Per- and Polyfluoroalkyl Substances (PFAS) Remediation Workshop

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Agenda

- Introduction to Workshop and Objectives
- Properties and Concerns with PFAS
- PFAS Remedial Options
- Break (10 minutes)
- R&D and Treatability Studies on Innovative Adsorption Media and Chemical / Electro-Chemical Processes
- Non-Destructive Case Studies
- Chemical Oxidation Case Study + Additional Research
- Wrap-Up / Summary of Current State of the Practice

PFAS Remediation Challenges

- New and fast-changing targets
  - Which PFAS?
  - Which cleanup levels?
  - Can we measure all PFAS?
  - Human and Eco risk

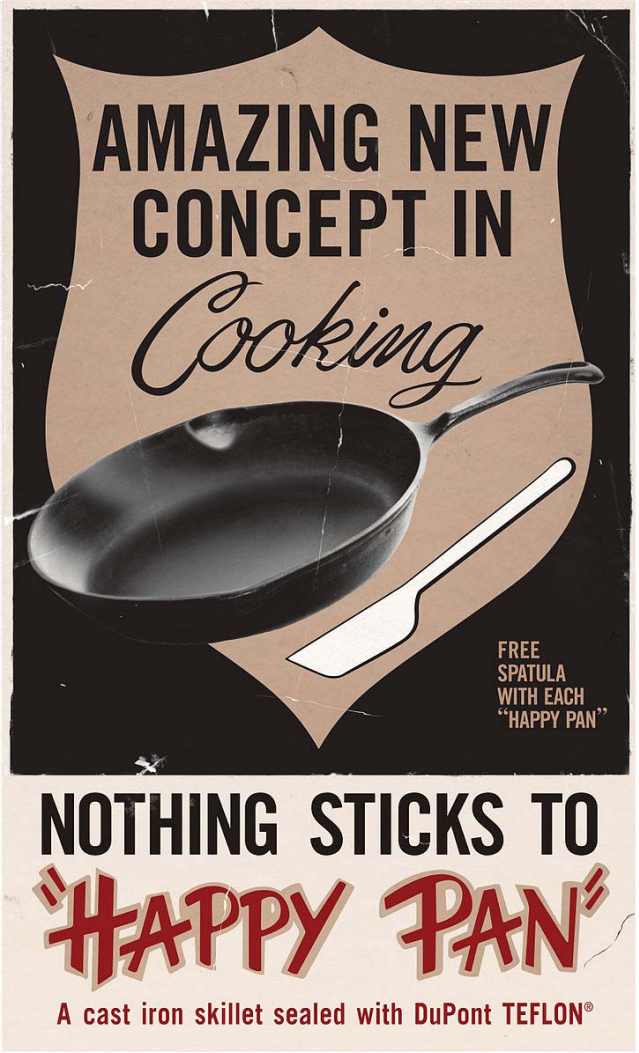
PFAS Remediation Challenges

- Other challenges
  - Transformation vs. mineralization
  - Risk of making things worse
  - Concentrated waste streams from non-destructive approaches need treatment

Properties and Concerns with PFAS

What are PFAS?

- Per- and polyfluoroalkyl substances
- Synthetic chemicals with at least one C-F bond
- C-F bonds are extremely strong
- USEPA master list includes 6,330 PFAS chemicals - and growing
- For nomenclature/acronyms, see ITRC PFAS fact sheet



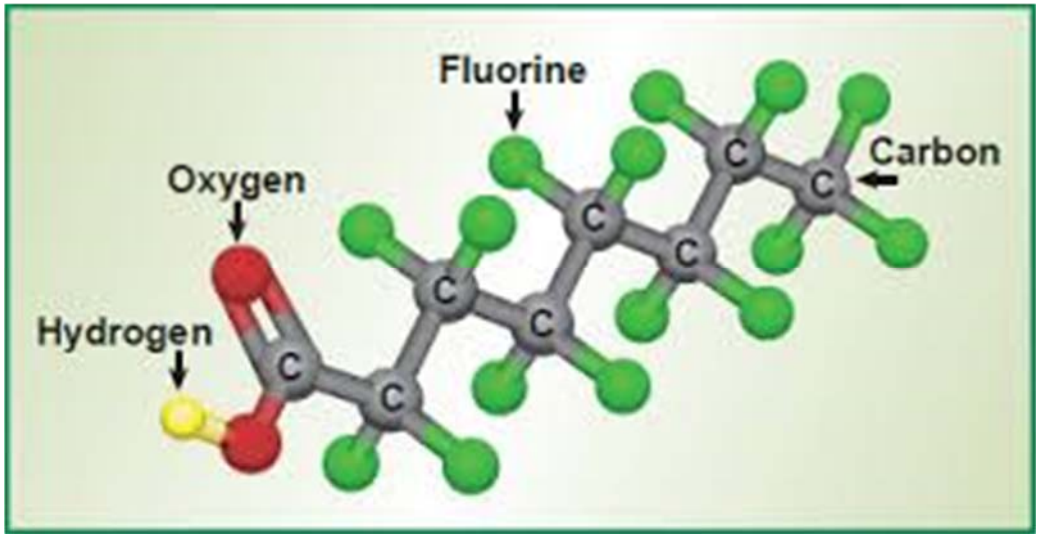
Credit: trozzolo

https://comptox.epa.gov/dashboard/chemical_lists/PFASMASTER
https://pfas-1.itrcweb.org/wp-content/uploads/2018/03/pfas_fact_sheet_naming_conventions__3_16_18.pdf

What are PFAS?

- Produced in the largest amounts in the US:
  - Perfluorooctanoic acid - PFOA (C8)
  - Perfluorooctane sulfonate - PFOS (C8)
- Typical PFAS properties:
  - Low to moderate water solubility
  - Low volatility
  - Resist biodegradation
    - C-F bond

PFOA



Credit: NIEHS – National Institutes of Health

Physical-Chemical Properties

Property	PFOA	PFOS	Benzene
Chemical Formula	$C_8HF_{15}O_2$	$C_8HF_{17}O_3S$	C_6H_6
Molecular Weight (g/mol)	414.09	500.13	78.11
Boiling Point (°C)	192.4	259	80
Vapor Pressure (mm Hg at 25 °C)	0.525	~0.002	86
Henry's Law Constant @ 25°C (unitless)	Not measurable	Not measurable	0.225
K_{oc} (temperature as specified)	115	371	79 (at 25 °C)
Solubility in Water (mg/L)	~9,500 (at 25 °C)	680 (temp. not stated)	1,780 (at 25 °C)

https://www.epa.gov/ground-water-and-drinking-water/drinking-water-health-advisories-pfoa-and-pfos

For other properties of other PFAS, try: https://clu-in.org/contaminantfocus/default.focus/sec/Per-_and_Polyfluoroalkyl_Substances_(PFASs)/cat/Chemistry_and_Behavior/#3

Properties of a Few Short-Chain PFAS Compared with PFOA and PFOS

PFAS	Water Solubility (mg/L)	Melting/ Boiling Point (°C)	Vapor Pressure (Pa)	Log Kow
PFOA	3,400		12.1	3.6
PFOS	519-570		3.31×10^{-4}	5.5-7.03
PFHxS	243.4	190/452	1.08×10^{-6}	2.2
PFHxA	29.5 <<29		121	2.51 3.12-3.26
PFBS	4,340	188/447	1.49×10^{-6}	0.26
8:2 FTOH	0.2-0.3		1.64	5.58
6:2 FTOH	19		22.1	4.54
4:2 FTOH	97	-44/113	1,330	3.07/3.30
6:2 FTAC	0.38		44.3	5.2

Orange denotes max/min

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https://www.researchgate.net/publication/299230070_Short-chain_Polyfluoroalkyl_Substances_PFAS_A_literature_review_of_information_on_human_health_effects_and_environmental_fate_and_effect_aspects_of_short-chain_PFAS

Widespread Occurrence

- Found worldwide in soil, air, water, wildlife, and humans
  - Including the Arctic and Antarctic
- 2015 study by U.S. National Health and Nutrition Examination Survey:
  - PFOA, PFOS, PFHxS, and PFNA detected in 97%–100% of the blood samples
- 2013-2015 Safe Drinking Water Act testing found PFAS > EPA health advisory(s) in:
  - 66 Water supplies
  - Serving more than 16 million Americans
  - In 33 states
- Large dilute plumes are common

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Credit: Jerzy Strzelecki

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4483690/

https://www.wateronline.com/doc/study-finds-that-millions-of-americans-get-water-from-pfas-laced-sources-0001

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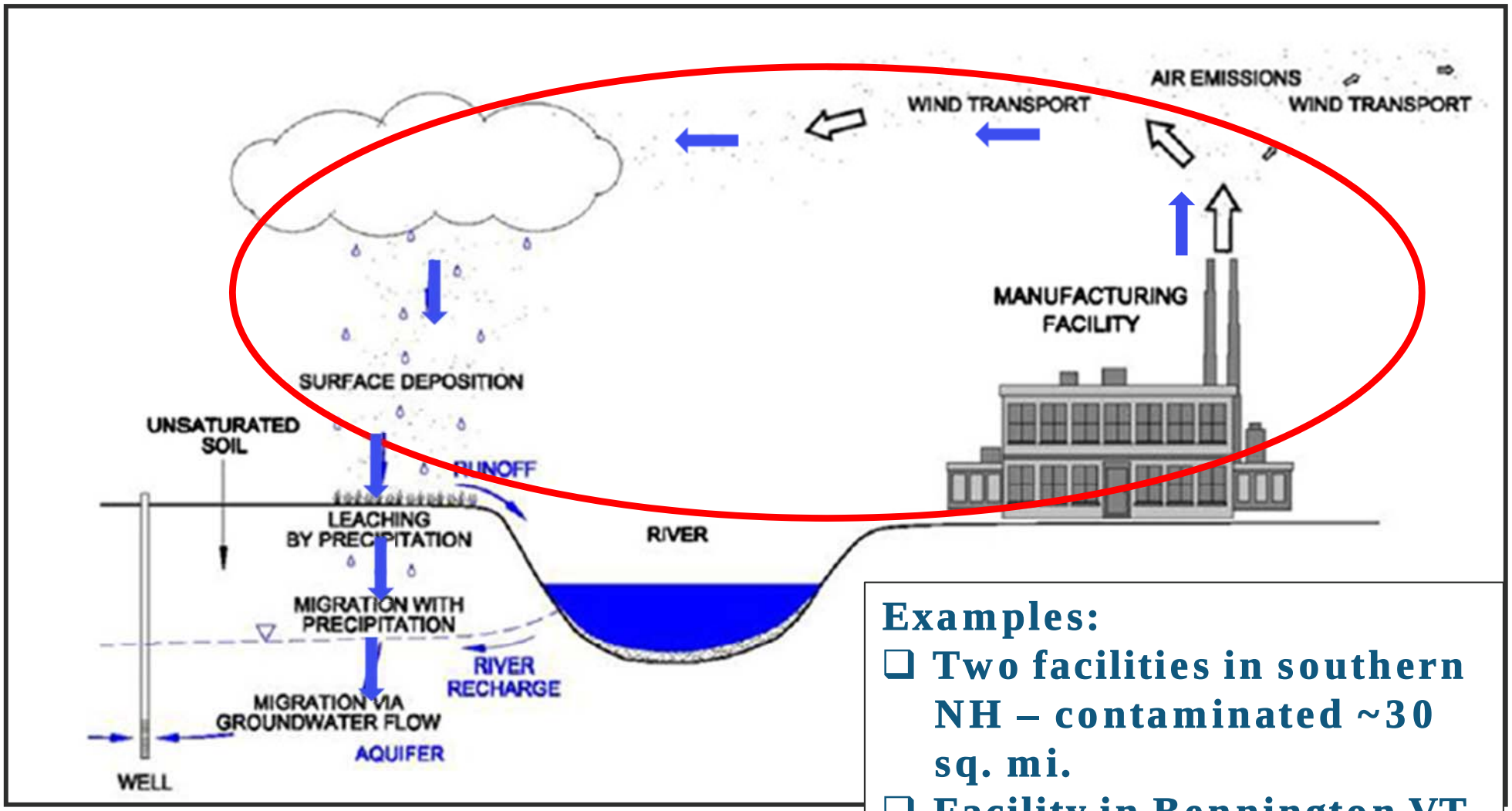
Air Transport – a Significant Pathway



Davis et al., 2007, *Chemosphere*

Examples:

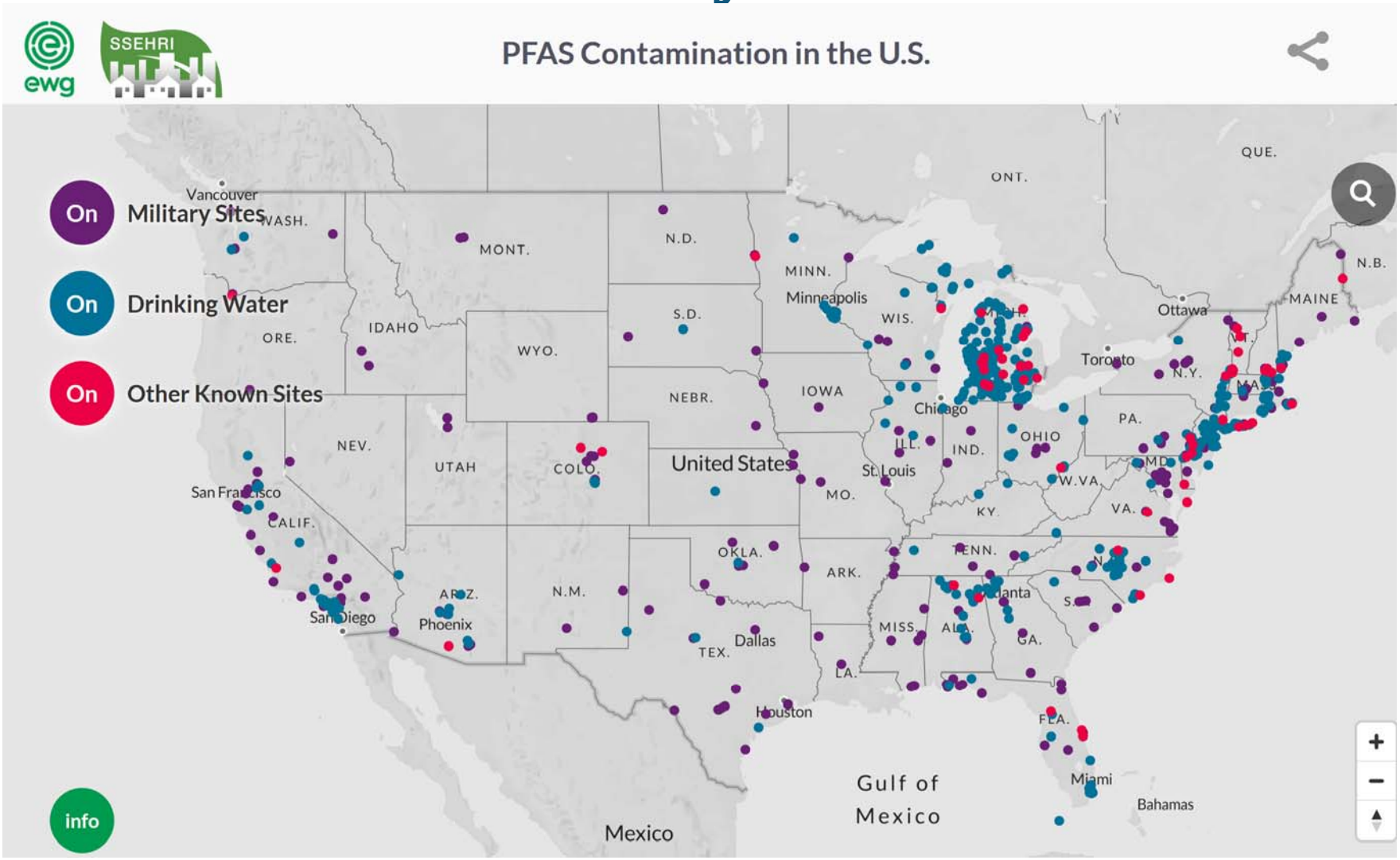
- **Two facilities in southern NH – contaminated ~30 sq. mi.**
- **Facility in Bennington VT – contaminated 10 miles downwind, ~120 sq. mi.**

Summary of Environmental Concentrations of PFOA and PFOS

Media	Low	High[b]
Outdoor air (pg/m^3)	<1	900,000
Indoor air (pg/m^3)	<5	12,100
Dust (ng/g)	<2.6	43,765
Surface water (ppb)	<1	67,000
Groundwater (ppb)	<0.1	619
Drinking water (ppb)	<0.0023	~100
Ocean water (pg/L)	<0.2	192,000
Food (ppb)	<1	118.29
Soil (ppb)	<0.17	104,000

https://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=1117&tid=237

PFAS in Tap Water and at Industrial and Military Sites



https://www.ewg.org/interactive-maps/2017_pfa/#.W6vqLvZRdPY accessed 9/17/2019

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US Department of Defense Groundwater Sampling

Credit: Airman 1st Class Amber Powell/Air Force

Component	Total Installations with known or suspected release of PFOS/PFOA (as of August 31, 2017)	Number of Installations Sampled where results exceeded EPA LHA (as of August 31, 2017)	Total number of groundwater wells sampled	Number of groundwater wells that tested above the EPA LHA
Army	64	9	258	104
Navy/USMC	127	40	1,368	784
Air Force	203	39	1,022	719
DLA	7	2	20	14
Total	401	90	2,668	1,621

DoD PFAS Task Force – 1st meeting 8/9/2019 – 1st priority PFOS and PFOA in DW

USMC = US Marine Corps; DLA = Defense Logistics Agency

https://www.militarytimes.com/news/your-military/2018/04/26/dod-126-bases-report-water-contaminants-harmful-to-infant-development-tied-to-cancers

https://www.defense.gov/explore/story/Article/1930618/dod-moving-forward-with-task-force-to-address-pfas/

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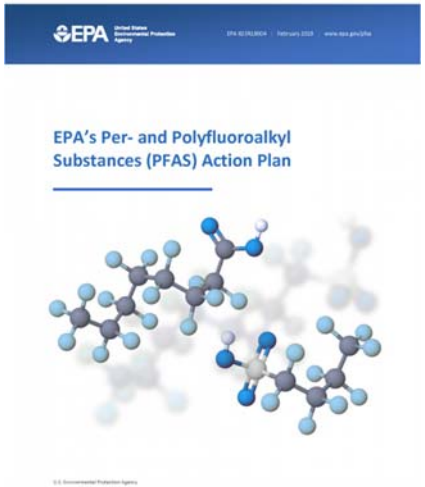
Concerns

- Low concentrations of concern
- Persist, travel long distances, and bioaccumulate
- Certain PFAS may
  - Reduce birth weight
  - Affect growth, learning, and behavior of infants and older children
  - Decrease women's fertility
  - Disrupt hormones
  - Increase cholesterol
  - Suppress immune system
  - Increase cancer risk
- Many PFAS not studied
- ITRC doc in draft will
  - Pull together risk/health effects info for PFAS
  - Final expected in 2019

Credit: Tom Cambareri

Standards and Guidelines

- EPA established health advisories for PFOA and PFOS
  - 70 ng/L or ppt (individually and combined)
  - For lifetime exposure from drinking water



- EPA has not established any PFAS Maximum Contaminant Levels
  - States aren't waiting for EPA
- Other requirements vary widely and change with time
  - Some states and countries are dealing with more than PFOA and PFOS
  - ITRC to update tables of standards and guidelines monthly

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https://www.epa.gov/ground-water-and-drinking-water/drinking-water-health-advisories-pfoa-and-pfos
https://www.epa.gov/sites/production/files/2019-02/documents/pfas_action_factsheet_021319_final_508compliant.pdf
https://pfas-1.itrcweb.org/fact-sheets/

US House Subcommittee on Environment and Climate Change passed 13 bills on PFAS on 9/26/2019:

- H.R. 535 - PFAS Action Act of 2019
- H.R. 2377 - Protect Drinking Water from PFAS Act of 2019
- H.R. 2533 - Providing Financial Assistance for Safe Drinking Water Act
- H.R. 2566 - Requires EPA to provide for a Safer Choice label for pots, pans, and cooking utensils that do not contain PFAS
- H.R. 2570 - PFAS User Fee Act of 2019
- H.R. 2577 - PFAS Right-To-Know Act
- H.R. 2591 - PFAS Waste Incineration Ban Act of 2019
- H.R. 2596 - Protecting Communities from New PFAS Act
- H.R. 2600 - Toxic PFAS Control Act
- H.R. 2605 - Prevent Release of Toxics Emissions, Contamination, and Transfer Act of 2019
- H.R. 2608 - PFAS Testing Act of 2019
- H.R. 2626 - PFAS Accountability Act of 2019
- H.R. 2638 – directs EPA to issue guidance minimizing use of AFFF containing PFAS

State of New Hampshire

- Adopted MCLs for 4 PFAS – monitoring/compliance required
- Suing makers of PFAS and PFAS fire-fighting foam
- Requiring monitoring at all GW discharge permit sites
- Requiring monitoring at most contaminated waste sites
- Sampling industrial air emissions at several facilities
- Sampling landfill leachate and assessing leachate off-gas
- Sampling drinking water
- Sampled ~45 streams
- Sampling fish

Credit: Steven G. Johnson

Credit: Ashley Felton

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State of New Hampshire - more

Credit: Keizers

- Biomonitoring humans
- Sampled ~80 private wells at fire stations
- Sampled
  - ~4,000 wells near potential PFAS sources
  - ~450 private wells randomly selected
- Developing surface water quality standards
- Likely will complete a study with USGS to develop approach for estimating soil leaching that is protective of GW
- Developing rules to ensure air emissions protect water quality
- Developing plan to determine which septic systems/registered discharges may be discharging PFAS
- Deer harvested near Pease AFB will likely be tested
- Connected ~800 homes to municipal water

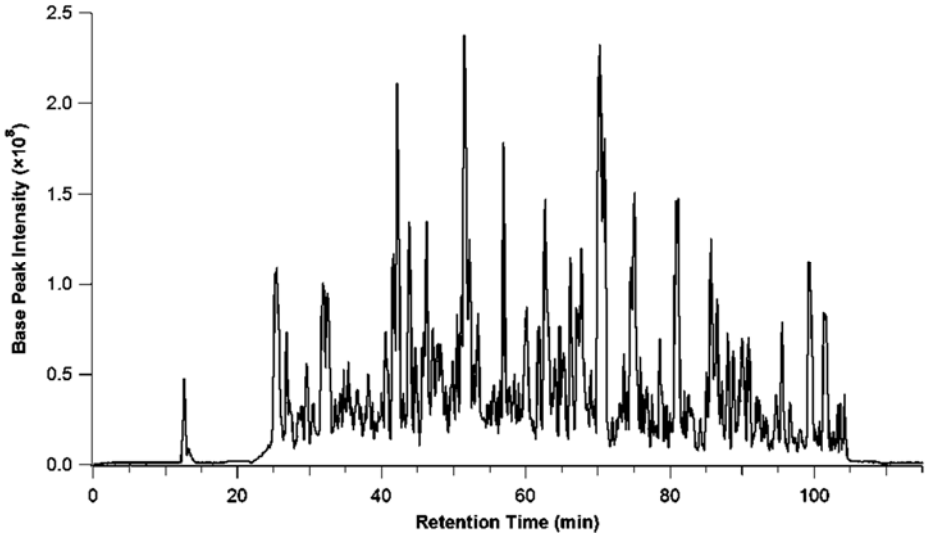
State of New Hampshire – more!

- Completed proficiency test of 5 labs NHDES uses
- Sampled GW near septage and biosolid land application sites and processing facilities
- Completing PFAS analysis of soil, GW, SW, and air near PFAS emission sites in southern NH
- Developing a legacy aqueous fire-fighting foam (AFFF) takeback and disposal program
- Surveyed fire departments to ID areas where AFFF may have been applied

Credit: National Inst. of Standards and Tech.

