magnetic field generated by low-frequency direct current (DC) between two electrodes
- Cross-hole imaging technique with electrodes placed in separate boreholes
- Applications
 - Geology (lithology, structure)
 - Hydrogeology (depth to water, preferential flowpaths, seepage detection)
- Borehole can be open or polyvinyl chloride (PVC)-cased
- Provides qualitative 2-D or 3-D map



Groundwater flowpaths at a tailings dam.

Willowstick Technologies, LLC. 2016. "Willowstick Technologies, LLC White Paper: A Patented Non-invasive Process to Accurately Model Preferential Groundwater Flow in Three Dimensions."

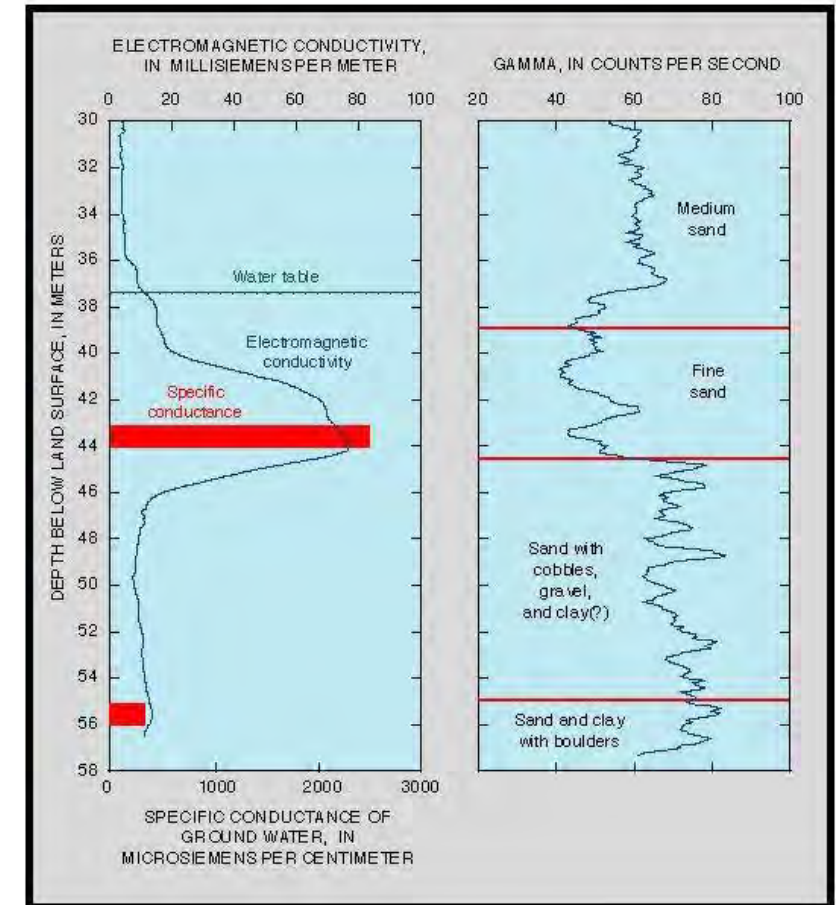
Electromagnetic induction (aka. induction resistivity) measures electromagnetic/magnetic properties of materials

Environmental Applications

- Bedrock structure and shale vs. sandstone differentiation
- Permafrost mapping
- Mapping groundwater contamination
- Groundwater salinity (e.g., saltwater intrusion over time)
- Monitoring changes in fluid conductivity (e.g., remediation efforts)
- Identifying tunnels, unexploded ordinance (UXO), utilities, drums, tanks, etc.

Can be used in open or PVC-cased wells

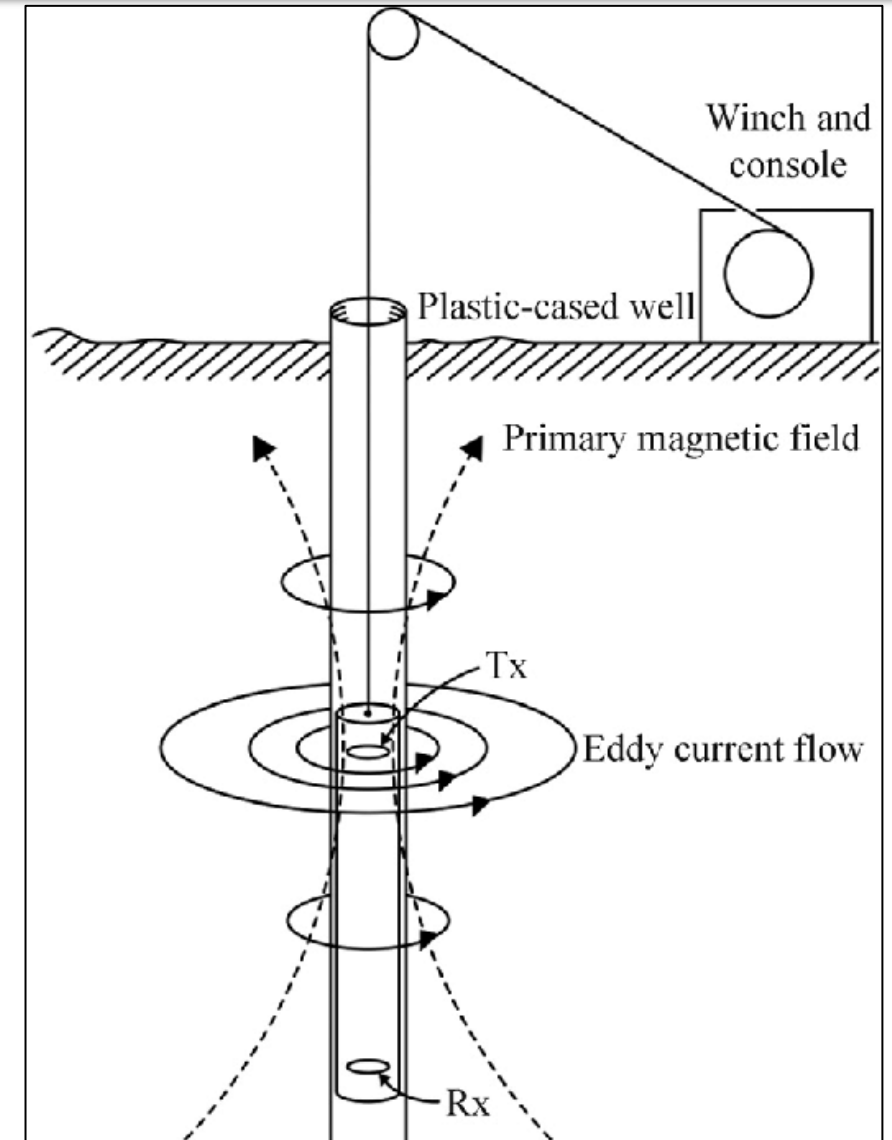
Low resolution results (~1 meter)



Source: CDM Smith – HRSC guidance for Groundwater Restoration Sites

How It Works

- Transmitter sends fixed frequency signal
- Signal induces currents in subsurface materials
- Induced currents create secondary magnetic field
- Receiver compares original signal to induced signal





Combined Methods

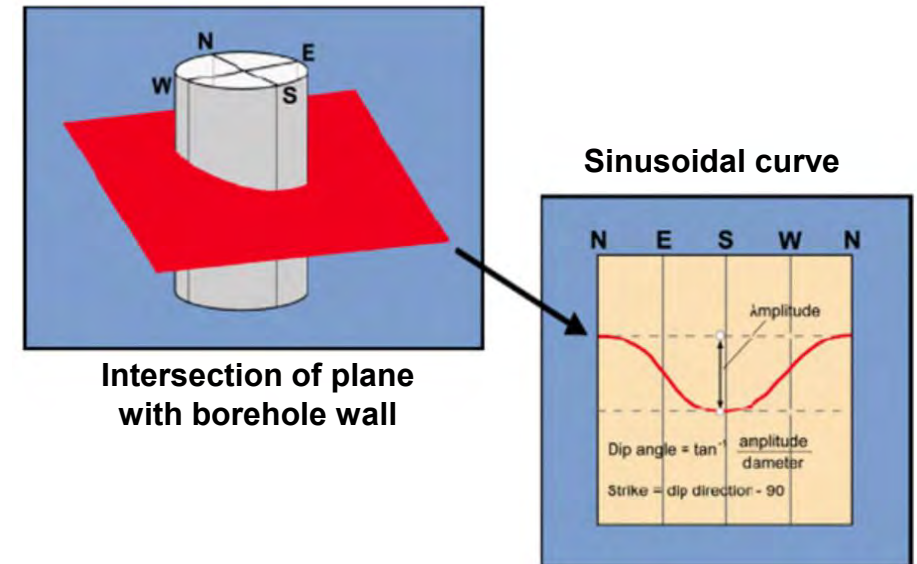


- **Acoustic Televiewer (ATV)**
- **Optical Televiewer (OTV)**

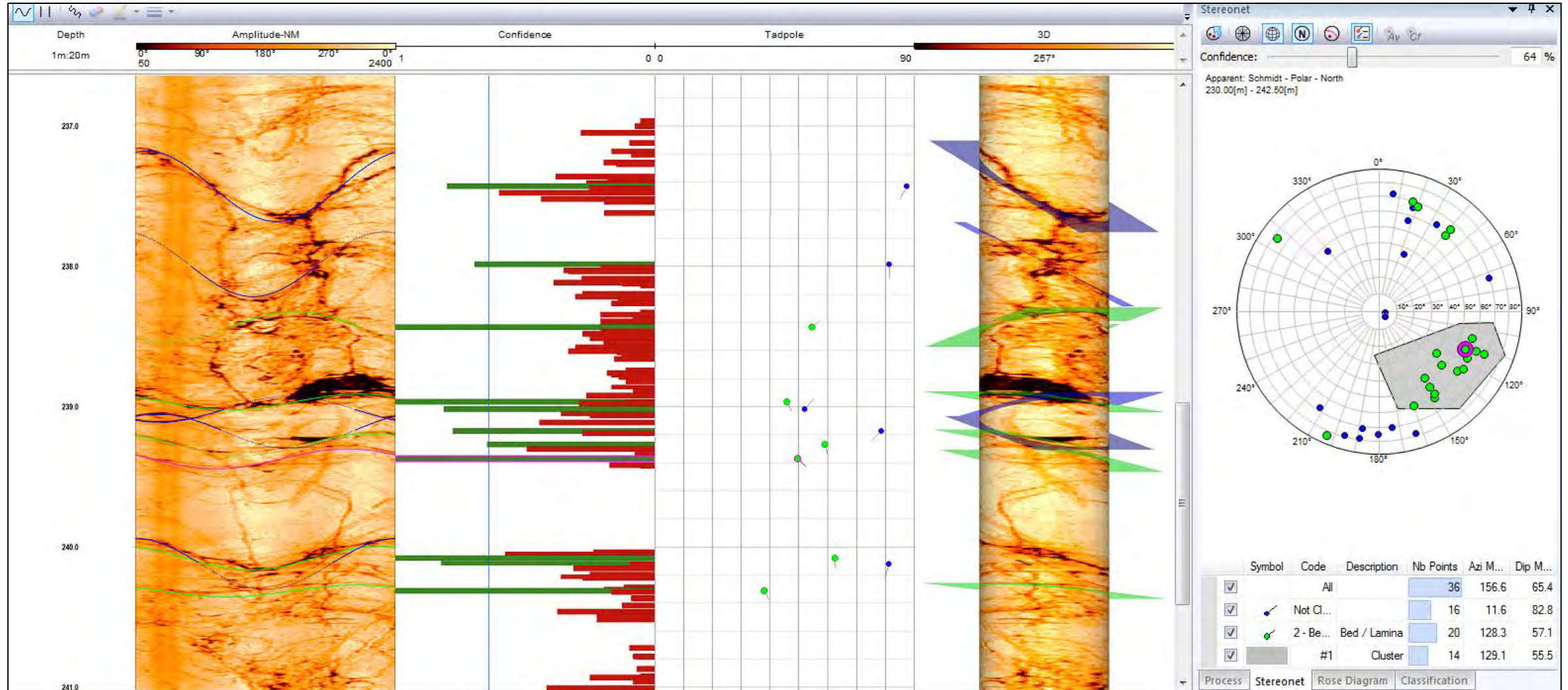
- 360° acoustic images of borehole wall or well casing
- Requires fluid-filled borehole (mud or water)
- Applications (open borehole)
 - Fractures/joints (depth, orientation)
 - Bedding contacts (depth, orientation)
 - Lithology/minerology characterization
 - Rock strength (weathered/unweathered)
 - Caliper
- Applications (cased borehole)
 - Casing inspection (thickness, corrosion, defects)
 - Scale detection
- Acoustic-caliper log
 - Borehole diameter used to estimate strike and dip of fractures and bedding
 - Low frequency transducer to better penetrate casing



Source: www.mountsopris.com

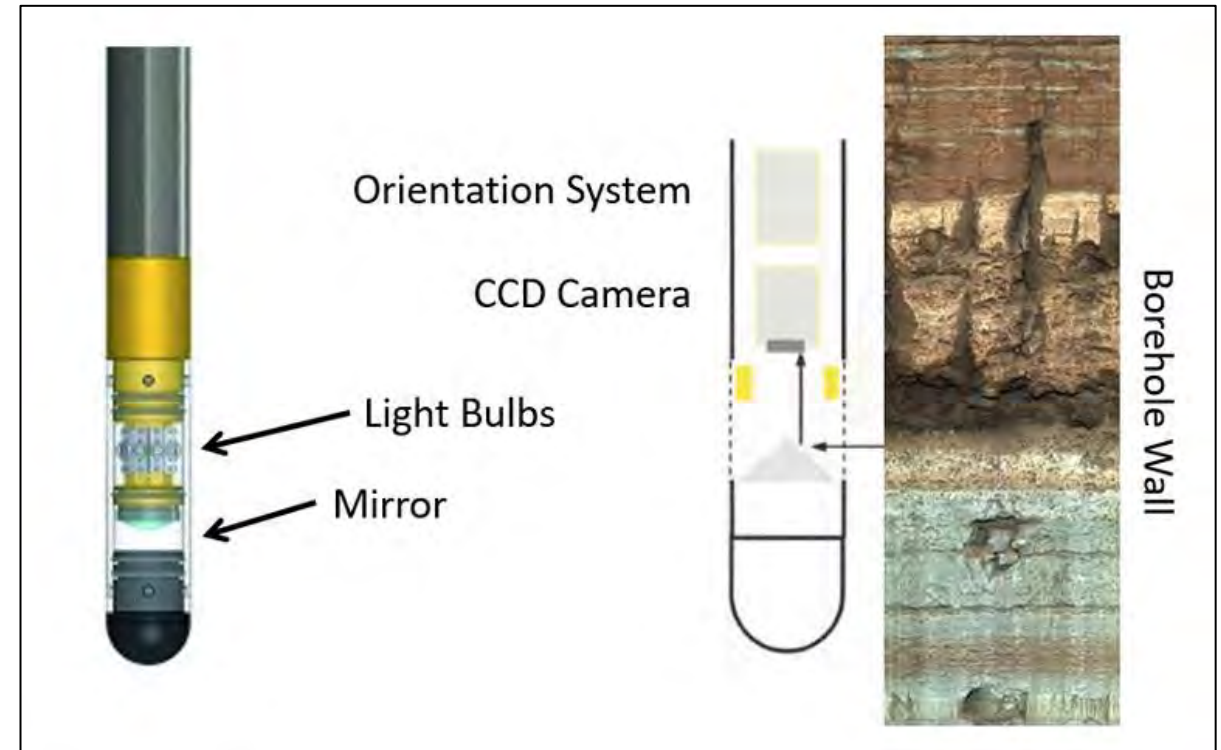


Acoustic Televiwer (cont.)

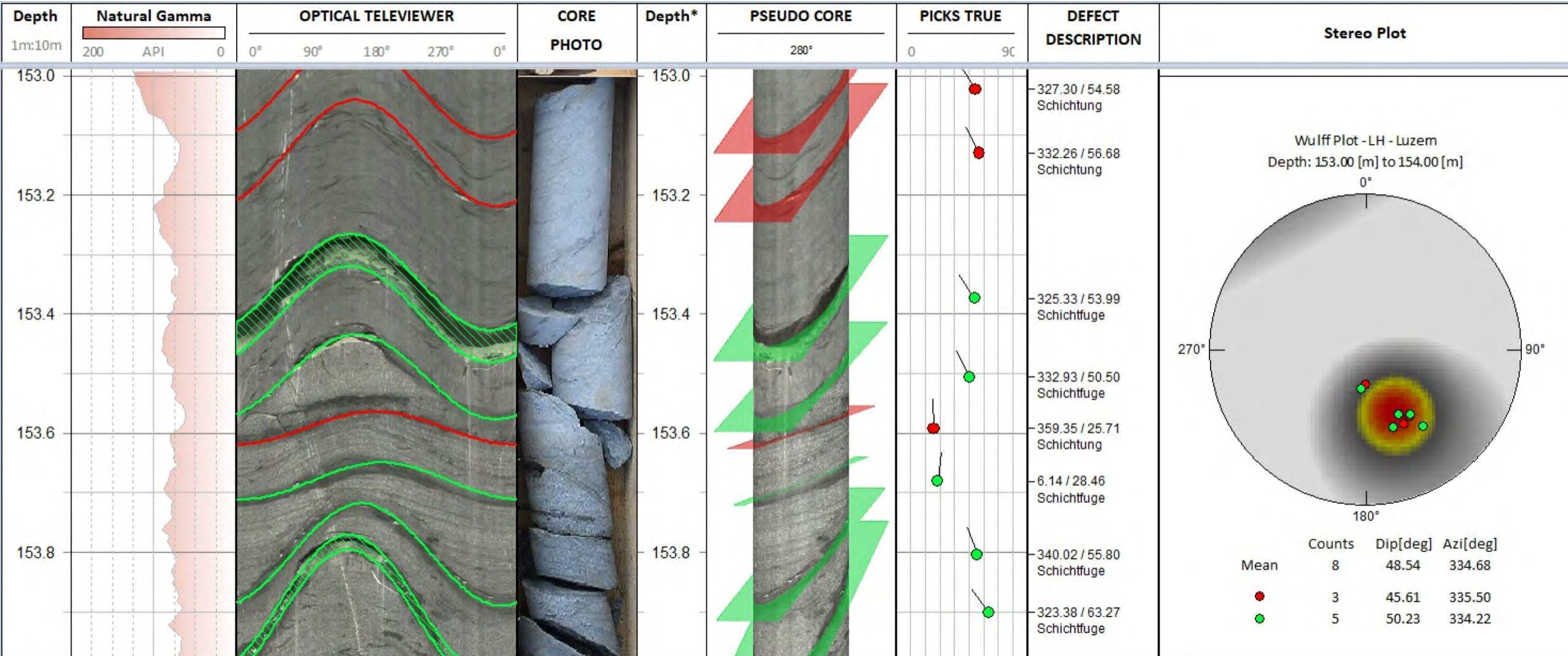


Source: www.mountsopris.com

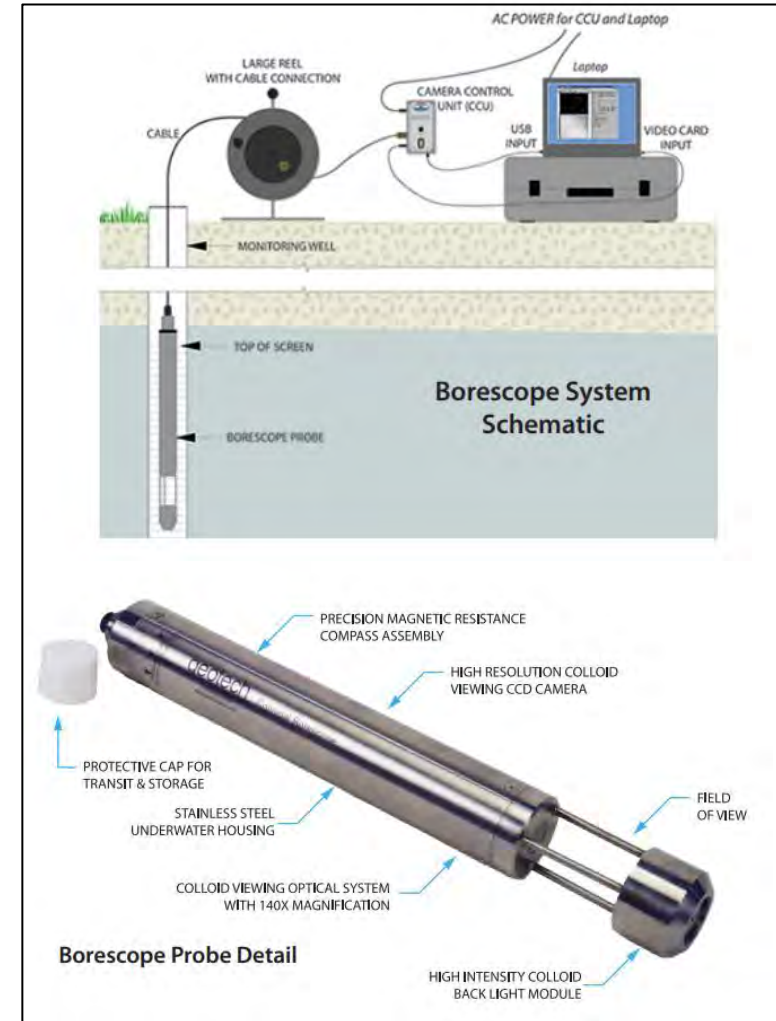
- **High-resolution 360° color images of borehole wall or well casing**
- **Conducted in air or clear water**
- **Applications (open borehole):**
 - Fractures/joints (depth, orientation)
 - Bedding contacts (depth, orientation)
 - Lithology/minerology characterization
 - Vuggy porosity
 - Breakout analysis
 - Rock quality (RQD, rock properties)
 - Planning for ancillary testing (flowmeter, hydraulic testing, sampling)
- **Applications (cased borehole):**
 - Casing inspection (corrosion, defects)
- **Challenges:**
 - Mud-cake
 - Muddy water
 - Small fractures lost in complex imagery
 - Identification of weathered zones



Optical Televiwer (cont.)

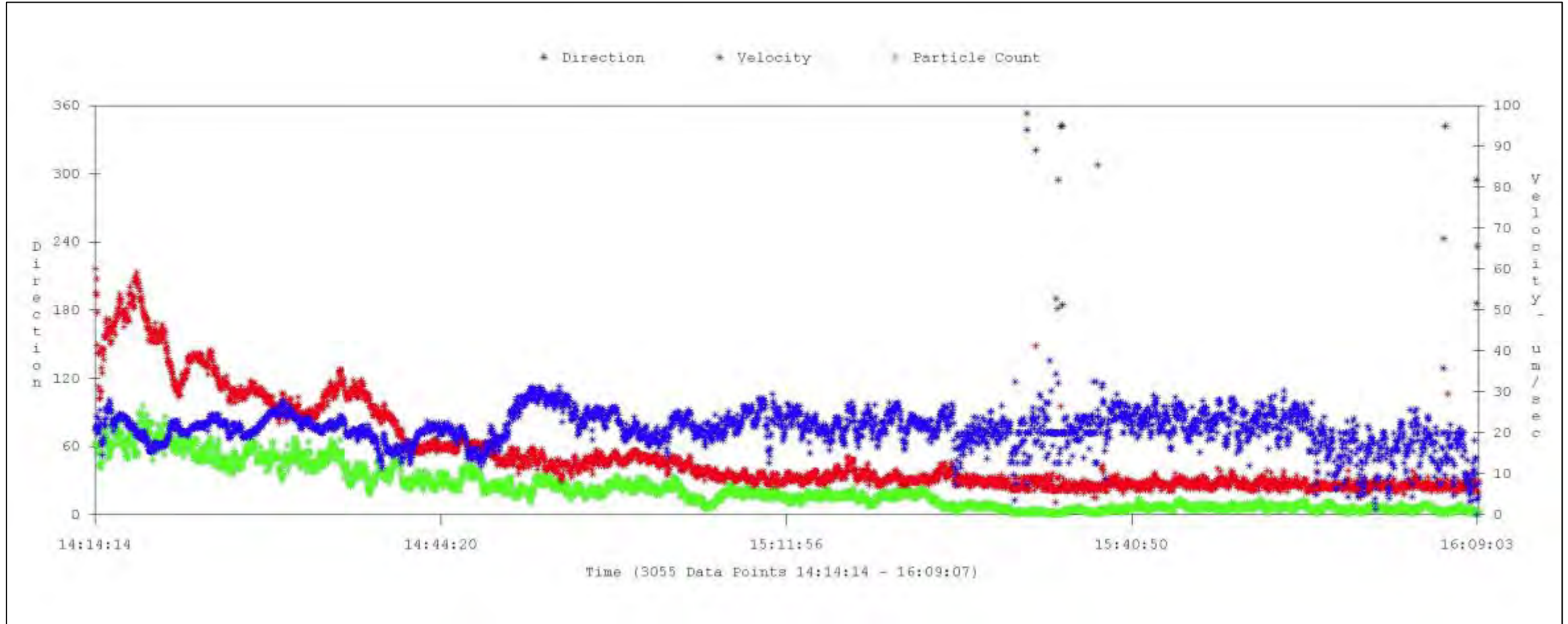


- Depth-specific *in-situ* measurements of naturally-occurring particles (1-10 μm) moving through borehole
- Consists of borescope probe, camera control unit, centralizer, well cable and reel, and processing software
- Observes horizontal flow at pore scale
- Directly measures:
 - Groundwater velocities (0-25 mm/sec)
 - Flow direction
 - Particle sizes



Source: www.geotechnenv.com

Colloidal Borescope (cont.)

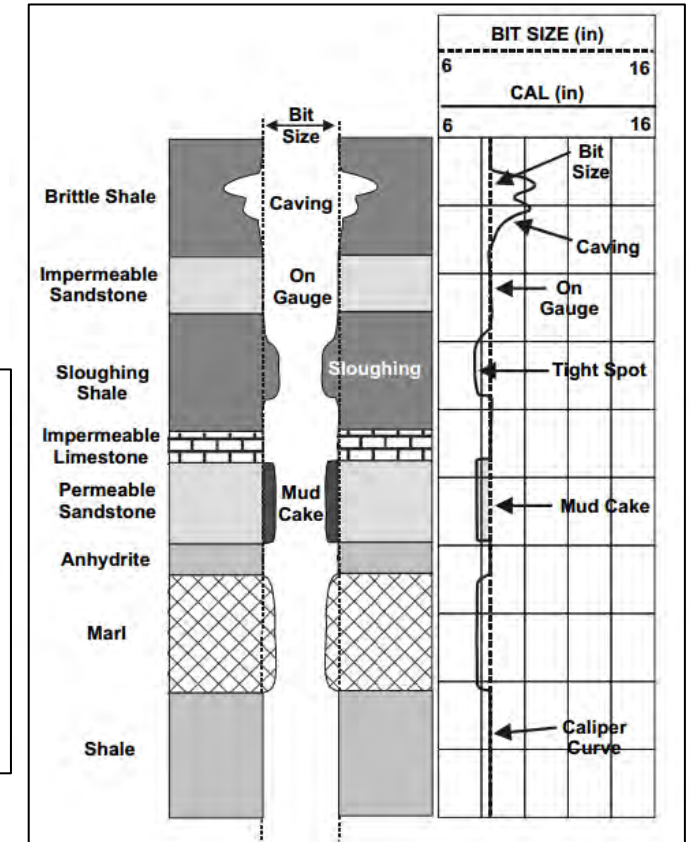


Source: www.usgs.com

- Tool provides a vertical profile of borehole or casing diameter
- Wireline-borehole method
- One or more tensioned (spring-loaded) mechanical arms
- Continuous logging to record size/shape of borehole
- Applications:
 - Formation voids or karst
 - Washouts
 - Sloughing
 - Mud cake buildup
 - Rugosity evaluation
 - Well casing joints assessments
 - Cement/grout volume estimates
 - Lithologic interpretations



Source: www.sparteksystems.com



Source: www.oilfieldteam.com



Scope and Cost Considerations

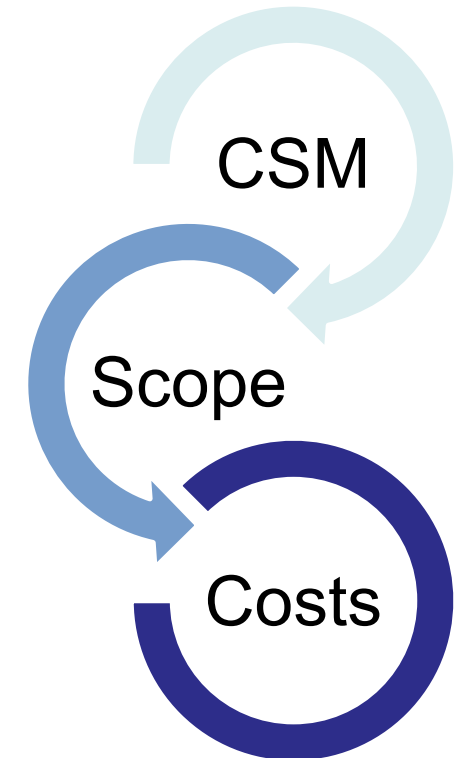


■ Scoping

- Site-specific CSMs (e.g., geology)
- Companion technologies
- Sequencing of companion technologies

■ Costing

- Equipment shipping
- Travel costs for both vendor and contractor staff
- Total linear feet and/or required time in the field
- Variable equipment rental rates among vendors





Takeaways



- **Borehole geophysics provides a suite of techniques for measuring physical properties of the subsurface through sensors placed in boreholes.**
- **Borehole geophysics technologies (standalone and complimentary) should be selected based on site-specific conditions and investigation objectives.**
- **Specific benefits include:**
 - High-resolution subsurface characterization with minimal disturbance, making it a critical tool for environmental site assessments, contaminant monitoring, groundwater management and remediation planning.
 - Improvements in time efficiency and a reduction in overall life cycle costs.



Supplementary HRSC Guidance



- HRSC guidance document for groundwater restoration at Air Force sites (April 2021)
- Topics covered include:
 - Building a CSM
 - HRSC tools
 - HR-CSM role in site life cycle
 - Implementing the HRSC guidance
 - HRSC demonstration case study
- AFCEC/CZTE contacts
 - Kent Glover (Air Force Subject Matter Specialist, Remedial Engineering Systems, kent.glover@us.af.mil)
 - Kurt Lee (Air Force Subject Matter Specialist, Remedial Engineering Systems, kurt.lee.3@us.af.mil)
 - Jeffrey L. Davis, PhD (Air Force Subject Matter Specialist, Remedial Engineering Systems, jeffrey.davis.90@us.af.mil)



Source: [CDM Smith Guide](#)



Thank you!

Matthew Spurlin, MS, CPG

Senior Hydrogeologist

Boulder, CO

Matthew.Spurlin@noblis.org



Your Success is Our Mission!



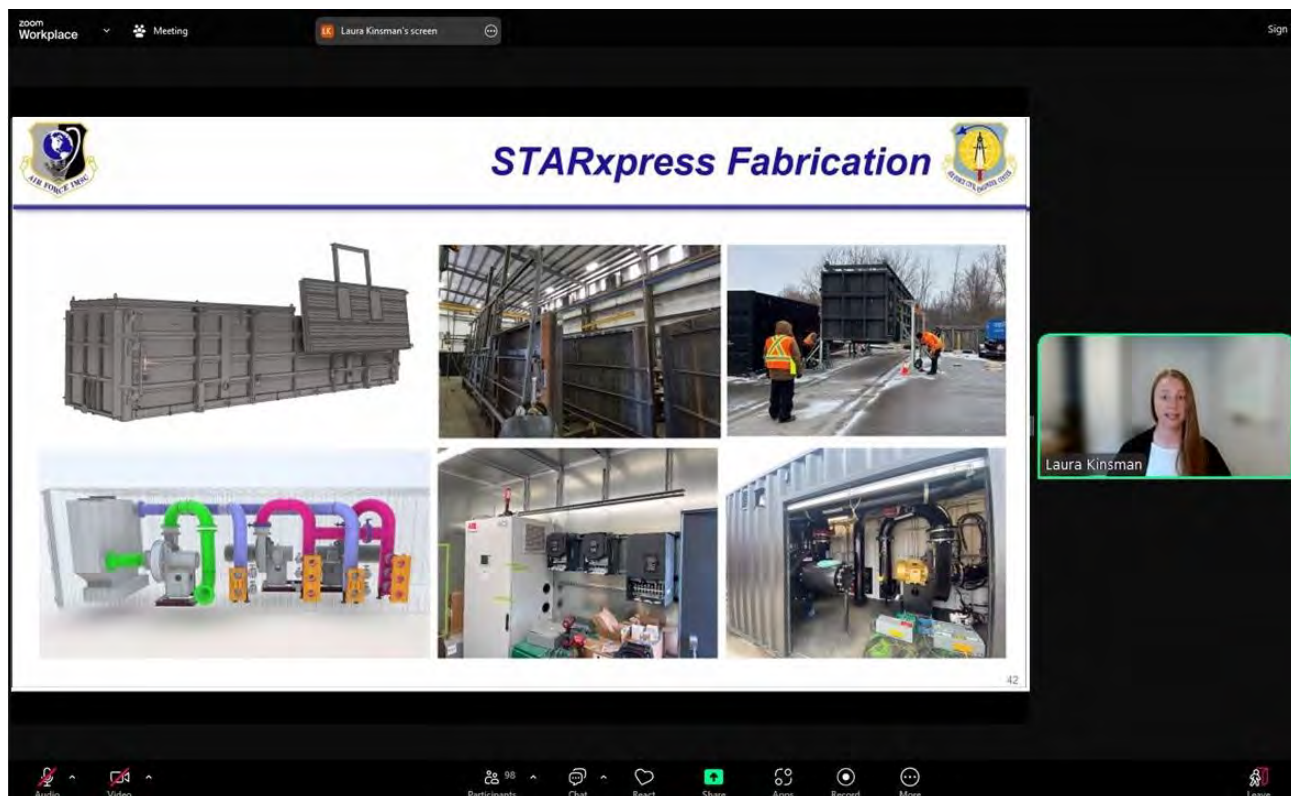
Air Force Civil Engineer Center

Restoration Technology Transfer Speakers Series July 2025

Smoldering Treatment of PFAS-Impacted Soil

Presenters: Laura Kinsman - Savron

Smoldering is an energy-efficient, flameless form of combustion that has been applied both in situ and ex situ to treat a wide range of contaminated soils and other organic wastes, including per- and polyfluoroalkyl substances (PFAS). A demonstration project was completed which evaluated PFAS destruction in soil using ex-situ smoldering. A total of ten tests were conducted in a pilot system (13 yd³ batches) to compare treatment under a wide range of conditions (i.e., initial PFAS concentrations, soil types, and moisture contents). Select batches also included co-treatment of spent granular activated carbon from an on-site groundwater treatment system. A summary of key findings and lessons learned from the field demonstration was presented. An update on other PFAS smoldering projects was also presented to provide a broader perspective on technology application and treatment effectiveness under various conditions.



Laura Kinsman describing the smoldering system.

This event and future events are updated and posted on the AFIT website at: <https://www.afit.edu/CE/index.cfm>.

