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PFAS: Beyond the Basics Training

Remediation Strategies & Treatment Technologies

- Conceptual Site Remedial Approach
- Source Area Soils
- Source Area GW
- GW Plume
- Treatment Residuals

Based on the Sept 2023 published PFAS-1 document. These topics are rapidly changing. Full citations are included in the PFAS-1 References list.

https://pfas-1.itrcweb.org/

ITRC PFAS Resources

ITRC PFAS: https://pfas-1.itrcweb.org/

Guidance Document

13 Fact Sheets

External Tables

PFAS Introductory Training

- Clu-In Archive: https://www.clu-in.org/conf/itrc/PFAS-Introductory/

Other video resources

- Available through links on: https://pfas-1.itrcweb.org
- Quick Explainer Videos
- Longer PFAS Training Modules
- Archived Roundtable Sessions

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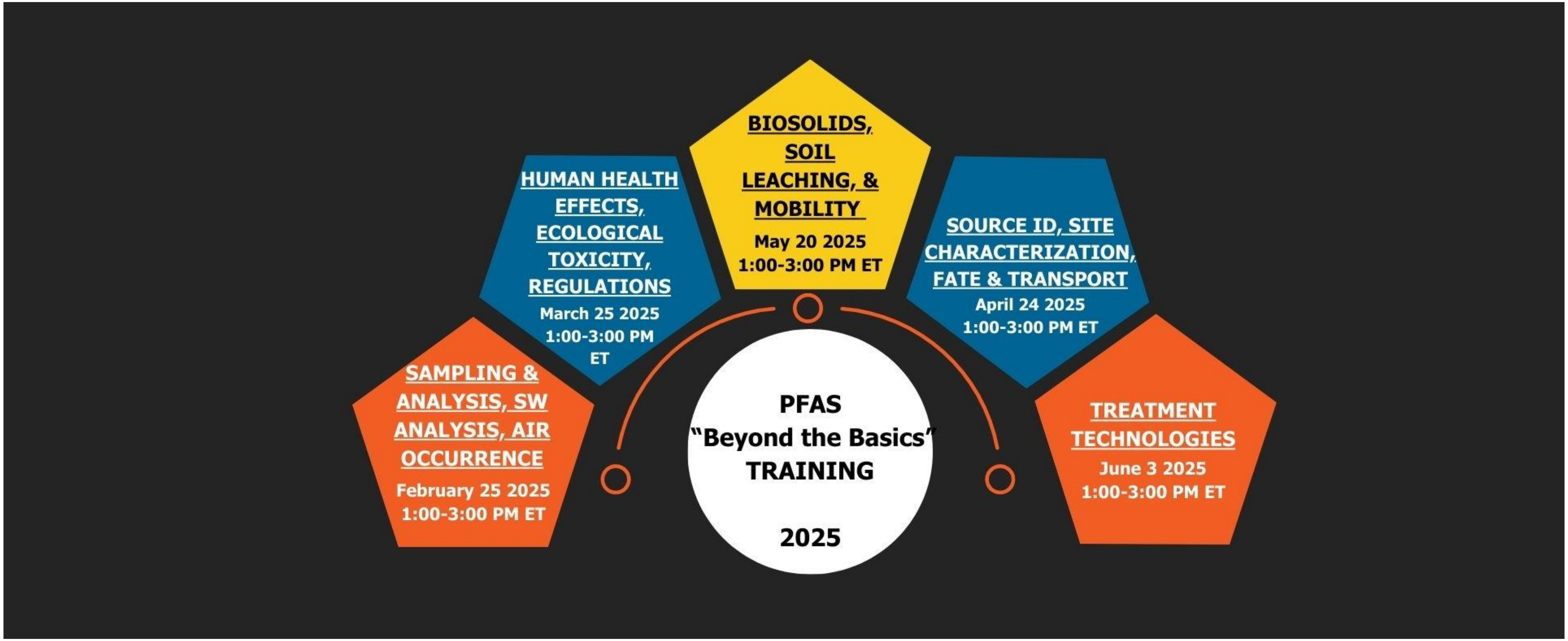
ITRC PFAS Team: "Beyond the Basics" Training



Learning Objectives

- What types of media, sources, and pathways might require intervention and treatment
- How are field-implemented PFAS remediation technologies commonly applied
- What developing technologies show promise for PFAS treatment
- How may integrated remedial strategies be applied
- What are the key considerations for applying field implemented and developing technologies

Treatment Technologies vs. Remediation Strategies

Treatment Technologies

- Application to specific impacted media to achieve desired treatment goals or objectives

Remediation Strategies

- Broader context
- Includes concepts surrounding targeted clean-up levels and monitoring
- May include deployment of multiple technologies
- Also addresses issues related to:
  - Administrative elements
  - Long-range planning
  - Restoration

Integrated Remedial Strategies

Develop CSM → Define Remedial Objectives → Identify Remedial Strategies

Select Treatment Technologies → Integrate Remedial Systems → Implement the Site Strategy → Operate & Maintain

Training Focus: Field-Implemented & Developing Technologies for

Source Area Soils

Source Area GW

GW Plume

Treatment Residuals

Unique Aspects for PFAS:

Limited Effective Technologies

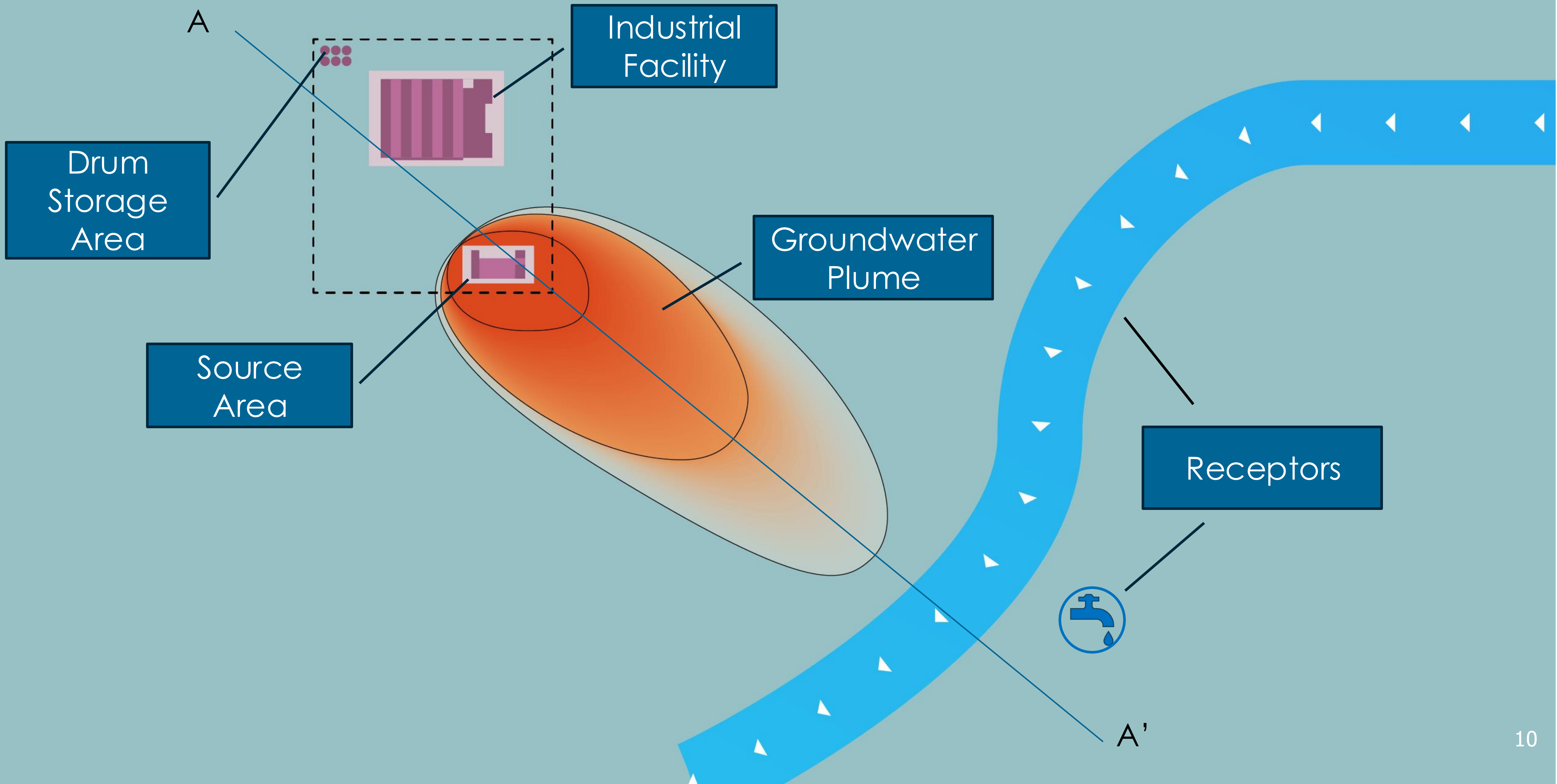
Extremely Low Cleanup Standards

Large Complex Plumes

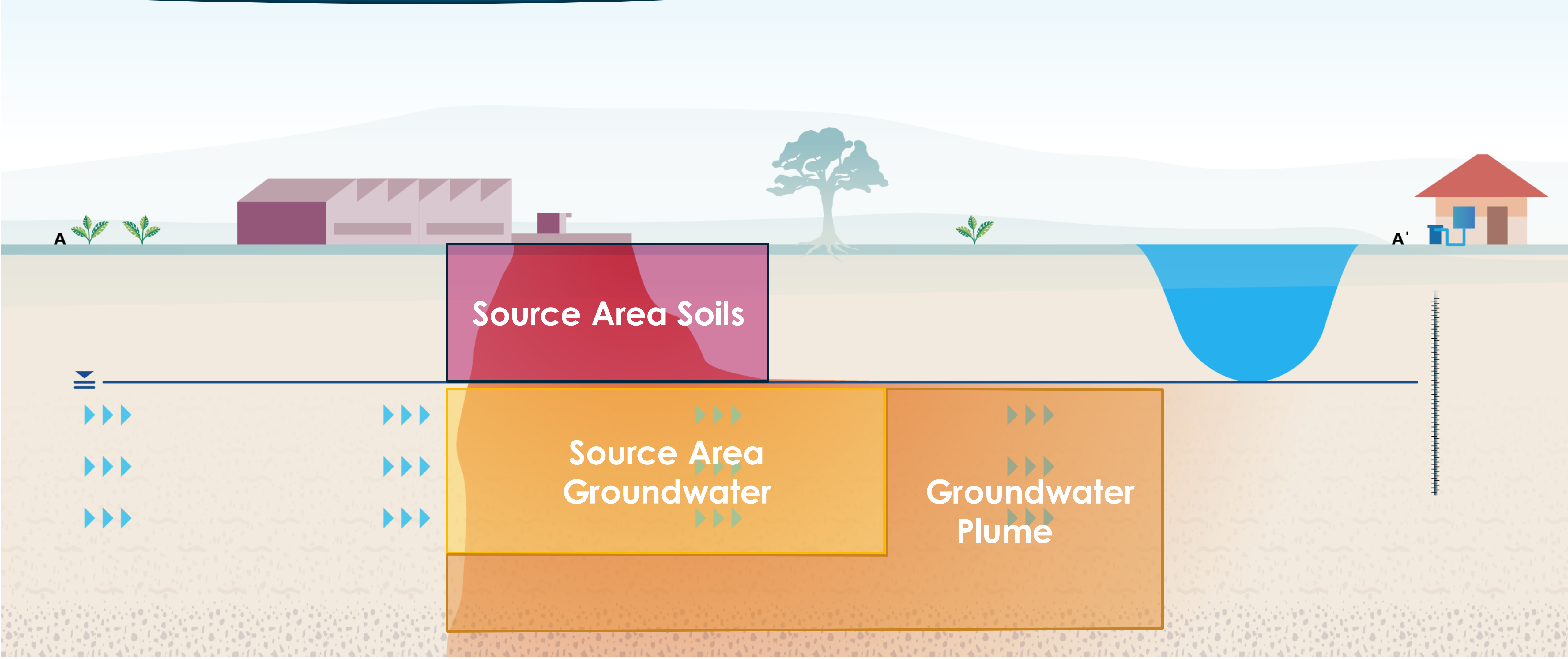
Limited Disposal Options

Probable Integration of Passive Approaches

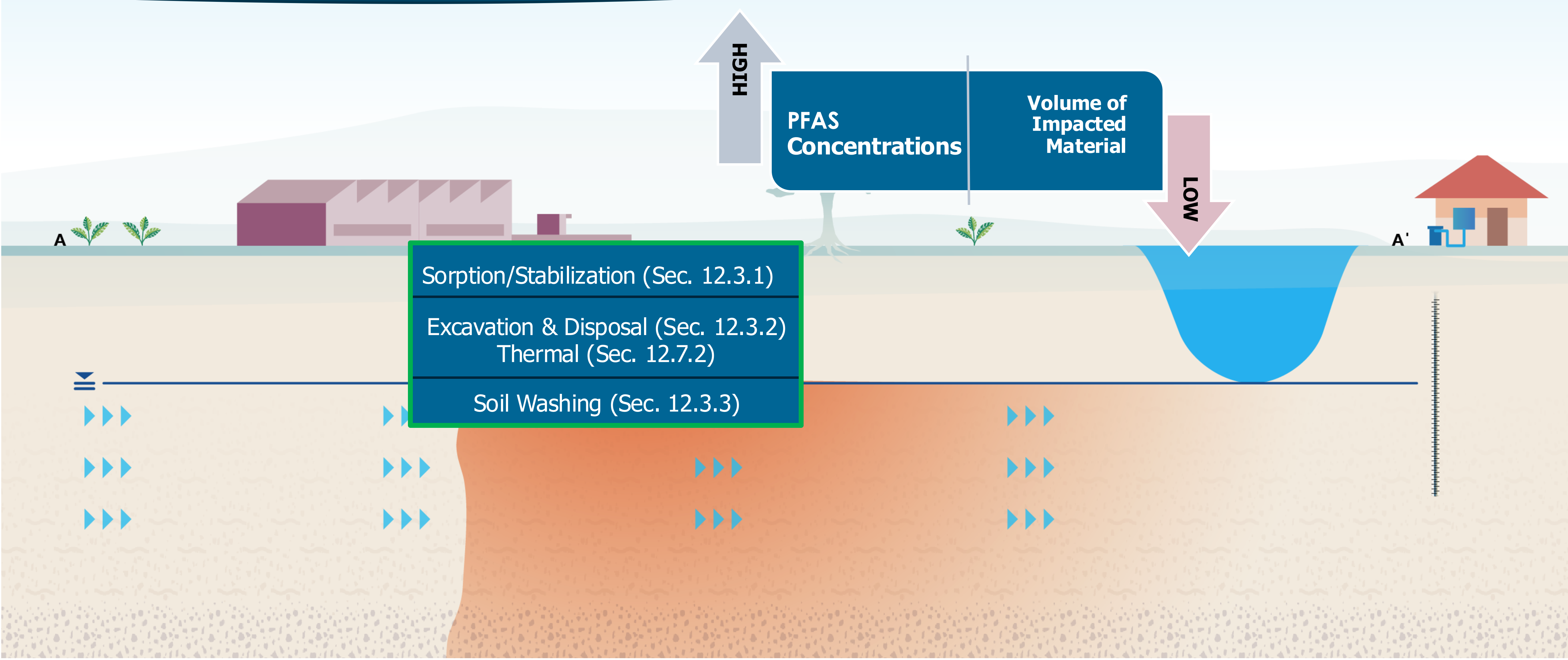
Example Conceptual Site Model (CSM)



Cross Section



Source Area Soils



Conventional Technologies

Field Implemented

- Excavation with offsite disposal in a permitted landfill, where allowed
  - Some landfills no longer will accept PFAS soils
  - Do not assume this is straightforward
- Excavation with offsite incineration
  - Destruction assumed but not well documented
  - US EPA, US DOD and other research programs looking closely at destruction

Photo courtesy of CH2M/Jacobs.
Used with permission.

