ESTCP

USER'S GUIDE

Removal and Destruction of PFAS and Co-Occurring Chemicals from Groundwater via Extraction and Treatment with Ion Exchange Media, and On-Site Regeneration, Distillation, and Plasma Destruction

Nathan Hagelin
Yousof Aly
Kaitlyn Chick
Jeff Heath
Eric Thompson
Cory Vowles
Wood Environment & Infrastructure Solutions Inc.

John Kornuc
Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC)

April 2023

ESTCP Project ER18-5015

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 30/03/2023	**2. REPORT TYPE** ESTCP User's guide	**3. DATES COVERED** *(From - To)* 7/23/2021 - 7/22/2024

4. TITLE AND SUBTITLE
Removal and Destruction of PFAS and Co-Occurring Chemicals from Groundwater via Extraction and Treatment with Ion Exchange Media, and On-Site Regeneration, Distillation, and Plasma Destruction

5a. CONTRACT NUMBER
21-C-0049

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Nathan Hagelin
Yousof Aly
Kaitlyn Chick
Jeff Heath
Eric Thompson
Cory Vowles
Wood Environment & Infrastructure Solutions Inc.

John Kornuc
Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC)

5d. PROJECT NUMBER
ER18-5015

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Wood Environment & Infrastructure Solutions Inc.
511 Congress Street
Portland, ME 04101

8. PERFORMING ORGANIZATION REPORT NUMBER
ER18-5015

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program
4800 Mark Center Drive, Suite 16F16
Alexandria, VA 22350-3605

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
ER18-5015

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This user's guide provides standard approaches and performance recommendations for the removal and destruction of per- and poly- fluoroalkyl substances (PFAS) and co-occurring chemicals from groundwater via extraction and treatment using regenerable ion exchange (IX), onsite recovery (distillation), and low-energy plasma destruction. This user's guide is prepared as an element of the technology transfer program associated with ESTCP project ER18-5015, awarded to Wood Environment & Infrastructure Solutions, Inc. (Wood) in 2019. Effective September 21, 2022, Wood Environment & Infrastructure Solutions, Inc. was acquired by WSP Global Inc. (WSP). Due to the acquisition, the company name has changed to WSP USA Environment & Infrastructure Inc. No other aspects of legal entity or capabilities have changed for this user's guide.

15. SUBJECT TERMS
PFAS, Co-Occurring Chemicals, Groundwater, Ion Exchange Media, On-Site Regeneration, Distillation, Plasma Destruction

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Nathan Hagelin
UNCLASS	UNCLASS	UNCLASS	UNCLASS	41	**19b. TELEPHONE NUMBER** *(Include area code)* 207-828-3508

ACKNOWLEDGMENTS

The project team gratefully acknowledges the financial and technical support provided by the Environmental Security Technology Certification Program (ESTCP). The project team also acknowledges the sponsor, Dr. John Kornuc, NAVFAC Engineering Service Center, as well as the technical team, including ECT2 and Clarkson University.

TABLE OF CONTENTS

FIGURES (embedded)

TABLES (embedded)

1 PURPOSE AND INTRODUCTION

1.1 PURPOSE

This user's guide provides standard approaches and performance recommendations for the removal and destruction of per- and poly- fluoroalkyl substances (PFAS) and co-occurring chemicals from groundwater via extraction and treatment using regenerable ion exchange (IX), onsite recovery (distillation), and low-energy plasma destruction. This user's guide is prepared as an element of the technology transfer program associated with ESTCP project ER18-5015, awarded to Wood Environment & Infrastructure Solutions, Inc. (Wood) in 2019. Effective September 21, 2022, Wood Environment & Infrastructure Solutions, Inc. was acquired by WSP Global Inc. (WSP). Due to the acquisition, the company name has changed to WSP USA Environment & Infrastructure Inc. No other aspects of legal entity or capabilities have changed for this user's guide.

This user's guide will help potential users who are interested in understanding the basic components of the PFAS treatment train (Figure 1). The user's guide provides information on the technology design, integration into existing treatment systems, and operations, which will be valuable to understand when considering the use of the PFAS treatment train to address users' PFAS groundwater remediation challenges.

Figure 1 **PFAS Treatment Train**

This user's guide is organized to provide users a summary of the ESTCP project objectives and outcomes, and the necessary background to understand the basics of the PFAS treatment train process and design (Sections 1–3). Section 4 of the user's guide provides cost information for a full-scale, 100 gallons per minute (gpm) PFAS treatment train; the basis of cost uses the same groundwater, site conditions, and treatment objectives as the pilot-scale PFAS treatment train. Sections 5–9 provide the user with comparisons to non-regenerable PFAS extraction and adsorption for insight into technology selection, design, and operation. Additional details on the pilot study, technology comparisons, and cost can be found in the Pilot Study Final Report (Wood, 2022).

1.2 INTRODUCTION

An ESTCP pilot-scale demonstration was conducted from October 2020 through July 2021 at former Pease Air Force Base (Pease) in Portsmouth, NH to further prove process effectiveness and develop scale-up criteria for integrating a PFAS treatment and destruction technology into existing groundwater treatment systems as originally demonstrated during the Treatability Study (Study) (Wood, 2020), submitted on April 17, 2020. There are currently two PFAS mitigation systems operating at Pease—Site 8 (former fire training area) and the Airfield Interim Mitigation System (AIMS). Site 8 is the location of an existing full-scale regenerable IX treatment system, including on-site regeneration and distillation (Figure 2), but not the plasma destruction technology. AIMS is the location of an existing full-scale single pass IX system. The pilot demonstration was conducted at Site 8.

IX Resin System

In-vessel IX Resin Regeneration System

Distillation Regeneration Recovery System

Figure 2 **Pease Site 8 Existing IX Regeneration and Distillation System**

2 PFAS TREATMENT TRAIN DESIGN

2.1 PILOT TEST PROCESS FLOW

The pilot study evaluated the effectiveness of the PFAS treatment train, consisting of four complementary technologies to remove PFAS from groundwater and generate a high-concentration, low-volume waste stream that can be destroyed on site. These technologies were as follows:

- Regenerable IX resin: Sorbix HC1 (a product supplied by ECT2 used in the pilot test) is a macroporous strong base anion exchange resin. The resin polymer structure is a copolymer made from polystyrene crosslinked with divinylbenzene. Sorbix HC1 removes PFAS preferentially to sulphate, bicarbonate/carbonate, and other common groundwater anions. Similar macroporous strong base anion exchange resins, such as ECT2's Sorbix A3F and Sorbix HC5, may also be used to remove PFAS from groundwater.
- Regeneration: solvent-brine solution for removal of PFAS from IX resin; IX resin reused for further PFAS removal.
- Recovery/Distillation: recovery of used solvent to be reused in future regenerations; solution with concentrated PFAS waste (still bottoms) remains. The pilot study used isopropyl alcohol (IPA) as the solvent, but ethanol and methanol may also be used.
- Low-energy plasma destruction: Plasma destruction of the still bottoms and recycling plasma effluent through the treatment train creates a closed-loop system that minimizes off-site disposal.

A process flow diagram of the Pilot Test treatment train is provided as Figure 3. Images from the Pilot Test are presented as Figure 4.

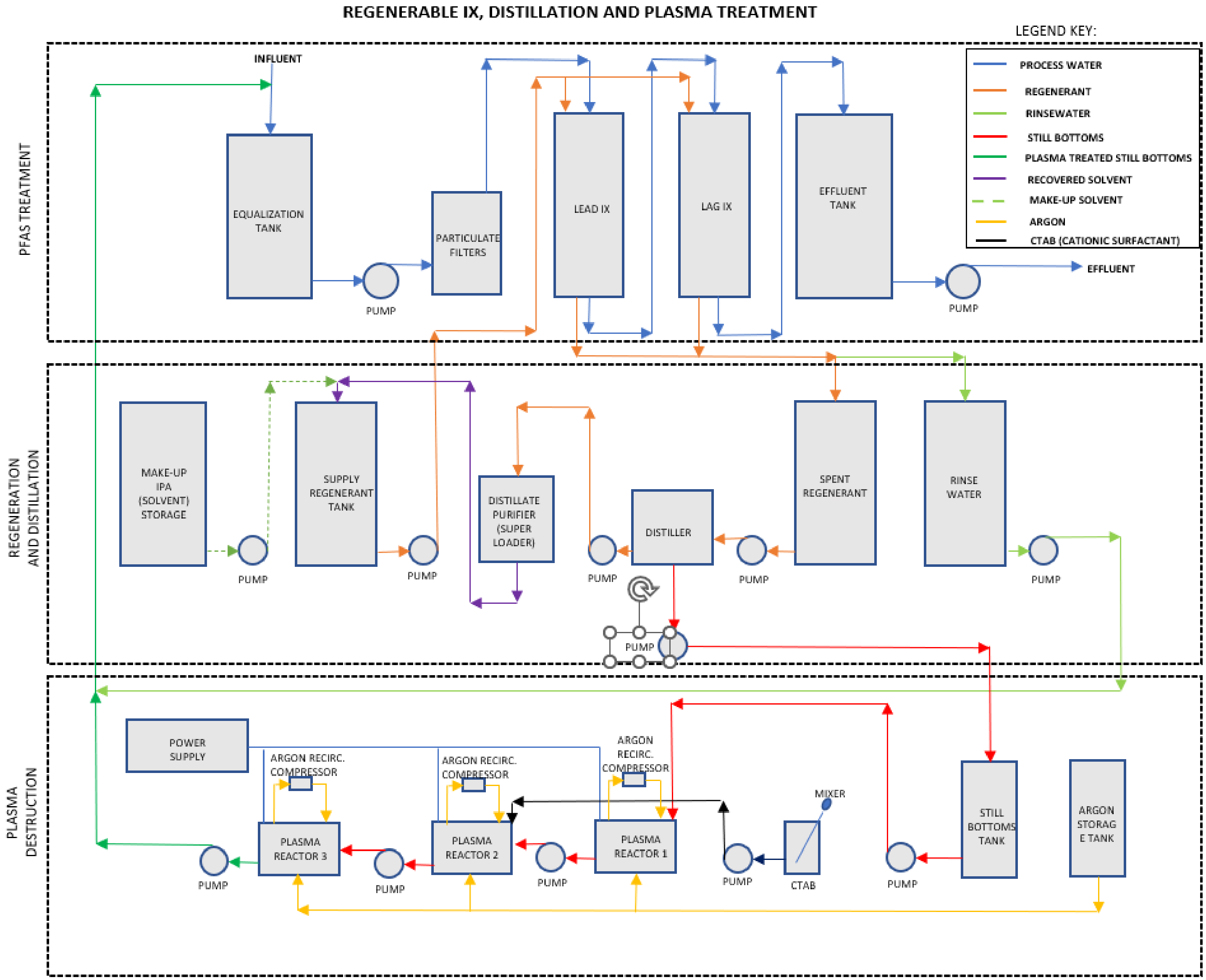


Figure 3 Pilot Test Process Flow Diagram

Note: Regenerant distillation comes with the added operations and maintenance requirements of managing flammable solvents (e.g., methanol, ethanol, and IPA) and potentially toxic (e.g., methanol) solvents on-site, and explosion-proof electrical requirements for electrical equipment near the regeneration and distillation process units.

