Naval Facilities Engineering Systems Command

TECHNICAL REPORT
FINAL

TECHNOLOGIES AND BEST PRACTICES FOR MANAGING WASTE STREAMS FROM THE INVESTIGATION AND REMEDIATION OF PER- AND POLYFLUOROALKYL SUBSTANCES

Prepared for NAVFAC EXWC under Contract No. N39430-16-D-1802

December 2021

Distribution Statement B: Distribution authorized to Authorized U.S. Government Agencies Only.
Requests Shall be Referred to NAVFAC EXWC.

REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB NO. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-12-2021

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From – To)*
Click here to enter text.

4. TITLE AND SUBTITLE
Technologies and Best Practices for Managing Waste Streams from the Investigation and Remediation of Per- and Polyfluoroalkyl Substances

5a. CONTRACT NUMBER
N39430-16-D-1802

5b. GRANT NUMBER
Click here to enter text.

5c. PROGRAM ELEMENT NUMBER
Click here to enter text.

6. AUTHOR(S)
Rick Wice, Battelle
Kavitha Dasu, Battelle

5d. PROJECT NUMBER
ESTS Task Order 44

5e. TASK NUMBER
Click here to enter text.

5f. WORK UNIT NUMBER
Click here to enter text.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Click here to enter text.

8. PERFORMING ORGANIZATION REPORT NUMBER
Click here to enter text.

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NAVFAC EXWC
Port Hueneme CA 93042

10. SPONSOR / MONITOR'S ACRONYM(S)
NAVFAC EXWC

11. SPONSOR / MONITOR'S REPORT NUMBER(S)
Click here to enter text.

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

13. SUPPLEMENTARY NOTES
TR-NAVFAC EXWC-SH-2209

14. ABSTRACT

Responding to per- and polyfluoroalkyl substances (PFAS)-impacted sites is a priority of the Navy's Environmental Restoration Program (ERP). The site investigations, monitoring, and interim remedial actions required to address these sites will produce both solid and liquid waste streams. The treatment and disposal of PFAS-containing investigation derived waste (IDW) presents unique challenges as treatment technologies and best practices for handling and disposition are currently evolving. The focus of this review is to provide a summary of PFAS IDW waste streams and the currently available technologies and approaches for managing PFAS IDW and other related wastes. This technical report also identifies emerging treatment technologies for PFAS IDW that may be applicable in the future.

15. SUBJECT TERMS
Click here to enter text.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF**	**19a. NAME OF RESPONSIBLE PERSON**
					Kelsey Pauxtis-Thomas
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER *(include area code)***
Click here	Click here	Click here	Click here	Click here	805-982-5054

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Table of Contents

List of Appendices

List of Tables

List of Figures

DISCLAIMER

ACRONYMS AND ABBREVIATIONS

AFFF	aqueous film forming foam
BRAC	Base Realignment and Closure
BV	bed volume
CaO	calcium oxide
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CNT	carbon nanotube
DoD	Department of Defense
DON	Department of the Navy
ECOS	Environmental Council of the States
EGLE	Michigan Department of Environment, Great Lakes, and Energy
EPA	Environmental Protection Agency
EREF	Environmental Education and Research Foundation
ERP	Environmental Restoration Program
ER	Environmental Restoration
ER,N	Environmental Restoration, Navy
ESTCP	Environmental Security Technology Certification Program
FOSA	perfluorooctane sulfonamide
GAC	granular activated carbon
GLWA	Great Lakes Water Authority
gpm	gallon per minute
GWET	groundwater extraction and treatment
HQ	Headquarters
IDW	investigation derived waste
IRP	Installation Restoration Program
ITRC	Interstate Technology Regulatory Council
IX	ion exchange
LPRO	Low pressure reverse osmosis
NAVFAC	Naval Facilities Engineering Systems Command
NAWC	Naval Air Warfare Center
NDAA	National Defense Authorization Act
PFAA	perfluorinated alkyl acid
PFAS	per- and polyfluoroalkyl substances
PFBA	perfluorobutane sulfonate

PFCA	perfluoroalkyl carboxylic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
PFO2HxA	perfluoro-3,5-dioxahexanoic acid
PFMOAA	2,2-difluoro-2-(trifluoromethoxy) acetic acid
PFPeA	perfluoropentanoate
PFSA	perfluoroalkyl sulfonate
PIC	product of incomplete combustion
POTW	publicly owned treatment works
ppt	part per trillion
RCRA	Resource Conservation and Recovery Act
RO	reverse osmosis
RPM	Remedial Project Manager
SERDP	Strategic Environmental Research and Development Program
TD	thermal desorption
TSS	total suspended solids
VEG	Vapor Energy Generator
WWTP	wastewater treatment plant

1.0 INTRODUCTION

Aqueous film forming foams (AFFFs) containing per- and polyfluoroalkyl substances (PFAS) are particularly effective in extinguishing hydrocarbon fuel fires. The historic use of PFAS-containing AFFF over several decades has resulted in releases to surface soils as a result of both firefighting training and emergency response operations at Department of Defense (DoD) installations. Responding to PFAS-impacted sites is a priority of the Navy's Environmental Restoration Program (ERP).

Among many PFAS, the long-chain perfluoroalkyl acids (PFAAs), including perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), have been extensively studied for impacts to the environment (Interstate Technology Regulatory Council [ITRC], 2021). Background information on PFAS can be found in ITRC's series of PFAS Factsheets (ITRC, 2021). The site investigations, as well as monitoring and interim remedial actions, required to address PFAS-impacted sites will produce both solid and liquid waste streams. The treatment and disposal of this PFAS-containing investigation derived waste (IDW) presents unique challenges as treatment technologies and best practices for handling and disposition are currently evolving.

The focus of this technical report is to provide a summary of typical PFAS waste streams and currently available treatment technologies and approaches for managing PFAS wastes from Navy Environmental Restoration (ER) sites. This technical report also identifies emerging treatment technologies for PFAS IDW that may be applicable in the future. Navy Remedial Project Managers (RPMs) and practitioners can utilize the report to identify applicable technologies and best practices for managing these waste streams based on site-specific needs.

The Navy has proactively identified active installations and Base Realignment and Closure (BRAC) sites where PFAS was potentially released. Historic releases of AFFF impacting groundwater, surface water, soils and sediments have been the primary focus of PFAS investigations at many installations. Other sources of PFAS may include historical industrial operations (e.g., chromium plating operations), wastewater treatment systems, and former landfills. Site inspections, remedial investigations, and remedial actions for PFAS releases follow the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process. Navy RPMs should follow the appropriate Department of the Navy (DON) PFAS Site Guidance in identifying areas of concern for PFAS under the CERCLA process (DON, 2020a).

Multiple investigative and remedial activities lead to the generation of PFAS IDW and other PFAS-containing wastes. Sampling for PFAS also generates both liquid and solid IDW. Many sites have been utilizing the existing groundwater extraction and treatment (GWET) systems already in place, by optimizing those systems to mitigate PFAS, and very few sites have installed GWET systems specifically for the treatment of PFAS. These GWET systems generate liquid and solid waste (i.e., granular activated carbon [GAC]) during the treatment process. At some locations, limited source area soil excavations have been performed as part of removal actions, generating solid IDW. Where Navy activities have potentially released PFAS off base, the Navy has implemented mitigation measures that may include site investigation activities, providing alternative water supplies, wellhead treatment, and groundwater monitoring, all of which can generate both solid and liquid IDW. Finally, in addition to CERCLA actions, as part of operations, AFFF system changeouts have been performed and more are planned. AFFF system changeouts or decommissioning may generate highly concentrated PFAS-impacted solid waste and rinse waters.

Although PFAS are not currently designated as hazardous substances or listed waste under the Resource Conservation and Recovery Act (RCRA), the United States Environmental Protection Agency (EPA) recently released a strategic roadmap with future plans to designate PFAS as a hazardous substance under CERCLA (EPA, 2021). However, PFAS are considered as emerging chemicals of environmental concern under the Navy's ERP to be addressed using the CERCLA process (per DoD Instruction 4715.18). Even though PFAS IDW currently is not classified as a hazardous waste, it involves special consideration as described in Section 2. Only a limited number of options are currently available for managing solid and liquid PFAS IDW and the DoD recognizes the need for new technologies to investigate and treat PFAS (DoD, 2020).

The focus of this technical report is primarily on commercially available technologies for PFAS-impacted soils/solids IDW treatment (Section 3.0) and for liquid PFAS IDW treatment (Section 4.0) including some types of remedial action waste. Best practices to minimize waste generation and for the handling, storage, and disposal of PFAS IDW are presented in Section 5.0. Appendix A also summarizes DoD and additional research on emerging PFAS treatment technologies under development.

2.0 BACKGROUND

Various PFAS waste streams are generated during site investigations, groundwater monitoring events, and interim remedial measures. PFAS wastes from ER sites typically include soil, groundwater, spent treatment media (e.g., resins), materials (e.g., spent bag filters), and wastewaters generated during removal actions. Depending on the presence of other releases at the ER site, PFAS-impacted solid and liquid IDW may also contain other co-contaminants. RPMs must plan for the type/volume of wastes that will be generated and include waste sampling, handling, treatment, and disposal into the scope for ER projects as appropriate.

This section summarizes the types of solid and liquid wastes that may be generated from PFAS-impacted ER sites. This review includes both PFAS IDW from site investigations, as well as other related wastes that may be generated from removal actions or remedial measures underway at PFAS sites.

2.1 Examples of PFAS-Impacted Solid Wastes

Examples of solid waste that may be generated include the following:

- *PFAS-Impacted Soil and Drill Cuttings*: During the installation of soil borings and monitoring wells, drill cuttings are produced. Drill cuttings may include unconsolidated materials (soils and sediments) and rock fragments depending on the geologic setting of a site. The nature and amount of drill cuttings will also depend on the drilling method used at the site. Direct push drilling generally produces the least volume of drill cuttings and mud rotary methods the most. Depending on the amount of material generated, drums or roll-off bins are generally used to contain the cuttings.
- *Spent GAC*: GAC is a commonly used adsorbent to treat groundwater for a wide range of chemicals including PFAS. GAC requires periodic removal and disposal after a number of bed volumes (BVs) have been treated.
- *Spent Resin (Disposal/One-Time Use)*: Like GAC, ion exchange (IX) resins are used to treat PFAS-impacted water. Most resins being used to treat PFAS-impacted water are designed for single use (e.g., disposable resins).
- *Filtered Sludge/Solids and Filter Bags*: Filtration systems will generate sludge that can potentially contain PFAS. Wellheads on GWET systems are frequently outfitted with filter bags that collect total suspended solids (TSS) from the groundwater that may also contain PFAS sorbed onto the solids. These disposable filters should therefore be handled as PFAS-containing solid waste.
- *Piping and Tanks Removed after AFFF Changeouts*: AFFF piping and tanks that may serve as an ongoing source of PFAS to the environment may be removed as part of a removal action.
- *Concrete Exposed to AFFF Spills and/or Fire Training Activities*: PFAS has been shown to adsorb into concrete at release sites. For example, it may adsorb to concrete structures that are part of a fire training area or where a concrete culvert was exposed to PFAS-impacted surface water; such concrete could be considered as a PFAS solid waste. This is an area of recent research to evaluate the adsorption and subsequent leaching of PFAS from concrete materials.