Conventional Technologies – Excavation

Field Implemented

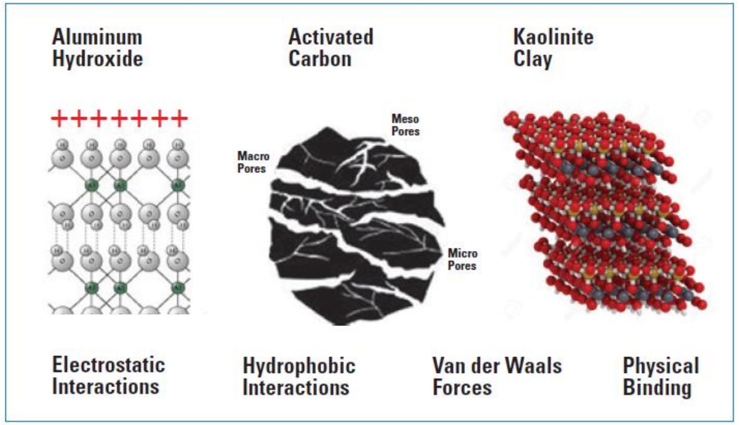
Considerations	Advantages	Disadvantages / Limitations
• Acceptability of relocating PFAS-impacted soil • Costs compared with other technologies • May need to combine with stabilization or thermal treatment prior to landfilling or reuse	• Well-demonstrated • Impacted soil removed from site and replaced with clean fill • Effectively removes source area and reduces future impacts to groundwater	• PFAS not destroyed but relocated to lined landfill • Some nonhazardous waste landfills won't accept • PFAS have been commonly seen in landfill leachate • Landfill should manage leachate • Rapidly changing regulations regarding hazardous classification of PFAS

PFAS-1, Section 12.3.2 Excavation and Disposal.

Soil Stabilization

Field Implemented

- In situ and ex situ approaches
  - Cost effective for smaller to moderate soil volumes
  - In situ possible with large diameter augers
- Amendments typically powder-based with high surface area
  - For example: powdered activated carbon, aluminum hydroxide, kaolin clay
  - Fully commercial & demonstrated



Images courtesy of Ziltek™ and AquaBlok Ltd. Used with permission.

Soil Stabilization

Field Implemented

Amendments	Design	Effectiveness	Limitations
▪ Activated carbon (powdered[1]) ▪ Aluminum hydroxide ▪ Kaolin ▪ Biochar ▪ Fly ash ▪ Concrete	▪ 2.5-5% wt/wt (Stewart and MacFarland 2017) using activated carbon blend w/inorganic minerals ▪ Bench/pilot testing - Design dosage - Adsorption capacity - Longevity	▪ Minerology/organic carbon - clays/silts ▪ High organic content[2] ▪ Ionic strength/pH - Polyvalent cations - Low soil pH ▪ High soil pH[3] ▪ Contaminant Characteristics - PFAS charge (cations more readily sorbed) - PFAS chain length (electrostatic vs hydrophobic interaction) ▪ Co-contaminants	▪ PFAS not destroyed ▪ In situ will increase soil volume – some soil removal/regrading ▪ Long-term stability - Sites with high incidence of flooding - High pH soils (e.g., concrete) - MEP (USEPA1320) ▪ Future remediation options limited

[1] Sörengård et al. 2020 shows powdered activated carbon outperformed other amendments of the 44 tested.
[2] Li, Oliver, and Kookana 2018 showed organic carbon of natural soils and sediments plays less of a role in PFAS sorption than once thought.
[3] Lath et al. 2018 showed environmental ranges of pH and ionic strength did not adversely affect binding of specialized amendment to PFOA.

Note: green text enhances effectiveness; red text decreases effectiveness

Soil Washing

Field Implemented

- Use of washing agent to separate PFAS from soil
- Fines (typically most of the PFAS) separated from coarse fraction
- Washing agent (e.g., water) subsequently treated/recycled or disposed
- Minimal waste residuals
- Full-scale system in Australia (completed) and Canada, some US pilot testing

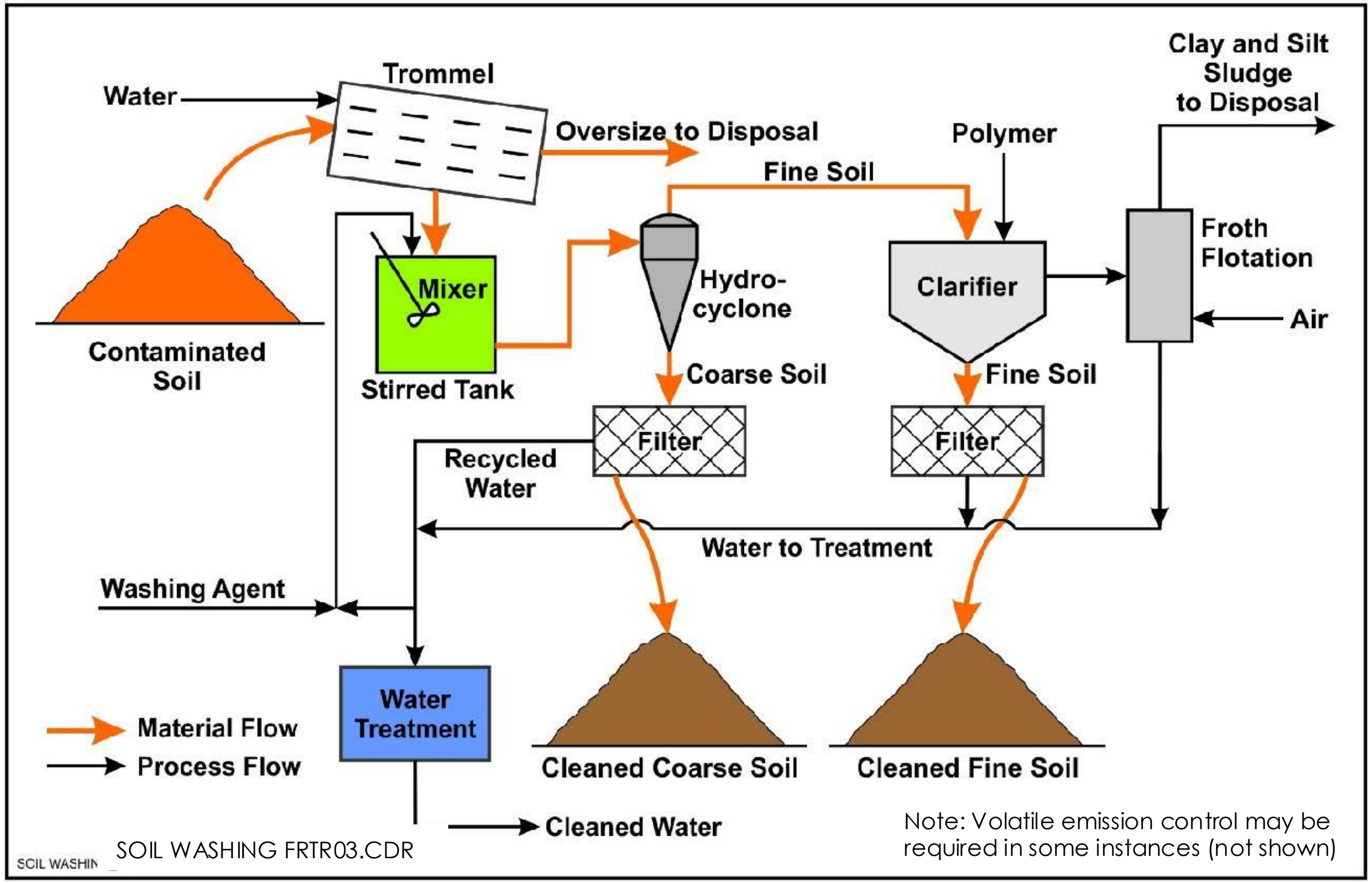


Figure Source: Federal Remediation Technologies Roundtable (FRTR) 2020. https://frtr.gov/matrix/Soil-Washing/

Soil Washing

Field Implemented

Considerations	Design	Mechanism/Effectiveness	Limitations
▪ Soil volume ▪ Less cost effective with increasing fines ▪ <25% silts and clays optimal	• Soil grain size distribution ▪ PFAS concentrations ▪ Soil throughput ▪ Wash solution (water, surfactant, solvent) ▪ Retention time ▪ Wash water – secondary treatment (e.g., GAC/IX) & residuals ▪ Soil fines further treated/disposed	Physical separation Separate coarse from fines Removal mechanisms Dissolution/suspension in aqueous phase Desorption using non-haz solvents Effectiveness (field pilots) 90-95% PFAS RE from coarse soil ESTCP[1] 88.6% RE from sand & -7.7%-61.8% RE from fines Becker[2] 99% RE from coarse soil and 89% RE from fines	▪ >50% silts/clays may not be viable ▪ Heterogeneity ▪ Inconsistent feed conditions ▪ Order of magnitude PFAS concentration differences ▪ PFAS w/higher distribution coefficients and lower solubility ▪ Soil cation exchange capacity

[1] Quinnan et al, 2022; ETSCP 2022
[2] Becker 2022; ESTCP 2022

Note: purple is residual waste that needs to be treated/disposed

Ex Situ or In Situ Thermal Desorption

Developing

- Suitable for all soil types
- Unsaturated zone source areas
- Requires 400C or higher temps, long duration, and off-gas treatment
- Removed PFAS from soil for off-gas treatment
- Bench tested a half-dozen times
- Multiple ESTCP field scale pilots and a dozen other SERDP/ESTCP projects

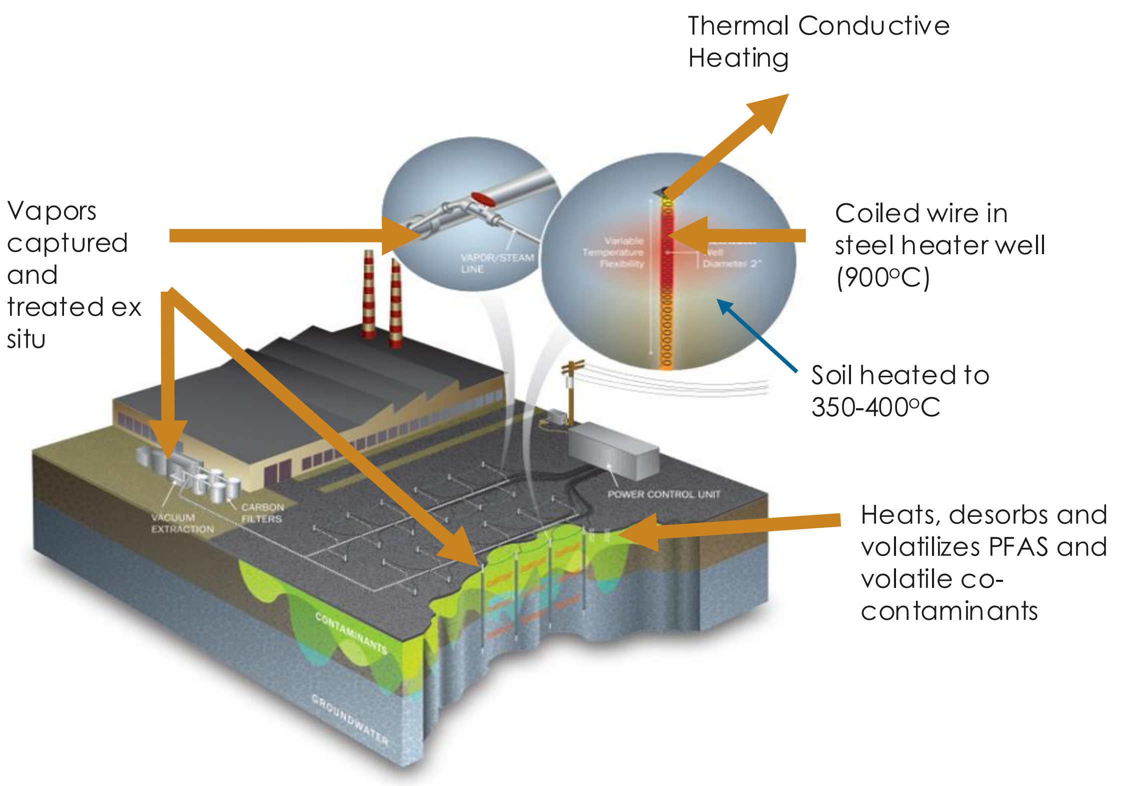


Image courtesy of Gorm Heron, TRS. Used with permission.

PFAS-1, Section 12.7.2 Thermal Treatment.

