Lessons Learned on Various In-Situ and Ex-Situ PFAS Treatment Technologies

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Overview

1. Remediation State of the Practice
   - Soil
   - Water (surface water, groundwater, drinking water)
2. Developing Alternatives For Treatment and Wood Updates
   - Soil and water treatment
   - Destruction

Remediation State of the Practice

Commercially available soil remediation options

- Excavation and On or Offsite Encapsulation - Proven
  - Effective but expensive, landfill disposal options limited by regulation
- Incineration – Proven, but limited facilities
  - Very expensive, generally used on low volumes at high concentrations
- Stabilization – Limited full-scale applications
  - RemBind™
    - Powdered reagent – Activated carbon, organic matter, and aluminum hydroxide
    - Added at ratio of 1-10% by weight, has shown >98.5% reduction in leaching
  - MatCARE™
    - Modified clay adsorbent
    - pH, clay content and organic content influence PFOS release from soil

Commercially available groundwater remediation options

Most proven options require pump and treat

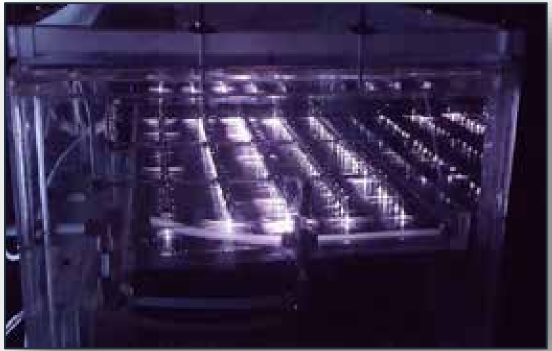
- Granular Activated Carbon (GAC)
  - Most ubiquitously used for water
- Ion Exchange
  - A potentially cost-effective alternative to GAC
- Reverse Osmosis
  - Effective for a wide variety of PFAS, up to 90% efficient
  - Reject water must be treated separately
- Nanofiltration – less proven
  - Effective removal of PFOS when calcium is present
- Foam Fractionation

Alternatives and Innovative Technologies

Developing treatment and destruction options

- Soil - mobilization, recovery and destruction
  - In-situ or ex-situ thermal desorption coupled with VES
  - In-situ liquid carbon

- Groundwater
  - Treatment
    - Non-regenerable ion exchange resins
    - Ozone fractionation
    - In-situ carbon and biochar
    - Regenerable IX resin
  - Destruction
    - Sonification
    - Electrochemical
    - Plasma



In-Situ Carbon

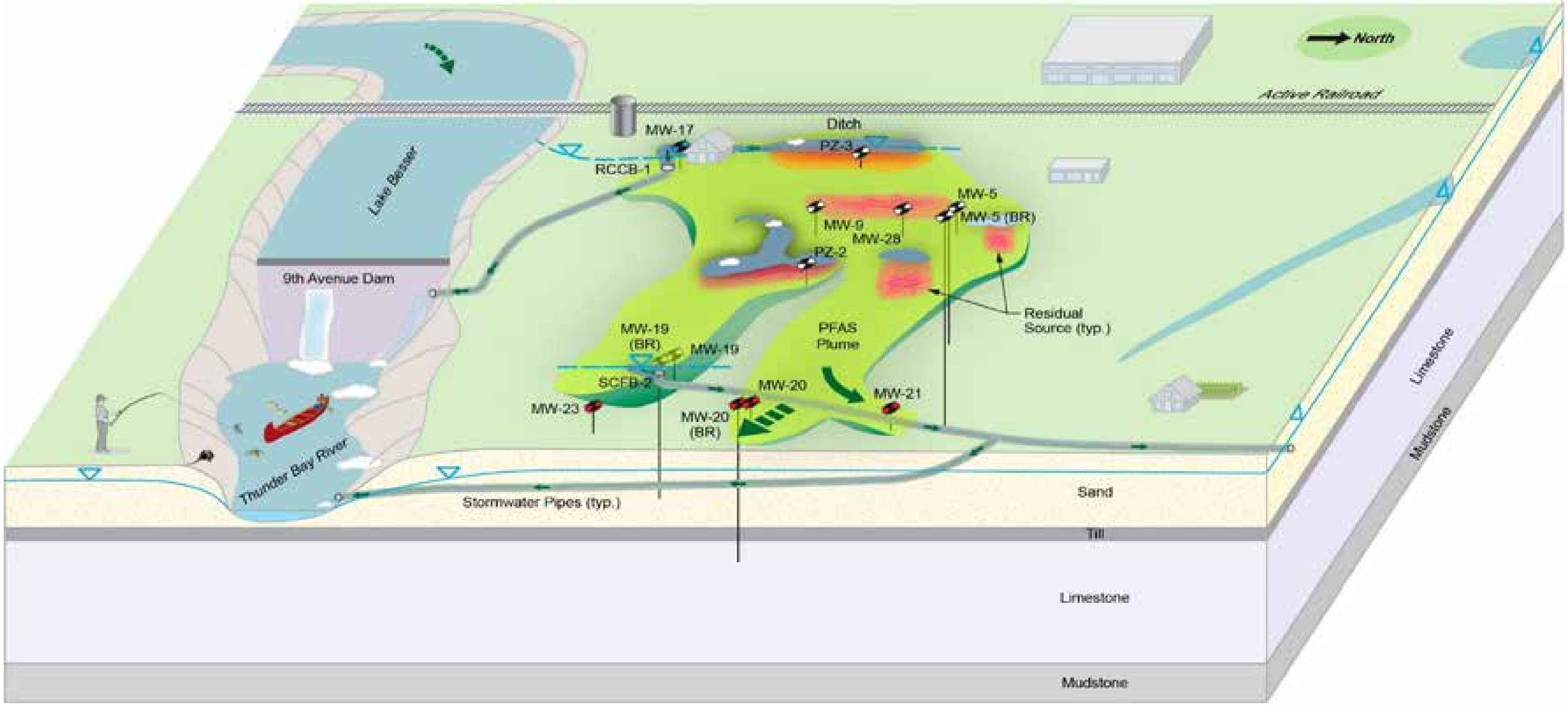
Case study

Alpena Hide and Leather Case Study –

BioChar Injection and Soil Mixing Pilots at a Former Tannery

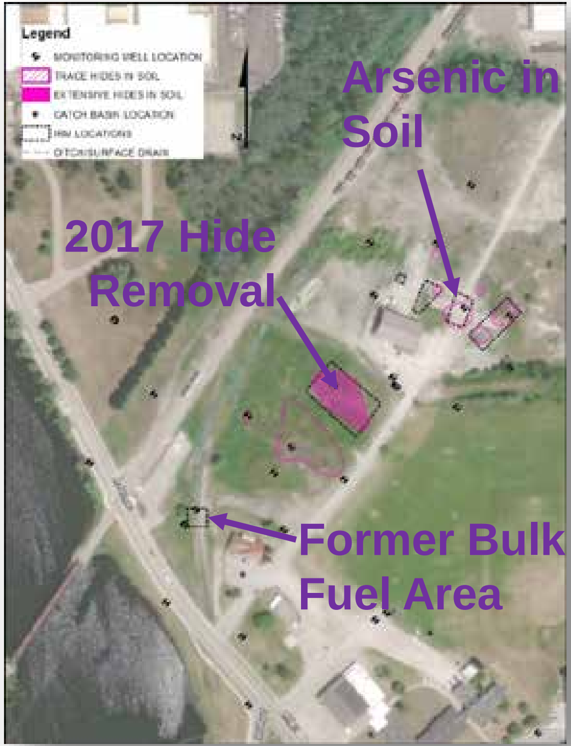
- Site setting/history
- Conceptual site model
- Brief description of pilot tests
- Performance metrics