Concrete wastes resulting from drilling or remedial activities should be evaluated to determine if it is a PFAS-impacted waste under applicable site conditions.

2.2 Examples of PFAS-Impacted Liquid Waste Streams

Examples of liquid waste streams that may be generated include the following:

- *Drilling and Well Development Water*: Liquid PFAS IDW will be created when both drilling and developing monitoring wells. The amount of water generated will depend on the drilling method used, the extent of the saturated zone that is drilled through, and the depth of the well. Sonic drilling is an example of a drilling method that would have less wastewater generation. The amount of water is generally limited to the minor return of water injected into the well and some formation water when cores and casings are retrieved. Another low volume water producing method is direct push drilling. Air rotary drilling through a water-producing zone may result in significant drill water return. Mud rotary drilling has additional handling steps since drilling mud requires dewatering and solidification prior to IDW disposal.
- *Groundwater Monitoring Well Purge Water Generated during Sampling*: Another source of liquid PFAS IDW is monitoring well purge water. The volume of water produced during sampling depends on the size/depth of the well and the aquifer characteristics (e.g., bedrock versus overburden wells). Purge water may also be generated during sampling of residential and municipal supply wells being sampled.
- *Equipment Rinse Water*: During site investigation activities and groundwater sampling events, equipment will be cleaned. The volume of the water will depend on the activity with drilling equipment generating more rinse water than groundwater sampling.
- *Water Generated from Dewatering of Soil Excavations during Removal Actions*: During site investigation activities, limited source soil removal actions or time critical removal actions may occur. At some of these excavations, dewatering may be needed. The volume of the water will depend on the presence of perched vadose zone water, the depth of groundwater, the permeability of the soil, and the size of the excavation. The volume of water generated during dewatering can be relatively large at some sites. The water often needs to be filtered to remove suspended solids which consequently generates a solid waste stream as discussed above. If treatment of the water before discharge is required, the storage and method of treatment must be planned in advance.
- *Backwash and Reverse Osmosis Reject Water*: If an on-site GWET system utilizes a filtration process, the backwash water from filter cleaning will be impacted with PFAS. If a reverse osmosis (RO) technology is used as part of the GWET system, the reject water will be impacted with PFAS.
- *Piping and Tanks Rinse Water after AFFF Changeouts*: Similar procedures to the cleaning of sampling equipment can be followed with washing/rinsing of piping and tank materials to remove the PFAS. The wash water would then be handled and treated as liquid PFAS waste.

2.3 Status of PFAS Waste Guidance

The regulations, policies, and guidance with respect to handling PFAS-impacted wastes are rapidly evolving at both the state and federal level. The status as of 2021 is summarized below, RPMs should confirm the latest requirements with their appropriate chain of command.

At the state level, the Environmental Council of the States (ECOS) published a compilation of state standards, advisories, and guidelines for PFAS (ECOS, 2020). The focus of the study was on overall PFAS guidance and cleanup standards, but the information collected by ECOS did not specifically address PFAS IDW issues. As of 2020, several states had initiated basic PFAS data collection surveys of their landfills and, in some cases, instituted landfill leachate sampling programs.

At the federal level, PFAS are not currently regulated as a hazardous waste under RCRA. As noted above, the EPA recently released a strategic roadmap with future plans to designate PFAS as a hazardous substance under CERCLA (EPA, 2021). Under the roadmap, EPA is scheduled to issue a Notice of Proposed Rulemaking to designate PFOA/PFOS as CERCLA hazardous substances. To designate additional PFAS beyond PFOA/PFOS as hazardous substances under CERCLA, EPA is scheduled to develop an Advanced Notice of Proposed Rulemaking in 2022. In addition to CERCLA and RCRA, EPA is also evaluating the use of its authorities under the Clean Water Act, Toxic Substances Control Act, and the Safe Drinking Water Act to inspect sites, collect data, and direct owners to act in regard to PFAS. This may also impact how PFAS wastes are managed in the future.

Section 343 of the National Defense Authorization Act (NDAA) 2022 is titled *Temporary Moratorium on Incineration by Department of Defense of Perfluoroalkyl Substances, Polyfluoroalkyl Substances, and Aqueous Film Forming Foam*. Section 343 contains several subsections that deal with PFAS treatment and disposal requirements as summarized below:

- Beginning no later than 120 days after the date of enactment of the NDAA 2022, the Secretary of Defense shall prohibit the incineration of covered materials.

- The prohibition may be lifted when the Secretary of Defense submits to the House and Senate Armed Services Committees a certification that the DoD is implementing interim guidance on the destruction and disposal of PFAS and PFAS-containing materials as published by the EPA Administrator under Sections 330 and 7361 of the NDAA 2020, or when the EPA Administrator publishes the Final Rule regarding the destruction and disposal of such materials. Section 7361 of the 2020 NDAA calls for the EPA to develop guidance for the destruction and disposal of PFAS and PFAS-containing materials. As discussed below, this EPA guidance was released in its draft form for public review and comment (EPA, 2020a).

- Requires the Secretary of Defense to submit to the Armed Services Committees of the House and Senate annual reports for three years on the incineration of the covered materials. The annual report will include the following information:

    - The total amount of covered materials incinerated.

- The temperature range at which the covered materials were incinerated.
- The location and facilities where covered materials were incinerated.
- Compliance with Section 330 of the NDAA of 2020.
- Recommendations for the safe storage of PFAS and PFAS-containing materials prior to destruction and disposal.

The temporary incineration moratorium under Section 343 of the NDAA 2022 calls for compliance with Section 330 of the NDAA 2020. The following is the language from Section 330 of the NDAA 2020:

The Secretary of Defense shall ensure that when materials containing PFAS or AFFF are disposed:

- *All incineration is conducted at a temperature range adequate to break down PFAS chemicals while also ensuring the maximum degree of reduction in emission of PFAS, including elimination of such emissions where achievable.*
- *All incineration is conducted in accordance with the requirements of the Clean Air Act (42 USC 7401 et seq.), including controlling hydrogen fluoride.*
- *Any materials containing PFAS that are designated for disposal are stored in accordance with the requirement under part 264 of title 40, Code of Federal Regulations.*
- *All incineration is conducted at a facility that has been permitted to receive waste regulated under subtitle C of the Solid Waste Disposal Act (42 USC 6921 et seq.).*
- *The requirements in subsection (a) only apply to all legacy AFFF formulations containing PFAS, materials impacted by a legacy AFFF release, and spent filters or other PFAS-impacted materials resulting from site remediation or water filtration that:*
    - *Have been used by the Department of Defense or a military department; or*
    - *Are being discarded for disposal by means of incineration by the Department of Defense or a military department; or are being removed from sites or facilities owned or operated by the Department of Defense.*

As required by the NDAA 2020, the EPA published the *Interim Guidance on the Destruction and Disposal or Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances* for public review and comment (EPA, 2020a). The interim guidance provides a summary of various non-consumer liquid, gas, and solid waste streams containing PFAS from facilities manufacturing or using PFAS. There is not a specific mention of IDW in the interim guidance. However, the guidance covers applicable materials such as spent water treatment media including activated carbon, ion exchange resins, and high-pressure membranes (reverse osmosis and nanofiltration).

The EPA interim guidance covers the use and cost of thermal technologies, landfilling, and underground injection wells for PFAS wastes. The interim guidance also includes waste treatment research needs and considerations for potentially vulnerable populations living near destruction and disposal sites. Thermal treatment technologies include a review of hazardous waste incinerators, carbon reactivation units, sewage sludge incinerators, municipal waste combustors, and thermal oxidizers. The guidance discusses the effectiveness of thermal processes in PFAS destruction and testing/monitoring considerations. The guidance presents a summary of landfilling of PFAS containing waste including the use and limitations of hazardous, municipal solid waste, ash monofills, industrial, construction, and demolition landfills. As required in the NDAA 2020, the EPA will finalize the guidance based on the latest technical data and in response to public comments to be issued no later than the statuary deadline of December 2023.

2.4 Navy PFAS IDW Guidance

In November 2020, Naval Facilities Engineering Systems Command (NAVFAC) issued an *Interim PFAS Site Guidance for Remedial Project Managers November 2020 Update* (Department of the Navy [DON], 2020a). The guidance covers sampling and analysis, investigations, risk assessments, applicable regulations, remedial action considerations, land use controls, and five-year reviews. A question and answer format was used to provide guidance on PFAS issues. In the site investigations section, IDW is included under item INV10 as follows:

INV10. How should investigation-derived waste (IDW) at PFAS sites be disposed?

- *Environmental investigations at potential PFAS sites will generate IDW. All IDW that is suspected to contain PFAS can be analyzed for these substances, and a copy of the analytical results should be provided to the disposal facility.*
- *Currently no PFAS meet the Federal definition of hazardous waste, and therefore, solid material may be able to be disposed as non-hazardous solid waste. If incineration is considered, RPMs should consult NAVFAC HQ and their ER Manager (for ER,N) or Base Closure Manager (for BRAC) to ensure current information is considered.*
- *For aqueous IDW, RPMs should consult with NAVFAC HQ and their ER Manager (for ER,N) or Base Closure Manager (for BRAC) for the most current technical considerations, limitations, and options.*

3.0 PFAS-IMPACTED SOIL AND SOLIDS DISPOSAL

This section describes commercially-available technologies to treat soil and solids impacted with PFAS including landfilling, solidification/stabilization, incineration, and thermal desorption. Table 3-1 provides descriptions of the technologies, advantages and limitations, the current demonstrated capabilities of the technologies, and references for additional information. Refer to Appendix A for additional waste treatment technologies under development, but not yet commercially available for full-scale treatment of solid PFAS IDW.

- *Landfilling*: In accordance with Navy guidance, PFAS-impacted waste must be analyzed for PFAS. Navy guidance also requires that the waste bill of lading or manifest document that the waste may include PFAS (DON, 2020a). PFAS are currently not characterized as a hazardous waste and can be disposed of in a RCRA D landfill which is approved for non-hazardous waste. These landfills are lined and often contain leachate collection systems. Increased regulatory and public scrutiny has already led to permitted landfills being much more conservative on accepting PFAS-impacted waste streams. It is recommended that the RPM confirm with the landfill operator whether the designated facility accepts PFAS-impacted waste prior to project implementation. PFAS-impacted materials should always be disposed of at permitted landfills that were designed with appropriate engineering and environmental controls (e.g., impermeable liners underneath and on top, leachate collection systems, etc.) so that the leachate from such landfills could be prevented from reaching the environment (e.g., groundwater, surface water, etc.). There may be state-specific restrictions already in place, or in development, that could change future disposal practices of PFAS-impacted material from being disposed of in landfills. PFAS-impacted soil can be stabilized or solidified before disposal into a landfill as discussed below. Spent GAC or single-use resin utilized for PFAS treatment can also be landfilled.