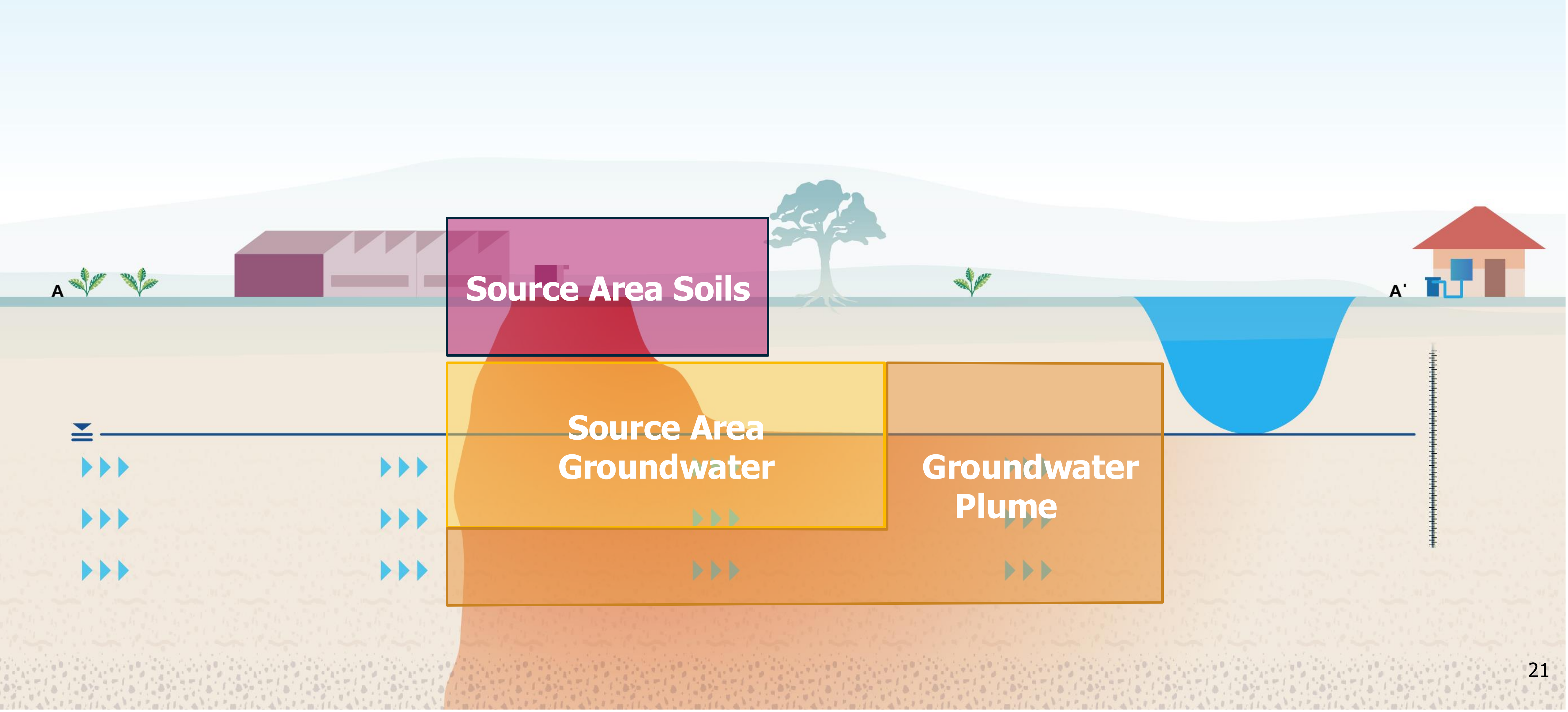
Ex Situ or In Situ Thermal Desorption

Developing

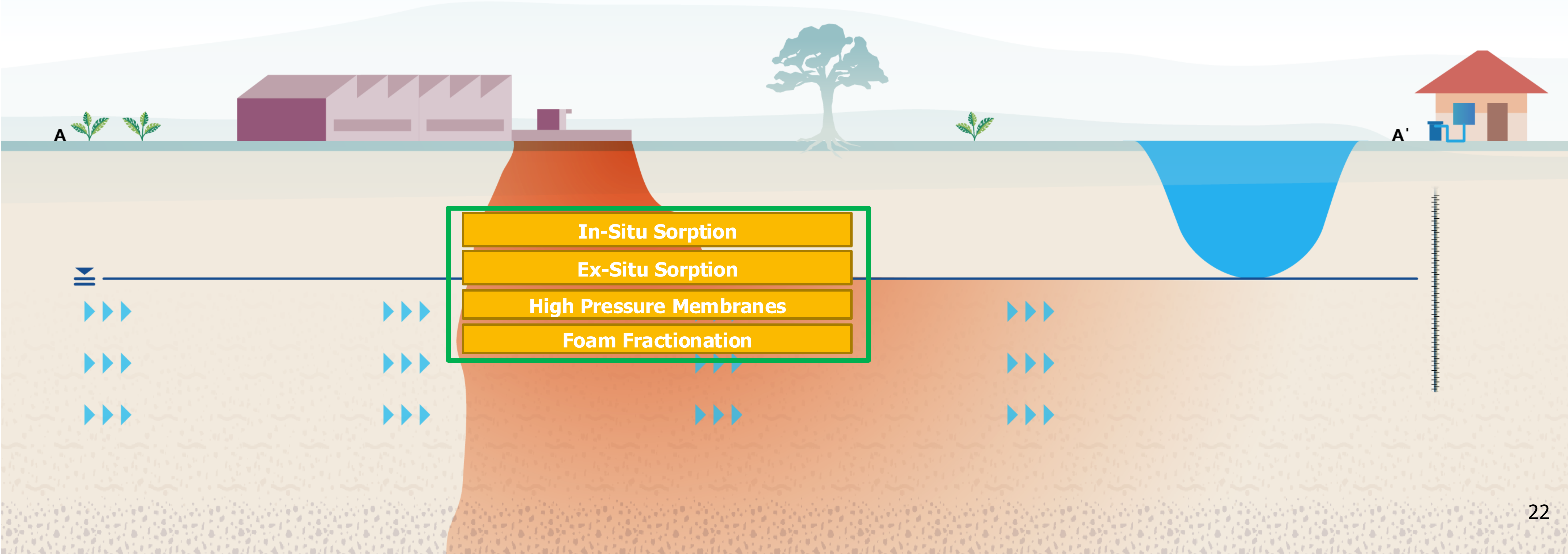
Considerations	Design	Effectiveness	Limitations
▪ Testing has been predominantly for ex situ	▪ High temperature thermal desorption and destruction (450° C – 954°C) ▪ Low temperature thermal desorption (350°C – 400°C) ▪ Off-gas treatment (e.g., air incineration with acid gas scrubber)	▪ Sufficient and evenly distributed temperature ▪ Bench-scale[1] w/low temperature thermal desorption 99.99% PFAS RE ▪ Field pilot[2] w/high temperature (450°C-954°C) >90% PFAS RE	▪ Typically not in situ ▪ Discharge of volatile PFAS ▪ Hydrogen fluoride gas/hydrofluoric acid emissions

1 Crownover et al. 2019; DiGuiseppi, Richter, and Riggle 2019
2 Endpoint Consulting 2016; Enviropacific 2017; Colgan et al. 2018; Grieco and Edwards 2019

Source Area Groundwater



Source Area Groundwater



In-situ and Ex-situ Treatment Considerations

Select Factors to Consider

- PFAS type and concentration
- Depth and areal extent of contamination
- Geology
- Depth to groundwater
- Co-contaminants and geochemistry
- Regulatory framework
- Site access

In-Situ	Colloidal activated carbon (CAC)	
Ex-Situ	Adsorption	Granular activated carbon (GAC)
		Ion exchange resin (IX)
	High pressure membranes	Nanofiltration (NF) and Reverse Osmosis (RO)
	Foam Fractionation	

PFAS-1, Section 12.2 Field-Implemented Liquids Treatment Technologies

Co-contaminants and Geochemistry

- PFAS removal or destruction is generally more efficient when co-contaminants and other water quality challenges are addressed first (pretreatment)
  - Some co-contaminants compete with PFAS for adsorption sites on treatment media
  - Some substances foul media designed to remove PFAS (e.g., inorganics and particulates)
- A complete water quality assessment is required and pilot scale treatability testing is highly recommended

Liquids Treatment – Resources

Treatment Technologies (Section 12.2)

- Sorption Technologies (Section 12.2.1)
  - Granular Activated Carbon (Section 12.2.1.1)
  - Ion Exchange Resin (Section 12.2.1.2)
- High Pressure Membranes (Section 12.2.2)
- Foam Fractionation Section 12.2.3)

Treatment Case Studies (Section 15.2)

- Granular Activated Carbon (Section 15.2.1)
- Ion Exchange Resin (Section 15.2.2)
- Foam Fractionation (Section 15.2.4)

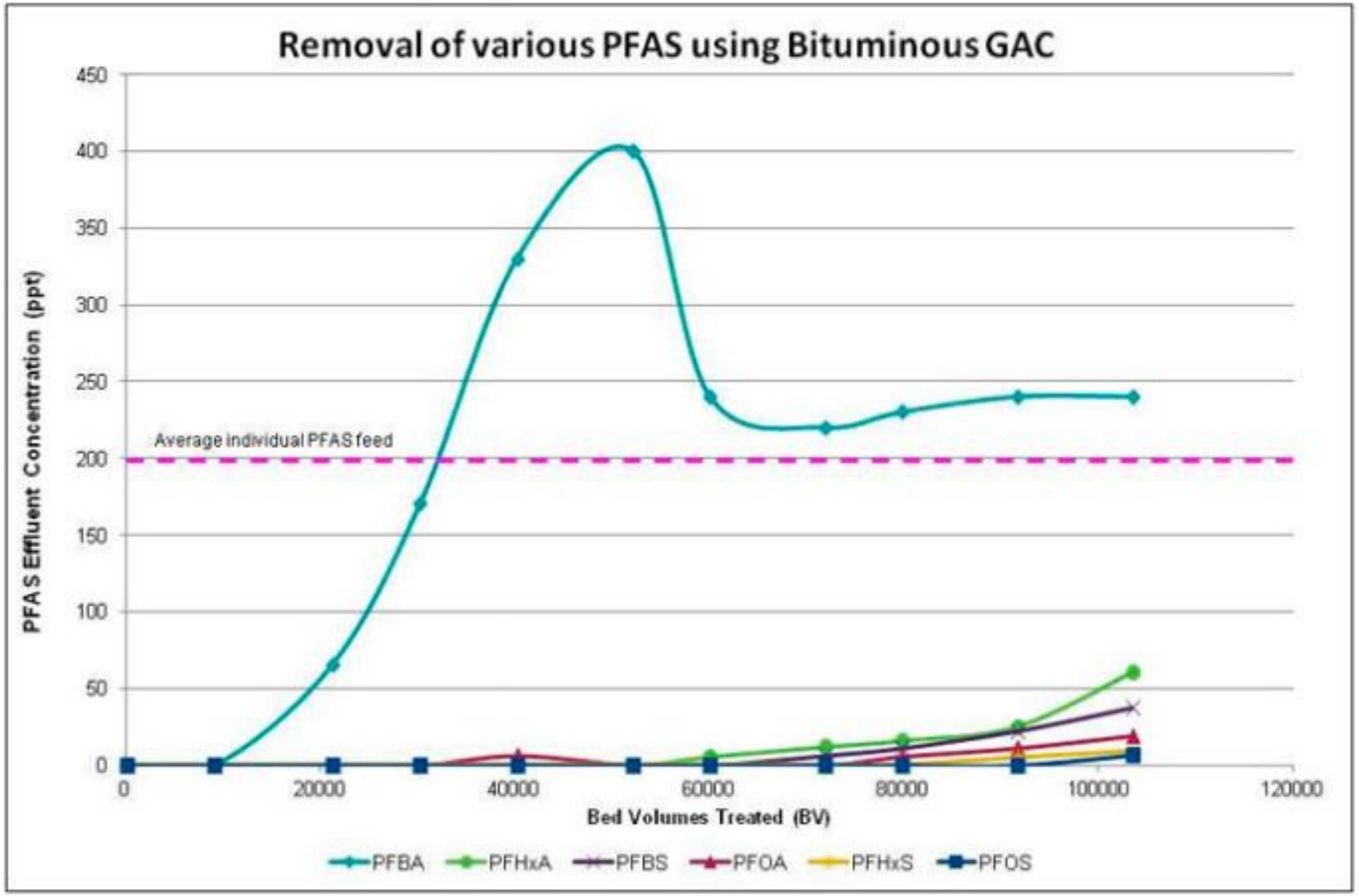
Field Implemented

Implemented in the field by multiple parties at multiple sites and the results have been well-documented in practice or peer-reviewed literature

Granular Activated Carbon (GAC)

Field Implemented

- Performance varies by carbon source, manufacturing methods, and site-specific conditions, including water quality
- PFAS adsorption capacity varies by chain length and functionality
  - Long-chains > short chains
  - PFSAs > PFCAs
- Spent GAC can be reactivated for reuse

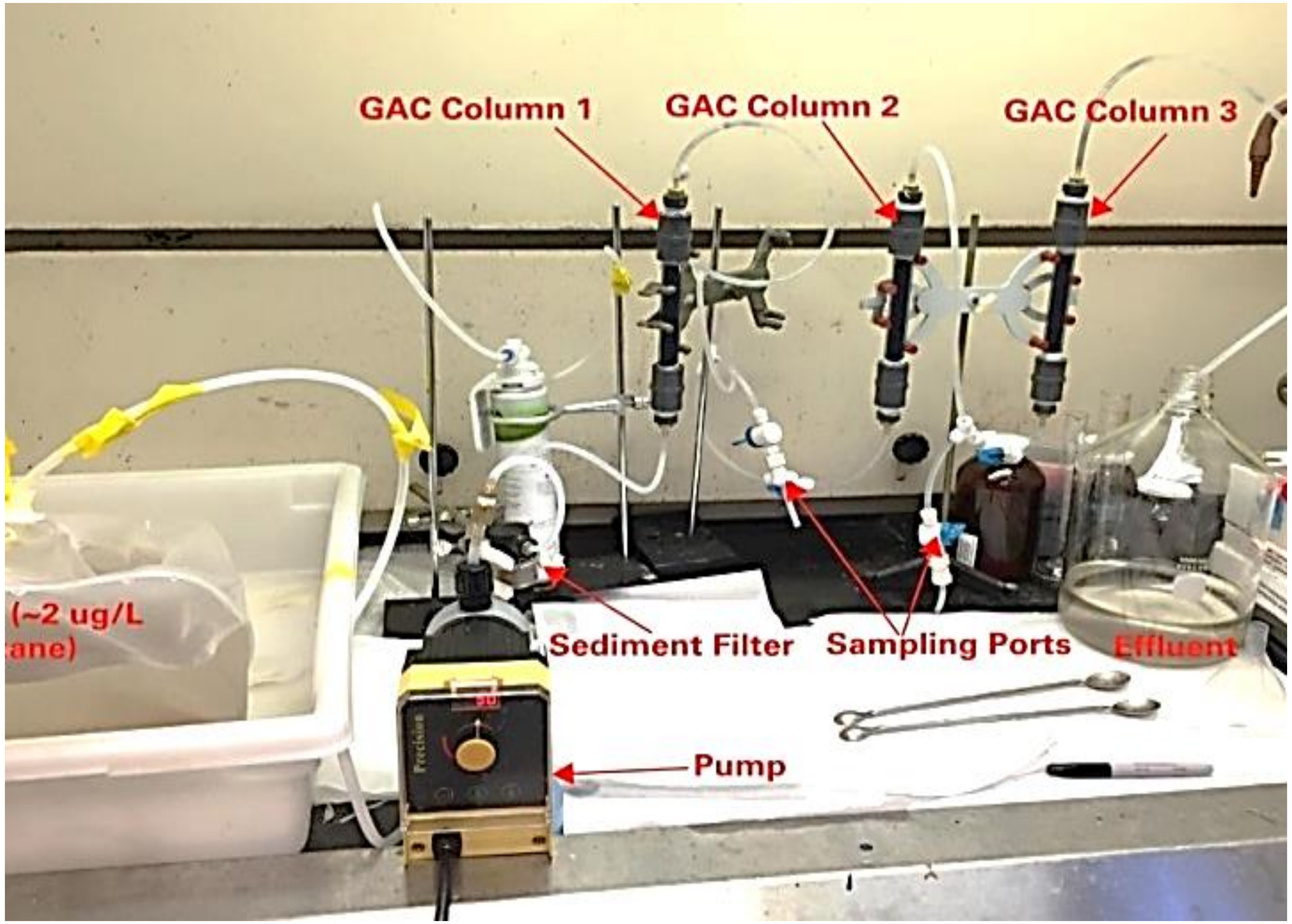


PFAS-1, Section 12.2.1.1. Figure 12-1. Example GAC removal curves at specific influent concentration. Source: Calgon Carbon Corporation. Used with permission.