POCs:

Joseph Dimisa, AFIT (joseph.dimisa@us.af.mil)

C.J. Garcia, CTR, Booz Allen Hamilton (carlos.garcia.56.ctr@us.af.mil)

Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)

Air Force Civil Engineer Center



Smoldering Demonstration for the Treatment of Per- and Polyfluoroalkyl Substances (PFAS) in Mixed Media

Laura Kinsman, M.E.Sc.
Senior Professional
Savron/Geosyntec
July 2025

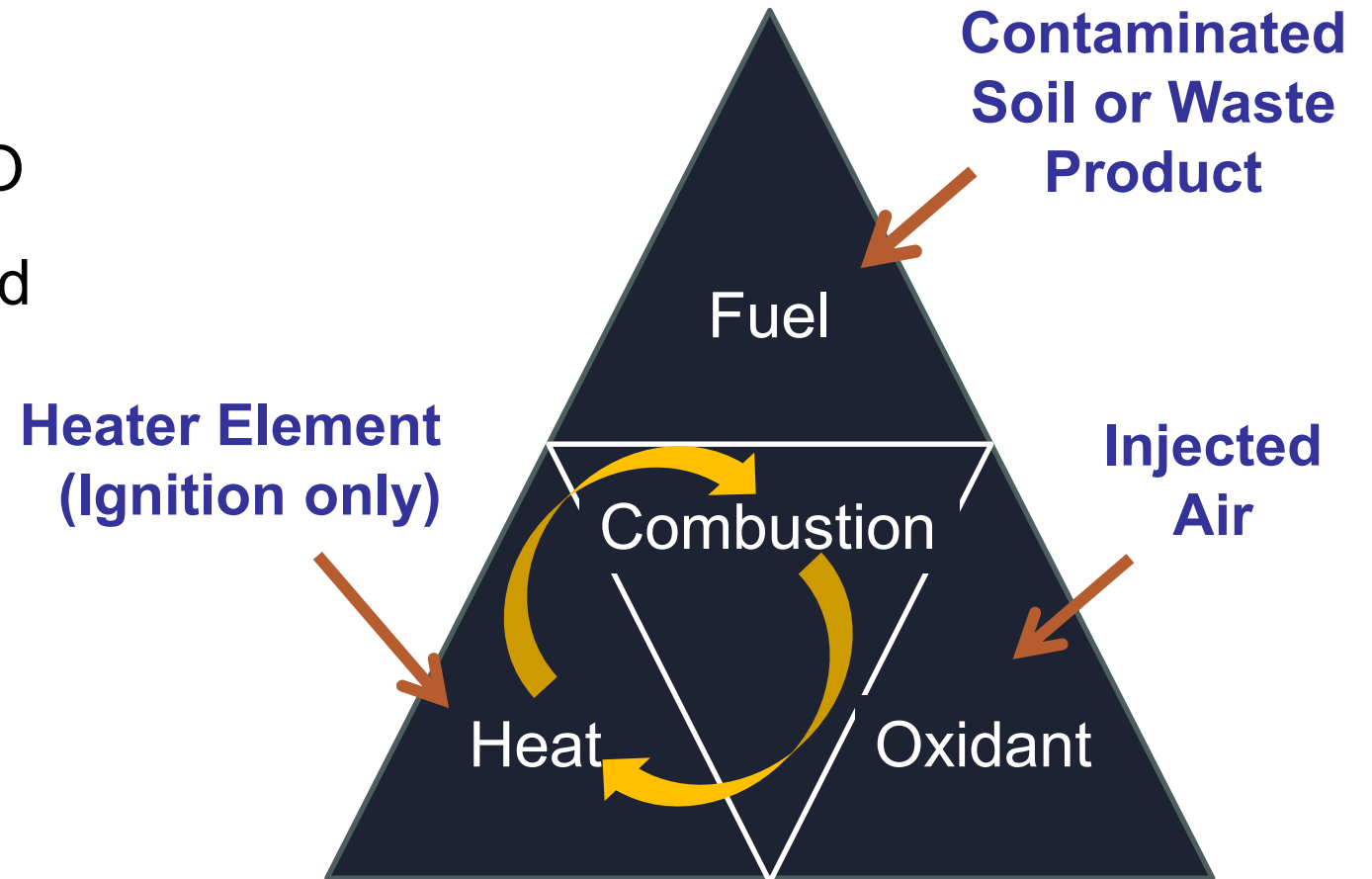


Main Presentation Schedule



- Technology Overview
- PFAS Smoldering
- Edwards AFB Demonstration
- Other PFAS Project Highlights
- Q&A

- Flameless, exothermic combustion reaction
- Converts organics to CO_2 & H_2O
- Porous matrix (i.e., soil) required





STAR



STAR_x

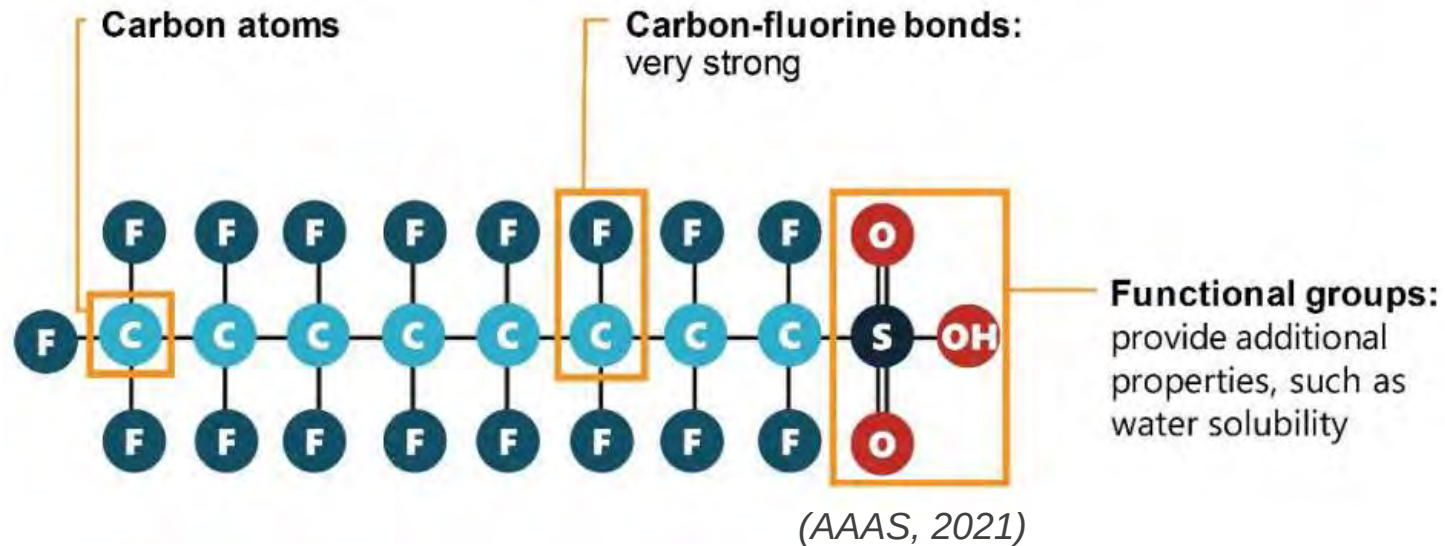


Full scale systems implemented at sites around the world for treating hydrocarbon-impacted soils and sludges



PFAS Smoldering

Strong chemical and thermal stability



Mineralization

- Increases with Temp > 700°C
- Maximizes with Temp > 900°C

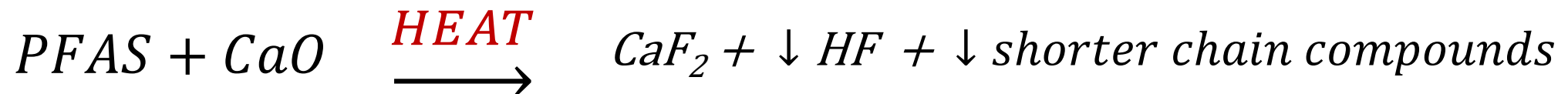
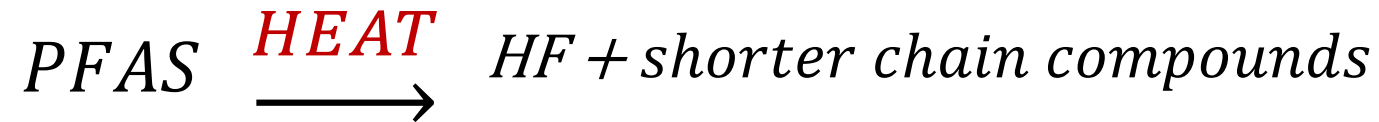
Vecitis et al., 2009; Wang et al., 2011; Watanabe et al., 2015; Yamada et al., 2005



PFAS Thermal Treatment

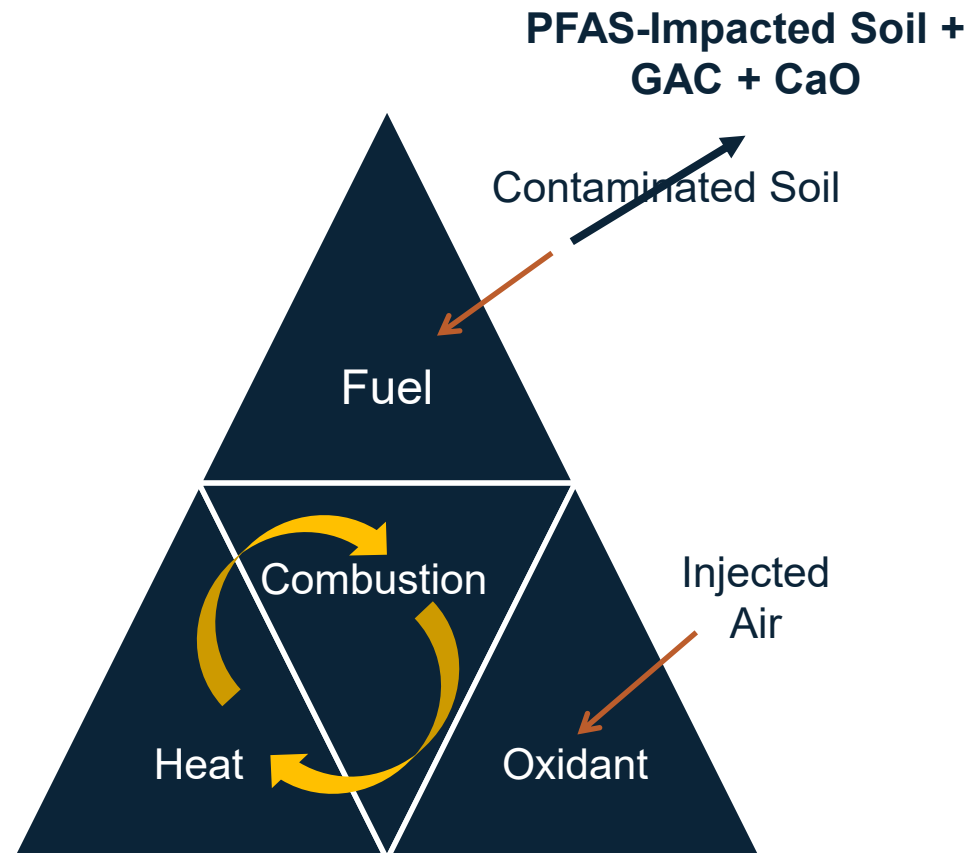


Calcium-based amendments used to improve PFAS destruction and minimize byproducts in emissions



(Wang et al., 2011, 2013, 2015)

Same energy-efficient, flameless form of combustion as used for hydrocarbon applications



For PFAS applications

- **Small quantities of surrogate fuel** (e.g., clean or spent GAC) used to sustain reaction and reach high temperatures required for PFAS destruction
- **Calcium oxide (CaO)** used to improve PFAS destruction and minimize byproducts in emissions



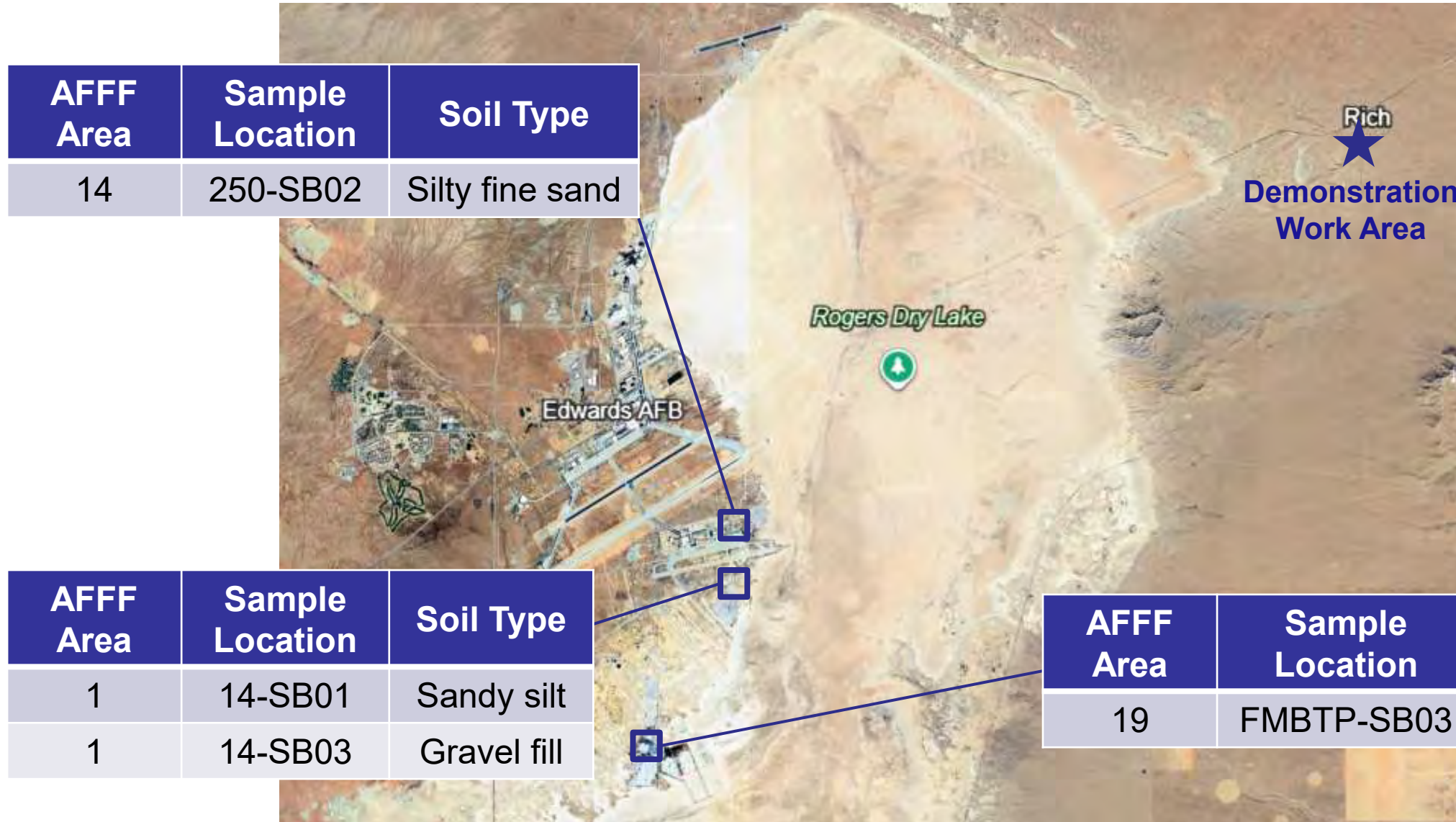
Edwards AFB Demonstration



- Dem/Val of STARx for variable PFAS-impacted feedstocks
 - Soil type, moisture content, co-contaminants, fuel type
- Co-treatment of spent GAC
- 10 x 10 m³ tests

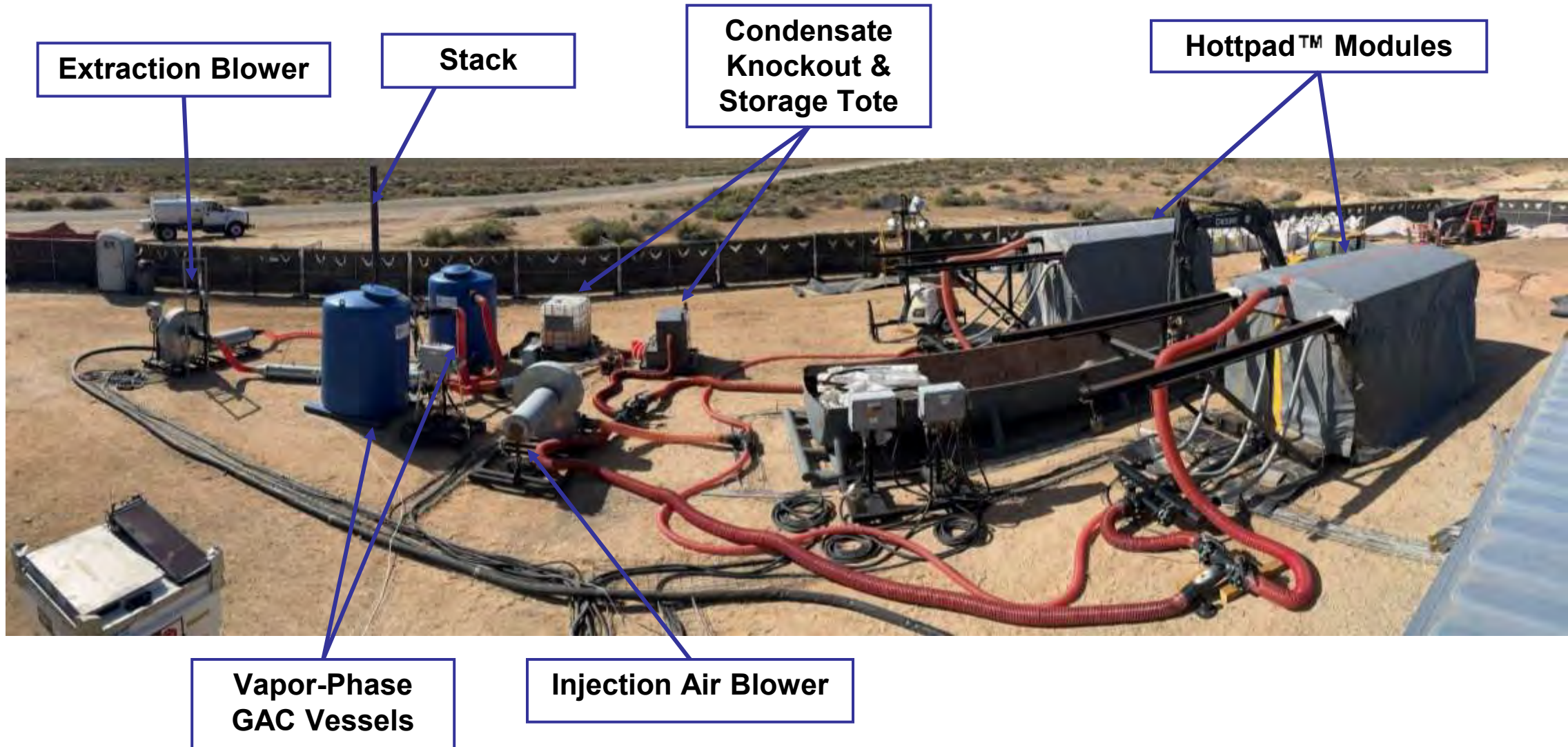


Demonstration Overview





Demonstration Overview





Demonstration Overview

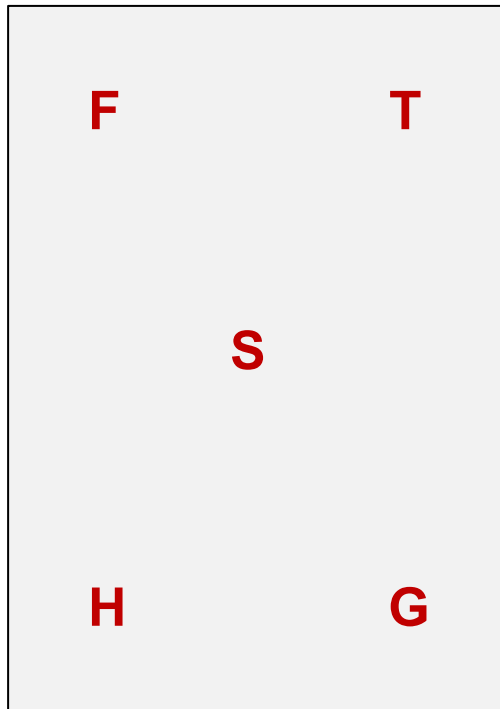


Test No.1	AFFF Area	Soil Type	Average Initial PFAS Concentration (µg/kg)	Carbon Concentration (g/kg)	Carbon Type	Cap Type	Moisture
1	14	Silty fine sand	3,605	35	Clean GAC	Limestone	n/a
2	14	Silty fine sand	2,425	35	Anthracite	Limestone	n/a
3	14	Silty fine sand	8,824	35	Spent GAC	Limestone	n/a
4	1	Sandy silt	3,349	35	Anthracite	Limestone	n/a
5	1	Gravel fill	5,456	35	Anthracite	Treated Soil	n/a
6	19	Clayey Silt	658	35	Anthracite	Treated Soil	n/a
7	19	Clayey silt	372	35	Spent GAC	Treated Soil	n/a
8	1	Sandy Silt	4,695	50	Anthracite	Treated Soil	Added 5%
9	1	Gravel fill	15,107	50	Spent GAC	Treated Soil	Added 15%
10	Various	Various	7,530	50	Various	Treated Soil	n/a

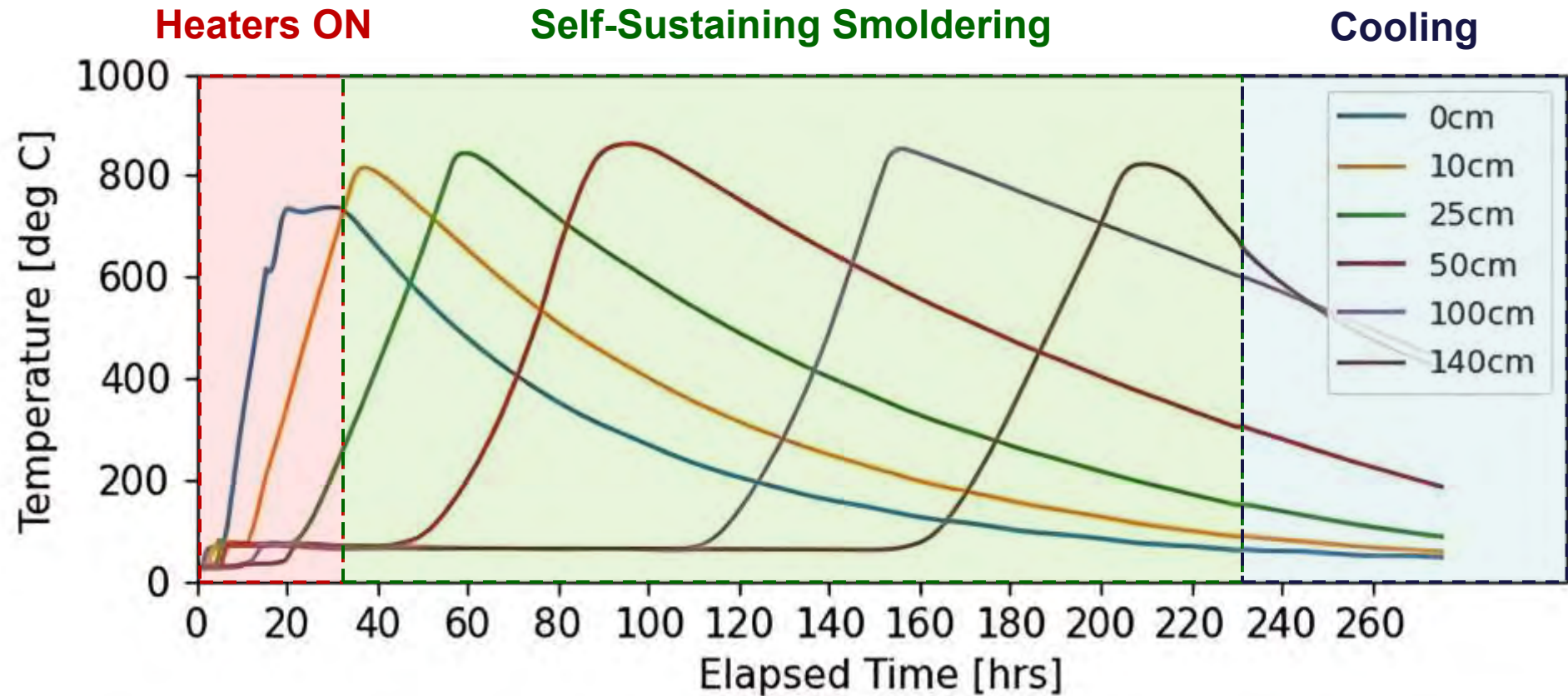


Soils amended with fuel and CaO, and loaded into Hottpad for treatment

BACK WALL



FRONT DOOR

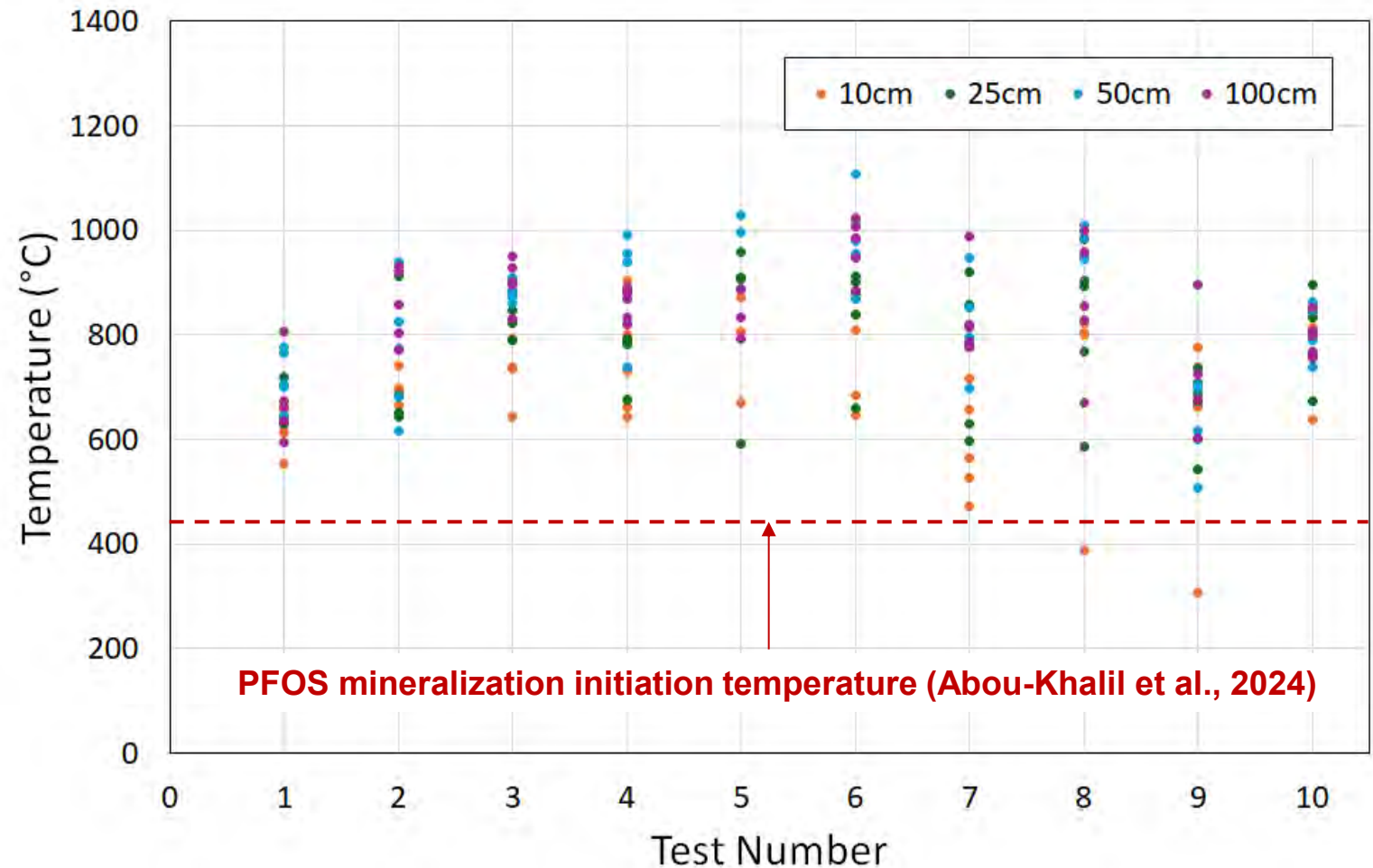


Bundle G

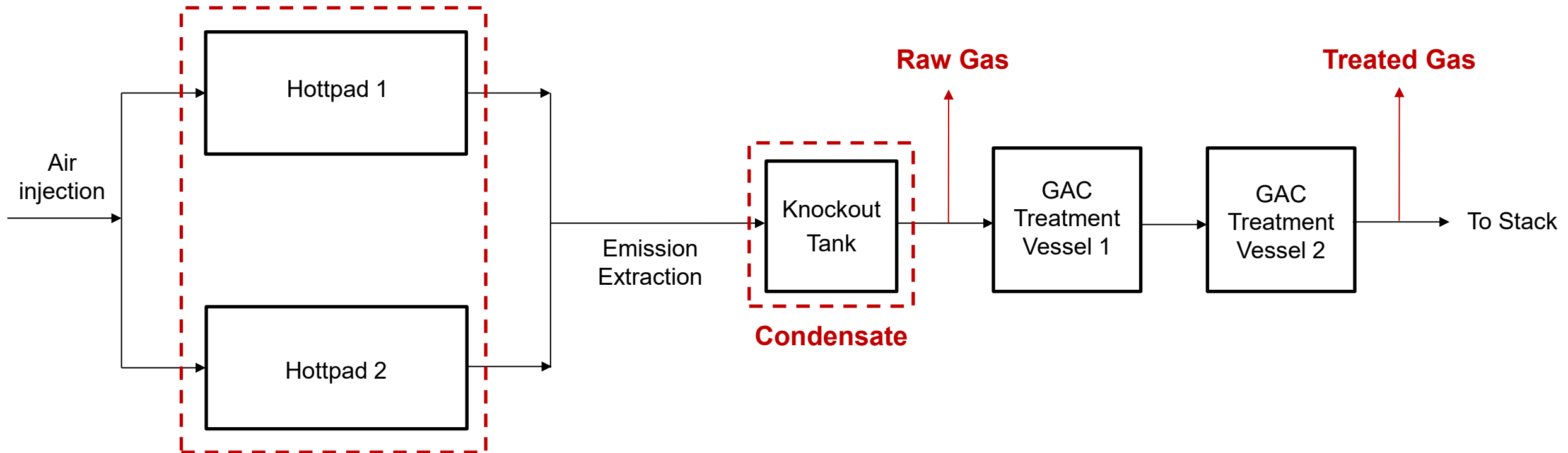


Soils after smoldering treatment

- ~100 m³ of PFAS-impacted soil processed
 - 15 April 2024 to 2 June 2024
- Self-sustaining smoldering achieved across all tests
- Average batch treatment time of 7 days
- Average peak smoldering temperature of 750°C



Pre-/Post-Treatment Soil





Soil Treatment Results



Test No.	Average Peak Temp (°C)	Total PFAS Concentration (as Equivalent Organic Fluorine)		Percent Reduction (%)
		Pre-treatment (µg/kg)	Post-treatment (µg/kg)	
1	644	2,324	19	99.2
2	737	1,813	26	98.6
3	784	5,689	26	99.5
4	782	2,153	50	97.7
5	851	2,639	53	98.0
6	842	414	25	94.0
7	696	235	19	92.1
8	746	3,017	40	98.7
9	634	9,619	43	99.6
10	770	4,820	227	95.3

Project Action Limits (µg/kg)	
PFOA	19
PFNA	19
PFBS	1900
PFHxS	130
PFOS	13
HFPO-DA	23

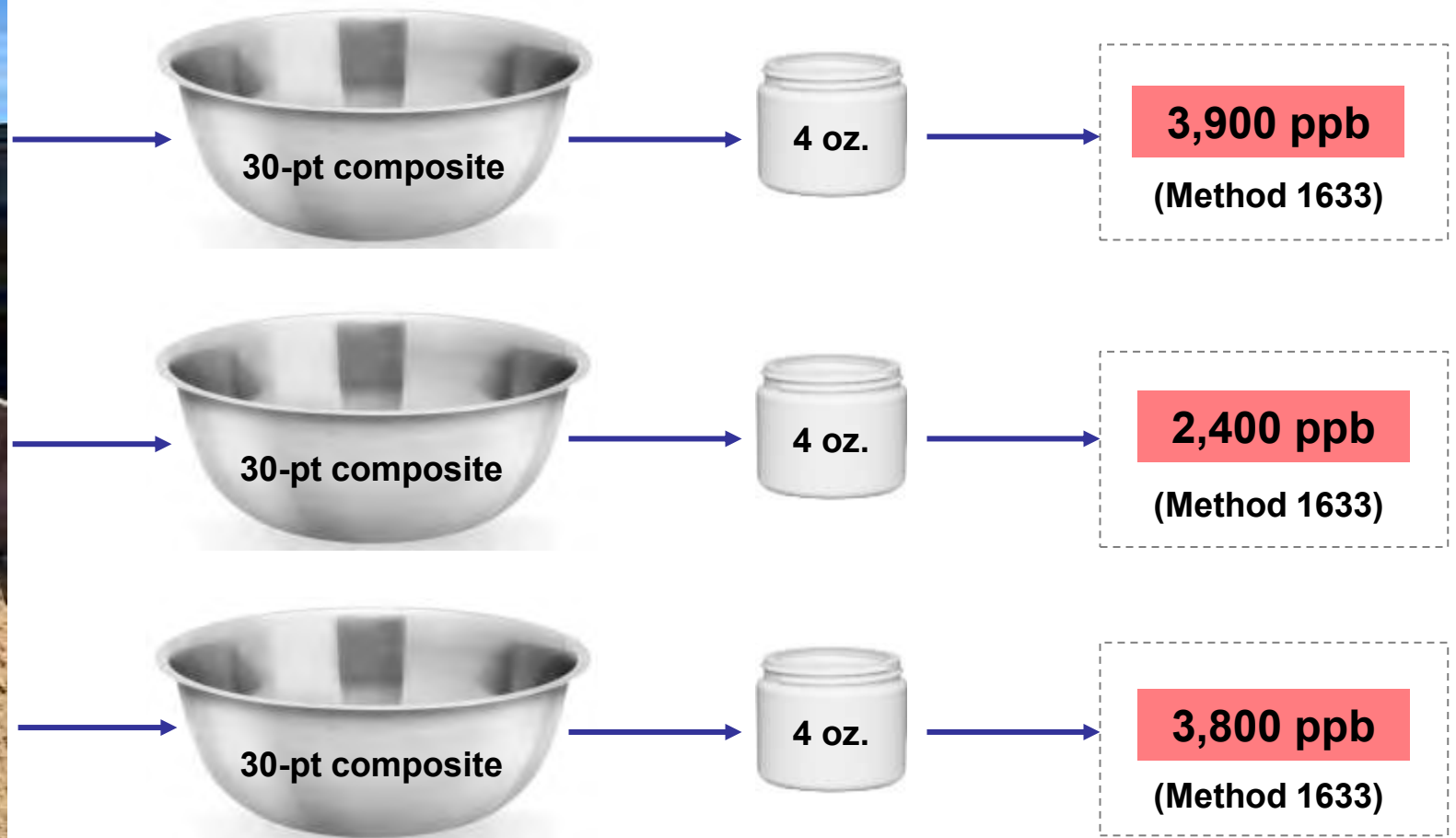
**All post-treatment soil samples
across all tests met PALs,
except for PFOS**