- *Solidification/Stabilization*: Solidification/stabilization involves adding amendments to the soil to bind to PFAS and reduce or remove the potential for PFAS to mobilize. These amendments include, but are not limited to, activated carbon, novel adsorbents, carbon nanotubes (CNTs), resins, minerals, biomaterials, and molecularly-imprinted polymers. Different sorbents were evaluated recently for the immobilization of PFAS on AFFF-impacted soils using synthetic precipitation leaching procedure (Barth et al., 2021). Addition of adsorbents to soil can mitigate environmental risk by reducing the long-term leaching potential of the source zones. To validate soil mixing with adsorbents as a feasible remediation technology for PFAS, long-term leachability testing is required at environmentally relevant conditions representing "worst case" scenarios. For anionic PFAAs, low pH leaching tests provide significantly less aggressive conditions as the low pH changes the dominant charges on sorbent materials to be positive and therefore aid in the adhesion of the anionic PFAAs to the sorbent. Further research is needed on appropriate leach tests to demonstrate that commercial products and new sorbents are effective over the long term.

- *Incineration*: As of December 2021, Congress has placed a temporary ban on the use of incineration for PFAS-impacted wastes under the NDAA 2022 (see Section 2.3). Prior to this temporary ban, EPA had conducted research into the use of multiple techniques including incineration to treat PFAS waste (EPA, 2020b). Previous research showed that for complete degradation, PFOA and PFOS must be destroyed with high temperature incineration at 1,000 to 1,200°C (Schultz et al., 2003; Yamada et al., 2005; Vecitis et al., 2009). Incomplete degradation of PFAS could potentially result in shorter-chain PFAS or products of incomplete combustion (PICs), which are of concern (EPA, 2020b). The use of incineration for PFAS-containing waste has been limited due to recent concerns on the formation of PICs. Additional research is currently underway to fully understand the fate of PFAS at incineration facilities. RPMs should maintain awareness of the temporary PFAS-waste incineration ban put in place under the NDAA 2022 and should therefore find alternate disposal approaches as long as the moratorium remains in effect.

- *Thermal Desorption*: Thermal desorption for PFAS involves heating PFAS-impacted soils to approximately 500 ºC to 600 ºC within large ex situ treatment plants using a rotary kiln with either gas burners or thermal screws to desorb PFAS into the gas stream. PFAS are then destroyed at greater than 1,000 ºC by catalytic oxidation in the afterburner. This is a partially demonstrated thermal technology. Further considerations are minimizing emissions of hydrofluoric acid or other PICs from the treatment system. Current research and development considerations for thermal desorption include optimizing performance through temperature refinement, effective vapor treatment (i.e., employing air stream catalytic oxidation, water treatment for condensate), and vapor-scrubbing issues to remove hydrofluoric acid and other byproducts generated. In a recent SERDP project final report, thermal tests confirmed that PFAS can be thermally desorbed from impacted soil at temperatures maintained above 350ºC (Hatton, 2020). Additionally, research has shown that calcium oxide (CaO) amendment to PFAS-impacted soils increases the efficiency of treatment, as it lowers the treatment temperature, and the overall production of hydrofluoric acid can be reduced.

Table 3-1. Soil and Solids Disposal PFAS Technologies

Technology	Description	Advantages	Limitations	Demonstrated Capability	Reference
Landfill					
Landfill	PFAS-impacted soil is transported to a permitted landfill.	• This method isolates PFAS-impacted soil from receptors.	• Truck hauling traffic affects the local community. • Disposal of PFAS waste to landfills potentially adds to the PFAS impact load in the landfill leachate. • PFAS-impacted soil may have to be stabilized or solidified before disposal into a landfill. • PFAS-impacted spent media must be replaced and shipped off site for landfill disposal. • Some states may require PFAS-impacted solids to be treated before landfilling. • More studies are needed on interactions of PFAS with landfill linings (ITRC, 2021).	Full-scale implementation.	ITRC. (2021). PFAS Treatment. Updated May. https://pfas-1.itrcweb.org/12-treatment-technologies/#12_4.
Thermal Treatment					
Incineration	Excavated soil and drill cuttings can be treated by high temperature incineration. Clean Harbors kilns (operating at 1,100 ºC) are capable of incinerating solids, liquids, and sludge (Clean Harbors, 2018). ***Note: There is a temporary moratorium on the use of incineration as of December 2021 under the NDAA 2022, consult with the chain of command on the latest status.***	• For complete degradation, PFAS has to be destroyed with high temperature incineration at 1,000 to 1,200 °C (Schultz, 2003; Yamada et al., 2005).	• Incineration can have significant cost implications alongside a large energy use requirement (ITRC, 2021). • In addition to cost and energy use, transportation, regulatory approvals, and final disposition of process residues should be evaluated (ITRC, 2021). • Incomplete degradation of PFAS could potentially result in shorter-chain PFAS or PICs (EPA, 2020b).	Full-scale implementation.	Clean Harbors. (2018). Environmental Services PFAS Treatments available at Lambton, Ontario, Facility. https://www.cleanharbors.com/sites/g/files/bdczcs356/files/2019-06/Clean-Harbors-Lambton-PFAS-Fact-Sheet.pdf EPA. (2020). Technical Brief. PFAS: Incineration to Manage PFAS Waste Streams. https://www.epa.gov/sites/default/files/2019-09/documents/technical_brief_pfas_incineration_ioaa_approved_final_july_2019.pdf ITRC. (2021). PFAS Treatment. May. https://pfas-1.itrcweb.org/12-treatment-technologies/#12_4 Schultz, M.M., D.F. Barofsky, and J.A. Field. (2003). Fluorinated Alkyl Surfactants. Environ. Eng.Sci. 20(5) 487-501. https://doi.org/10.1089/109287503768335959 Yamada, T., P.H. Taylor, R.C. Buck, M.A. Kaiser, and R.J. Giraud. (2005). Thermal Degradation of Fluorotelomer Treated Articles and Related Materials. Chemosphere 61, 974-984. https://doi.org/10.1016/j.chemosphere.2005.03.025
Thermal Desorption (TD)	TD for PFAS involves heating excavated soil to approximately 500 ºC to 600 ºC within large ex situ treatment plants using a rotary kiln with either gas	• High temperatures can vaporize the chemicals or potentially destroy them (ITRC, 2021). • Technologies are available for in situ and ex situ implementation.	• Thermal treatment is an energy-intensive remediation method (ITRC, 2021). • Community impacts include managing the risks of potential vapor intrusion from volatile co-contaminants (ITRC, 2021). • Vaporized chemicals have to be captured and destroyed in off-gas treatment (ITRC, 2021). • Capturing the off gases can be a challenge (Mahinroosta and Senevirathna, 2020).	Partially demonstrated. The use of this technology for PFAS-impacted soil is still developing. Limited data sets are available, and several data gaps still exist. Additionally, no documented examples of in situ thermal treatment	ITRC. (2018). Remediation Technologies and Methods PFAS. March. Mahinroosta, R., and L. Senevirathna. (2020). A Review of the Emerging Treatment Technologies for PFAS Contaminant in Soils. Journal of Environmental Management 255, 109896. Ross, I., J. McDonough, J. Miles, P. Storch, P. Thelakkat Kochunarayanan, E. Kalve, J. Hurst, S. Dasgupta, and J. Burdick. (2018). A review of emerging technologies for

Table 3-1 (continued). Soil and Solids Disposal PFAS Technologies

Technology	Description	Advantages	Limitations	Demonstrated Capability	Reference
	burners or thermal screws to desorb PFAS into the gas stream. Temperatures as low as 350 ° C may desorb PFAS. PFAS are then destroyed at greater than 1,000 °C by catalytic oxidation in the afterburner (Ross et al., 2018).		- The ability of this technology to volatilize the higher molecular weight precursors, which seems likely to have higher boiling points than the PFAAs, is also of concern (Ross et al., 2018). - Rotary kilns for TD can be large, and the mobilization cost and associated production rate should be considered when evaluating TD (Ross et al., 2018). - Further, less cohesive soils may require pretreatment and/or longer treatment times, which may also influence the sensible price point for this technology (Ross et al., 2018).	for PFAS-impacted soil have been identified (ITRC, 2021).	remediation of PFAS. Remediation, 28(2), 101-126. https://onlinelibrary.wiley.com/doi/pdf/10.1002/rem.21553
Solidification/Stabilization					
Solidification/ Stabilization	Amendments added to the soil that bind to PFAS and immobilize PFAS, resulting in reduced potential for PFAS to mobilize. These amendments include activated carbon and carbon nanotubes, resins, minerals, biomaterials, and molecularly imprinted polymers (ITRC, 2021). Laboratory tests should be conducted using site-specific soils and the stabilizing amendment before field application to ensure success (ITRC, 2021).	- Amended soil can be mixed with concrete and other stabilizers to better trap the PFAS (ITRC, 2021). - Organoclays are used because they are environmentally benign, have a high sorption capacity, and can be easily modified to enhance their sorption capacity with mesopores (ITRC, 2021). - A laboratory study recently evaluated different sorbents for immobilization of PFAS on AFFF-impacted soils using synthetic precipitation leaching procedure (Barth et al., 2021). - RemBind® is a blend of aluminum hydroxide, carbon and clays designed to bind long-and short-chain PFAS (Kempisty et al., 2018). RemBind™ is added to the soil at an addition rate of 1% to 5% and mixed while adding water to achieve a final moisture content of around 20% to 30%. The treated soil is fixed for 24 hours and the remediation process is complete (Hinrichsen, 2019). - The long-term stability of the RemBind™ reaction has been successfully tested using EPA Method 1320 which simulates 1,000 years of stability in an acid rain environment in an improperly lined landfill (Hinrichsen, 2019).	- Sorption and stabilization do not destroy PFAS, and information on the long-term stability of amendments for PFAS remediation is a data gap that currently limits their use (ITRC, 2021). - PFAS type affects sorption in that PFAS often occur as mixtures, including PFAS of different chain lengths with varying sorption characteristics (ITRC, 2021). - An example of a site condition that can affect sorption is high organic matter in soil, which can foul carbon sorbents with competing compounds (ITRC, 2021). - Biomaterials such as chitosan, straw, and quarternized cotton do not perform as well as other sorbents, and the biomaterials may eventually degrade (Du et al., 2014). - Rembind™ and powdered activated carbon applications showed effective stabilization of longer-chain PFAS, compared to shorter-chain PFAS (Sörengårda et al., 2019).	- Full-scale implementation (RemBind™ utilized in Australia and Sweden). - In Sweden, around 3,000 tons of soil at 710 to 1,100 µg/kg PFAS was excavated, stabilized, leachability tests performed. The stabilized soil was cleared for disposal, and landfilled (Hinrichsen, 2019).	Barth, E., J. McKernan, D. Bless and K. Dasu. (2021). "Investigation of an Immobilization Process for PFAS Contaminated Soils." Journal of Environmental Management 296:113069. Du, Z., S. Deng, Y. Bei, Q. Huang, B. Wang, J. Huang, and G. Yu. (2014). Adsorption Behavior and Mechanism of Perfluorinated Compounds on Various Adsorbents – A review. Journal of Hazardous Materials (274):443-454. Hinrichsen, H. (2019). Stabilization of PFAS Contaminated Soil Two Full Scale Projects in Sweden. Envytech Clean-up Conference. https://ziltek.com/wp-content/uploads/2019/09/Envytech-Clean-Up-Conference-2019.pdf ITRC. (2021). PFAS Treatment. Updated May. https://pfas-1.itrcweb.org/12-treatment-technologies/#12_4 Sörengårda, M., D. Klejab, and L. Ahrens. (2019). Stabilization and Solidification Remediation of Soil Contaminated with PFAS. Journal of Hazardous Materials 367: 639–646. www.doi:10.1016/j.jhazmat.2019.01.005