Analytical Challenges

- Low detection limits
- Cross-contamination
- Choosing analytes
- Finding lab standards



Credit:Cwenger

- Widely varying chemical/physical characteristics of PFAS
- Fast-changing regulatory requirements and analytical methods

EPA Method 537 - List of 14 Compounds

Perfluorooctanoic acid (PFOA)
Perfluorooctane Sulfonate (PFOS)
Perfluorobutanesulfonic acid (PFBS)
Perfluoroheptanoic acid (PFHpA)
Perfluorohexane Sulfonate (PFHxS)
Perfluorononanoic acid (PFNA)
Perfluorohexanoic acid (PFHxA)
Perfluorodecanoic acid (PFDA)
Perfluoroundecanoic acid (PFUdA)
N-methyl perfluorooctanesulfonamidoacetic acid (MeFOSAA)
Perfluorododecanoic acid (PFDoA)
N-ethyl perfluorooctanesulfonamidoacetic acid (EtFOSAA)
Perfluorotridecanoic acid (PRTrDA)
Perfluorotetradecanoic acid (PFTeDA)

Other Lab Analyses

- EPA 8328, for all matrices except DW, expected to be final 2020
  - Much like the 537M method that many labs are now using
- Fluoride analysis – can be used to:
  - Evaluate extent of bio or chem remediation that releases fluoride from PFAS
  - High detection limits of ~20 ug/L
- Total organic fluorine – an emerging technique in the US but commercially available in Australia – can be used to:
  - Screen sites for PFAS
  - Locate PFAS plumes
  - Estimate total mass of PFAS present
  - Verify remediation is complete
  - Reporting limits as low as ~1 ug/L, ~20 ug/kg

Credit: Eurofins

- Particle-induced gamma emissions analysis
  - Academic only (requires a costly photon accelerator)
  - Inexpensive soil and water analysis for total fluorine (organic and inorganic)

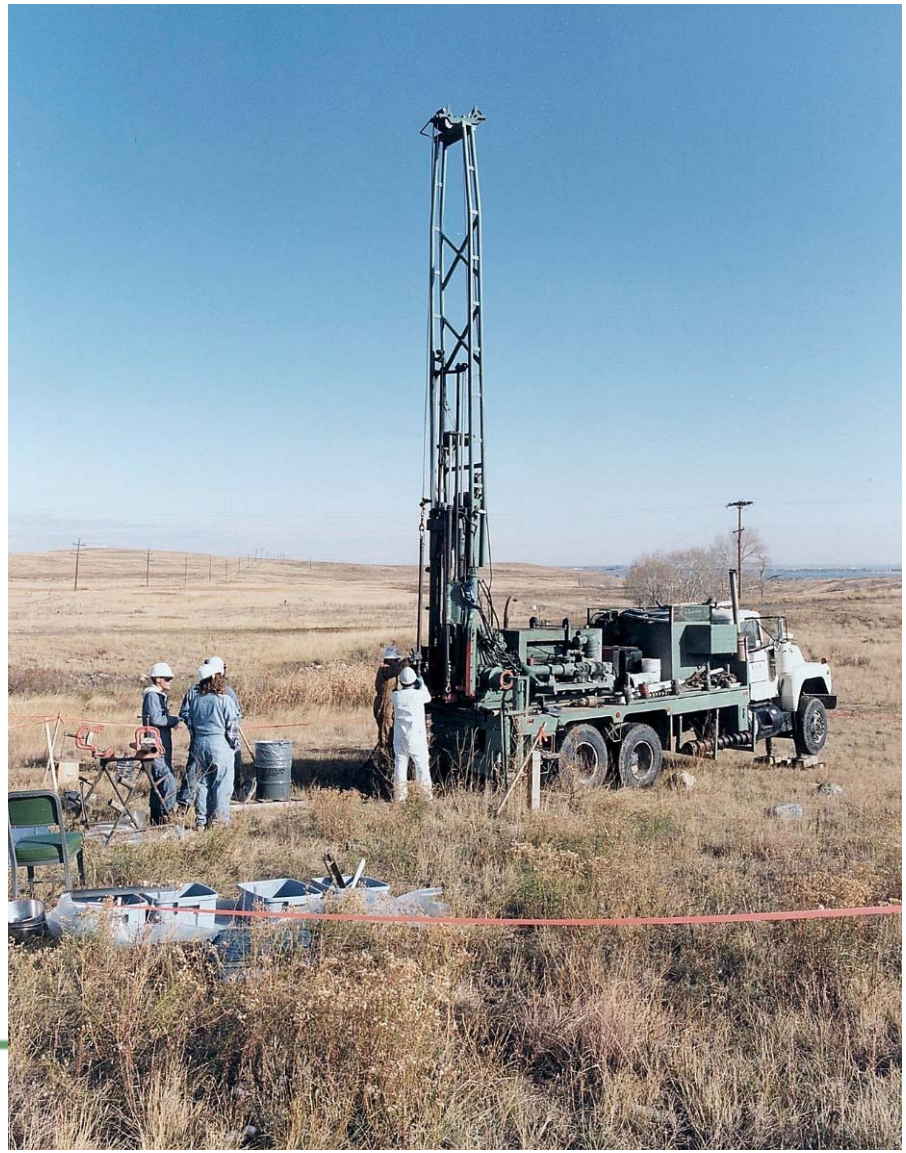
Transformation and Precursors

- Perfluorinateds don't naturally transform
- Oxidizable polyfluorinateds ("precursors") should eventually transform to perfluorinateds
  - Biotically or abiotically cleave at a carbon not fully fluorinated
- Total Oxidizable Precursors (TOP) analysis quantifies the total mass of precursors present
  1. Analyze sample by Method 537 Modified
  2. Oxidize the sample
  3. Analyze again by Method 537 Modified

  The difference indicates the mass of precursors in sample

Site Management Strategy

- Protect receptors from immediate exposure
- Complete site assessment to ID
  - All sources
  - All contaminants of concern
  - All pathways
  - Full nature and extent
- Control Source Area
- Remediate dissolved plume
- Monitored natural attenuation



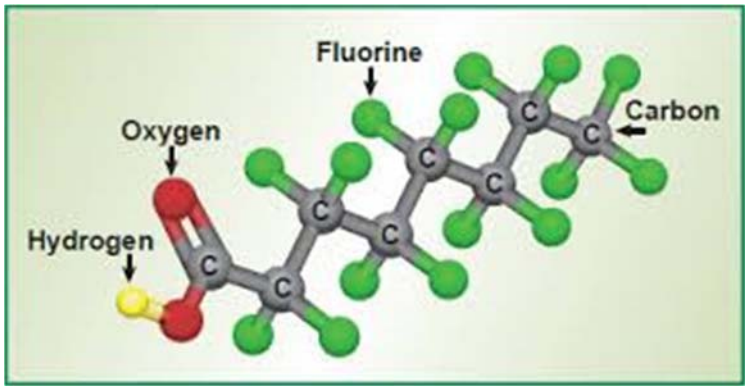
Credit: US Department of Energy

PFAS
Fate and Transport Mechanisms

PFAS Fate and Transport

- F&T of PFAS includes mechanisms not typically considered for other common contaminants (e.g., benzene)
  - $K_d = f_{oc} \times K_{oc}$ - is common retardation consideration for non-PFAS
- Perfluorinated compound properties (e.g. PFOA)
  - Surfactant
  - Charged head = potential for ion exchange (IX)
    - Pers typically negatively charged
    - Poly's can be anionic, cationic or zwitterionic
  - Uncharged body

PFOA



NIEHS – National Institutes of Health

PFAS Fate and Transport

- Mechanisms for attenuation / retardation of PFAS are more complex
  - Volatilization – minor, except for certain precursors
  - Interfacial influences – enrichment at interface – reduces surface tension
    - Air-water interface
    - NAPL-water interface
    - Smaller C # PFAS not as affected
    - Can dominate vadose zone transport / retardation

PFAS Fate and Transport

- Mechanisms for retardation of PFAS are more complex (contd.)
  - Partitioning into bulk NAPLs (e.g. petroleum)
    - Especially for FTOH's
  - Solid-phase adsorption
    - Partitioning onto organic matter
    - Electrostatic adsorption on aquifer materials
      - Charged head interacts with charges on mineral surfaces
      - Lower pH and higher clay mineral content (with pH dependency on surface charge) can increase adsorption

PFAS Fate and Transport

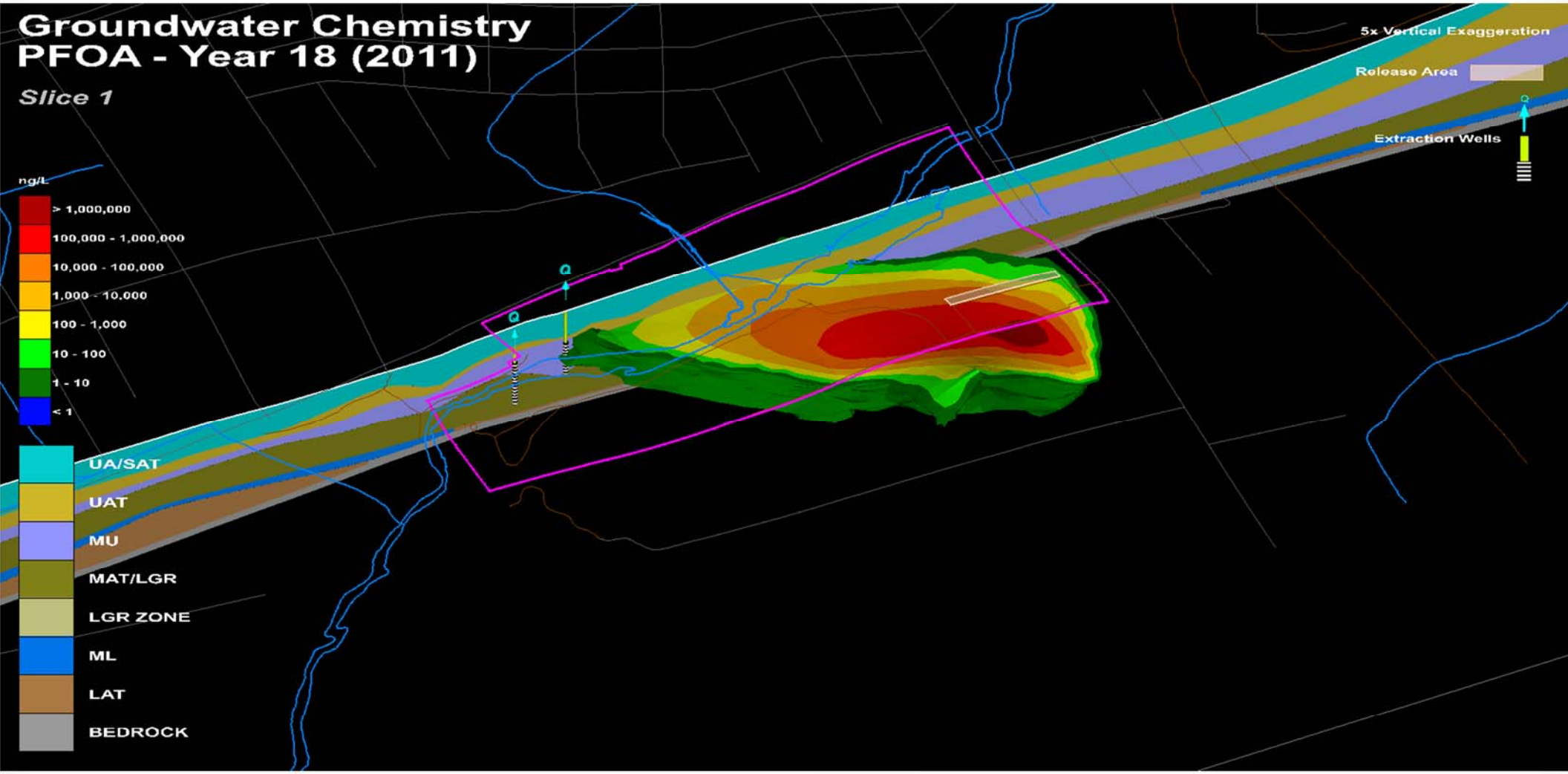
- Mechanisms for retardation of PFAS are more complex (contd.)
  - Transformation of precursors into Perfluorinated can occur
- Combined retardation mechanisms for PFAS can be significantly greater than traditional solid-phase adsorption alone
- Common to consider site-specific treatability to estimate F&T
- PFAS NAPL's may exist at some sites??

PFAS Hydrogeological Modelling

- Remediation of sand and gravel drinking water aquifer in North America has been on-going for over 25 years
- Organic chemicals in groundwater caused by historical waste management practices at a chemical manufacturing site
- PFAS foam materials release occurred in the northeast corner of the site
- 3-D groundwater flow and transport model developed for the site was used to simulate PFAS migration

PFAS Hydrogeological Modelling

- Model results show that PFAS largely migrates in groundwater within more permeable units, similar to organic contaminants, which were the focus of a on- and off-site groundwater remediation system
- The model predictions show that the on-site containment system prevents off-site PFAS migration
- Additional model validation and monitoring evaluations will be conducted to confirm the model predictions and evaluate the effectiveness of the remediation technologies in use for aquifer cleanup



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Question

Which one of the following statements is false:

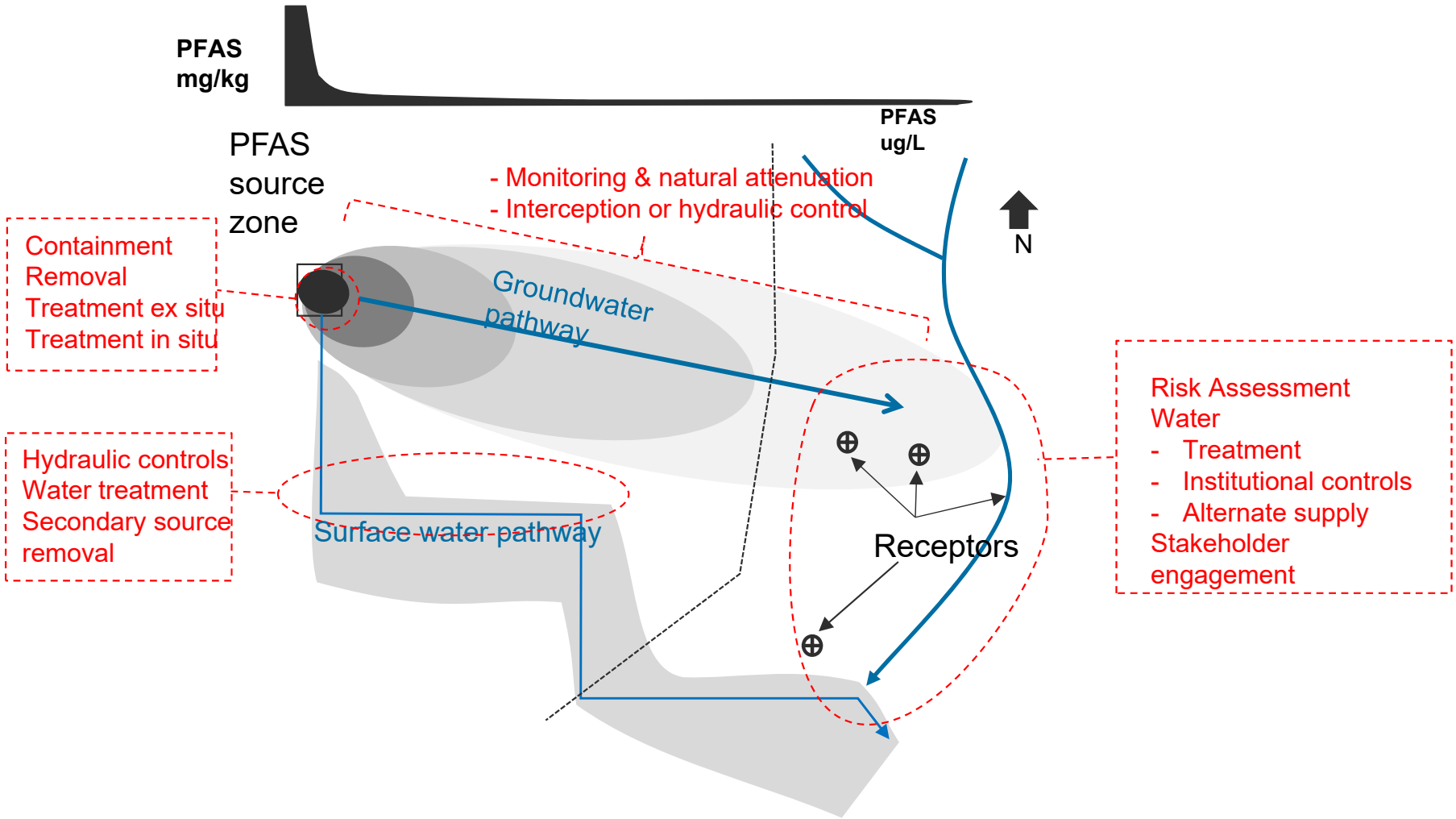
1. PFAS are not very volatile
2. PFAS can be positively or negatively charged or net neutral
3. Retardation can be reliably estimated by: $K_d = f_{oc} \times K_{oc}$
4. Perfluoroalkyl chemicals are more stable than polyfluoroalkyl chemicals

Global State of PFAS Remediation Practice

Global State of PFAS Remediation Practice

- ❑ Whole Site View
- ❑ Remedial Trends
- ❑ Risk Assessment
- ❑ Fingerprinting
- ❑ US Issues

Whole Site View



Remedial Trends

- Risk Management
- Drinking Water Management/Treatment
- Source Removal/Incineration
- Containment/Mitigation
- Many Research Studies, Trials and Progress (e.g., in situ thermal, and soil washing)

Typical Risk Assessment Supporting Remediation

- Human Health
  - Unlikely adverse effects from drinking groundwater (29 years same source and for this specific site)
  - Potential effects to workers from soil, groundwater and surface water
  - Remediation and management, including:
    - Alternative water supply and/or treatment
    - Remove heavily impacted soils
    - Surface water diversion
    - Monitoring to determine if concentrations are stable, increasing, decreasing

Typical Eco Risk Assessment Supporting Remediation

- Ecological
  - Soil, groundwater, surface water, and biota, with bioaccumulation assessment by food web modeling
  - High potential for unacceptable risks (birds and mammals for this particular site) in highly impacted habitat areas (e.g., ponds)
  - Low potential from larger surface water bodies
  - Remediation and management, including:
    - Source removal and habitat management
    - Limit impacted surface water discharges
    - Monitoring to determine if concentrations are stable, increasing, decreasing
  - Fish advisories are conservative

US Issues

- State Litigation
  - Many states have sued manufacturers
  - Some settlements
- State Regulations
  - Increasing standards due to lack of EPA MCLs etc.
  - Trend to ban AFFF by state agencies
- Liability Avoidance/Delay
  - No sampling unless regulatory order
  - TSDF Acceptance
  - Not accepting waste
  - Requiring sampling/unrealistic varied criteria

Expect: Continued Conflicts/Uncertainty/ Litigation/State Led Actions/ Varied Treatment and Disposal Criteria

Treatment Cost Ramifications

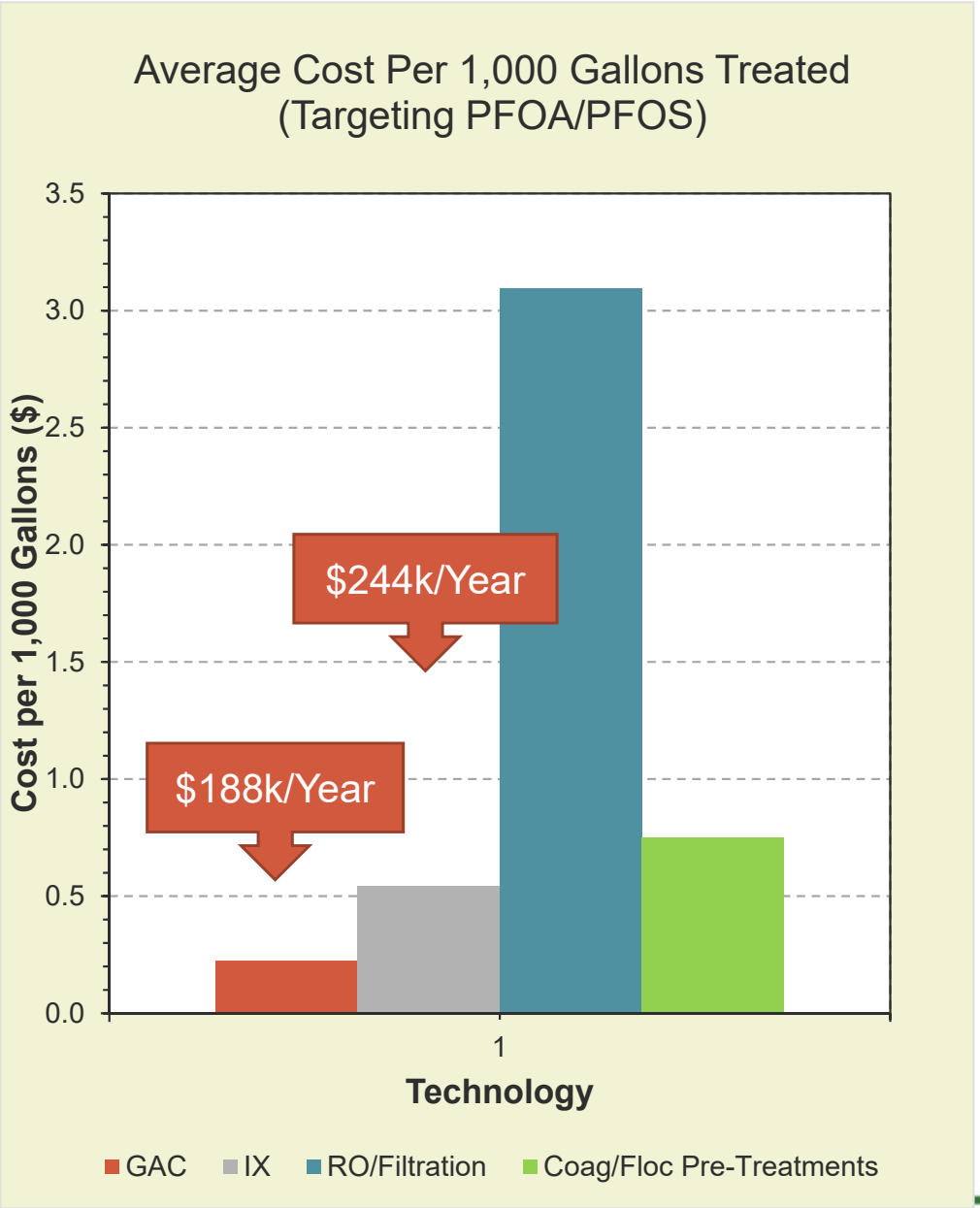
- Regulatory environment is fluid
- GAC may be working effectively for now….
- Matter of time before C = 4 PFAS regulated?
  - NHDES adopts strictest standards in U.S. (Sep-2019)
  - PFOA (C=8) – 12 ppt
    - PFOS (C=8) – 15 ppt
    - PFHxS (C=6) – 18 ppt
    - PFNA (C=9) – 11 ppt
  - More frequent GAC changeouts?

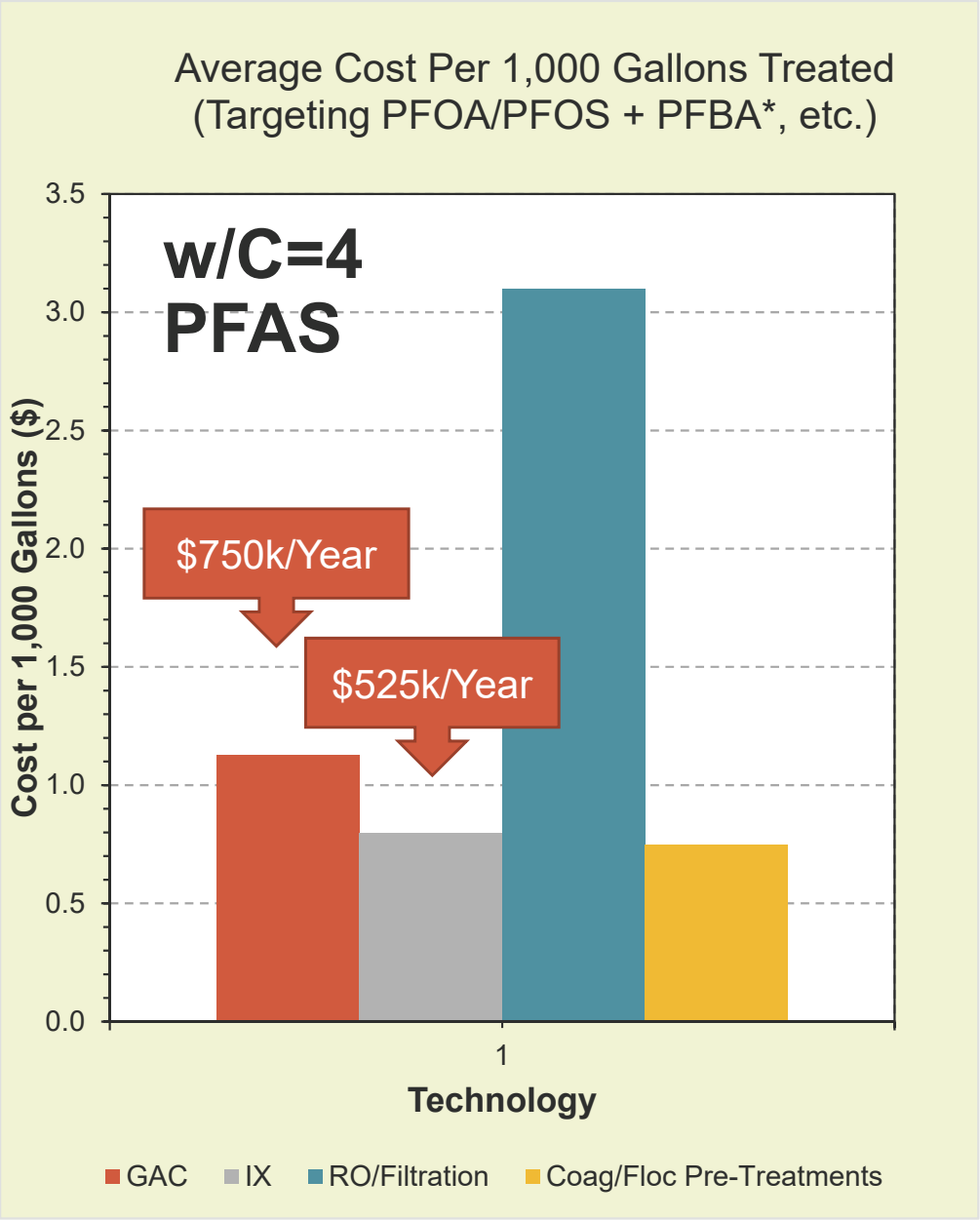
Impact of Breakthrough

- Industry Reports – PFOA/PFOS:
  - Coconut GAC has lower capacity (10,000 BV +/-)
  - Coal-Based (Re-agglomerated Bituminous GAC) longer life
    - 70,000 to over 150,000 BV reported for PFOA/PFOS
  - IX reportedly better (~5 to 10 times capacity – but verified?)
- Short Chain - PFBA/PFBS
  - GAC breaking through at <10,000 BV
  - IX working better for PFBS, but early break through with PFBA

May Need 5 to 10 times MORE GAC (or Resin) For C=4

Example System: 1 to 3 MGD Municipal





*Assumes up to 5-fold increase in GAC change-out rates due to PFBA breakthrough (may vary)
Cost ranges obtained from actual system costs and from available industry standard cost data

Question

What's the best PFAS disposal technology?