PFOS Soil Treatment Results – Test 1



Pre-Treatment Soil

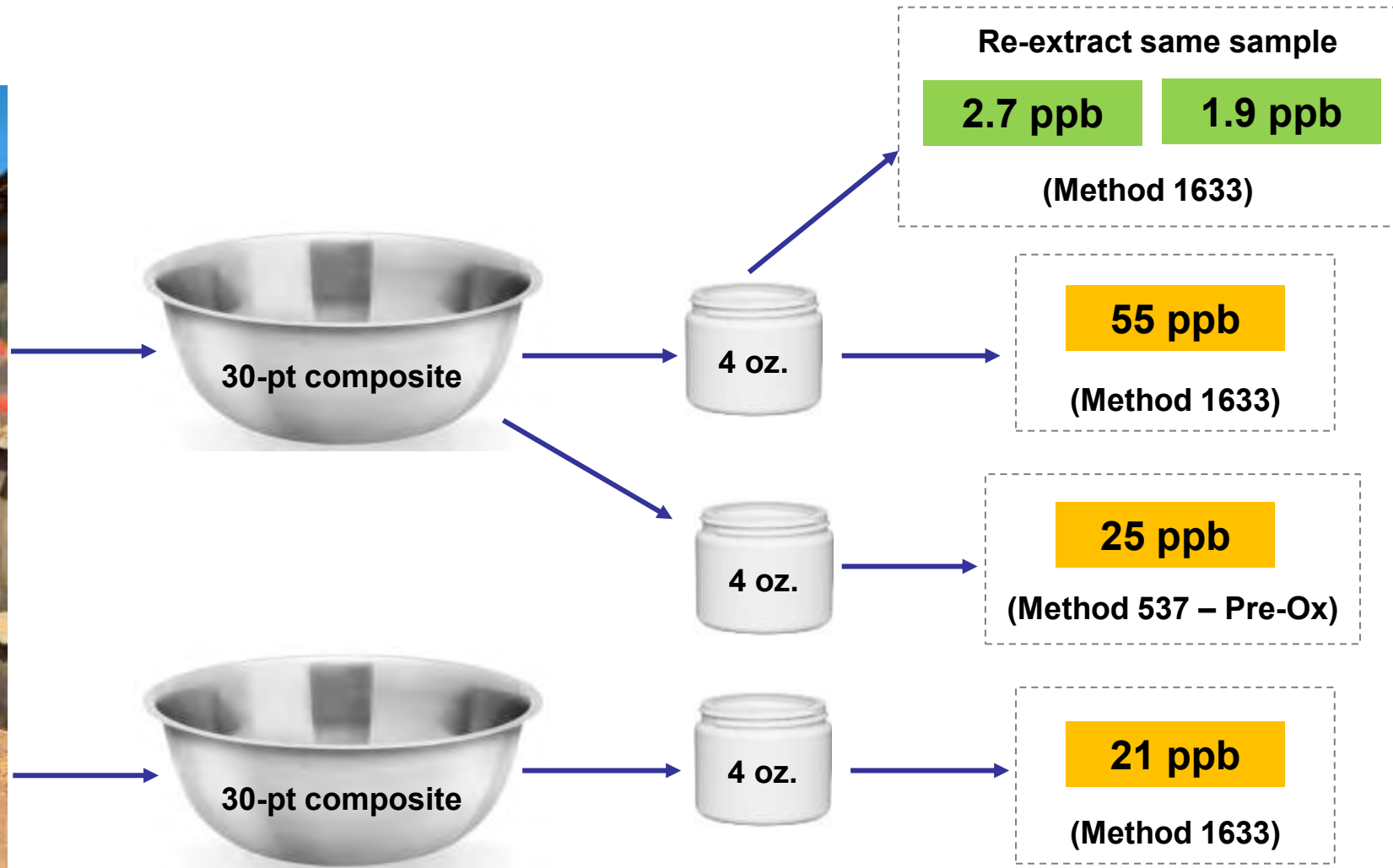




PFOS Soil Treatment Results – Test 1



Post-Treatment Soil

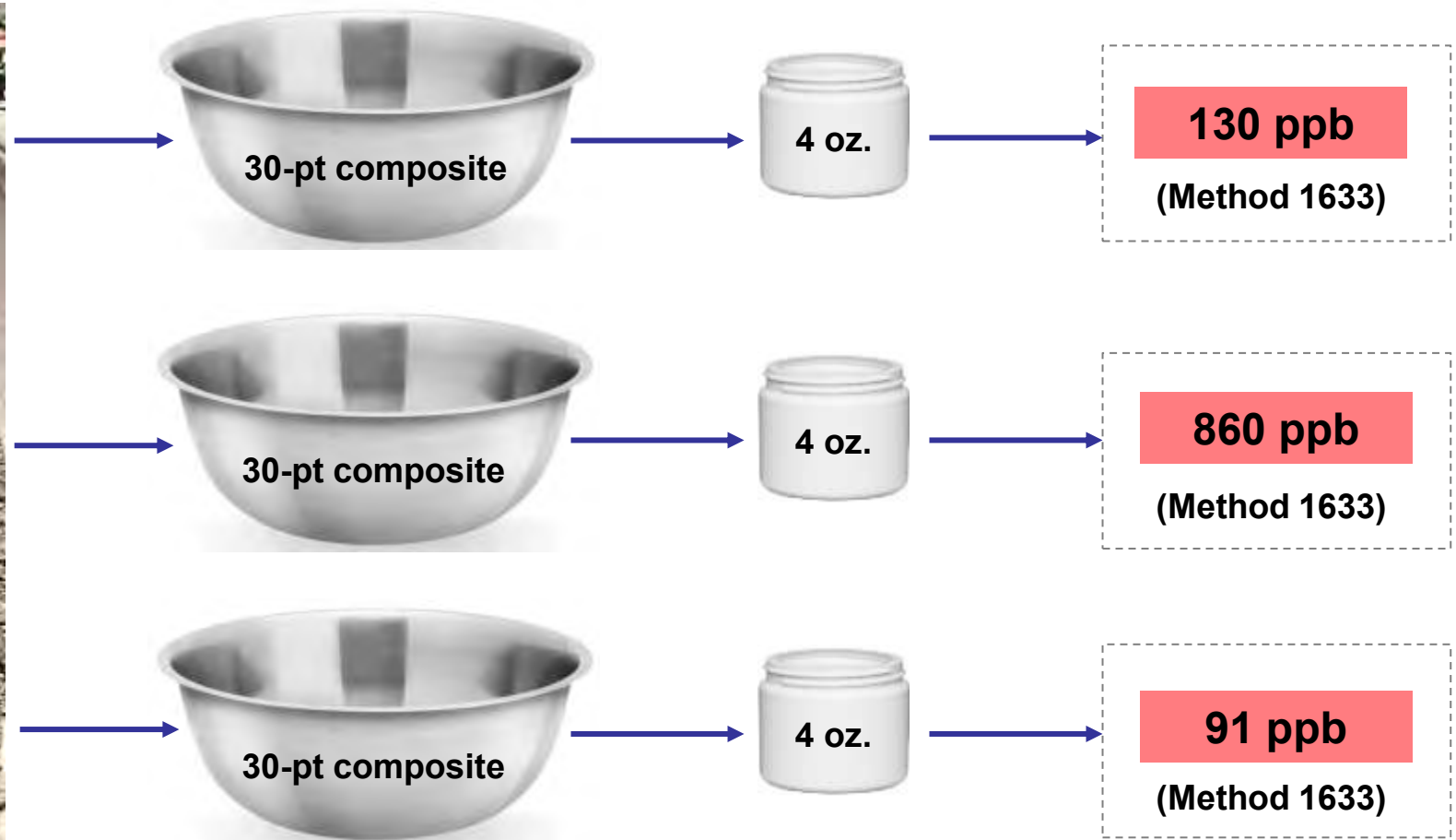




PFOS Soil Treatment Results – Test 6

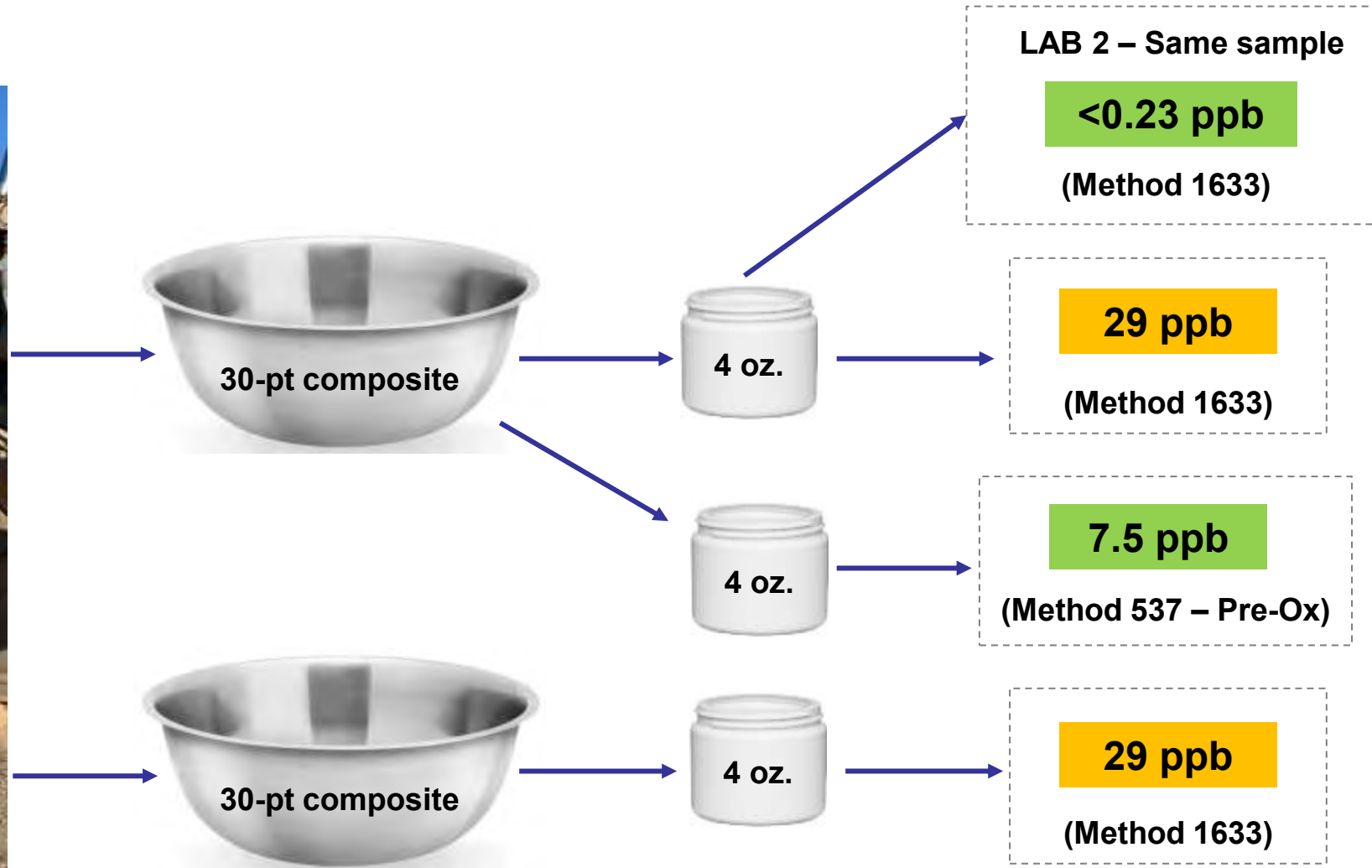


Pre-Treatment Soil



PFOS Soil Treatment Results – Test 6

Post-Treatment Soil



PFOS Soil Treatment Results

- Heterogeneous soil samples – lab extractions typically avoid larger grain fractions ($>1/4"$)



Initial Sample

PFOS = 25 ppb



Fine

PFOS = 23 ppb



Intermediate

PFOS = 1.1 ppb

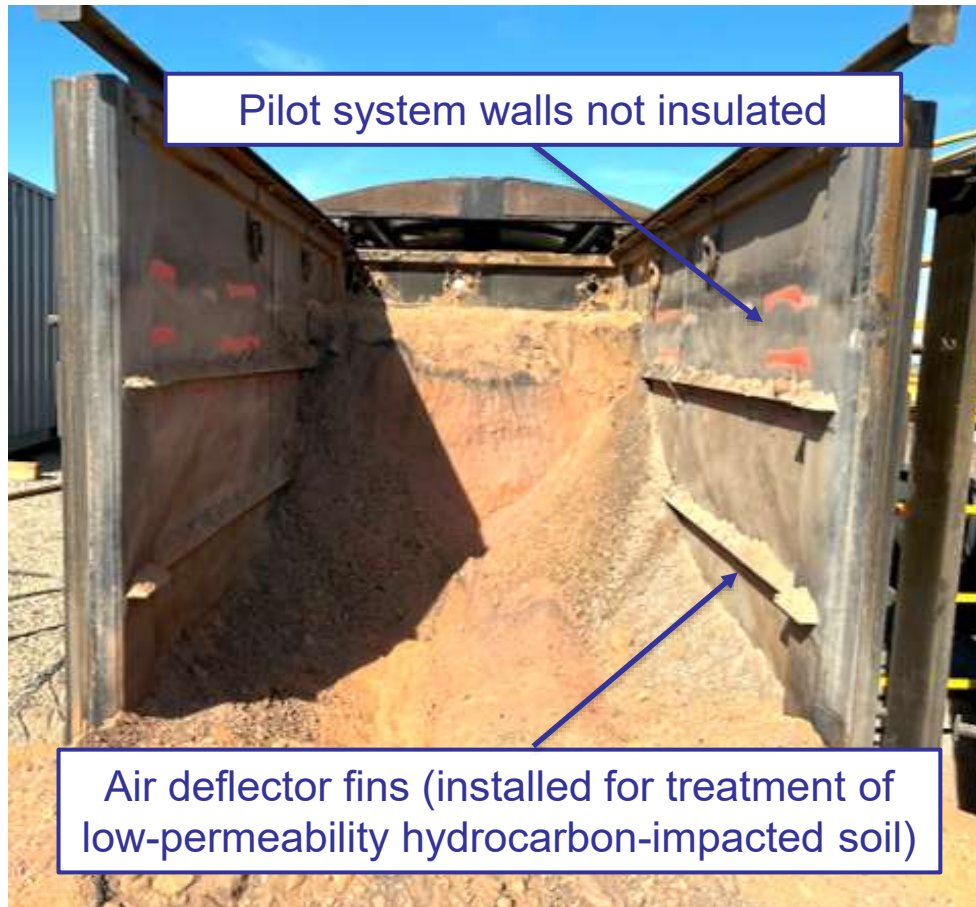


Large

PFOS = 0.33 ppb

Preferential selection of finer-grained soils for analysis may cause a high bias of PFAS results in post-treatment soil

- Boundary effects suspected to be cause of PFOS remaining at low levels above PAL



- Wall samples collected from Tests 8 – 10



TEST 8

2,224 ppb

(Method 1633)

TEST 9

182 ppb

(Method 1633)

2,287 ppb

(Method 1633)

TEST 10

1,152 ppb

(Method 1633)

**Supplemental
lab testing
conducted to
further
investigate**



Soil Treatment Results – TOP Assay



- Total oxidizable precursor (TOP) samples collected before treatment from Test 5 and 8, and after treatment from all tests
 - Precursors observed in pre-treatment soils
 - Post-treatment soils had minimal precursor presence (<30% RPD)

TOP Assay Results	TEST 5		TEST 8	
	Before Treatment	After Treatment	Before Treatment	After Treatment
Pre-Oxidation (µg/kg) ¹	2573	70.4	2773.5	15.5
Post-Oxidation (µg/kg) ¹	3304	99.2	3470.7	9.0

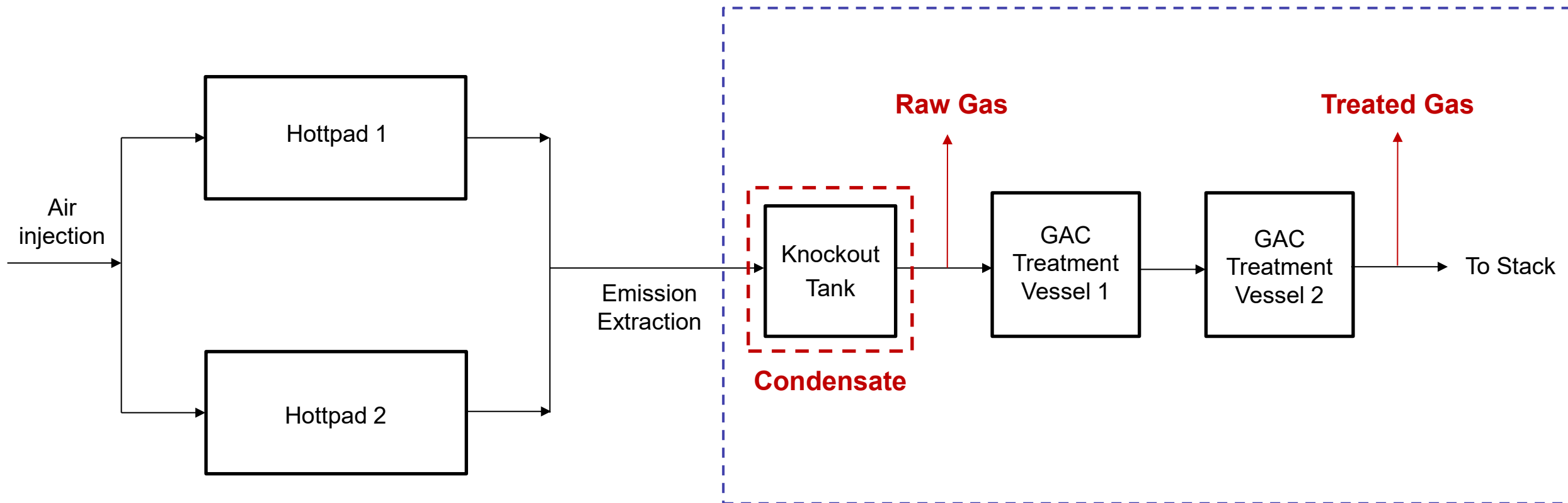
¹ Converted to equivalent organic fluorine mass

- Extractable organic fluorine (EOF) samples collected before and after treatment from all tests
 - Relatively high detection limits (>130 ug/kg)
 - Post-treatment results less than detection limits for all but two samples





Emissions Characterization





Emissions Characterization

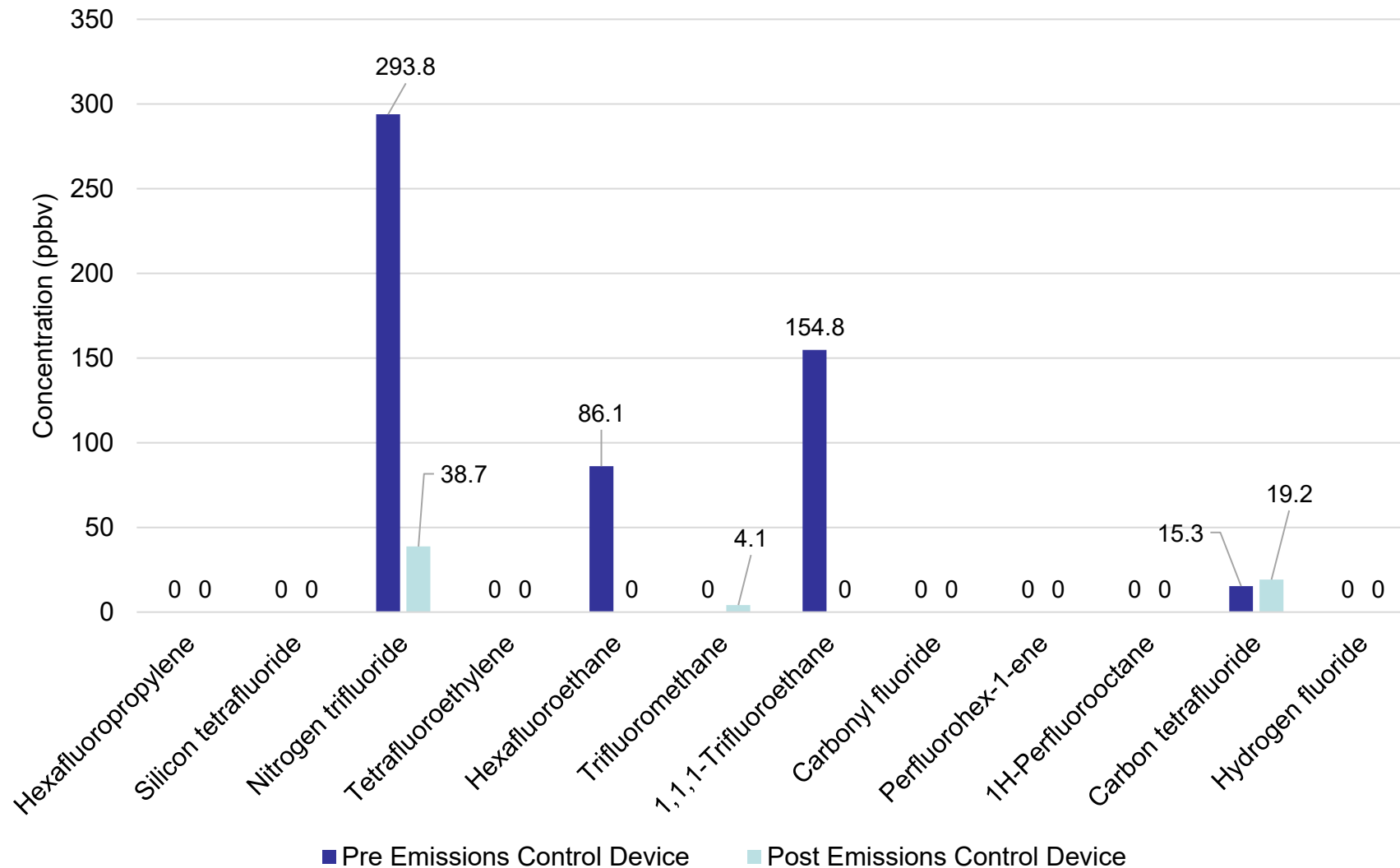


Test	Sampling Period	Fluorine Mass Recovery (%)		
		HF Impinger	GAC Sorption Tubes (PFAS)	XAD Tubes (PFAS)
1 / 2	Ignition / OFF	0.26	0.15	0.0015
3 / 4	Ignition / Steady State	0.034	0.04	0.0004
5 / 6	Steady State	0.27	0.03	0.0013
7 / 8	Cooling / Steady State	0.16	0.20	0.0019
9 / 10	Cooling / Steady State	0.53	0	0.0015

- <0.01% of total fluorine mass present in liquid condensate



Emissions Characterization - FTIR



**Smoldering is
destroying
(not volatilizing)
PFAS**



Zero reported safety incidents



Excellent destruction of PFAS

- <1% of fluorine detected in emissions / liquid condensate



Some PFOS remained in soil at low levels (90.7 – 99.6% removal efficiency, but sometimes still exceeding PALs)



Significant variability in post-treatment soil analytical results (across same lab, different labs, different methods)

- PFAS concentrated on fines, which is preferentially included in typical lab subsampling procedures for heterogeneous soils



Reduced treatment along Hottpad walls likely impacting overall pile results

- Analytical TAT limited ability to adapt testing plan in the field



Supplemental Lab Testing



Supplemental Lab Testing



Test Objective

- Compare wall temperature data under various conditions (i.e., with/without air deflector fins and with/without insulation)

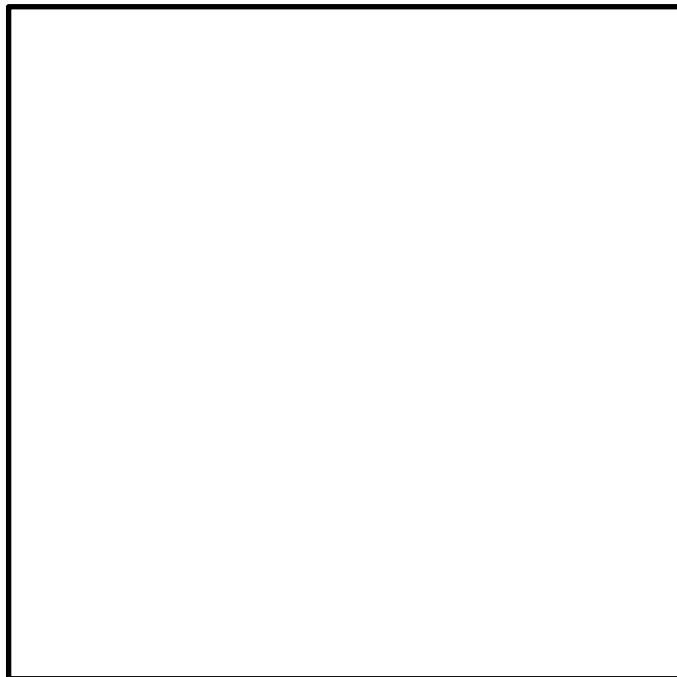
Supplemental lab testing completed using Savron's Rapid Screening Tool (RST)



Supplemental Lab Testing



✓ Insulated
✗ Air Fin



✓ Insulated
✓ Air Fin

✗ Insulated
✓ Air Fin

✗ Insulated
✗ Air Fin

Effect of Insulation

Distance from Wall	Uninsulated Wall	Insulated Wall
1"	302°C	649°C
2"	648°C	750°C

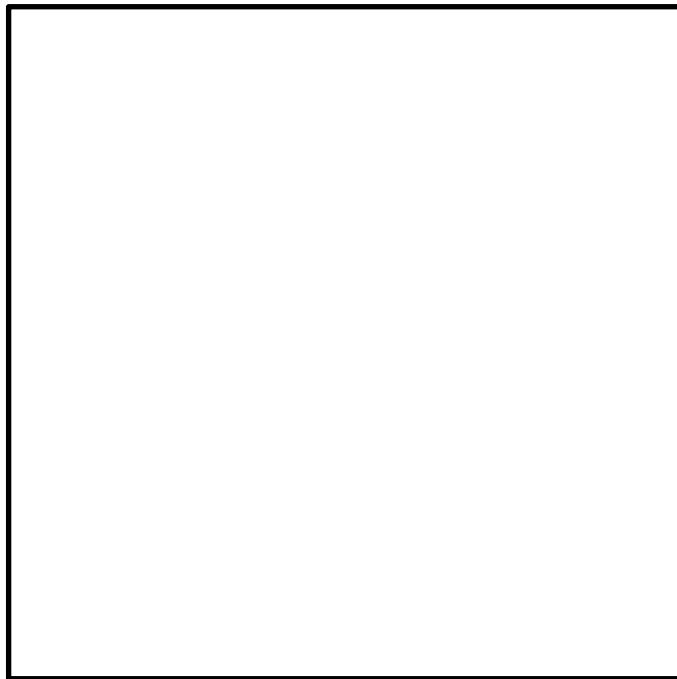
Reduced temperatures
(and PFAS treatment) may
be expected within ~1-2"
of uninsulated walls



Supplemental Lab Testing



✓ Insulated
✗ Air Fin



✓ Insulated
✓ Air Fin

✗ Insulated
✓ Air Fin

✗ Insulated
✗ Air Fin

Effect of Air Fins

Distance from Wall	Insulated Wall (With Air Fin)	Insulated Wall (No Air Fin)
1"	418 - 551°C	649°C
2"	536 - 682°C	750°C

Presence of air fins appears to exacerbate wall effects for both insulated and uninsulated walls



Zero reported safety incidents



Excellent destruction of PFAS

- <1% of fluorine detected in emissions / liquid condensate



Significant variability in post-treatment soil analytical results (across same lab, different labs, different methods)

- PFAS concentrated on fines, which is preferentially included in typical lab subsampling procedures for heterogeneous soils



Simple system modifications can be implemented to improve treatment for high concentration soils

- Addition of wall insulation
- Removal of air fins



ESTCP / DIU Project: Joint Base Elmendorf Richardson (JBER)

Rapid On-Site Treatment



Pilot (10 m³)



STARxpress (35 m³)

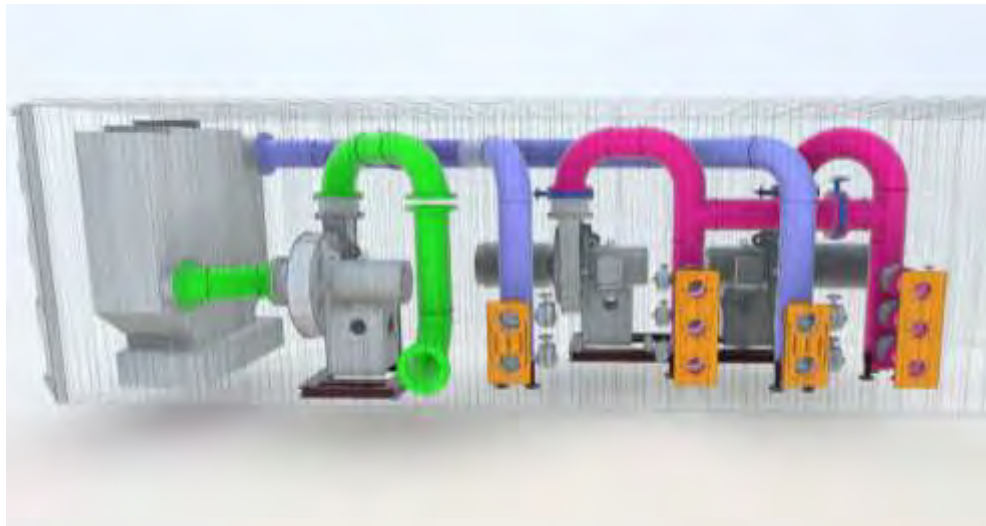


HP-250 (250 m³)

Scalable Solutions



STARxpress Fabrication





STARxpress Field Implementation





STARxpress Field Implementation





STARxpress Field Implementation

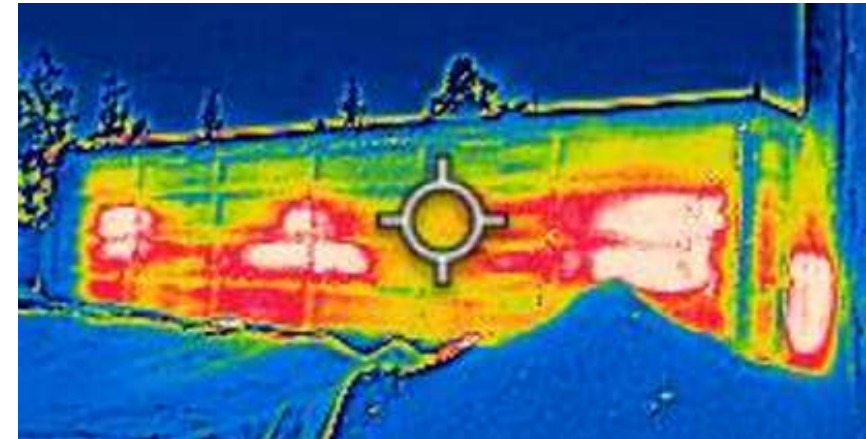




Demonstration Results (ER23-8373)



- 440 yd³ of soil processed in 10 batches
- Self-sustaining smoldering demonstrated across all batches
 - >700°C treatment temperatures
- Average batch cycle time ~8 days
 - Includes loading/unloading
- >96% operational uptime





Post-Treatment Soil Sampling Results



Post-Treatment Soil (10 batches)					
Analyte	DoD Screening Level (µg/kg)	ADEC MTG Soil Cleanup Level (µg/kg)	Average (µg/kg)	Max (µg/kg)	Min (µg/kg)
PFBA	7,800	-	0.01	0.11	ND
PFPeA	-	-	0.05	0.40	ND
PFHxA	3,200	-	0.02	0.29	ND
PFHpA	-	-	0.01	0.12	ND
PFOA	0.070	1.7	0.02	0.16 ¹	ND
PFPeS	-	-	0.00	0.02	ND
PFHxS	130	-	0.03	0.24	ND
PFOS	0.63	3.0	0.23	1.60 ²	ND
6:2 FTS	-	-	0.17	1.00	ND
8:2 FTS	-	-	0.05	0.51	ND
PFOSA	-	-	0.00	0.04	ND
ADONA	-	-	0.00	0.02	ND
PFMPA	-	-	0.00	0.04	ND

¹ Exceeded DoD screening level for PFOA in 2 batches; ² Exceeded DoD screening level for PFOS in 1 batch

³ Pre-treatment PFAS concentrations (sum of Method 1633 compounds) ranged from 24.5 to 197.8 µg/kg



STARxpress Plant Study



Unamended

Compost

Fertilizer

July 1 2024



Aug 21 2024

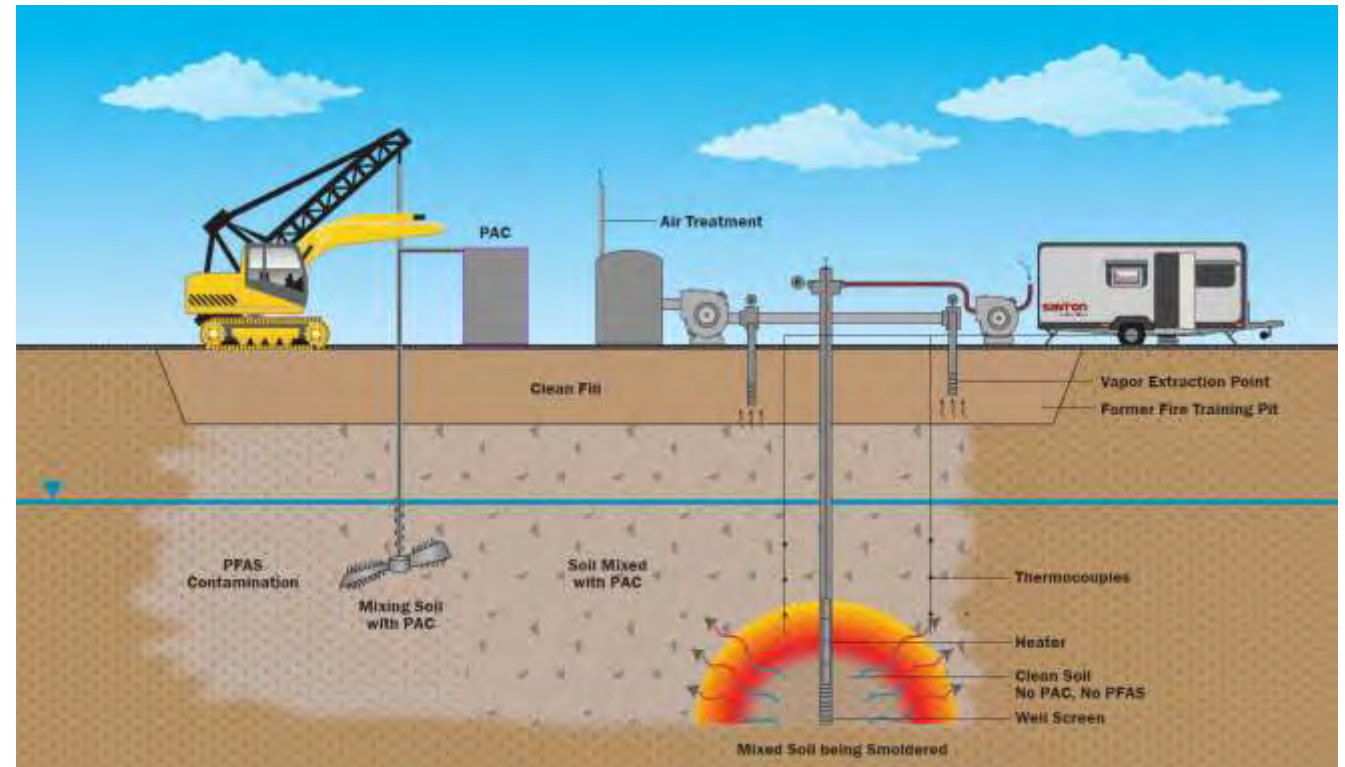




ESTCP Project: In Situ PFAS Smoldering

ESTCP In Situ Smoldering (ER22-7470)

- Demonstration of PFAS destruction in a source zone
- 4 ignition points, 500 m³ soil volume
- In-situ soil mixing for carbon amendments





ESTCP In Situ Smoldering (ER22-7470)





Summary



- PFAS can be successfully destroyed in soil using smoldering
- CaO enhances PFAS destruction at lower temperatures and simplifies vapor treatment
- STARxpress is a commercially available system with demonstrated success
- Minor system modifications required for treating high concentration PFAS-impacted soils
- Additional work on analytical variability / post-treatment sampling methodology recommended



Thank You



Questions?