Pre-Design GAC Testing

Field Implemented

- Pilot Testing
  - Use breakthrough data to compare carbon types, and optimize media usage rates
  - Results are specific to water quality conditions tested
- Rapid Small-Scale Column Tests (RSSCT)
  - Bench-scale test using finely ground GAC
  - Much less time consuming than pilot testing
  - However, field performance sometimes differs from RSSCT predictions



Example RSSCT set up

Ion Exchange (IX) Resins

Field Implemented

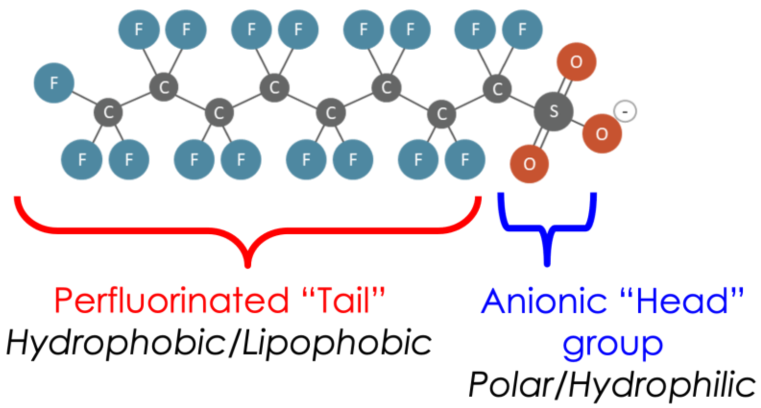
High PFAS adsorption affinity driven by electrostatic (head) and hydrophobic (tail) interactions

Smaller footprint than GAC due to shorter contact time

Common, competing ions can reduce bed life

Operation costs dependent on water quality and pretreatment needs

Perfluorooctane sulfonate (PFOS)



PFAS images used with permission from M. Olson, Trihydro.

IX Regeneration

Field Implemented

Regeneration of most PFAS-selective IX resins with conventional brine solutions is not feasible

Some can be regenerated using co-solvents in addition to brines

Wastes may be destroyed with destructive technologies

Payback relative to single-use media is application and site-specific

Pretreatment requirements to protect regenerable IX can impact life cycle cost

Regenerated resins may not be used for drinking water applications

GAC/IX at High PFAS Concentrations

Field Implemented

PFAS concentrations higher than a few µg/L may lead to impractically frequent media changeouts

Media regeneration may extend viability of IX

However, GAC/IX may still be used in combination or in addition to other technologies

High concentration PFAS streams may favor alternative technologies

Membrane Filtration

Field Implemented

Reverse Osmosis (RO)

- Effective for long- and short-chain PFAS

Nanofiltration (NF)

- Molecule size/charge dependent

PFAS-1, Section 12.2.2 Reverse Osmosis (RO).
Photo and graph source: Scott Grieco, Jacobs. Used with permission.

Membrane Filtration

Field Implemented

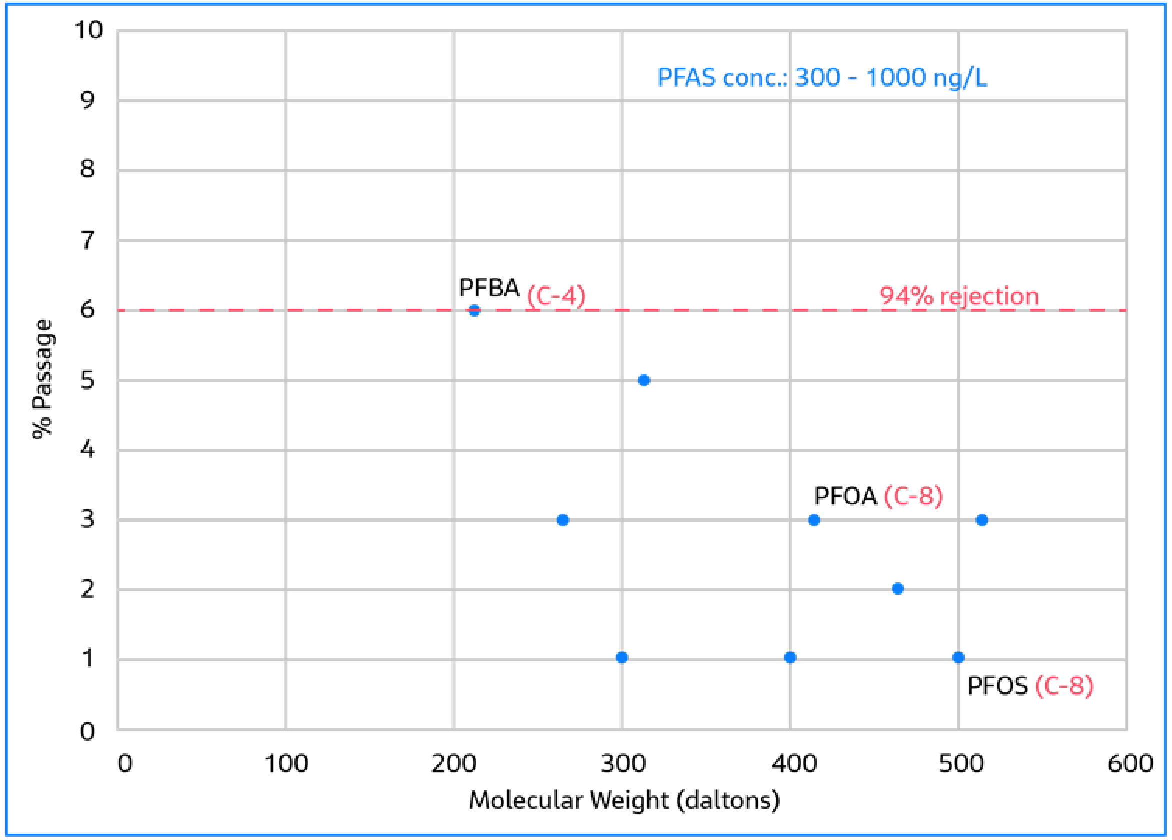
Advantages

- Effective barrier for PFAS of concern
- Provide dual role for softening and inorganics removal
- Can be effective for polar organics

Concerns

- Expense/energy use
- Pretreatment requirements for high concentrations of organic solvents and strong oxidants
- Managing liquid concentrate

PFAS Passage through Dow NF-270 (polypiperzazineamide) membrane (MWCO = 200 daltons)



Adapted from Appleman et al., 2013

Foam Fractionation

Field Implemented

Removal/concentration of amphiphilic species

- Adsorption onto rising gas/liquid interfacial surfaces
- Foamate overflows weir or recovered under vacuum
- Long-chains > short chains (adsorption coefficients)
- PFSAs > PFCAs (adsorption coefficients)

Lead or sole treatment (depending upon criteria)

Mobile or fixed installations

Pretreatment considerations

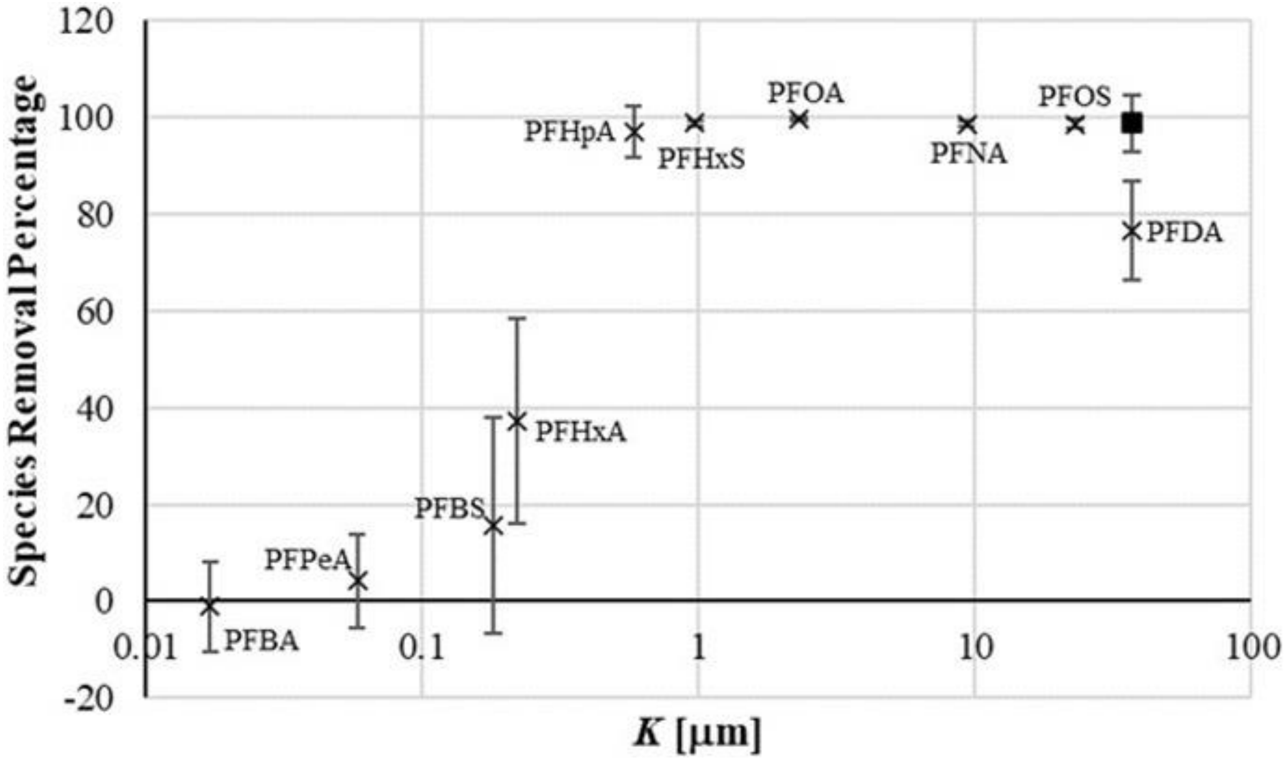
- Filtration (e.g., free-phase oil and grease, high TSS)
- Explosive vapors (>LEL)
- Auto-acid dosing to prevent scaling and post foam fractionation precipitation in polishing treatments

PFAS-1, Section 12.2.3 Foam Fractionation
Case Study PFAS-1, Section 15.2.4.2

Foam Fractionation

Field Implemented

- Operational modes
  - Stripping (wet) – higher PFAS removal; greater volume of foamate
  - Enrichment (dry) – lower PFAS removal; lower volume of foamate
- Single or multi-stage with batch, semi-batch or continuous operation
- 10 to 60 minute hydraulic retention time (HRT) per primary vessel
- Optimization: aeration, HRT, foam boosters



Select PFAS species removal vs. adsorption coefficient (K)

Foam Fractionation – Foamate Enrichment

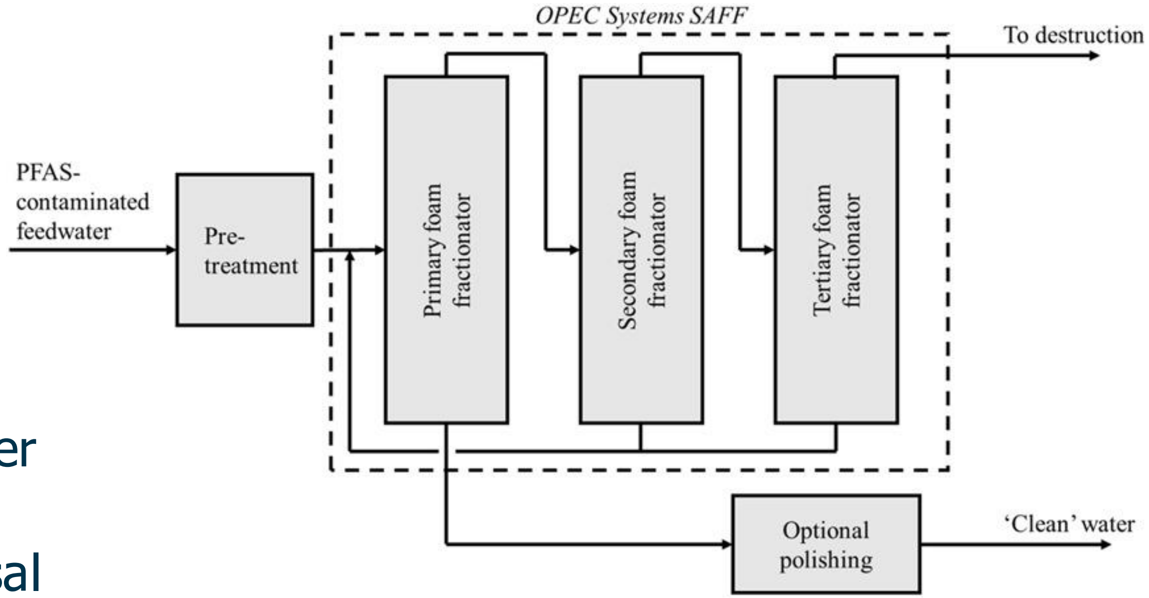
Field Implemented

Highly enriched/low volume aqueous waste

- Concentrates PFAS, surfactants, and suspended solids
- 5-50x enrichment single stage FF (no vacuum)
- Up to 1,000,000x enrichment in three stage FF
- Pair with destruction technologies in treatment train approach

Low operational expenses

- High compatibility/resilience with complex wastewater chemistry
- Avoidance of exhausted media replenishment/disposal
- Primary cost is electric consumption (pump, foam boosters)