Conceptual site model

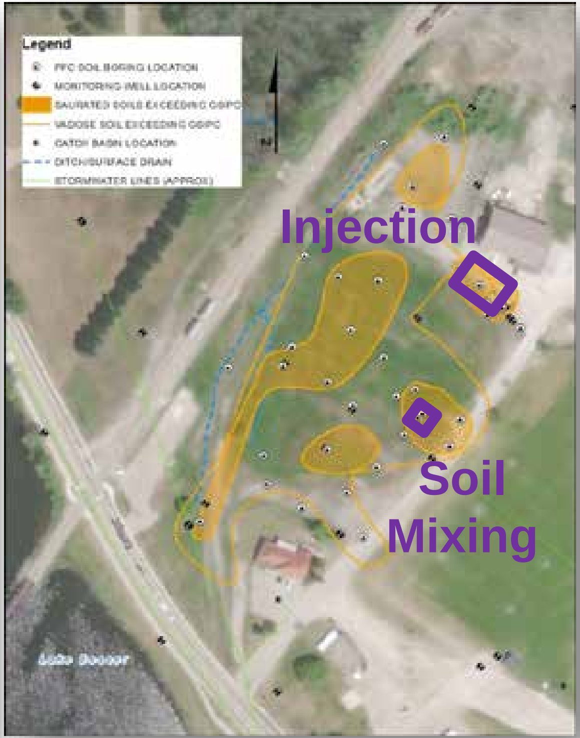


Not To Scale

Conceptual site model



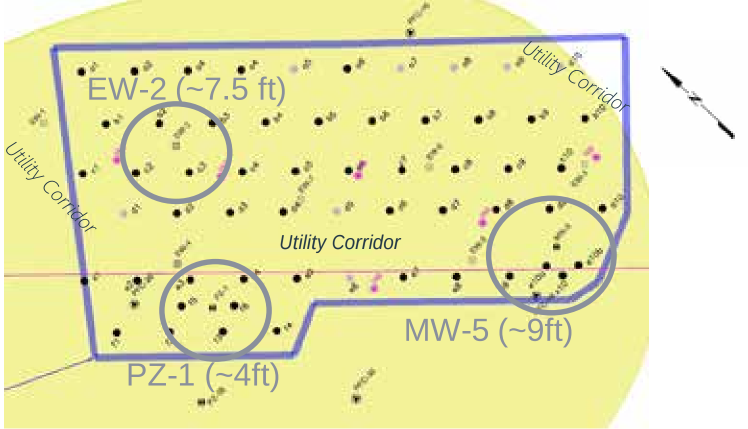
Non-PFAS Contaminants

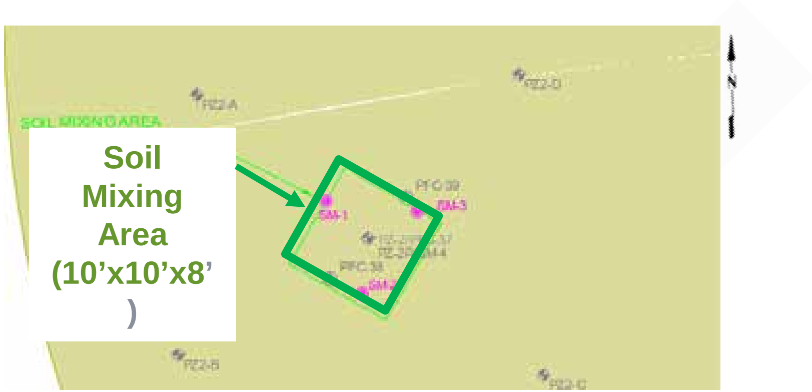


PFAS in Soil

PFAS in Groundwater

BAM pilot tests





BAM-Ultra™ Injections:

- Vacuum truck extraction to enhance injections
- Injection pressures of 40 – 100 psi
- Bottom up injection (2-ft. lifts, 2-10 ft. bgs)
- 100 gallons of 12.4% BAM-Ultra™ solution injected at 46 intervals/locations (5,300 pounds)
- Variable loading rates based on ROIs

BAM-X™ Soil Mixing:

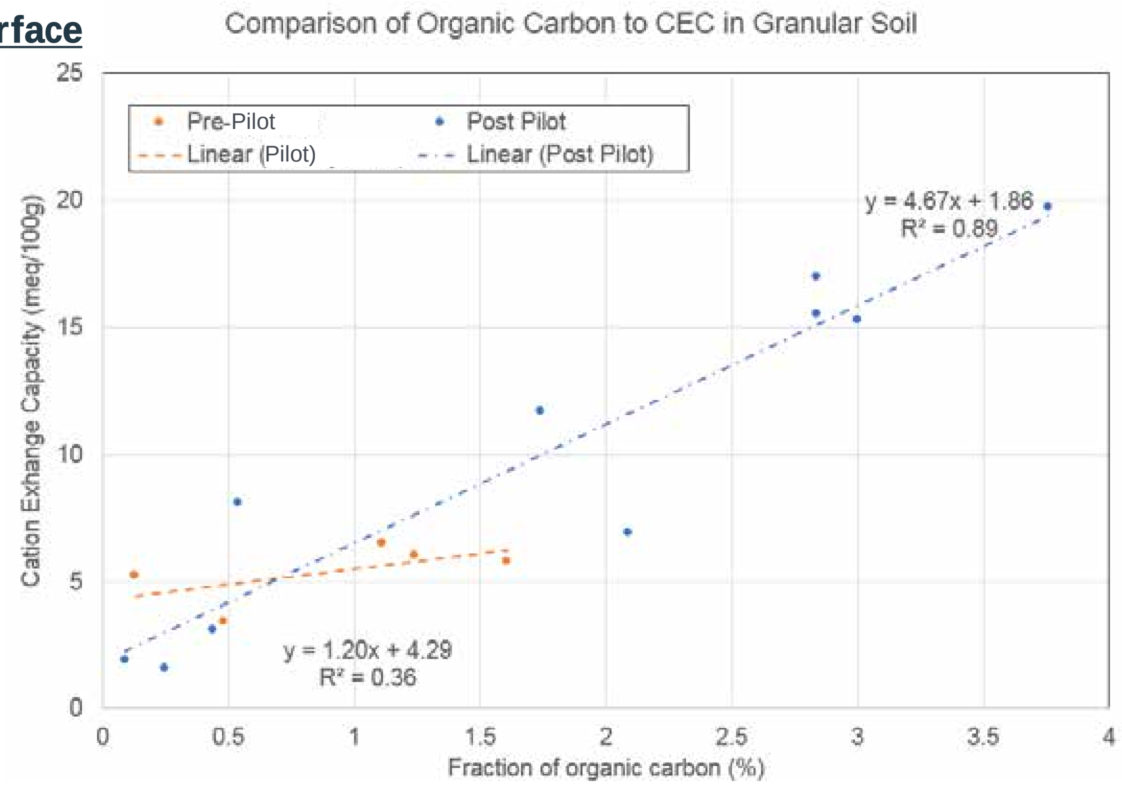
- Excavator bucket mixing
- Mixed from surface to 8 ft. bgs (included vadose zone application)
- 1,600 pounds of BAM-XTM
- 1.5% loading rate by mass
- Mixed in place – no waste generated

Pilot test - soil results

PFOS in soil at 4 – 5 feet below ground surface

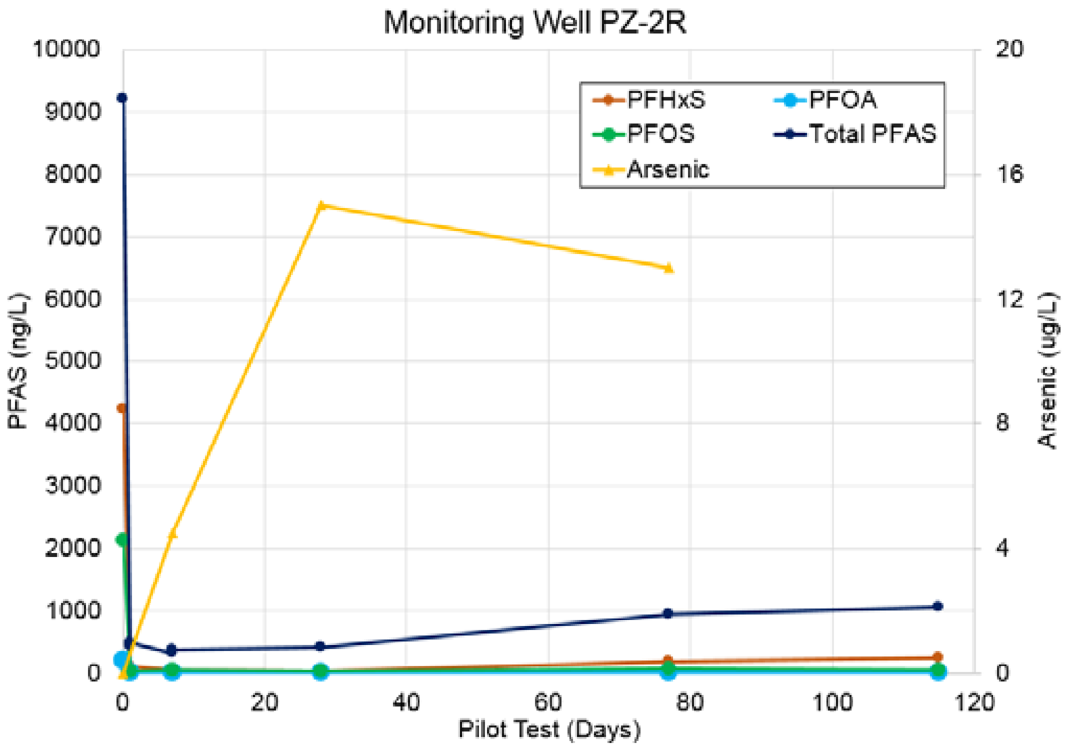
Test	Control	Injection Area	Soil Mixing
SPLP	122 – 112	74.4 (39%)	36.3 (68%)
TCLP	707	68.4 (90%)	35.7 (95%)