Your Success is Our Mission!



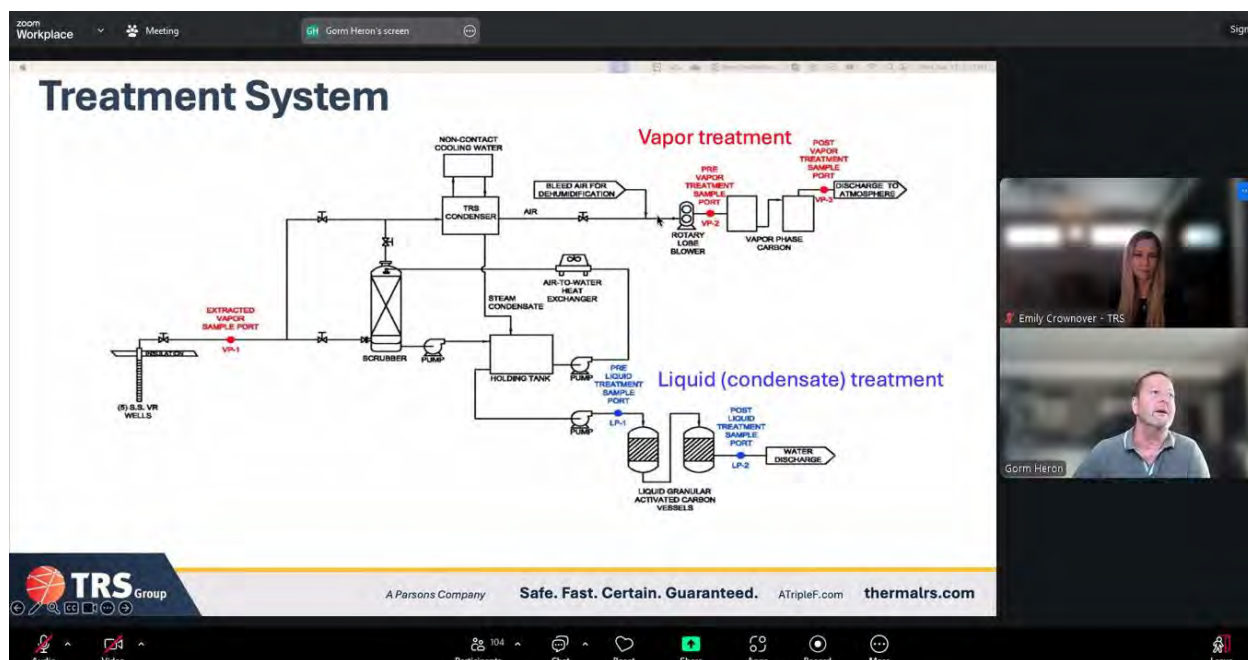
Air Force Civil Engineer Center

Restoration Technology Transfer Speakers Series August 2025

Smoldering Treatment of PFAS-Impacted Soil

Presenters: Gorm Heron & Emily Crownover – TRS Group, Inc.

This presentation covered TRS's experience with laboratory and field treatment of PFAS-impacted soils. The data includes mechanisms for PFAS removal, treatment temperature and energy demand and how to treat the PFAS aboveground to ensure minimal environmental emissions. TRS has completed three ESTCP-funded field projects for PFAS impacted soil piles, a fire-training area in-situ and a constructed soil pile for treatment of 2,000 cubic yards. Specifically, engineering solutions that minimize energy usage and optimize PFAS treatment were presented.



Emily Crownover and Gorm Herson describe the smoldering treatment system.

This event and future events are updated and posted on the AFIT website at: <https://www.afit.edu/CE/index.cfm>.

POCs:

Joseph Dimisa, AFIT (joseph.dimisa@us.af.mil)

C.J. Garcia, CTR, Booz Allen Hamilton (carlos.garcia.56.ctr@us.af.mil)

Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)



Webinar Structure



	<u>Restoration Technology Transfer Webinar Series – eDASH Archive</u>
5 min	Welcome and Administrative Business
45 min	Main Presentation – <i>Thermal Desorption of PFAS-Impacted Soil</i>
10 min	Questions and Answers
5 min	Final Thoughts

Air Force Civil Engineer Center



Thermal Desorption of PFAS-Impacted Soil

Gorm Heron, Ph.D.
Emily Crownover, Ph.D.
TRS Group, Inc.
August 2025



Thermal Desorption of PFAS – Impacted Soil

Gorm Heron, Chief Technology Officer
Emily Crownover, Managing Principal Engineer

TRS Group, Inc. A Parsons Company
Safe. Fast. Certain. Guaranteed.
ATripleF.com

thermalrs.com

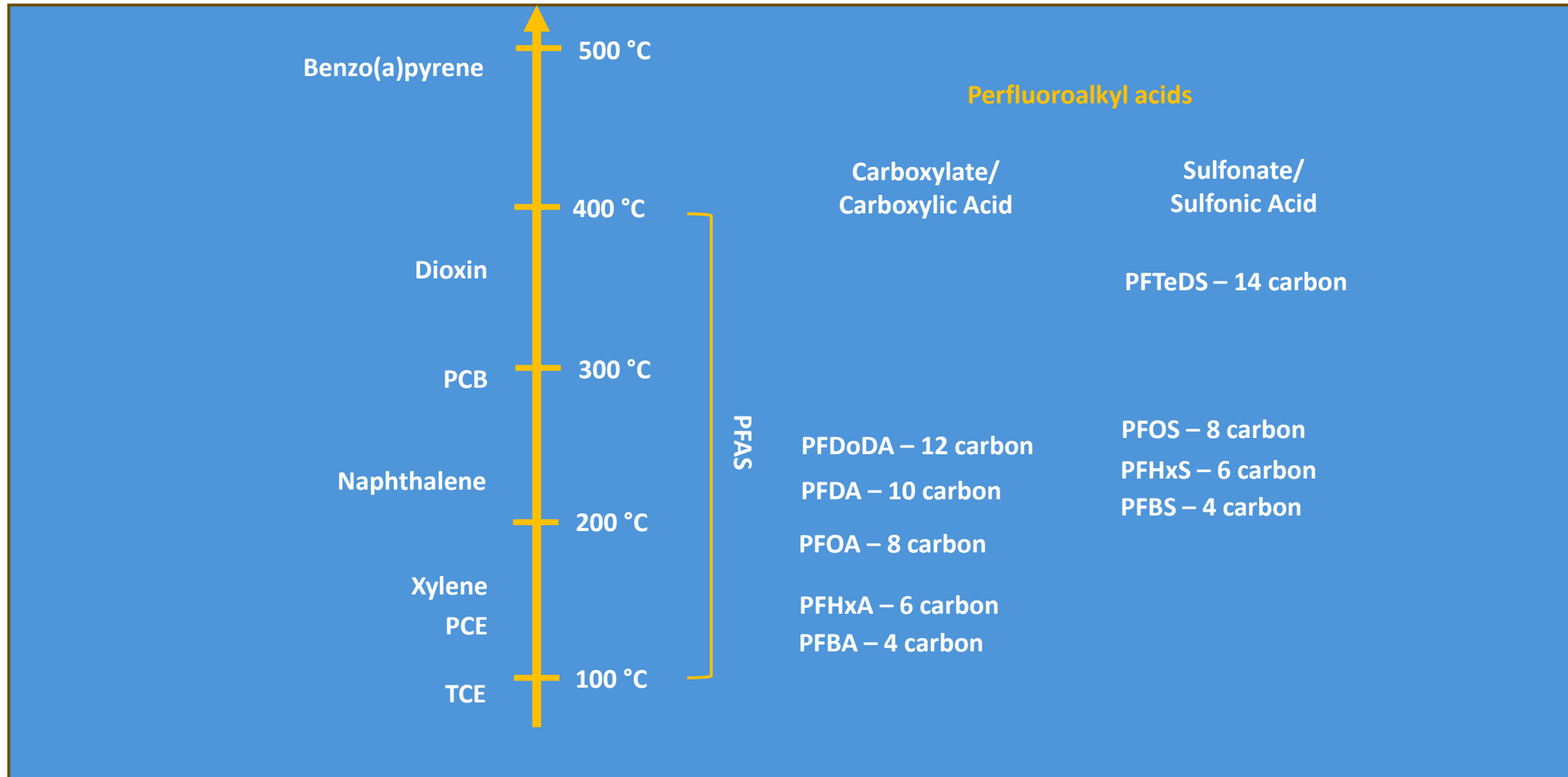


TRS PFAS Projects

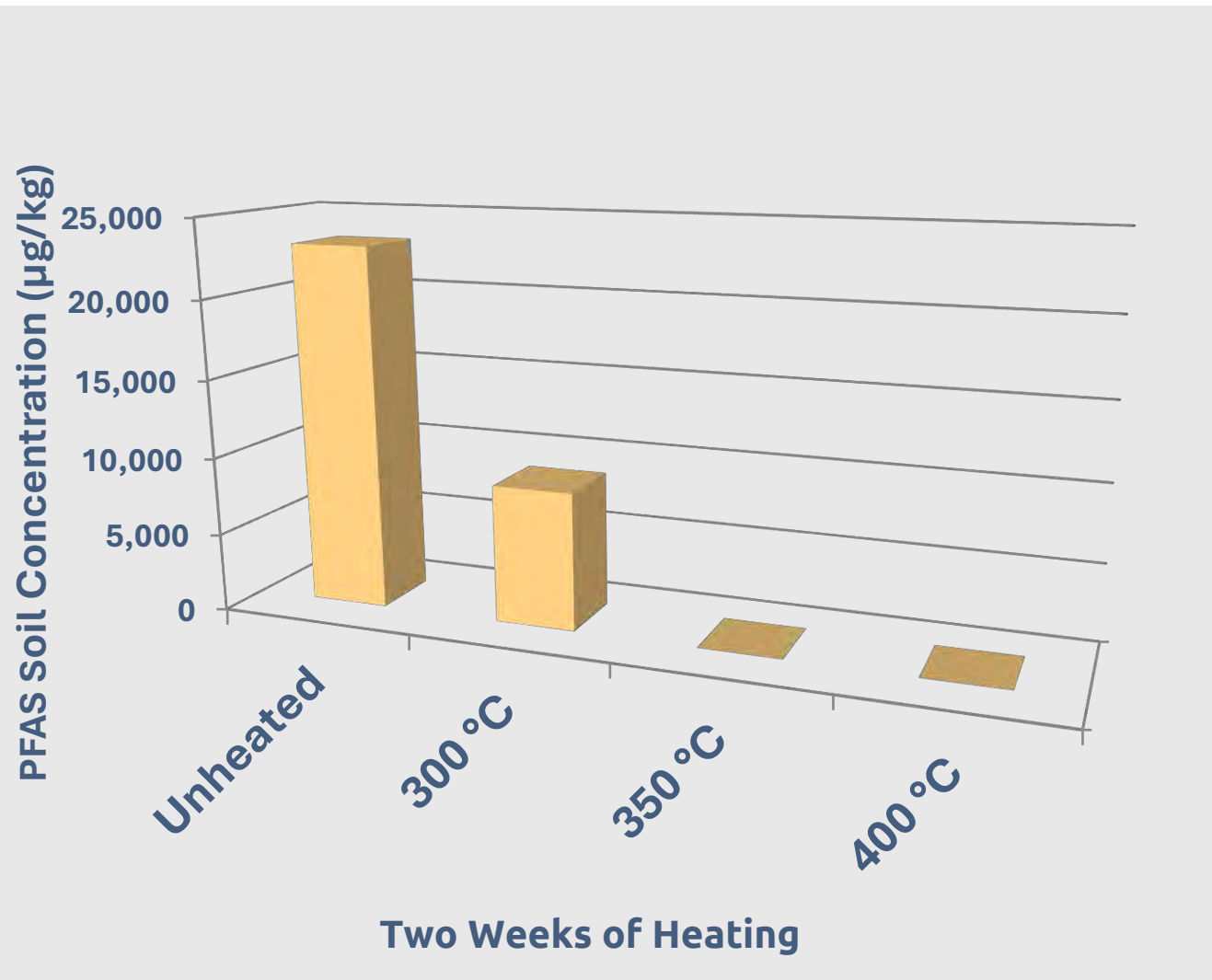
- TCH – 400°C
- Patented technology
- Ex situ / in situ
- On site vapor and condensate treatment
- Near non-detect PFAS concentrations after treatment



Boiling Points



Laboratory Testing

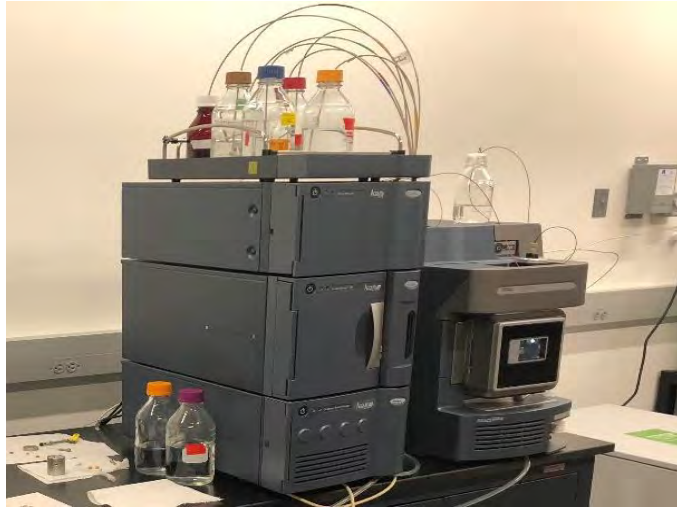


PFAS	Starting Concentration (ug/kg)	300 °C % reduction	350 °C % reduction	400 °C % reduction
PFOS	21000	61.90%	99.92%	>99.999%
PFBA	91	93.85%	99.82%	>99.999%
PFPeA	100	92.60%	<99.8%	>99.999%
PFBS	41	58.54%	99.80%	>99.999%
PFHxA	200	95.30%	99.96%	>99.999%
PFHpA	27	86.67%	98.63%	>99.998%
PFHxS	1600	51.88%	99.84%	>99.999%
PFNA	16	96.81%	<98.75%	>99.997%
PFDS	48	75.00%	<99.58%	>99.999%
PFOA	64	92.97%	99.22%	>99.865%

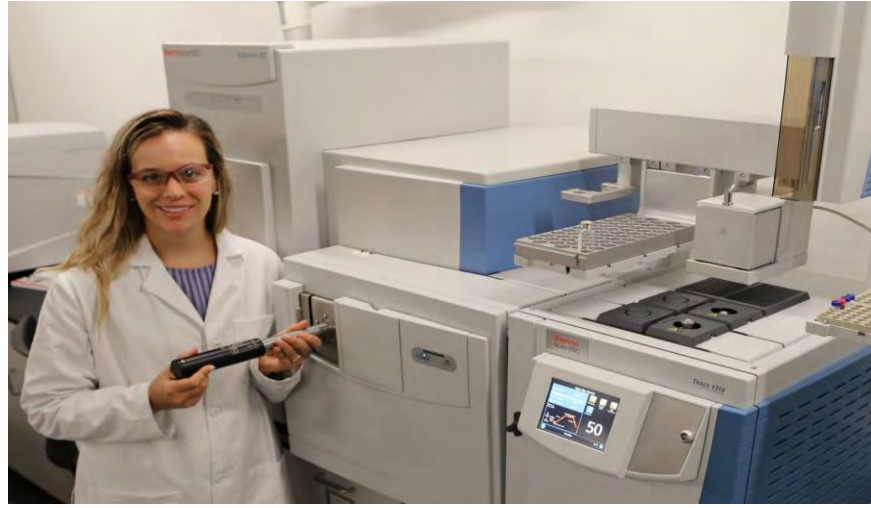
Crownover et al. 2029. Remediation; 29:77-81

Targeted & Non-Targeted PFAS Analysis

Waters uHPLC Xevo TQ-S



Thermo GC QExactive Orbitrap

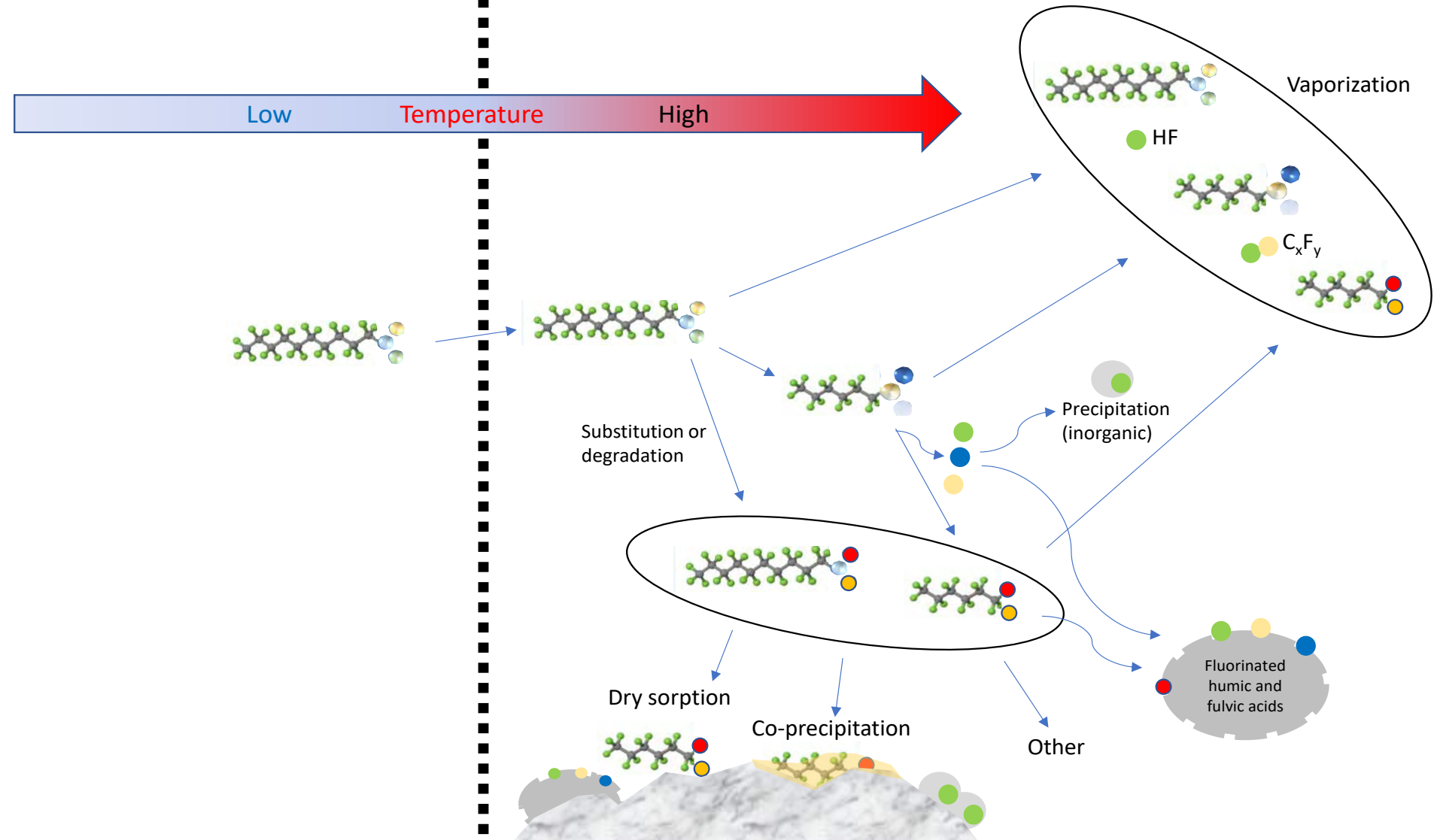


Thermo LC QExactive HFX Orbitrap



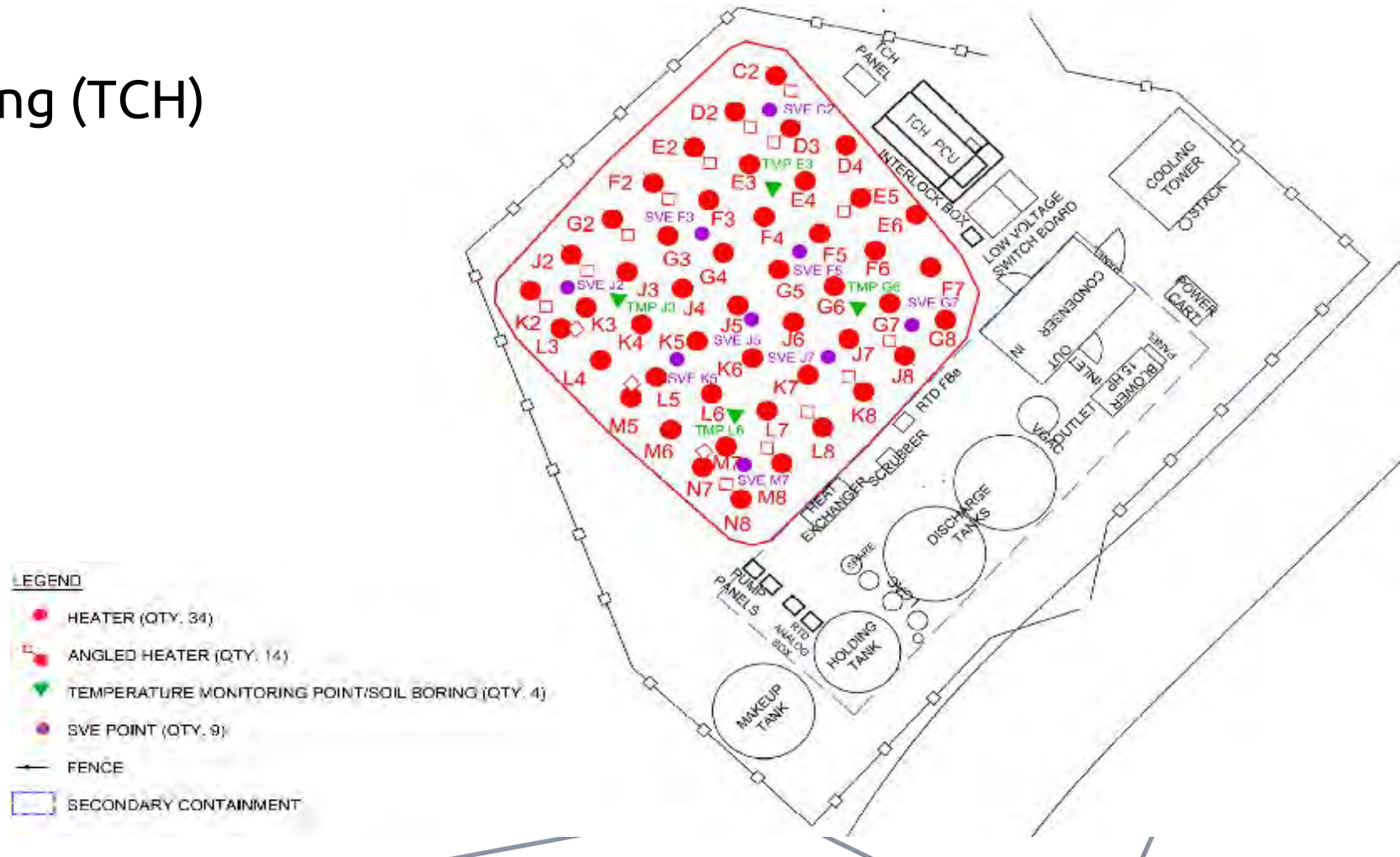
- Targeted analysis of up to 28 PFAS using Waters uHPLC-MS/MS
- Verification by an ELAP-certified laboratory (Battelle Memorial, Norwood, MA)
- Non-targeted analysis using high resolution liquid- and gas-chromatograph Thermo Orbitrap mass spectrometers to detect reaction by products.

PFAS Reactivity

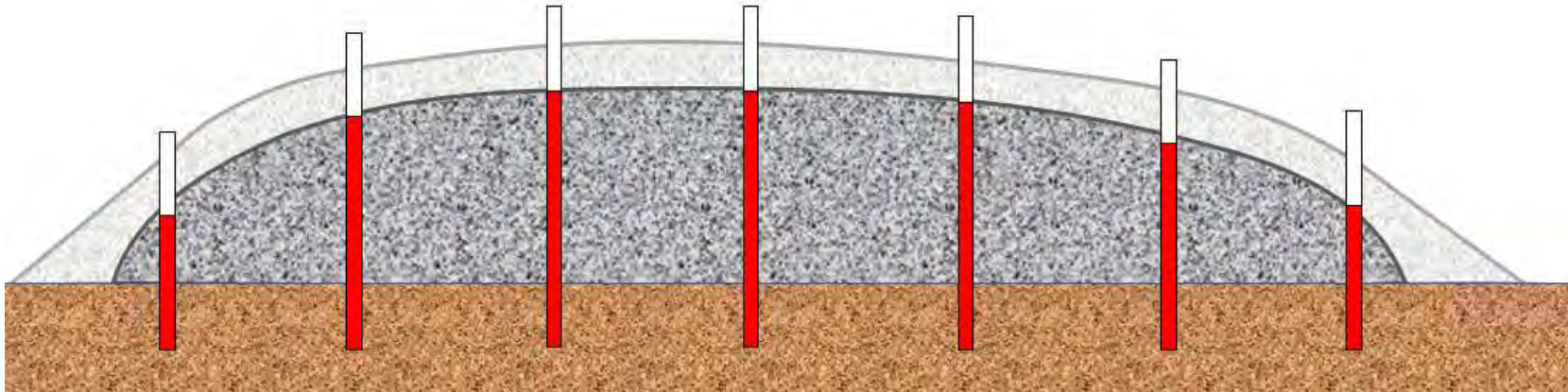


Eielson Air Force Base, Alaska

- Thermal conduction heating (TCH)
- *Ex situ* pile
- 350-400°C for 10 days
- Soil samples
- Vapor, liquid monitoring



Eielson Air Force Base, Alaska



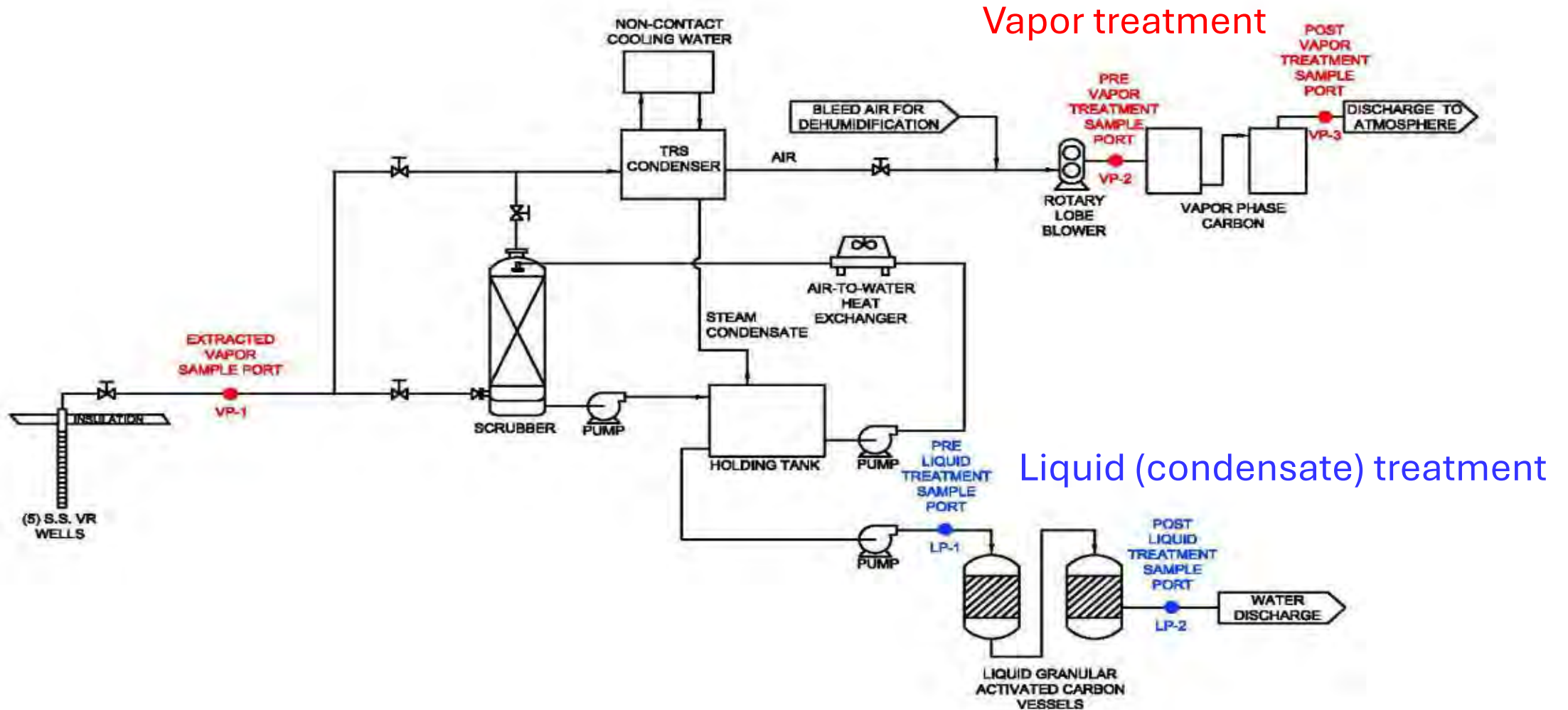
Stockpile Construction



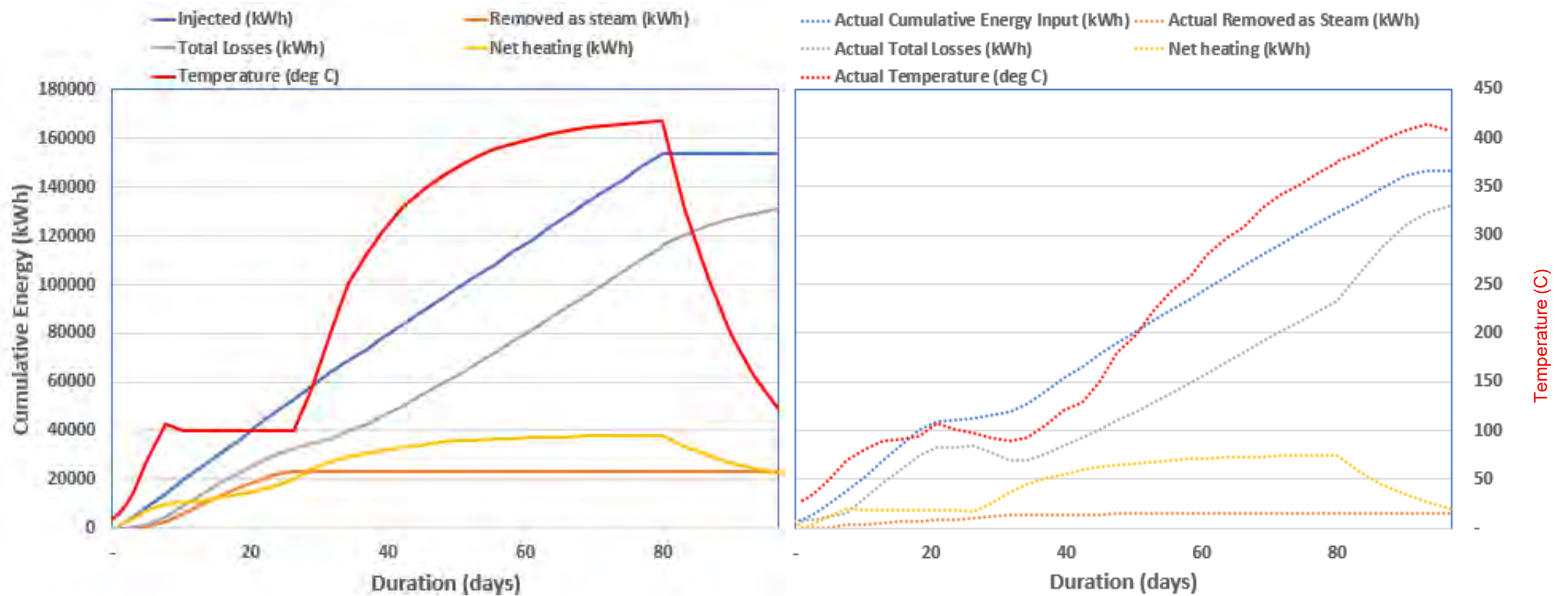
Winter Operation



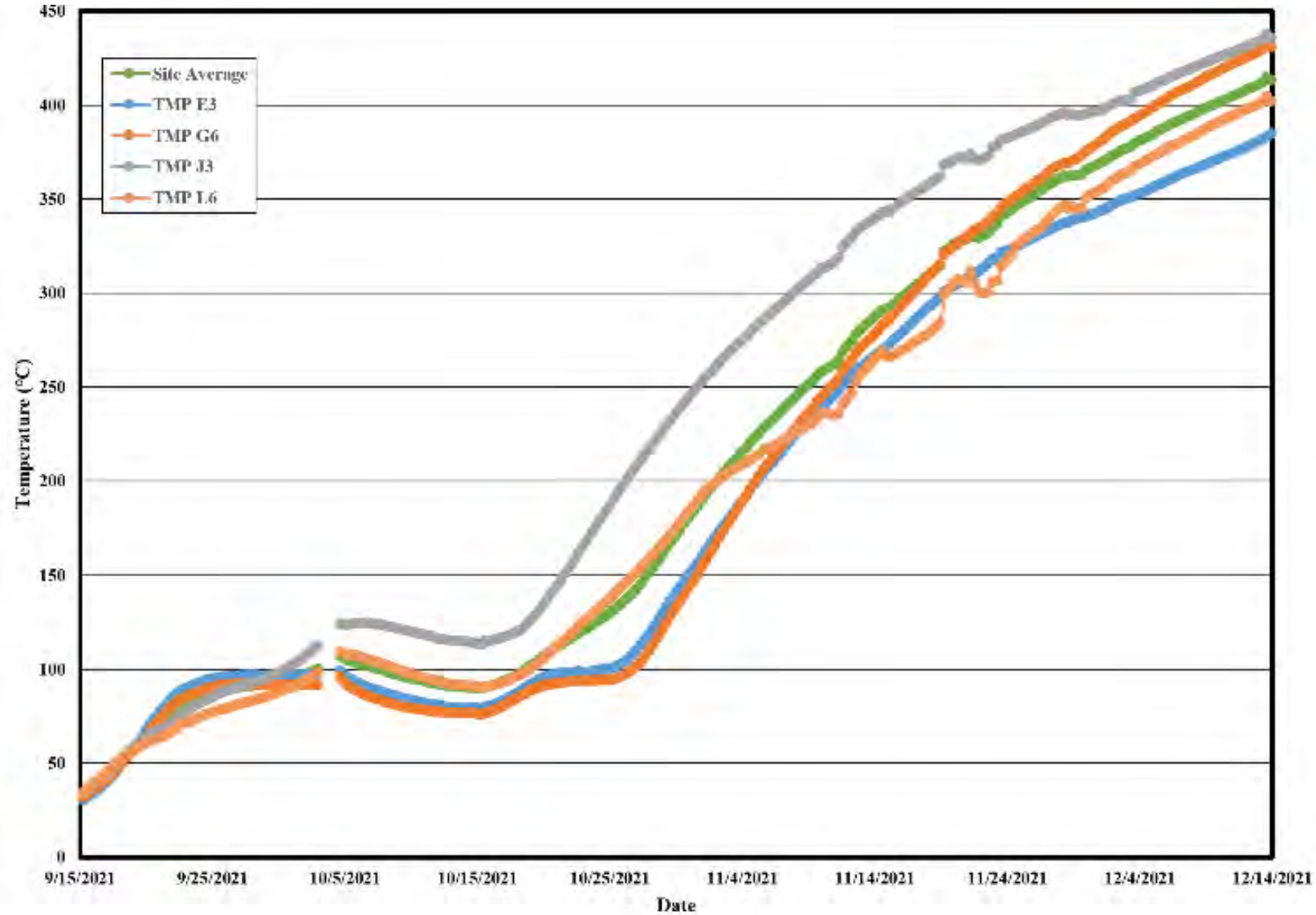
Treatment System



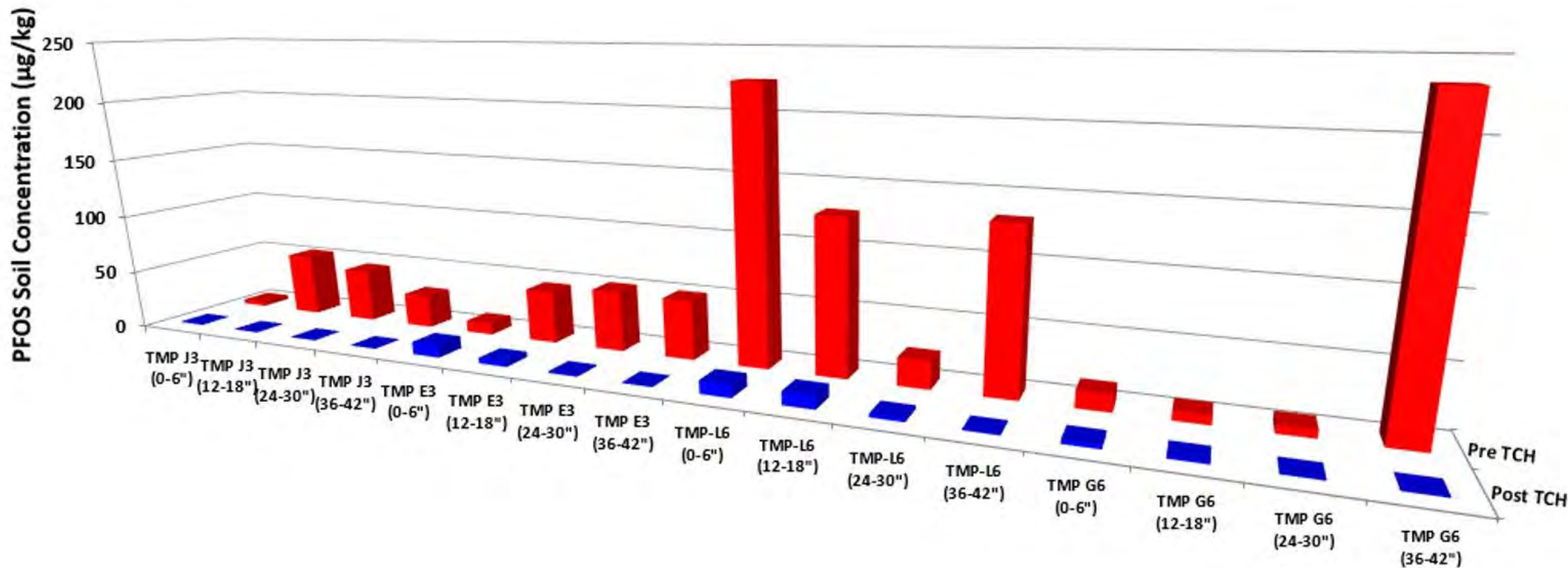
Energy Balance



Soil Pile Temperatures



PFOS and PFOA Results



**all post treatment samples below PFOA detection limits*

Eielson AFB Results

- 350-400°C reached in 88 days of heating
- PFOA treated to non-detect
- PFOS reductions from 272 to below 4 µg/kg
- Soil that reached >400°C was non-detect for all PFAS
- Energy usage close to double the net demand due to heat losses