Figure 4 **Pilot Test Equipment Photos**

2.2 PILOT STUDY OBJECTIVES

The goal of this Pilot Study was to further refine and demonstrate the effectiveness of the PFAS treatment train and provide guidance on how to integrate the treatment train into existing co-occurring chemical treatment systems. One of the key objectives of the pilot study was to evaluate if the pilot test treatment train would work as a low-waste, closed-loop solution for PFAS treatment and see how it would compare to other extraction-adsorption technologies in common use today. A summary of the performance objectives for the pilot test is provided as Table 1.

Table 1 Summary of Performance objectives

Performance Objectives	**Yes (Achieved)**
Removal efficiency of 95% for all PFAS (in regenerable IX resin)	✓
100% of resin can be reused	✓
95% of Total PFAS mass recovered from resin	✓
95% of regeneration solvent can be reused	✓
PFAS concentration in recovered distillate below 10 microgram/Liter (µg/L)	✓
Less than 10% reduction in resin performance for 5 loading/regeneration cycles	✓
Destroy 90% of PFAS mass (Plasma)	✓
Evaluate cost effectiveness	✓
Pretreatment: Removal of co-occurring chemicals (Fe, Mn < .05 mg/L; total organic carbon (TOC), total suspended solids (TSS) < 1 milligram/Liter [mg/L])	No, minor exceedance observed. However, intent of protecting resin from co-occurring chemicals (Fe, Mn, and TOC) influent water achieved.
Plasma destruction of PFAS below 70 parts per trillion (ppt) (individually)	All compounds except Perfluorobutanoic acid (PFBA). Based on reaction kinetics, additional 100 hours (hrs.) needed for plasma destruction of PFBA.

2.3 PILOT TEST DESIGN AND FIELD TESTING

The pilot system utilized approximately 2 gpm of extracted groundwater taken from extraction well 6028 (EW 6028) at the influent header to the Site 8 treatment plant. EW 6028 was chosen due to its low iron/manganese concentration and high total PFAS concentration in relation to other wells at the site. The Pilot System operated as follows:

- The pilot system's pretreatment process units (multimedia, bag, and cartridge filtration) reduced remaining co-occurring chemicals (primarily iron and manganese) concentrations to ensure the IX resin's PFAS removal capacity was not affected by fouling or adsorption of co-occurring chemicals.
- Two 1.5 cubic foot HC1 IX resin vessels in series (lead/lag) were used to remove PFAS from the groundwater and send treated groundwater back to the existing treatment plant headworks.
- IX resin in the lead vessel was regenerated using an IPA and brine solution to remove PFAS mass from the IX resin. The regenerated vessel was returned to service in the lead position to evaluate PFAS removal capacity of the regenerated resin over successive loading and regeneration cycles.
- Rinse water from regeneration was placed in a storage tank and metered back into the pilot system influent for re-treatment.
- Spent regenerant was distilled to recover IPA, then polished through an IX resin (Super Loader or distillate purifier) for reuse in subsequent regenerations. Fresh IPA was added to the recovered IPA to make up for dilution in the regenerant supply due to water carryover with the distillate.
- The PFAS mass in the still bottoms (concentrated PFAS waste collected at the bottom of the distillation tank) was treated through plasma destruction. Due to the COVID-19 pandemic, most of the plasma treatment efforts were conducted offsite at Clarkson's laboratory with the last two batches treated on-site.

- 30 gallons of treated still bottoms were supplied by Clarkson and bled into the pilot system influent during the last loading cycle of the pilot test to determine impact on treatment performance.

2.4 SITE PREPARATION AND MOBILIZATION

Typical preparation for field activities for retrofitting the PFAS treatment train into an existing pump and treat (P&T) system includes: coordination with the local authorities (permitting, code enforcement, fire department, utility providers, etc. as applicable); three-phase power service installation (if not already existing on-site), mobilization of treatment equipment; and on-site setup of the system. If a new P&T system is installed, then additional field activities will include treatment building, utilities, extraction well installation (including associated excavation and trenching), system startup and shakedown, and final system commissioning.

3 PFAS TREATMENT TRAIN PERFORMANCE ASSESSMENT

3.1 PRETREATMENT REQUIREMENTS

The main objective of the pretreatment is to remove co-occurring chemicals that otherwise would lower the efficiency of the primary chemical of concern removal by IX resin. Pretreatment requirements vary from site to site depending upon the type and concentration of co-occurring chemicals and the natural geochemistry of the groundwater. IX resins may require pretreatment processes to remove dissolved metals, TOC, total dissolved solids (TDS), TSS, and volatile organic compounds (VOC) to maximize the resin's capacity for PFAS removal. Pretreatment requirements should be carefully evaluated for all adsorptive media treatment processes used for PFAS removal. Baseline characterization of the influent water quality is required, and bench-scale testing will verify the appropriate type of pretreatment process(es) required.

Pretreatment during the pilot study consisted of bag, multimedia, and cartridge filtration to remove particulate from the water prior to IX treatment. Samples were collected pre- and post-filtration from the system for iron, manganese, TOC, TSS, chloride, sulfate, nitrate, hardness, alkalinity, conductivity, and TDS during the pilot study. The objectives of pretreatment were:

- Total and dissolved iron and manganese below 0.05 mg/L
- TOC below 1 mg/L
- TSS below 1 mg/L
- VOCs non-detect

The objectives of pretreatment were achieved with the following exceptions.

- TOC average excludes several data points that were considered anomalies (higher than expected), most likely due to the presence of recycled rinse water containing IPA.
- Although iron and TOC were slightly above the performance objectives, no adverse effects due to fouling or resin PFAS capacity were noted during the pilot study, suggesting that the pretreatment objective was set unnecessarily low.

3.2 RESIN PERFORMANCE

An IX resin to be used at a site should be evaluated for PFAS removal capacity as part of the site-specific resin selection process. A photo of various IX resins available in the market today is provided in the Figure 5 below. The functional group on each resin differs and these functional groups are responsible for the exchange capacity of the resin. For the pilot test, Sorbix HC1 was selected for its excellent performance during the treatability testing conducted in the early stages of this ER18-5015 project (Wood, 2020).

Figure 5 **IX Resins**

Typical IX resin supply vendors may have in-house data for PFAS removal capacity, though site-specific treatability testing is recommended to:

- Fully understand and quantify pre-treatment requirements.
- Select the best resin(s) and regenerant(s) based on site-specific PFAS compounds as well as treatment objectives.
- Understand the PFAS loading capacity and level of treatment that can be expected (e.g., need for additional polishing such as single pass resin).
- Determine number of bed volumes (BV) prior to breakthrough of PFAS to determine regeneration frequency.
- Provide a basis for estimation of the capital and long-term operation and maintenance (O&M) costs associated with the selected treatment train.

The quantitative pilot test objective was to demonstrate that the Sorbix HC1 IX resin used at the Site was able to consistently treat the incoming groundwater (post-Fe removal) to levels at or below the EPA Lifetime Health Advisory. The success criteria to evaluate completion of the objective included:

- Combined perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) <70 ppt for 5,000 BVs
- Non-target PFAS removal >95%

The pilot test ran six loading cycles total between October 20, 2020, and July 13, 2021. Each loading cycle ran between approximately 6,000 and 7,500 BVs. In total, the system treated almost 400,000 gallons, or approximately 40,000 BVs. Generally, one month of run time was required per loading cycle during the pilot to meet the 5,000 BV treatment target.

Loading cycles were typically run longer than the 5,000 BV target to provide insight into breakthrough characteristics of the resin beyond the 70 ppt goal. Flow throughput per cycle also varied based on staff availability to collect the end of cycle samples and perform regeneration and distillation operations. Figure 6 below shows the treatment performance of the lead and lag IX resin vessel effluents vs. the target treatment goal of less than 70 ppt PFOS and PFOA combined. The lead vessel experienced break though of the 70 ppt PFOS and PFOA limit at or before the 5000 BV in most loading cycles. The lag IX resin vessel effluent remained below the detection limit through the duration of the pilot except as described in Section 3.3 below.