4.0 PFAS-IMPACTED LIQUIDS DISPOSAL

This section describes technologies that may be implemented at full-scale during the ERP to treat liquids impacted with PFAS including GAC, IX resins and other sorption media, and membrane treatment. Different types of PFAS-impacted liquid waste streams with the potential to be generated at ER sites are described in Section 2.2. The most common and readily available method for treatment of liquid PFAS IDW is treatment using GAC or resins. To date, the Navy has utilized GAC (with flocculation pretreatment for suspended solids in some places), resins, and liquid augmentation (solar ponding) to treat liquid PFAS IDW. Table 4-1 includes descriptions of the technologies available at full-scale, advantages and limitations, the current demonstrated capabilities of the technologies, and references for additional information. As described in Appendix A, several emerging technologies are under development, but not commercially available for full-scale treatment of liquid PFAS IDW.

- *GAC*: GAC is made from organic materials, such as coal and coconut, is highly porous and provides a large surface area for chemical contact (ITRC, 2021). GAC systems have become the baseline against which all new adsorbent technologies targeting PFAS removal from water are compared (Ross et al., 2018). GAC treatment can be used for any aqueous-based treatment application, such as municipal drinking water, groundwater, point-of-use residential, industrial wastewater, and landfill leachate (ITRC, 2021). Column studies must be performed to evaluate the entire mixture of PFAS present in the influent to the extent practicable (Ross et al., 2018). Use of GAC may not be feasible if natural organic matter is also present in waters to be treated. Co-contaminants may influence the optimal BVs before chemical breakthrough occurs. GAC removal of the target chemicals occurs through adsorption and/or biofiltration (CDM Smith, 2018). Either virgin or reactivated GAC can be used for most applications (Ross et al., 2018). Column studies show that virgin GAC and thermally-reactivated GAC have similar removal rates and breakthrough times (Brewer, 2017). GAC media unit cost is lower than IX media, but typically utilizes a larger and taller infrastructure footprint than IX systems (CDM Smith, 2018). GAC can be inefficient at removing PFOA (Oliaei et al., 2013) and becomes progressively less effective for removing shorter-chain PFAS. The spent media must be replaced and shipped off site either for disposal by landfilling or to be regenerated/reactivated for reuse consistent with applicable federal and state regulations (ITRC, 2021).
- *IX Resins and Other Adsorptive Media*: Chemical removal from water is achieved by the attraction of the negatively charged functional groups to positively charged functional groups within the resin. A variety of resins containing different functional groups are available (Arcadis, 2016). Resins are designed to have higher adsorption capacity for some PFAS, and significantly faster reaction kinetics compared to GAC (Conte et al., 2015). IX can also be employed after GAC as a polishing step in a treatment train configuration (Ross et al., 2018). While IX is more expensive than GAC by weight and often requires pretreatment, the potential for higher adsorption capacities, shorter contact times, smaller equipment footprints, and the ability to regenerate may be more favorable for some applications (Higgins and Dickenson, 2016; Merino et al., 2016). Regenerable IX media offers a net positive cost-benefit for sites with PFAS concentrations in water to be treated at greater than 10 µg/L. However, the regeneration process requires energy and creates a concentrated waste stream that must be managed. Disposal or treatment of the regenerant stream can be problematic and expensive.

Spent single-use IX media requires disposal by landfilling, or other means such as treatment in a cement kiln due to the media's thermal energy value (Ross et al., 2018).

Full-scale IX systems are currently in operation in Australia and a full-scale system was installed in the United States in 2017. In April 2018, ECT2 set up a full-scale 200 gallon per minute (gpm) regenerable IX system (Sorbix RePure, lead/lag/polish vessels with distillation for reuse of regeneration solution) at Former Pease Air Force Base Site 8 which has processed 17.9 million gallons of PFAS-impacted groundwater (as of May 2019), which is then reinjected back into the aquifer (ECT2, 2019). Purolite single-use resin (PFA694E) has been field tested at full-scale and pilot-scale sites including at Horsham Well 10, a Pennsylvania drinking water system well. One liter of resin has treated over 456,000 liters of water to non-detect PFAS levels. At the Warminster Well 26 drinking water system well, 285,000 BVs have been treated before effluent reached the 70 ppt PFAS level (Boodoo et al., 2017).

Other types of adsorbents that have been used for PFAS include powdered activated carbon, polymers, maize straw derived ash, alumina, and montmorillonite (ITRC, 2021). Laboratory testing on Fluro-Sorb® has demonstrated a removal efficiency of between 85% and 93% with water containing three concentrations of PFAS ranging from 550 to 5,500 ppt. This novel adsorbent is in the development stage; laboratory- and field-scale pilot tests are ongoing (Allen et al., 2019). Biochar is a carbon-rich, porous solid synthesized from biomass, such as wood or manure, through "pyrolysis" (Ahmad et al., 2014). As summarized in Appendix A, the use of biochar could be an alternative to GAC for PFAS treatment, although variability in biochar properties relative to GAC may affect reliability (Xiao et al., 2017).

- *Membrane Treatment*: Membrane filtration refers to a variety of separation technologies based on the nominal size of the membrane pores. Bench-scale studies indicate that the membrane molecular weight cut-off of nanofiltration/RO is probably the most important factor for removal of PFAS for these technologies; other factors, such as ionic charge, may also influence performance (ITRC, 2021). For groundwater applications, the suspended solids and water geochemistry must be assessed and managed to prevent fouling or deterioration of the membrane. Membrane treatment also generates a low volume, high concentration waste which requires treatment or disposal (Ross et al., 2018). RO separates compounds from water solutions by passing pressurized water across a semipermeable membrane. Treated water (permeate) passes through the membrane and the rejected water (concentrate) is collected for disposal or further treatment, depending on the nature of the compounds and particles present (ITRC, 2021). RO systems are expensive and typically employed with large-scale drinking water systems (Ross et al., 2018). RO is typically the costliest membrane technology for removal due to high capital cost and energy demand (CDM Smith, 2018).

  RO has been investigated in bench-scale studies and pilot plants for wastewater and drinking water PFAS applications and is considered a partially developed technology (ITRC, 2021). RO has been shown to be effective in removing PFAS regardless of chain length (Higgins and Dickenson, 2016) and is also expected to be effective at removing many types of PFAA precursors. PFOS removal greater than 99% was achieved using four different types of membranes over a wide range of feed concentrations, from 0.5 to 1,500 mg/L (Tang et al., 2006). Membranes are highly susceptible to fouling; therefore, an anti-scaling chemical and/or pretreatment is critical for RO. RO requires power for high-pressure pumps and the management of concentrate, which can be energy intensive. The chemical-rich brine rejected by RO must be disposed of appropriately (ITRC, 2021).

Nanofiltration provides high water flux at low operating pressure (Izadpanah and Javidnia, 2012). In general, nanofiltration membranes have lower rejection rates (95%) than RO (> 99%), because nanofiltration membranes have larger pores (Rahman et al., 2014). As summarized in Appendix A, nanofiltration is considered a partially developed technology because available data on the removal of PFAS are limited to laboratory-scale tests. Reported rejections were generally greater than 95% for PFAS with molecular weights ranging from 214 g/mol to 713 g/mol (Steinle-Darling and Reinhard, 2008; Appleman et al., 2013). However, lower rejections were observed for PFPeA and perfluorooctane sulfonamide (FOSA)—about 70 and 90%, respectively (Steinle-Darling and Reinhard, 2008).

4.1 Off-Site Discharge and Potential Discharge Restrictions

Wastewater treatment plant (WWTP) operators at publicly owned treatment works (POTW) are becoming more aware of and managing PFAS in influent streams. For liquid PFAS IDW, POTW discharge may or may not be allowable. If allowed, permits may be required as discharge to the sanitary sewer system is considered an “off-site” discharge from a CERCLA site. The permit will likely establish acceptable PFAS concentrations. And an agreement may be required in the form of written permission to discharge and/or a formal industrial pretreatment permit granted by the POTW or relevant wastewater authority. The POTW should be contacted prior to the generation of the PFAS liquid waste in order to establish availability of discharging to the system and if allowed, the pretreatment requirements and the permitting process requirements. Depending on the PFAS concentration in the wastewater, pretreatment units using GAC or resin will most likely be the most available technology.

In 2019, at the Environmental Education and Research Foundation (EREF) Summit on PFAS in Leachate and Groundwater, several WWTP operators mentioned that they are starting to assess PFAS sources discharging to their systems. For example, the Great Lakes Water Authority (GLWA) in southeast Michigan operates a facility that services 76 communities. GLWA has implemented a program to identify PFAS sources, implement efforts to reduce or eliminate PFAS sources, monitor for PFAS at the treatment works, and take actions as necessary to protect surface water quality. As part of the GLWA program, the utility is directing sources to develop best management plans to reduce PFAS in their discharge (GLWA, 2019). Michigan Department of Environment, Great Lakes, and Energy (EGLE) requested all the WWTPs that are receiving industrial wastewater to sample their discharge effluents and assess the possible sources of PFAS. Growing concerns of PFAS in biosolids from WWTPs is also driving more programs to test biosolids, assess the influent flow streams, and develop new ways of disposing of WWTP biosolids. Work in this area is relatively new and additional state regulations and guidance should be expected.