Leachate results in ng/L (percent reduction)



Soil mixing pilot test – groundwater results

- **PZ-2R; Soil Mixing Area (~1.5% Loading Rate)**

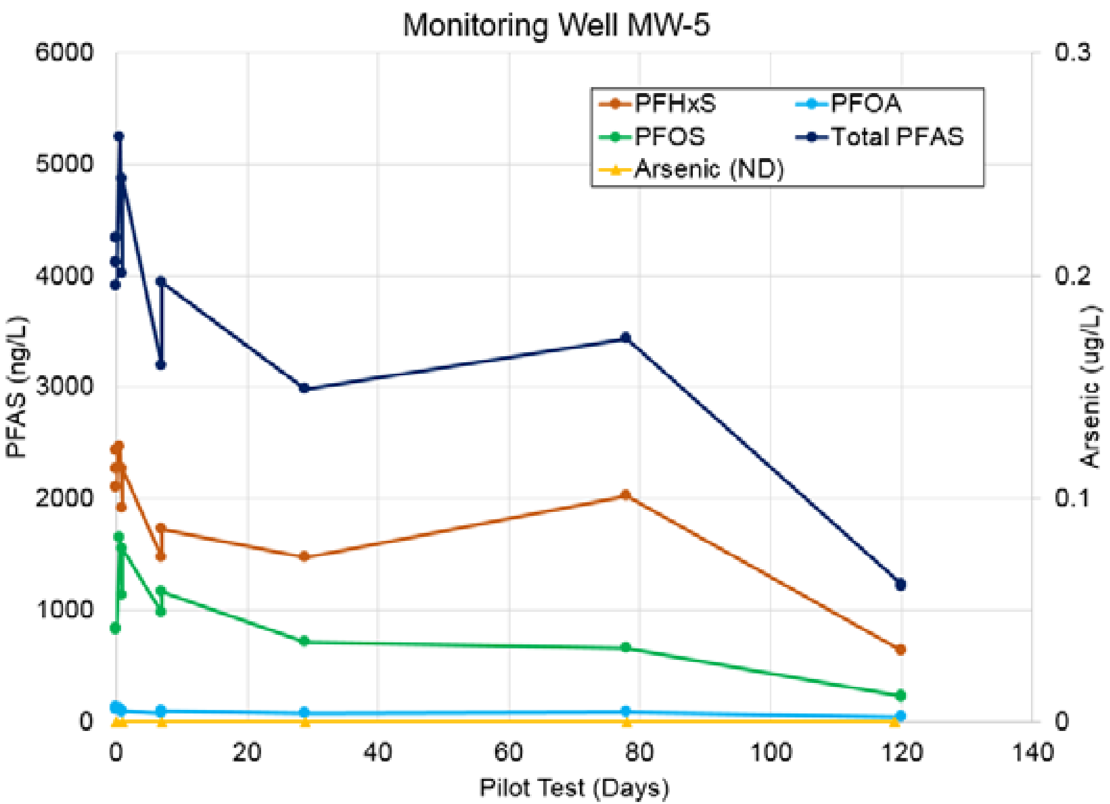


PFAS	Percent Reduction
PFBA	-13.0
PFBS	77.5
PFHxA	84.2
PFHxS	94.2
6:2FTS	97.7
PFOA	94.7
PFOS	97.5
T-PFAS	88.6

- Hydraulic Conductivity
  Pre-Test = 11 ft./day
  Post Test = 0.9 ft./day

Injection pilot test - groundwater results

- **MW-5; 9-ft Injection Array (~0.4% Loading Rate)**



PFAS	Percent Reduction
PFBA	28.2
PFBS	82.9
PFHxA	67.7
PFHxS	71.8
6:2FTS	77.3
PFOA	66.6
PFOS	73.2
T-PFAS	70.5

- Hydraulic Conductivity
Pre-Test = 3.4 ft/day
Post Test = 7.5 ft/day

Ex-Situ Regenerable Ion Exchange Resin

Case study

Former Pease Air Force Base Case Study – Regenerable Ion Exchange Resin System

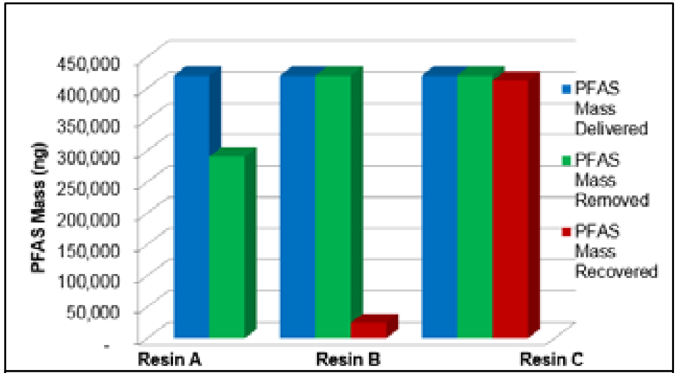
- Site setting
- Project development
- Full-scale implementation
- Start-up and operation
- Performance to date

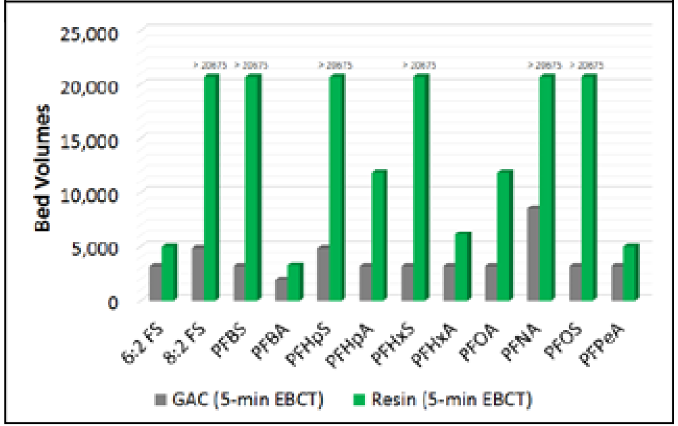
Site setting

- PFOS and PFOA first identified in 2013
- Drinking water impacts confirmed in 2014
- Base-wide investigations started
- Interim actions initiated

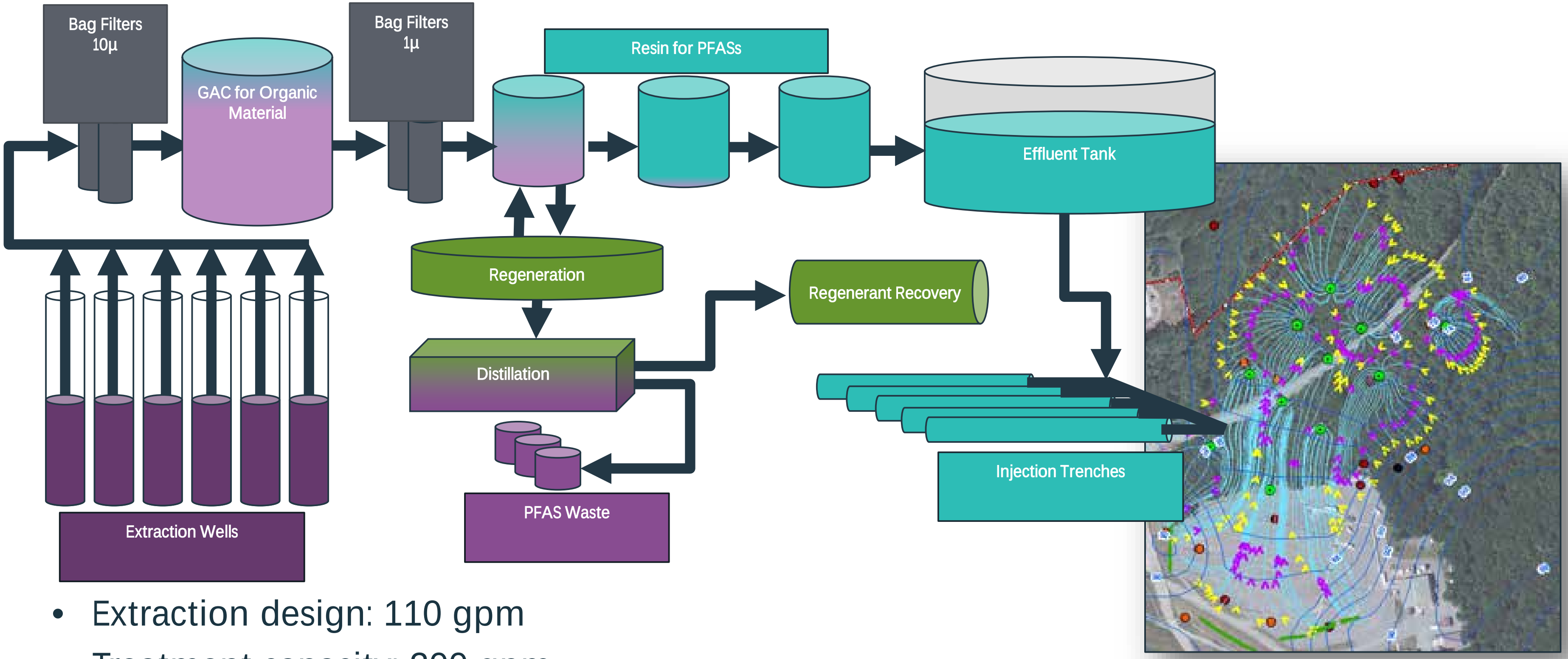
Project development – 2015 bench/pilot testing