- ❑ Incineration
- ❑ Plasma
- ❑ Don't use them in the first place in high risk situations
- ❑ All of the above

PFAS Remedial Options

Topics Covered

- Non-Destructive Technologies
  - Adsorption
  - Ion-Exchange
  - Filtration
  - Isolation
- Destructive Technologies
  - Chemical
  - Thermal
  - Biological

Non-Destructive Technologies

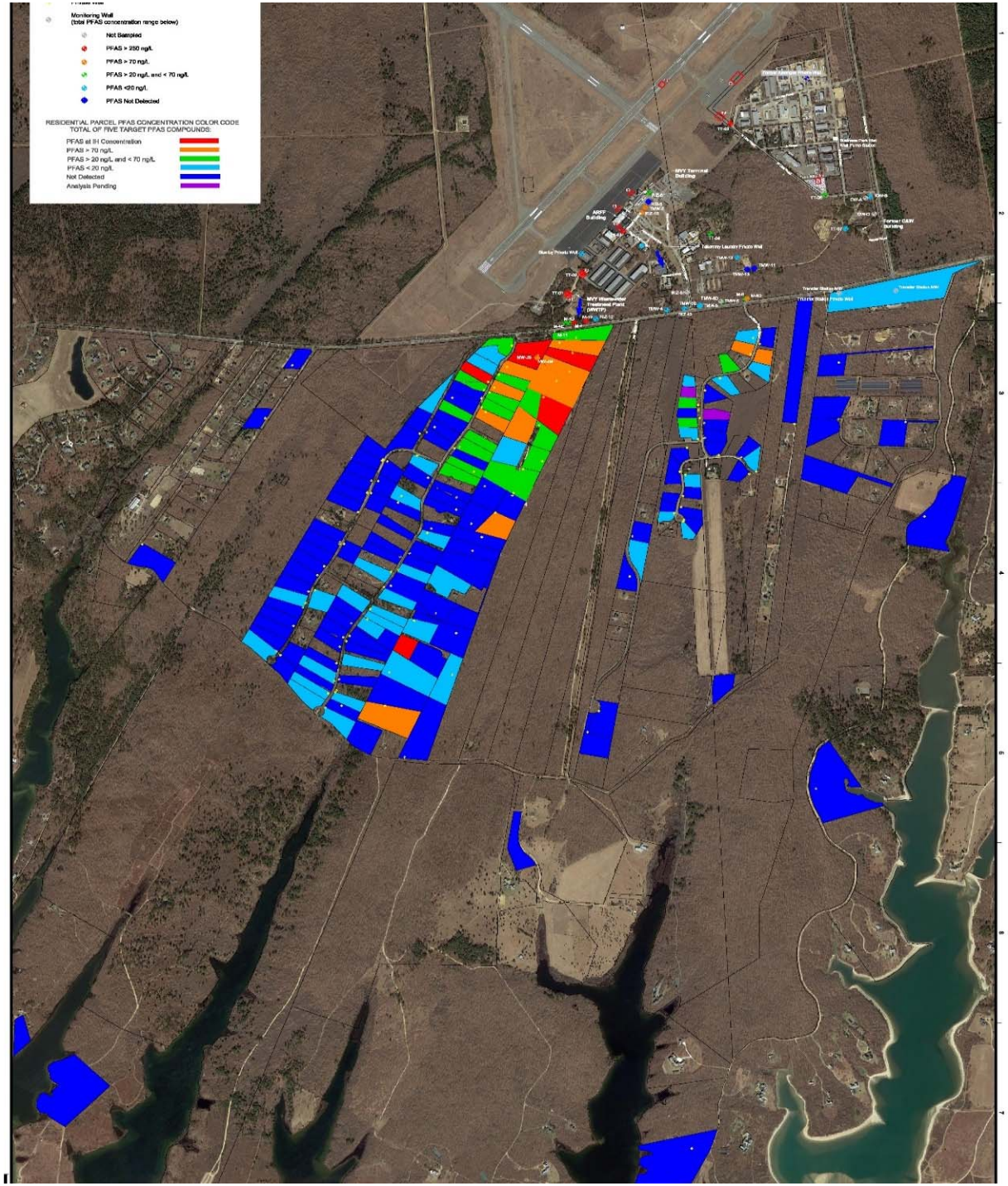
Most applicable for low concentration – high volume flows

Why???

Adsorption

- Most commonly used PFAS remediation technology
- Produces concentrated PFAS waste
- Carbon-based systems
  - Ex-situ activated carbon systems (GAC or PAC)
  - Biochar (form of charcoal) – less consistent and kinetically slower?
  - In-situ injectable carbon-based systems
  - Competition with organics for adsorption sites – influent may require pretreatment
- Clays or blend of sorbent-based systems
  - e.g., Rembind™, MatCARE™
  - Part isolation?

Treatability studies are needed



PFAS Impacts Downgradient of AFFF Area

- 200 homes sampled
- 40 point-of-entry-treatment (POET) systems installed

Courtesy of Tetra Tech, Inc.

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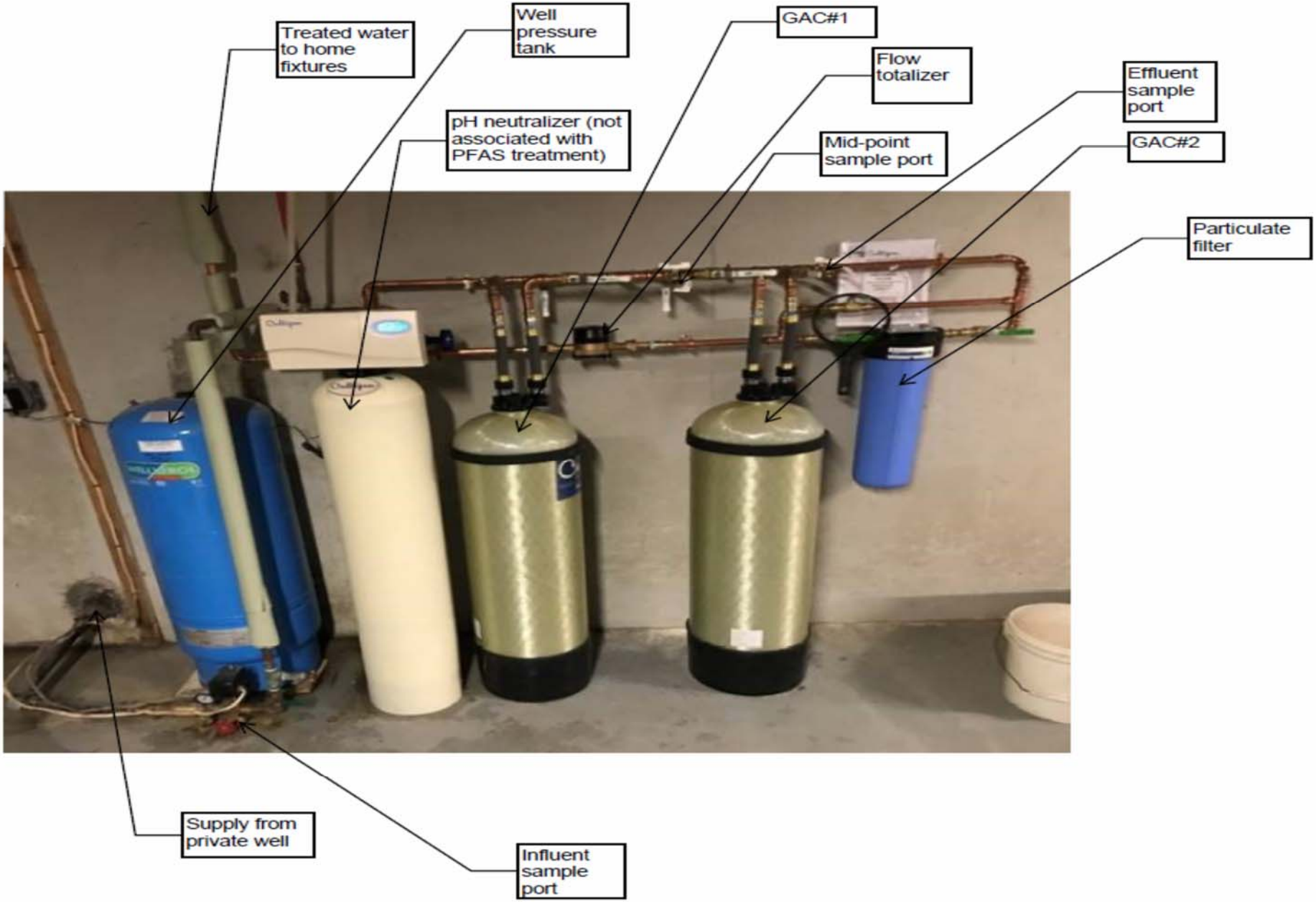

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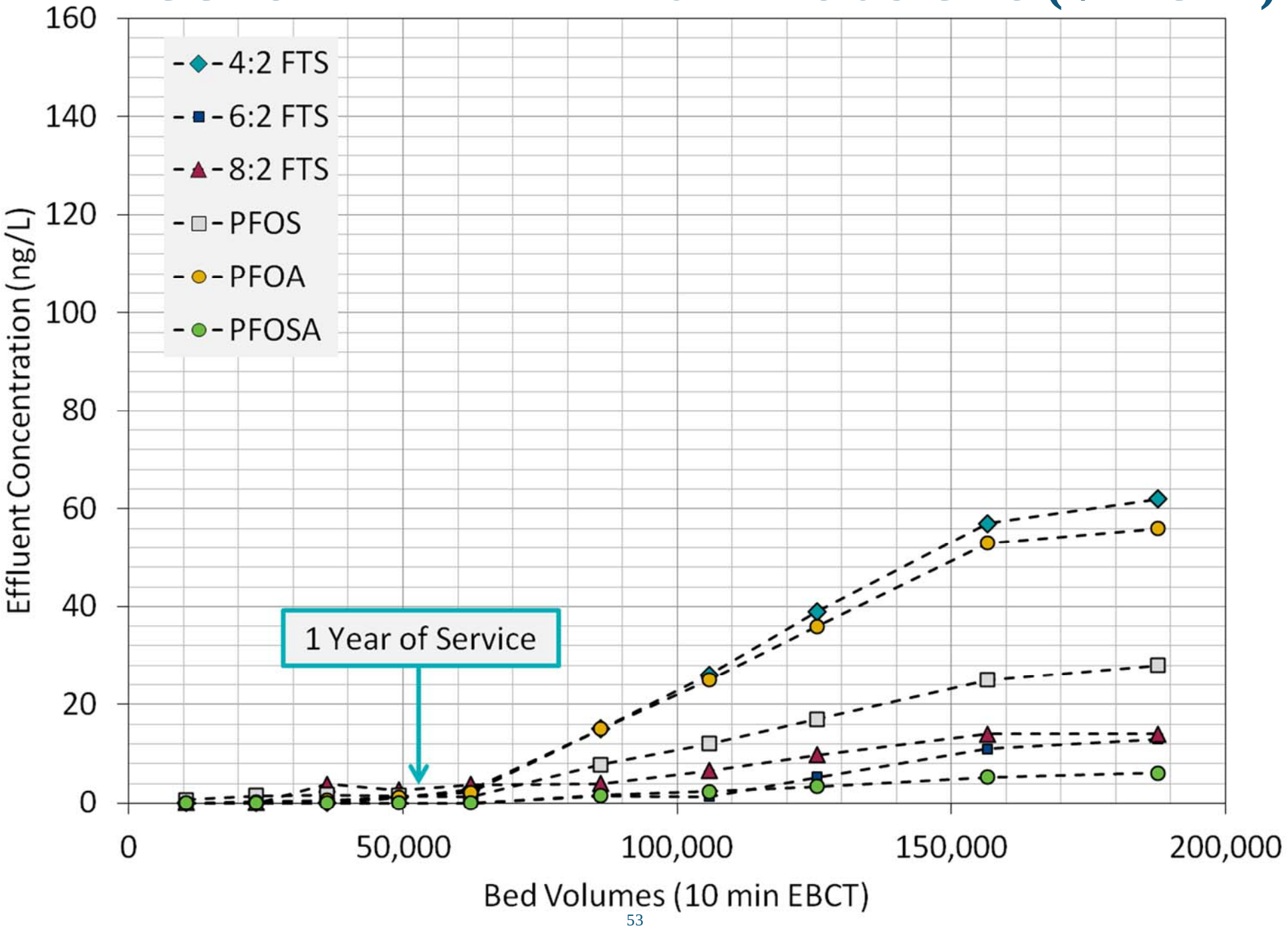
GAC COMPARISON
TEST CONDITIONS

OPERATING PARAMETERS

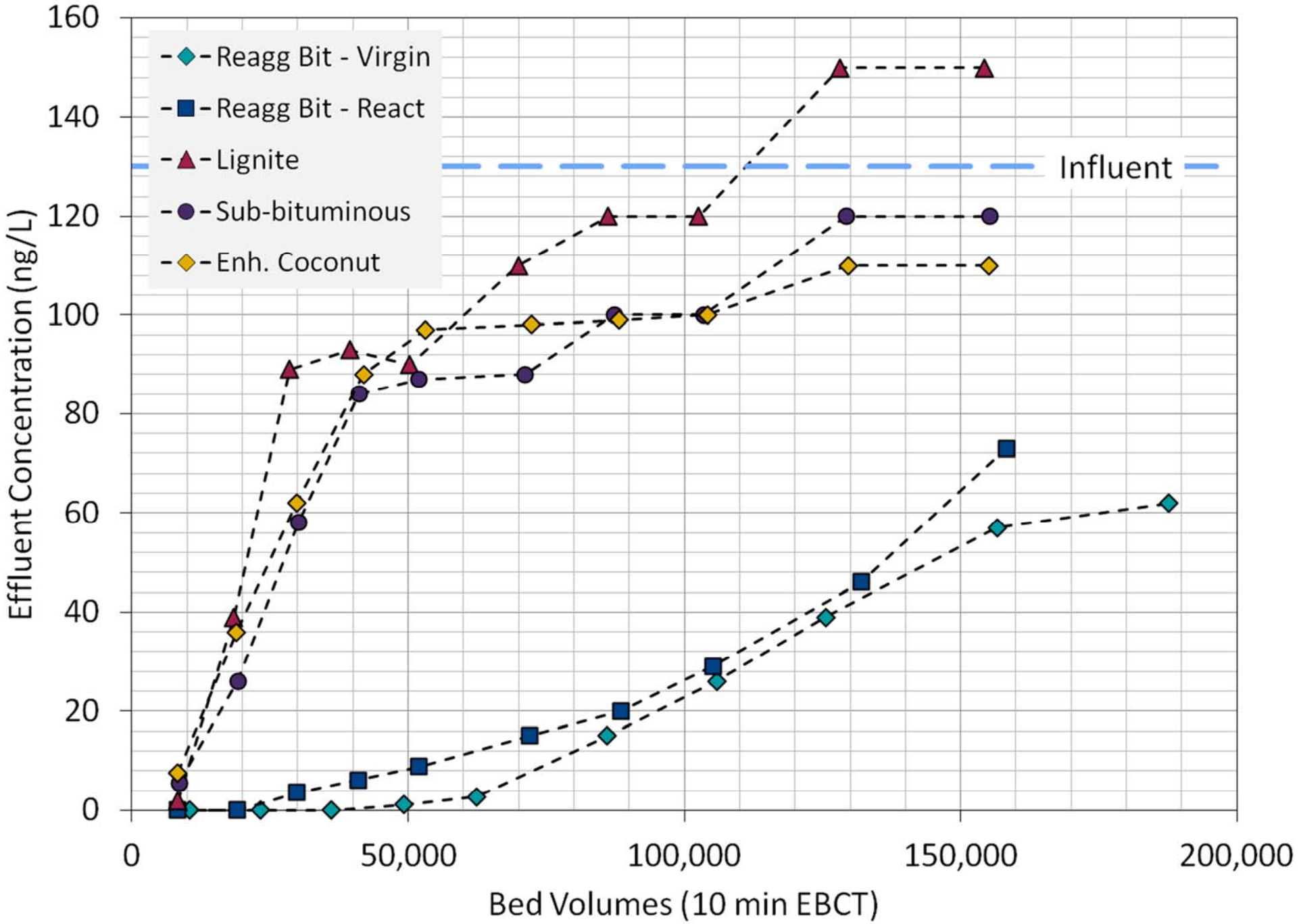
- 10 minutes empty-bed contact time (EBCT)
- Pennsylvania groundwater spike with PFAS

Compound	Abbreviation	Avg. Influent Concentration (ng/L)
4:2 Fluorotelomer Sulfonic Acid	4:2 FTS	130
6:2 Fluorotelomer Sulfonic Acid	6:2 FTS	43
8:2 Fluorotelomer Sulfonic Acid	8:2 FTS	56
Perflurooctanesulfonic Acid	PFOS	153
Perflurooctanoic Acid	PFOA	177
Perflurooctane Sulfonamide	PFOSA	39

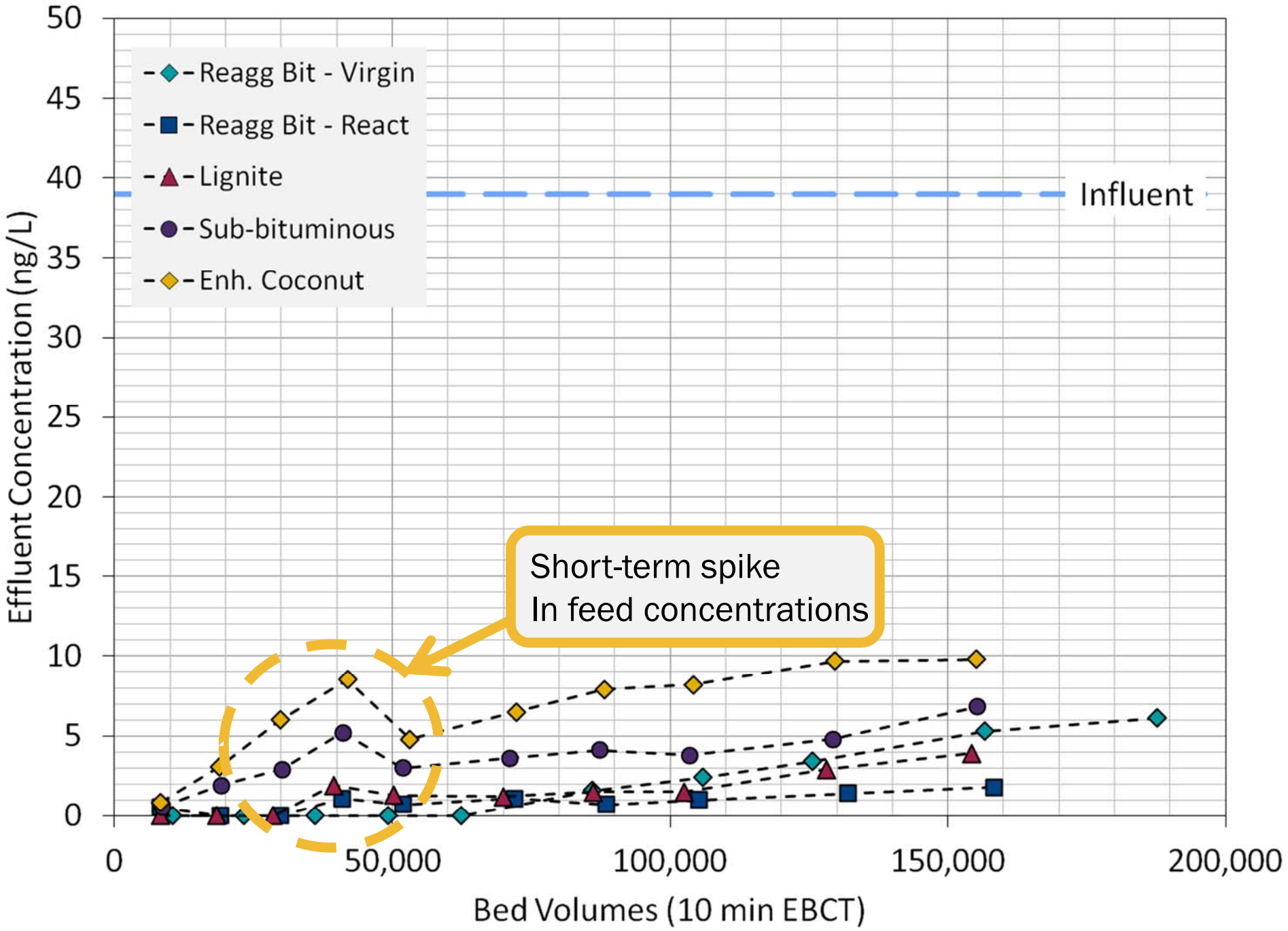
PFAS BREAKTHROUGH CURVES REAGGLOMERATED BITUMINOUS GAC (VIRGIN)



PFAS BREAKTHROUGH CURVES
4:2 FTS



PFAS BREAKTHROUGH CURVES
PFOSA



In-Situ Injectable Carbon-Based Systems

PLUME STOP Liquid Activated Carbon – what is it?

- A highly dispersive, injectable adsorbent and microbial growth matrix, for biodegradable contaminants

- Colloidal activated carbon (1 – 2 µm)
  - Size of a bacterium – suspends as 'liquid'
  - Huge surface area – extremely fast adsorption

- Proprietary anti-clumping / distribution supporting surface treatment (patent applied for)
  - Enables wide-area, low-pressure distribution through the soil matrix without clogging

Courtesy Regenesis

Longevity?