SAFF® Process Flow Diagram

Figure Source: Burns et al. 2021. Figure 1. Creative Commons CC-BY

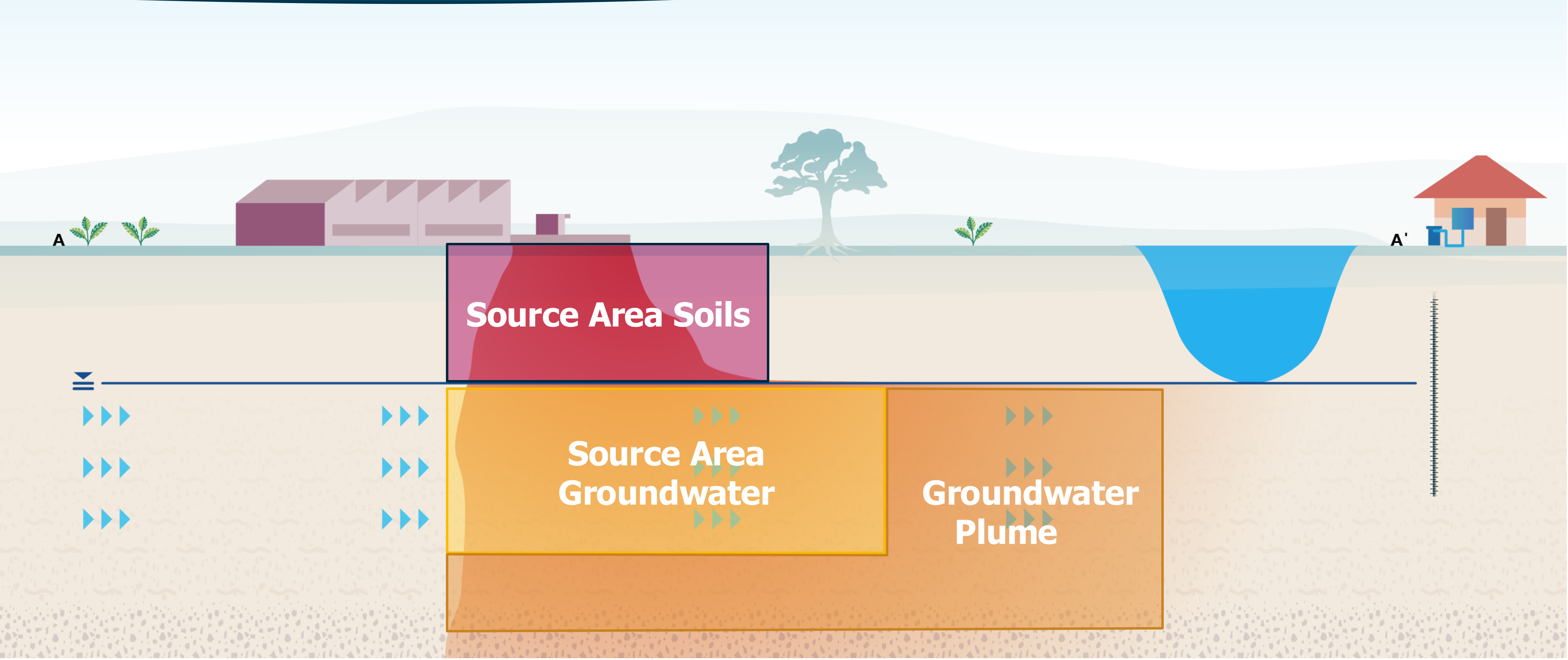
Case Study: Foam Fractionation

- SAFF® compared to SAFF ® +AIX polished water
- No foam boosters (co-surfactants) added
- 3-year field trial converted into additional 5-year remediation contract
  - Expanded groundwater extraction well network combining trace/high PFAS concentration zones
- Highly concentrated foamate
  - Economic disposal or destruction
  - Reduces site liabilities
- Treated water reuse on site
  - Irrigation, dust suppression, aquifer injection well

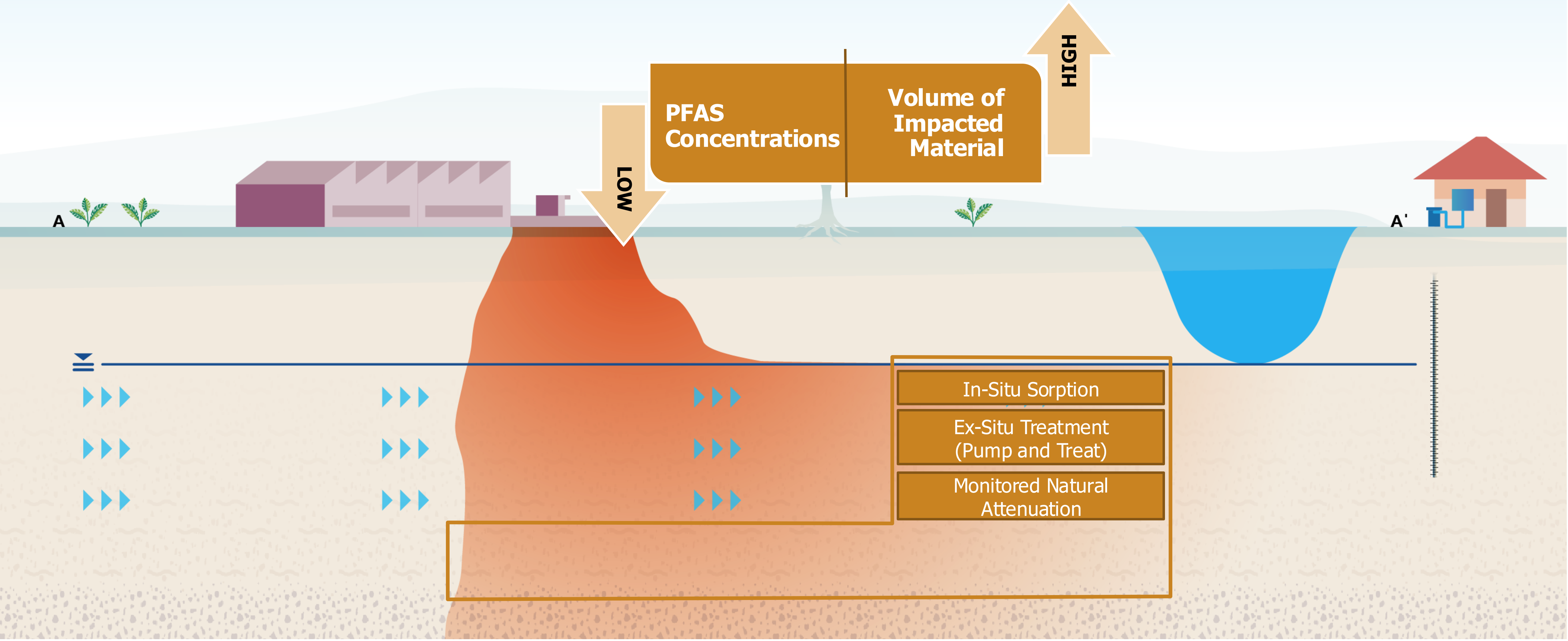
Figure Source: Burns et al. 2021. Figure 2. Creative Commons CC-BY

Questions

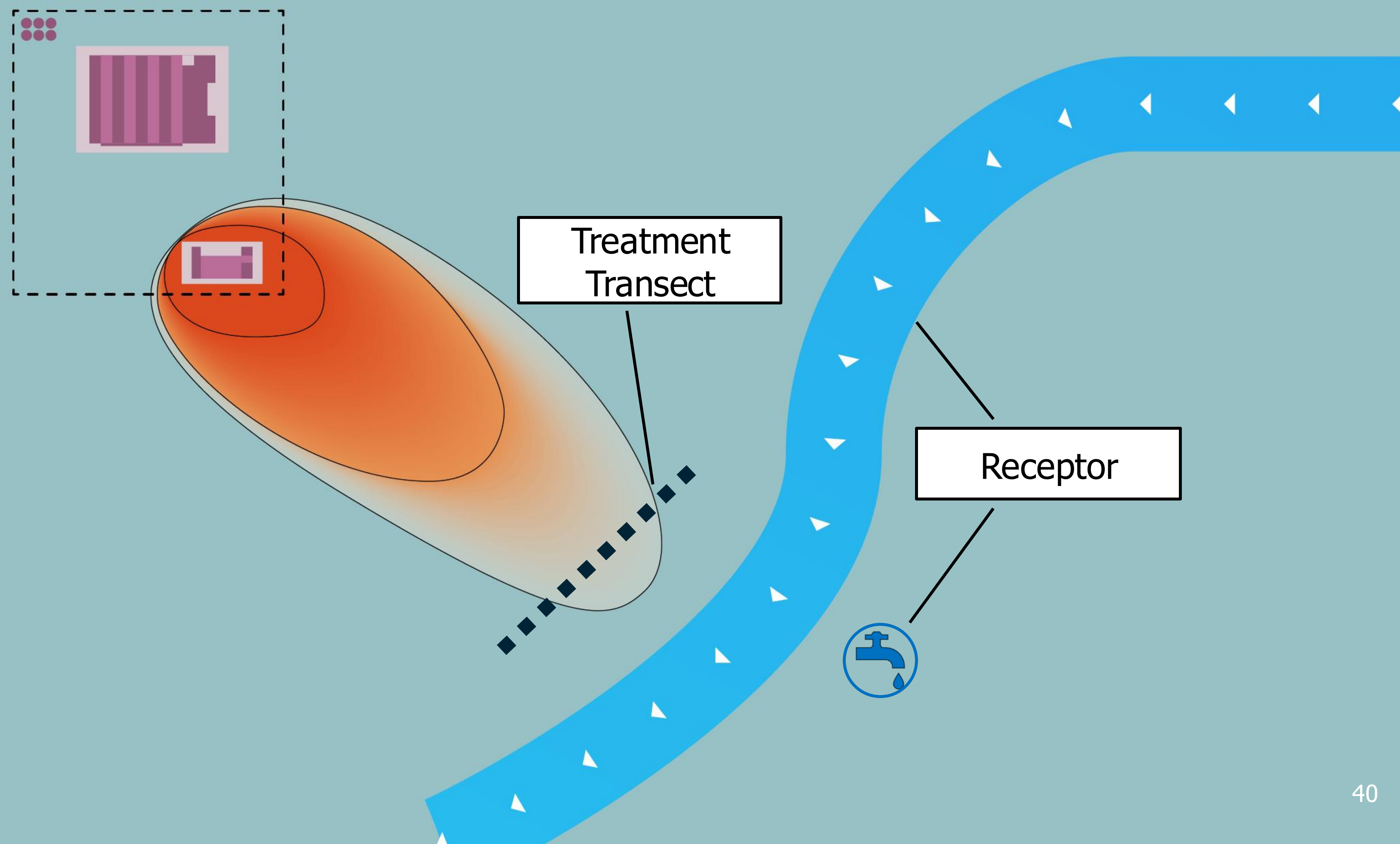
Groundwater Plume



Groundwater Plume



Groundwater Plume – In-Situ Sorption



In Situ Sorption – Colloidal Activated Carbon (CAC)

Field Implemented

Highly sorptive activated carbon particles ~2 microns in diameter dispersed in water

Small enough to move through soil pores and distribute within PFAS contaminated aquifer zone

CAC particles permanently coat aquifer matrix

Source: Photo used with permission from S. Wilson, Regenesis

PFAS-1, Section 12.2.4 In Situ Remediation with Colloidal Activated Carbon.

In Situ Sorption – Colloidal Activated Carbon (CAC)

Field Implemented

- CAC is injected directly into PFAS contaminated aquifer zone
- Creates an *in-situ* filter
- PFAS is immediately sorbed out of groundwater and bound to the CAC-coated aquifer matrix
- PFAS is immobilized from migration, removing exposure pathway to downgradient receptors

In Situ Sorption – Colloidal Activated Carbon (CAC)

Field Implemented

Advantages

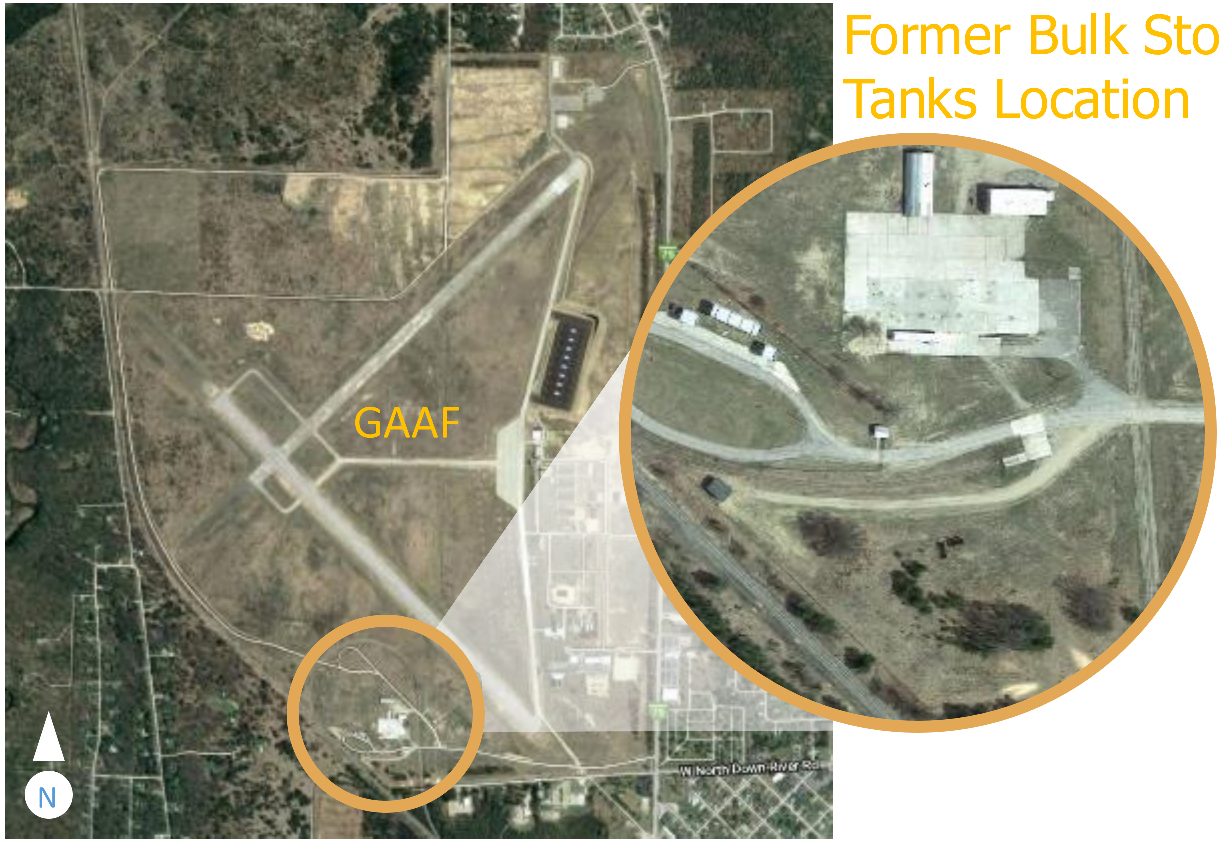
- Minimizes risk of PFAS exposure to downgradient receptors
- No PFAS waste generated
- No operation/maintenance
- Very resilient vs climate change compared to pumping approaches
- Treats co-mingled PFAS/hydrocarbon/VOC Plumes