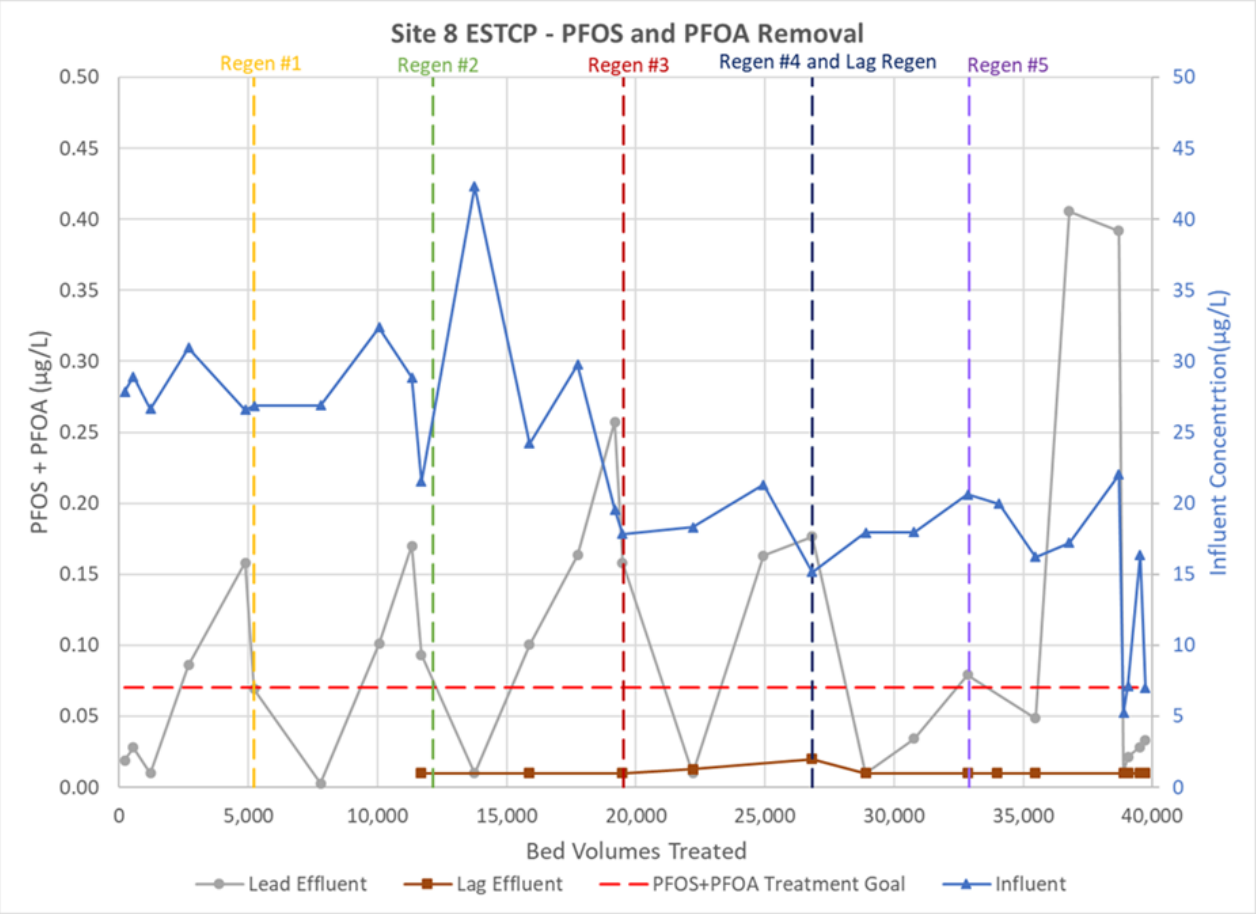


Figure 6 IX Resin PFOS and PFOA Removal

3.3 NON-TARGET PFAS REMOVAL >95%

Evaluation of non-target PFAS helps with comprehensive profiling of PFAS loading and general O&M of the system (resin regeneration, rotation of the lead and lag vessels, etc.). In many cases and jurisdictions, there will be remedial action objectives set for PFAS compounds in addition to PFOA and PFOS; understanding the efficiency and effectiveness of the PFAS treatment train to remove individual PFAS may be a determining factor in technology or media selection. For compounds that are more difficult to treat, the shorter chain PFAS compounds, the frequency of regeneration, or alternatively media change out will determine the lifecycle cost.

During the Pilot Test, the Sorbix HC1 IX resin vessels removed 95% or more of analyzed PFAS compounds until the end of cycle 4. Normally, regenerable IX resin vessels would be rotated after regenerations, i.e., the regenerated vessel moves into the lag position, and the lag vessel becomes the new lead vessel. This rotation of vessels keeps total effluent coming out of the lag vessel consistent and low. However, to determine the impact on performance, this pilot test utilized a designated lead vessel to stress the IX resin with as many regenerations and PFAS loading cycles as the schedule allowed.

This operational setup produced a slow buildup of PFAS compounds on the lag vessel as PFAS compounds leaked through the lead vessel during each loading cycle. To continue maintaining the target 95% or greater removal of PFAS through the IX resin, the lag vessel was regenerated concurrently with the lead vessel at the end of the fourth loading cycle. This one-time lag vessel regeneration successfully restored the IX resin’s PFAS removal capacity for the remainder of the pilot test.

Figure 7 below shows the treatment performance of the lag IX resin vessel effluent vs. the target treatment goal of 95% or greater removal of non-target PFAS compounds during the Pilot Test.

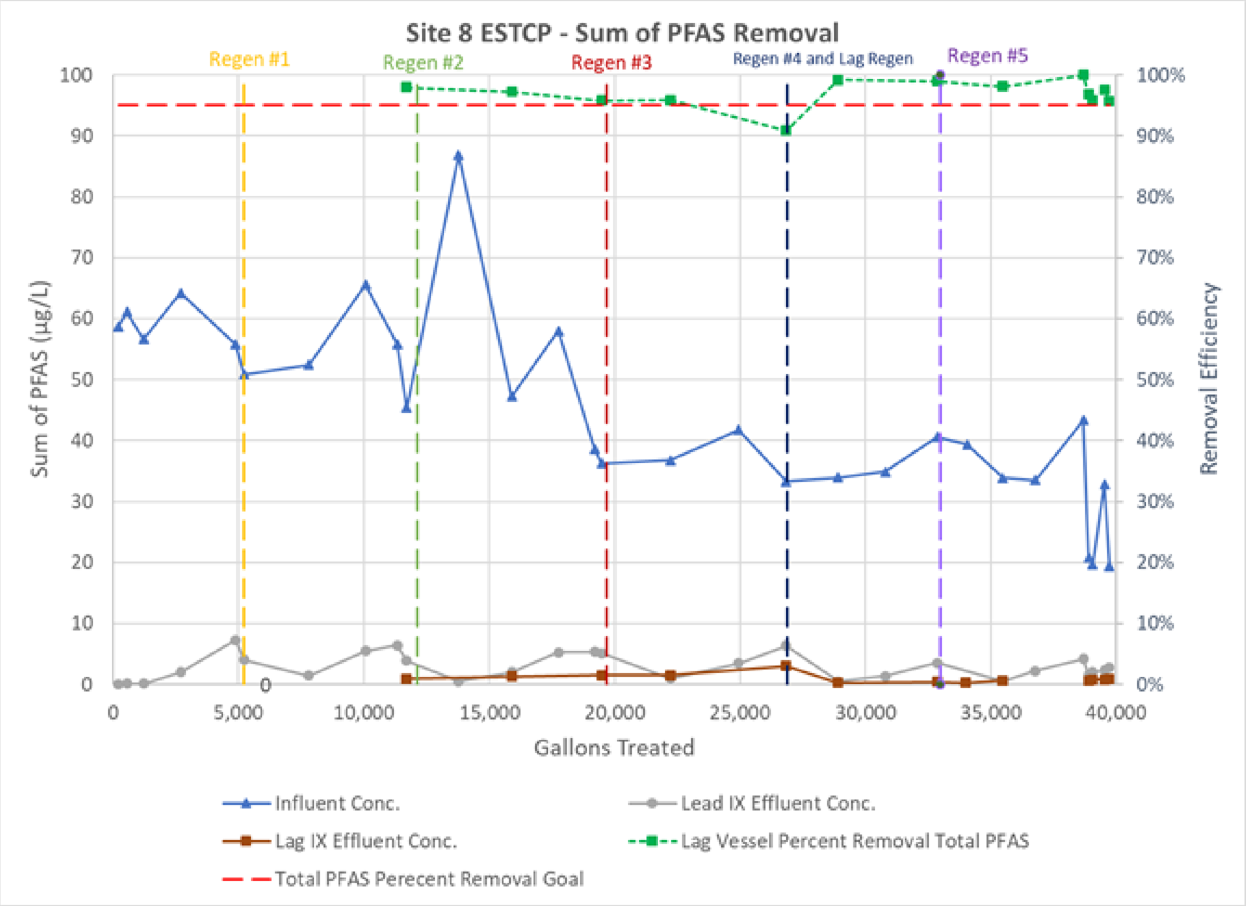


Figure 7 IX Resin Sum of PFAS Removal

3.4 RE-USE OF RESIN AND REGENERANT

Regeneration and re-use of IX resin is critical to the sustainability and effectiveness of the PFAS treatment train. The success criteria used during Pilot Test to demonstrate on-site IX resin regeneration included:

- 100% of resin can be reused during 6-month demonstration
- 95% of Total PFAS mass recovered from resin
- 95% of regeneration solvent can be reused
- PFAS concentration in recovered distillate below 10 µg/L
- Less than 10% reduction in resin performance for 5 loading/regeneration cycles

These objectives were achieved with observations and exceptions, listed below:

- The original HC1 IX resin loaded at the start of the pilot test remained in use for the duration of the test and continued to provide PFAS treatment effectively, meeting PFAS removal performance objectives.
- Mass balance calculations were sensitive due to the PFAS concentrations in the spent regenerant being four orders of magnitude higher than influent and effluent concentrations, producing recovery percentages appearing to be over 100% for several regenerations. This effect can be observed due to reaction kinetics that favor the removal of certain PFAS over others, typically longer chain compounds are preferred over shorter chain compounds. It is possible for less-preferentially removed compounds to build up over time on the IX media, but then as more-preferentially removed compounds enter the media, they will displace the other compounds to such an extent that over a period there is less of that less-preferentially removed compound coming into the vessel than leaving the vessel.
- The amount of regeneration solvent, IPA, recovered, was estimated based on analytical data for IPA percentage on the still bottoms, and calculated values of starting IPA percentage in the respective batches of spent regenerant. The distillation system recovered over 95% of solvent from the spent regenerant solution for each of the four completed distillation cycles.
- PFAS concentrations in the recovered distillate after treatment in the distillate purifier IX resin vessel initially exceeded 10 µg/L due to the distiller's design. As a simple solvent recycler, the unit had a higher potential for PFAS carryover due to foaming. The solvent recycler was modified with a distillation column to improve distillate purity. The majority of PFAS compounds in the treated distillate were Perfluorooctane sulfonamide (FOSA-1) and N-Methylperfluorooctanesulfonamide (N-MeFOSA), compounds which were simply not removed at all by the IX resin in the distillate purifier. Even so, recovered distillate treated by the distillate purifier IX resin vessel only slightly exceed 10 µg/L after installing the distillation column.
- Both PFOS and PFOA removal and total PFAS removal remained within 10% of the first loading cycle removal efficiency for each of the regenerated loading cycles. Table 2 below shows removal efficiency for sum of PFAS and PFOS+PFOA for each loading cycle (alternating shades of blue), with the sample closest to 5,000 BVs treated per cycle highlighted in yellow.

Table 2 Resin Removal Efficiency

Bed Volumes Treated	Total PFAS Removal Efficiency	PFOS and PFOA Removal Efficiency
216	99.90%	100.00%
549	99.80%	100.00%
1,217	99.70%	100.00%
2,687	96.90%	99.90%

4,889	86.90%	99.70%
5,226	92.10%	99.90%
2,568	97.30%	100%
4,841	91.70%	99.80%
6,101	88.40%	99.70%
6,472	91.40%	99.80%
1,618	99.40%	100.00%
3,744	95.70%	99.80%
5,605	90.90%	99.70%
7,046	86.20%	99.30%
7,339	85.80%	99.60%
2,734	97.30%	100%
5,457	91.80%	99.60%
7,348	81.00%	99.50%
2,072	98.60%	100.00%
3,946	96.10%	99.90%
6,018	91.20%	99.80%
2,612	98.40%	99.90%
3,926	93.30%	98.80%
5,841	90.30%	99.10%
6,038	92.30%	100.00%
6,209	89.50%	99.90%
6,672	93.00%	99.90%
6,873	85.50%	99.80%

3.5 PLASMA DESTRUCTION

On-site plasma destruction of PFAS in the concentrated still bottoms was a novel application attempted during this study for the first time at field scale. The prospect of on-site PFAS destruction in liquid media at concentration in the 100s of parts per million range, representing four to five orders of magnitude concentration increase over groundwater, represented a significant opportunity to reduce PFAS waste and the associated challenges and liability associated with off-site disposal or destruction. Today’s full-scale regenerable IX systems typically load the still bottoms onto solid media for off-site management. Onsite plasma treatment, with plasma effluent returned to treatment train influent, provides a closed-loop, low-waste alternative to mainstream proven technologies.