Table 4-1. Liquids Disposal PFAS Technologies

Technology	Description	Advantages	Limitations	Demonstrated Capability	Reference
Adsorption					
Granular Activated Carbon (GAC)	GAC is made from organic materials, such as coal and coconut, is highly porous and provides a large surface area for chemical contact (ITRC, 2021). Treatability studies must be performed to evaluate the entire mixture of PFAS present in the influent to the extent practicable (ITRC, 2021).	• GAC is a demonstrated technology and is currently the most common water treatment method used for PFAS (ITRC, 2021). • GAC removal of the target chemical occurs through adsorption and/or biofiltration (CDM Smith, 2018). • Either virgin or reactivated GAC can be used for most applications (ITRC, 2021). • Column studies show that virgin GAC and thermally reactivated GAC have similar removal rates and breakthrough times (Brewer, 2017). • Commercial facilities in the United States conduct thermal reactivation of spent GAC, which can provide a more sustainable and less costly replacement option than virgin GAC and off-site disposal. Regenerable media presents sustainability benefits (ITRC, 2021). • GAC systems have become the baseline against which all new adsorbent technologies targeting PFAS removal from water are compared (Ross et al., 2018). • Recent research indicates that some PFAAs can be destroyed on GAC surfaces at temperatures as low as 700 ºC during the reactivation process (Ross et al., 2018). • Coconut shell-based and coal-based GAC can both be effective (CDM Smith, 2018). • GAC media unit cost is lower than IX (CDM Smith, 2018). • Typical bed life: 50-120,000 BVs (at 10 min empty bed contact time) (CDM Smith, 2018). • Larger and taller infrastructure footprint than IX (at 10 min empty bed contact time) (CDM Smith, 2018).	• The GAC adsorption capacity can vary considerably by media and chemical (ITRC, 2021). • Adsorbent media must be removed and replaced when it becomes spent (ITRC, 2021). • The spent media must be replaced and shipped offsite either for disposal or to be regenerated/ reactivated for reuse consistent with applicable federal and state regulations (ITRC, 2021). • The shorter breakthrough times for PFAS with five carbon atoms have lower GAC removal efficiencies (ITRC, 2021). • GAC can be inefficient at removing PFOA (Oliaei et al., 2013) and becomes progressively less effective for removing shorter-chain perfluoroalkyl carboxylic acids (PFCAs) such as PFHxA, perfluoropentanoate (PFPeA), PFBS, and perfluorobutane sulfonate (PFBA) as the chain length diminishes (Inyang and Dickenson, 2017; McCleaf et al., 2017). • There are currently no published studies on the effectiveness of GAC in removing cationic, zwitterionic, and anionic precursor compounds; however, a recent theoretical study suggests some precursors are unlikely to be effectively removed by GAC (Xiao et al., 2017). • Its ability to remove short-chain PFAAs is less robust, and its ability to remove PFAA precursors is largely uncharacterized (Ross et al., 2018). • Use of GAC may not be feasible if co-contaminants or natural organic matter are also present in waters to be treated (Ross et al., 2018). Therefore, it is important to fully understand the presence and concentrations of potential co-contaminants. • Initial backwash is required (CDM Smith, 2018).	Full-scale implementation	Brewer, J. Calgon Corporation. (2017). Granular Activated Carbon: A Proven Solution for PFAS, Presentation at the Cleanup Conference, September. CDM Smith. (2018). Advanced Treatment Options for the Northwest Water Treatment Plant. https://www.brunswickcountync.gov/wp-content/uploads/2018/04/CDM-Smith-Brunswick-Final-Report-April-2018.pdf Inyang, M. and E.R.V. Dickenson (2017). The Use of Carbon Adsorbents for the Removal of Perfluoroalkyl Acids from Potable Reuse Systems. Chemosphere, 184, 168–175. https://doi.org/.10.1016/j.chemosphere.2017.05.161 ITRC. (2021). PFAS Treatment. Updated May. https://pfas-1.itrcweb.org/12-treatment-technologies/#12_4 McCleaf, P., S. Englund, A. Ostlund, K. Lindegren, K. Wiberg, and L. Ahrens. (2017). Removal Efficiency of Multiple Poly- and Perfluoroalkyl Substances (PFAS) in Drinking Water Using Granular Activated Carbon (GAC) and Anion Exchange (AE) Column Tests. Water Research, 120, 77–87. https://doi.org/10.1016/j.watres.2017.04.057 Oliaei, F., D. Kriens, R. Weber, and A. Watson. (2013). PFOS and PFC Releases and Associated Pollution from a PFC Production Plant in Minnesota (USA). Environmental Science and Pollution Research, 20(4), 1977–1992. https://doi.org/10.1007/s11356-012-1275-4 Ross, I., J. McDonough, J. Miles, P. Storch, Thelakkat P. Kochunarayanan, E., Kalve, J. Hurst, S. Dasgupta, and Burdick. (2018). A review of emerging technologies for remediation of PFAS. Remediation, 28(2), 101-126. https://onlinelibrary.wiley.com/doi/pdf/10.1002/rem.21553 Xiao, X., B.A. Ulrich, B. Chen, and C.P. Higgins. (2017). Sorption of Poly- and Perfluoroalkyl Substances (PFAS) Relevant to Aqueous Film Forming Foam (AFFF)-Impacted Groundwater by Biochars and Activated Carbon. Environmental Science & Technology, 51(11), 6342–6351. https://doi.org/10.1021/acs.est.7b00970

Table 4-1 (continued). Liquids Disposal PFAS Technologies

Technology	Description	Advantages	Limitations	Demonstrated Capability	Reference
Ion Exchange (IX) and Other Sorption Media	IX uses synthetic, polymeric resins to remove PFAS from water (ITRC, 2021). In the IX process, chemicals are removed through a substitution reaction using a resin (CDM Smith, 2018). The chemical removal from water is achieved by the attraction of the negatively charged functional group to the positively charged functional group within the resin. A variety of resins containing different functional groups are available (ITRC, 2021). Other types of adsorbents that have been used for PFAS include powdered activated carbon, polymers, maize straw derived ash, alumina, and montmorillonite (ITRC, 2021).	• IX resins are considered suitable for low concentration and high-volume water treatment applications (ITRC, 2021). • IX resin has higher adsorption capacity for some PFAS and significantly faster reaction kinetics compared to GAC (Conte et al., 2015). • While many IX resins are effective for either long- or short-chain PFAS, more novel resins are reported to have higher sorption capacities for both long-chain and some short-chain PFAS compared with GAC (Zaggia et al., 2016). • IXs can be employed after GAC as a polishing step in a treatment train configuration (Ross et al., 2018). • Certain single-use IX media have been identified that may have higher usage capacities for short-chain PFAS (ITRC, 2021; Purolite, 2019). • While IX media are more expensive than GAC by weight and often require pretreatment, the potential for higher adsorption capacities, shorter contact times, smaller equipment footprints, and the ability to regenerate may be more favorable for some applications (Higgins and Dickenson, 2016; Merino et al., 2016). • Smaller and shorter infrastructure footprint than GAC (3 min empty bed contact time) (CDM Smith, 2019). • Typical bed life: 250-300,000 BVs (with 3 min empty bed contact time) (CDM Smith, 2019). • Not as extensively utilized as GAC (CDM Smith, 2019).	• The distillate residue is a concentrated PFAS waste that can be managed by off-site treatment (for example, incineration or possibly chemical oxidation) (ITRC, 2021). • Spent single-use IX media requires incineration or other treatment for disposal, resulting in an increased carbon footprint (ITRC, 2021). • Regeneration solutions may present exchange system and treated water corrosion issues if media are not rinsed thoroughly prior to being placed back in service (ITRC, 2021). • Spent adsorptive media are typically incinerated at high temperature (greater than 1,000 ºC) or thermally regenerated at a specialist facility, thereby adding to the overall management cost (ITRC, 2021). • A water sample containing a mixture of anionic, cationic, and zwitterionic PFAS may require a treatment train of different resins to remove different charged species (Ross et al., 2018). • IX media unit cost is higher than GAC (CDM Smith, 2019). • Likely impact on chloride-to-sulfate ratio for corrosion control (CDM Smith, 2019). • Backwash recommended with some resins (CDM Smith, 2019). • Many naturally occurring co-contaminants within aquifers or municipal waste streams are present at concentrations orders of magnitude greater than PFAS, resulting in significant competition with PFAS for adsorption sites (Ross et al., 2018). • Total dissolved solids may exert a considerable ionic strength influence and can inhibit electrostatic adsorption of PFAS onto the IX media (Ross et al., 2018).	• Full-scale IX systems are currently in operation in Australia, and a full-scale system was installed in the United States in 2017 (ITRC, 2021). • Field tested at Horsham, Pennsylvania Well 10, drinking water supply well. One liter of resin has treated over 456,000 liters of water to non-detect PFAS levels (Purolite, 2018). • At Warminster Well 26 a drinking water supply well, 285,000 BVs have been treated before reaching 70 part per trillion (ppt) PFAS levels (Purolite, 2019). • At a military site in Pennsylvania, with an inlet concentration of 20,000 ppt PFAS, a system with GAC and resin has achieved greater than 20 months of operation with non-detect levels (Boodoo et al., 2018). • ECT2 set up a full-scale 200 gallon per minute (gpm) regenerable IX system (Sorbix™ RePure, lead/lag/polish vessels with distillation for reuse of regeneration	Boodoo, F., O. Baumann, and N. Backman. (2018). Short and Long Chain PFAS Removal with Single-Use Selective Ion Exchange Resin. CDM Smith. (2018). Advanced Treatment Options for the Northwest Water Treatment Plant. https://www.brunswickcountync.gov/wp-content/uploads/2018/04/CDM-Smith-Brunswick-Final-Report-April-2018.pdf CDM Smith. (2019). PFAS Clean-up Approaches GAC vs Anion Exchange Resin. https://www.cdmsmith.com/-/media/Insights/PFAS-Treatment-Options/PFAS-March-Newsletterdocx.pdf Conte, L., L. Falletti, A. Zaggia, and M. Milan. (2015). Polyfluorinated Organic Micropollutants Removal from Water by Ion Exchange and Adsorption. Chemical Engineering Transactions 43: 2015. ECT2. (2019). Case Study. Pease Site 8: Regenerable Resin System for Groundwater Remediation. https://www.ect2.com/case-study/pease-site-8-regenerable-resin-system-for-groundwater-remediation/ Higgins, C., and Dickenson, E.R. (2016). Treatment and Mitigation Strategies for Poly- and Perfluoroalkyl Substances. WRF Report 4322. Denver, CO: Water Research Foundation. ITRC. (2021). PFAS Treatment. Updated May. https://pfas-1.itrcweb.org/12-treatment-technologies/#12_4 Merino, N., Qu, Y., Deeb, R.A., Hawley, E.L., Hoffmann, M.R., and Mahendra, S. (2016). Degradation and Removal Methods for Perfluoroalkyl and Polyfluoroalkyl Substances in Water. Environmental Engineering Science, 33(9), 615–649. https://doi.org/10.1089/ees.2016.0233 Purolite. 2018. PFAS Case Study – Horsham PA. Removal of PFAS Contamination in Horsham Township, PA Water Supply. https://www.purolite.com/index/core-technologies/industry/potable---groundwater/PFAS-In-Our-Environment/best-pfas-treatment-option/treatment-and-removal-of-pfas-horsham-township. Purolite 2019. PFAS Removal: Choosing the Appropriate Technology. With New Regulations, Consider the Need to Also Remove PFBS and Other Short-Chain PFAS. *https://www.purolite.com/index/core-technologies/industry/potable---groundwater/PFAS-In-Our-Environment/best-pfas-treatment-option/PFAS-Removal--Choosing-the-Appropriate-Technology* Zaggia, A., L. Conte, L. Falletti, M. Fant, and A. Chiorboli. (2016). Use of Strong Anion Exchange Resins for the Removal of Perfluoroalkylated Substances from Contaminated Drinking Water