Limitations

- Longevity dependent on PFAS composition, rates of discharge, co-contaminants, dosing, application design
- Effectiveness dependent on adequate distribution through PFAS-containing zones
- Potentially cost prohibitive for large, deep plumes
- Requires routine monitoring to evaluate the need for potential reinjection events

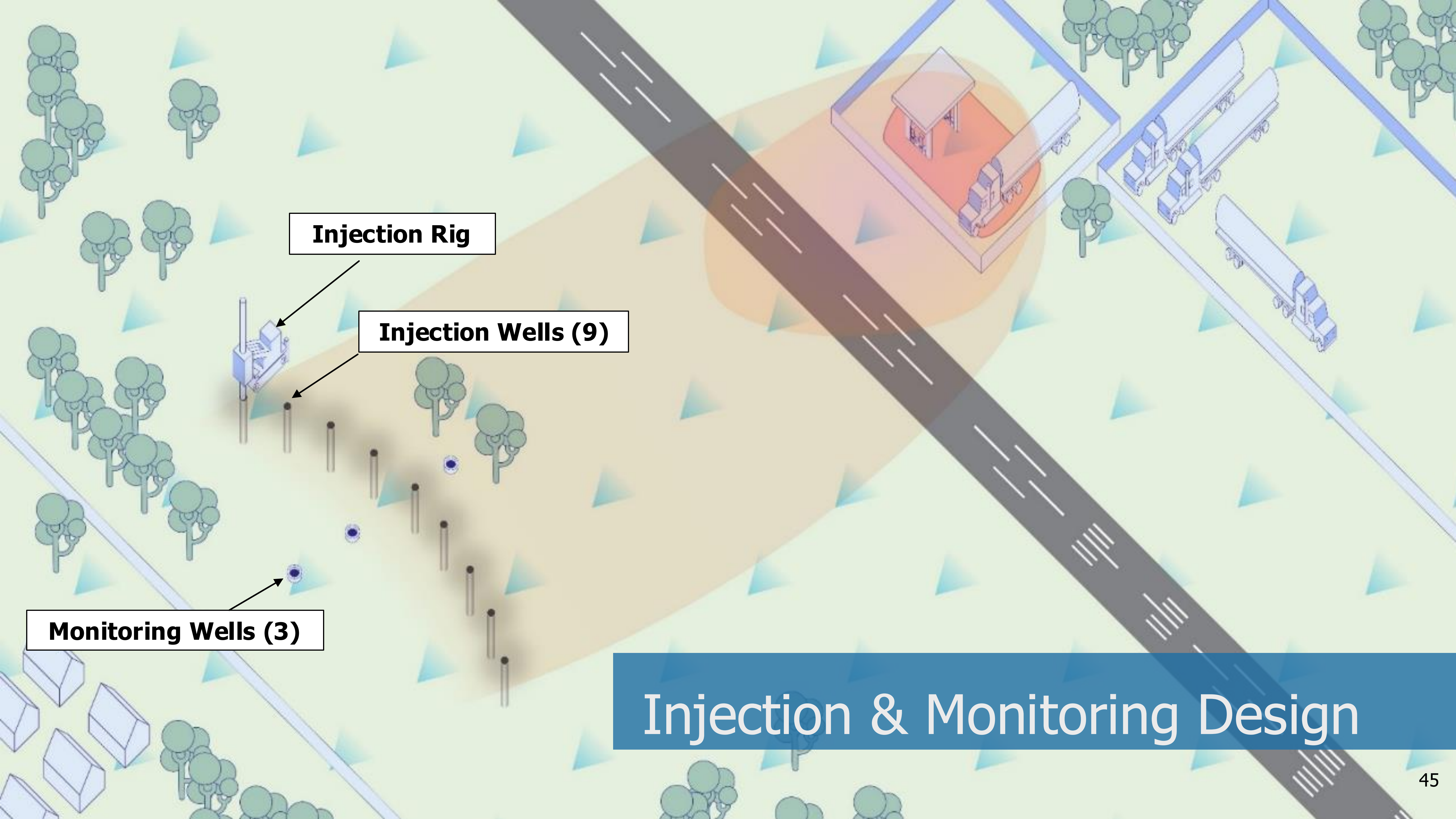
Case Study: PFAS in Groundwater, Crawford County, MI

Former Bulk Storage Tanks Location



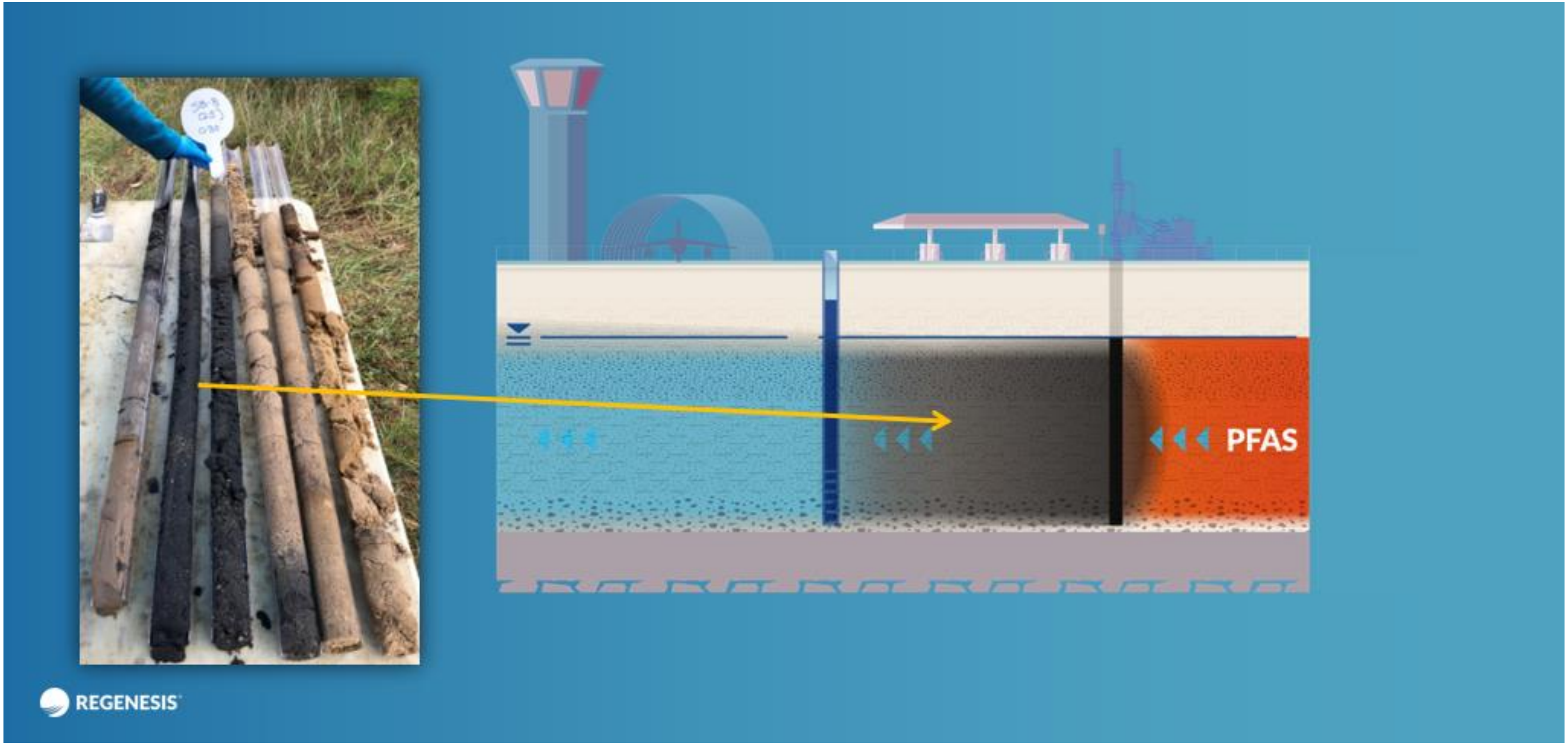
Site Details

GW Velocity	250 ft/yr
Vertical Treatment Interval	15’-27’ bgs.
Injection Wells	9
Soil Type	Sand & Gravel, some clay layers
Sensitive Receptors	Residences, Surface water bodies, Property Boundary
Contaminants of Concern	8 µg/L PCE, 130 ng/L Total PFAS (PFOS, PFHxS)



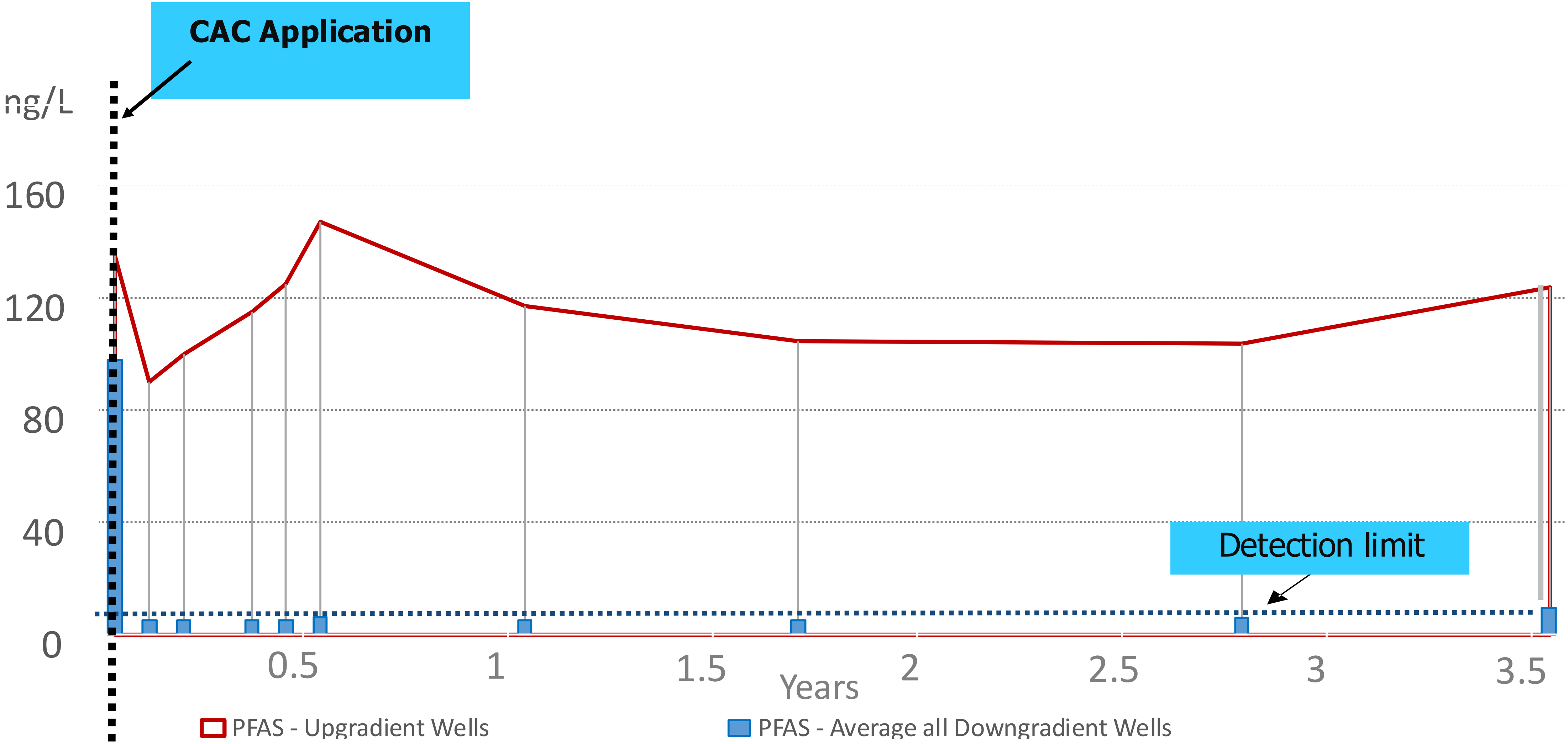
Injection & Monitoring Design

Case Study: CAC-Distribution Confirmation



PFAS-1, Section 15.2.3 Colloidal Activated Carbon, Figure 15-17

Case Study: Performance Monitoring (PFAS)