Plasma is an ionized gas consisting of a quasi-neutral mixture of neutral species, positive ions, negative ions, and electrons. Plasma-based water treatment uses electricity to convert water into a mixture of highly reactive species (i.e., plasma) that rapidly and non-selectively degrade recalcitrant organic chemicals of concern. The low energy plasma used during the Pilot Test included argon gas bubbles to bring PFAS to the gas-water interface near where the plasma is generated by applying a potential difference between two metal electrodes. Reductive species generated from plasma, such as solvated electrons and argon radicals, play a key role in PFAS destruction (breaking the C-F bond). Figure 8 below shows a schematic of the plasma and its field demonstration that was provided by DMAX Plasma Inc. of Potsdam, NY.

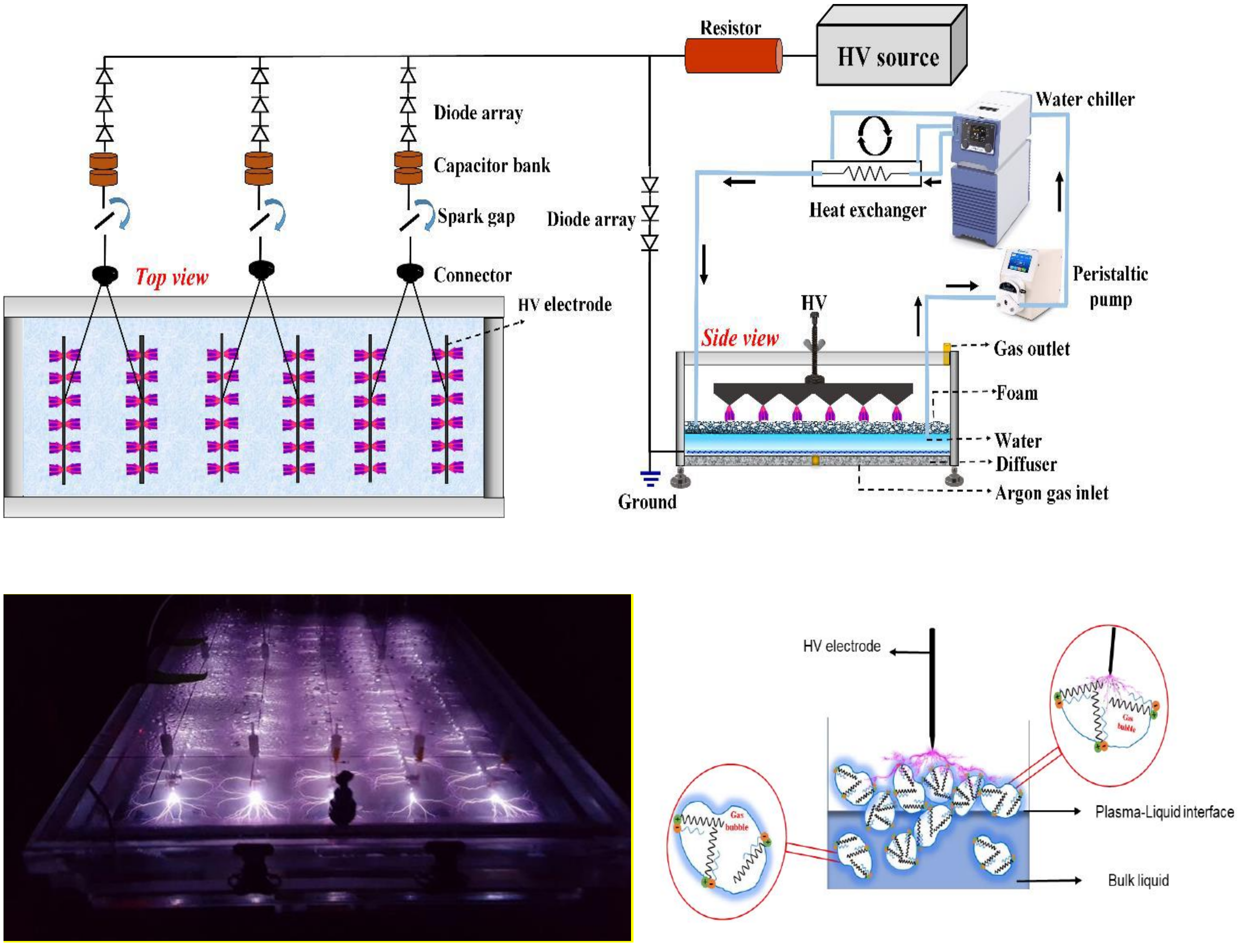


Figure 8 A Plasma reactor layout, a photo of bench scale plasma treatment unit, and a schematic of Plasma Destruction, courtesy of Clarkson University

The quantitative pilot test objective of plasma destruction was to reduce PFAS to below 70 ppt on an individual PFAS compound basis. Plasma treatment occurred using three batch stages: high concentration reactor (A), low concentration reactor (B), with cetyltrimethylammonium bromide (CTAB, cationic surfactant) addition and polishing reactor (C) (also with CTAB addition) to minimize the impact of PFAS desorption from reactor components. Still bottoms may have to be diluted before plasma treatment to limit excessive foaming in the plasma reactor. During the Pilot Test, still bottoms were diluted 10X using purified water prior to treatment. The PFAS concentrations in the still bottoms and the laboratory reports are provided in the Pilot Test Report (Wood, 2022).

The initial testing confirmed that the 0.2 mM CTAB dose improved short chain perfluoroalkyl acids (PFAA) removal but inhibited the degradation of long-chain PFAAs removal. Figure 9 below shows interaction of CTAB and Perfluorobutanesulfonate (PFBS) through electrostatic attraction.

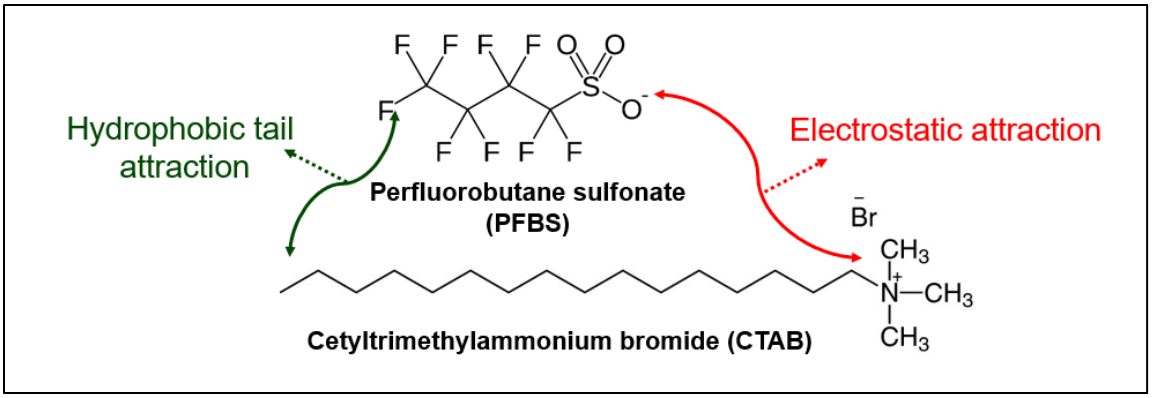


Figure 9 **CTAB and PFBS Interaction**

Plasma PFAS destruction of precursor, long chains, and short chains are provided on Figure 10,11, and 12 respectively.

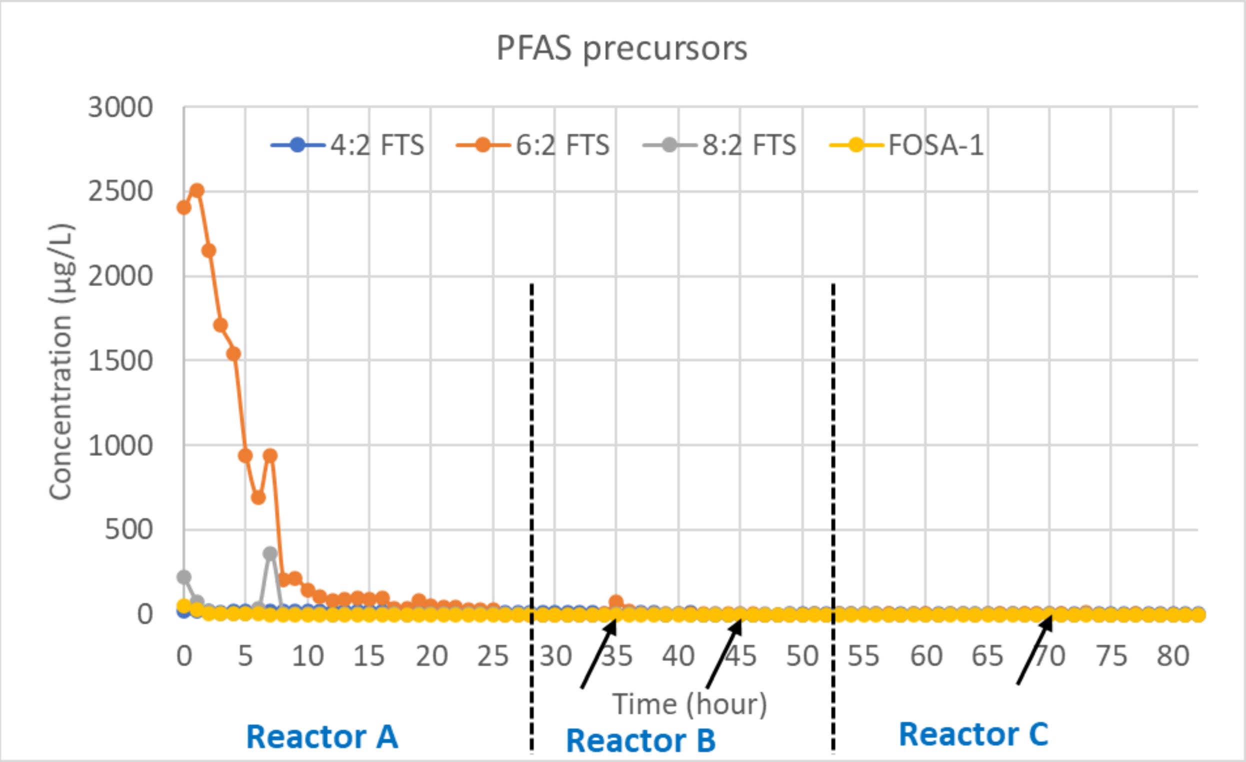


Figure 10 **Plasma PFAS Precursor Removal (arrowheads pointing to CTAB addition timing)**