- Bench-scale testing identified an IX resin for PFAS removal that could be regenerated
- Wood contracted by the Air Force to perform pilot-scale testing of ECT2’s regenerable IX resin and coal-based GAC
- After 6-months of testing and five loading cycles
  - IX resin substantially more effective at PFAS removal
  - IX successfully regenerated





Full-scale implementation - design



- Extraction design: 110 gpm
- Treatment capacity: 200 gpm

Full-scale implementation - construction

Full-scale implementation – treatment process

Pretreatment bag filters & GAC

IX resin vessel skid

IX resin polish vessels

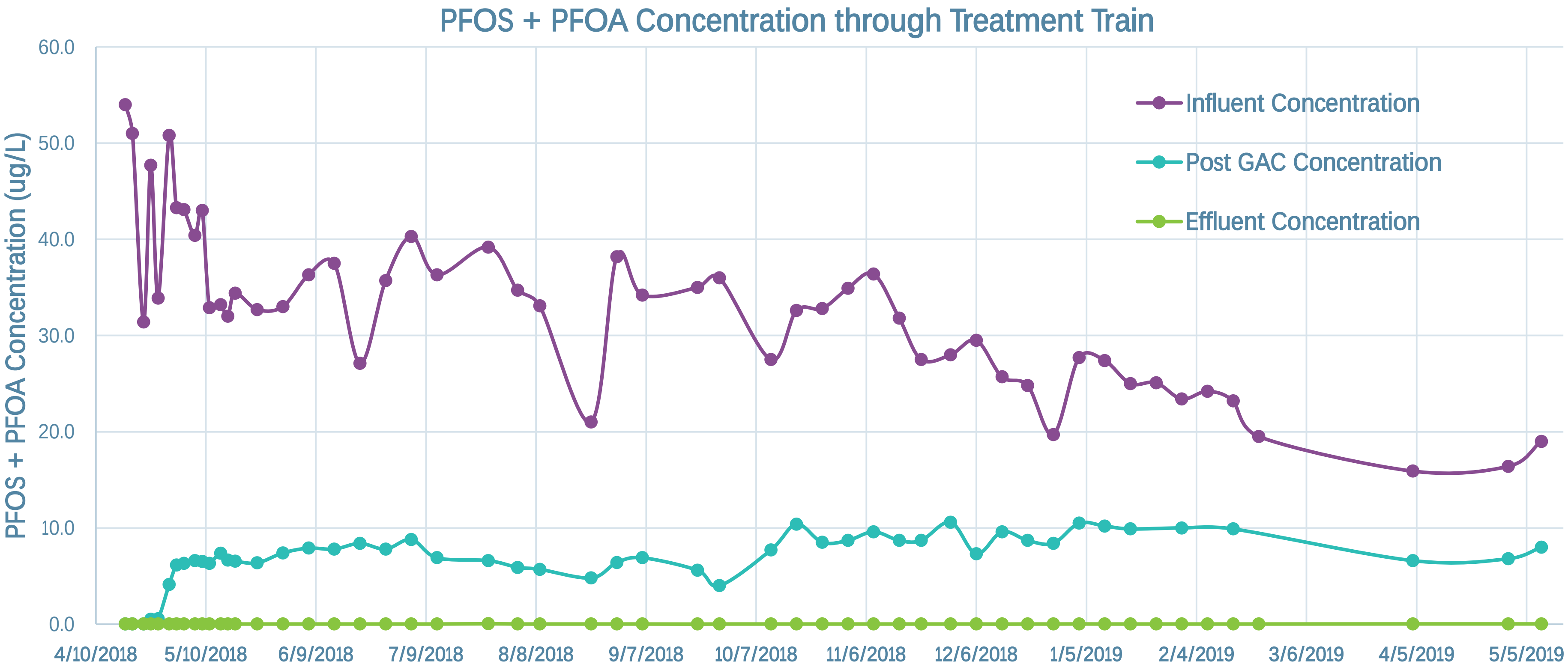
Full-scale implementation –regeneration process

Regeneration skid

Distiller

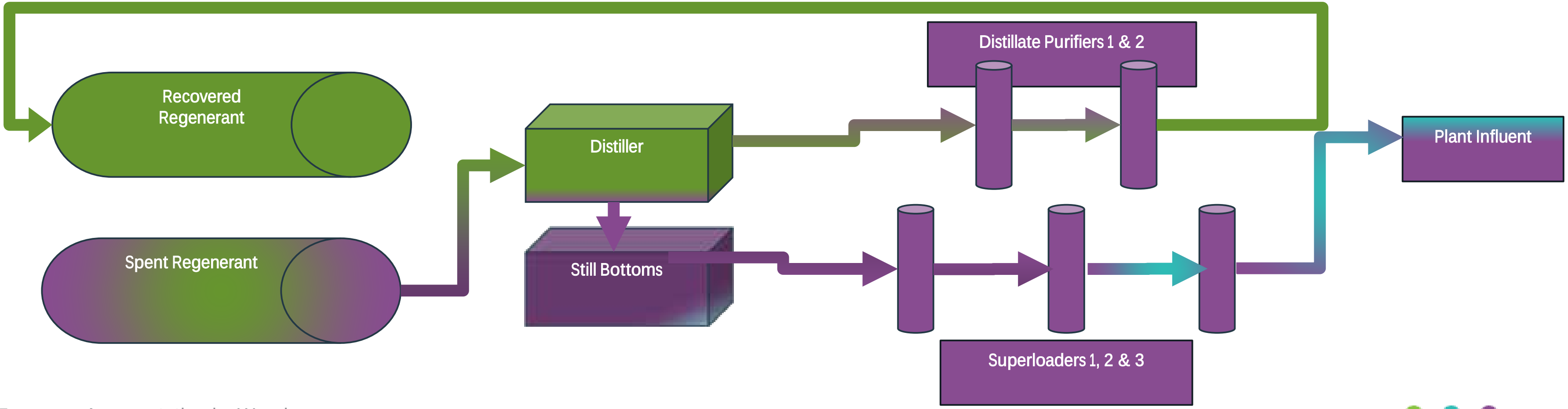
Still bottoms and superloader

Start-up and operations



Start-up and operations - regeneration

Sample Location	PFOS (µg/L)	PFOA (µg/L)
P-7200 Effluent - Regenerant Recovery Pump (Distiller Influent)	25	16
Superloader 1 inlet (Still Bottoms)	540	220
Post Superloader 1	0.19	0.010 U
Post Superloader 2	0.12	0.010 U
Post Superloader 3	0.086	0.010 U
T-7420 Influent -Distallate Purifier	0.50	2.9
T-7420 Effluent - Distillate Purifier #1	0.015 U	1.1
T 7430 Effluent - Distillate Purifier #2	0.015 U	0.010 U



Destruction Technology

Wood - ongoing research and development

Strategic Environmental Research and Development Program (SERDP) U.S. DoD Basic and Applied Research Program

Awarded: "Combined In-Situ/Ex-Situ Treatment Train for Remediation of PFAS Contaminated Groundwater"

Environmental Security Technology Certification Program (ESTCP) U.S. DoD Technology Demonstration and Validation

Awarded: "Removal and Destruction of PFAS and Co-Contaminants from Groundwater"

Research Team:

Clarkson

ect2

NAVFAC

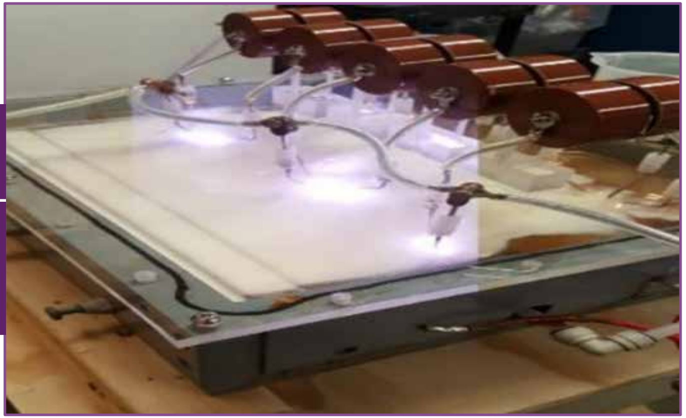
wood.