Table 4-1 (continued). Liquids Disposal PFAS Technologies

Technology	Description	Advantages	Limitations	Demonstrated Capability	Reference
				solution) at Former Pease Air Force Base Site 8. As of May 2019, 17.9 million gallons of PFAS-impacted groundwater has been processed and reinjected back into the aquifer (ECT2, 2019).	in Batch and Continuous Pilot Plants. Water Research, 91, 137–146. https://doi.org/10.1016/j.watres.2015.12.039
	IX Regeneration	• IX regeneration is a chemical process; the only demonstrated successful regeneration solution is a solvent-brine solution (Amec Foster Wheeler, 2017) and the regenerant solution can be distilled for reuse. • Regenerable IX media offers sustainability benefits (PFAS concentrations ≥ 10 µg/L), but the process for regenerating requires energy and creates a concentrated waste stream that must be managed (ITRC, 2021).	• Disposal or treatment of the regenerant stream can be problematic and expensive (ITRC, 2021). • The distillate residue is a concentrated PFAS waste that can be managed by off-site treatment (for example, incineration or possibly chemical oxidation) (ITRC, 2021). • Regeneration solutions may present exchange system and treated water corrosion issues if media are not rinsed thoroughly prior to being placed back in service (ITRC, 2021). • Current pricing supports single use IX media with off-site incineration because concentrating a liquid waste stream can be difficult and dangerous (Ross et al., 2018).		Amec Foster Wheeler. (2017). Site 8 Pilot Test Results Report, Former Pease Air Force Base. Prepared for Air Force Civil Engineering Center, Joint Base San Antonio – Lakeland, Texas. Ross, I., J. McDonough, J. Miles, P. Storch, Thelakkat P. Kochunarayanan, E., Kalve, J. Hurst, S. Dasgupta, and Burdick. (2018). A review of emerging technologies for remediation of PFAS. Remediation, 28(2), 101-126. https://onlinelibrary.wiley.com/doi/pdf/10.1002/rem.21553
	Novel Adsorbent	Fluoro-Sorb®, novel adsorbent (Allen et al., 2019; OCWD, 2021). • Laboratory testing on Fluoro-Sorb® demonstrated a removal efficiency of between 85 and 93% with water containing three concentrations of PFAS ranging from 550 to 5,500 ppt (Allen et al., 2019).	• Laboratory- and field-scale pilot testing are ongoing and will be used to validate design considerations for in situ stabilization of a PFAS-impacted source zone, a passive groundwater treatment system (permeable reactive barrier), and an active sediment cap (Allen et al., 2019).	Pilot-scale implementation	Allen, J., M. Geary, and C. Hornaday. (2019). In Situ Remedy for PFAS-Contaminated Source Zone, Groundwater and Sediment, Battelle Sediments Conference. https://www.battelle.org/docs/default-source/conference-proceedings/2019-sediments-conference-proceedings/a7.-characterization-and-remediation-of-pfas-contaminated-sediments-media/104.pdf?sfvrsn=82981879_2 OCWD 2021. Orange County Water District PFAS Phase I Pilot-Scale Treatment Study Final Report. https://www.ocwd.com/media/9829/2021-03-24_ocwd-pfas-pilot-i_finalreport.pdf
Physical Separation					
Reverse Osmosis (RO)	RO separates compounds from water solutions by passing pressurized water across a semipermeable membrane (ITRC, 2021).	• The use of RO/nanofiltration as advanced drinking water treatment is still limited, but both technologies have been shown to be successful for the removal of longer-chain (greater than C5) PFAAs (Loi-Brugger et al., 2008; Tang et al., 2006). • PFOS removal greater than 99% was achieved using four different types of membranes over a wide range of feed concentrations, from 0.5 to 1,500 mg/L (Tang et al., 2006). • Some PFAS, such as GenX, PFMOAA and PFO2HxA, would require very frequent changeout of GAC and IX for removal as opposed to RO. RO is the most robust technology for protecting against	• Influent pretreatment is critical for RO membranes because of their spiral-wound design (ITRC, 2021). • Membranes are highly susceptible to fouling because some accumulated material cannot be removed from the membrane surface (ITRC, 2021). • RO requires power for high-pressure pumps and the management of concentrate, which can be energy intensive (ITRC, 2021). • The chemical-rich brine rejected by RO must be disposed of appropriately (ITRC, 2021).	Pilot-scale implementation	CDM Smith. (2018). Advanced Treatment Options for the Northwest Water Treatment Plant. https://www.brunswickcountync.gov/wp-content/uploads/2018/04/CDM-Smith-Brunswick-Final-Report-April-2018.pdf Higgins, C., and E.R. Dickenson. (2016). Treatment and Mitigation Strategies for Poly- and Perfluoroalkyl Substances. WRF Report 4322.Denver, CO: Water Research Foundation. ITRC. (2021). PFAS Treatment. Updated May. https://pfas-1.itrcweb.org/12-treatment-technologies/#12_4

Table 4-1 (continued). Liquids Disposal PFAS Technologies

Technology	Description	Advantages	Limitations	Demonstrated Capability	Reference
		unidentified chemicals. Greatest protection from future unidentified PFAS (CMD Smith, 2018). - RO is normally used in the drinking water industry for removal of PFAS and other chemicals. Tang et al. (2007) reports on a study of thin film composite polyamide RO membranes, where 99% removal of PFOS was achieved with several types of membranes at concentrations >1 mg/L. - RO has been shown to be extremely effective in removing PFAS regardless of chain length (Higgins and Dickenson, 2016) and is also expected to be effective at removing many types of PFAA precursors.	- RO systems are expensive and typically employed with large-scale drinking water systems (Ross et al., 2018). - For groundwater applications, the suspended solids and water geochemistry must be assessed and managed to prevent fouling or deterioration of the RO/nanofiltration membrane (Ross et al., 2018). - This approach also generates a low volume, high concentration rejectate waste which requires treatment or disposal, as these processes do not destroy PFAS (Ross et al., 2018). - RO is typically the costliest of the membrane technologies for removal, due to high capital cost and energy demand (CDM Smith, 2018). - Low pressure reverse osmosis (LPRO) is susceptible to fouling, thus an anti-scaling chemical and/or a pretreatment step may be required to reduce fouling (CDM Smith, 2018).		Loi-Brügger, A., S. Panglisch, G. Hoffmann, P. Buchta, and R. Gimbel. (2008). Removal of Trace Organic Substances from River Bank Filtrate – Performance Study of RO and NF Membranes. Water Science and Technology: Water Supply 8(1): 85-92. Ross, I., J. McDonough, J. Miles, P. Storch, Thelakkat P. Kochunarayanan, E., Kalve, J. Hurst, S. Dasgupta, and Burdick. (2018). A review of emerging technologies for remediation of PFAS. Remediation, 28(2), 101-126. https://onlinelibrary.wiley.com/doi/pdf/10.1002/rem.21553 Tang, C.Y., Q.S. Fu, A.P. Robertson, C.S. Criddle, and J.O. Leckie. (2006). Use of Reverse Osmosis Membranes to Remove Perfluorooctane Sulfonate (PFOS) from Semiconductor Wastewater. Environmental Science and Technology 40: 7343-7349. Tang, C.Y., Q.S. Fu, C.S. Criddle, and J.O. Leckie. (2007). Effect of Flux (Transmembrane Pressure) and Membrane Properties on Fouling and Rejection of Reverse Osmosis and Nanofiltration Membranes Treating Perfluorooctane Sulfonate Containing Wastewater. Environ. Sci. Technol. 41: 2008-2014.

5.0 FORMER NAVAL AIR WARFARE CENTER WARMINSTER PFAS IDW CASE STUDY

Former Naval Air Warfare Center (NAWC) Warminster is an 824-acre facility located in Bucks County, Pennsylvania. NAWC ceased operations on September 30, 1996 under the BRAC Program. The majority of the NAWC has been transferred to the private sector. Land transferred to the private sector has been developed as a residential neighborhood, retirement community, and multi-purpose business park. In addition, some land has been developed as a public park.

The NAWC was listed on the Superfund National Priorities List in 1989, and remedial actions for soil and groundwater were formalized in CERCLA Records of Decisions per the Federal Facility Agreement. The groundwater remedies for several operable units included the construction and operations of a GWET system to remove chlorinated solvents and other chemicals to below remedial action levels before discharging to streams. The NAWC GWET effluent criteria were modified by the state to include the PFOA and PFOS health advisory levels.

Figure 5-1 provides a schematic of the GWET system. The current NAWC GWET system includes the following components:

- Groundwater extraction from Area A, C, and D extraction wells;
- Groundwater transfer pumps;
- IX system for hexavalent chromium removal;
- Equalization tank;
- Bag filtration for particulates and solids;
- Air stripper to remove chlorinated solvents;
- Liquid-phase GAC adsorption (two vertical cylindrical pressure vessels operating in series, each containing 20,000 pounds of GAC); and
- Approximately one mile discharge pipe to a local stream.

In 2017, a PFAS Remedial Investigation was initiated at the NAWC. Remedial investigation activities included installing new monitoring wells, geophysics, and packer testing, and monitoring well sampling. Monitoring well drilling and development work over a two-year period generated significant amounts of liquid IDW in the several hundred-thousand-gallon range. Well packer testing and sampling generated water in the hundreds of gallon range. The large volume of liquid PFAS IDW was more than anticipated and disposal options were found to be costly.

The NAWC GWET system was considered for liquid PFAS IDW treatment because the treatment system is able to remove PFOA and PFOS to below the lifetime health advisory levels. The GWET system was not running at full capacity because some extraction wells were turned off due to the successful treatment of chlorinated solvents from some areas. Approximately 20 to 30 gpm of liquid PFAS IDW could be introduced into the GWET system.

Liquid PFAS IDW from investigation activities was transported from the well sites to the GWET system using vacuum trucks and stored in several 20,000-gallon frac tankers near the treatment plant to allow for settling of suspended solids and to have sufficient storage capacity for the drilling water. Several 2,000- to 4,000-gallon vacuum trucks were used to transfer the water between the wells and frac tankers in order to keep up with the rate of water generated during remedial investigation activities. The liquid PFAS IDW water was pumped from the frac tankers to the treatment plant through two 50-micron bag filters in series to remove suspended solids and particulates. The second bag filter used a smaller weave to further reduce fine particulates entering the GWET system, because fine particulates may reduce GAC effectiveness and lifespan.