- PLUME STOP Liquid Activated Carbon loading can be designed, based on non-destruction of PFAS, to theoretically provide long-term control

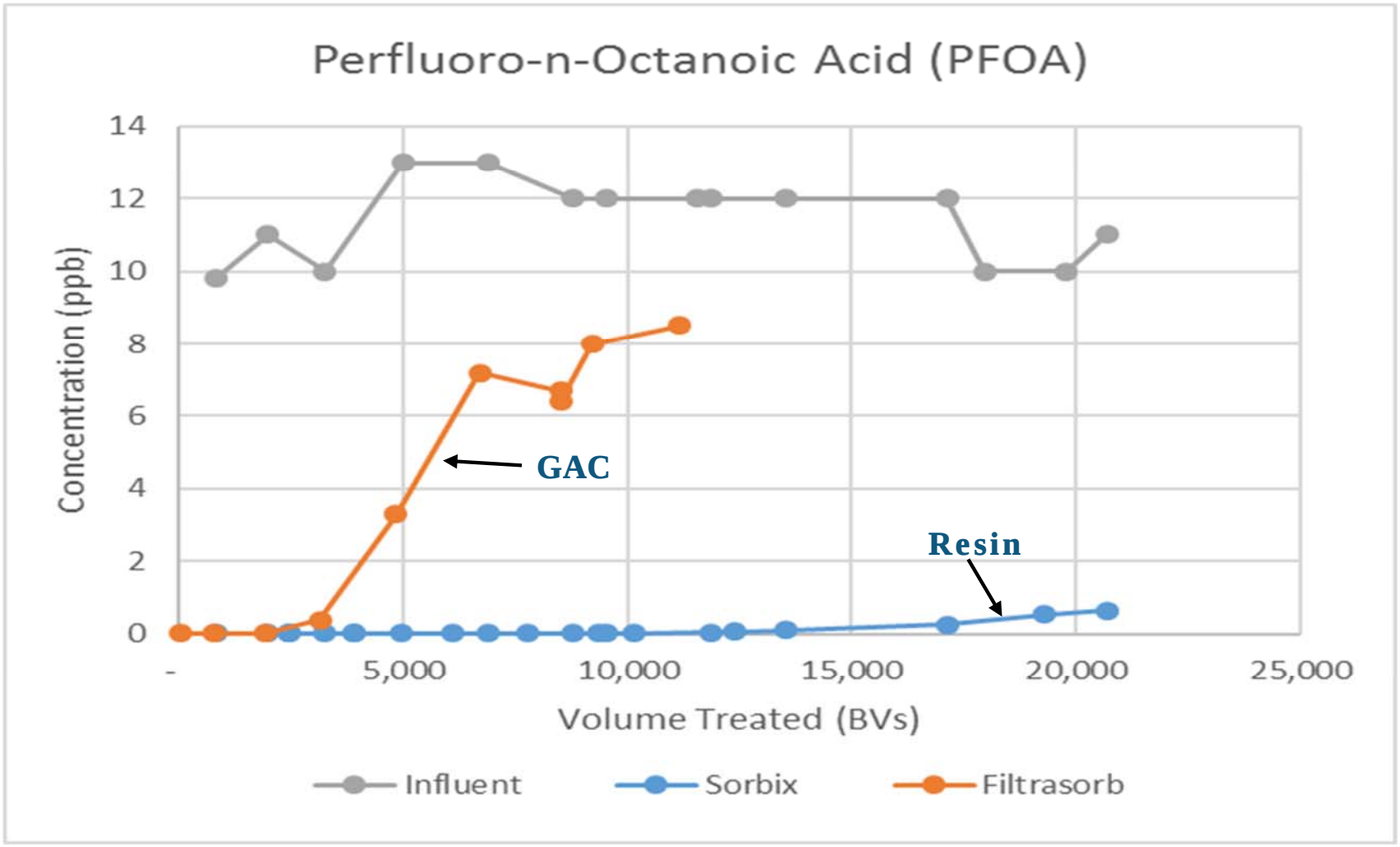
- A few questions to consider
  - Will carbon adsorptive capacity degrade and bleed PFAS?
  - Will competition for adsorption sites occur and release PFAS?
  - Will geochemical changes occur to affect adsorption?
  - Will all PFAS to adsorbed?

Adsorption/Ion Exchange

- Synthetics resins – gaining traction due to capacity/effectiveness
  - Combination IX and adsorption
  - Produces concentrated PFAS waste
  - Faster kinetics and higher capacities = smaller reactor size
  - Higher product cost – requires site-specific cost-benefit analysis
  - Ongoing work on single use IX and shorter chain PFAS adsorption

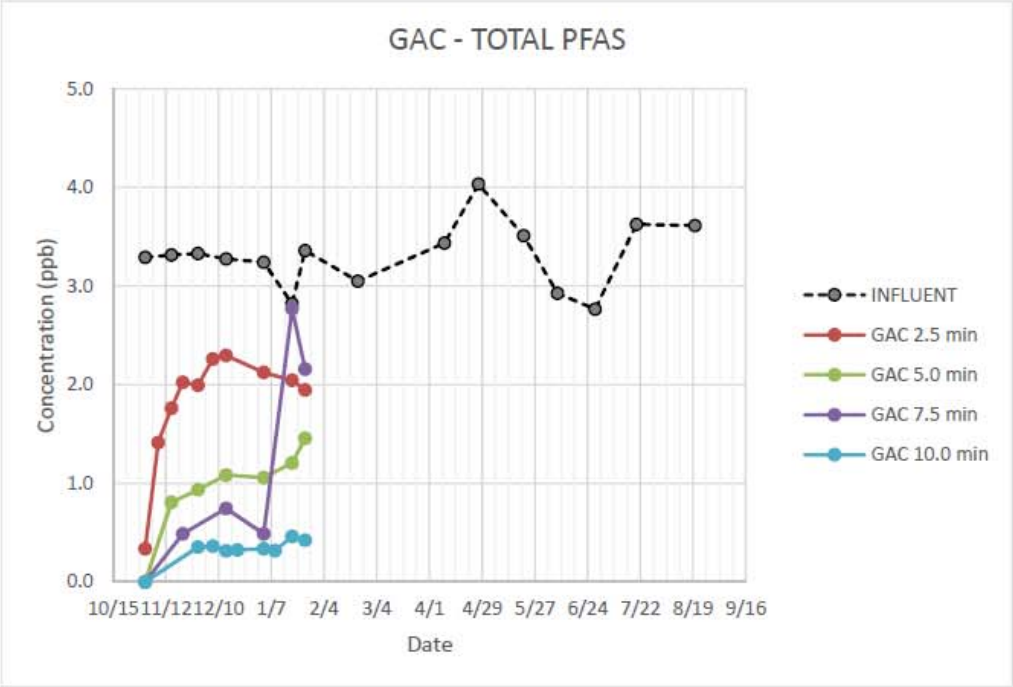
Treatability studies are needed

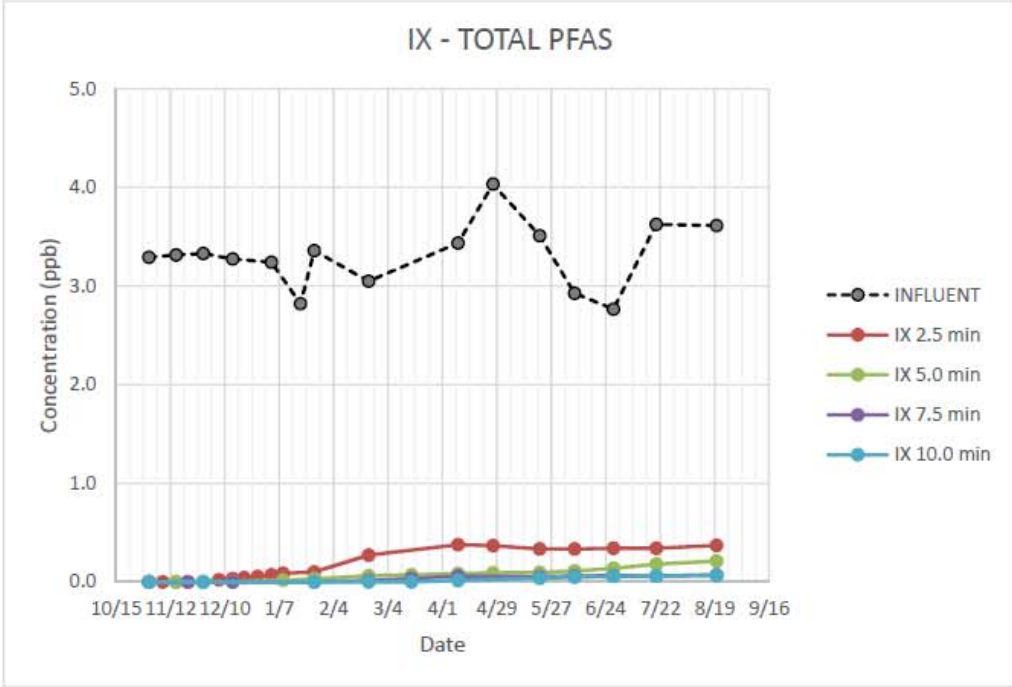
PFOA Breakthrough at 5-min EBCT



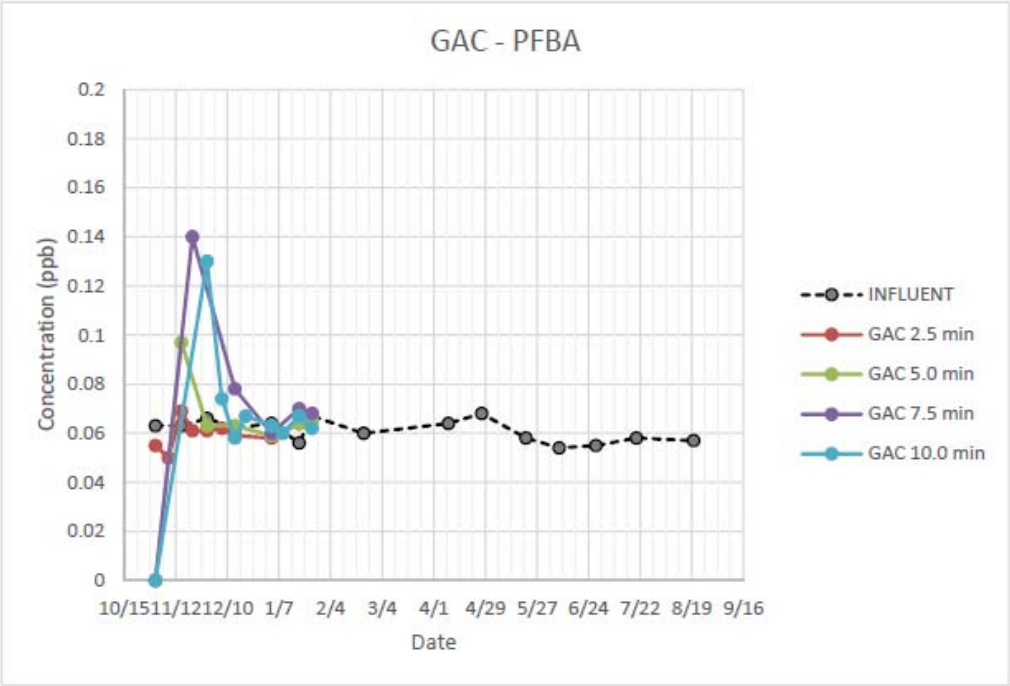
BV = bed volumes EBCT = empty bed contact time

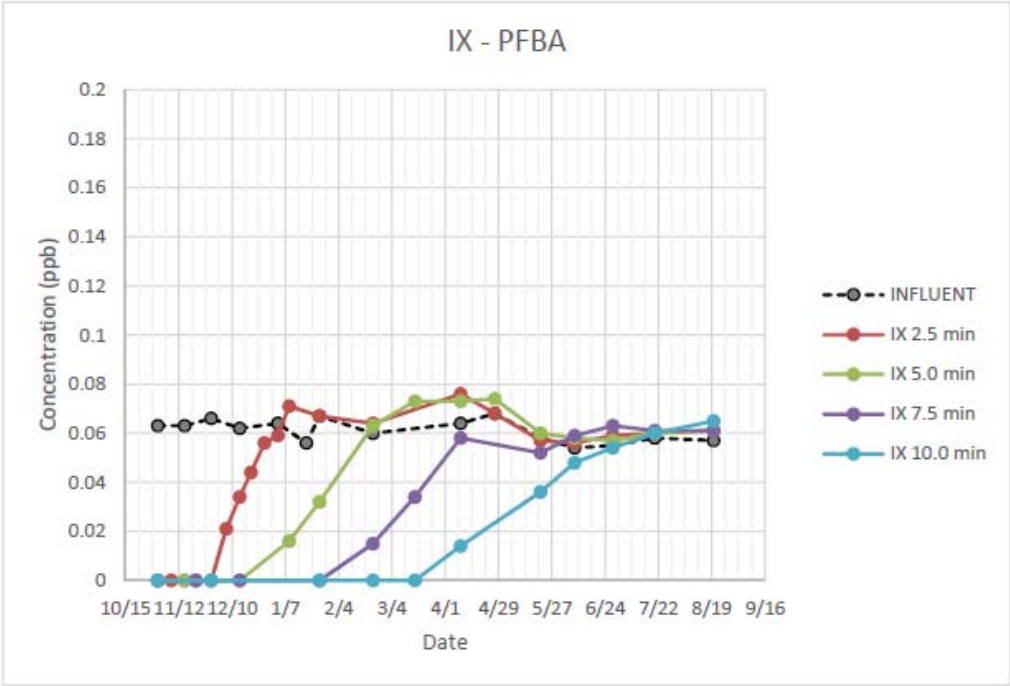
GAC and IX Removal Comparison
(Total Analyzable PFAS)





GAC and IX Removal Comparison
(Short chain removal comparison – PFBA)





Adsorption/Ion Exchange

- Other natural materials (mainly R&D)
  - Modified natural mined materials
    - Surface charge
    - Surface area
  - Produces concentrated PFAS waste
  - Additional R&D will be discussed by Fred later

Treatability studies are needed

Filtration

- Nanofiltration (NF)
  - Ultra- and microfiltration low effectiveness
- Reverse Osmosis
  - >90% effective most PFAS
- Pretreatment maybe needed due to potential for filter clogging
- Treatment trains may be needed to achieve ppt levels cost-effectively (dependent on influent PFAS concentration)
- Produces concentrated PFAS waste

Filtration

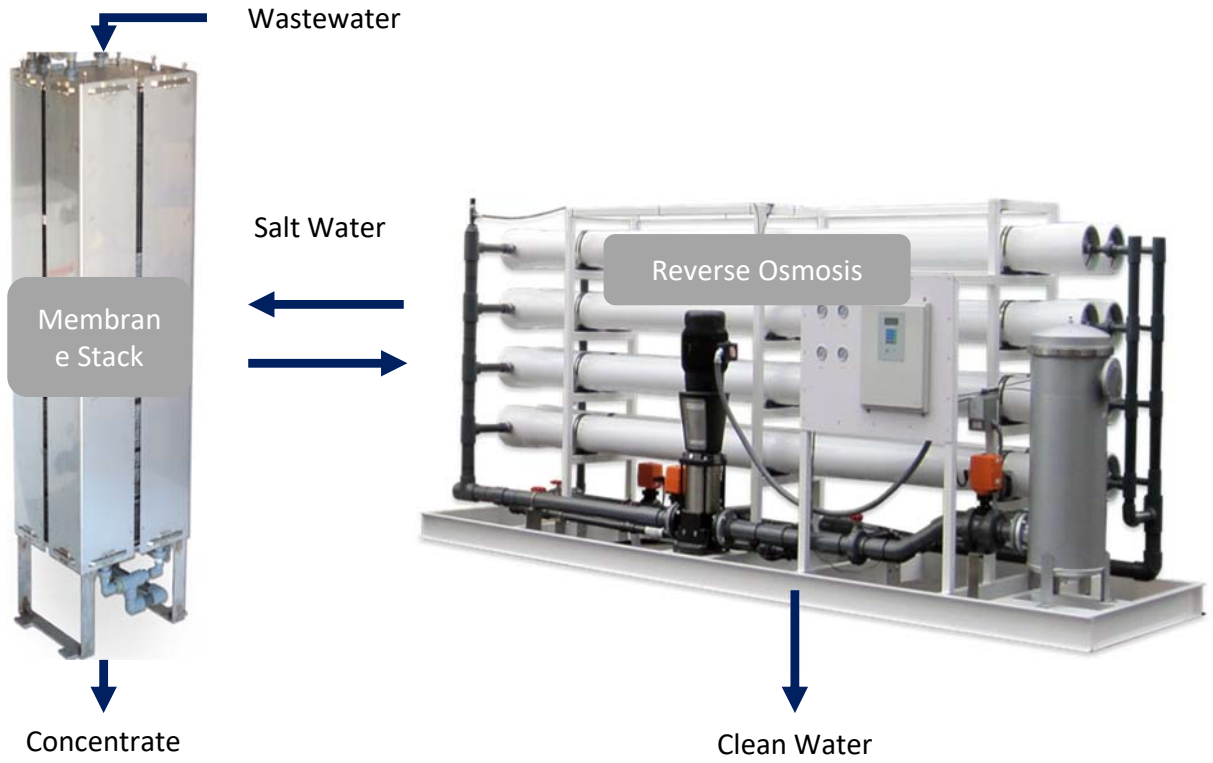
- NF or RO Pretreatment
  - PerfluorAd – not really filtration but coagulation - flocculation
    - Electro-coagulation as alternate
  - Ozofractionation – separation on ozone / air microbubbles (as foam) due to PFAS surfactant properties
    - Ozone may treat co-contaminants and transform Poly's to Per's
- Produces concentrated PFAS waste

Treatability studies are needed

XDD ENVIRONMENTAL
Do it right. Do it once.

Digested Organics Two-Step Reverse Osmosis™

- Patented high-flux and low-fouling Forward Osmosis membrane
- Reverse Osmosis system
- Automated controls
- 3-4 year expected membrane life



Ideal for: **Brewery Wastewater, Ultrafiltered Manure, Leachates, Low-TSS Wastewaters**

Landfill Leachate PFOA and PFOS Removal with TSRO

Parameter	Leachate	TSRO Permeate	% Removal
Total solids (mg/L)	10,500	1,170	89%
BOD (mg/L)	N/A	<9	N/A
Total Kjeldahl Nitrogen (mg/L)	963	22	98%
Ammoniacal Nitrogen (mg/L)	928	21	98%
Organic nitrogen (mg/L)	35	1.3	96%
Phosphorus (mg/L)	4.8	0.10	98%
Potassium (mg/L)	551	7.5	99%
Sulfur (mg/L)	1,350	<0.5	100%
Calcium (mg/L)	79	0.22	99.7%
Magnesium (mg/L)	138	<0.1	100%
Sodium (mg/L)	2,120	468	78%
Iron (mg/L)	7	0.06	99%
Manganese (mg/L)	0.12	<0.005	100%
Zinc (mg/L)	0.10	<0.01	100%
Copper (mg/L)	0.08	<0.01	100%
Conductivity (mS/cm)	17	2.72	84%
pH S.U.	6.55	5.69	N/A
PFOA + PFOS (ppt)	**1,612**	**<2.0**	**100%**

PFAS Removal
GAC vs. IX vs. RO

Issues to Consider

EPA is evaluating these issues to document where and when they will be an issue

Granular Activated Carbon (GAC)	**GAC run time for short-chained PFAS (shorter run time)** **Potential overshoot of poor adsorbing PFAS if not designed correctly** **Reactivation/removal frequency** Disposal or reactivation of spent carbon
Anion Exchange Resin (PFAS selective)	**Run time for select PFAS (shorter run time)** **Overshoot of poor adsorbing PFAS if not designed correctly** Unclear secondary benefits Disposal of resin
High Pressure Membranes	**Capital and operations costs** Membrane fouling Corrosion control Lack of options for concentrate stream treatment or disposal

70

CalgonCarbon
A Kuraray Company

Destructive Technologies

Most applicable for high concentration – low volume flows

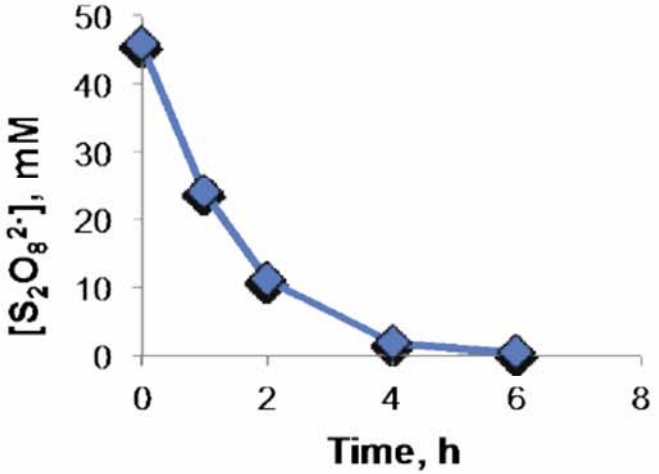
Oxidative / reductive technologies – redox manipulation

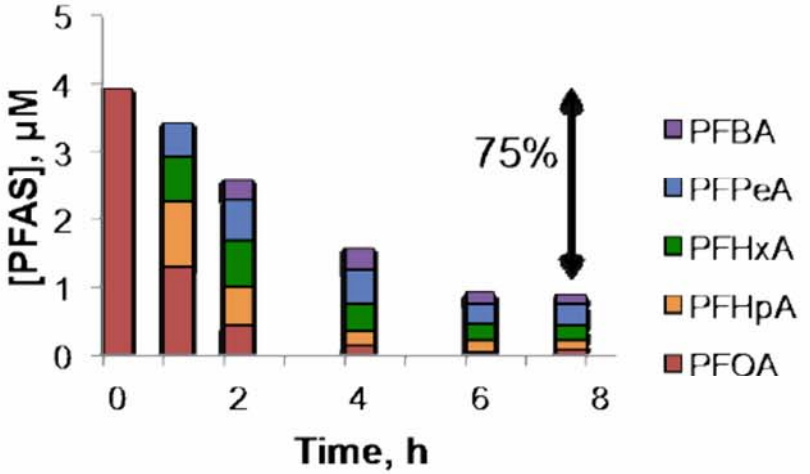
- Showing promise, but many unanswered questions
- Can treat many of the co-contaminants
- Common theme is high energy and/or diverse reactive species needed and significant reaction time (e.g., electrochemical, plasma, photolysis)
  - UV photolysis generates aquated / hydrated electron with potential = 2.9V
  - Electrochemical using Boron Doped Diamond Electrode some success with PFAS, but not fully with sulfonates
    - Other effective mixed metal electrodes are being evaluated e.g. titanium suboxides Ti_4O_7
  - Zero valent iron (ZVI) at high temperature and pressure or with catalyst has some success with PFOS

<u>Treatability studies are needed</u>

Heat-Activated Persulfate on PFOA

PFOA in Deionized Water





Conditions:

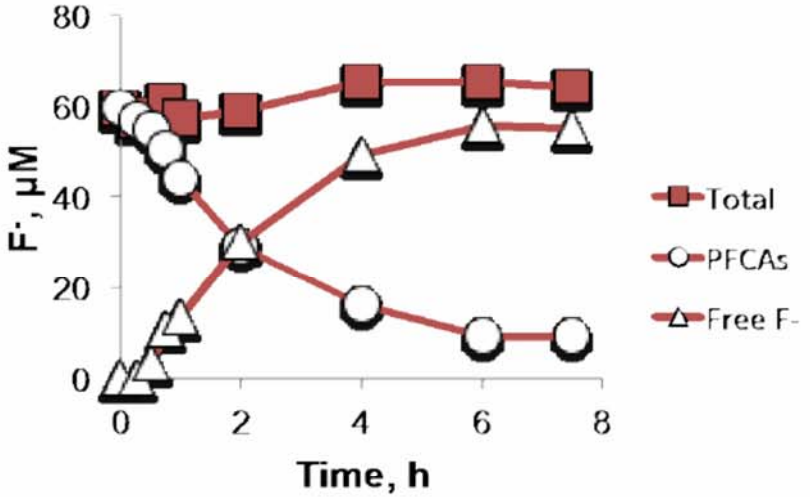
$[S_2O_8^{2-}]_0$ = 50 mM,

$[PFOA]_0$ = 4 µM

unbuffered (pH < 3) H_2O,

T = 85° C

Bruton and Sedlak, in review



SERDP recent focus / R&D on PFAS Investigation–Derived Wastes

(not complete set below)

- Treatment Train
  - Physical adsorption, advanced oxidation, and reductive defluorination
  - AOP, Hydrated / aquated electron defluorination, membrane-based concentration
- Electrochemical - numerous processes and electrode materials
  - Combined photo/electrochemical reduction
- Thermal
  - Using calcium hydroxide amendments to lower energy use
  - Thermal desorption coupled with Indirect Thermal Desorption/Thermal Oxidation
  - Smoldering combustion
- Other oxidation / reduction processes (Plasma, AOP - ARP – see later case study)
- Nanoscale Technologies

<u>Treatability studies are needed</u>

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Do it right. Do it once.

Biodegradation

- Evidence of transformations of Polys via natural and enhanced processes
  - Typical byproduct is Per's
  - Levels of fluoride in many groundwaters up to low mg/L levels
- Very limited research to date showing biodegradation of Pers
  - Recent R&D suggested *Acidimicrobium A6* achieved 60% reduction in PFOA and PFOS over 100-day incubation, requires iron and acidic soil conditions
  - Observations of reductive pathways (thermodynamically favorable) with formation of lower C Pers
- PFAS range of applicability may be limited
- Question on whether can treat to the proposed standards
  - Polishing needed?