Ongoing R&D – PFAS destruction via PLASMA

- Work presented by Clarkson University at Battelle Remediation Conference, May 2018.
- Enhanced contact, low energy plasma reactor for two applications
  - Treatment of investigation derived waste – low C aqueous solutions
  - Treatment of still bottom waste from regenerable IX – high C brine solution
- Technology demonstrated for IDW (discussed in the following slides)
- Technology under development for still bottoms – two R&D projects starting now for SERDP and ESTCP

Prototype Plasma Reactor for high C PFAS

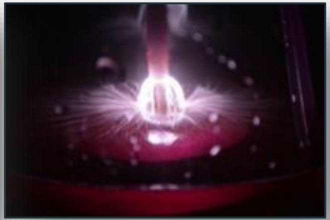
Inventors: Mededovic and Holsen, Clarkson University



On-going R&D – PLASMA for PFAS destruction

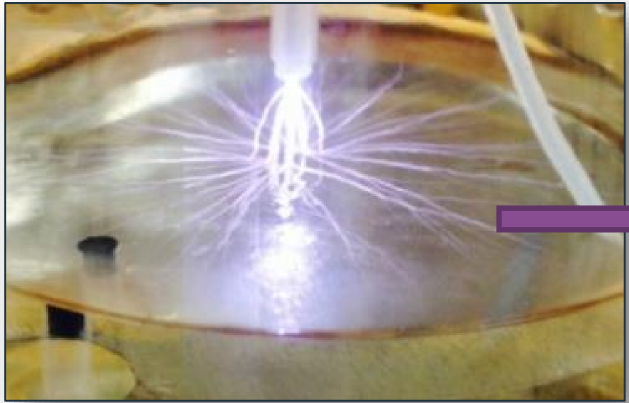
- Plasma is an ionized gas consisting of a quasi-neutral mixture of neutral species, positive ions, negative ions, and electrons.
- Electrical discharge plasma formed *directly in* or *above* water makes use of OH radicals to oxidize and aqueous electrons to chemically reduce organic and inorganic compounds.
- Benefits of plasma-based water treatment:
  - Physical effects such as generation of ultraviolet-range radiation (UV), shockwaves capable of inducing cavitation, and high temperatures capable of thermally decomposing molecules.
  - No chemical additives are required.
  - Wide variety of reactive chemical species (OH, e_{aq}^-, e^-, O, H, H_2O_2, O_2, HO_2).



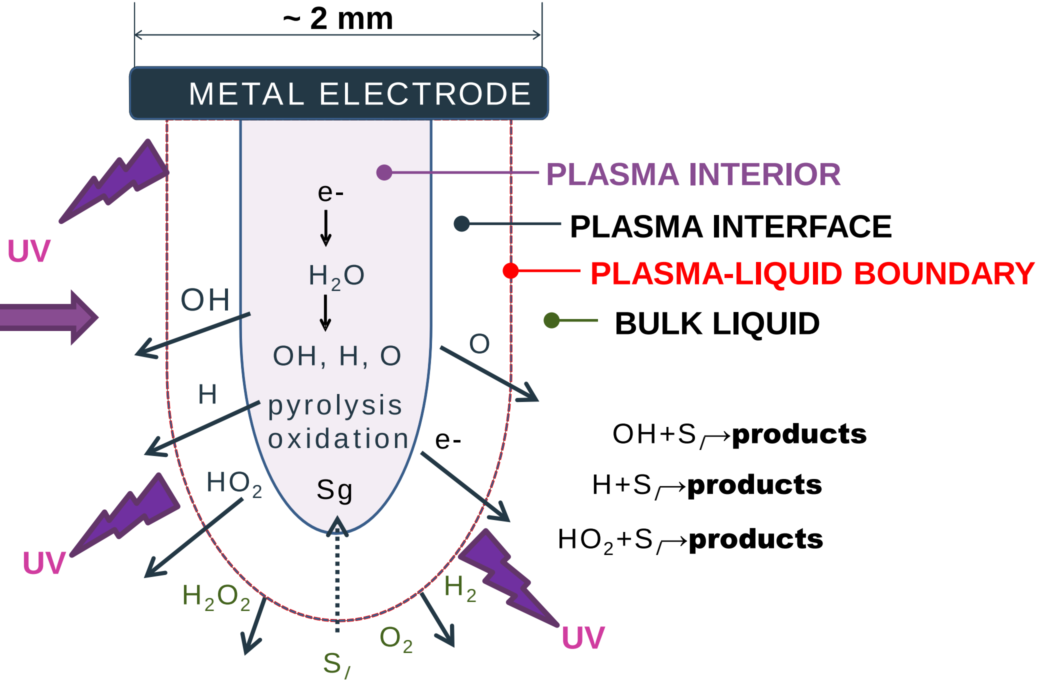
Pictures: Plasma Research Laboratory, Clarkson University

Plasma formation



Plasma in argon gas contacting water

Courtesy of: Plasma Research Laboratory, Clarkson University

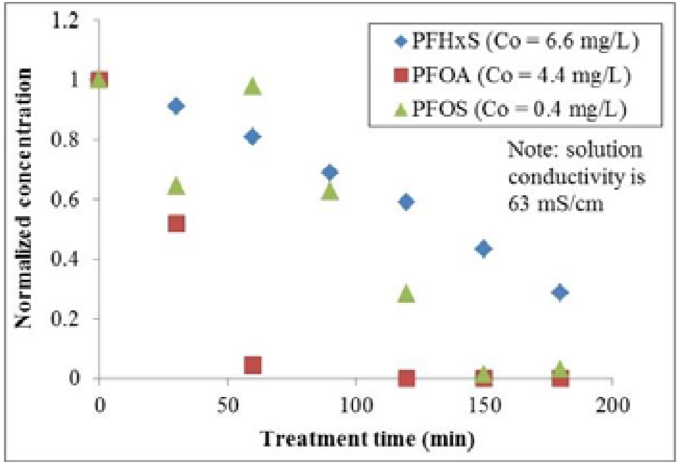


S_l =liquid solute S_g =gas solute

Plasma summary

- Emerging as a viable technology
  - Proven field demonstration (high C still bottom PFAS treated to ND)
  - Study results expected November 2019.
- Potentially applicable for:
  - Destruction of regenerant waste
  - IDW destruction
  - Not for continuous flow at this time
- More efficient and is relatively unaffected by the presence of co-contaminants.
- Mechanisms of PFAS destruction involves electrons and plasma (argon) ions.
- Market availability next step (mobile unit available)

Potential no-waste solution



Treatment of high C still bottom waste

Courtesy of: Plasma Research Laboratory, Clarkson University

Lessons Learned

Lessons Learned

- In-situ Carbon
  - Biochar effectively reduced PFAS in groundwater
  - Biochar has less sorption of short chain carboxylic acids
  - Soil ion exchange capacity may have as much or more effect on PFAS sorption than fraction of organic carbon
  - Soil mixing biochar had favorable results when evaluating with long term leaching test

- Ex-situ Regenerable IX Resin
  - Biggest challenge was iron fouling at front end of plant
  - GAC can be a workhorse
  - Fire protection can drive project costs and logistics for regeneration technology

- Plasma Destruction
  - No commercially available onsite destruction technologies
  - Developing treatment technologies show promise for greater removal capacity and potential onsite application.

Questions?

Thank you!