Beale Air Force Base



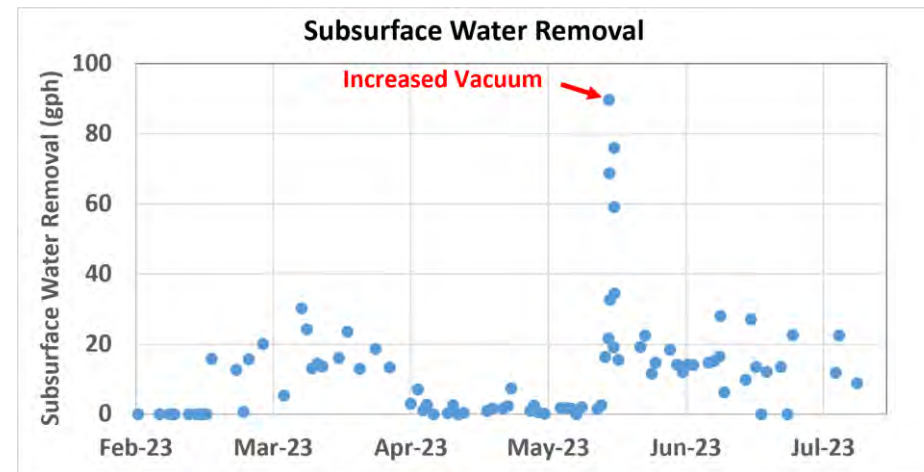
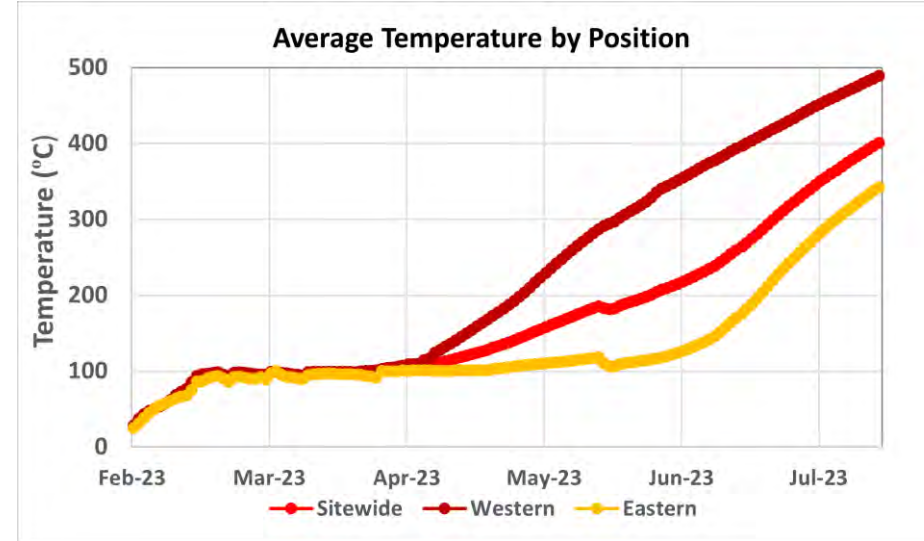
Jacobs

BATTELLE

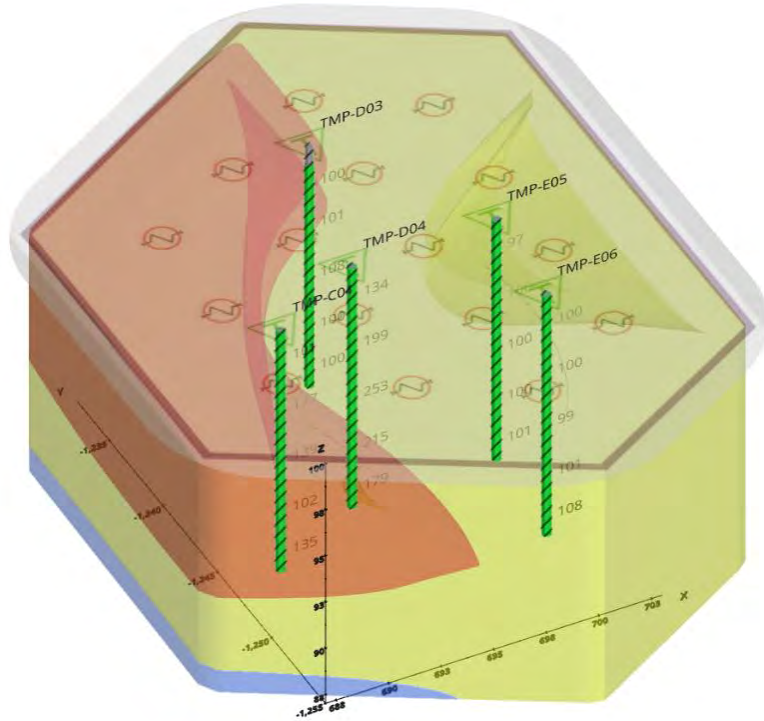


Beale Air Force Base

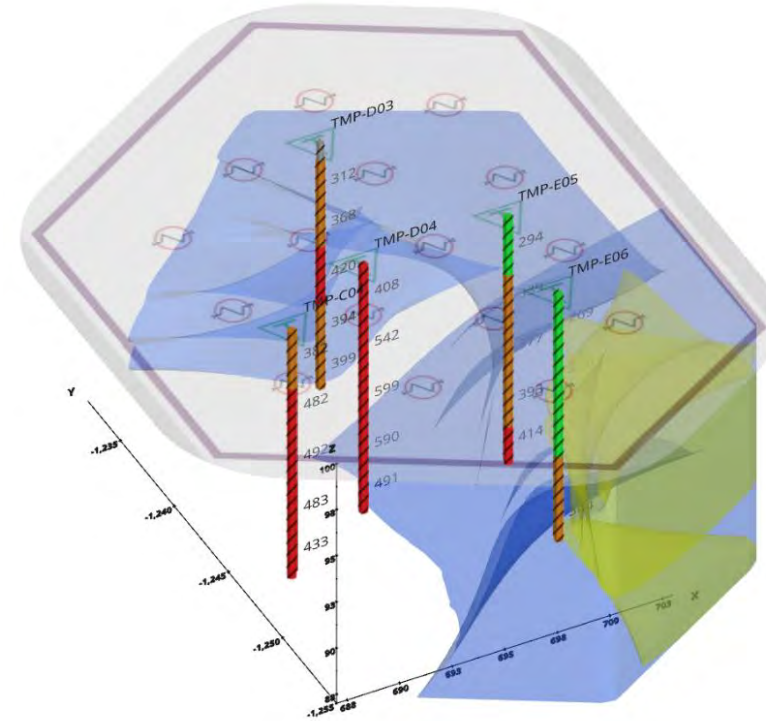
- 20.5 weeks of heating
- 403.6°C peak average site temperature
- Slower eastern heating rate
- 4.6-fold higher water removal than anticipated
- 99+ percent in soil heated to 350-400 C



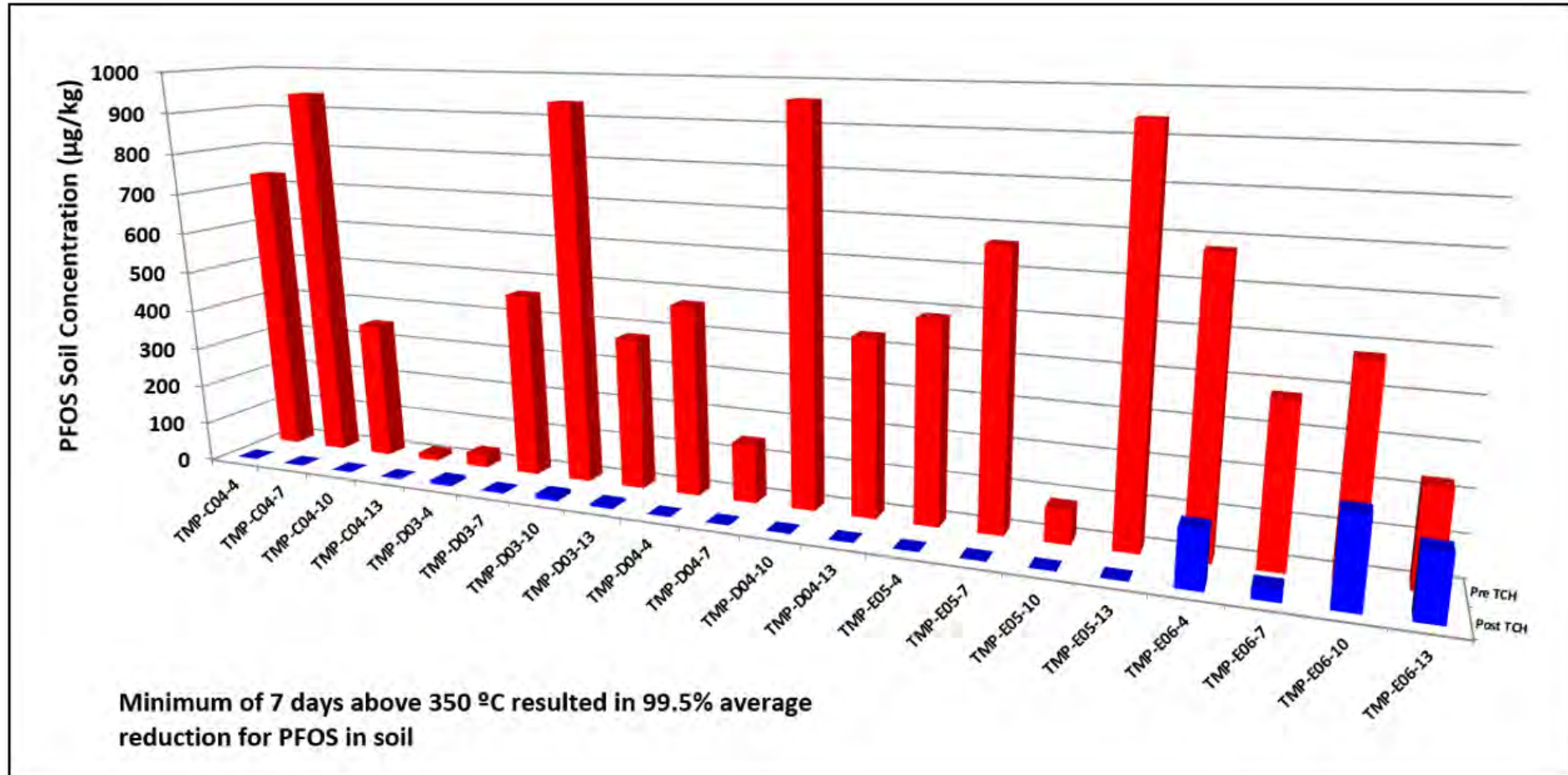
Soil Concentration Reductions



- Total PFAS :: >1,900 ng/g
- Total PFAS :: 126 - 1,900 ng/g
- Total PFAS :: 13 - 126 ng/g



- Temperature :: >500 °C
- Temperature :: 300 - 500 °C
- Temperature :: 100 - 300 °C



- Post-treatment soil concentrations:
 - Average **PFOA** = 0.071 µg/kg (all samples)
 - Average **PFOS** = 1.75 µg/kg (350 C for 7 days)

Beale AFB Results – in situ TCH

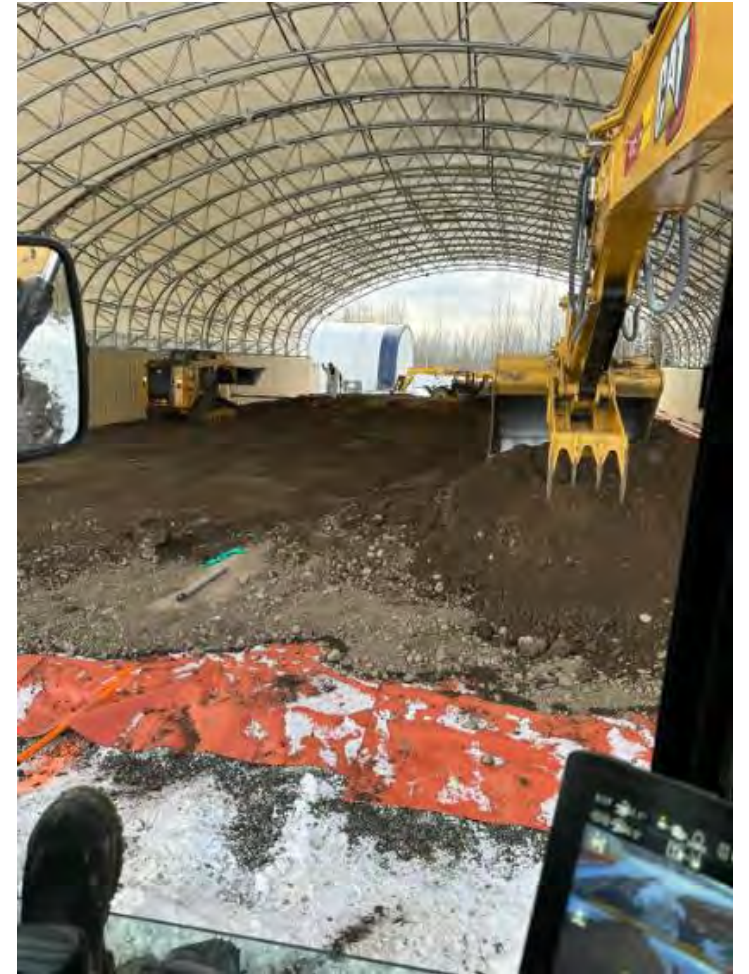
- Starting PFAS concentrations 1,000-2,000 µg/kg
- 350-400°C reached in 144 days of heating
- Perched water slowed heating on one side
- 99.5% reduction in soil PFAS concentrations
- Future projects will include controls for water infiltration



Joint Base Elmendorf-Richardson



Joint Base Elmendorf-Richardson



Joint Base Elmendorf-Richardson



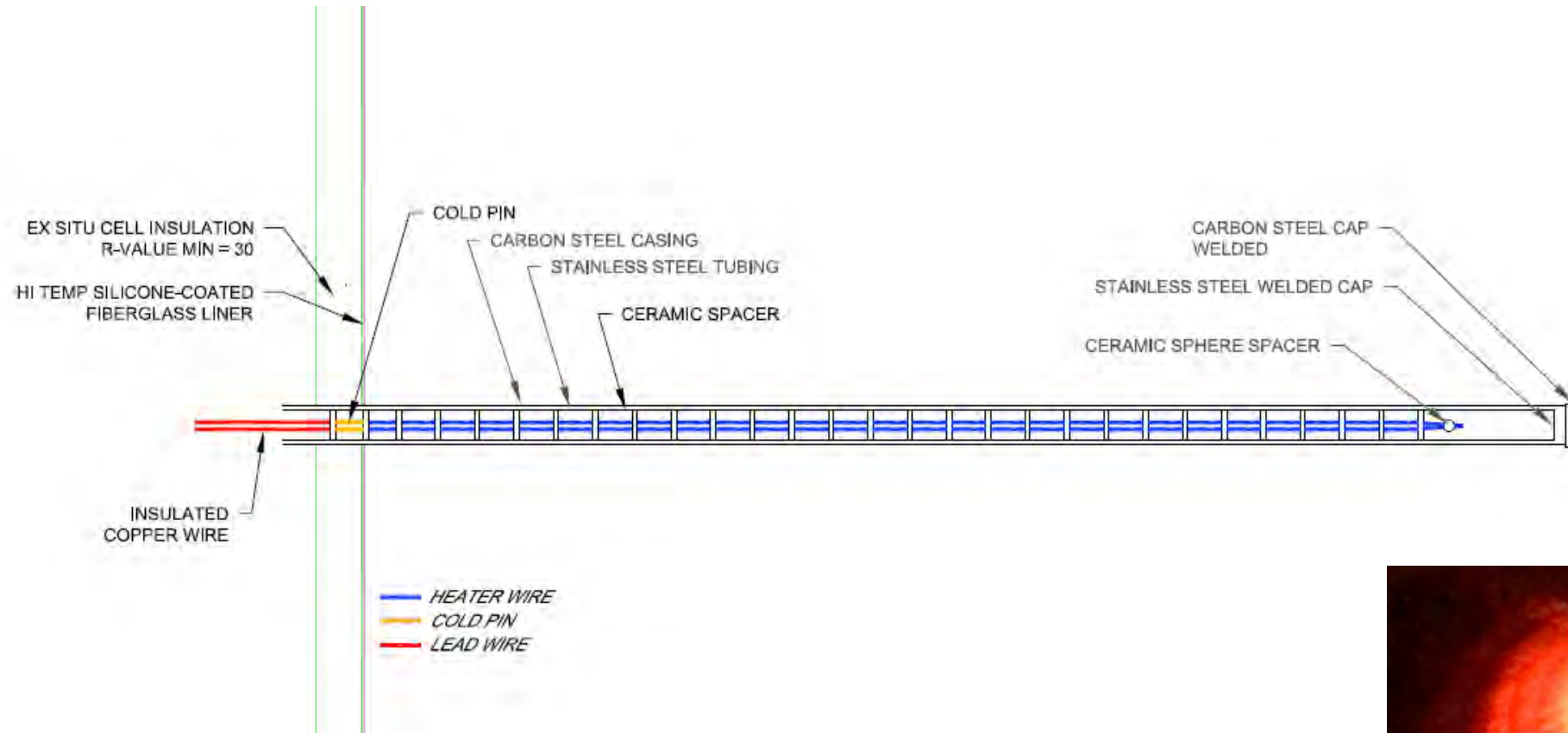
Joint Base Elmendorf-Richardson



Joint Base Elmendorf-Richardson



Heater

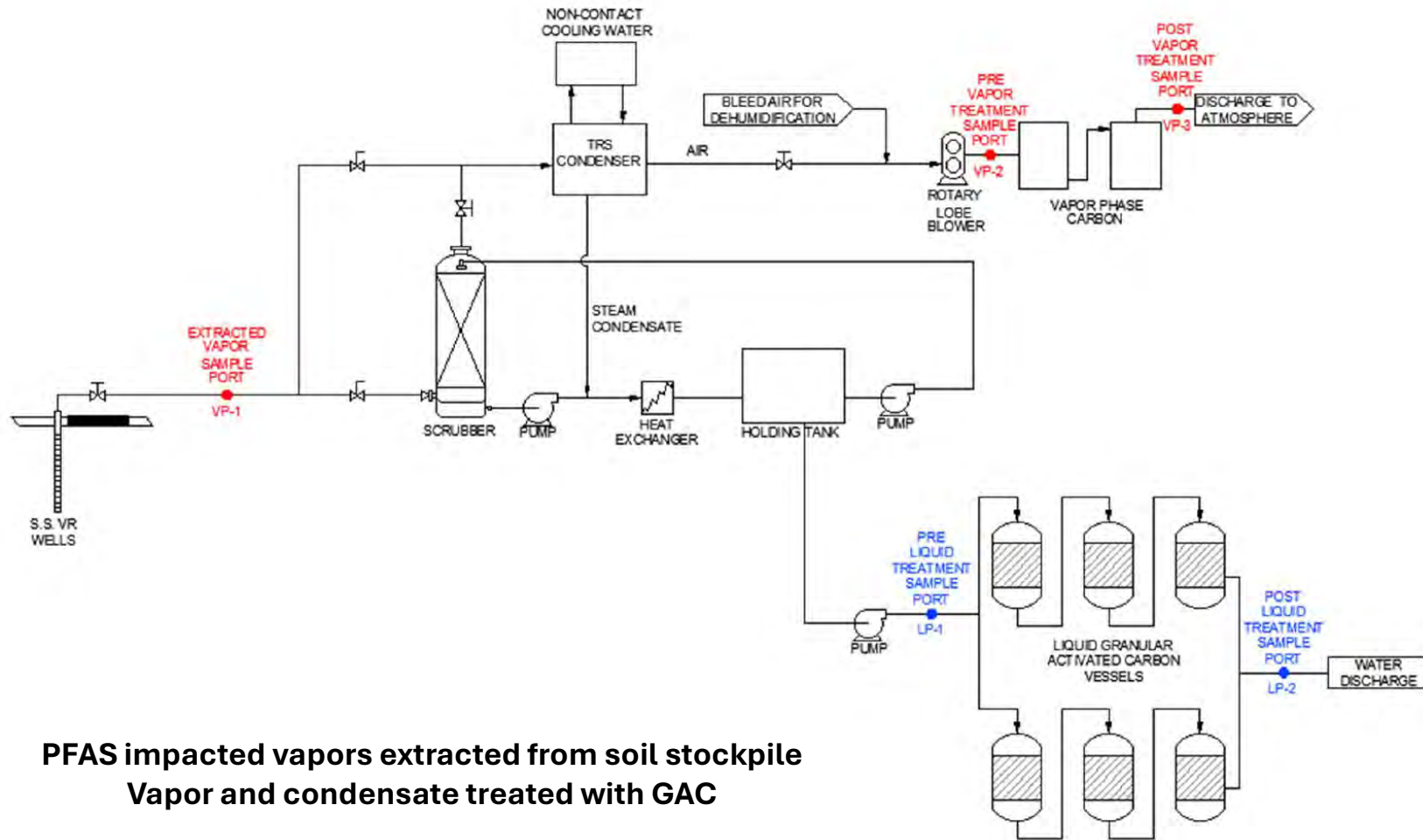


Joint Base Elmendorf- Richardson

- 2,000 cubic yards
- Engineered pile
- Insulated
- Horizontal TCH

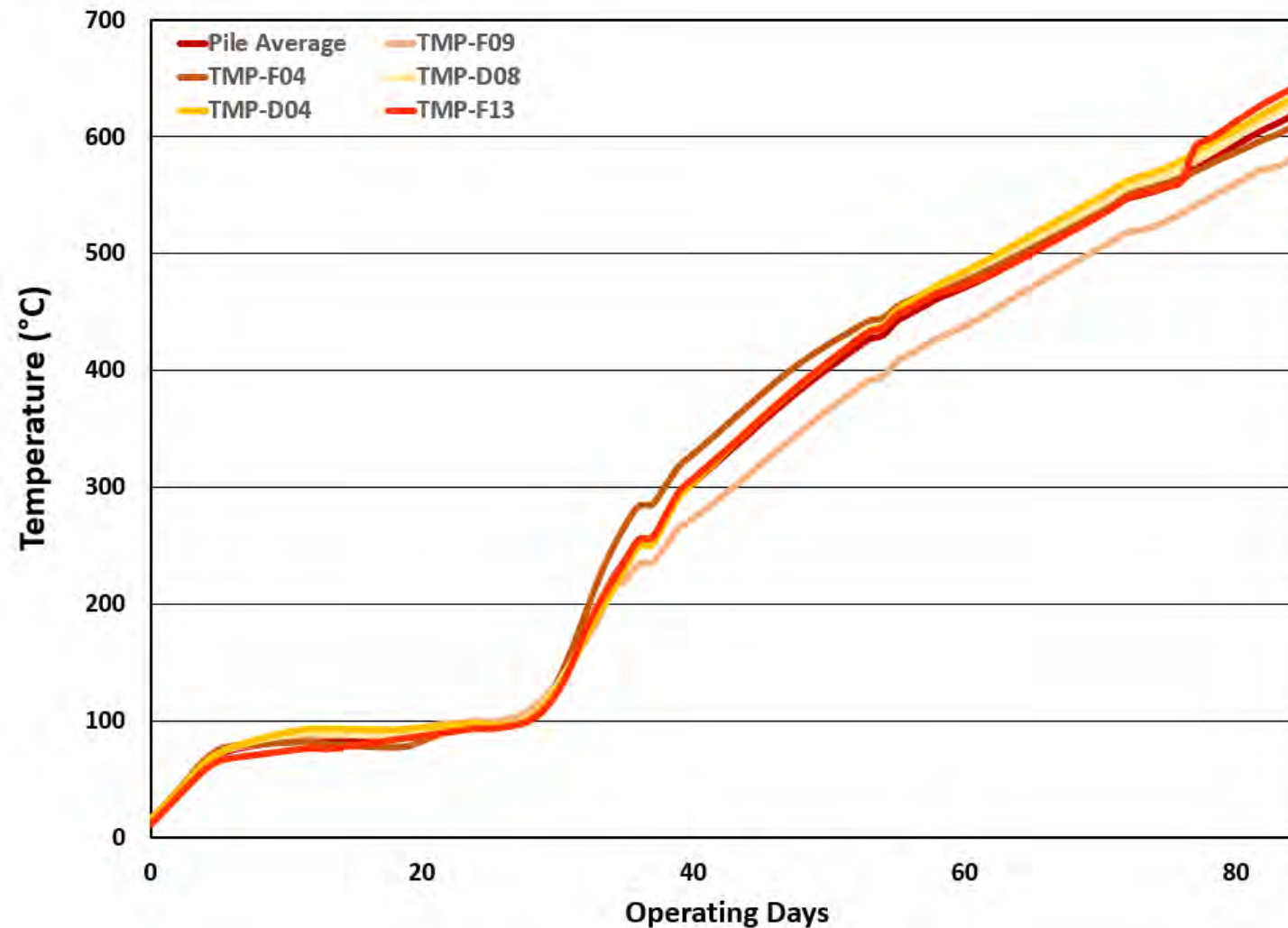


Vapor Treatment



PFAS impacted vapors extracted from soil stockpile
Vapor and condensate treated with GAC

JBER Soil Pile Temperatures



710,000 kWh

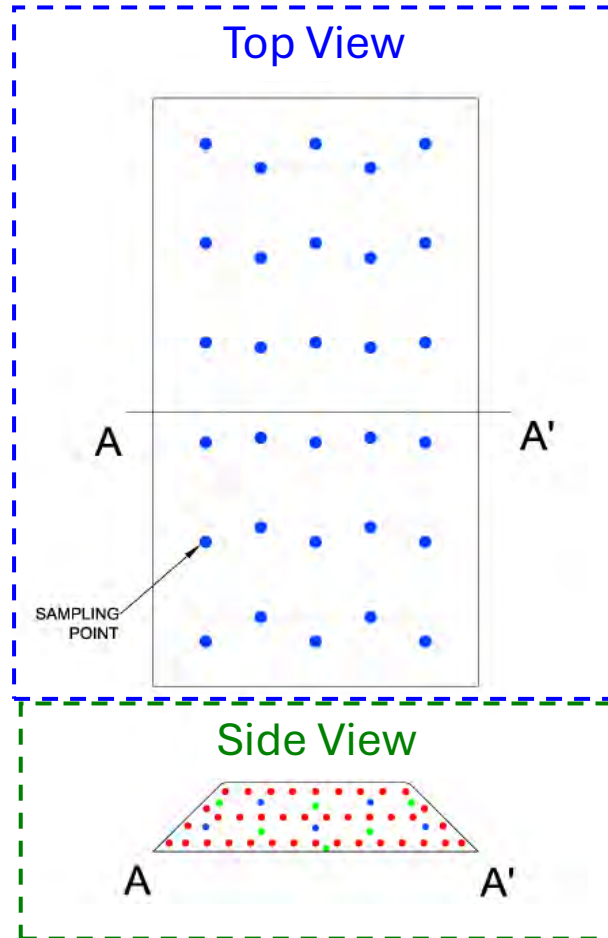
2,000 cy

355 kWh/cy

JBER Soil Pile Temperatures

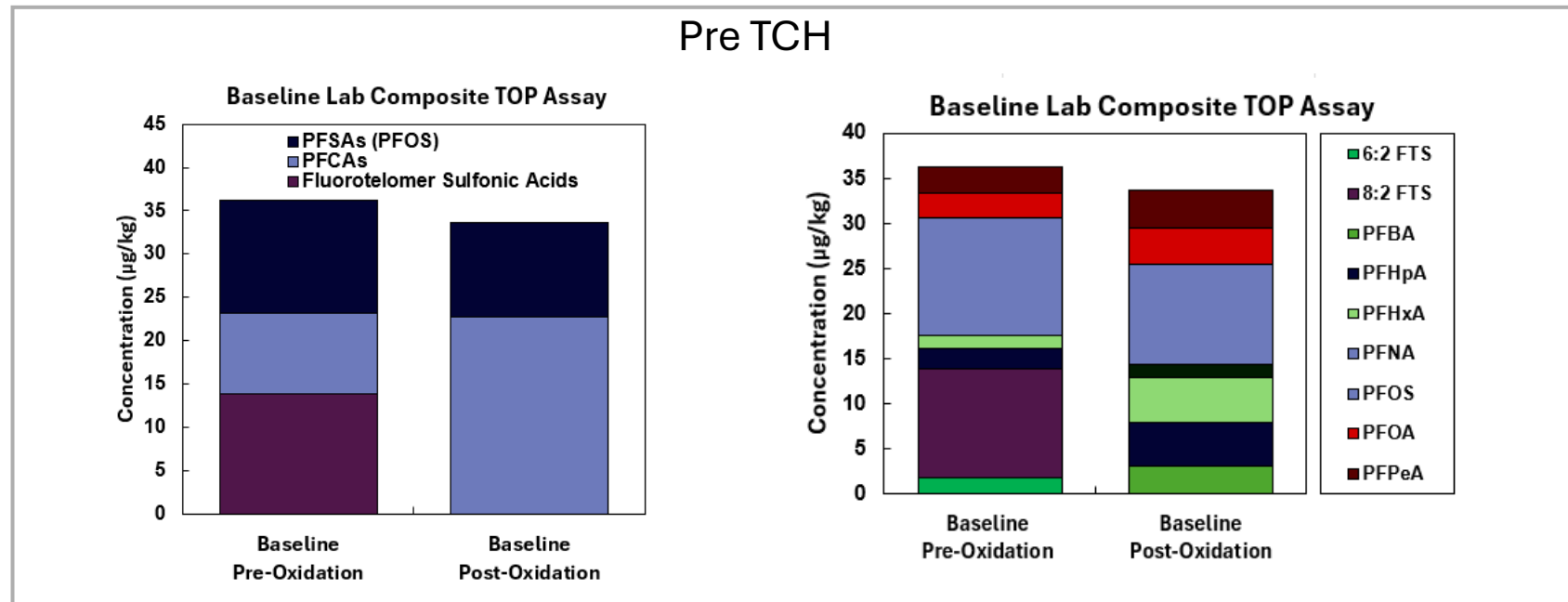


JBER Soil Sample Locations



- Co-located soil sample and temperature sensor
- Horizontal heater
- Vapor extraction point

JBER Soil Total Oxidizable Precursor Assay



Post TCH composite soil sample **below detection limits** for all targeted PFAS (EPA Method 1633) and post-TOP assay (post-oxidation)

All 30 discrete soil samples **below detection limits** for all 1633 PFAS analytes, except three J qualified analytes below reporting limits

JBER Soil Results

All Locations Summary Table

Analyte	JBER Soil - Post TCH Max Concentrations (µg/kg)	Sample Location(s) Above ND	EPA Residential Soil RSL (TR 1E-06, THQ 0.1) (µg/kg)	ADEC MTG Soil Cleanup Level (µg/kg)	Laboratory Detection Limit (µg/kg)
PFBA	ND	-	7800	-	0.15 - 0.18
PFPeA	ND	-	-	-	0.0088 - 0.011
PFHxA	0.027 J	F04-60.8	3200	-	0.014 - 0.17
PFHpA	ND	-	-	-	0.02 - 0.026
PFOA	ND	-	0.019	1.7	0.07 - 0.085
PFNA	ND	-	19	-	0.05 - 0.066
PFDA	ND	-	-	-	0.039 - 0.051
PFBS	ND	-	1900	-	0.006 - 0.0079
PFPeS	ND	-	-	-	0.017 - 0.023
PFHxS	ND	-	130	-	0.018 - 0.024
PFOS	ND	-	0.63	3	0.023 - 0.028
6:2 FTS	ND	-	-	-	0.051 - 0.067
8:2 FTS	ND	-	-	-	0.049 - 0.065
PFOSA	ND	-	-	-	0.026 - 0.034
ADONA	0.16 J	D04-35.6	-	-	0.0079 - 0.011
PFMPA	ND	-	-	-	0.0052 - 0.0069
5:3 FTCA	ND	-	-	-	0.09 - 0.12
7:3 FTCA	ND	-	-	-	0.14 - 0.19

Qualifier

J

Qualifier Description

Result is less than the RL but greater than or equal to the MDL and the concentration is an approximate value.