Other Destructive Technologies
(less sensitive to PFAS type)

- Thermal destruction
  - ~1100°C
- Plasma
  - Plasma is reactive ionized gas
- Sonolysis
  - Ultrasonic waves (can produce cavitation – bubble surface can reach several thousand oK and high pressures – hundreds of atmospheres)
  - Also can form free radicals (e.g., $OH^{\cdot}$)

Treatability studies are needed

Thermal Treatment Options

Facilities in New England

First 3 below – 2-stage thermal desorption followed by thermal destruction of PFAS vapors

- ❑ **Clean Earth Loudon (ESMI NH)**
- ❑ **Clean Earth Fort Edward (ESMI NY)**
- ❑ **Clean Earth Plainville (CT)**
- ❑ **Clean Earth Mobile Services**
  - ➢ On Site Low Temperature Thermal Desorption (LTTD) units

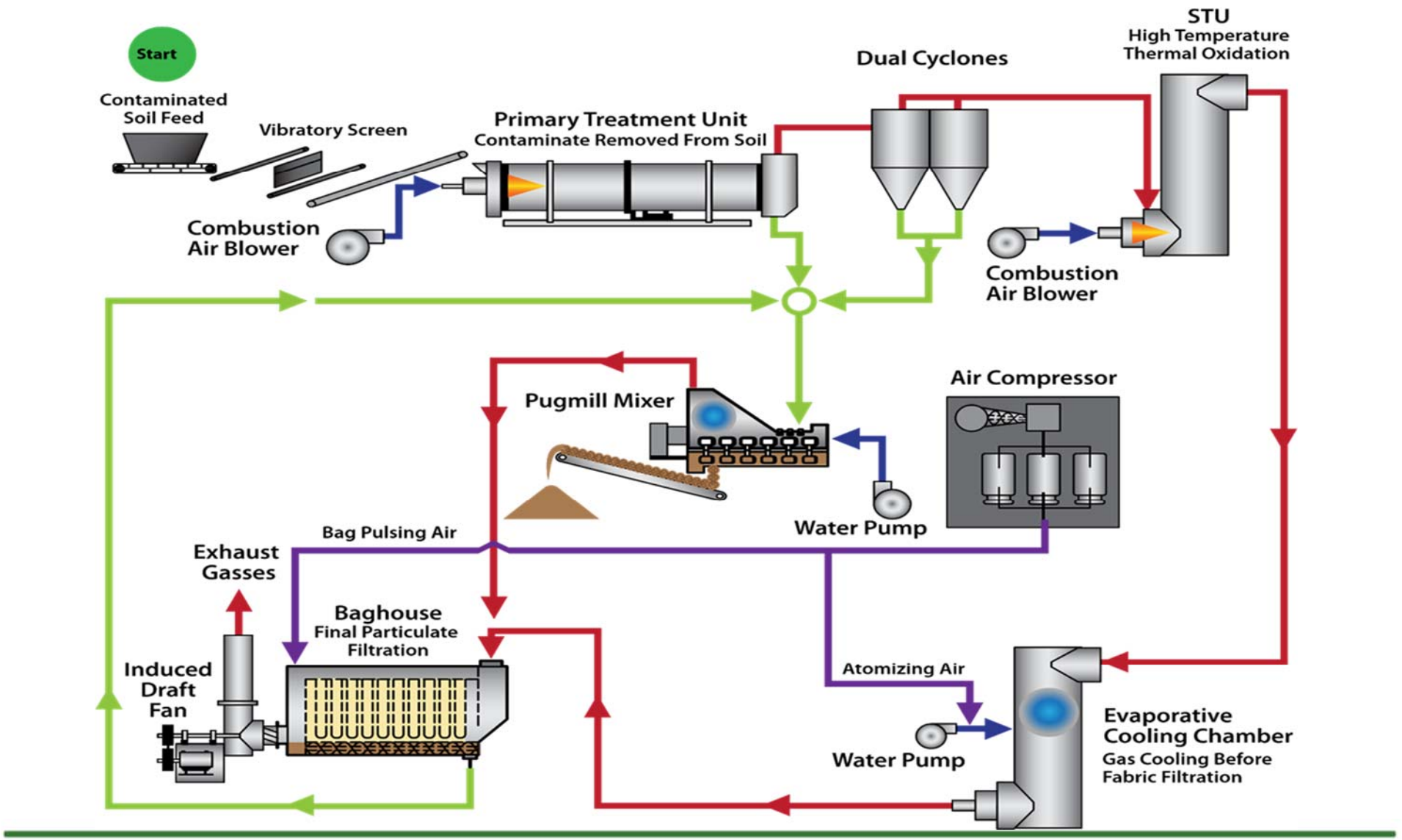
Thermal Treatment Operating Principles

- What is Low Temperature Thermal Desorption (LTTD)?
  - < 1,000 °F (>1,000 °F = incineration)

- Utilizes heat to physically separate contaminants from soil
  - Rotary Kiln (volatilization and steam stripping)
  - Volatilization (temperature ranges from 550-900 °F)

- Contaminants in gas stream are thermally oxidized
  - Thermal oxidation (range from 1,500-2250 °F)
  - Immediate quench of gas stream (to 420°F)
  - Bag house (particulate removal)
  - Effluent stack (CECT equipped with wet scrubber)

Thermal Treatment Process Diagram



Clean Earth Fort Edward Initial RD&D

PFAS Thermal Treatment Demonstration

- New York State Department of Environmental Conservation (NYSDEC) Led PFAS Treatment Test
- 22.6 Tons Treated in December 2018 & February 2019
- High Soil Organic Matter (SOM) at over 7%
- Primary Treatment Unit temperature 910-940 ^{o}F, Secondary Treatment Unit temperature 1800 ^{o}F
- Treatment Goal of 72 ppb for total of PFOA and PFOS
- **No stack testing due to small sample size**

Pre & Post Primary and Secondary Treatment for Total Mass (ug/kg)

Substance	Pre-Primary Treatment (ppb)	Post-Primary Treatment (ppb)	Post-Primary Removal Efficiency	Post-Secondary Treatment (ppb)	Post-Secondary Removal Efficiency
Perfluorobutanoic acid (PFBA)	0.42	ND	100%	ND	100%
Perfluoropentanoic acid (PFPeA)	0.63	ND	100%	ND	100%
Perfluorohexanoic acid (PFHxA)	0.70	ND	100%	ND	100%
Perfluoroheptanoic acid (PFHpA)	1.10	ND	100%	ND	100%
Perfluorooctanoic acid (PFOA)	**4.50**	**ND**	**100%**	**ND**	**100%**
Perfluorononanoic acid (PFNA)	2.90	ND	100%	ND	100%
Perfluorodecanoic acid (PFDA)	5.70	ND	100%	ND	100%
Perfluoroundecanoic acid (PFUnA)	3.00	ND	100%	ND	100%
Perfluorododecanoic acid (PFDoA)	2.20	ND	100%	ND	100%
Perfluorotridecanoic acid (PFTriA)	0.94	ND	100%	ND	100%
Perfluorotetradecanoic acid (PFTeA)	0.88	ND	100%	ND	100%
Perfluorobutanesulfonic acid (PFBS)	0.09	ND	100%	ND	100%
Perfluorohexanesulfonic acid (PFHxS)	0.24	0.05	78.1%	ND	100%
Perfluoroheptanesulfonic acid (PFHpS)	0.55	0.05	90.3%	ND	100%
Perfluorooctanesulfonic acid (PFOS)	**88.00**	**7.65**	**91.3%**	**ND**	**100%**
Perfluorononanesulfonic acid (PFNS)	0.04	ND	100%	ND	100%
Perfluorodecanesulfonic acid (PFDS)	0.13	ND	100%	ND	100%
Perfluorooctanesulfonamide (FOSA)	1.15	ND	100%	ND	100%
(NMeFOSAA)	3.35	ND	100%	ND	100%
(NEtFOSAA)	6.40	ND	100%	ND	100%
Total PFAS	**122.91**	**7.76**	**93.7%**	**ND**	**100%**

Pre & Post Primary and Secondary Treatment by SPLP (ng/kg)

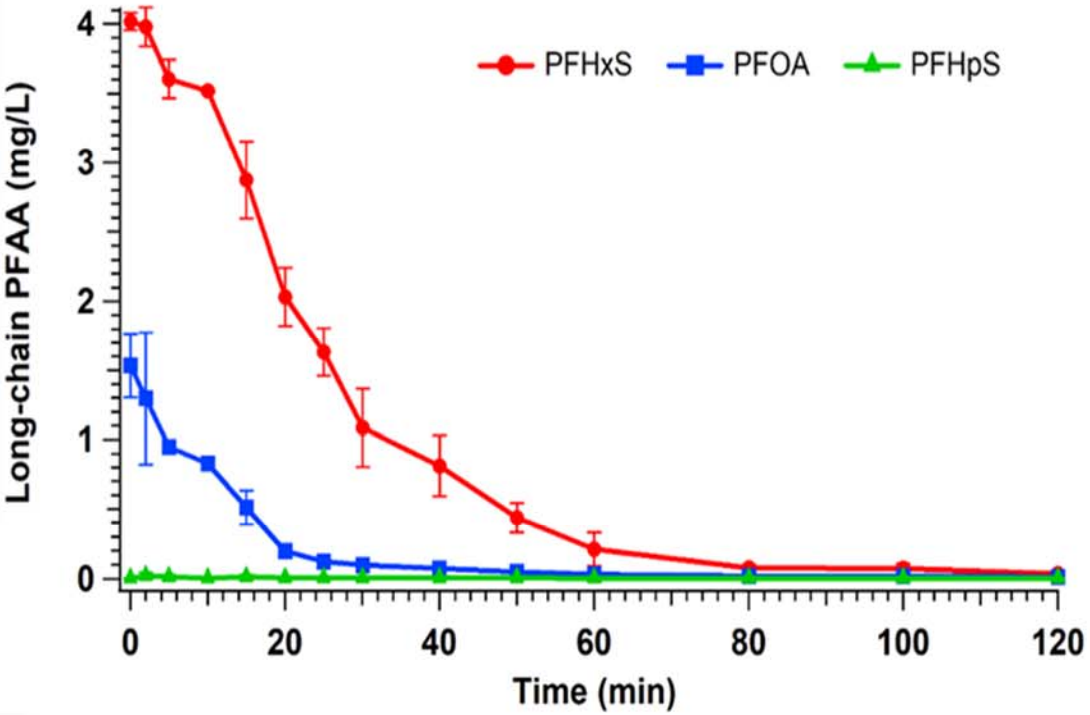
Substance	Pre-Primary Treatment (ppt)	Post-Primary Treatment (ppt)	Post-Primary Removal Efficiency	Post-Secondary Treatment (ppt)	Post-Secondary Removal Efficiency
Perfluorobutanoic acid (PFBA)	29.38	ND	100%	ND	100%
Perfluoropentanoic acid (PFPeA)	15.30	ND	100%	ND	100%
Perfluorohexanoic acid (PFHxA)	10.85	ND	100%	ND	100%
Perfluoroheptanoic acid (PFHpA)	14.50	ND	100%	ND	100%
Perfluorooctanoic acid (PFOA)	**109.50**	**0.44**	**99.6%**	**ND**	**100%**
Perfluorononanoic acid (PFNA)	68.00	ND	100%	ND	100%
Perfluorodecanoic acid (PFDA)	18.80	ND	100%	ND	100%
Perfluoroundecanoic acid (PFUnA)	1.40	ND	100%	ND	100%
Perfluorododecanoic acid (PFDoA)	0.65	ND	100%	ND	100%
Perfluorotridecanoic acid (PFTriA)	ND	ND	N/A	ND	N/A
Perfluorotetradecanoic acid (PFTeA)	0.57	ND	100%	ND	100%
Perfluorobutanesulfonic acid (PFBS)	ND	0.44	N/A	ND	N/A
Perfluorohexanesulfonic acid (PFHxS)	3.65	0.60	83.5%	ND	100%
Perfluoroheptanesulfonic acid (PFHpS)	7.28	0.47	93.5%	ND	100%
Perfluorooctanesulfonic acid (PFOS)	**527.50**	**20.50**	**96.1%**	**ND**	**100%**
Perfluorononanesulfonic acid (PFNS)	ND	ND	N/A	ND	N/A
Perfluorodecanesulfonic acid (PFDS)	ND	ND	N/A	ND	N/A
Perfluorooctanesulfonamide (FOSA)	ND	ND	N/A	ND	N/A
(NMeFOSAA)	ND	ND	N/A	ND	N/A
(NEtFOSAA)	ND	ND	N/A	ND	N/A
Total PFAS	**807.37**	**22.45**	**97.2%**	**ND**	**100%**

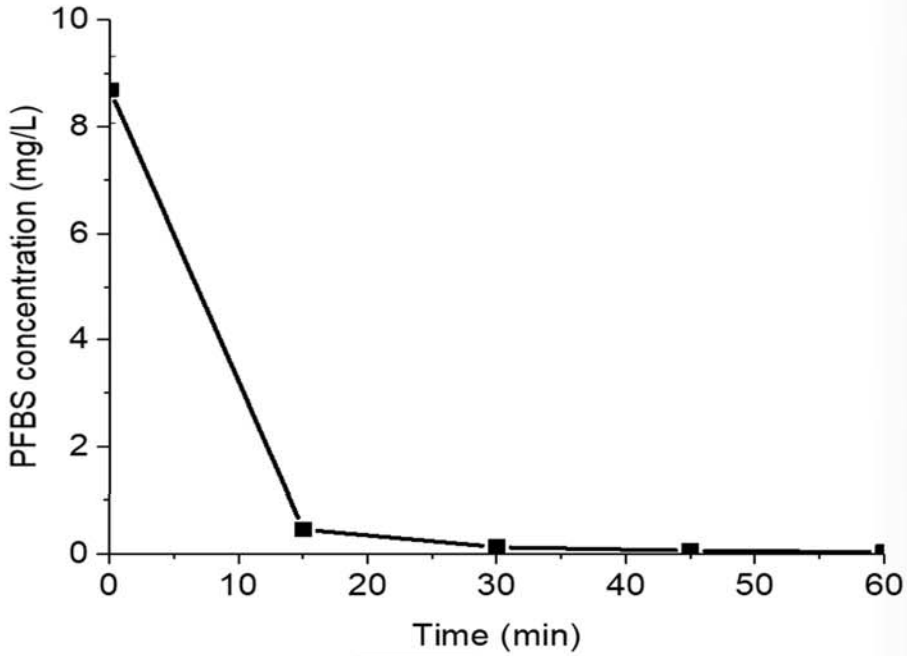
Promising destruction technology for still bottoms - Plasma

- Plasma is reactive ionized gas
  - Electrical discharge plasma makes use of OH radicals to oxidise, and aqueous electrons to chemically reduce (i.e., break the C-F bonds), the PFAS compounds
  - Benefits of plasma-based water treatment:
    - Wide variety of reactive chemical species (OH, e_{aq}^-, e^-, O, H, H_2O_2, O_2, HO_2)
    - Physical effects are also important: UV radiation, cavitation and thermal decomposition
    - No chemical additives are required

Pictures: Plasma Research Laboratory, Clarkson University

Promising destruction technology for still bottoms - Plasma





Question

What is the most common active remedial technology currently being used for PFAS?

1. Bioremediation
2. Adsorption/filtration
3. Soil vapor extraction
4. Pump and Treat
5. Dig and Haul

6. Isolation by injection of the 50's B-movie monster "The Blob"

Question

To break apart the carbon-fluorine bond, we need:

- ❑ Low energy technologies
- ❑ High energy technologies
- ❑ Chuck Norris
- ❑ Biological processes

R&D and Treatability Studies on Innovative Adsorption Media and Chemical / Electro-Chemical Processes

Global Research

- Partners
- Study Topics
- Alkaline Ozonation
- XDD GHD Studies

GHD Partners

- Private sector
- Public sector
- Technology vendors
- Laboratories
- Academic partners
- Industrial associations
- Paid services, in-kind services, and grant programs

Research Areas

- Drinking Water/Groundwater/Leachate Treatment
  - Natural/Novel Absorbents
  - Electrochemical
  - UV/OX
  - Alkaline Ozonation
  - Fractionation

Research Areas

- Soil/Sediment/Biosolids/Building Materials Stabilization and Leachability
- Analytical Techniques (Lab and Field)
- Landfill Gas Sampling and Treatment
- Fate and Transport
- Risk Assessment
- Digital Forensics

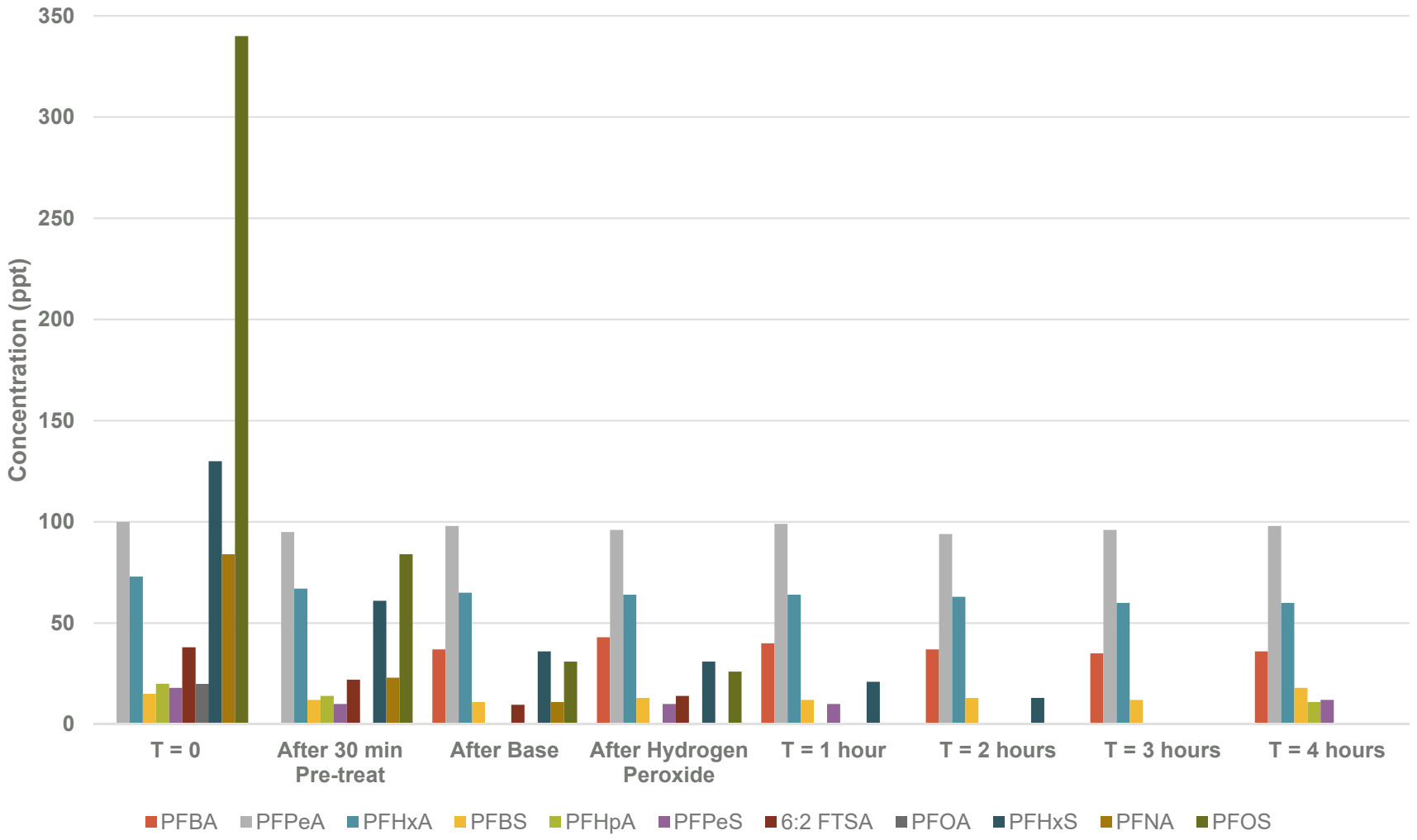
GHD PFAS Project – Michigan Groundwater 1

Evaluation of treatment alternatives for impacted groundwater

- Constituents requiring treatment:
  - PFAS (e.g., PFOS at 750 ng/L)
  - Phosphorus (180 ug/L)
  - Mercury (8 ug/L)

- Constituents potentially requiring pre-treatment:
  - Total organic carbon (20 - 30 mg/L)

Case Study – Michigan Groundwater 1 Alkaline Ozonation Tests



Case Study – Alkaline Ozonation Tests

- Treatment includes initial low pH (3 – 4) ozonation, followed by alkaline pH adjustment with hydrogen peroxide ozonation
- PFOS and PFOA is non-detect after 1 hour of treatment
- Currently testing surfactant properties of PFAS and changing pH may cause separation in the bench scale tests – Whole Bottle Analysis
- Follow-on testing will include spiked certified-PFAS free water

GHD XDD – Drinking Water Source

Part 1

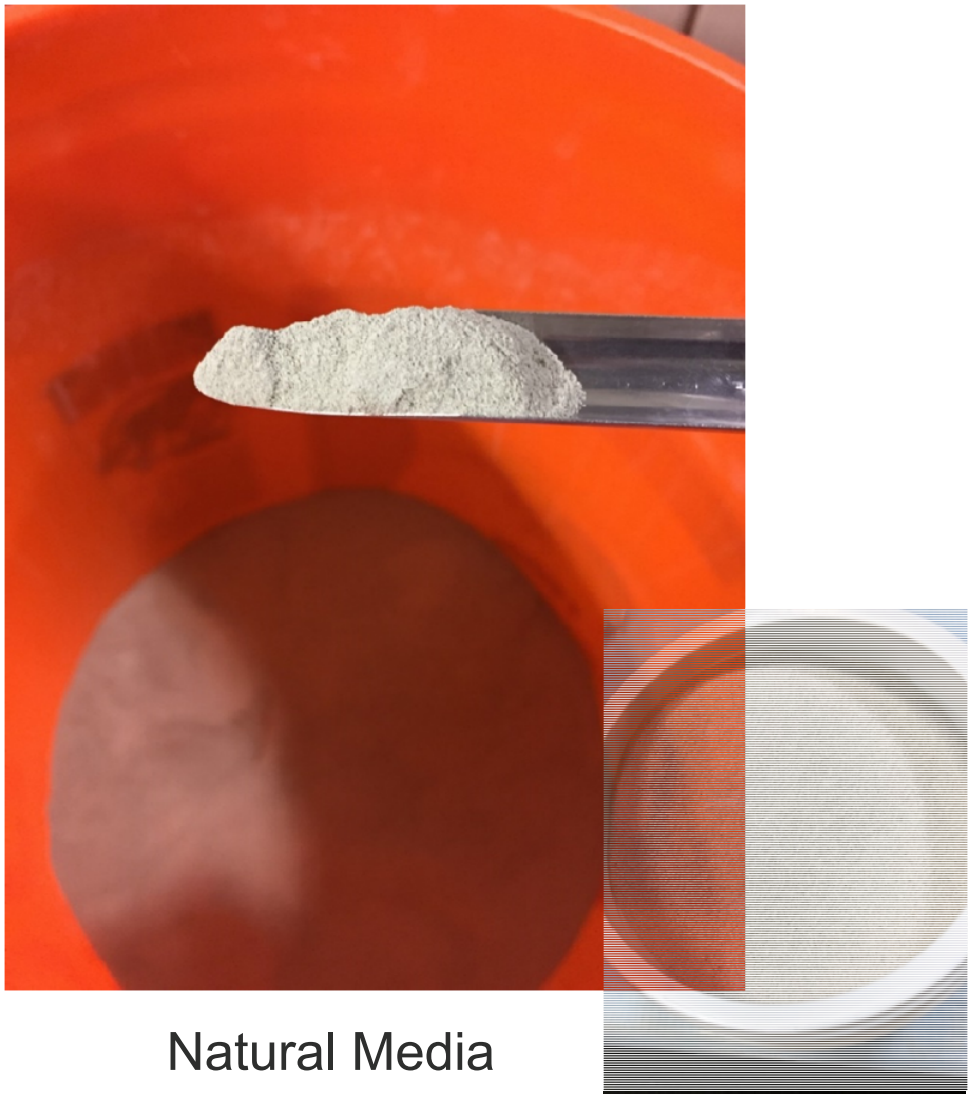
- Low-cost modified natural absorbents
- Multiple trials to optimize modifications
- Larger scale treatment on best modified absorbents

Part 2

- Electrochemical for concentrated regeneration waste versus thermal treatment
- Overall practical application and cost effectiveness vs GAC and IX