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Thank you to Collaborators:
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Nathan Hagelin - Wood
Rob Singer – Wood
Len Mankowski - Wood

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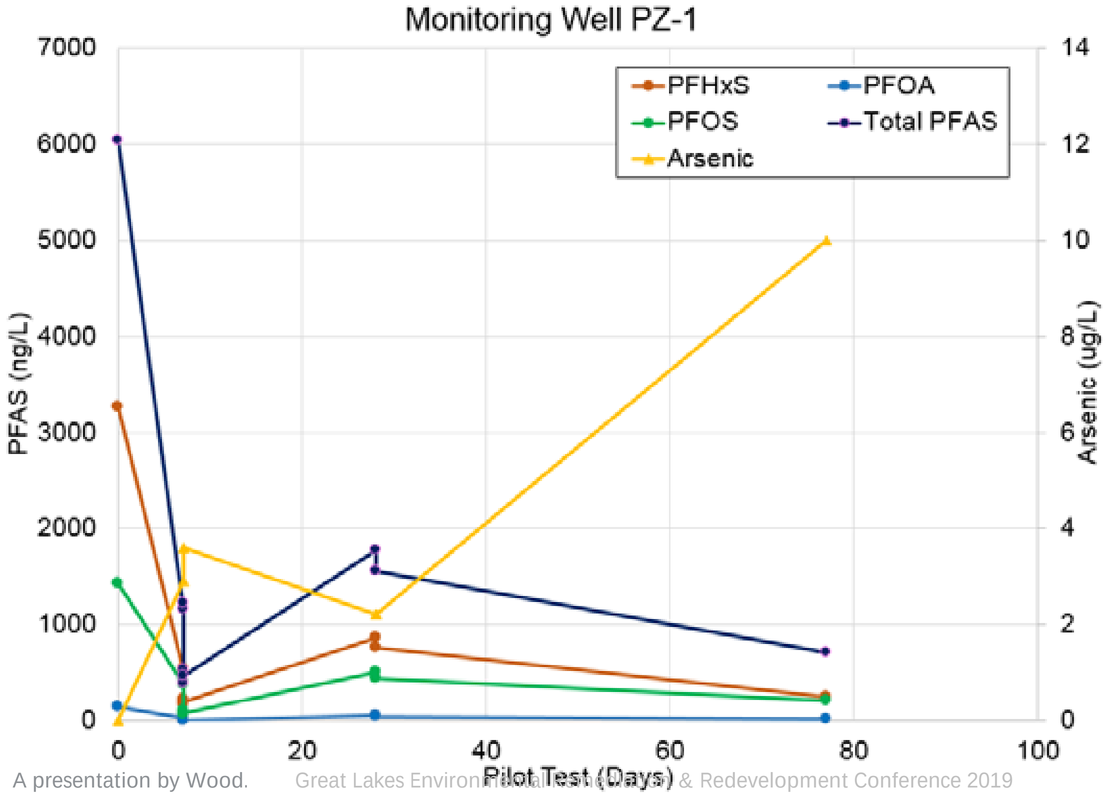
3. http://www.npr.org/sections/thetwo-way/2016/08/09/489369852/federal-data-shows-firefighting-chemicals-in-u-s-drinking-water-sources
4. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=988342
5. https://emergency.cdc.gov/cerc/resources/templates-tools.asp

Injection pilot test - groundwater results

- PZ-1; 4-ft. Injection Array (~1% Loading Rate)

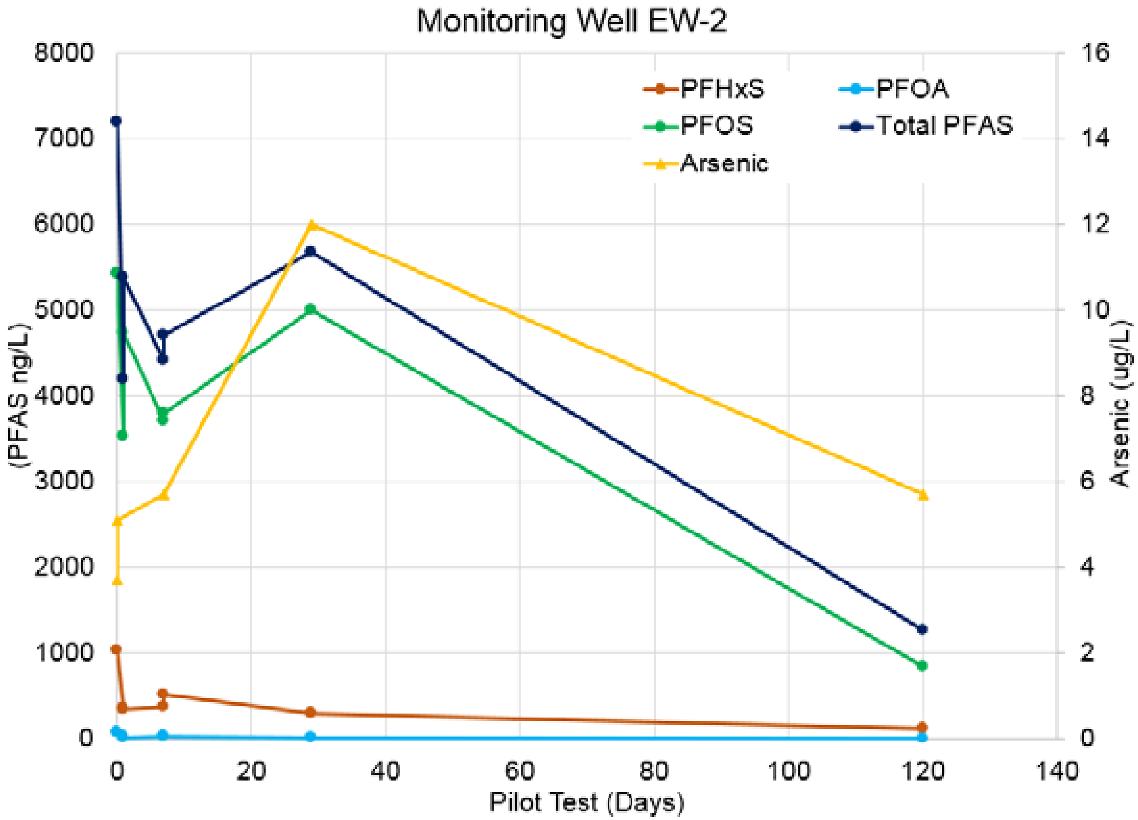


PFAS	Percent Reduction
PFBA	50.6
PFBS	85.6
PFHxA	83.7
PFHxS	92.4
6:2FTS	91.6
PFOA	89.7
PFOS	85.2
T-PFAS	88.3

- Hydraulic Conductivity
  Pre-Test = 11 ft./day
  Post Test = 8.0 ft./day

Injection pilot test - groundwater results

- **EW-2; 7.5-ft Injection Array (~0.5% Loading Rate)**



PFAS	Percent Reduction
PFBA	-35.9
PFBS	82.9
PFHxA	43.6
PFHxS	88.5
6:2FTS	83.6
PFOA	86.5
PFOS	84.4
T-PFAS	82.4

Case study

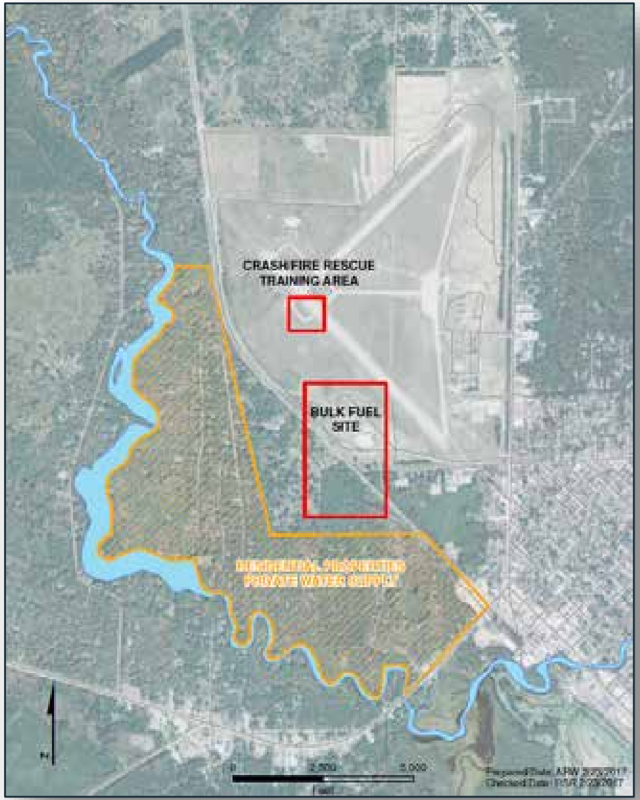
Camp Grayling Case Study –

Colloidal Activated Carbon in a Low Centration PCE Plume

- Site setting
- Conceptual site model (injection area)
- Brief description of pilot test
- Performance metrics/mechanisms