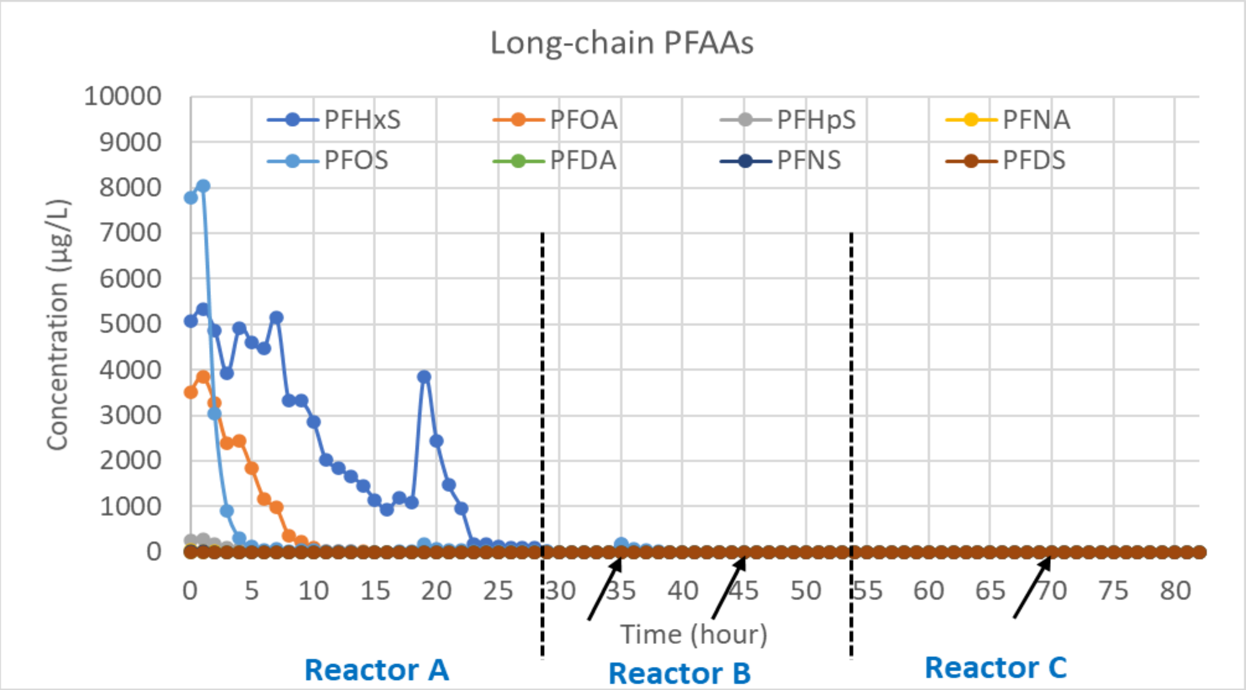


Figure 11 Plasma Long-Chain PFAA Removal (arrowheads pointing to CTAB addition timing)

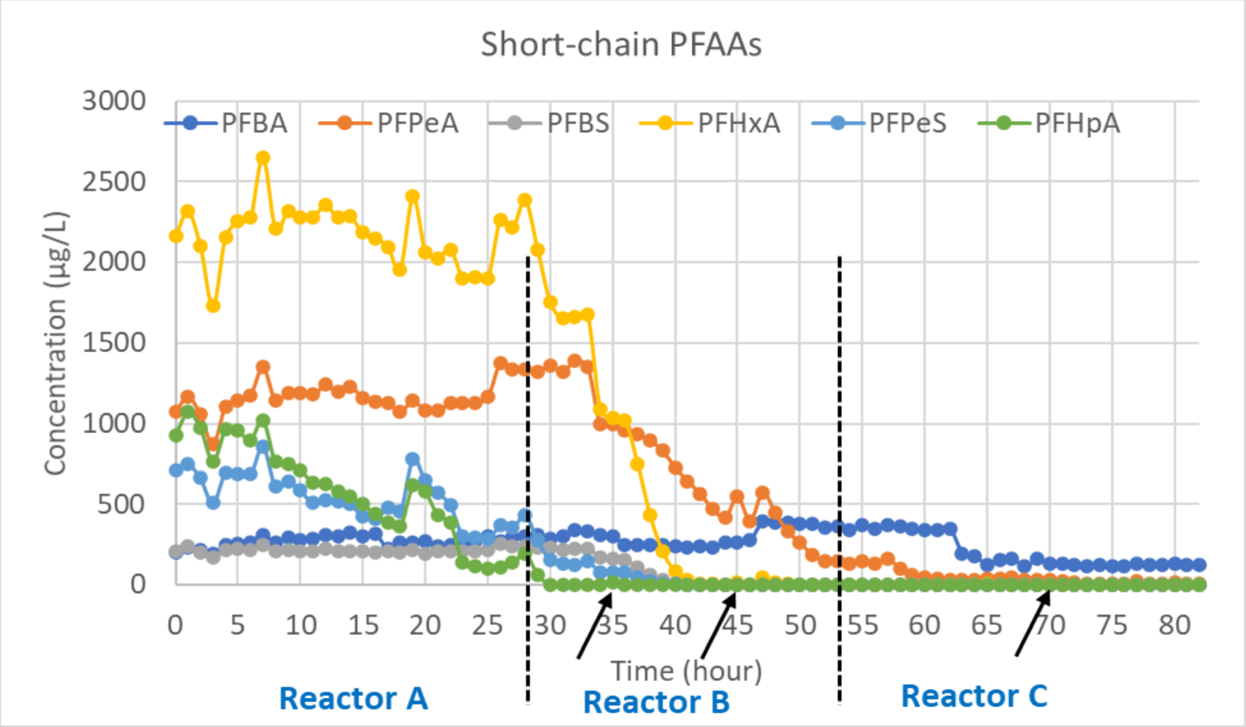


Figure 12 Plasma Short Chain PFAA Removal (arrowhead pointing to CTAB addition timing)

Note: dotted black lines (figures above) show the treated solution was transferred from one reactor to another as indicated by Reactor A, B, and C in blue text, and 0.2 mM CTAB concentration was added at 35th, 45th, and 70th hours, which are indicated by black arrows.

During final testing, in the presence of CTAB, all the PFAS precursors were removed to below detection limit (BDL) after 100 hours of the treatment. All the long-chain PFAAs, except Perfluorooctanesulfonate (PFOS, removed to 0.5 µg/L) were removed to below detection limit (BDL) at 110 hours of treatment. All the short chain PFAAs, except PFBA (~96%) were also removed to BDL after 120 hours of treatment. Using the PFBA concentration from 82 to 120 hours, PFBA removal was found to follow first order removal kinetics which indicated that an additional treatment of 115 hours would decrease the PFBA concentration to below the treatment goal. It should be noted that the slower short chain PFAA removal was because they can be produced as byproducts from longer chain PFAS destruction and also they have a decreased capacity to be transported to the gas-liquid interface where plasma is generated. The project team anticipates configuring the PFAS treatment train to have the plasma effluent return to the head of the treatment train. Obtaining these quantitative treatment goals may not be necessary in a closed-loop system where the plasma effluent is recycled. Greater than 99% destruction of PFAS was achieved, which achieves a noteworthy waste minimization standard. It will be a site-specific, operational decision how long to run the plasma destruction system.

4 COST ASSESSMENT

4.1 COST MODEL

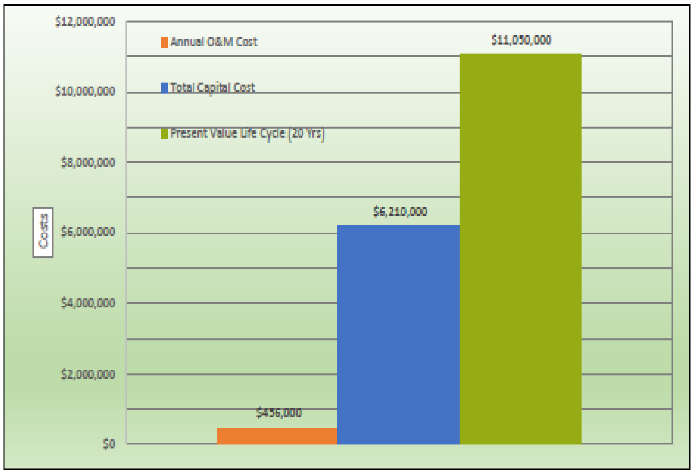
Each potential site presents its own unique considerations with respect to location, site conditions (physical and hydrogeologic), regulatory criteria, co-occurring chemicals, pretreatment requirements, effluent limits, existing treatment systems, and prior remedial efforts. Therefore, a site-specific cost model should be developed for estimation of capital costs for regenerable IX with plasma destruction based on these site-specific constraints. A detailed list of the basis of the cost model, assumptions, cost drivers, and cost analysis is presented in the Pilot Study Final Report (Wood 2022) submitted to ESTCP in June 2022. A present worth analysis for a scaled-up, 100 gpm treatment system designed to treat groundwater with the characteristics of Site 8 at Pease is presented in the Figure 13 below.

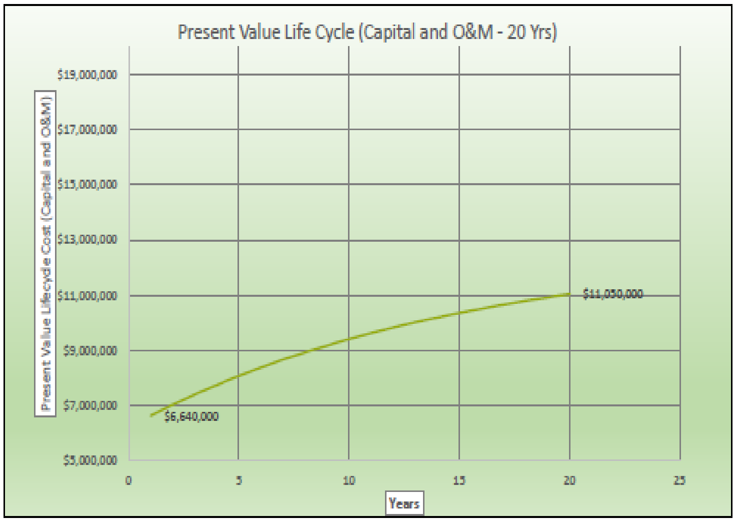
PRESENT WORTH ANALYSIS

Discount Rate	0.07	from Demonstration Plan 9/2020
Life Cycle Period	20	years (assumed)

	Regenex IX	
Equipment Cost	$	1,440,000
Building Cost	$	3,730,000
Capital Cost	$	5,170,000
20% Contingency	$	1,034,000
Total Capital Cost	$	6,210,000
Present Value of Capital Cost	$	6,210,000
Annual O&M Cost	$	456,000