Batch Equilibrium Reactor Experiments

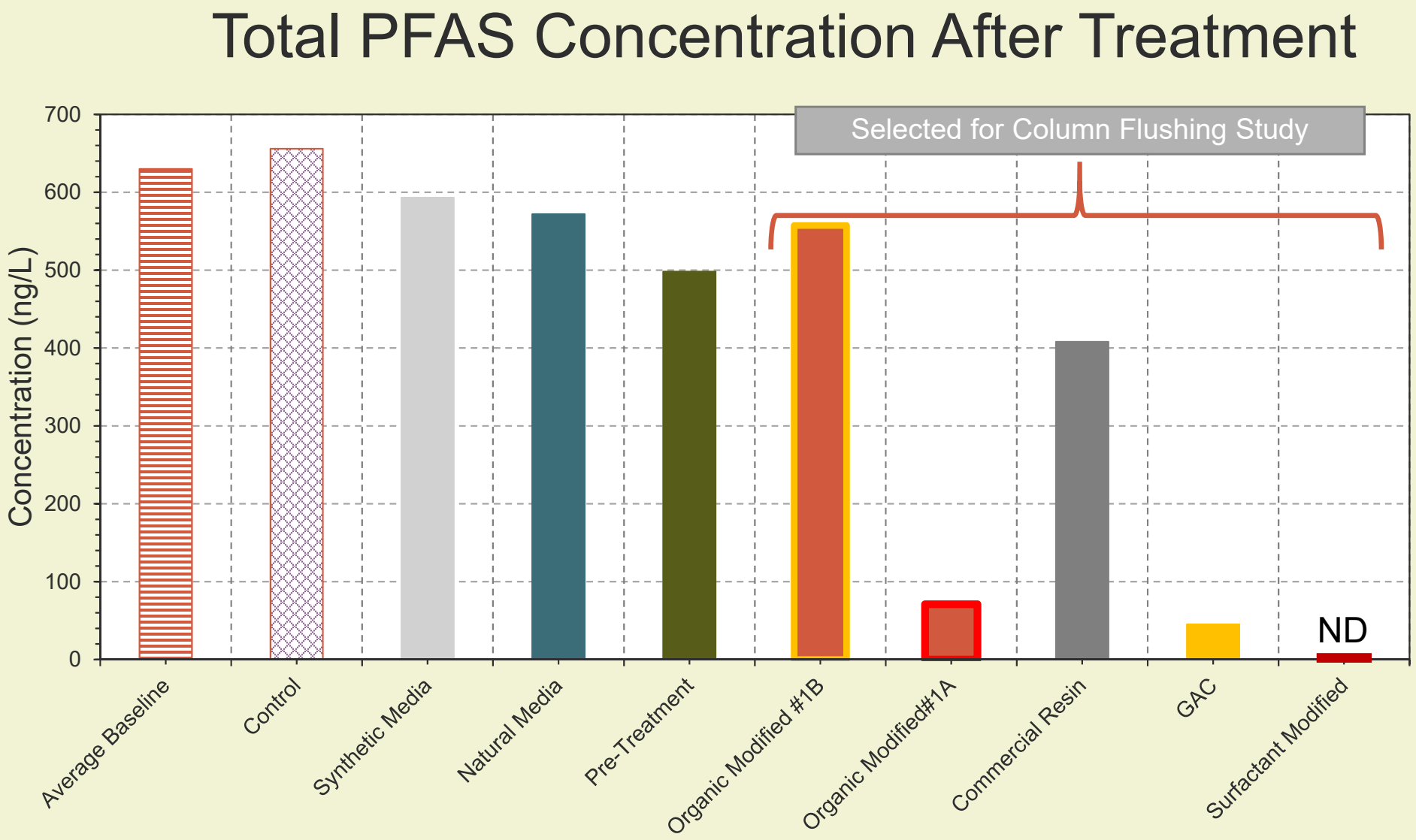
- Natural Media
- Synthetic Media
- Commercial Resin
- Surfactant Modified
- Organic Modified
- GAC
- Pre-Treatment



Natural Media

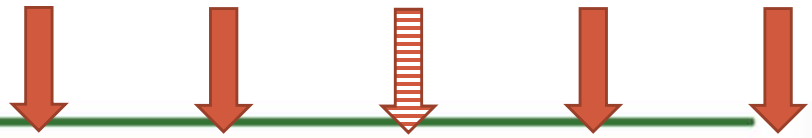
Resin

Batch Equilibrium Testing Results



Batch Testing Results

Compound	Carbon Length	Average Baseline	Control	Synthetic Media	Natural Media	Pre-Treatment	Commercial Resin	Organic Modified #1A	Organic Modified #1B	GAC	Surfactant Modified
PFOA	8	534	556	504	483	82	329	34	450	40	ND <1.9
PFOS		6	5	4	3	ND <2	ND <2	ND <1.9	15	ND <2	ND <1.9
PFHpA	7	56	58	53	52	51	46	15	54	3	ND <1.9
PFHpS		ND<2	ND <2	ND <2	ND <1.9	ND <2	ND <2	ND <1.9	0	ND <2	ND <1.9
PFHxA	6	17	18	16	16	17	17	12	18	ND <2	ND <1.9
PFHxS		4	5	2	4	4	2	ND <1.9	3	ND <2	ND <1.9
PFPeA	5	7	7	7	7	7	7	7	7	ND <2	ND <1.9
PFPeS		ND<2	ND <2	ND <2	ND <1.9	ND <2	ND <2	ND <1.9	0	ND <2	ND <1.9
PFBA	4	4	4	4	4	4	4	ND <1.9	4	ND <2	ND <1.9
PFBS		3	3	3	3	3	3	3	3	ND <2	ND <1.9
Total PFAS		630	656	593	572	498	408	71	557	45	ND <1.9
Reduction		**--**	**--**	**9.6%**	**12.8%**	**24.1%**	**37.8%**	**89.2%**	**11.5%**	**93.1%**	**100.0%**



Selected for Column Flushing Study

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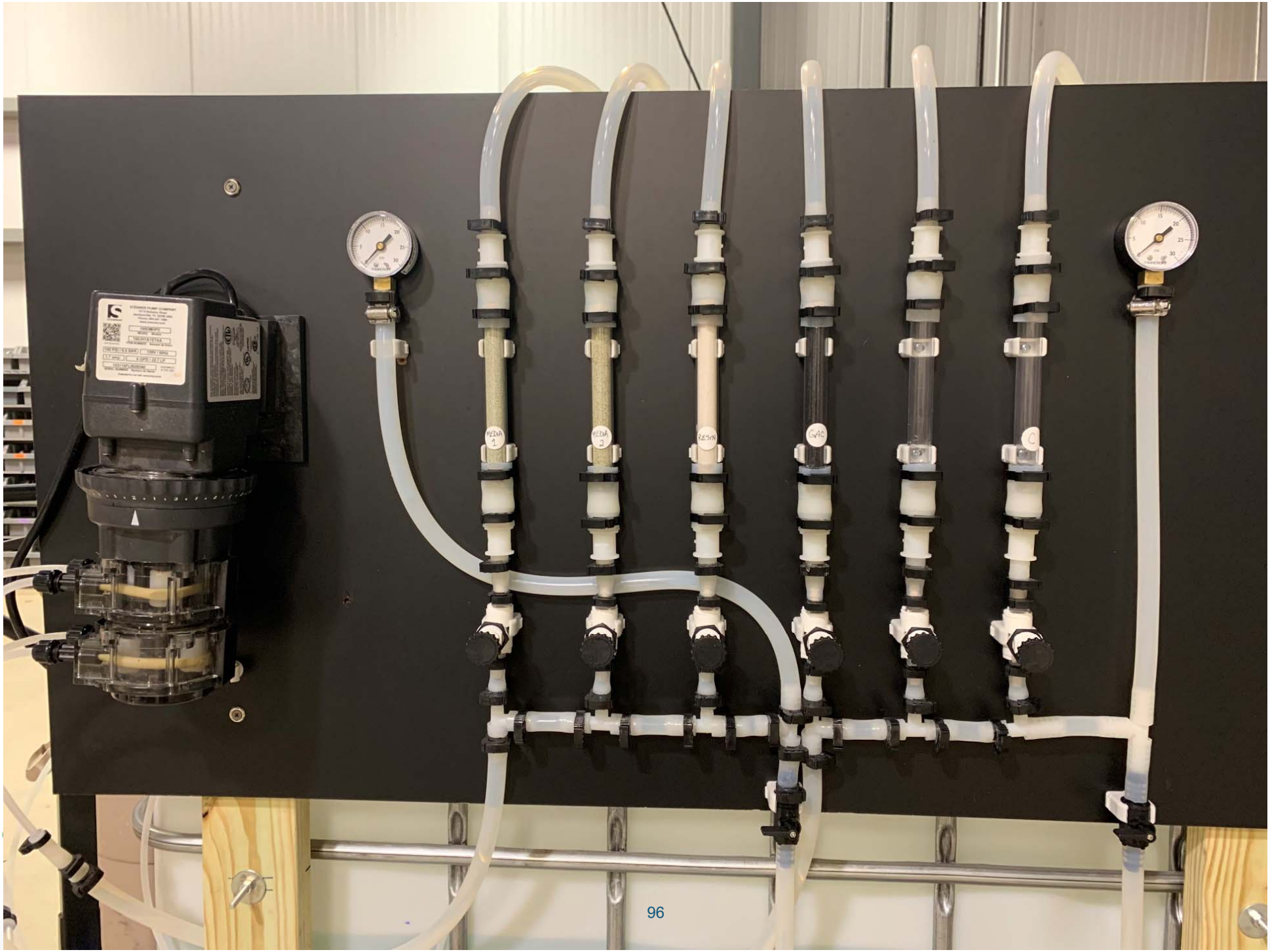
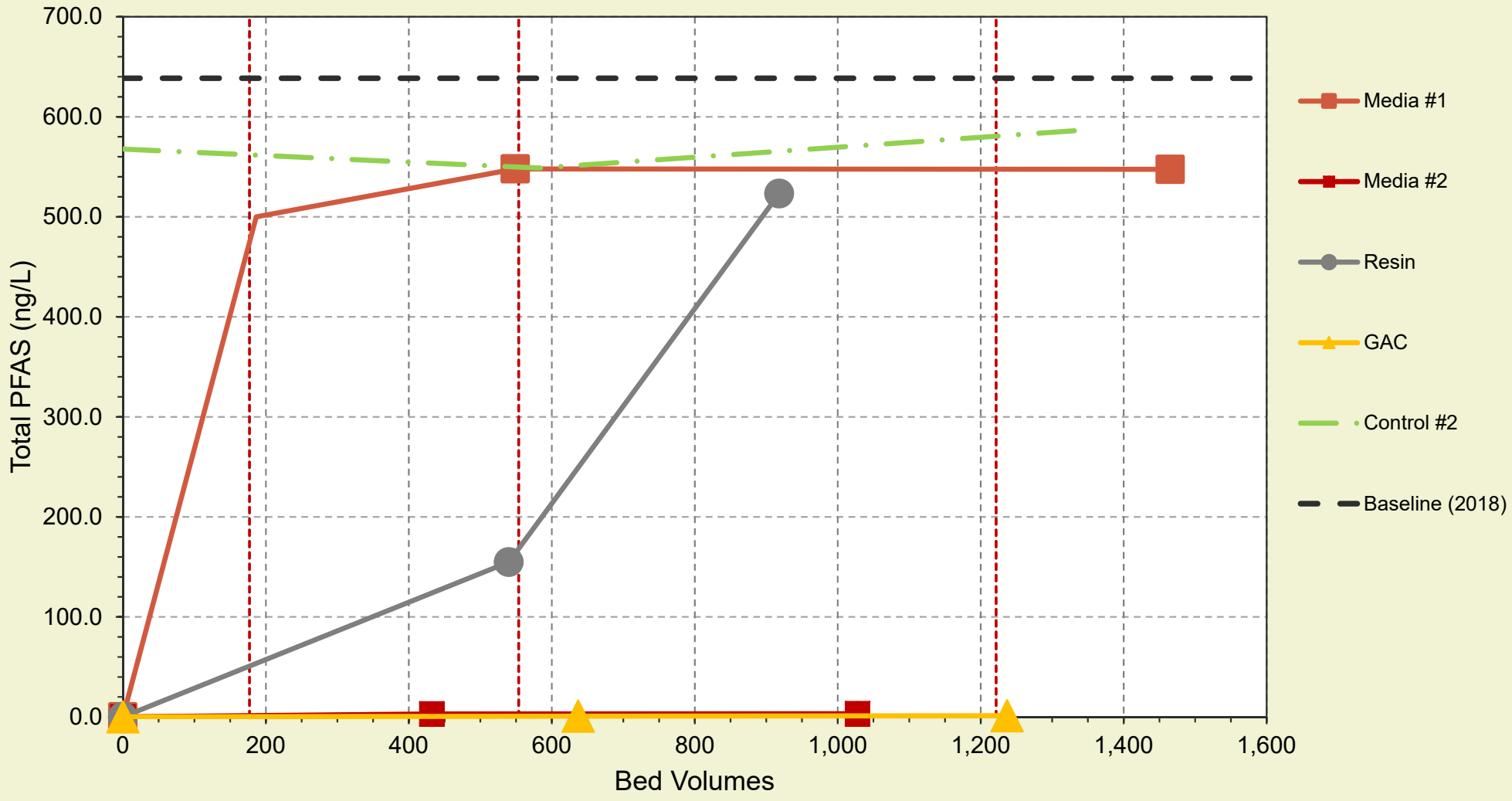
Do it right. Do it once.

Column Apparatus



Column Flushing Experiments



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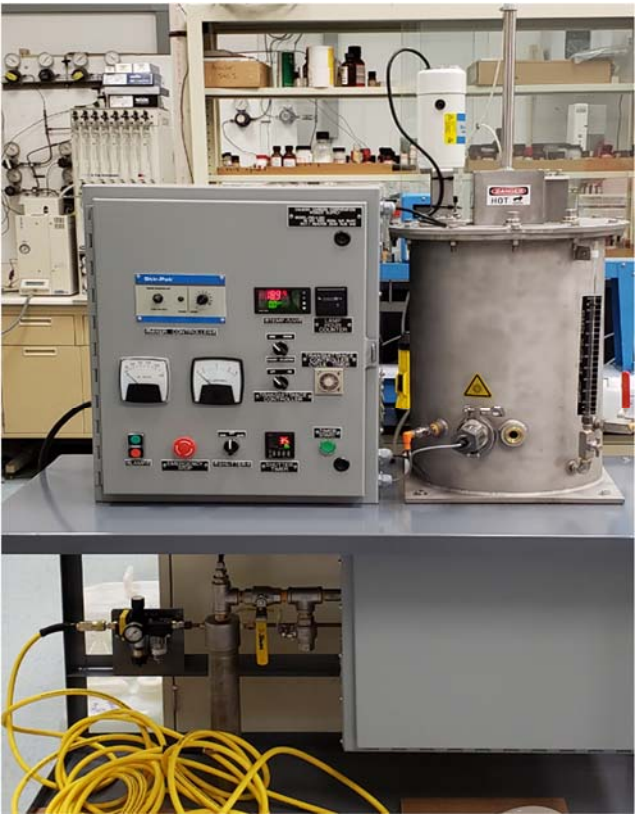
Study is in progress

UV Batch Reactor Oxidation and Reduction Studies



For oxidation: The water was pH adjusted to 2.5 using 1:1 sulfuric acid. After pH adjustment, 0.357 g/L of persulfate was added to the sample and mixed for 15 mins. After mixing, the sample was transferred to the batch reactor via the sampling port using silicone tubing.

For reduction: The water was pH adjusted to 10 using 25% NaOH. After pH adjustment, 50 mg/L of potassium iodide was added to the sample along with 1 mg/L of humic acid and mixed for 15 mins. After mixing, the sample was transferred to the batch reactor via the sampling port using silicone tubing. The sample in the reactor was subjected to a 30 minute nitrogen bubbling pre-treatment.

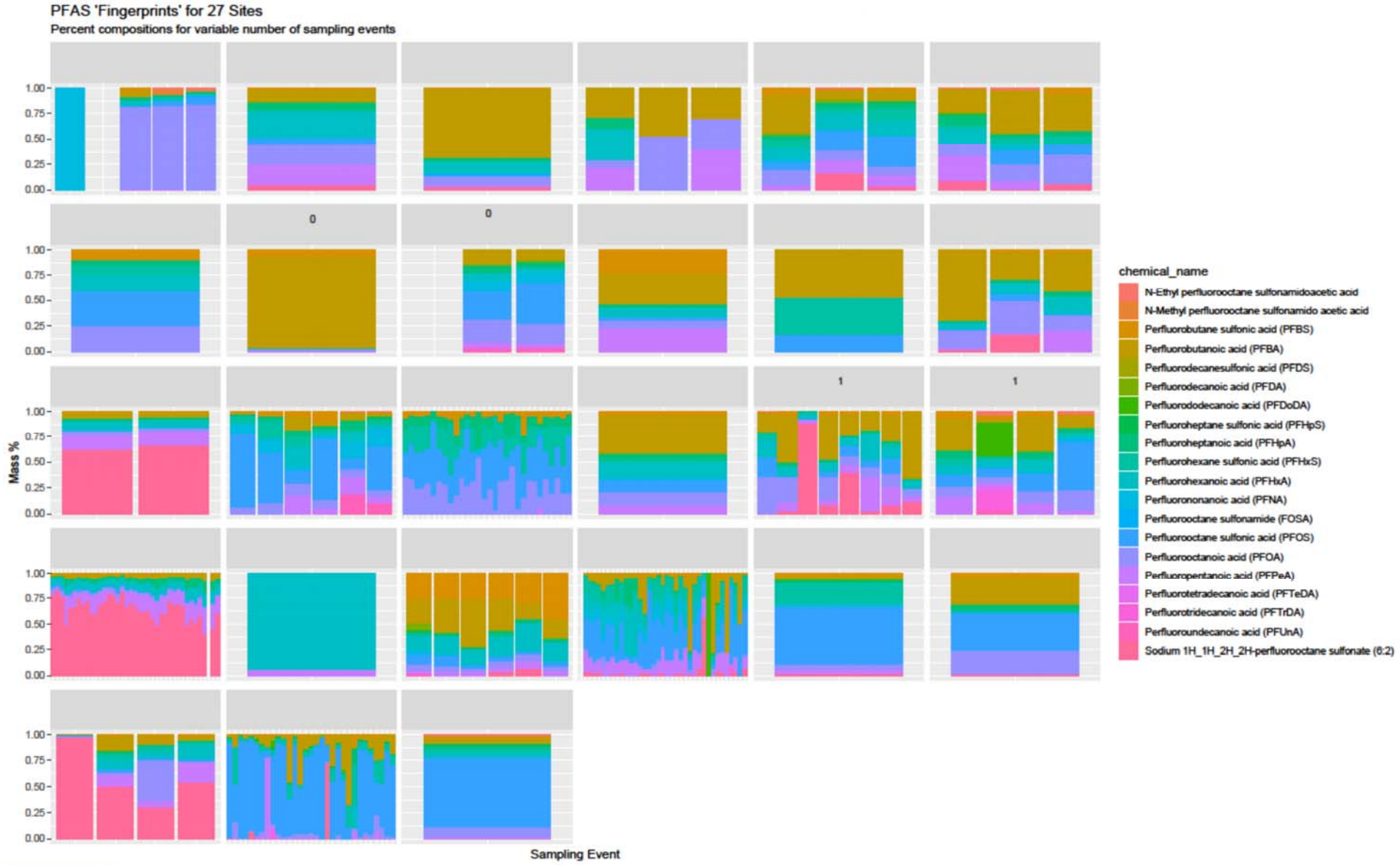
Table 1				
UV-Oxidation-Drinking Water Source - XDD				
PFAS Treatability Study				
		Initials	T = 0	T = 4 hrs
Parameters	**Units**			
Perfluorobutanoic acid (PFBA)	ng/L	4.2	3.9	4.4
Perfluoropentanoic acid (PFPeA)	ng/L	7.1	7.6	7.6
Perfluorohexanoic acid (PFHxA)	ng/L	17	16	18
Perfluoroheptanoic acid (PFHpA)	ng/L	62	58	29
Perfluorooctanoic acid (PFOA)	ng/L	550	520	500
Perfluorononanoic acid (PFNA)	ng/L	1.3 J	0.47 J	0.55 J
Perfluorodecanoic acid (PFDA)	ng/L	1.2 J	ND (1.9)	ND (1.9)
Perfluorobutanesulfonic acid (PFBS)	ng/L	2.8	2.6	3.0
Perfluoropentanesulfonic acid (PFPeS)	ng/L	0.48 J	ND (1.9)	0.47 J
Perfluorohexanesulfonic acid (PFHxS)	ng/L	4.3 B	4.1 B	4.4 B
Perfluorooctanesulfonic acid (PFOS)	ng/L	6.9	5.4	5.4

Table 2				
UV-Reduction-Drinking Water Source - XDD				
PFAS Treatability Study				
		Initials	T = 0	T = 4 hrs
Parameters	**Units**			
Perfluorobutanoic acid (PFBA)	ng/L	3.6	3.8	4.4
Perfluoropentanoic acid (PFPeA)	ng/L	6	6.1	6.7
Perfluorohexanoic acid (PFHxA)	ng/L	16	15	15
Perfluoroheptanoic acid (PFHpA)	ng/L	50	53	51
Perfluorooctanoic acid (PFOA)	ng/L	450	480	470
Perfluorononanoic acid (PFNA)	ng/L	0.50 J	0.42 J	0.50 J
Perfluorobutanesulfonic acid (PFBS)	ng/L	2.4	2.4	2.8
Perfluoropentanesulfonic acid (PFPeS)	ng/L	0.40 J	0.37 J	0.35 J
Perfluorohexanesulfonic acid (PFHxS)	ng/L	3.5 B	3.8 B	3.7 B
Perfluoroheptanesulfonic Acid (PFHpS)	ng/L	ND (1.8)	0.34 J	0.30 J
Perfluorooctanesulfonic acid (PFOS)	ng/L	4.9	14	13

GHD XDD - Drinking Water Treatment Next Steps

- ❑ Test alkaline ozonation testing
- ❑ Modify doses of oxidant/reductant for UVOX testing
- ❑ Electrochemical studies on column flushings

Fingerprinting to Support Remediation



Question

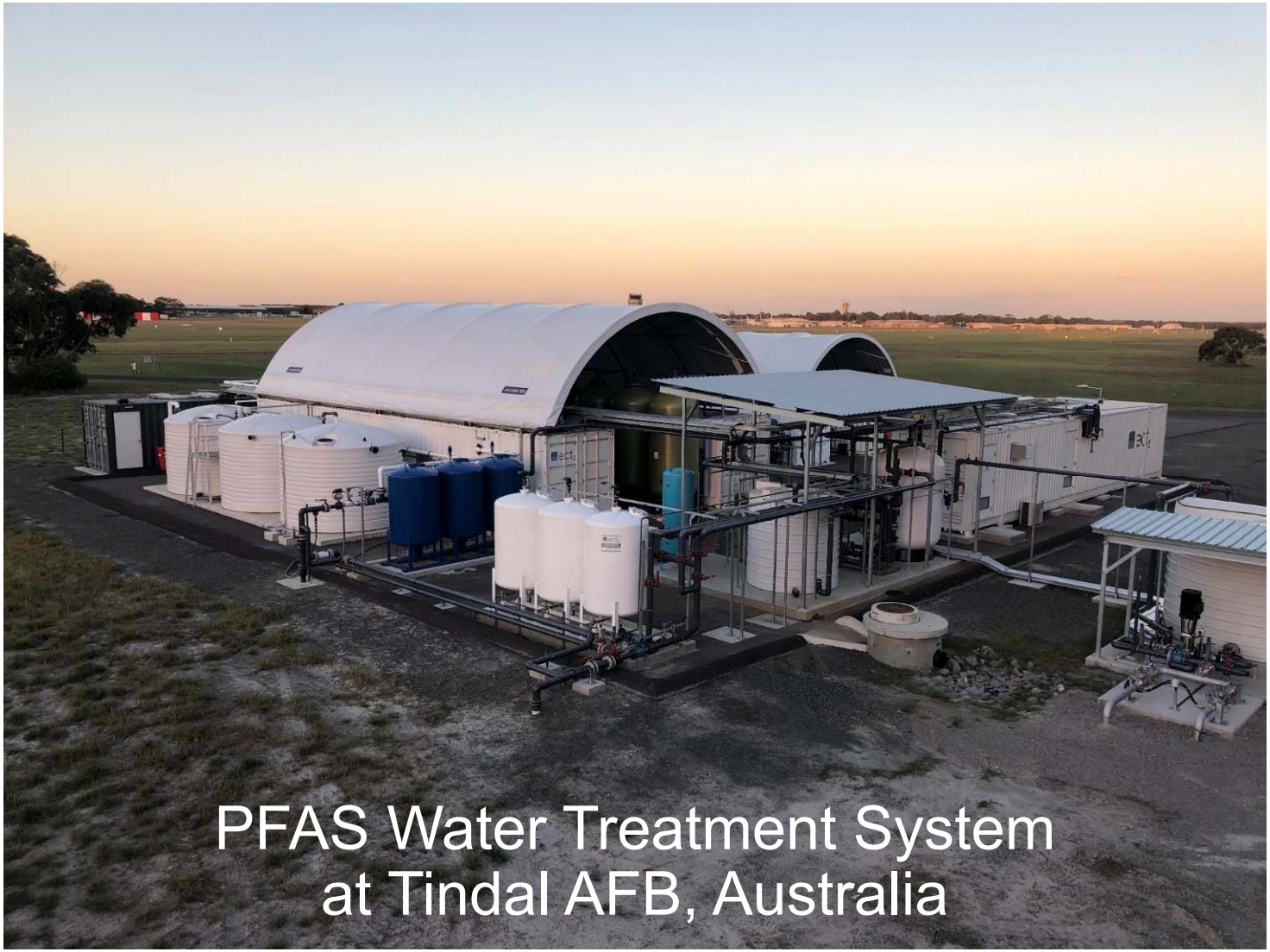
What is the most important research tool?