PFAS-1, Section 15.2.3 Colloidal Activated Carbon

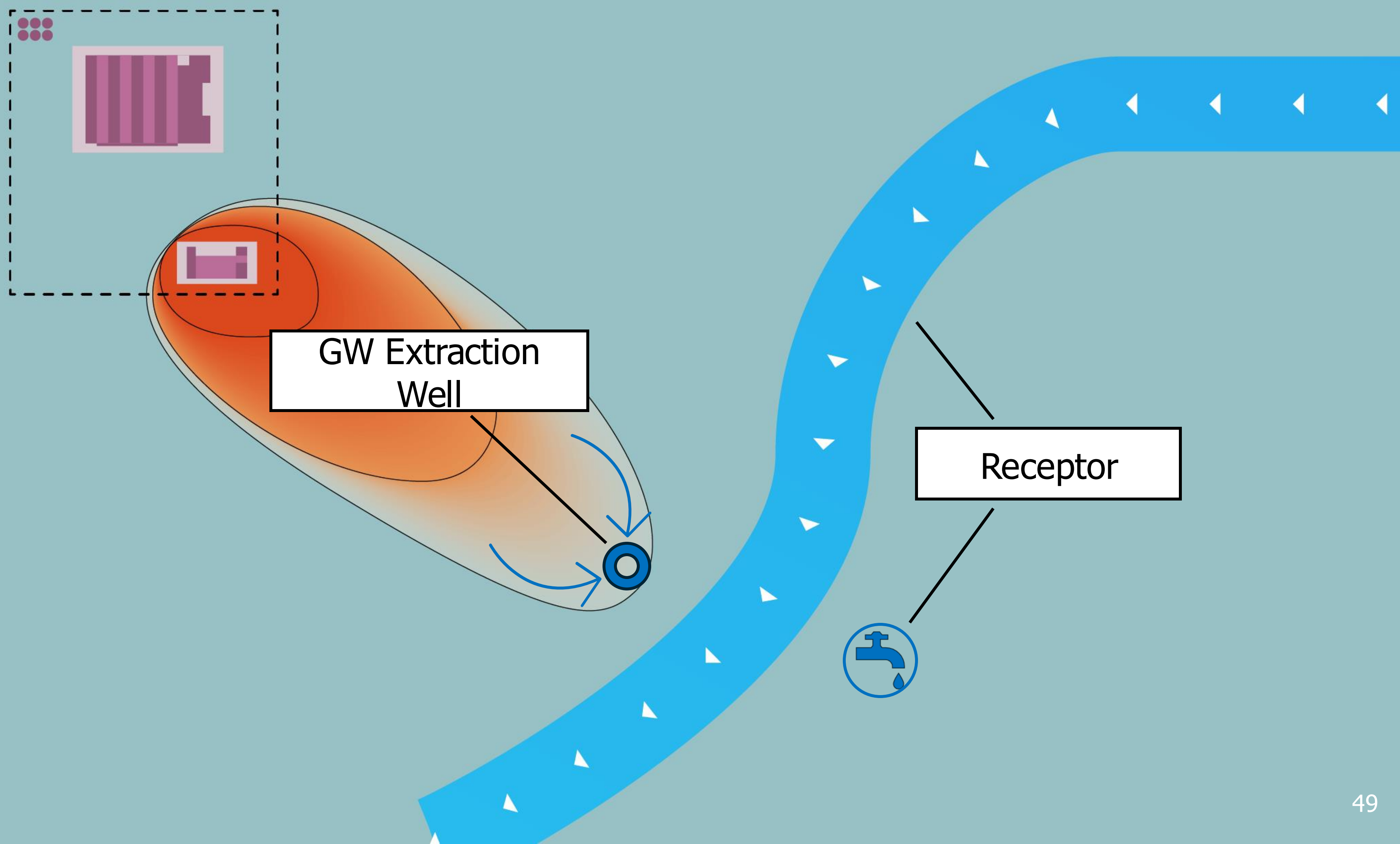
Case Study: Summary

Sustained reductions in total PFAS at or below detection limits for >4 years

No PFAS waste for disposal or destruction

Longevity is expected to last decades

Groundwater Plume Mgmt – Pump & Treat



Groundwater Plume Mgmt – Pump & Treat

Main objective of **hydraulic containment** as opposed to PFAS mass removal

Similar ex-situ treatment technologies as for high concentration liquids – **treatment train** approach

- Emphasis on separating and concentrating

Active treatment methods:

- Sorption – GAC and IX
- High pressure membranes
- Foam fractionation

Groundwater Plume Mgmt – Pump & Treat

Advantages

Employs treatment technologies not suitable for in-situ approaches

Ex-situ treatment trains can be designed to treat many contaminants

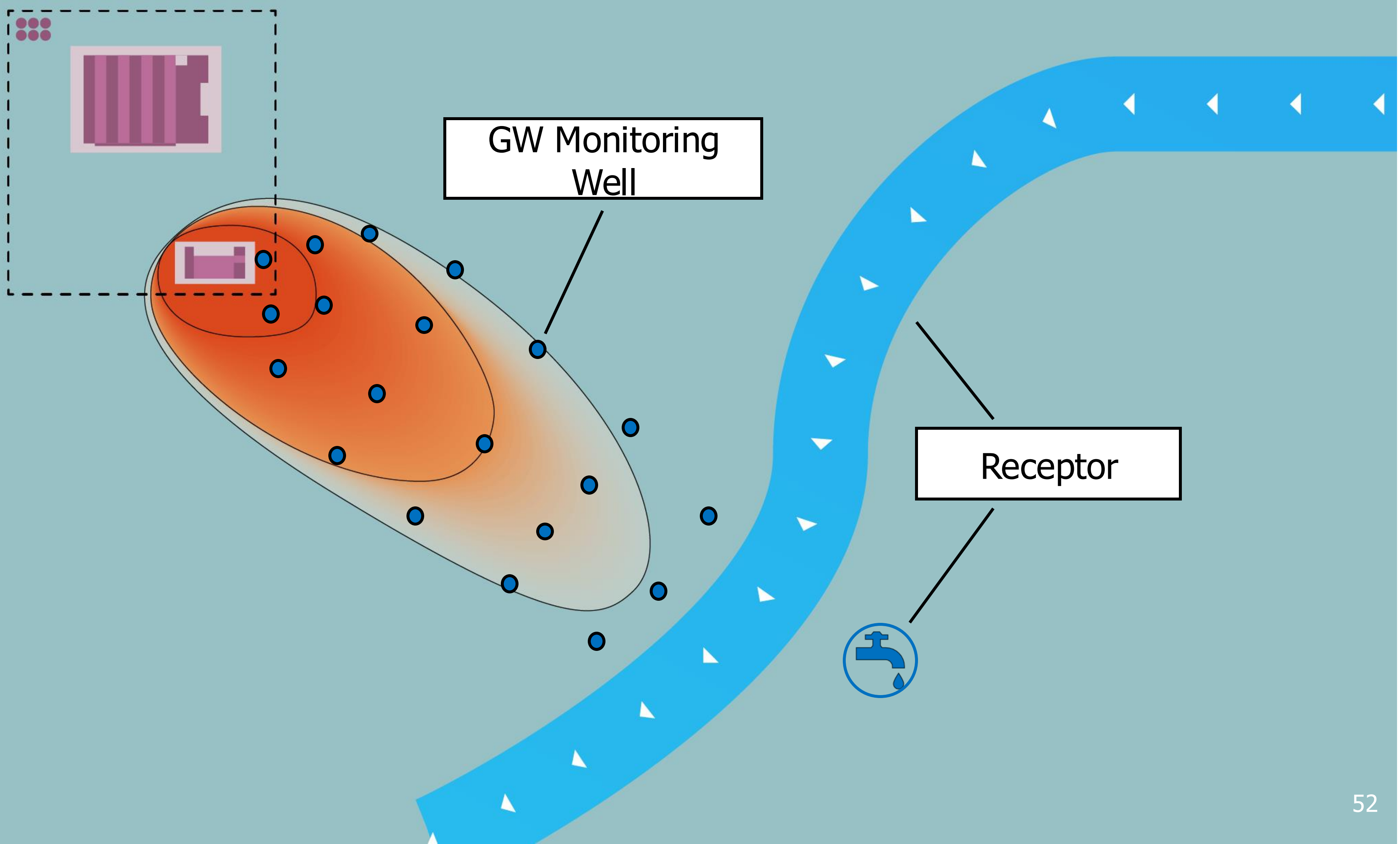
Limitations

Challenges for large, dilute, and/or disjointed plumes

Sustainability concerns:

- Treatment complex construction
- Utilities
- Water collection and pumping
- Discharge infrastructure

Groundwater Plume – Monitored Natural Attenuation (MNA)



Groundwater Plume Mgmt – Monitored Natural Attenuation

Limitations

Most applicable for sites with:

- Stable plume
- Long travel time to potential receptors
- Low/decreasing mass discharge rates

Lack of sufficient data for most PFAS sites

- Robust data sets are needed to establish appropriate supporting lines of evidence for MNA

MNA is **not** a "walk away" approach – evaluate with caution

PFAS-1, Section 12.6.7, Monitored Natural Attenuation

Groundwater Plume Mgmt – Monitored Natural Attenuation

Attenuation processes for PFAS may include:

- Dispersion
- Dilution
- Sorption
- MNA has been applied for both organic and inorganic contaminants

Not all degrade; some are attenuated through nondestructive processes

- MNA of PFAS is analogous to MNA of non-degrading inorganic contaminants/metals

Groundwater Plume Mgmt – Monitored Natural Attenuation

Scenario 1:

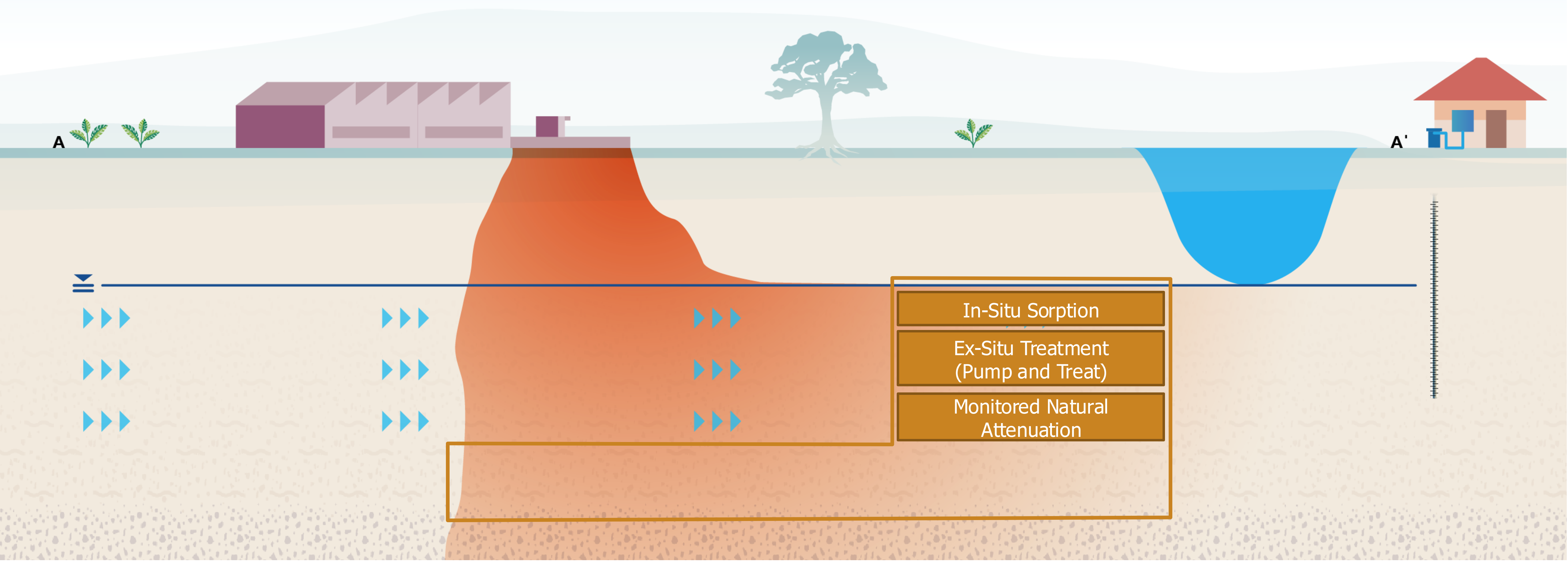
Final remedy component for plume segments where data demonstrate natural attenuation trends that can **achieve comparable outcomes versus active treatment technologies** for time frames to attain the remediation objectives

For example, lower parts per trillion plumes or distal plume segments; scatter/random PFAS detections that do not represent a defined plume

Scenario 2

MNA is a final treatment train step to reach low parts per trillion cleanup levels once **active treatment has reached a defined interim treatment objective or plateau** condition/point of diminishing returns (assuming lines of evidence supporting MNA has been established)

Groundwater Plume



High Concentration Waste Management

Solids

- Spent adsorbent media
- Mechanical filtration
- Precipitates
- Soil fines from soil washing

Liquids

- Foam fractionation (foamate)
- Membrane concentrate
- Liquid from soil washing
- Regenerable resin brines

Residuals Management – Treatment Options

Solids

- Disposal (subtitle C or D)
- High temperature incineration or thermal treatment
- Thermally reactivated carbon
- Limited application/developing technologies
  - SCWO
  - Pyrolysis and gasification

Liquids

- Disposal
- Deep well injection
- High temperature incineration
- Limited application/developing technologies
  - SCWO
  - Electrochemical oxidation
  - HALT
  - Plasma
  - Sonolysis
  - UV-sulfite hydrated electrons

Incineration for PFAS-Contaminated Media

- Temperatures and residence times in excess of minimum required (1100°C and 2 seconds)
- Practitioners should confirm vendor licensing and operational status prior to shipping wastes for disposal

Pros	Cons
1. Only readily available disposal technology that has the potential to result in the destruction of PFAS 2. Destruction has been documented in laboratory studies 3. Some are designed to handle flue gases and scrubber wastes 4. Generators may be able to obtain a disposal certification from the incineration facility	1. Temperatures, residence times, and emissions controls may not be adequate to fully degrade PFAS at some facilities 2. Potential for partial decomposition of PFAS to shorter carbon chain-length PFAS 3. Difficulty handling high-water content wastes 4. Current regional and local moratoria exist in some locations against incinerating PFAS waste

USEPA. 2024. Interim Guidance on the Destruction and Disposal Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances – Version 2. https://www.epa.gov/pfas/interim-guidance-destroying-and-disposing-certain-pfas-and-pfas-containing-materials-are-not

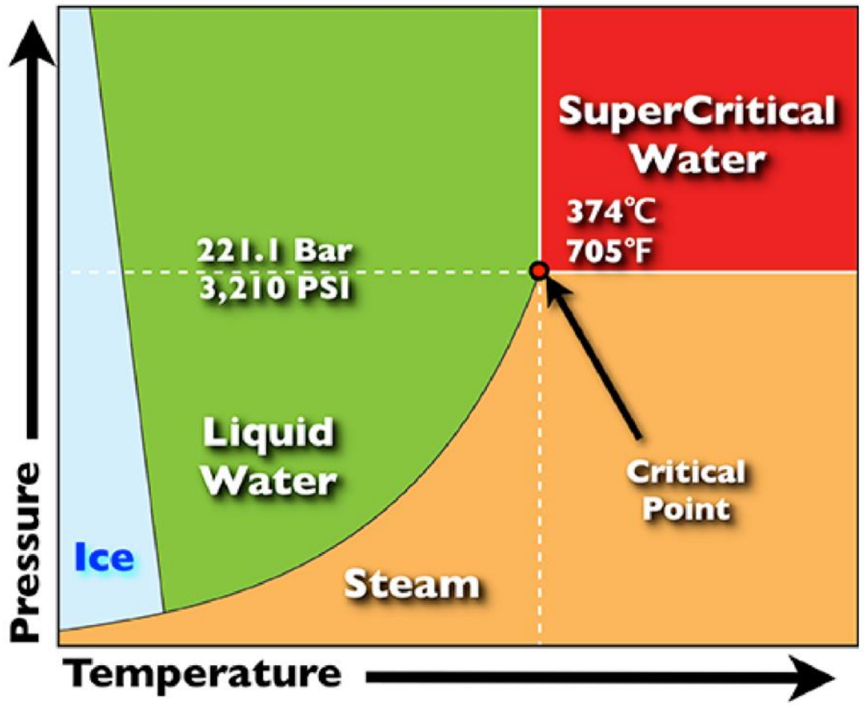
PFAS-1, Section 12.4 Incineration.