Conclusions

- Thermal conduction heating (400°C)
- Three field demonstrations completed
- Energy usage 355 kWh/cy at JBER
- All PFAS below or near detection limits
- Commercially available now
- DIU success memo in preparation

Acknowledgements



Jacobs





Thank you!

Gorm Heron, Ph.D.

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Emily Crownover, Ph.D.

Managing Principal Engineer

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Your Success is Our Mission!



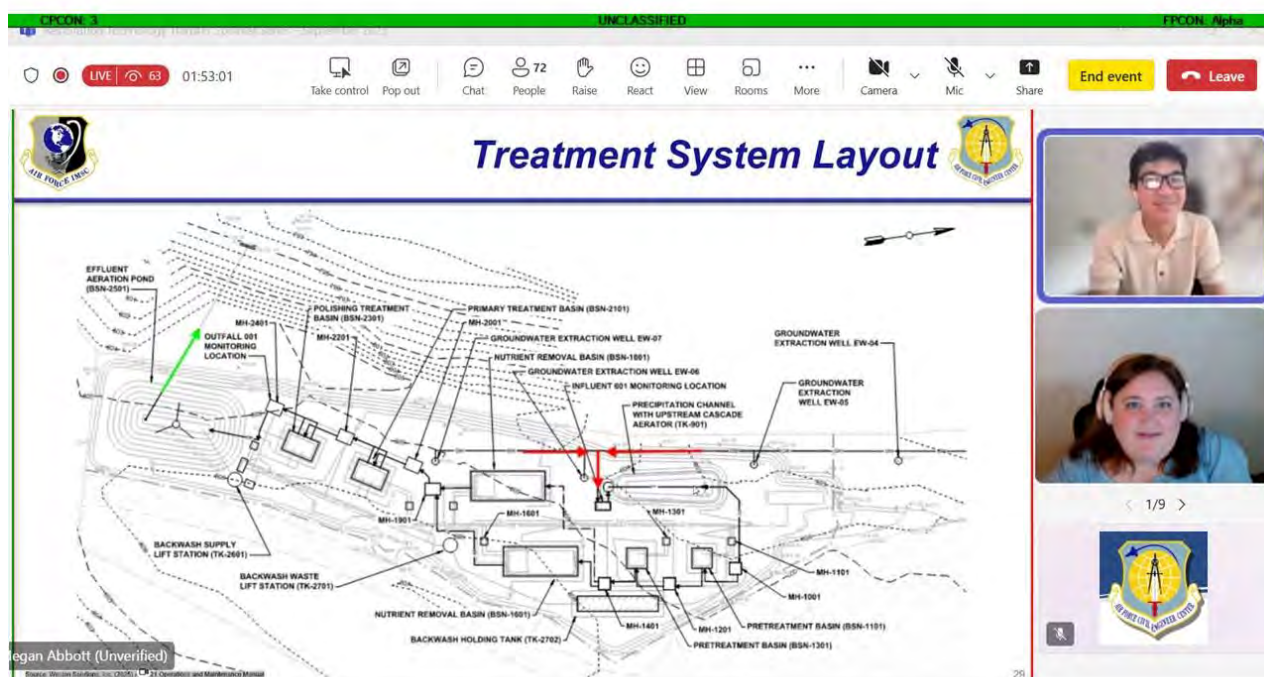
Air Force Civil Engineer Center

Restoration Technology Transfer Speakers Series September 2025

Pilot Study & Full-Scale Remedy Using Adsorbent Technology for PFAS Remediation

Presenters: Zoom Nguyen & Megan Abbott – Weston Solutions

Historical use of AFFF resulted in surface and groundwater contamination at a U.S. Air Force Base. A long-term pilot study was conducted to compare various adsorbents and to select one optimal for removal of PFAS from impacted surface water & groundwater with complex water quality at the site. The first of its kind biological filtration and lined gravity basin were constructed for full-scale remedy. This presentation discussed relevant results, observations, and lessons learned from the pilot study and results associated with the full-scale remedy to-date.



Zoom Nguyen and Megan Abbott describing the field treatment system setup.

This event and future events are updated and posted on the AFIT website at: <https://www.afit.edu/CE/index.cfm>.

POCs:

Joseph Dimisa, AFIT (joseph.dimisa@us.af.mil)

C.J. Garcia, CTR, Booz Allen Hamilton (carlos.garcia.56.ctr@us.af.mil)

Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)



Webinar Structure



	<u>Restoration Technology Transfer Webinar Series – eDASH Archive</u>
5 min	Welcome and Administrative Business
45 min	Main Presentation – <i>Wright-Patterson AFB Pilot Study & Full-Scale Remedy</i>
10 min	Questions and Answers
5 min	Final Thoughts

Air Force Civil Engineer Center



Wright-Patterson AFB Pilot Study & Full-Scale Remedy

Megan Abbott, PE & Zoom Nguyen
Weston Solutions, Inc.
September 10, 2025



Agenda



- Site background
- Pilot study objectives
- Pilot study design
- Results & lessons learned
- Summary of full-scale treatment system
- Q&A



Site Background



- Wright-Patterson AFB (Dayton, OH)
- AFFF Area 21 – firefighting training
- GW contaminated primarily with PFOA & PFOS

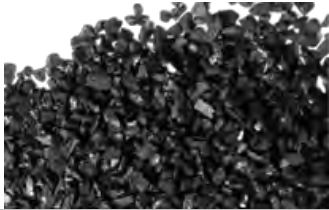


- Evaluate pretreatment options for iron/manganese removal
- Estimate PFAS treatment efficacy & media longevity for:
 - Granular activated carbon (GAC)
 - Anion exchange resin (IX)
 - Surface-modified organoclay FluoroSorb (FS)
 - Surface-modified organoclay HS-PF
- Capital (CAPEX) & operating cost (OPEX) estimation
- Select media for full-scale implementation
- Design Objectives:
 - Reduce migration of PFAS offsite towards the Mad River
 - Effluent PFOA and PFOS below 2016 EPA LHA of 70 ng/L



Source: Zielinski, J. (2023), Weston Solutions, Inc.

Primary PFAS Treatment Media

Parameters	GAC	AER	NS	HS-PF
Picture	 Source: Britannica.com, 2025, granular activated carbon	 Source: Britannica.com, 2025, ion-exchange-resin	 Source: CETCO, Fluorosorb 200 Cut Sheet, 2025	 Source: Hydrosil, Intl. HS-PF Cut Sheet, 2025
Maturity	Highest	Lower	Lower	Lowest
Primary PFAS removal mechanism	Hydrophobic interaction	Electrostatic + hydrophobic interaction	Hydrophobic interaction	Electrostatic + hydrophobic interaction
Recommended EBCT (mins)	8-12	1-3	1-3	10-20
Footprint requirement	Higher	Lower	Lower	Higher
Cost	Lowest	Highest	Middle	Middle
Long-chain PFAS removal effectiveness	High	Higher	Higher	Higher
Short-chain removal effectiveness	Lower	Higher	Lower	Lower



Pilot Test Design



Media	Trial No.	Start Date	Finish Date	Gallons Treated	Bed Volumes Treated	EBCT per Column (minimum)
Greensand	1 of 1	3/23/22	4/13/22	2,449	1,250	9.8
50/50 Zeolite GAC Blend	1 of 1	3/23/22	8/18/22	31,966	24,484	3.3
HS-PF	1 of 1	3/23/22	6/2/22	8,007	58,875	0.7
GAC	1 of 2	3/23/22	5/7/22	5,215	15,977	1.6
GAC	2 of 2	5/30/22	8/18/22	9,055	5,548	8.2
FluoroSorb	1 of 1	3/23/22	8/18/22	16,663	122,522	0.7
Ion Exchange Resin	1 of 2	3/23/22	7/7/22	11,485	84,449	0.7
Ion Exchange Resin	2 of 2	7/9/22	8/18/22	4,661	34,272	0.7
Polishing (FluoroSorb)	N/A	6/23/22	8/18/22	29,163	6,619	4.4



Pilot Treatment System Container



- Custom containerized pilot treatment system assembled by Clear Creek Systems for on-site pilot treatment at Area 21.



- Preliminary and primary treatment media trial columns.

Influent Flow Control Board



- Influent cartridge filters, flow meters and flow totalizers.

Effluent Sampling Board

- Effluent sample taps and aeration tank to increase dissolved oxygen to >5 mg/L prior to discharge.





Influent Water Quality

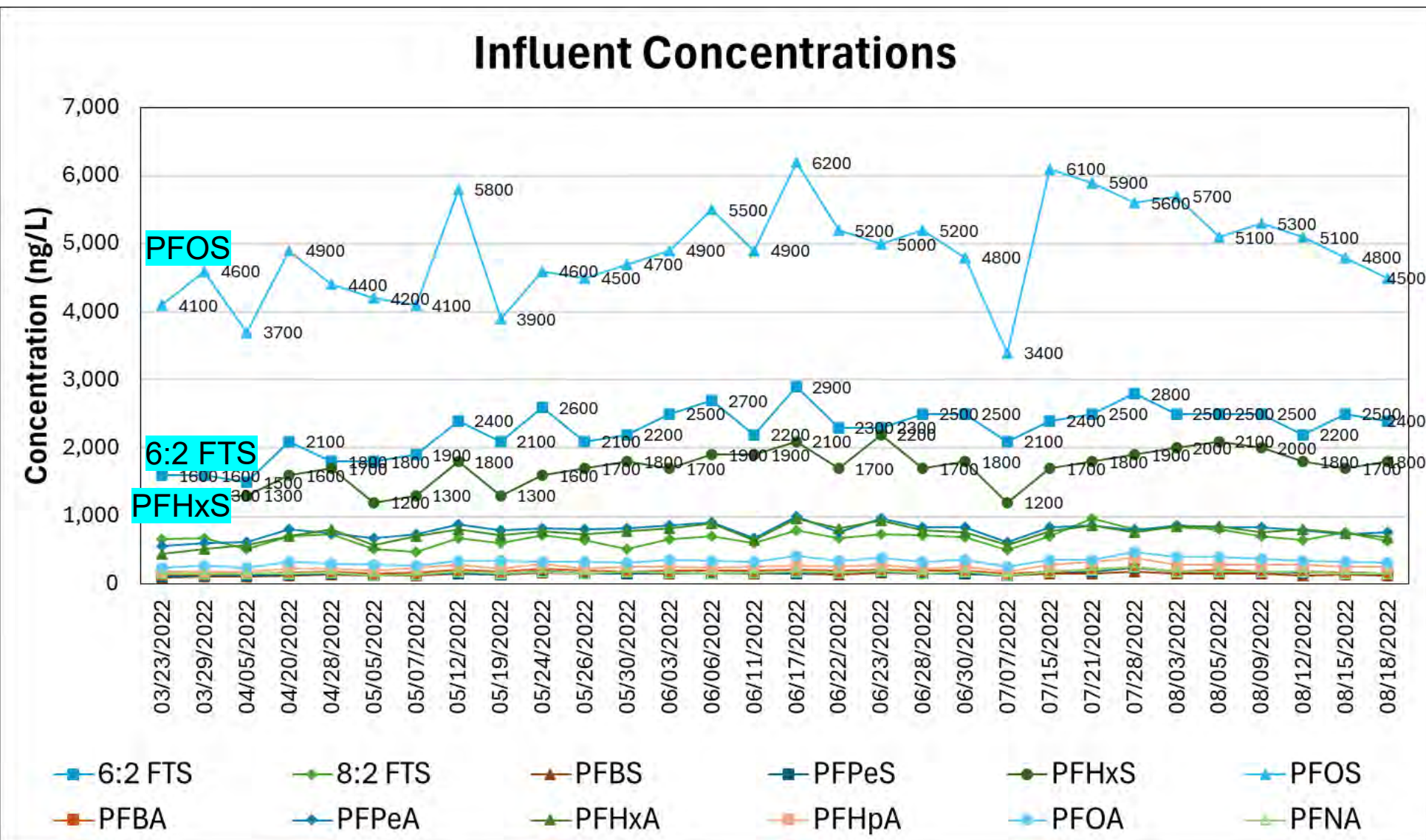


Parameter	Minimum	Maximum	Average	Units
Ammonia	0.42	0.46	0.45	mg/L
Calcium	120	140	135	mg/L
Iron	3.5	7.3	4.8	mg/L
Manganese	0.53	0.73	0.61	mg/L
TPH DRO	65	300	147.9	µg/L
TPH GRO	40	89	73.6	µg/L
TPH ORO	47	500	165.2	µg/L
PFOA	61	480	320	ng/L
PFOS	30	6,200	4,624	ng/L
Alkalinity	390	460	437	mg CaCO3/L
Hardness	430	490	465	mg/L
TDS	220	1,100	508	mg/L
Ferrous Iron	2.0	4.8	3.7	mg/L
TOC	1.8	1.9	1.8	mg/L

- Elevated TOC
- Elevated Fe/Mn
- High TDS
- Hard water
- Other co-contaminants besides PFAS

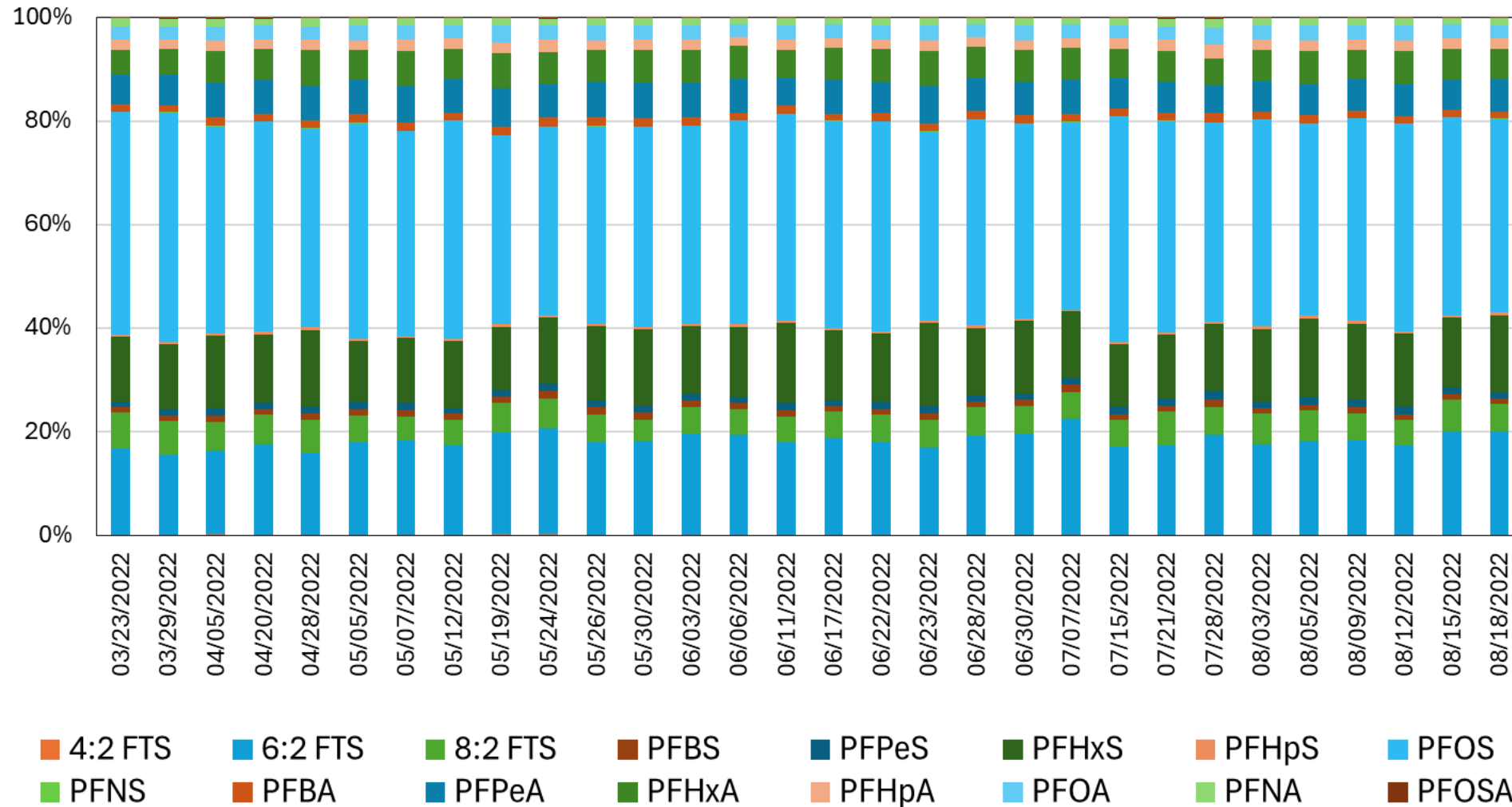


Influent PFAS Concentrations



- Some fluctuations in influent concentration over time ($\pm 30\%$)
- PFOS, 6:2 FTS and PFHxS are the predominant PFAS detected in GW

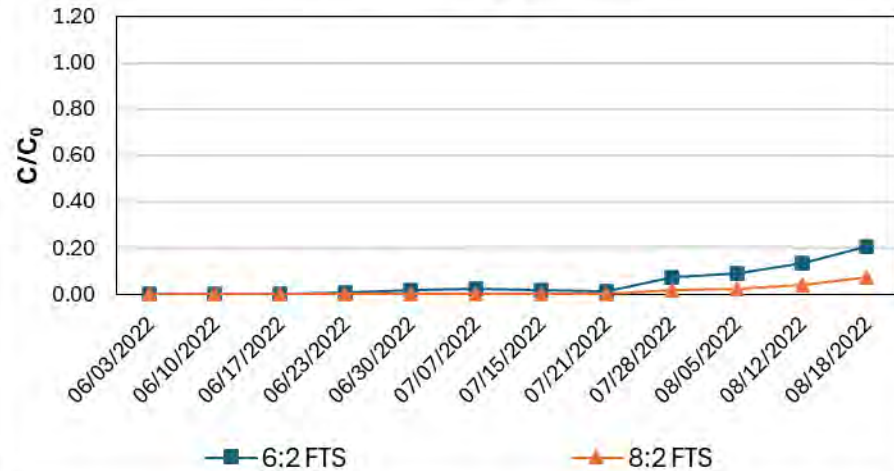
Influent Composition



- While PFAS concentrations fluctuated, little to no changes in PFAS composition were observed over time.

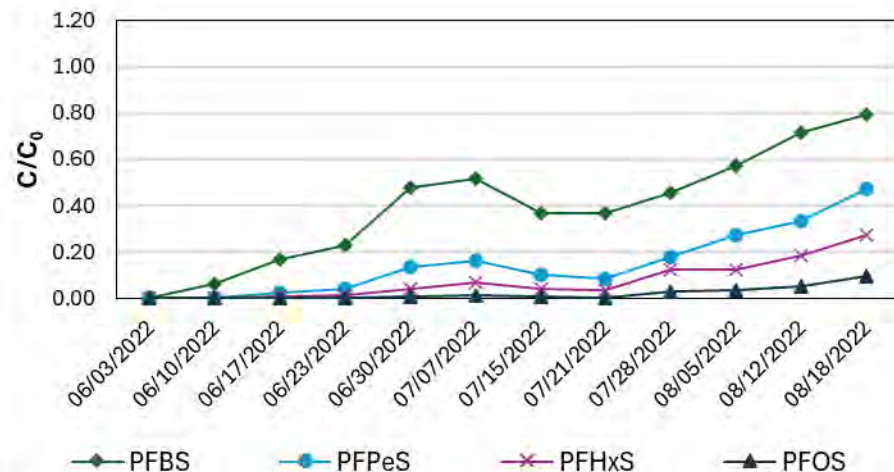
GAC Performance (8.2-min EBCT)

FTS Breakthrough in GAC

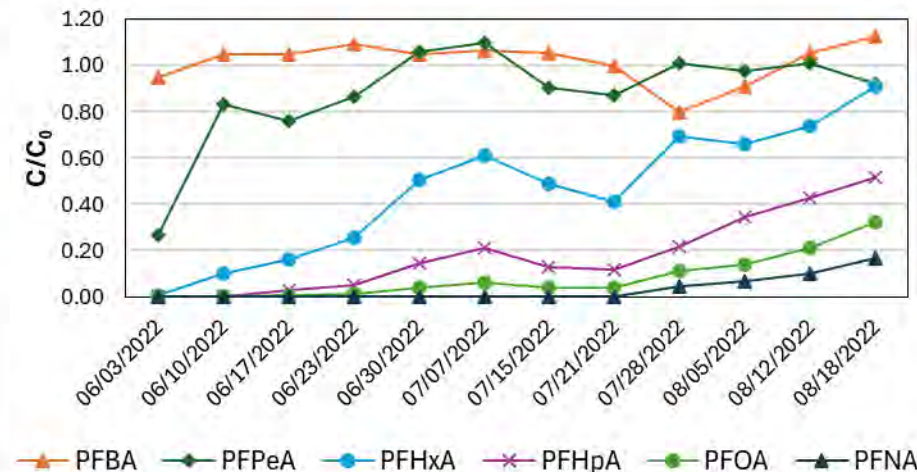


- Short-chained PFAS broke through faster than long-chained counterparts.
- Near immediate breakthrough of PFBA.
- PFCAs broke through faster than PFSA's and FTS's for a given homolog.
- 10% PFOS and 30% PFOA breakthrough at end of pilot study.

PFSA Breakthrough in GAC

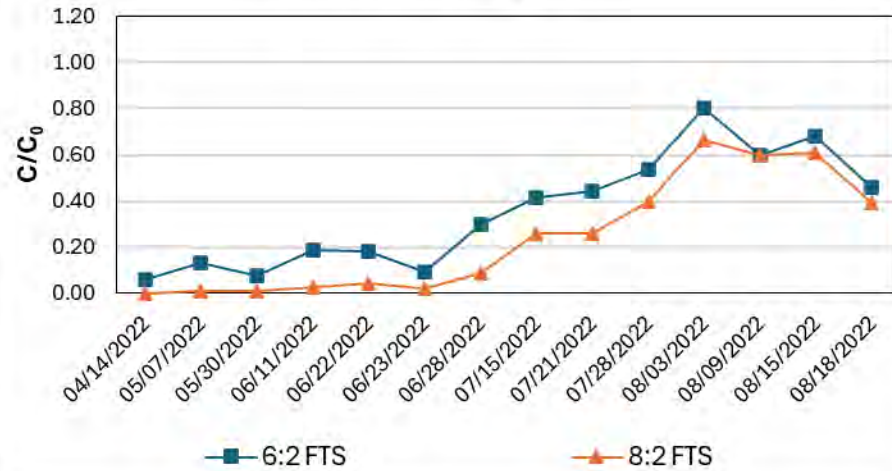


PFCa Breakthrough in GAC



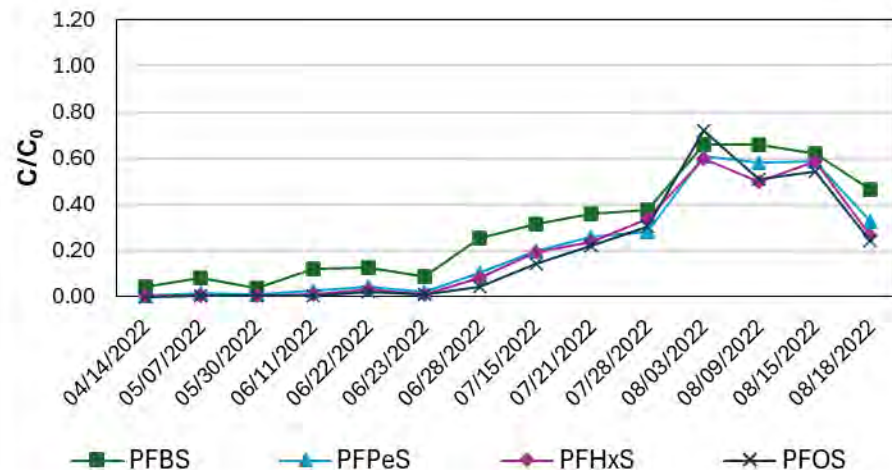
FS Performance (0.7-min EBCT)

FTS Breakthrough in FS

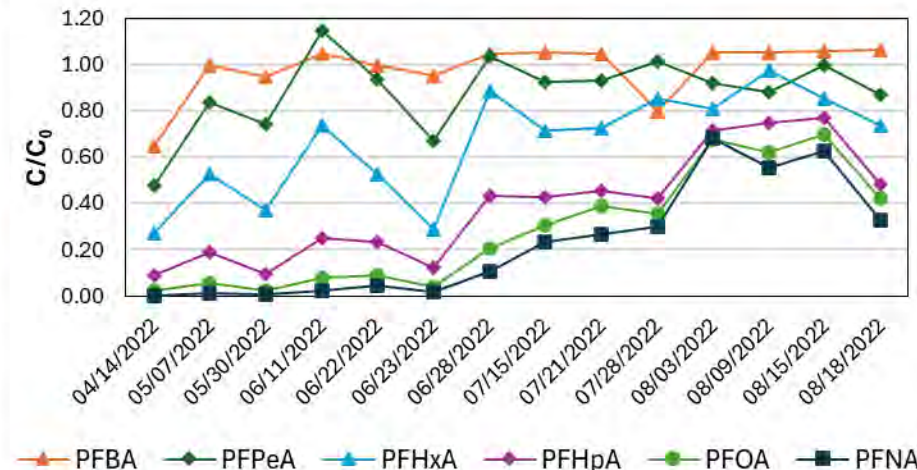


- Similar PFAS breakthrough trends observed with GAC.
- Fast breakthrough of short-chained PFAS including PFBA.
- 20% PFOS and 40% PFOA breakthrough at end of pilot study.
- Substantially more GW treated over the same testing period due to shorter EBCTs.

PFSA Breakthrough in FS



PFCA Breakthrough in FS

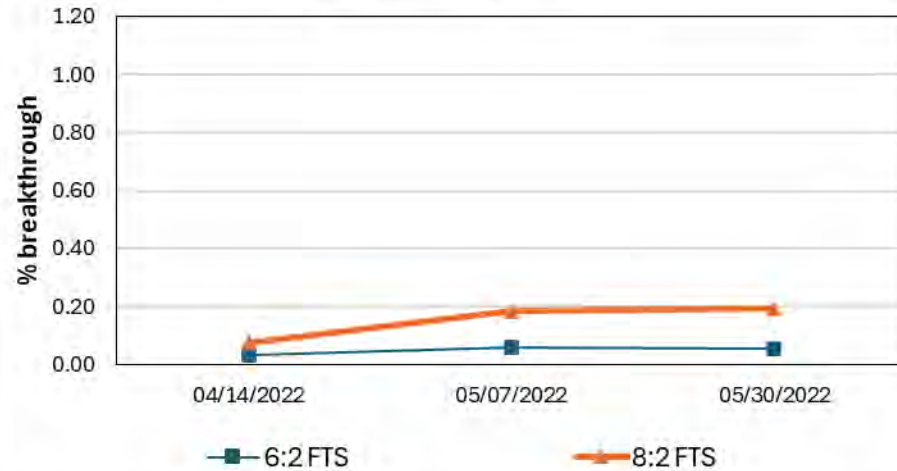




HS-PF Performance (0.7-min EBCT)

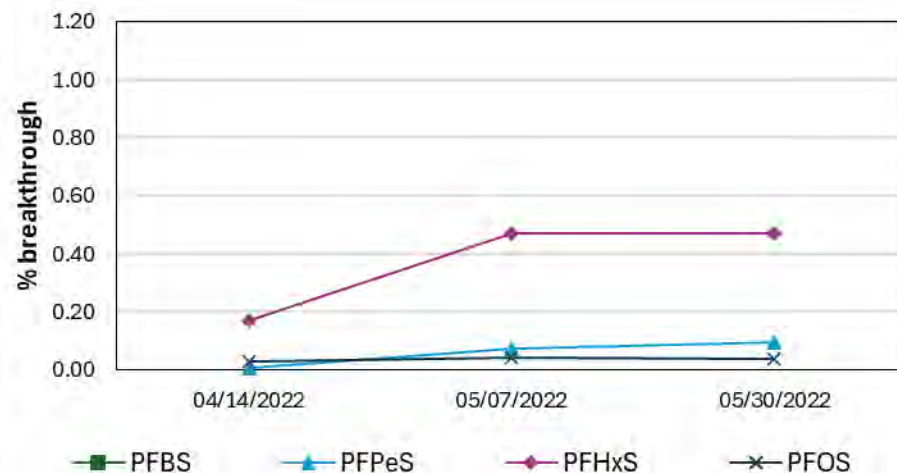


FTS Breakthrough in HS-PF

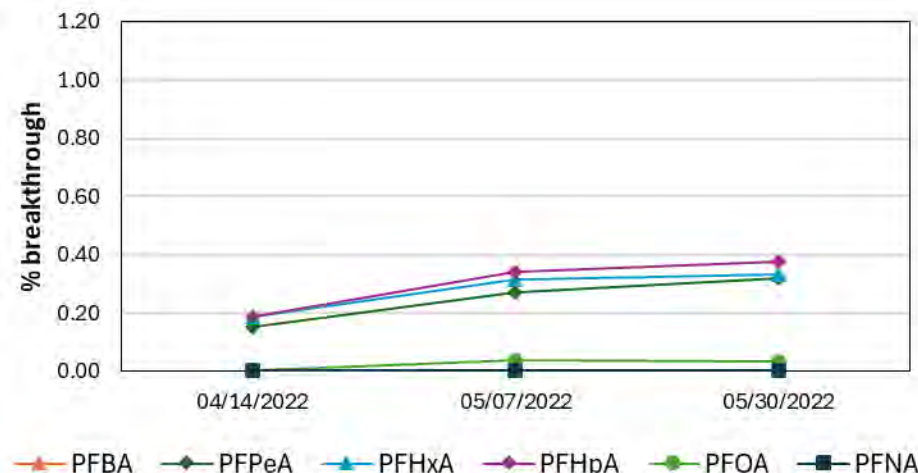


- Similar PFAS breakthrough trends observed with FS and GAC.
- Immediate breakthrough of short-chained PFAS including PFBA.
- 5% PFOS and PFOA breakthrough after 1.5 month of testing.
- Total EBVs treated ~60K EBVs or 8K gals.

PFSA Breakthrough in HS-PF



PFCA Breakthrough in HS-PF

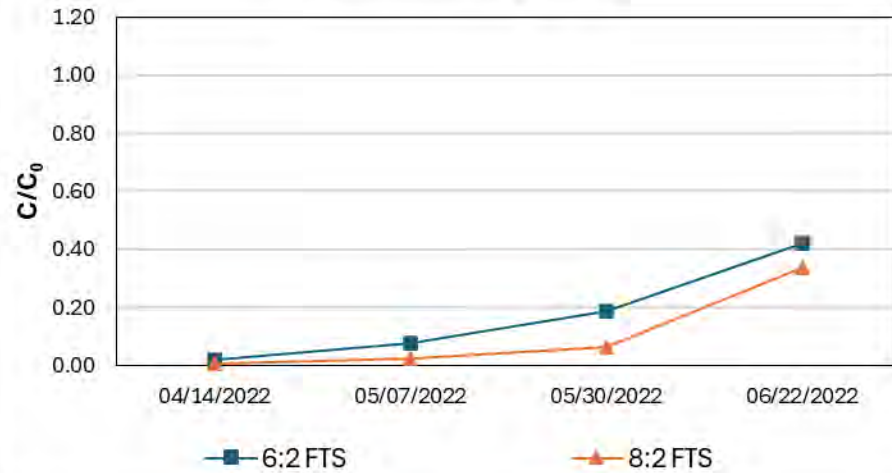




IX Performance (0.7-min EBCT)

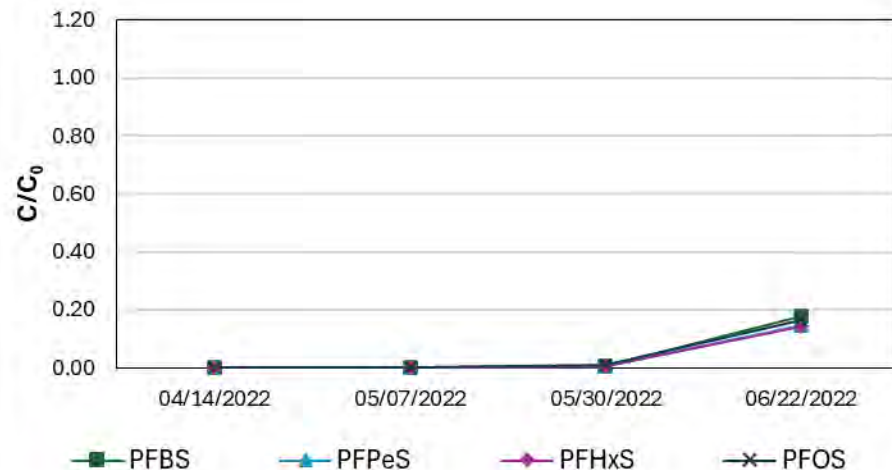


FTS Breakthrough in IX

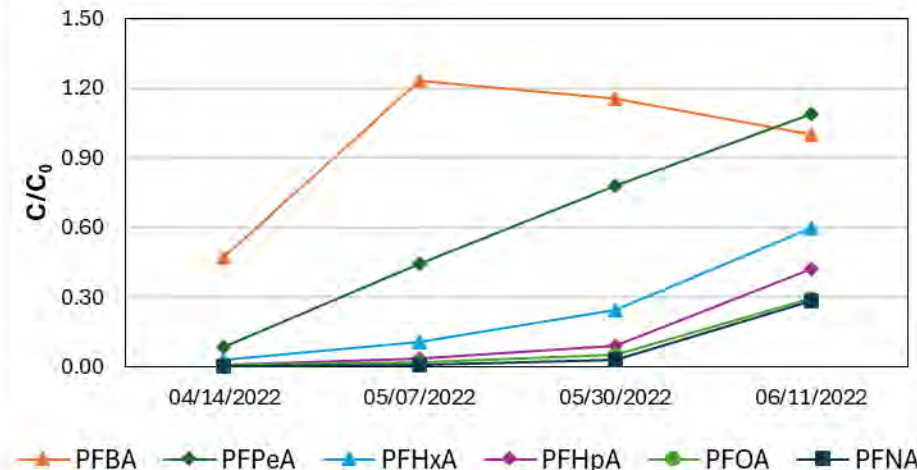


- Similar PFAS breakthrough trends observed with other media.
- Better treatment of short-chains than GAC & FS.
- 20% PFOS and 30% PFOA breakthrough after 2 months.