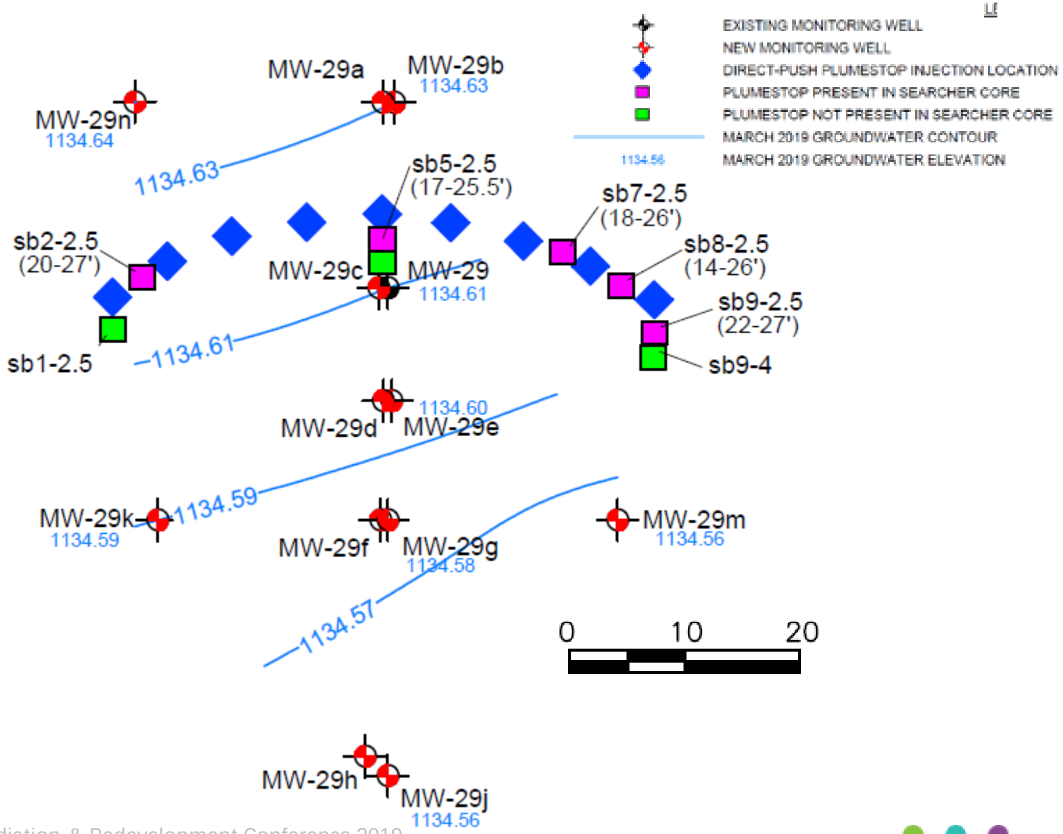
Conceptual site model

- Former fire training area
- Bulk fuel area
  - Pump and treat system in place
  - Previous hydrogen release compound (HRC) injections
- Compounds in groundwater
  - Historically SVOCs
  - Low level PCE (<10 ug/L)
- PFAS detected 2016
  - T-PFAS – 228 ng/L
  - PFOS – 110 ng/L
  - PFOA – 6 ng/L
- Shallow groundwater
  - Shallow Groundwater
  - Aquifer primarily sand
  - Depth to water: 14-15 feet
  - Depth to Clay: 27 feet



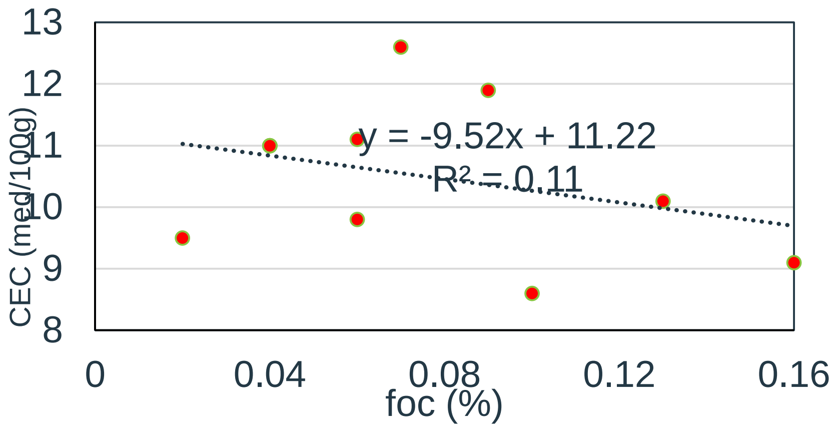
2018 PlumeStop™ injection pilot

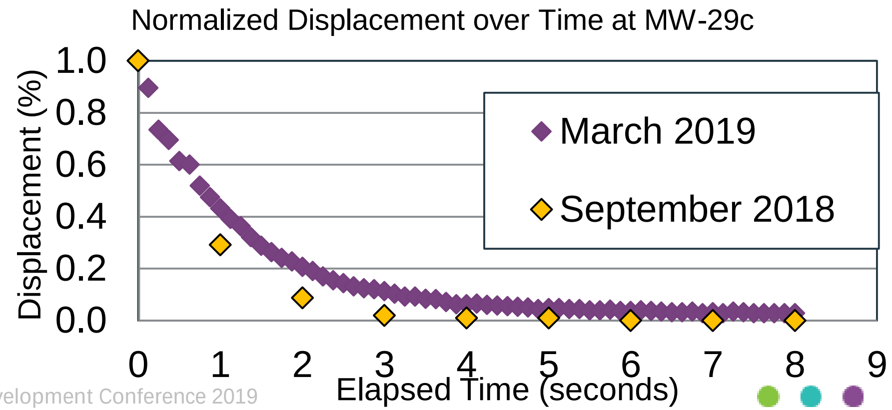
- PlumeStop™ injected October 2018
- Nine locations on 5-foot centers.
- 2400 lbs. ea. of PlumeStop™ & PlumeStop Stout™ (8-10,000 mg/L; ~ 750-1,000 gallons/pt)
- Bottom-up application (1-ft. to 3-ft. lifts; 14-26 ft. bgs)
- Injection pressures/flow rates up to 90 psi at 8 gpm



Camp Grayling Airfield – soil results

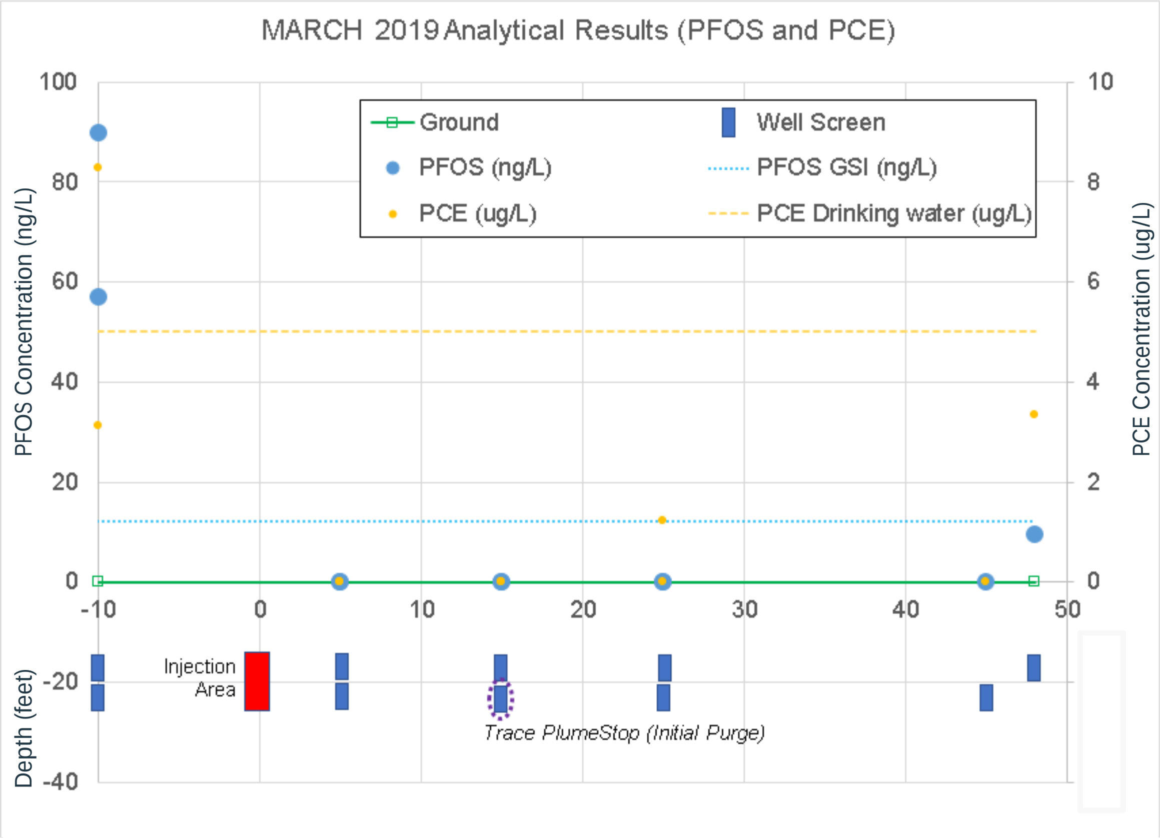
- Physical testing:
  - f_{oc} increased slightly
  - No significant change in CEC
  - No apparent correlation of CEC to f_{oc}
  - Pre-/post-injection slug test results relatively unchanged (Remains Fast!)