Year	Annual O&M Cost		Present Value of O&M Costs		Present Value Life Cycle (20 Yrs)	
1	$	456,000	$	426,168	$	6,640,000
2	$	456,000	$	398,288	$	7,038,288
3	$	456,000	$	372,232	$	7,410,520
4	$	456,000	$	347,880	$	7,758,400
5	$	456,000	$	325,122	$	8,083,522
6	$	456,000	$	303,852	$	8,387,374
7	$	456,000	$	283,974	$	8,671,348
8	$	456,000	$	265,396	$	8,936,744
9	$	456,000	$	248,034	$	9,184,778
10	$	456,000	$	231,807	$	9,416,585
11	$	456,000	$	216,642	$	9,633,227
12	$	456,000	$	202,469	$	9,835,697
13	$	456,000	$	189,224	$	10,024,921
14	$	456,000	$	176,845	$	10,201,765
15	$	456,000	$	165,275	$	10,367,041
16	$	456,000	$	154,463	$	10,521,504
17	$	456,000	$	144,358	$	10,665,861
18	$	456,000	$	134,914	$	10,800,775
19	$	456,000	$	126,088	$	10,926,863
20	$	456,000	$	117,839	$	11,050,000





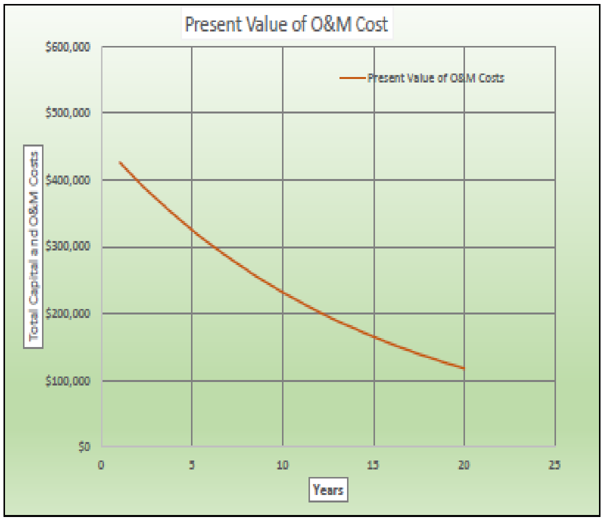


Figure 13 **Present Worth Analysis**

4.2 COST ANALYSIS

This study, as well as other applications, have demonstrated that regenerable IX for PFAS treatment is effective and robust, and that it offers specific advantages discussed below; however, regenerable IX may not always be preferred. A generalized representation of when regenerable IX might be preferred is presented here:

- When sustainability has highest priority over other evaluation criteria. Regenerable IX coupled with low energy plasma destruction of PFAS provide a closed-loop, low-waste solution that has intrinsic sustainability and liability benefits.
- When Influent concentrations are high, and the flowrates are moderate to high, regenerable IX becomes more cost effective as flow rate and concentration increase. That is because, under typical circumstances, regeneration is less expensive than media change outs.
- When in locations or circumstances where offsite media disposal or reoccurring media purchase is not practical.
- When building footprint, capital costs, and HVAC O&M costs can be reduced by housing equipment in insulated steel cargo shipping containers, i.e., Conex boxes. If the need for explosion proof equipment and building can be reduced (e.g., performing regeneration and distillation outside), it could provide additional cost savings for this alternative.
- When the treatment horizon is expected to be long—several years or more—allowing the lower O&M costs to offset the higher capital cost over time.
- When PFAS treatment goals are strict or include short chain PFAS compounds. Low PFAS treatment goals or short chain compounds prone to earlier breakthrough will increase media changeout or regeneration frequency and may increase regenerable resin's cost-effectiveness.

Conditions when regenerable IX would likely not be the lowest lifecycle cost solution include:

- Large flowrate rate treatment of low PFAS concentration in influent, e.g., large scale drinking water treatment.
- Where trained onsite labor is not available throughout the year.

Cost savings may be gained by construction of a separate facility with the capacity to provide regenerations to multiple sites located within a few hundred miles of the centralized regeneration facility. This facility would be much larger than a site-specific regeneration system and would be able to provide the following kind of regeneration options:

- Option1: Swap out of the entire spent IX vessel(s) and replacement with a regenerated vessel(s) to save system downtime, transportation of the spent vessel and subsequent regeneration at the central facility. This option would be suitable when IX vessels are not too large for transport by truck, adequate onsite labor is not available, and minimal system downtime is desired.
- Option 2: Onsite vacuum of the IX beads and refilling IX vessels with new IX beads. This option would be suitable when transportation of large IX vessels is not practical or cost effective and adequate onsite labor is available. This option would require additional labor and handling considerations both at the site and the central regeneration facility.

5 COMPARISON OF THE REGENERABLE IX TREATMENT TRAIN WITH GAC AND SINGLE PASS IX

5.1 TECHNOLOGY COMPARISON FRAMEWORK

A comparison of regenerable IX, granular activated carbon (GAC) and single pass IX for a 100 gpm PFAS treatment system modeled after Pease Site 8 is presented in Table 3 below. The data provided in the table is a combination of data provided by vendors, extrapolation from the column and pilot testing efforts, operational experience, and engineering estimate. The data provided in the table can help in the decision framework for designing a new treatment system or upgrading an existing treatment system.

Table 3 Comparison of GAC, Single Pass IX, and Regenerable IX Resin

Parameter	GAC	Single Pass IX Resin	Regenerable IX Resin	Source of Information	Selection Consideration
Typical Media Vessel Size	High	Low (~80% lower than GAC size)	Low (~50% lower than GAC size)	Operational experience, based on recommended EBCT of 2 min for single pass IX, 5 minutes for regenerable IX, and 10 minutes for GAC	Reduced building footprint favors IX over GAC
Capital Cost (media) for 100 gpm system	$45,000 (6,000 lbs GAC- estimate provided by Calgon Carbon)	$27,600 (120 CF, based on AIMS Site PFA694 resin cost)	$18,960 (120 CF, cost provided by ECT2)	Vendor provided data	High cost and frequent change out for single pass media likely favors the regenerable IX
Typical Media Cost ($/CF) (using 33.7 lb/CF for F400 GAC)	67-135	230-350	150-250	Based on the vendor data collected during Site 8 column test and pilot test	
Solid Media Offsite Disposal Cost ($/lb)	High	High	Low	Solid waste disposal at RCRA Subtitle C Landfill for Department of Defense PFAS waste	Disposal cost will vary based on the site location.
Average Sorption/IX Capacity (mg of PFAS/g of Media) and Bed Volume* for a breakthrough of 70 ppt (PFOS+PFOA); *BV is based on a flowrate of 100 gpm at conc of approximately 24 ppb of PFOS and PFOA)	0.75 mg/g (+/-10%) @ 10 min EBCT; BV-Low, 3600 (Based on Site 8 Testing)	1.2mg/g (+/-50%) @ 2 min EBCT for Purelite PFA694E resin; BV-High 32,000 (Extrapolation and rounding based on Column Test data and vendor data)	0.56mg/g (+/-50%) @ 4.7 min EBCT for HC1 IX resin; BV-Medium 4,400 (Based on Site 8 Pilot Test)	Average capacities based on Site 8 treatability and pilot testing	Regenerable resin should be kept fresh by using site appropriate regeneration frequency. Regenerate shortly after breakthrough. Bed volume may vary site to site- and site-specific testing may be needed
Typical Flowrate (Q) and PFAS Concentration Suitability	Suitable at Low to High Q and Medium Concentration	Suitable at Medium to High Q and Low Concentration	Suitable at Medium to High Q and High Concentration	Based on two sites (AIMS and Site 8 at Pease) operational experience	Site specific testing may be needed at high Q to evaluate operational parameters
Short Chain PFAS Removal	Low	High	Low, managed by regeneration frequency and vessel configuration. Resin regeneration provides the capability to optimize short chain PFAS removal efficiency.	Based on Site 8 pilot and column test	Site-specific testing may be needed to meet discharge standards
Electricity Consumption	Medium	Medium	High, when complemented with onsite Plasma destruction of PFAS	Operational experience	Energy cost may influence technology selection

Table 3 Comparison of GAC, Single Pass IX, and Regenerable IX Resin

Parameter	GAC	Single Pass IX Resin	Regenerable IX Resin	Source of Information	Selection Consideration
Building Cost for a 100-gpm system (includes 5,200 square feet, 4,000 psi slab, HVAC, electrical controls, office space and bathroom)	Medium $2-$3M	Medium $2-$3M	High ~$3-4M (includes explosion proof building)	Engineering estimate based on an existing treatment system at Site 8	Building cost will vary significantly based on the geography. If regeneration can be performed outside the building in permanently warmer climates, it would provide cost savings as explosion proofing will not be required.
Annual O&M Cost	Medium (less site visits and operational requirements but higher media use and changeout)	Low (less site visits and operational requirements, less frequent change outs than GAC)	Low materials cost as media changeout is not required but multiple site visits of full-time operator required for system operations	Based on two sites (AIMS and Site 8 at Pease) and operational experience	As the frequency of regeneration and single pass media change out increase, the likelihood of regenerable IX being lifecycle lower cost increases. This is because the cost to regenerate will typically be lower than the cost for media change-out.
Remedial Action Objectives (RAOs)	if PFOS and PFOA RAOs are lower than 70 PPT, and/or short chain compounds have ROAs, GAC becomes more expensive due to early breakthrough and frequent change outs	If PFOS and PFOA RAOs are lower than 70 PPT, and/or short chain compounds have ROAs, single pass becomes more expensive due to early breakthrough and frequent change outs	if PFOS and PFOA RAOs are lower than 70 PPT, and/or short chain compounds have ROAs, regenerable IX will become more cost effective if regeneration is cheaper than media change out	Based on two sites (AIMS and Site 8 at Pease) and operational experience	While evaluating site specific RAOs, consider that regulatory criteria are in flux and trending downward and tending to include more compounds than just PFOA and PFOS. A treatment train designed to meet today's remedial action objectives may be inadequate to meet future ROAs. In particular, as short chain PFAS are added to the ROAs and early breakthrough becomes a consideration, media change outs will increase in frequency, driving costs higher, and likely merit a reconsideration of the treatment train.
Sustainability	Medium (if GAC is reactivated and reused)	Low (needs offsite disposal)	High (can be regenerated onsite, low waste solution when coupled with plasma destruction of PFAS). Waste minimization may decrease where pre-treatment processes (e.g., clarification, filtration, TOC removal) may also remove PFAS and these waste. streams may require off-site disposal as PFAS waste.	Based on two sites (AIMS and Site 8 at Pease) operational experience.	Sustainability may become more important than other criteria in future.

5.2 CRITICAL VARIABLES IN THE TECHNOLOGY SELECTION

The five critical variables that would help in PFAS treatment train technology selection are flowrate, influent concentrations, bed volume, sustainability, and regulatory environment/remedial action objectives (RAO). Figure 14 below provides a qualitative correlation of these variables relative to the three technologies evaluated. For example, when influent concentrations are high and flowrate is high as well, regenerable IX generally may be a better technology over single pass IX and GAC, due to lower lifecycle cost. Typically, regenerable IX should not be considered for concentrations less than 10 ppb of total PFAS; however, regenerable IX should still be evaluated in circumstances where sustainability is extremely important and in remote areas with transportation challenges for replacement media and waste disposal (e.g., facilities on islands, etc.).