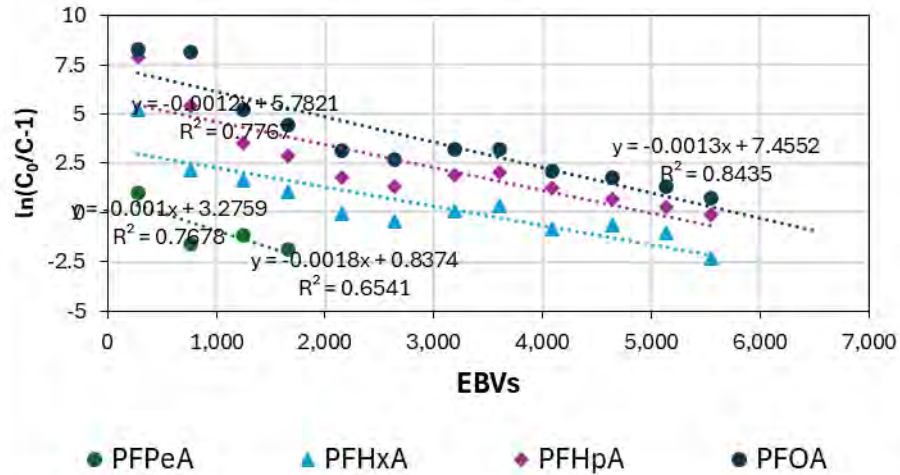
PFSA Breakthrough in IX



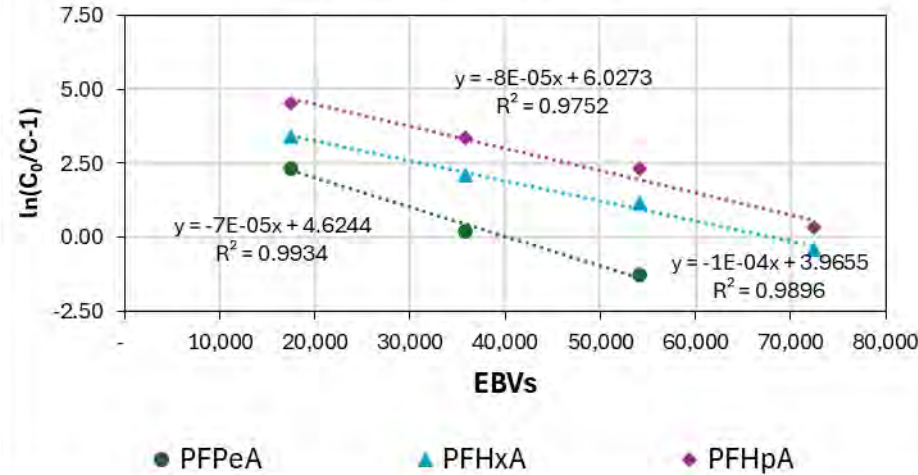
PFCA Breakthrough in IX



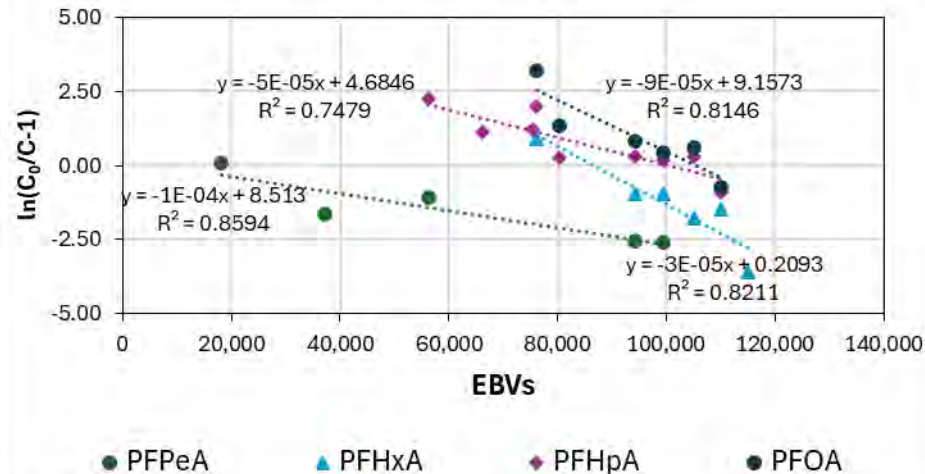
PFCA Breakthrough in GAC



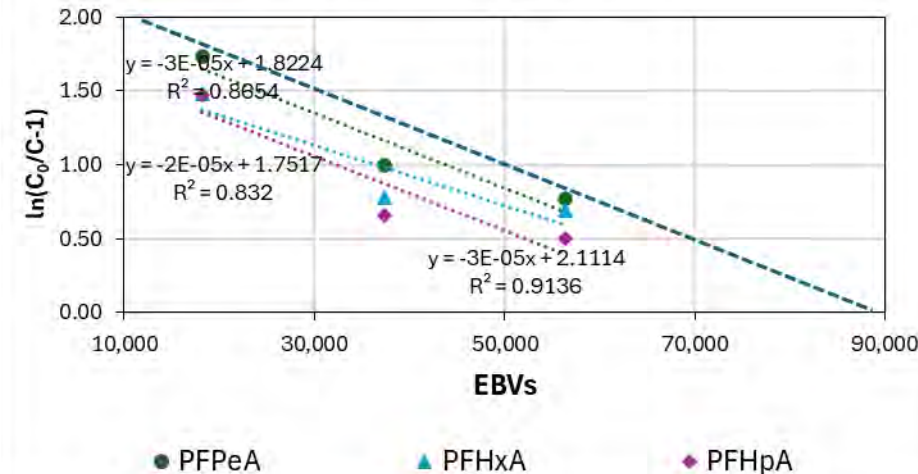
PFCA Breakthrough in IX



PFCA Breakthrough in FS



PFCA Breakthrough in HS-PF



- PFAS breakthrough profiles are well described by the Thomas model
- All regression lines are parallel to each other
- Different y-intercepts
- Y=0 intercept = 50% breakthrough
- Allows for PFAS breakthrough prediction



Breakthrough Prediction



Media	EBCT (mins)	Estimated 50% breakthrough (EBVs)		
		PFBA	PFOA	PFOS
GAC	8.2	Immediately	6,000	6,600
IX	0.7	10,000	90,000	100,000
FS	0.7	Immediately	105,000	120,000
HS-PF	0.7	Immediately	85,000	100,000

- Immediate PFBA breakthrough in GAC, FS, and HS-PF
- FS, HS-PF & IX are substantially more effective in removing long-chain PFAS (PFOA & PFOS) than GAC
- FS was ~20% more effective than IX re: long-chain removal
- IX performed similarly to HS-PF with respect to long-chain removal
- IX was the best performer re: short-chain removal
- Observed media longevity for FS & IX similar in drinking water applications
- Very fast PFOA & PFOS breakthrough seen with GAC compared to typical drinking water applications

Critical Factors in Media Selection

- PFAS treatment efficacy
- Media longevity
- Media availability
- Cost
- Available footprint
- Regulatory preference
- Influence of site-specific water quality on treatment
- Impacts on secondary water quality



GAC



IX



FS

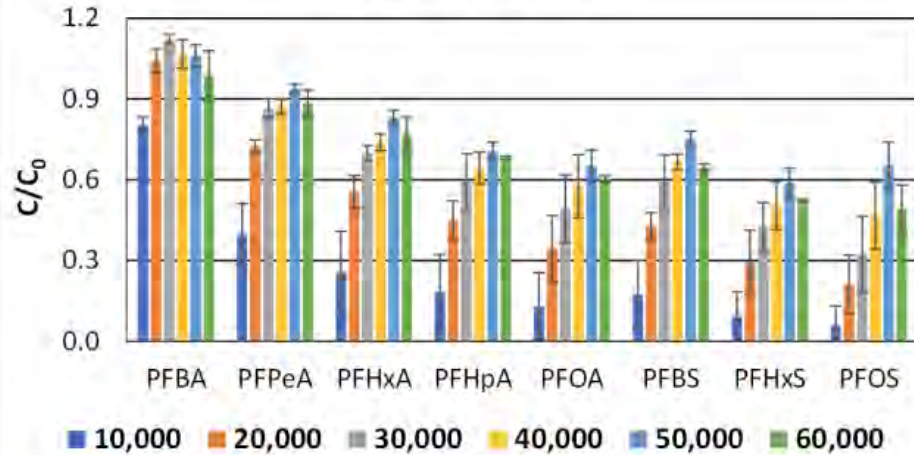


HS-PF

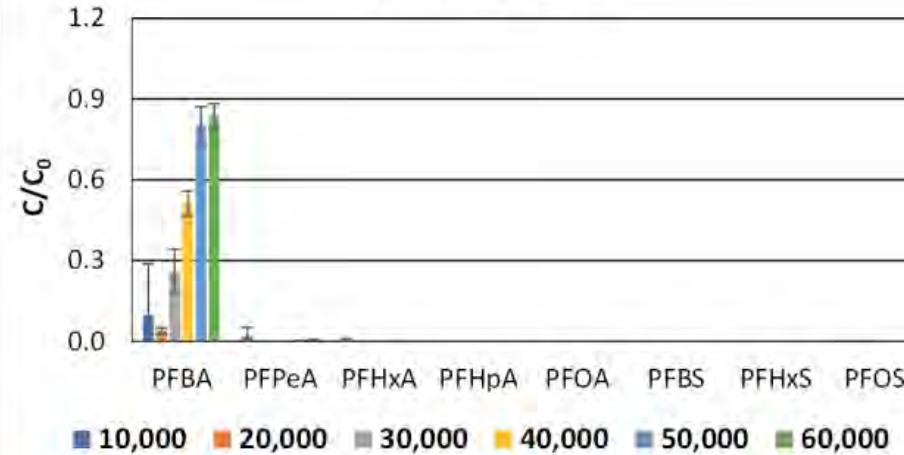
Impacts of Water Quality

TOC – data from other prior studies

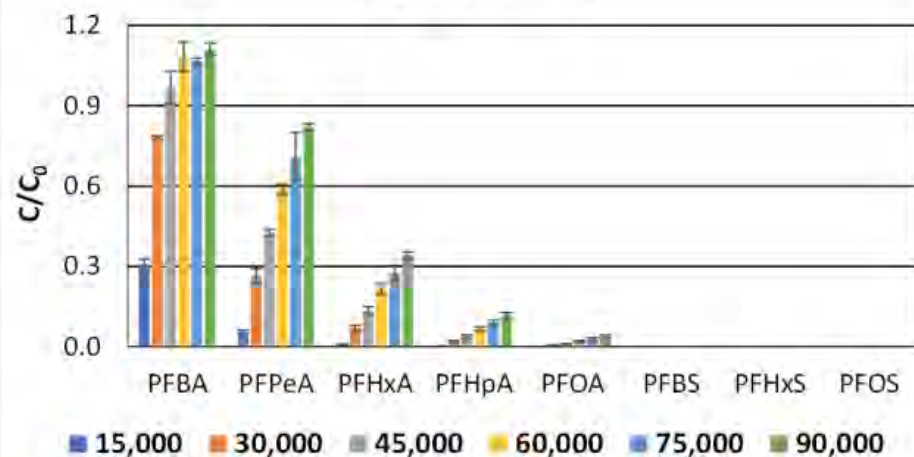
High TOC GAC



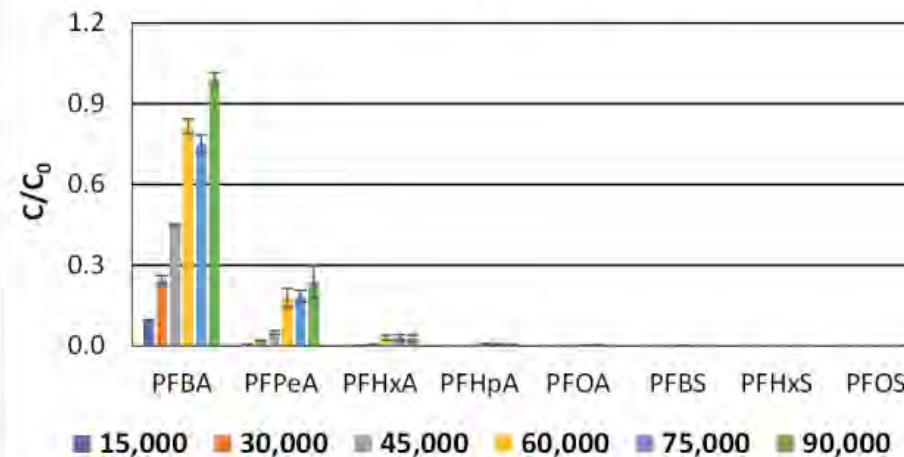
Low TOC GAC



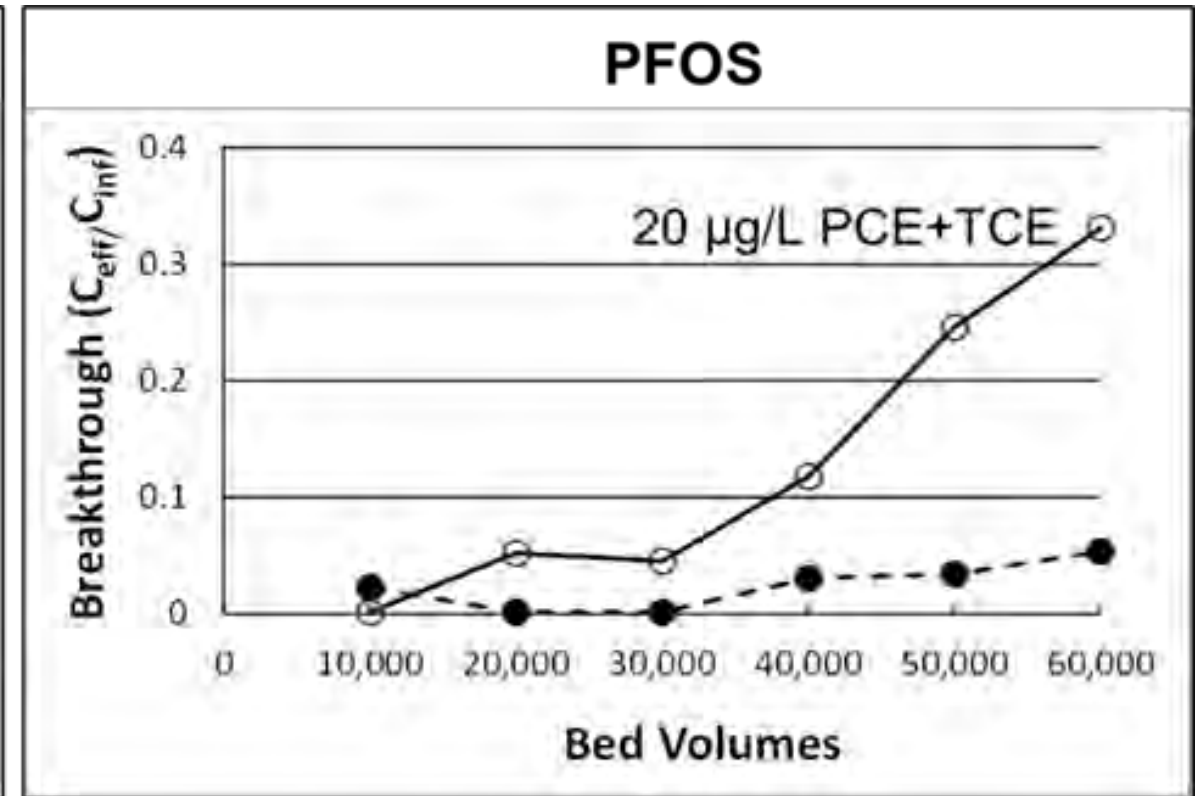
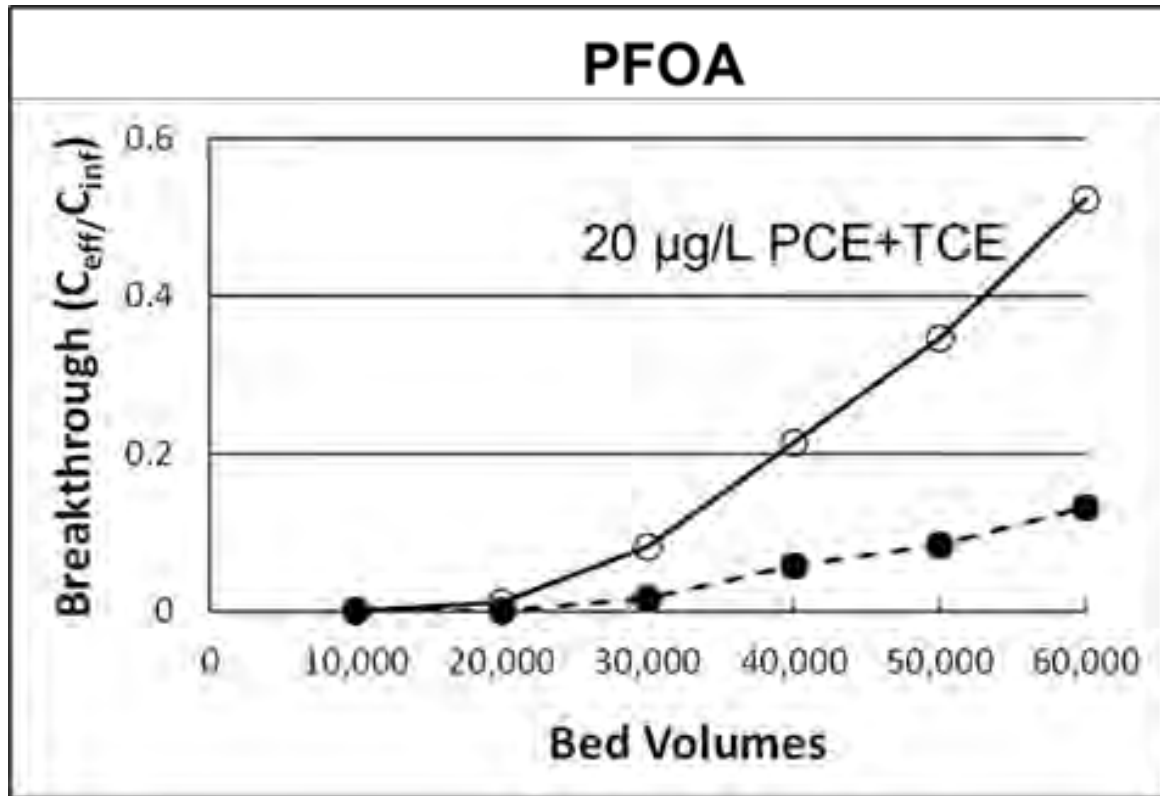
High TOC AER



Low TOC AER



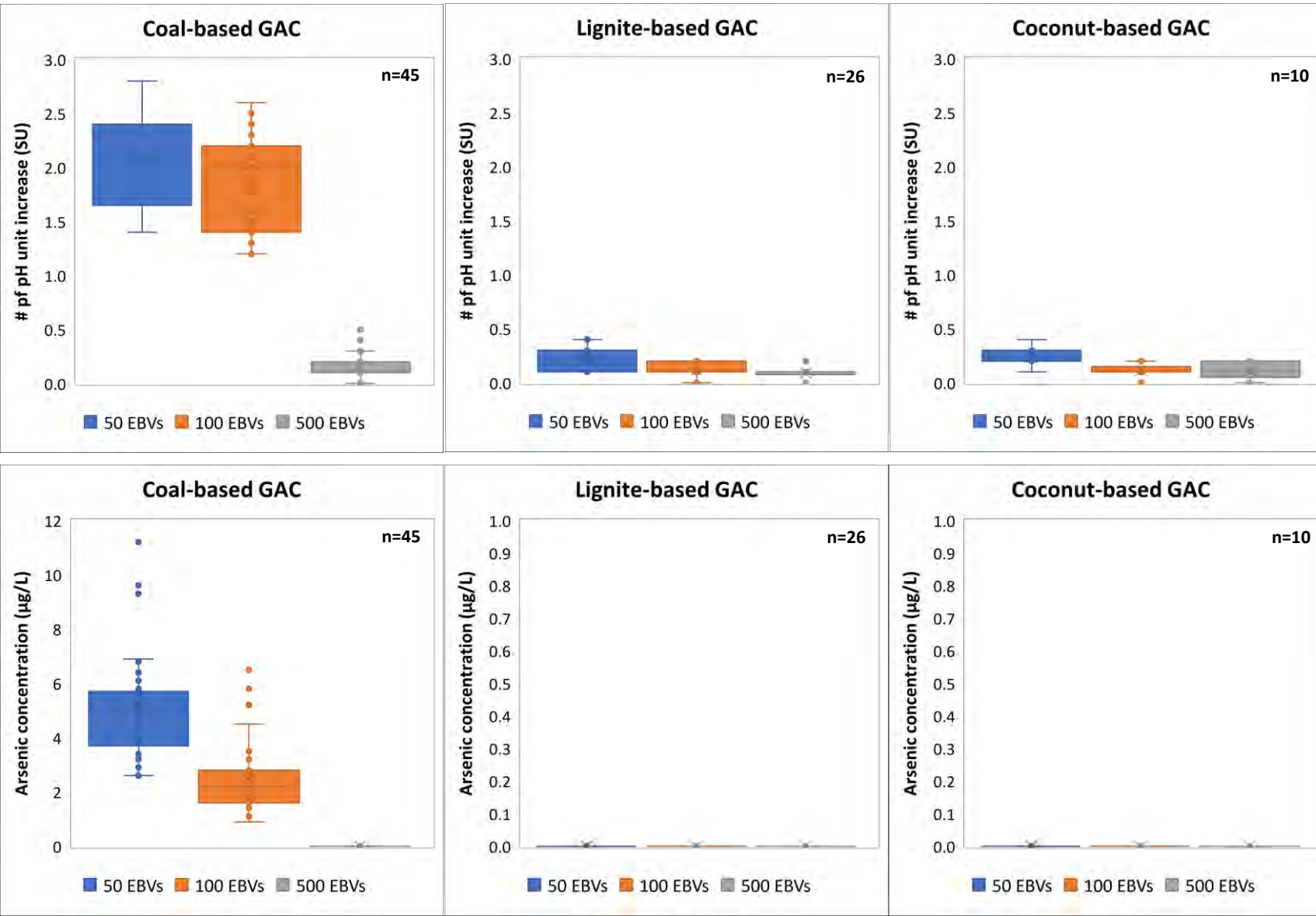
- TOC can detrimentally impact both GAC & AER performance.
- Adverse impacts seen with PFAS removal effectiveness, media longevity & hydraulics.



- Trace amount of cVOCs (open circles) can result in ~40-50% faster PFAS breakthrough in GACs.

Unintended Treatment Consequences

pH & arsenic mobilization



- Transient pH increases (up to 3 pH units) & arsenic mobilization (to MCL) seen with coal-based GAC
- No such impacts observed with lignite- or coconut-based GAC

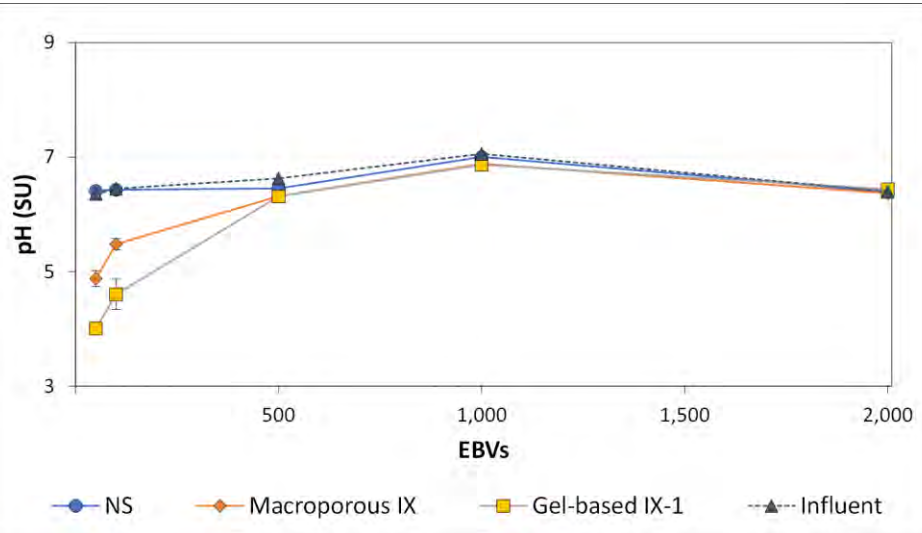


Unintended Treatment Consequences

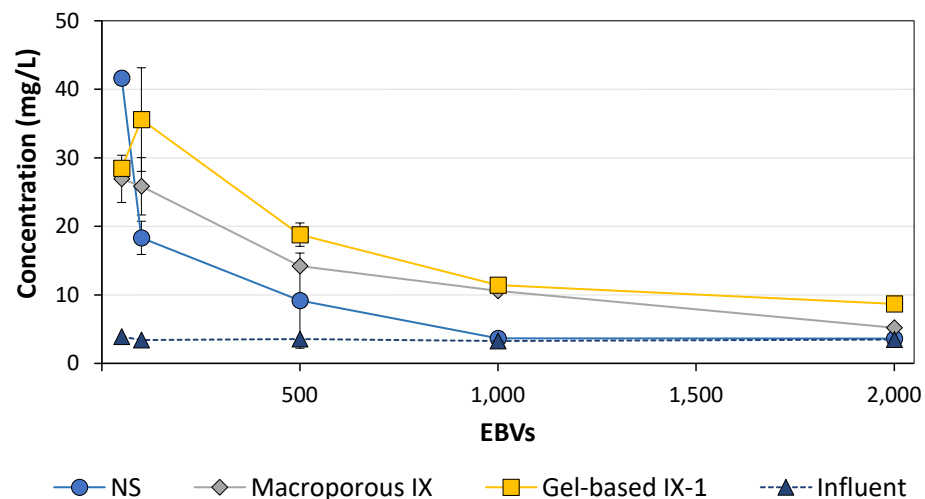
pH reduction & changes in Chloride:Sulfate Mass Ratio (CSMR)



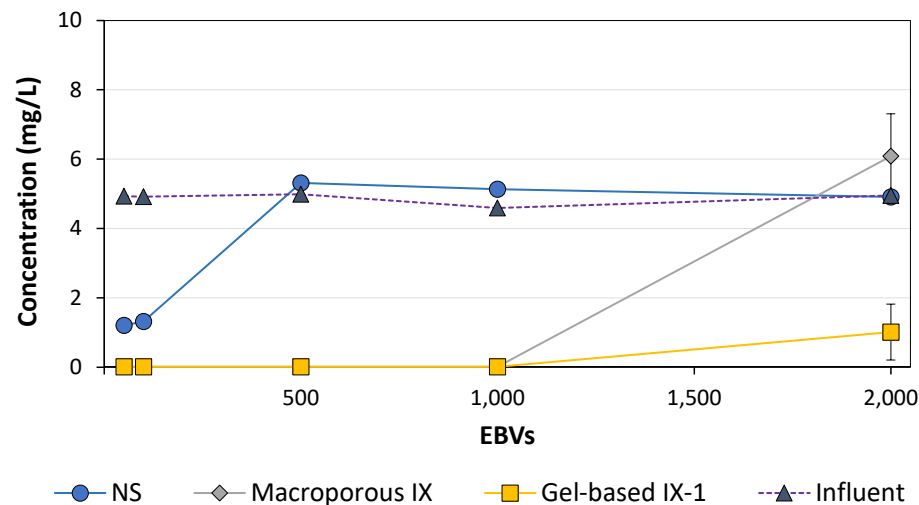
- Transient pH reduction with IX
- Transient changes in CSMR & increased potential for lead mobilization with IX



Chloride in Column Effluent



Sulfate in Column Effluent

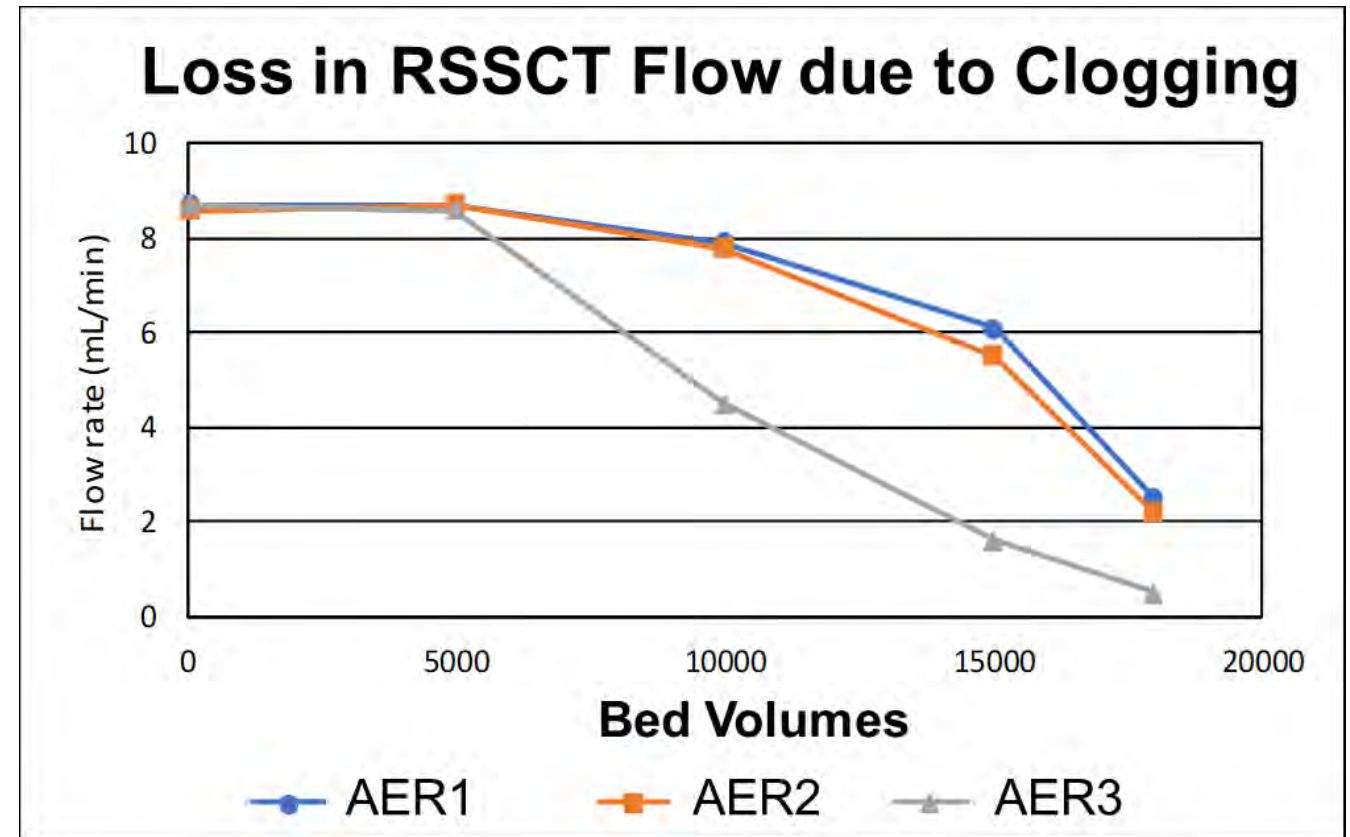


Unintended Treatment Consequences

Hydraulic issues with IX



Source: Nguyen, Z.