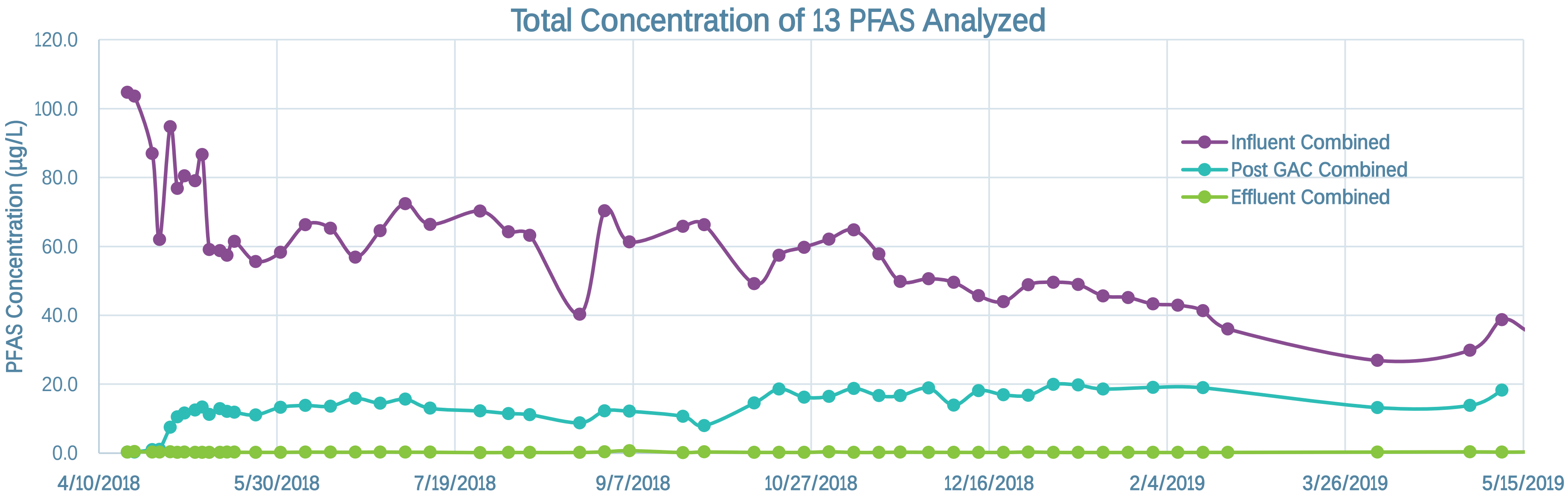


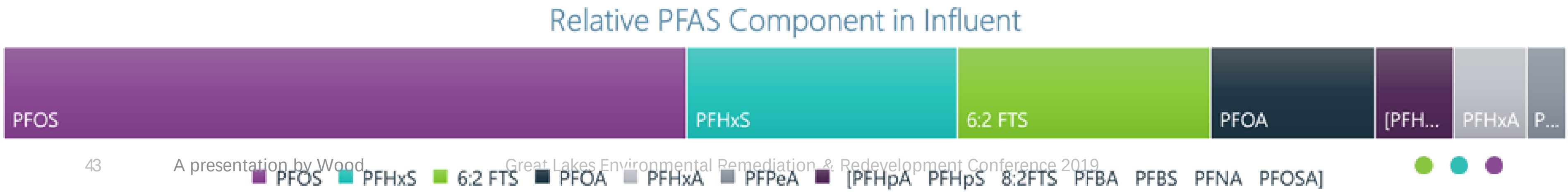
Time series results

- Baseline
  - PFOS = 70/40 ng/L
  - PFHxS = 60/50 ng/L
  - PFPeA = 10 ng/L (deep)
  - PCE = 8.28/3.12 ug/L
- October 2018 (4 weeks)
  - No PFAS detected (shallow and deep downgradient wells)
  - PCE = 1.22 ug/L (shallow)
  - PlumeStop™ spreading
- March 2019 (~ 6 months)
  - PFOS = 9.6 ng/L in shallow downgradient well (~50 ft.)
  - PCE detected in shallow wells at 25 and 50 ft. downgradient
  - PlumeStop™ - no further downgradient expression

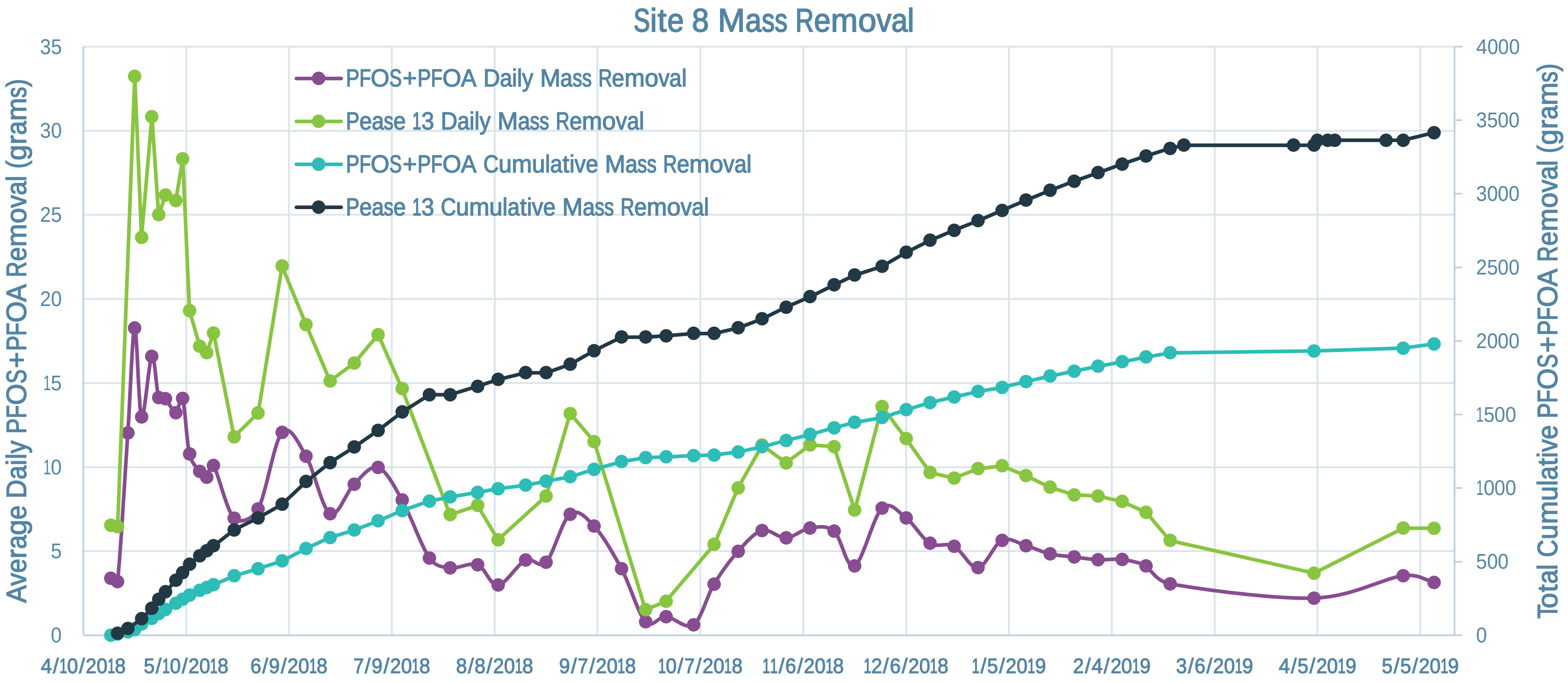


Start-up and operations





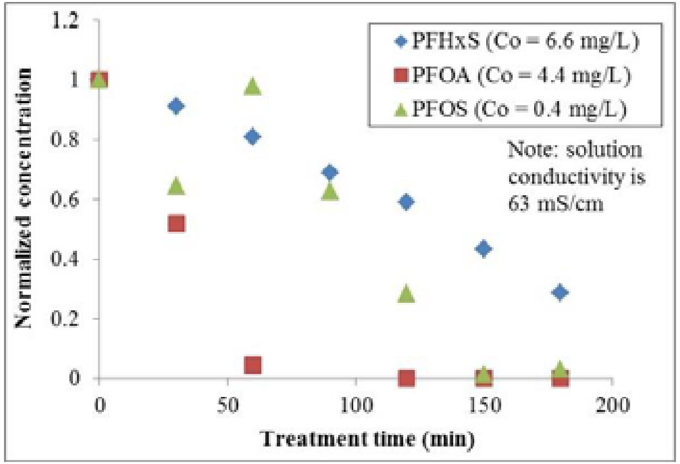
Start-up and operations



Next steps

- Complete ongoing column studies
- Refine media selection criteria
- Operate/optimize non-regenerable IX system
- Continue site-specific evaluations
- Optimize plasma destruction on high C still bottoms
- Complete SERDP and ESTCP projects

Potential no-waste solution



Treatment of high C still bottom waste