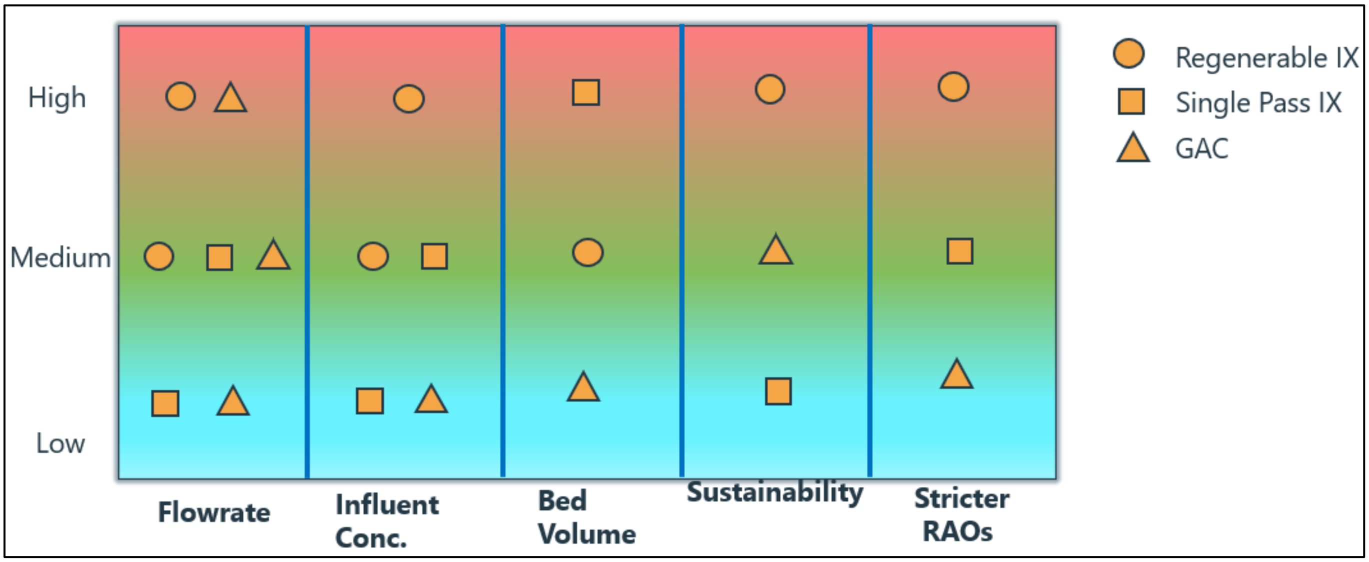


Figure 14 **Critical Variables in Technology Selection**

The influence of stricter RAOs is considerable. This project was established around an interim, non-enforceable human health criteria for drinking water, that because of a lack of understanding of PFAS and an undeveloped regulatory framework at the time, became a default RAO applied widely for approximately four years. That health advisory for one compound, PFOA, formerly 70 ppt, is now established at 0.004 ppt, more than five order of magnitude lower, but also non-enforceable. Setting the ROA that low essentially mean no PFAS can pass through a groundwater treatment system. As such, critical cost drivers, such as frequency of media change out and frequency of regeneration, change dramatically.

Keep in perspective that the cost model presented herein is based around 70 ppt for combined PFOS and PFOA concentration, which is no longer, a relevant RAO. The project team believes, however, that the near certainty of stricter RAOs in the future, in particular the pending maximum chemicals (of concern) levels (MCL) for PFOS and PFOA, will generally favor the lifecycle cost of the regenerable IX treatment train since higher frequency media change outs for single pass media result in higher operations and maintenance costs.

6 CONSIDERATIONS FOR OPERATION AND MAINTENANCE

The routine O&M activities based on the operational experience at Site 8 and from the Pilot Test are listed below. The user should note that the O&M activities will vary on the size of the treatment plant and number of treatment steps included on the treatment train. The project team has limited the O&M considerations to in-plant systems and excluded the systems outside the plant that extract and covey water to the plant.

Many of these considerations pertain to pre-treatment, and at Site 8, pretreatment has been both a challenge and an opportunity to understand and refine the processes that protect the IX media and optimize the removal of PFAS. The primary, but not the only “co-occurring chemical” at the existing Site 8 full-scale treatment plant was dissolved iron, naturally occurring in the formation at approximately 10 mg/L in the combined influent from the well-field. The plant was not designed with an understanding of the iron in the well field; the iron-removal systems were retrofitted, designed, and constructed after the treatment plant was commissioned. This caused the treatment plant to run at reduced capacity, primarily using the lower-iron wells in the well field, while the iron removal systems were designed, constructed, and proved out, for a period after commissioning in 2018.

Routine O&M Activities:

- Change out Pre- and Post- GAC bag filters if included in the treatment train as pre-treatment or post treatment step. This will also include cleaning bag filter housing.
- If clarification is used at Site (performed at Site 8), then periodic inspection of the clarifier including inspecting interior of the clarifier for sludge accumulation and cleaning of clarifier based on a field determination.
- Inspect coagulant pump (used at Site 8) including metering pump valve seats and balls for deterioration; deterioration may indicate incorrect material selection.
- Perform jar testing with process water to confirm appropriate pre-treatment chemical dosages at least weekly. Jar testing was done weekly at Site 8 to confirm appropriate pre-treatment chemical dosing.
- At Site 8, batches (150 gallon) of 1% v/v anionic polymer for pre-treatment dosing was used. Additional O&M activities with step included periodic inspection of polymer metering pump and tubing.
- Backwash IX resin and/or LGAC beds. Manually/automated backwash of IX resin bed when differential pressure exceeds baseline pressure based on manufacturers specifications.
- Resin regeneration is a multistep process that involves using solvent-brine solution to flush the IX resin for removal of PFAS from the resin. A typical regeneration would involve brine flush at a flow rate of 2 bed volume/hour (BV/hr), flush with regenerant solution at a flow rate of 2 BV/hr, rinse with potable water at a flow rate of 4 BV/hr.
- For an average flowrate of 100 gpm, a treatment system with two 60 cubic feet regenerable IX units, regeneration would be required every 14 days and each regeneration would take 24 full-time labor hrs. For 27 regeneration events per year, a total of 639 hrs. will be required.
- Spent regenerant solution from each event is recycled using a distillation process. Batch distillation of spent regenerant solution is performed by heating the spent regenerant to a design temperature where alcohol is

recovered through vaporization and collected in a condensate collection tank. The number of the distillations required would be dependent on the size of the distiller used in the treatment equipment setup at a site.

- Manually decant the cone-bottom settling tank (used at Site 8).
- If the treatment system has a sludge press for solids removal, then O&M activities also include emptying of the sludge pressed material into 55-gallon drums for off-site disposal, typically as a PFAS waste, cleaning of sludge press filters, and inspection of effluent pump.
- Cleaning of sludge recirculation valves, check valves, flow meters and sight glass.
- The addition of pretreatment may necessitate a second operator, based on the size and capacity of the treatment plant.
- In plasma reactors, ensure that initial bubbling is very slow to avoid excess foaming and argon bubbling is manually increased overtime as PFAS is destroyed.
- In plasma reactors, surfactant addition should be optimized over time for each site based on the type and dose of surfactant chosen.
- For full-scale implementation, additional O&M consideration related to plasma destruction may be developed over time, based on the scale of the plasma system. Based on the pilot test experience, a complete list could not be developed.
- Run the distiller to recover solvent and prepare for the next regeneration event. This includes going through the series of distillations after a regeneration to separate out enough clean regenerant to perform the next regeneration.
- Because of the high iron content and biofouling issues at Site 8, manual backwash was required. Manually backwash the IX resin when differential pressure exceeds 300% of baseline pressure. Backflow requires beds to be operated in downflow configuration with adequate free space to backwash. Under optimal conditions, where pretreatment systems are properly designed and operated, manual backwash would likely not be required.
- Clean IX resin skid wye strainers, these strainers mechanically remove solids and enhance the resin longevity.
- Routing or processing of solvent collected from distiller through distillate purifier (super loader) vessel (IX resin) before sending to regeneration tank to remove any PFAS compounds that are carried over with solvent during distillation. This process was automated at site 8 but may be performed manually at other sites based on the site-specific requirements.
- Annual Inspection of fire alarm system.
- Periodic inspection of still bottom air-cooled chiller.
- Regenerable IX with plasma destruction may require a full-time operator to operate the plasma units and periodic addition of surfactant.

7 IMPLEMENTATION ISSUES

The list of implementation issues provided below is based on the operational experience during the pilot test and current operations at the full-scale system at Site 8. These issues are presented below to help with additional design considerations:

- Pretreatment for co-occurring chemicals (metals, TOC, TSS, TDS, VOCs, etc.): based on the site-specific co-occurring chemicals, pretreatment requirement can increase building size and require a larger footprint for pretreatment vessels. These need to be carefully evaluated prior to design of any full-scale system.
- Downflow versus up-flow operation of the resin beds and the ability to backwash as required. It many settings, there may be an advantage to operate in a downflow mode in partially filled vessels to allow up-flow backwashing to remove fouling from the media as required. Based on the pilot and full-scale observations, the treatment system should be fitted with both downflow and up-flow valving to reduce operations and maintenance costs.
- Biofouling can be observed in any IX/GAC vessels, especially during long periods of down time required by maintenance activities, leading to pressure drop. Treatment equipment should include provisions for addressing these issues (backwashing and/or biocide addition) that could possibly negatively affect the resin/GAC performance.
- Consider the use of single pass IX after regenerable IX as a polishing step (based on pilot and full-scale Site 8 operations data). This might be particularly advantageous if the influent stream has short chain PFAS compounds which require removal to meet regulatory requirements (especially PFAS with less than 6 carbon chain lengths, e.g., PFBA) which have lower demonstrated removal efficiencies using regenerable IX compared to single use. Alternatively, the regeneration cycle length can be reduced to accommodate enhanced removal of short chain PFAS.
- Waste minimization may be reduced if pretreatment before regenerable IX and tertiary treatment after plasma destruction are required. These wastes could potentially include spent filters, sludge, as well as spent media (as applicable) requiring disposal as PFAS containing wastes.
- If regeneration and distillation cannot be performed outside (dependent on geographical location and climatic conditions) the equipment building, equipment and appurtenances must follow electrical classification requirements for flammable solvents.
- Identify discharge requirements for the system effluent to select appropriate regenerant (e.g., methanol may be regulated in the discharge permit, but IPA may not). This would be dependent on the regulatory authority's requirements.
- Spent regenerant after distillation, distillate purification, and/or plasma destruction treatment have a high salt concentration but can be bled back into the system to avoid off-site disposal. The waste stream would be highly diluted depending on full-scale system flow; however, the high salt content may pose discharge concerns depending on discharge location (e.g., sewer, on-site reinjection, or surface water).
- The distillation system should be appropriately designed to account for foaming (observed during the pilot study) to minimize PFAS carry over in the distillate.
- Application of plasma for concentrated still bottom destruction has not been deployed at full-scale for large flowrates. Implementation challenges and operational inefficiencies at full-scale may include large equipment footprint, need for adequate retention time for plasma-liquid contact at high flowrate and high PFAS concentration, energy demands, and labor for operation. It does appear, based upon its simplicity and single component configuration, that this technology could be a good fit for full-scale application.