Supercritical Water Oxidation – (Liquid and Solids)

Developing

Technology

- Water >374°C and pressure of 221.1 bar is considered "supercritical"
- Under these conditions, certain chemical oxidation processes are accelerated
- SCWO Technology was developed for other recalcitrant organics back in 1980s and is mature



Design Considerations

- Oxidation source (air, oxygen, hydrogen peroxide)
- Air flow rate, corrosion control, temperature profile to heat and cool down, calorific values, particle size for solid wastes, feedstock pumpability, GHG generation, energy consumption

PFAS-1, Section 12.6.3.12 Supercritical Water Oxidation.

Figure Source: Jonathan Kamler, Attribution-Share Alike 4.0 International

Supercritical Water Oxidation – (Liquid and Solids)

Developing

Advantages

- Complete destruction of PFAS and PFAS-laden solids
- Short reaction time (seconds)
- Equally effective for long and short chain PFAS
- Works for other COCs
- Low energy requirements with heat recovery
- Commercially available

Limitations

- High capital cost for scale-up system
- Energy efficient only when running 24/7
- Chemical amendments (e.g. co-fuel) may be needed
- Inability to treat high salinity feedstock

Photo Source: J. Follin, General Atomic. Used with permission.

Hydrothermal Alkaline Treatment (HALT) (Liquids and Solids)

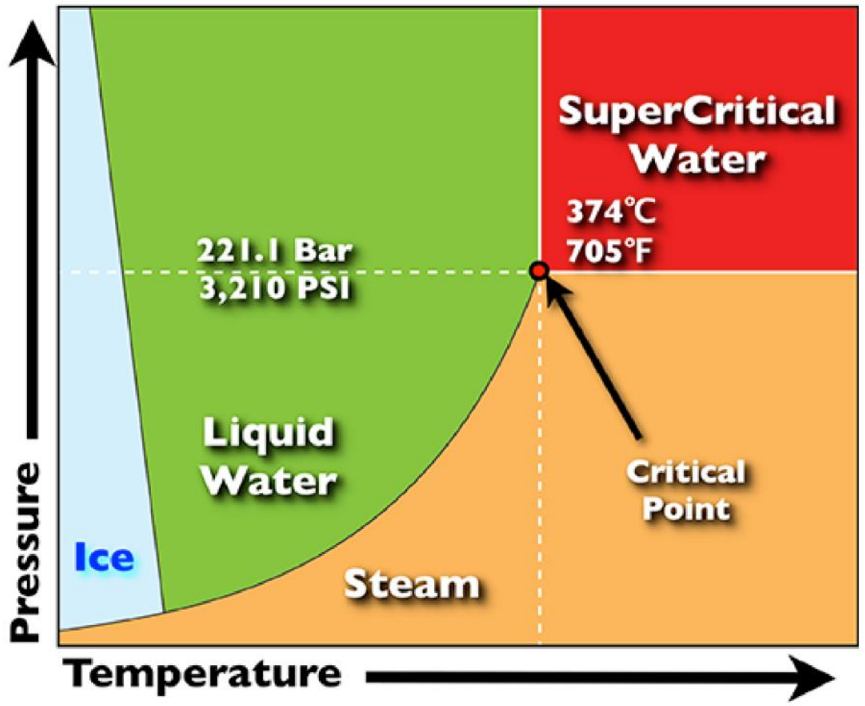
Developing

Technology

- Slightly cooler than supercritical conditions:
  - ~350 °C (660 °F)
  - 248 bar (3600 psi)
  - NaOH amendment
- PFAS mineralized, creates NaF and KF

Applications

- Bench scale-tested in a SERDP project
  - AFFF stockpiles, fire training pond water, leachate and foam fractionate
- Limited field pilot demonstrations ongoing



Hydrothermal Alkaline Treatment (HALT) (Liquids and Solids)

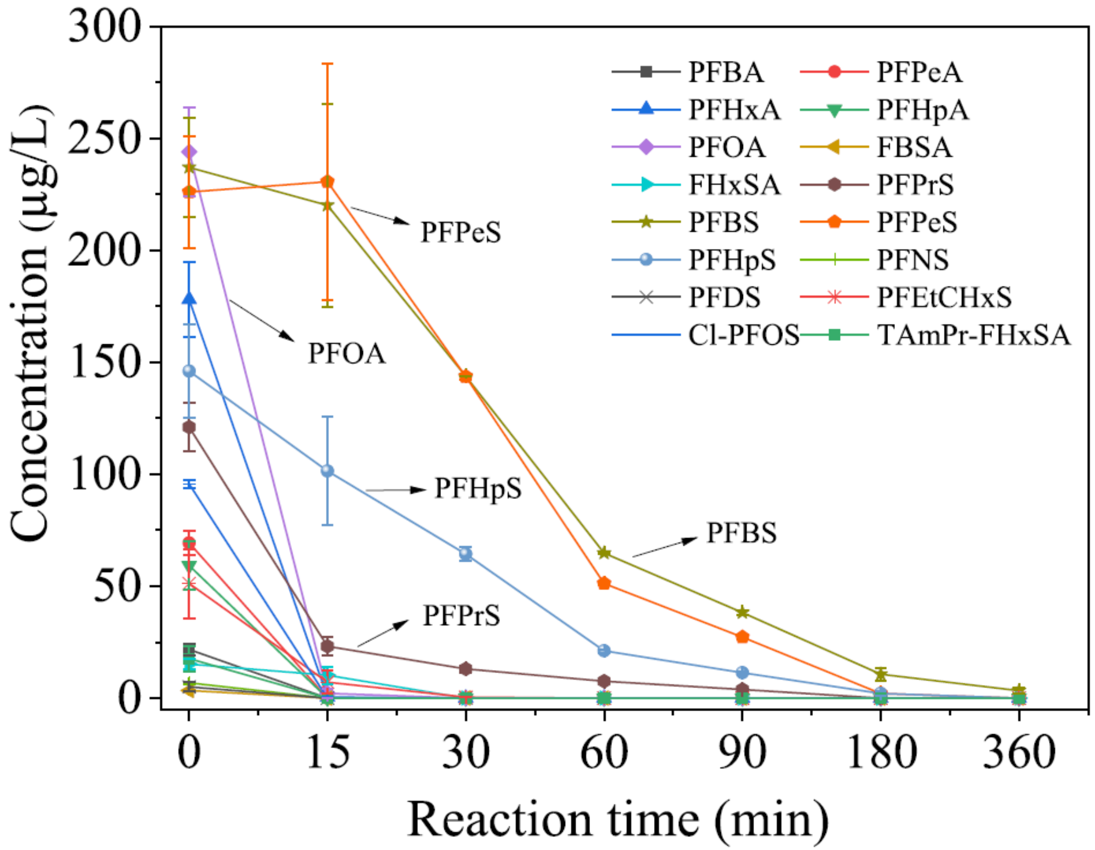
Developing

Advantages

- High destruction
- Short residence time
- Treat high salinity water
- Low energy requirements with heat recovery
- Effective for short and long chain PFAS
- Potential to regenerate spent GAC

Disadvantages

- Need common chemical amendment for pH requirement
- Less demonstrated and still developing



Electrochemical Oxidation (Liquids)

Developing

Technology

- Electrochemical cells containing reactive anodes and cathodes (the electrodes) are used to destroy PFAS concentrates
- Electrode materials matter (Boron-doped diamond, MMO, titanium suboxide, etc.)
- Uses direct current (DC) to mineralize PFAS
- PFAS removal and destruction through direct electrochemical destruction, indirect oxidation, some sorption and PFAS foam generation
- Not selective on which contaminants to destroy
- Perchlorate generation is directly related to chloride concentrations in waters

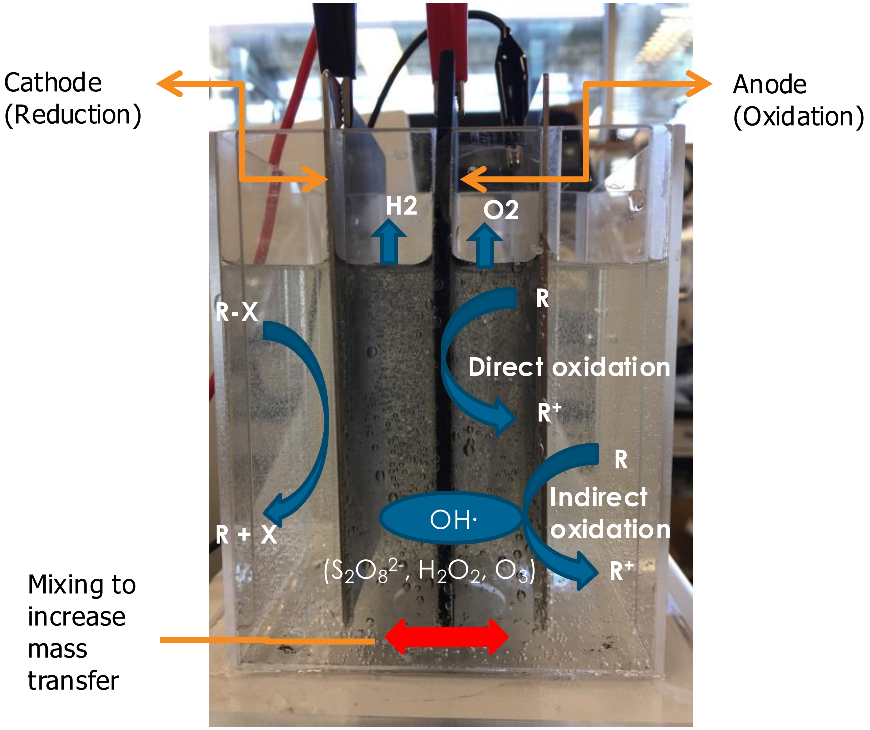


Figure Source: R. Gwinn, AECOM. Used with permission.

Electrochemical Oxidation (Liquids)

Developing

Design Considerations

- Recirculation necessary to increase PFAS contact with electrodes
- Electrode selection, current density, reaction time, reactor size, ionic strength, perchlorate generation, pH
- Best for low volume high concentration liquids

Advantages

- More advanced understanding on mechanisms, effectiveness and scalability

Limitations

- Shorter chain PFAS generation
- Long reaction time for complete destruction
- Perchlorate treatment
- Not suitable for large volumes of water/liquid

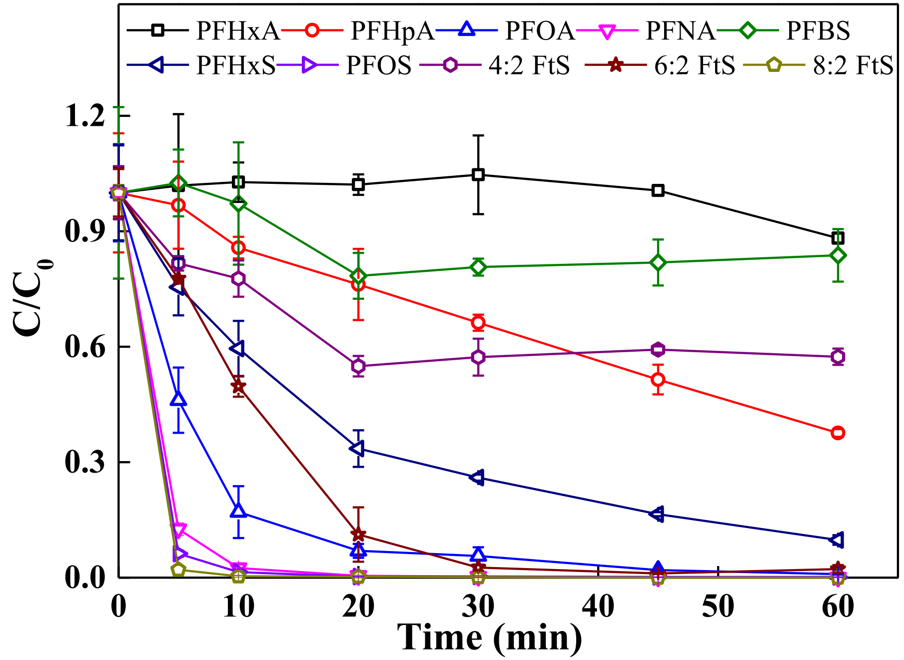


Figure 2A. Removal of 10 PFAS over time by zinc anode (C0 = 0.5 µM, current density = 5.0 mA cm^{-2}, 20 mM Na_2SO_4). (ER18-1278)

Reference: SERDP ER18-1278
"An Electrocoagulation and Electrooxidation Treatment Train to Degrade Perfluoroalkyl Substances and Other Persistent Organic Contaminants in Groundwater" Final Report (2022) www.serdp-estcp.mil

Electrochemical Oxidation (Liquids)

Developing

Potential and developing applications

- High PFAS concentrations in groundwater
- Foam concentrates
- Landfill leachates
- Regenerable IX waste stream

Future research areas

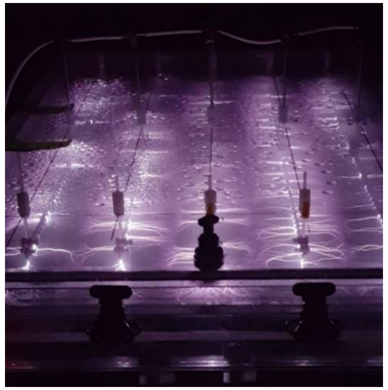
- Flow through reactors
- Low-cost, durable electrode materials with consistent performance
- Lowered generation of unwanted byproducts (shorter chain PFAS and perchlorate)
- Coupled electrochemical reactions (coagulation and oxidation)
- Achieving cleanup criteria for discharge

Photo courtesy of Shangtao Liang, AECOM, used with permission.

Plasma Treatment

Developing

- Plasma formed by means of electrical discharge between high voltage source and electrical ground
- Electricity used to generate highly reactive species that diffuse into water
  - OH•, O, H•, HO_2•, O_2•–, H_2, O_2, H_2O_2 and hydrated electrons (e–aq)
- Gas pumped through diffuser
  - Air or argon have been used
  - Some configurations rely on a bubble layer on the surface that concentrates PFAS



Photos courtesy of Selma Mededovic, Clarkson.

Stratton, G.R., et al. (2015). Chemical Engineering Journal, 273: 543-550.

Stratton, G. R., et al., (2017). Environmental Science & Technology 2017, 51(3):1643-1648.

PFAS Treatment Technologies: Takeaways

Few technologies are considered fully field-implemented for liquids and soils:

- Liquids: Sorption (ex situ with GAC or IX, in situ with CAC), membrane filtration, foam fractionation
- Soil: Excavation & disposal, sorption/stabilization, soil washing

Additional technologies have had limited applications

- Liquids: Surface-modified clays, underground injection
- Soil: Thermal desorption

There are many developing technologies, including destructive technologies

Treatment trains (combinations of unit processes) should be considered

Treatability and pilot studies are often required

Substantial research happening: DOD, USEPA, others

Questions

Feedback Form & Certificate:
https://www.clu-in.org/conf/itrc/PFAS-BTB-Trtmnt/