Biofouling Seen at Wright-Patterson





Lessons Learned from Pilot Study



- Pretreatment is needed for optimal PFAS removal.
- Many factors may influence PFAS treatment effectiveness including:
 - Water geochemistry
 - PFAS composition & concentration
 - Perfluorinated chain length & function group
 - Presence of co-contaminants
- Commercial media performed differently:
 - Very quick PFAS breakthrough with GAC
 - IX/FS/HS-PF outperformed GAC
 - IX was the best performer re: short-chain removal
 - FS was the best performer re: long-chain removal

Full-Scale Implementation



Lined gravity upflow polishing basin operating at over 150 gpm



Second PFAS removal system using extraction wells & gravity flow basin system



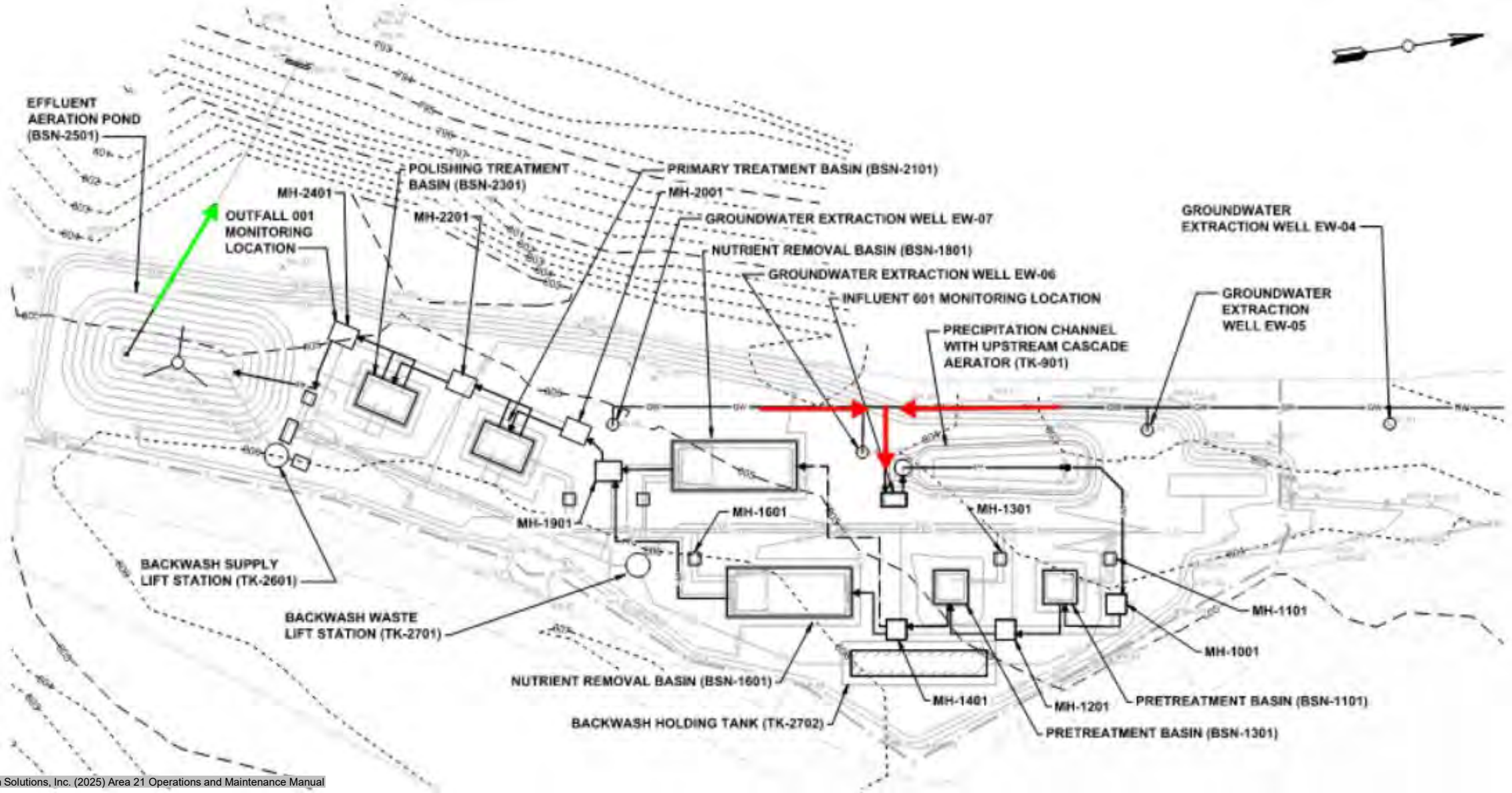
Full-Scale Implementation



Overview of completed Area 21 Treatment System

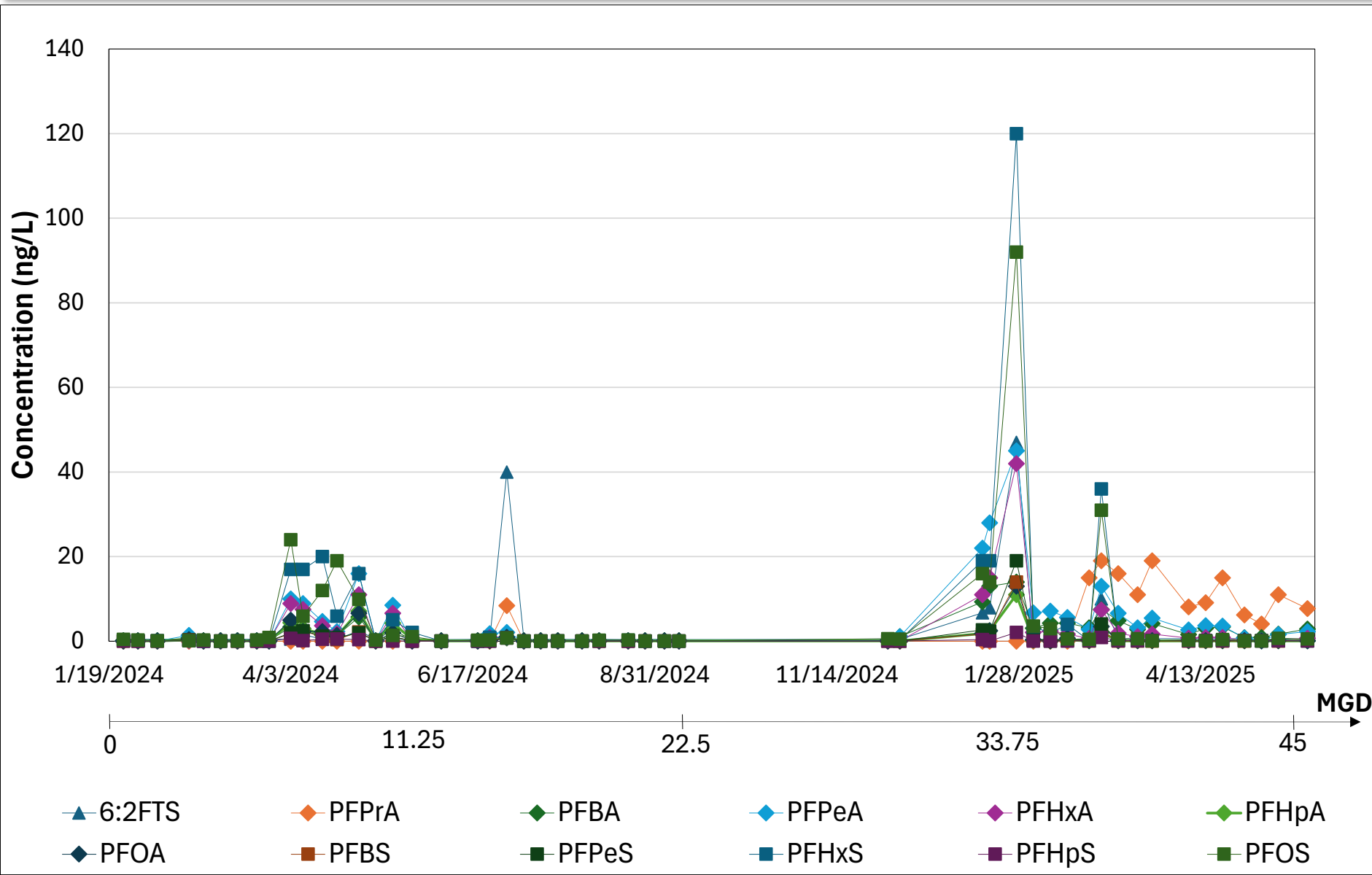


Treatment System Layout





Effluent Results at Outfall 002 (MH-1201)



- 6 months of full-scale ops
- ~45M gals treated to-date
- PFAS spikes in effluent are attributable to a valve failure issue (now fixed)
- Influent:
 - PFOA: ~ 50 ng/L
 - PFOS: ~300 ng/L



Thank You



Questions?

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Your Success is Our Mission!



Air Force Civil Engineer Center

Restoration Technology Transfer Speakers Series
December 2025

PFAS Surface Water Treatment Using SAFF + DE-FLUORO

Presenters: Zach Pierce, PE (Allonnia) & Rebecca Mora (AECOM)

Allonnia and AECOM completed a PFAS water treatment demonstration at a PFAS-impacted surface water outfall in Southern California. The demonstration aimed to validate foam fractionation (SAFF®) and electrochemical oxidation (DE-FLUORO®) PFAS treatment technologies to enable on-site PFAS separation, concentration, and destruction with minimal offsite waste disposal. The webinar covered the technology function and implementation, project results, challenges, and lessons learned for future applications of these technologies.



Zach Pierce and Rebecca Mora describing the SAFF + DE-FLUORO field setup.

This event and future events are updated and posted on the AFIT website at: <https://www.afit.edu/CE/index.cfm>.

POCs:

Joseph Dimisa, AFIT (joseph.dimisa@us.af.mil)

C.J. Garcia, CTR, Booz Allen Hamilton (carlos.garcia.56.ctr@us.af.mil)

Kurt Lee, AFCEC/CZTE (kurt.lee.3@us.af.mil)



Webinar Structure



	<u>Restoration Technology Transfer Webinar Series – eDASH Archive</u>
5 min	Welcome and Administrative Business
30 min	Main Presentation – <i>PFAS Surface Water Treatment at March ARB Using SAFF + DE-FLUORO</i> – Allonnia & AECOM
10-15 min	Questions and Answers
5 min	Final Thoughts

Air Force Civil Engineer Center

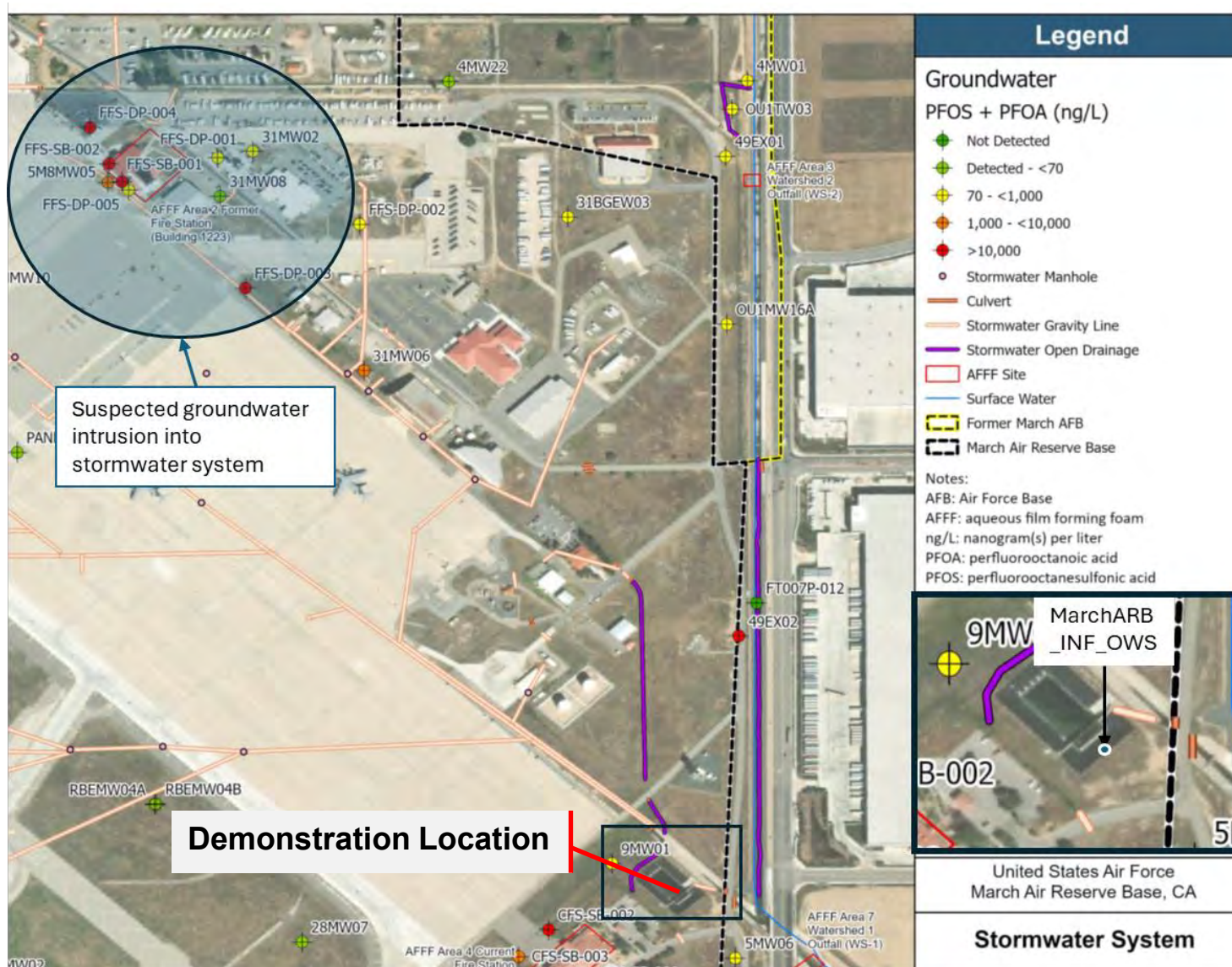


PFAS Surface Water Treatment at March ARB Using SAFF + DE-FLUORO

Zach Pierce (Allonnia)
Rebecca Mora (AECOM)

December 10, 2025

Site Identification



- Project location identified by AFCEC as known area where future PFAS treatment may be needed
- Runoff captured throughout March ARB is diverted to holding basin and oil water separator prior to discharge to surface channel
- Water includes surface water from various sources as well as likely groundwater intrusion
- “Dirtiest” water Allonnia has treated for US DoD across seven demonstrations
- Logical equipment placement location off 8th street, behind fire department



Project Objective & Background: Demonstrate a Closed-Loop Solution



1

SEPARATION

2

CONCENTRATION

3

DESTRUCTION



PFAS MOLECULE
(hydrophilic anionic
functional head chemistry)

AIR BUBBLE
(air/water interface)

PFAS MOLECULE
(hydrophobic fluorinated tail)

SAFF Separation Mechanism

Foam Fractionation:

Rising air bubbles separate PFAS to surface in foam layer

- Hydrophilic head: orients in water
- Hydrophobic tail: orients in air-bubble
- Ambient air, no containerized gases

Bench Scale Testing

SAFF® Bench Scale Test

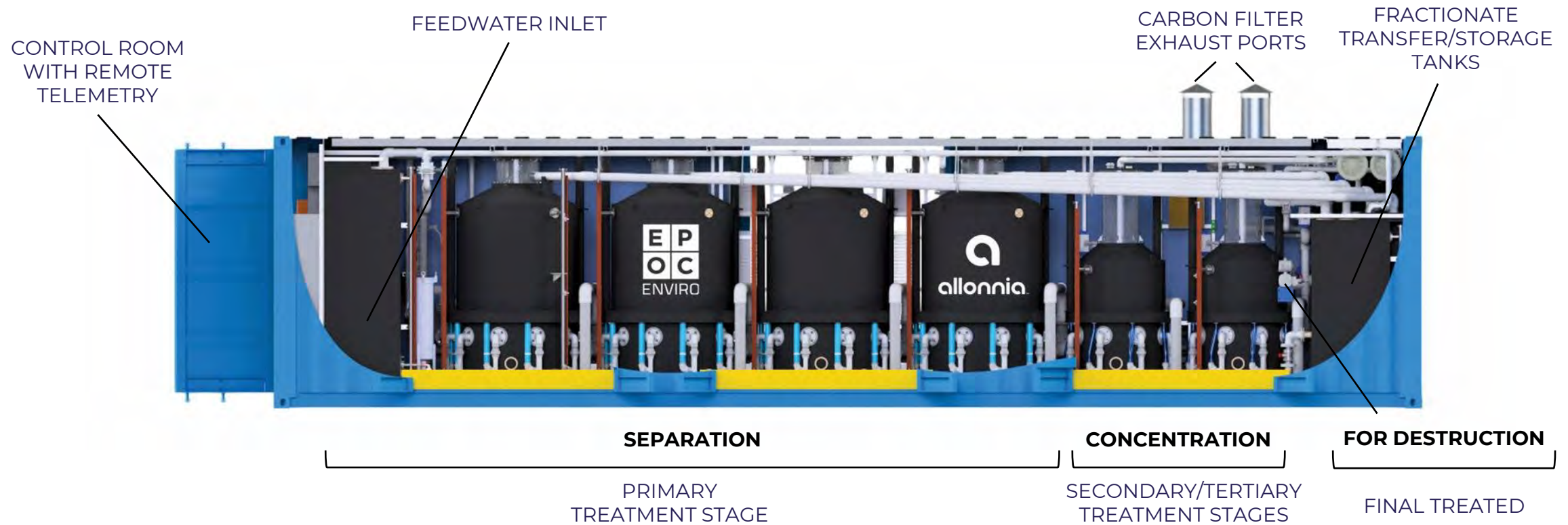
- Site water sample tested in Allonnia's Boston Laboratory
 - Estimate waste concentration factor
 - Estimate booster dosing requirements
 - Estimate PFAS removal
- Water did not readily foam, bio-derived and biodegradable non-ionic foaming booster was selected
- Good correlation between bench and pilot for waste reduction and PFAS removal.
- No destruction bench testing was completed due to low waste volumes available for testing. Bench testing for destruction would be recommended for similar future efforts due to project challenges





The SAFF40[®]

Containerized Water Treatment Plant

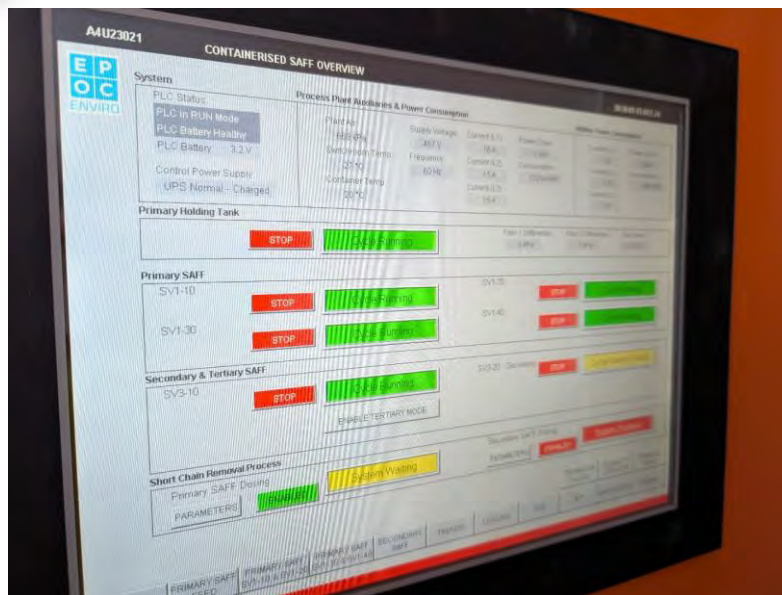




The SAFF40[®]

Containerized Water Treatment Plant

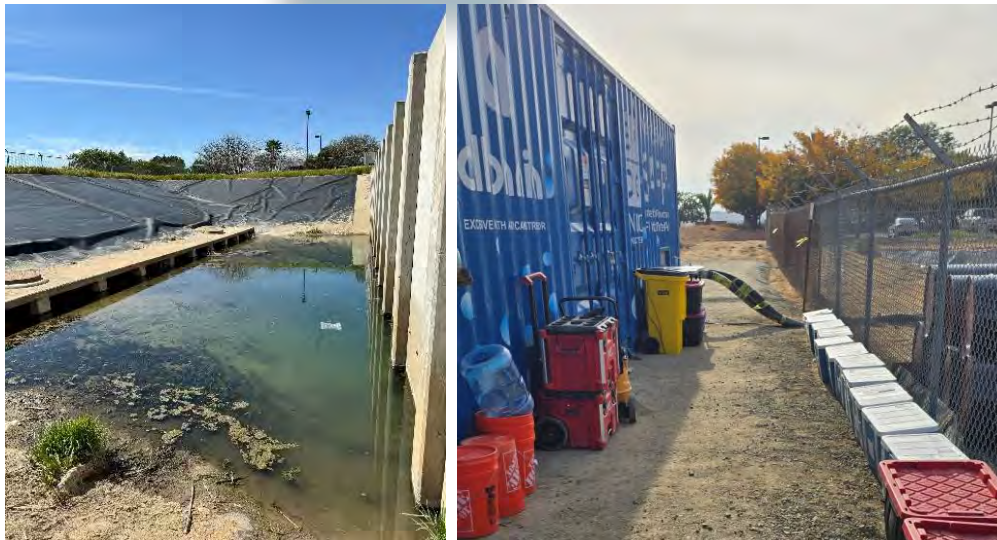




Automated remote controls allowed for 24/7 operation and notification when (for example), our onsite generator failed. Treatment volumes and waste generation was monitored remotely when possible.



Feedwater Inlet



- The system is capable of handling high TOC, TSS, TDS, and other metals.
- Zero pretreatment was needed before the SAFF system for this demonstration, despite visible algae, dissolved and suspended solids
- This was the “dirtiest” water we have treated for US DoD to date, with 800-1,000 mg/L

Primary Fractionation



- Air is introduced to the PFAS-impacted water and the foam fractionation process is initiated
- Four vessels create a semi-batch process separating >99% of PFOS+PFOA and >66% of total RSL compounds including short chains.
- Influent is concentrated by ~10x in this stage





SAFF PFAS Removal Summary



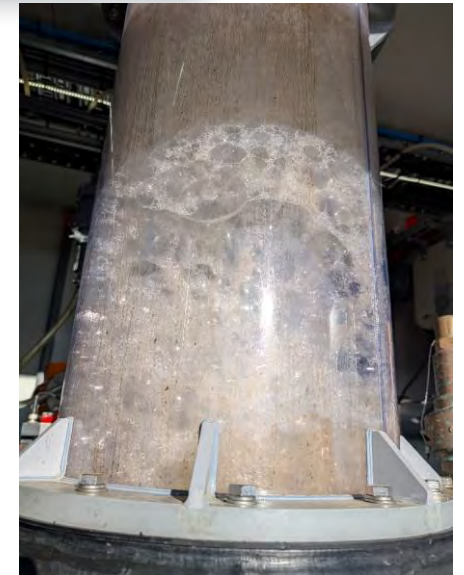
	DoD RSLs	Influent Average (Optimized)	Effluent Average (Optimized)	Percent Removal Average (Optimized)
PFBA	1,800	104	106	-1.9%
PFHxA	990	335	309	7.8%
PFOA	4	113	< 1.4	> 99%
PFNA	10	4.5	< 1.0	> 77%
HFPO-DA	10	1.2	0.63	--
PFBS	2,000	86	84	2.6%
PFHxS	10	599	< 9.1	> 98%
PFOS	4	389	< 0.93	> 99%
SUM PFAS with RSLs	--	1631	509.16	68.8%

- Treatment objective (DoD RSLs) met for all analytes under optimized SAFF treatment settings
- Treatment objective met for all analytes other than PFHxS, PFOS for all other operating conditions tested
- Little to no short chain PFAS removal, but influent concentrations were below DoD RSLs (common for dilute historical AFFF contamination)
 - Removal can be boosted using different foaming additives

Secondary and Tertiary Fractionation



- The PFAS concentrate from primary treatment moves into the secondary and tertiary treatment vessels for an additional 950x concentration.
- Waste volume reduction is key to enabling “closed-loop” treatment scheme feasibility





Waste Destruction



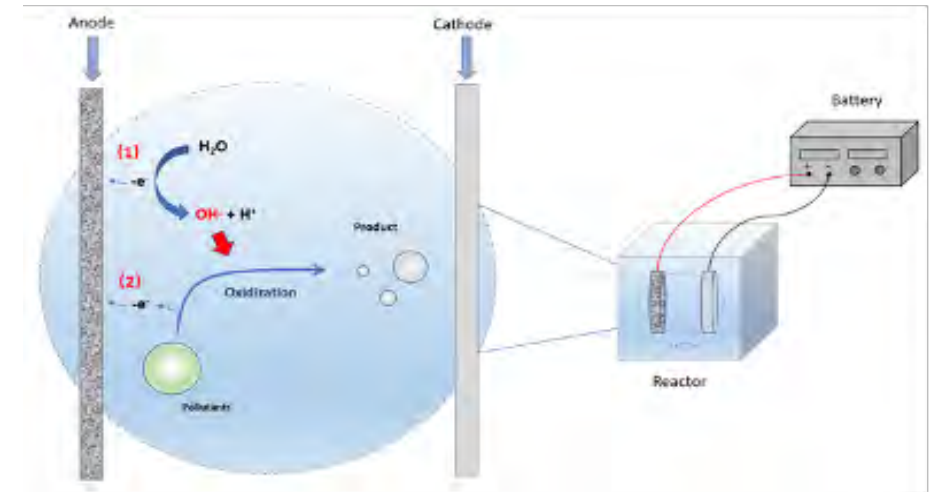
Volume of water treated by SAFF: 1,370,000 gal
Concentrated PFAS solution after SAFF sent for destruction:
115 gal tertiary concentrate
348 gal secondary concentrate



- Tertiary and Secondary concentrate was drained to 55-gal drums for treatment by AECOM's DE-FLUORO system.
- For every 9,500 gal treated, SAFF generated 1 gal of tertiary foam concentrate for destruction.
- Additional tests were conducted for destruction of secondary concentrate with or without booster attempting to improve PFAS destruction.

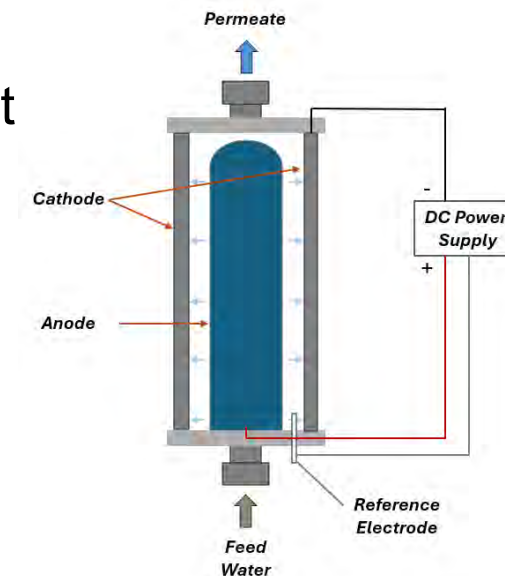
■ Electrochemical Oxidation

- Direct current applied to electrodes driving anodic oxidation reactions either through reactive oxygen species (e.g., $\text{OH}^\bullet$) or via direct electron transfer
- EO defluorinates and mineralizes PFAS
- Thoroughly researched via ER-2717, ER18-1320



■ Magnéli phase titanium suboxide ($\text{Ti}_n\text{O}_{2n-1}$)

- Conductive, robust, high oxygen evolution potential, low cost
- Porous ceramic, enabling REM operation
- Large surface area for direct oxidation on anode
- Scalable/modular design
- Full-scale commercial systems already in place treating non-PFAS contaminants



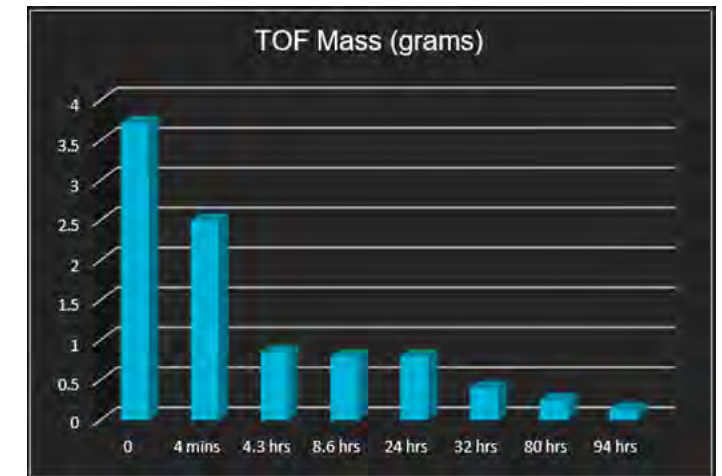


Background on DE-FLUORO®



- Patent awarded to UGA and licensed by AECOM
- Marketed globally as DE-FLUORO®
- Eight systems have been designed and built ranging from bench, to demonstration, to commercial scale and are currently in operation
- Two previous AFCEC BAAs funded
 - BAA108 at Wright-Patterson AFB
 - BAA2128 at Travis AFB
- Systems can run unstaffed/remotely monitored, no significant chemical addition, and under ambient conditions
- 2024: Official start of partnership with Aquatech
 - Global leader in water and process technology solutions
 - Aquatech adds expertise in: scale-up, manufacturing, logistics, O&M, and proven delivery models

16

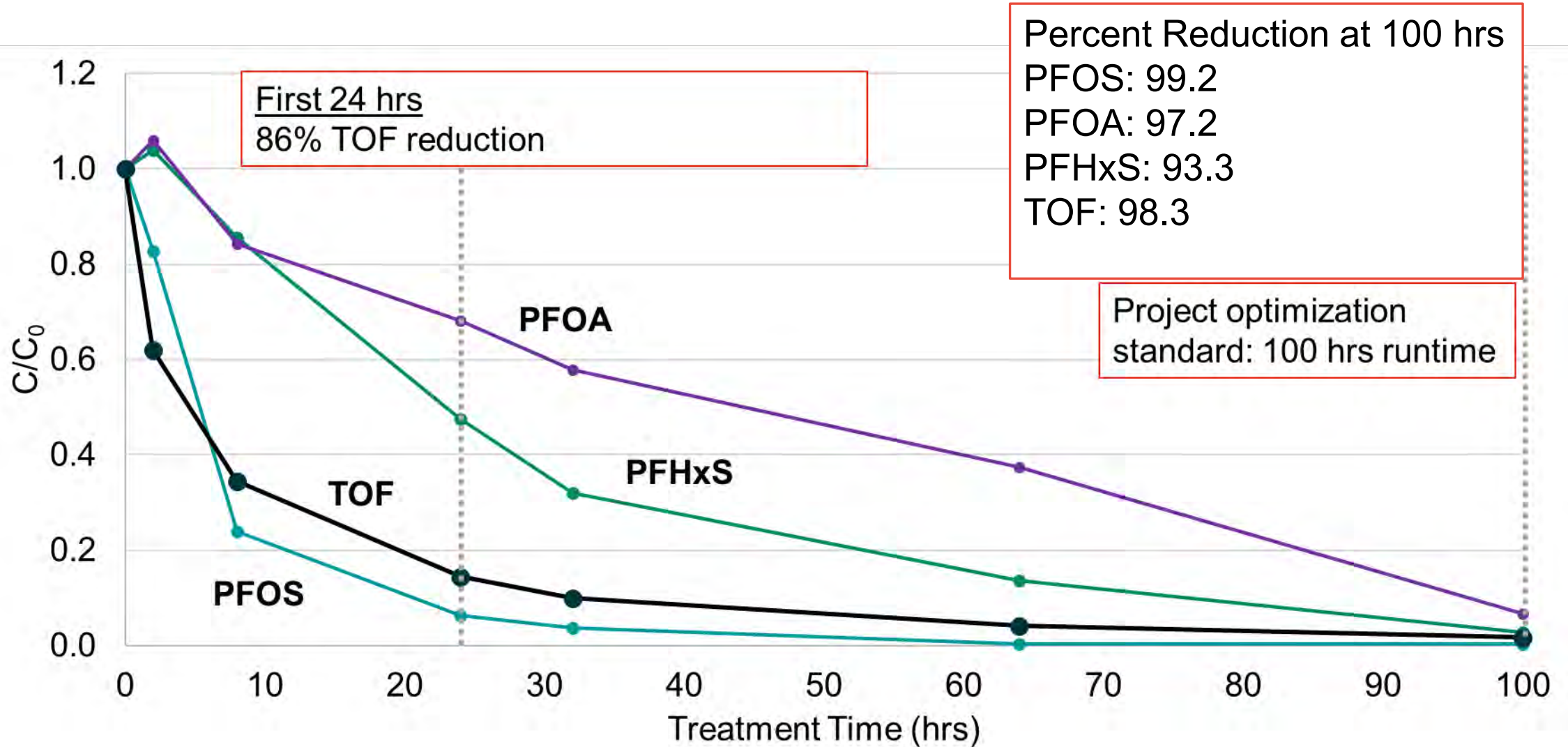


Top: AECOM's Meg EO system in operation to treat PFAS-containing rinsewater. Bottom: Reduction in Total Organic Fluorine (TOF) during the field demonstration



SAFF + DE-FLUORO® Experience







March ARB – DE-FLUORO® – Batch 1



- Treated tertiary fractionate with high concentration of saponin booster
- No decrease in current/voltage, no elevated pressures during operation
- Sight glass in reactor showed typical behavior for oxidation
- Water had high turbidity; decreased over time due to inline filter



- Significant buildup on cathodes – never seen before - color matched saponin
- Buildup caused bridging, short circuiting, and electrode damage
- Little to no PFAS treatment
- TOC was the most significant component; likely related to high concentrations of saponin
- Minimal PFAS in the residue

Photos of Cathodes at T136

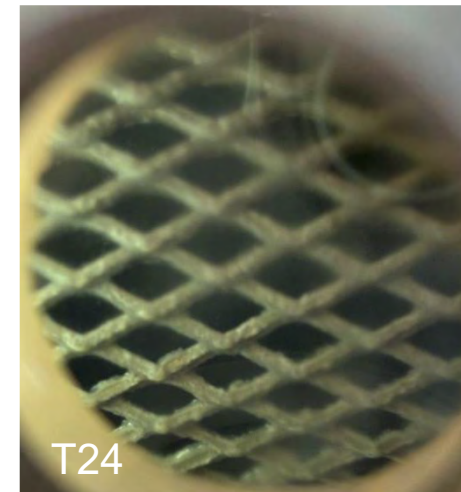
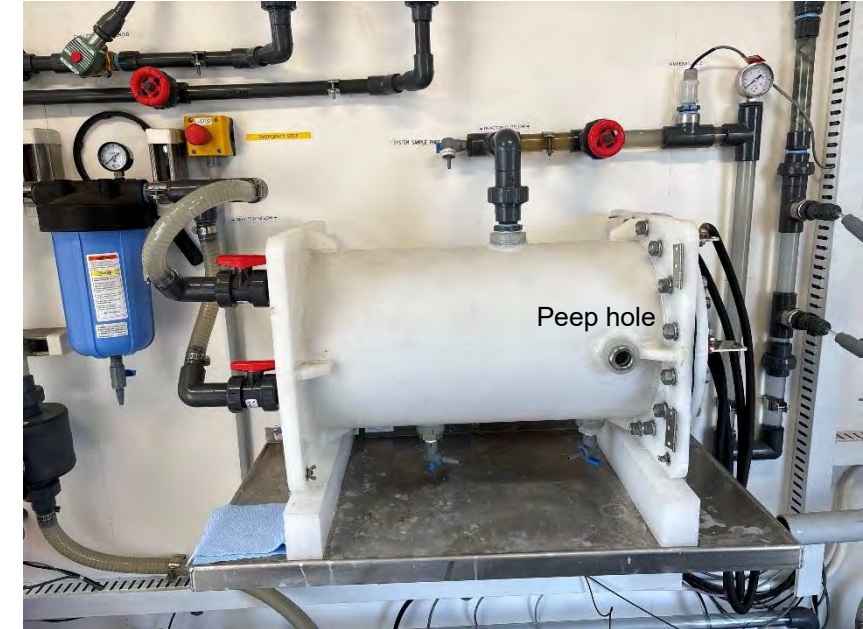


Batch 2 Updates:

- Installed spare reactor (used)
- Treated secondary fractionate instead of tertiary to reduce saponin concentration by ~8x
- Additional pre-filtering (down to 0.2 um) to remove any solids
- Increased current density
- At each sampling point, turned off reactor and inspected cathodes for buildup

Results/Observations:

- No decrease in current/voltage or elevated pressures
- Sight glass showed buildup on cathode and decreased bubbling
- Paused treatment at T40 to await data, which indicated no significant treatment
- Analysis of residue indicated TOC and calcium were the main components and residue looked different from Batch 1



Batch 3 Updates:

- Reinstalled cleaned reactor from Batch 1
- Purged saponin from the SAFF and generated secondary fractionate free of saponin (Based on previous SAFF + DF experience in MN)
- Same operational settings as Batch 1; just no saponin

Results/Observations:

- Sight glass showed bubbling slowing down and buildup on cathode
- Cathode buildup looked different again – more like salt
- Paused treatment at T64 to await analytical data, no significant treatment
- Anodes in reactor slightly damaged during Batch 1, which may have affected treatment of Batch 3
- Analysis of residue indicated calcium was the main component
- Influent water quality indicated higher calcium compared to water quality of other sites where DE-FLUORO had been demonstrated





March ARB – DE-FLUORO® Summary



- First DE-FLUORO® project to see this type of buildup on the electrodes
 - Concentrates generally originated from groundwater – more favorable water quality
 - One surface water project (MN) was from a creek (vs. stormwater runoff at March ARB)
- Buildup on the electrodes affected DE-FLUORO®'s ability to operate properly
- Surface water characteristics can vary significantly from site to site
 - DE-FLUORO® bench test was not performed prior to field implementation due to minimal foamate volume from SAFF bench test; however, in hindsight, a bench test on the surface water may have revealed electrode issues
 - Need to pursue more thorough understanding of parameters that can affect system performance and site suitability
- Sensitivity to water quality parameters and foam fractionation boosters must be considered when selecting a destructive technology



Key Takeaways



- Foam fractionation is suitable for stormwater treatment with minimal pre-treatment requirements; however, booster addition may be needed
 - Minimal pre-treatment requirements allow surface water storage and TOC, solids co-contamination
 - Higher PFAS concentrations or limited optimization flexibility could require post-SAFF polishing via media, increasing cost and pre-treatment requirements
- Boosters are becoming more common in foam fractionation. Destructive technologies need to evaluate which ones may affect their system performance.
- SAFF + DE-FLUORO is a viable treatment train for treating PFAS in surface water based on performance at other sites; however, water quality needs to be evaluated for site suitability



Thank You



Questions?



Your Success is Our Mission!