8 RECOMMENDED TECHNOLOGY SELECTION AND DESIGN PROCESS FOR GROUNDWATER EXTRACTION AND TREATMENT FOR PFAS USING ION EXCHANGE MEDIA OR GAC

A stepwise process and decision framework is recommended for potential users to help in technology selection and application, specific here to regenerable vs single pass IX and GAC.

1. Conduct a desktop evaluation and literature review to understand the current, proven, and optimized treatment configurations for groundwater extraction and treatment for PFAS that are applicable and available for your unique treatment challenge. New and customized treatment processes and media are coming to market from the vast, ongoing PFAS research and development programs.
2. Establish your remedial action objectives. The regulatory landscape is fast evolving. Many technologies have been proven against already outdated standards. Attaining new lower and expanded criteria has a major impact on technology selection, as discussed previously in this user’s guide. EPA has promised MCLs for PFOA and PFOS this year (2022), which will become a de facto RAO in many settings.
3. Determine how and where you will measure performance within your treatment train, what criteria will you use for regeneration and/or replacement of treatment media, and what configuration of treatment vessels will be used. For example, if you choose to use three treatment vessels in series—lead, lag, and polish—you may consider loading the lead vessel to capacity and establish your change out based on breakthrough in the lag vessel.
4. Select treatment processes and media for testing based on your literature review and demonstrated performance, availability, and cost considerations.
5. Bench Test the selected processes and media using site groundwater to select the most efficient and cost-effective solution for your application and to determine the scaled-up vessel size and bed volumes. Note that sustainability can outweigh cost considerations under certain circumstances.
6. Evaluate the pretreatment requirements based on site-specific groundwater quality. Will you need metals removal, organic carbon removal, and particulate filtering to protect the PFAS treatment media? Determine whether your pretreatment processes will also remove PFAS. Metals precipitation and organic carbon removal using GAC may remove a significant fraction of your PFAS load which in turn will impact waste minimization, disposal options, cost, and sustainability, to the detriment of the regenerable IX benefits.
7. Develop plans for a pilot scale evaluation at the selected site(s) including a process flow diagram, basis of design/goals (including methods for measurement of success) and identify any implementation requirements for conducting the pilot test. Implementation requirements could include site access/security concerns, availability of necessary utilities, local permitting (for temporary structures, electrical, fire department notification, etc.) as well as availability of vendors, contractors, and operating personnel.
8. Execute your pilot test until satisfactory results/project goals are obtained; adjust/adapt and optimize your treatment train based on observations and data collected during the test.
9. Develop plans and specifications for your full-scale system based on pilot test results. This will require involvement of multiple engineering disciplines (civil, mechanical, structural, electrical, process, hydrogeological, etc.) depending on the size and complexity of the processes selected. Regulatory agencies (state, federal, and local) should be consulted throughout the design process to ensure that all site-specific requirements are met.

9 DESIGN CONSIDERATIONS

Design considerations that are unique to the PFAS treatment train are discussed below. These are not exhaustive, but will influence the processes, configuration, construction, and operation and should be top-of-mind when considering the PFAS treatment train.

- A main driver of process selection and design configuration will be regulatory limits and discharge criteria, and type, i.e., sanitary sewer, stormwater sewer, infiltration/injection, or surface water discharge.
- Utilities/infrastructure—site access, available area for system footprint, availability of 3 phase power, etc. Small sites (area wise) may not have sufficient space, which will also drive process selection.
- Pretreatment requirements—primarily as it pertains to metals (iron/manganese), TDS and TOC should be evaluated during pilot test and during design stage. Oxidation/precipitation/flocculation/clarification/filtration may be required as part of the pretreatment. Low levels of dissolved metals can be achieved possibly by filtration (multimedia) only (e.g., AIMS Site). Based on the operational experience (e.g., Site 8 and AIMS—lessons learned) use of bag filters even at low levels of metals, TSS and TDS is not recommended as it is labor intensive and results in additional waste being generated. Flocculants and sludge from pretreatment will contain PFAS and therefore will be a PFAS waste, reducing the waste minimization benefit of regenerable IX.
- If GAC is used for pretreatment of TOC, expect substantial reduction of PFAS after a change out will occur; however, GAC efficiency will be short lived, and breakthrough of TOC may occur. Spent GAC becomes a PFAS waste stream and therefore reduces the waste minimization benefit of regenerable IX.
- PFAS influent concentrations—more frequent regeneration will be required for short chain PFAS compounds that may breakthrough the resin earlier than the long-chain PFAS compounds if strict treatment goals exist for short chain compounds.
- Regenerant selection—Methanol had discharge limit values at Site 8 and required biotreatment prior to dilution with effluent for final discharge (methanol was used for regeneration at site 8). Designers should evaluate the differences in environmental discharge requirements and regeneration performance before selecting a solvent for regeneration.
- Foaming decreases the efficiency of plasma treatment and dilution of still bottoms may be required to control foaming. At Site 8 Pilot Test, 10x dilution of still bottoms was performed that resulted in efficient plasma destruction.
- Explosion proof requirements of the treatment building may be driven by local authorities and code. If regeneration and distillation is performed outside using portable vessels, explosion proofing requirements may be reduced. Certain situations that may prohibit performing work outside include sensitive locations (residential, public, etc.), locations with prolonged snow conditions, locations close to overhead power lines, etc. Even if outside, certain equipment will need to be explosion proof (distiller, pumps, sensors, etc.) that are in contact with regenerant.
- Application of plasma for concentrated still bottom destruction has not been deployed at full-scale for large flowrates. The designer should include additional contingencies for implementation challenges and operational inefficiencies at full-scale that may include large equipment footprint, need for adequate retention time for plasma-liquid contact at high flowrate and high PFAS concentration, energy demands, and labor for operation.
- Consider including a “polishing” step with single pass IX after treatment using regenerable IX to help ensure that no PFAS compounds exceed discharge limitations (Site 8 treatment train). If a polishing step using single pass media is used, the spent media will be a PFAS waste and therefore reduces the waste minimization benefit of regenerable IX.
- Designers should plan on additional storage in the treatment building, do not undersize anything to save on the capital cost (tanks/building/equipment)—(Site 8, lesson learned). Building should include areas for

storage of spare parts, expendables, and conducting maintenance activities (re-building of pumps and other equipment).

- Include a separate room for electrical, control panel, and remote telemetry equipment—moisture may cause corrosion of these components over time.

10 BIBLIOGRAPHY

Wood, 2020. Treatability Study Report, ESTCP Project Number: ER18-5015, Former Pease Air Force Base Prepared for Air Force Civil Engineering Center, Joint Base San Antonio – Lakeland, Texas, April 17.

Wood, 2022. Pilot Study Final Report, ER18-5015 Removal and Destruction of PFAS and Co-Occurring Chemicals from Groundwater via Extraction and Treatment with Ion Exchange Media, and On-Site Regeneration, Distillation, and Plasma Destruction. Environmental Restoration Projects. June.

Useful References (Not directly referenced in this report)

Amec Foster Wheeler, 2017a, Perfluorinated Compounds Release Response at Multiple BRAC Bases, Site 8 Pilot Test Results Report, Former Pease Air Force Base, Treatability Report Final, March.

Amec Foster Wheeler, 2017b, PFAS Column Study, Treatability Report Final, July 11.

Amec Foster Wheeler, 2019a. Site Selection Memo, ESTCP Project Number: ER18-B3-5015 Removal and Destruction of PFAS and Co contamination from Groundwater Prepared for Air Force Civil Engineering Center, Joint Base San Antonio – Lakeland, Texas, February 8.

Amec Foster Wheeler, 2019b. Performance Objectives Report, ESTCP Project Number: ER18-B3-5015 Removal and Destruction of PFAS and Co contamination from Groundwater Prepared for Air Force Civil Engineering Center, Joint Base San Antonio – Lakeland, Texas, February 8.

Amec Foster Wheeler, 2019c. Treatability Study Work Plan, ESTCP Project Number: ER18-B3-5015 Removal and Destruction of PFAS and Co contamination from Groundwater Prepared for Air Force Civil Engineering Center, Joint Base San Antonio – Lakeland, Texas, March 7.

Wood, 2020. Demonstration Plan, ER18-5015 removal and destruction of PFAS and co-occurring chemicals from groundwater via extraction and treatment with ion exchange media, and on-site regeneration, distillation, and plasma destruction. September.

Kempisty, D. M., Xing, Y., & Racz, L, 2018. Chapter 14, “Ion Exchange for PFAS Removal,” In S. Woodard (Ed.), Perfluoroalkyl Substances in the Environment: Theory, Practice, and Innovation (Environmental and Occupational Health Series) (1st ed., pp. 325–352). CRC Press.

Kempisty, D. M., Xing, Y., & Racz, L, 2018. Chapter 21, “Case Study: Pilot Testing Synthetic Media and Granular Activated Carbon for Treatment of Poly- and Perfluorinated Alkyl Substances in Groundwater,” In S. Woodard (Ed.), Perfluoroalkyl Substances in the Environment: Theory, Practice, and Innovation (Environmental and Occupational Health Series) (1st ed., pp. 467–484). CRC Press.

Lu Wang, Michael Nickelsen, Sheau-Yun (Dora) Chiang, Steven Woodard, Yaye Wang, Shangtao Liang, Rebecca Mora, Raymond Fontanez, Hunter Anderson, Qingguo Huang, 2021.Treatment of perfluoroalkyl acids in concentrated wastes from regeneration of spent ion exchange resin by electrochemical oxidation using Magnéli phase Ti4O7 anode, Chemical Engineering Journal Advances, Volume 5, 100078, ISSN 2666-8211.

Raj Kamal Singh, Nicholas Multari, Chase Nau-Hix, Steven Woodard, Michael Nickelsen, Selma Mededovic Thagard, and Thomas M. Holsen, 2020. Removal of Poly- and Per-Fluorinated Compounds from Ion Exchange Regenerant Still Bottom Samples in a Plasma Reactor Environmental Science & Technology 2020, 54, 13973−13980.

Shangtao Liang, Rebecca Mora, Qingguo Huang, Rachael Casson, Yaye Wang, Steven Woodard, Hunter Anderson, 2022. Field demonstration of coupling ion-exchange resin with electrochemical oxidation for enhanced treatment of per- and polyfluoroalkyl substances (PFAS) in groundwater, Chemical Engineering Journal Advances, Volume 9, 100216, ISSN 2666-8211