1. Funding$$$
2. Sound science
3. Great engineering
4. Collaboration

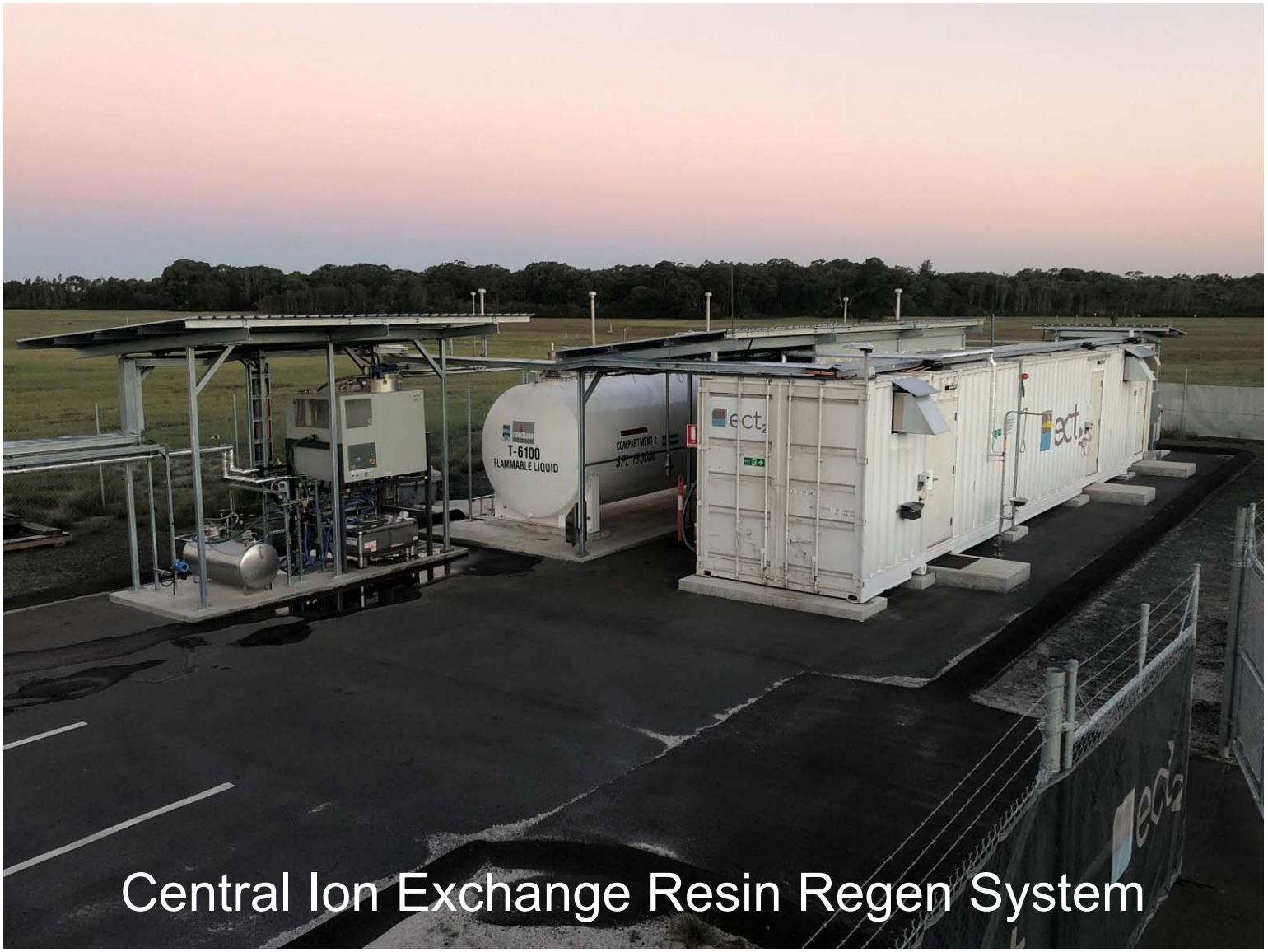
Non-Destructive Case Studies (3)

Background

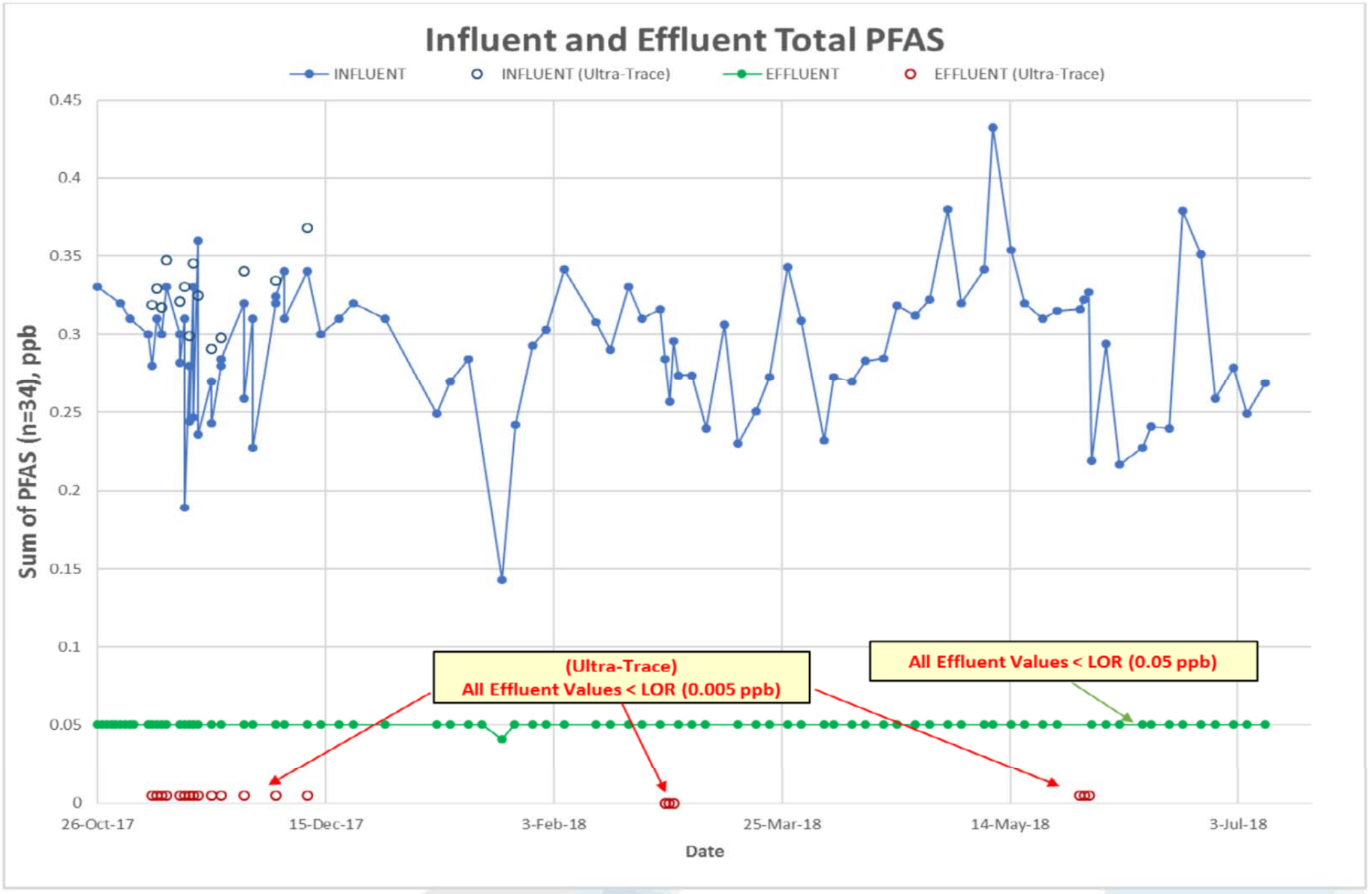
- Historical AFFF use at Tindal air base in Australia
- Resulted in PFAS contamination of groundwater
- Plume migrates off base toward River
- Has impacted potable water supply well for neighboring town (Katherine)
- Influent PFAS concentrations average 310 ng/l
- Responsible party responded swiftly by diverting a turnkey, modular, 200-gpm PFAS removal system that was bound for another site



PFAS Water Treatment System
at Tindal AFB, Australia



Central Ion Exchange Resin Regen System


Influent and Effluent Total PFAS
INFLUENT
INFLUENT (Ultra-Trace)
EFFLUENT
EFFLUENT (Ultra-Trace)
Sum of PFAS (n=34), ppb
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
(Ultra-Trace)
All Effluent Values < LOR (0.005 ppb)
All Effluent Values < LOR (0.05 ppb)
26-Oct-17
15-Dec-17
3-Feb-18
25-Mar-18
14-May-18
3-Jul-18
Date

MUNICIPAL CASE STUDY

CONTEXT

Municipality in New York encounters PFAS in drinking water

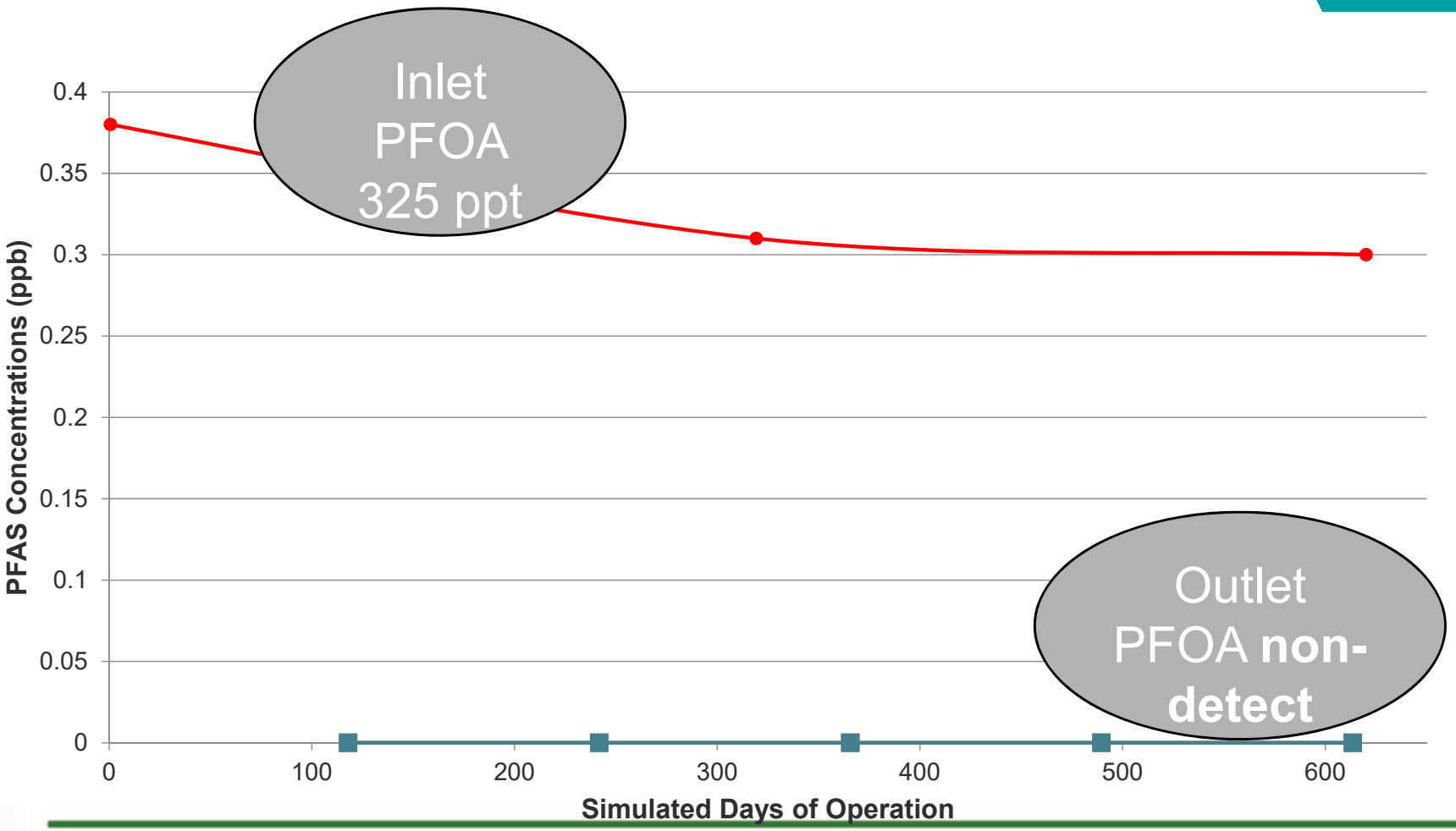
APPROACH

Lab Column Test

Determine efficacy of proposed treatment system

- Two x 12-ft diameter vessels, lead-lag operation
- 40,000 lb GAC per vessel
- 13 minutes contact time

LAB DATA



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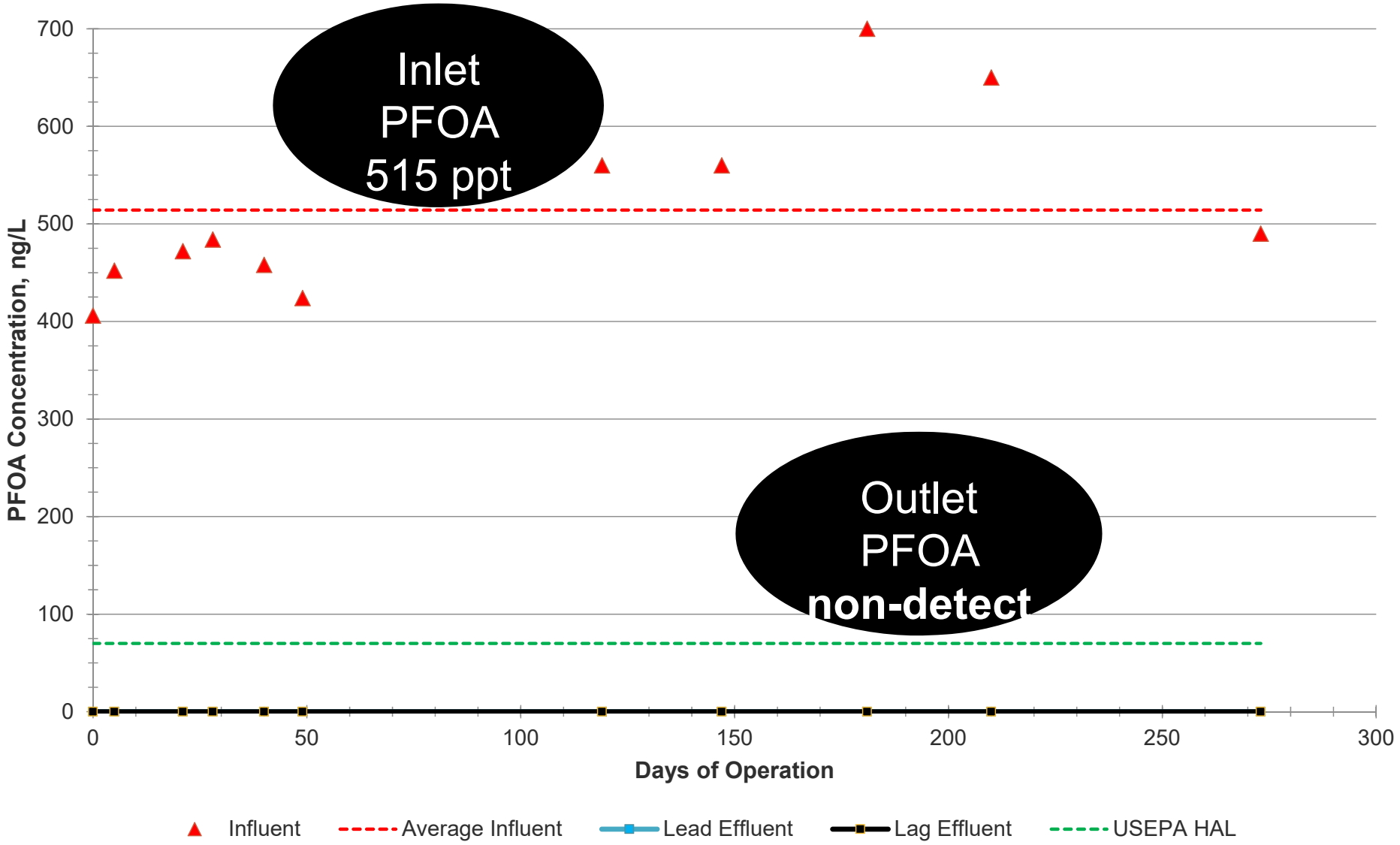
FIELD DATA



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CASE STUDY
FORMER FURNITURE FACILITY

ONTARIO, CANADA

BACKGROUND

Initial Driver: Hydrocarbons

- Mixed chain lengths, 100 – 5,000 µg/L

Formation

- Silty sand – till based with sand seams
- Water at 3 – 5’ below grade

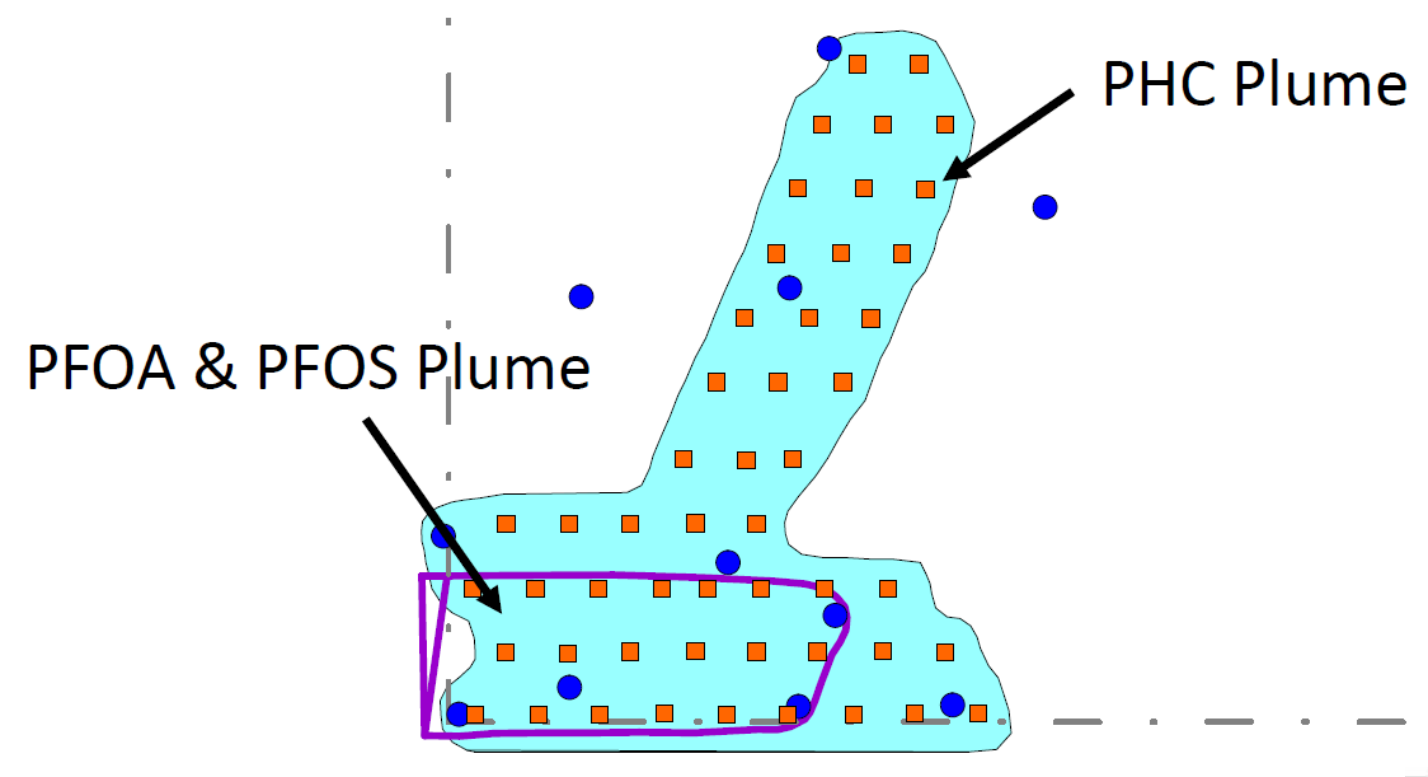
Former Fire Training Area

- History of furniture manufacturing
- PFAS tested for just in case and found!