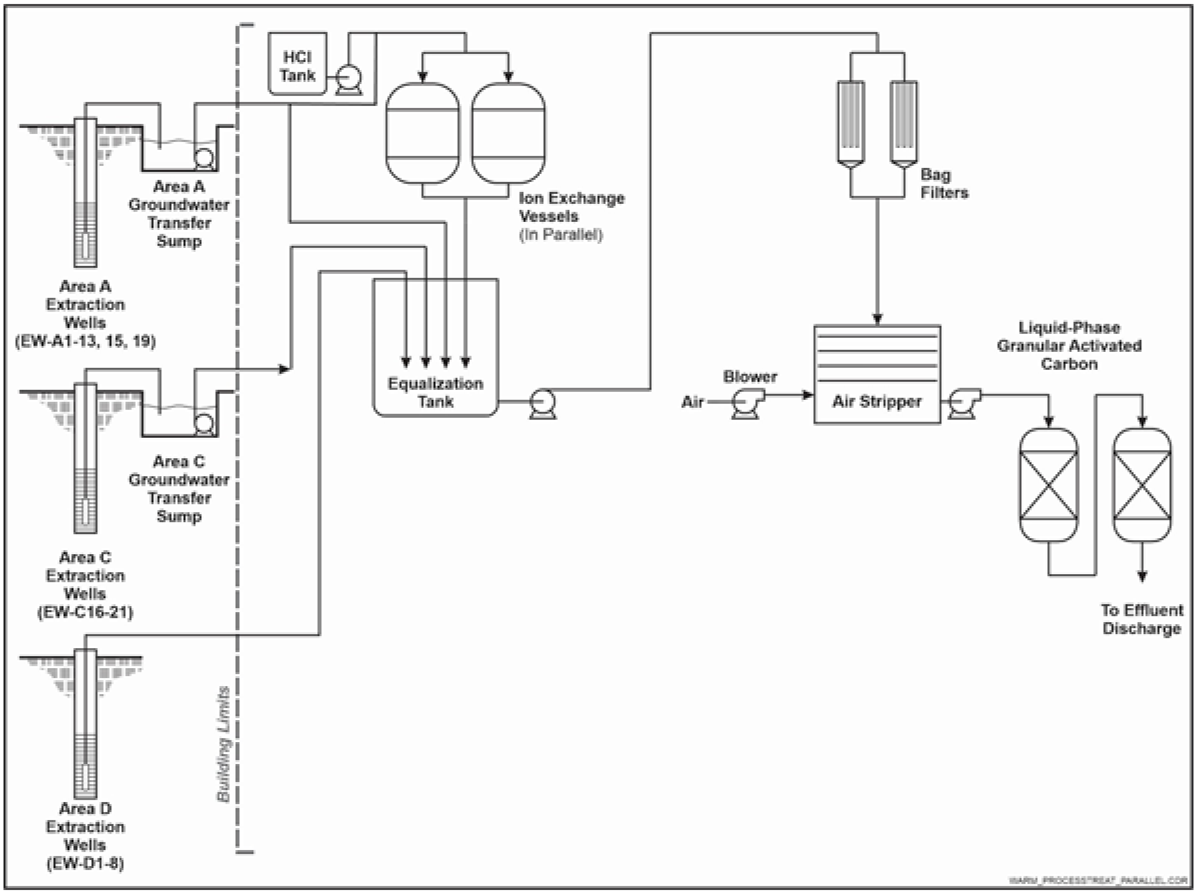

Figure 5-1. NAWC Warminster GWET Process Flow Diagram for Treatment System

The use of the existing NAWC GWET system to properly dispose of liquid PFAS IDW negated the cost of off-site treatment and enabled the remedial investigation to maximize efforts on investigation rather than IDW management. Operational impacts of introducing liquid PFAS IDW to a GWET system need to be well considered. The additional PFAS loading to a GWET system may shorten the life of filtration media. In addition, the frac tankers may require a considerable area for storage.

6.0 BEST PRACTICES

Commercially available options are currently limited for the treatment and disposal of PFAS IDW. The uncertainty and timing of legislation making PFAS-containing wastes hazardous and the growing reluctance of unsecured landfills to take PFAS-containing materials may further reduce disposal options. Recent concern for the effectiveness of incineration have resulted in a temporary moratorium on this option for DoD PFAS wastes (see Section 2.3). Several promising liquid PFAS IDW technologies are under development, but commercial deployment is not imminent. Liquid treatment adsorption technologies (e.g., GAC and resins) are currently being used at full scale at many sites globally. Emerging liquid destruction technologies that appear to be closest to being available commercially are plasma and electrochemical technologies, which are best suited for high concentration waste streams. RemBind^{TM} for soil treatment is being used commercially at full scale. Technology performance concerns and the potential narrowing of waste treatment and disposal options increase the need to reduce PFAS IDW amounts to the extent possible. The following are best practices recommended to reduce waste and/or to arrange for PFAS IDW disposal:

Overall Best Practices for Waste Minimization and Disposal

- As part of the site investigation planning, identify and verify possible IDW treatment and disposal options. For sites where PFAS data have not been obtained, assumptions should be based on expected concentrations from similar PFAS site types (as a surrogate for planning purposes).
- As part of the planning process, plan for longer than average on-site storage of IDW and account for higher handling/storage costs. Consider secure and longer-term storage methods (more secure covered soil piles and bulk water storage options such as frac tanks).
- For site investigations, use drilling methods such as direct push that minimize the amount of soil IDW. For monitoring wells, evaluate the potential resulting IDW from the planned drilling method.
- State-specific restrictions may be in place for the use of incineration and federal guidelines are evolving. In December 2021, a temporary moratorium was enacted on the incineration of PFAS-impacted wastes under the NDAA 2022. Contact the chain of command for the specific site for the latest status on the use of incineration for PFAS-containing waste.
- Do not mix high PFAS-impacted IDW with low concentration PFAS IDW.

Best Practices for Solids Handling and Disposal

- Avoid mixing higher and lower concentration PFAS soils during site investigations.
- Determine if there are soils (above the groundwater zone with PFAS) that are not impacted and segregate those from PFAS-impacted soils. Several states are developing soil screening levels so RPMs will need to check the current regulations where the site is located.
- Separate waste based on location (i.e., source versus delineation) as their concentration level may vary considerably.

- Sample the material in smaller batches. For example, sample solid PFAS waste in batches as produced, so any low level or non-detect waste can be easily disposed.
- Consider using double-lined RCRA D or RCRA C landfills.
- Identify available receiving facilities early in the planning process.

Best Practices for Liquid Handling and Disposal

- Avoid mixing higher and lower concentration PFAS liquid wastes.
- To preserve PFAS removal efficiency in various technologies, reduce TSS before treating impacted water. Consider adding pretreatment technology and develop a plan to handle/dispose of the resulting PFAS-containing solids.
- For groundwater sampling, use low flow methods to reduce the volume of purge water.
- Where appropriate and with reasonable cost, consider using dedicated sampling equipment. At sites with frequent sampling, dedicated equipment may be less labor intensive and generate lower volumes of rinse water.
- Identify available receiving facilities early in the planning process.

7.0 REFERENCES

Ahmad, M., A. Rajapaksha, J. Lim, M. Zhang, N. Bolan, D. Mohan, M. Vithanage, S. Lee, and Y. Ok. 2014. "Biochar as a Sorbent for Contaminant Management in Soil and Water: A Review." *Chemosphere*, 99: 19-33.

Al-Amoudi, A. and R. Lovitt. 2007. "Fouling Strategies and the Cleaning System of NF Membranes and Factors Affecting Cleaning Efficiency." *Journal of Membrane Science*, 30, 4-28.

Allen, J., M. Geary, and C. Hornaday. 2019. "In Situ Remedy for PFAS-Contaminated Source Zone, Groundwater and Sediment," Battelle Sediments Conference.

Amec Foster Wheeler. 2017. "Site 8 Pilot Test Results Report, Former Pease Air Force Base. Prepared for Air Force Civil Engineering Center, Joint Base San Antonio – Lakeland, Texas."

Appleman, T., E. Dickenson, C. Bellona, and C. Higgins. 2013. "Nanofiltration and Granular Activated Carbon Treatment of Perfluoroalkyl Acids." *Journal of Hazardous Materials*, 260, 740-746.

Arcadis. (2016). Environmental fate and effects of poly and perfluoroalkyl substances (PFAS). June. https://www.Arcadis.eu/wp-content/uploads/2016/06/Rpt_16-8.pdf

Barth, E., J. McKernan, D. Bless, and K. Dasu (2021). "Investigation of an immobilization process for pfas contaminated soils." *Journal of Environmental Management* **296**: 113069.

Birk, G. and D. Alden. 2017. "Ex Situ Treatments of Aqueous Film-Forming Foam Impacted Water," Presented at the Fourth International Symposium on Bioremediation and Sustainable Environmental Technologies.

Boodoo, F., Campos, J., and Kennedy, S. 2017. Removal of PFOA, PFOS and Other PFAS Substances Using Ion Exchange. Originally presented at the International Water Conference®: November 12-16, 2017. https://www.purolite.com/index/core-technologies/industry/potable---groundwater/PFAS-In-Our-Environment/best-pfas-treatment-option/pfoa-pfos-pfas-removal-using-ion-exchange.

Boodoo, F., O. Baumann, and N. Backman. 2018. Short and Long Chain PFAS Removal with Single-Use Selective Ion Exchange Resin.

Brewer, J. 2017. "Granular Activated Carbon: A Proven Solution for PFAS," Presentation at the Cleanup Conference. Calgon Corporation.

CDM Smith. 2018. Advanced Treatment Options for the Northwest Water Treatment Plant.

Cheng, J., D. Vecitis, H. Park, B. Mader, and M.R. Hoffmann. 2008. "Sonochemical Degradation of Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoate (PFOA) in Landfill Groundwater: Environmental Matrix Effects," *Environmental Science and Technology*, 42:21, 8057-8063.

Cheng, J., D. Vecitis, H. Park, B. Mader, and M. Hoffmann. 2009. “Sonochemical Degradation of Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoate (PFOA) in Groundwater: Kinetic Effects of Matrix Inorganics,” *Environmental Science and Technology*, 44:1, 445-450.

Choi, H. 2018. Chemical Decomposition Combined with Physical Adsorption for the Treatment of Investigation-Derived Waste Containing PFASs. ER18-1482.

Christenson. 2020. Removing PFAS in Investigation Derived Wastes (IDW) with Electrocoagulation and Electrochemically Activated Persulfate | Research Project Database | Grantee Research Project | ORD | US EPA. Small Business Innovation Research (SBIR) Grant No. 68HERC20C0033.