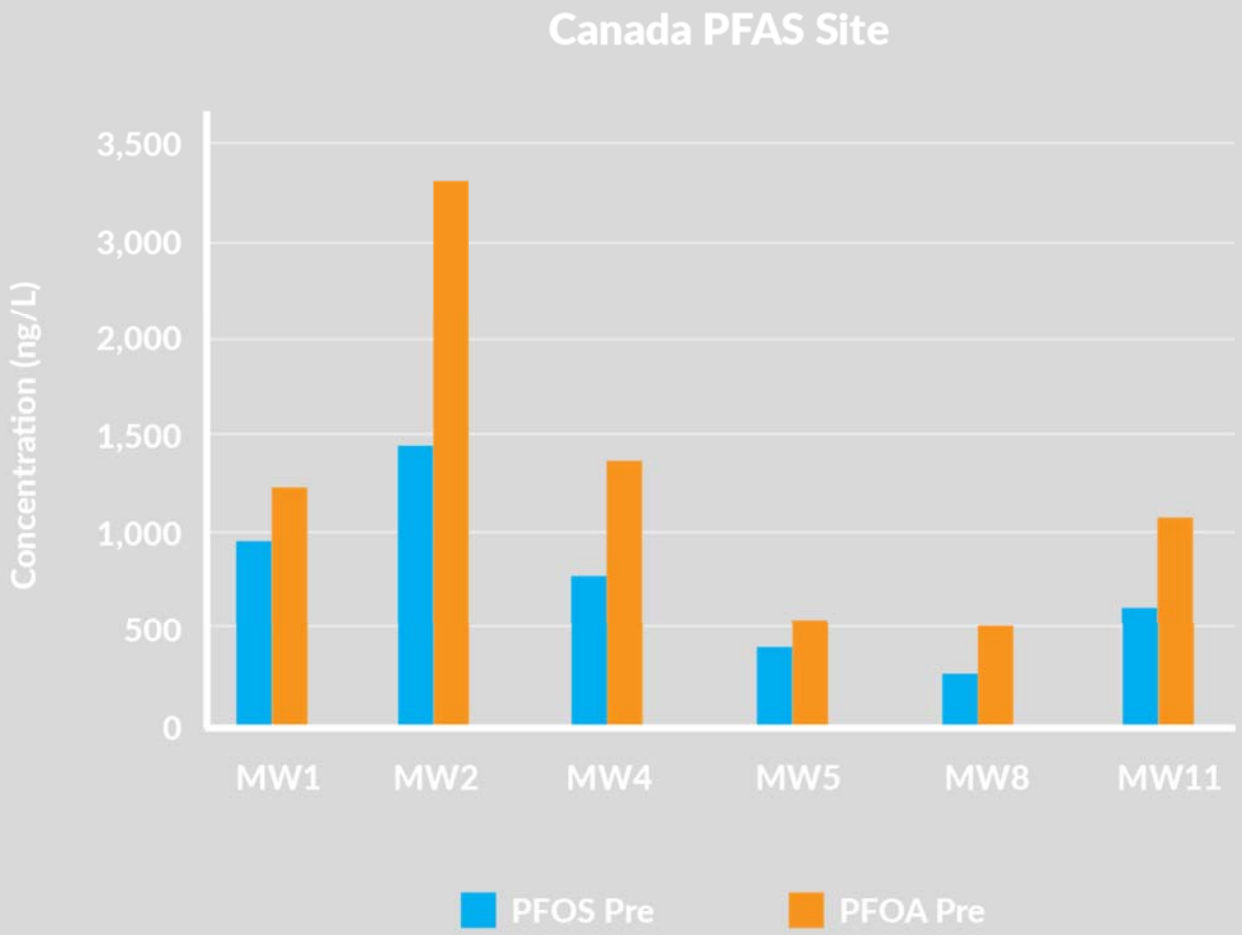
Rick McGregor

INSITU REMEDIATION SERVICES

PLUME AREA DIAGRAM

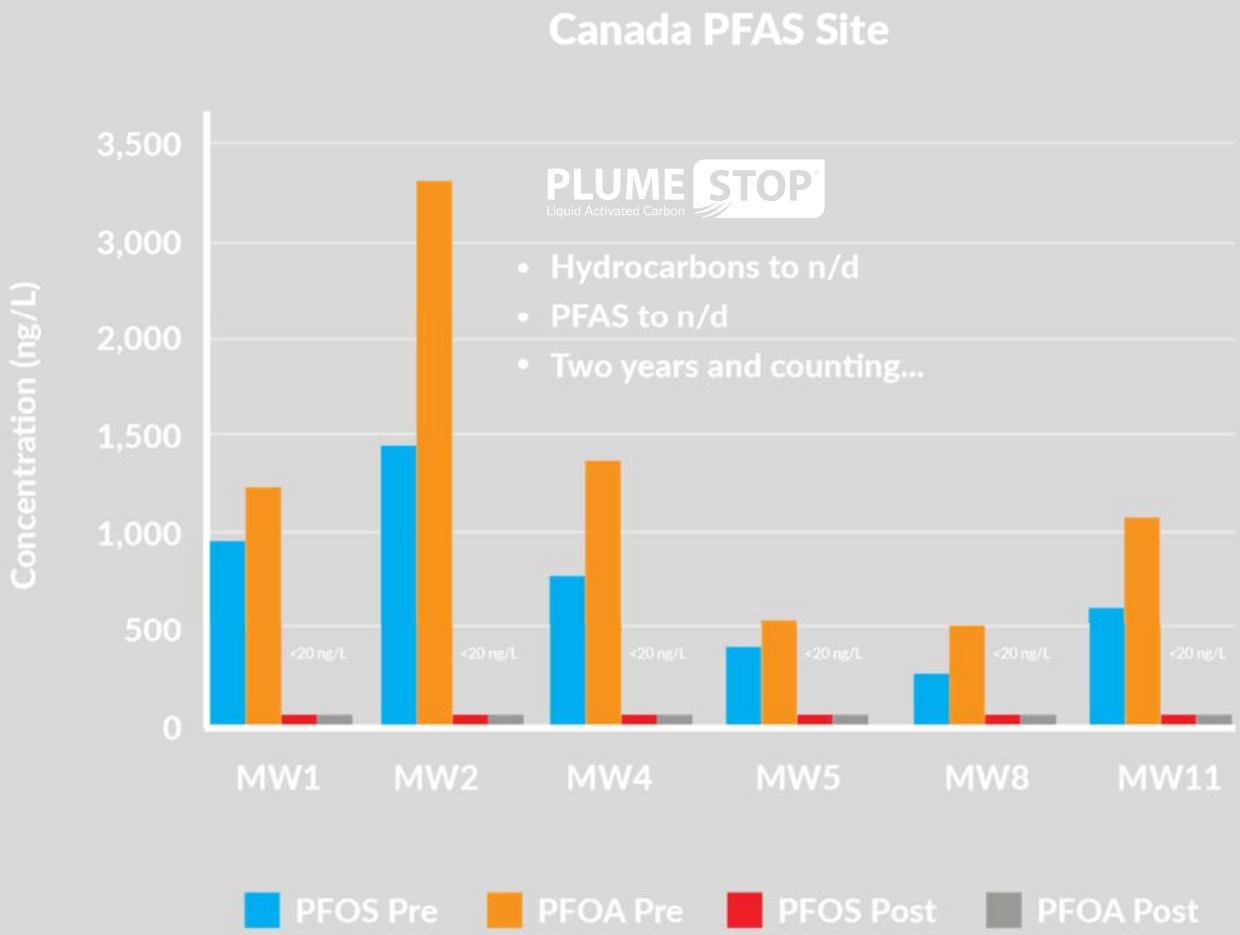


PFAS FORMER FURNITURE SITE



Site Location:
Ontario, Canada

PFAS FORMER FURNITURE SITE



Site Location:
Ontario, Canada

Chemical Oxidation Case Study + Additional Research

Remediation of Mixed Organics and PFAS Compounds with OxyZone®, XCT® A Combined Remedy

Raymond Ball, Ph.D., P.E., L.S.P.

www.en-chem.com

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OxyZone® Chemistry

- Patented persulfate-based oxidant mixture safe to apply under buildings
- Small site footprint, generation entirely enclosed
- Requires fresh water source and electrical hookup
- Equipment designed and built in-house
- Previously proven effective for in-situ treatment of conventional contaminants

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Field Demonstration Test of Mixed Organics (PFAS) Remediation

Summary of 9-month Field Demonstration

- Fire Training Area (FTA) at Joint Base Langley-Eustis, Hampton, VA with mixed organic wastes, aqueous film forming foam (AFFF) released to soil and GW
- OxyZone® Injection test cell of 20 feet by 30 feet
- Successful treatment of aromatic and chlorinated VOCs
- Groundwater PFAS results showed statistically significant concentration decrease
- PFAS destruction confirmed by lab bench-scale testing

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Field Demonstration – Hydrogeological conditions

- Historical military FTA where AFFF released
- Complex geology, shallow GW (1-2'), low GW velocity, tidal influenced
- Surficial (shallow and intermediate) aquifer underlain by a clay confining unit
- Shallow (2-10' bg) – silty sands and organic silt (K=0.5 m/d)
- Intermediate (10-20' bg) - Highly permeable poorly sorted sands (K=4.9 m/d)

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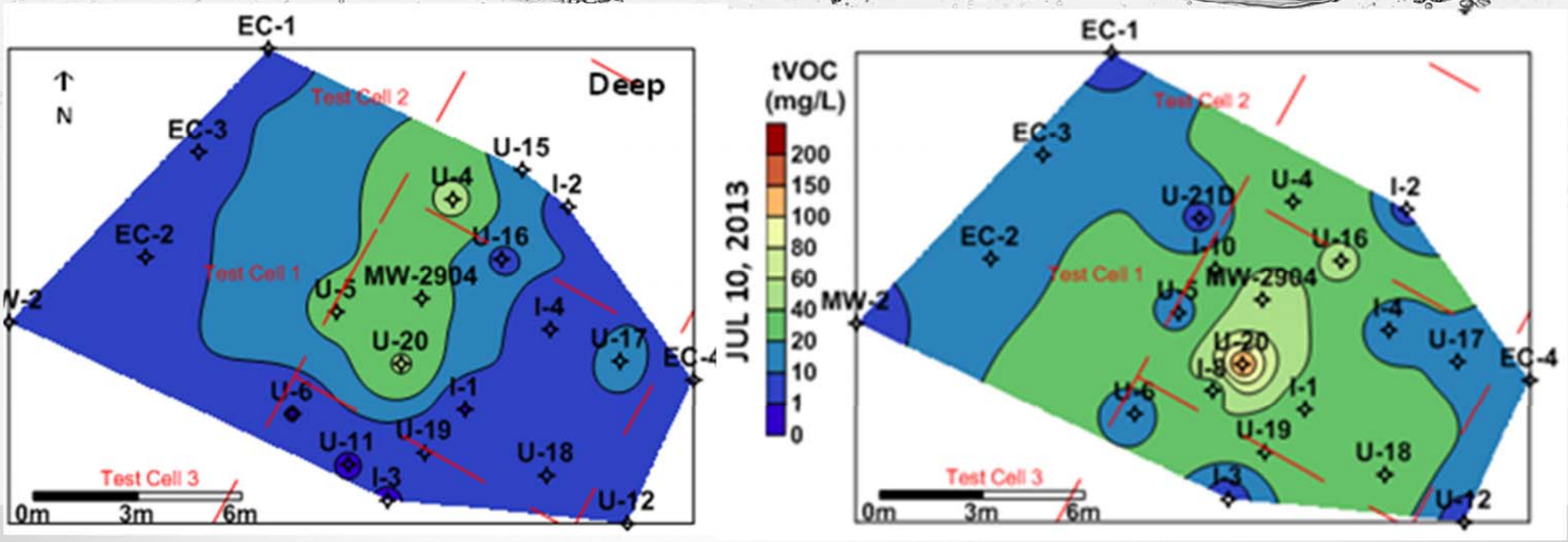
Impact of XCT® on Total VOC Concentration in Groundwater

XCT® is a patented biodegradable carbohydrate mixture to enhance the solubility of organic contaminants for subsequent efficient oxidation by OxyZone®



Baseline prior to injections

After 1st XCT Injection (VOCs increased)

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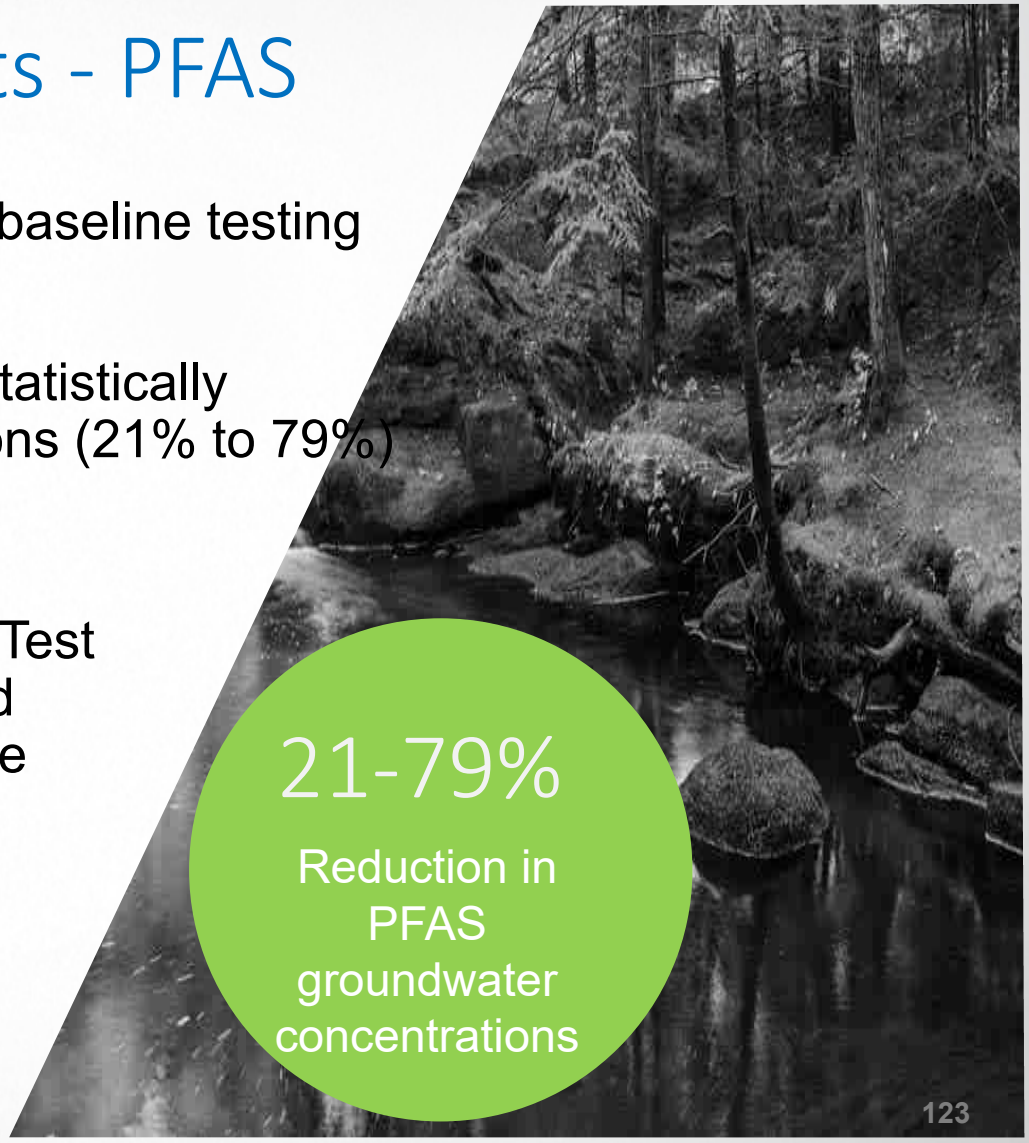
Field Demonstration Results - PFAS

- 9 different PFAS were discovered during baseline testing
- Groundwater data analysis supported a statistically significant reduction in PFAS concentrations (21% to 79%) in groundwater
- Statistical comparison of wells within the Test Cell to those outside the Test Cell showed PFAS concentrations decreased within the Test Cell and not outside



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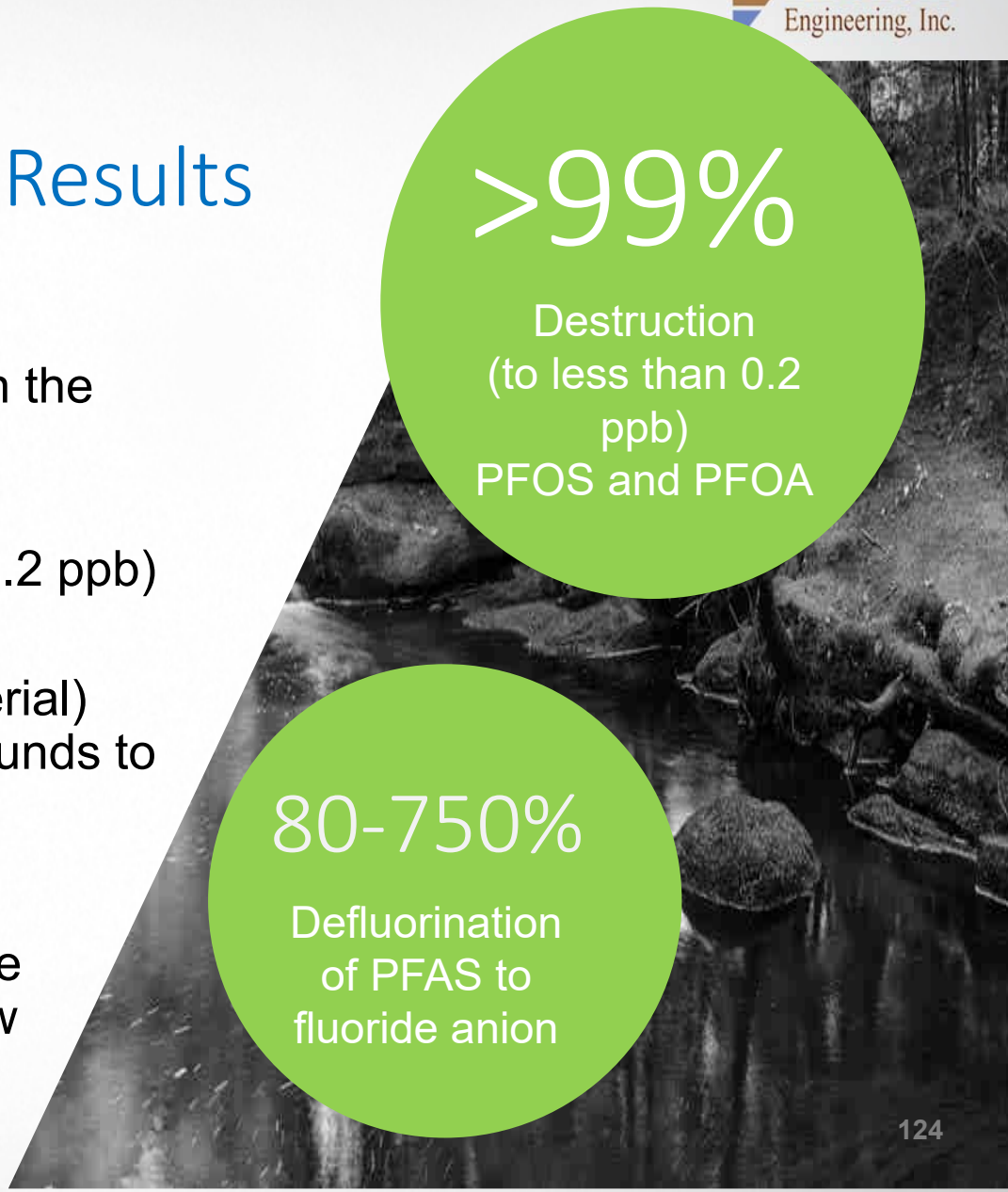
Case Study – Summary of Results

In-House Bench Scale Testing

- Subsequent evaluation of OxyZone® in the laboratory repeatedly confirmed PFAS destruction and de-fluorination
- Up to 99.9% destruction (to less than 0.2 ppb) of PFOS and PFOA
- 80 - 750% (depending on starting material) defluorination of organofluorine compounds to fluoride anion

Conclusion

- Results indicate that OxyZone® has the capability to decrease PFAS to very low concentrations, either in-situ or ex-situ.



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Innovative Treatment of Investigation Derived Waste Polluted with PFAS Contaminants

SDERP ER-18-1545

Objectives

- Test an Ex-Situ destructive technology for On-Site treatment of PFAS present in soil and water investigation derived waste (IDW)

OxyZone® Technology

- Flexible chemistry with multi-stage treatment approach
- OxyZone® chemistry is based on powerful sulfate, hydroxyl, and superoxide radical pathways and ozone gas

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Treatment of Investigation Derived Waste containing PFAS

Soil Washing

What is Investigation Derived Waste?

- ❑ It is the soil and groundwater from subsurface investigation activities or from pumping tests

Why do we care about it?

- ❑Any IDW containing PFAS that leaves the Site is a potential liability

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Treatment of Investigation Derived Waste containing PFAS

Technical Approach

- **Semi-Batch Treatment of IDW Water**
- **Semi-Batch Treatment of IDW Soil**
- **Testing of Semi-Batch Continuous Flow Soil Slurry and Water**

Bench Scale Slurry Reactor

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Treatment of Investigation Derived Waste containing PFAS

Results to Date

- ❑ **Soil Washing with OxyZone**
- ❑ **Ex-Situ Water Treatment with OxyZone**
- ❑ **Combined Soil Washing and IDW Water Treatment with OxyZone**
- ❑ **On-going studies to find lowest PFAS concentrations achievable**

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Treatment of Investigation Derived Waste containing PFAS by Soil Washing

Bench-Scale Slurry Reactor

XCT ®

- 98% of adsorbed PFAS from IDW soil within a few hours. Leaching test on treated soil fraction shows that the 14/15 compounds in the leachate were each below 70 ppt, and one slightly above

OxyZone®

- Initial treatment of 20% by weight soil slurry with OxyZone® resulted in 81% decrease in total PFAS, with 98% decrease in PFOS, 56% reduction in PFOA within a few hours, with a very small increase in concentration of shorter carbon chain PFAS observed

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Lessons Learned /Data Gaps

- ❑ **Fluoride can be valuable analytical tool to assist with real-time assessment of experiments**
- ❑ **A mass balance on known PFAS and fluoride is desirable, but difficult to achieve at PFAS concentrations in the ppb range or lower**
- ❑ **Achieving a mass balance in a soil slurry is more challenging due to the natural fluoride concentration in the soil**

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Lessons Learned /Data Gaps

- **The effect of treatment (destruction) efficiency on precursors should also be investigated.**
- **The effect of treatment (destruction) efficiency on branched versus linear perfluoralkyl compounds should be investigated.**
- **To optimize PFAS chemical destruction, different chemical reagent conditions may be needed for sulfonates versus carboxylates.**

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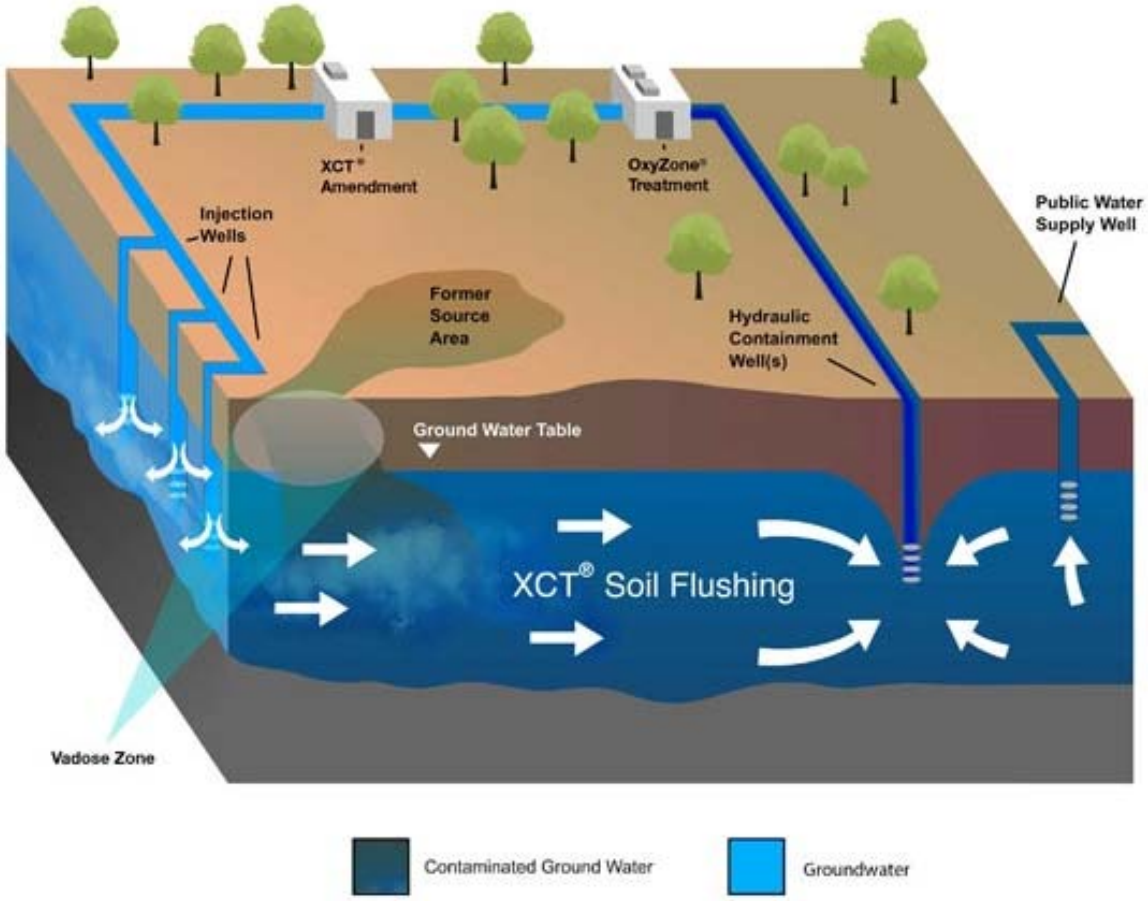
Combined In-Situ / Ex-Situ Remedy using XCT® and OxyZone®

- ❑In-Situ Contaminant Soil Flushing
- ❑Migration Control at a Property Boundary
- ❑Aboveground Treatment & Reinjection
- ❑Drinking Water Well Protection



XCT® Combined In-Situ & Ex-Situ Treatment

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Summary

XCT® and OxyZone® process technology applications:

- ❑ **In-Situ Remedy**
- ❑ **Ex Situ Water Treatment**
- ❑ **Ex Situ Soil Washing Treatment**
- ❑ **Combined In Situ/Ex Situ Remedy**

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Acknowledgements

- Tom Boving, Ph.D., Co-Principal Investigator, and Dylan Eberle, Ph.D., University of Rhode Island (for Field Demonstration effort)

- AFCEC, for funding the Field Demonstration Project, FA8903-11-C-8804: Chemical Oxidation and Inclusion Technology for Expedited Soil and Groundwater Remediation
- Strategic Defense Environmental Restoration Program Tom Boving, Ph.D.,Univ. of Rhode Island ER-18-1545

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Question

How can you be sure that there is destruction of PFAS during testing:

1. Decrease in PFAS
2. Mass balance
3. Decrease in fluoride
4. Increase in fluoride
5. You can't

Last Thoughts

- PFAS on most people's radar screen for just a few years

- PFAS remediation very challenging:
  - Moving targets – which PFAS need to be remediated and to what concentrations?
  - Large number of chemicals with varying properties
  - Low concentrations of concern
  - Many data gaps and analytical difficulties
  - Complexity due to chemical transformations
  - Thin track record of many remediation technologies

Last Thoughts

- Technologies that are currently most promising for PFAS water treatment
  - GAC and other adsorbents
  - Ion exchange / adsorption resins
  - Filtration (Nanofiltration, reverse osmosis)
    - pretreatment and/or post-treatment may be needed
  - Redox manipulation

- Technologies that are currently most promising for PFAS soil treatment
  - Thermal desorption / destruction
  - Isolation
  - Soil washing

Last Thoughts

- Technologies that are currently most promising for PFAS high concentration waste streams
  - Thermal destruction
  - High energy systems mainly in R&D or early trials
    - Electro-chemical
    - Oxidative-reductive
    - Plasma
- Treatability studies are usually necessary:
  - Select the best technology(s)
  - Optimize remediation design
  - Minimize the risk of unintended consequences

Questions

For any questions that we cannot get to during the Q/A period, please feel free to contact the presenters:

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Raymond Ball (rball@en-chem.com)
Fred Taylor (Fred.Taylor@ghd.com)