Clean Harbors. (2018). Environmental Services PFAS Treatments available at Lambton, Ontario, Facility. https://www.cleanharbors.com/sites/g/files/bdczcs356/files/2019-06/Clean-Harbors-Lambton-PFAS-Fact-Sheet.pdf

Conte, L., L. Falletti, A. Zaggia, and M. Milan. 2015. “Polyfluorinated Organic Micropollutants Removal from Water by Ion Exchange and Adsorption,” *Chemical Engineering Transactions*, 43, 2257-2262.

Dasu, K., X. Xia, D. Siriwardena, T. P. Klupinski and B. Seay (2022). "Concentration profiles of per- and polyfluoroalkyl substances in major sources to the environment." *Journal of Environmental Management* **301**: 113879.

Department of Defense (DoD). 2020. PFAS Task Force Progress Report. March.

Department of the Navy (DON). 2020a. Interim Per- and Polyfluoroalkyl Substances Site Guidance for NAVFAC RPMs, Naval Facilities Engineering Command. Available at: https://www.navfac.navy.mil/content/dam/navfac/Specialty%20Centers/Engineering%20and%20Expeditionary%20Warfare%20Center/Environmental/Restoration/er_pdfs/gpr/2020%20November%2024%20Final%20NAVFAC%20Interim%20PFAS%20Guidance%20FAQs.pdf

Department of the Navy (DON). 2020b. Limited Site-Specific Relief to Aqueous Film Forming Foam (AFFF) Removal and Disposal Requirements within the United States, Office of the Deputy Assistant Secretary of the Navy (Environment). July.

Du, Z., S. Deng, Y. Bei, Q. Huang, B. Wang, J. Huang, and G. Yu. 2014. “Adsorption Behavior and Mechanism of Perfluorinated Compounds on Various Adsorbents – A Review,” *Journal of Hazardous Materials*, 274, 443-454.

ECT2. 2019. Rapid Deployment of PFAS Removal System for Town Water Supply in Katherine, Australia.

Environmental Council of States (ECOS). 2020. Processes and Considerations for Setting PFAS State Standards.

Environmental Protection Agency (EPA). 2020a. Interim Guidance on the Destruction and Disposal or Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances. https://www.epa.gov/pfas/interim-guidance-destroying-and-disposing-certain-pfas-and-pfas-containing-materials-are-not.

Environmental Protection Agency (EPA). 2020b. Technical Brief. Per- and Polyfluoroalkyl Substances (PFAS): Incineration to Manage PFAS Waste Streams. https://www.epa.gov/sites/default/files/2019-09/documents/technical_brief_pfas_incineration_ioaa_approved_final_july_2019.pdf

Environmental Protection Agency (EPA). 2021. News Release. EPA Administrator Regan Announces Comprehensive National Strategy to Confront PFAS Pollution. https://www.epa.gov/newsreleases/epa-administrator-regan-announces-comprehensive-national-strategy-confront-pfas

Fernandez, N., L. Rodriguez-Freire, M. Keswani, and R. Sierra-Alvarez. 2016. "Effect of Chemical Structure on the Sonochemical Degradation of Perfluoroalkyl and Polyfluoroalkyl Substances (PFASs)," *The Royal Society of Chemistry, Environmental Science: Water Research and Technology*, 2, 975-983.

Giri, R. 2011. "Factors Influencing UV Photodecomposition of Perfluorooctanoic Acid in Water," *Chemical Engineering Journal*, 180, 197-203.

Gole, V., A. Fishgold, R. Sierra-Alvarez, P. Deymier, and M. Keswani. 2017. "Treatment of (Per) Fluorooctanesulfonic Acid (PFOS) Using a Large-Scale Sonochemical Reactor," *Separation and Purification Technology*, 194, 104– 110.

Gole, V., R. Sierra-Alvarezb, H. Pengc, J. Giesyc, P. Deymiera, and M. Keswania. 2018. "Sonochemical Treatment of Per- and Poly-Fluoroalkyl Compounds in Aqueous Film-Forming Foams by Use of a Large-Scale Multi-Transducer Dual-Frequency Based Acoustic Reactor," *Ultrasonics - Sonochemistry*, 45, 213-222.

Great Lakes Water Authority (GLWA). 2019. PFAS Panel Perspective. Environmental Education and Research Foundation (EREF) Summit on PFAS in Leachate and Groundwater in Ypsilanti, Michigan.

Halsen, T. 2018. Plasma Based Treatment Processes for PFAS Investigation Derived Waste. ER18-1624.

Hatton, J. 2020. Field Demonstration of Infrared Thermal Treatment of PFAS-Contaminated Soils from Subsurface Investigations. Final Report ER18-1603.

Higgins, C. and E. Dickenson. 2016. Treatment and Mitigation Strategies for Poly- and Perfluoroalkyl Substances. WRF Report 4322. Denver, CO: Water Research Foundation.

Hinrichsen, H. 2019. "Stabilization of PFAS Contaminated Soil Two Full Scale Projects in Sweden," Envytech Clean-up Conference.

Inyang, M. and E. Dickenson. 2017. “The Use of Carbon Adsorbents for the Removal of Perfluoroalkyl Acids from Potable Reuse Systems,” *Chemosphere*, 184, 168–175.

ITRC 2021. PFAS Technical and Regulatory Guidance Document. Updated May 2021. https://pfas-1.itrcweb.org/12-treatment-technologies/ (accessed October 2021).

Izadpanah, A. and A. Javidnia. 2012. “The Ability of a Nanofiltration Membrane to Remove Hardness and Ions from Diluted Seawater,” *Water*, 4, 283-294.

Javaherian, M. 2016. Bench-Scale VEG Research & Development Study: Implementation Memorandum for Ex-Situ Thermal Desorption of Perfluoroalkyl Compounds in Soils.

Javaherian, M. 2018. VEG Technology In-Situ and Ex-Situ Treatment of Soils Enhanced Oil & NAPL Recovery.

Jin, L., P. Zhang, T. Shao, and S. Zhao. 2014. “Ferric Ion Mediated Photodecomposition of Aqueous Perfluorooctane Sulfonate (PFOS) Under UV Irradiation and its Mechanism,” *Journal of Hazardous Materials*, 271, 9-15.

Kempisty, D., Y. Xing, and L. Racz. 2018. *Perfluoroalkyl Substances in the Environment: Theory, Practice, and Innovation*. Taylor and Francis Group.

Koster van Groos, P. 2018. Small-Scale Thermal Treatment of Investigation-Derived Wastes Containing Per- and Polyfluoroalkyl Substances (PFAS). ER18-1556.

Lang, J. R., B. M. Allred, J. A. Field, J. W. Levis and M. A. Barlaz (2017). "National estimate of per- and polyfluoroalkyl substance (pfas) release to u.S. Municipal landfill leachate." Environmental Science & Technology **51**(4): 2197-2205.

Lin, H., Y. Wang, J. Niu, Z. Yue, and Q. Huang. 2015. “Efficient Sorption and Removal of Perfluoroalkyl Acids (PFAAs) from Aqueous Solution by Metal Hydroxides Generated In Situ by Electrocoagulation,” *Environmental Science and Technology*, 49:17, 10562-9.

Liu, J. 2018. High-Performance Treatment of PFASs from Investigation-derived Waste: Integrating Advanced Oxidation-Reduction and Membrane Concentration. ER18-1497.

Loi-Brügger, A., S. Panglisch, G. Hoffmann, P. Buchta, and R. Gimbel. 2008. “Removal of Trace Organic Substances from River Bank Filtrate – Performance Study of RO and NF Membranes,” *Water Science and Technology: Water Supply*, 8:1, 85-92.

Lyu, X., W. Li, P. Lam, and H. Yul. 2015a. “Insights into Perfluorooctane Sulfonate Photodegradation in a Catalyst-Free Aqueous Solution,” *Scientific Reports*, 5, 9353.

Lyu, X., W. Li, P. Lam, and H. Yu. 2015b. “Boiling Significantly Promotes Photodegradation of Perfluorooctane Sulfonate,” *Chemosphere*, 138, 324-327.

Mahinroosta, R. and L. Senevirathna. 2020. “A Review of the Emerging Treatment Technologies for PFAS Contaminant in Soils,” *Journal of Environmental Management*, 255, 109896.

Major, D. 2019. Demonstration of Smoldering Combustion Treatment of PFAS-impacted Investigation-Derived Waste. SERDP Project ER18-1593.

McCleaf, P., S. Englund, A. Ostlund, K. Lindegren, K. Wiberg, and L. Ahrens. 2017. “Removal Efficiency of Multiple Poly- and Perfluoroalkyl Substances (PFASs) in Drinking Water Using Granular Activated Carbon (GAC) and Anion Exchange (AE) Column Tests,” *Water Research*, 120, 77–87.

Merino, N., Y. Qu, R. Deeb, E. Hawley, M. Hoffmann, and S. Mahendra. 2016. “Degradation and Removal Methods for Perfluoroalkyl and Polyfluoroalkyl Substances in Water,” *Environmental Engineering Science*, 33:9, 615–649.

Moriwaki, H., Y. Takagi, M. Tanaka, K. Tsuruho, K. Okitsu, and Y. Maeda. 2005. “Sonochemical Decomposition of Perfluorooctane Sulfonate and Perfluorooctanoic Acid,” *Environmental Science & Technology*, 39:9, 3388-3392.

OCWD. 2021. Orange County Water District PFAS Phase I Pilot-Scale Treatment Study Final Report. https://www.ocwd.com/media/9829/2021-03-24_ocwd-pfas-pilot-i_finalreport.pdf

Oliaei, F., D. Kriens, R. Weber, and A. Watson. 2013. “PFOS and PFC Releases and Associated Pollution from a PFC Production Plant in Minnesota (USA),” *Environmental Science and Pollution Research*, 20:4, 1977–1992.

Pillai, S. 2018. Ex Situ Remediation of Investigation-Derived Wastes containing PFAS by Electron Beam Technology. ER18-1620.

Popovic, J., Thorn, J., Jones, A., and J. Kornuc. 2020. Evaluation of a drop-in waste volume reduction method for liquid investigation derived waste containing per-and polyfluoroalkyl substances. *Journal of Environmental Management*.

Purolite. 2018. PFAS Case Study – Horsham PA. Removal of PFAS Contamination in Horsham Township, PA Water Supply. https://www.purolite.com/index/core-technologies/industry/potable---groundwater/PFAS-In-Our-Environment/best-pfas-treatment-option/treatment-and-removal-of-pfas-horsham-township. *Accessed 10/13/2021.*

Purolite. 2019. PFAS Removal: Choosing the Appropriate Technology. With New Regulations, Consider the Need to Also Remove PFBS and Other Short-Chain PFAS. https://www.purolite.com/index/core-technologies/industry/potable---groundwater/PFAS-In-Our-Environment/best-pfas-treatment-option/PFAS-Removal--Choosing-the-Appropriate-Technology- *Accessed 10/13/2021.*

Rahman, M. 2014. “Removal of Perfluorinated Compounds from Ultrapure and Surface Waters by Adsorption and Ion Exchange.” Doctor of Philosophy thesis, University of Waterloo, Ontario, Canada.

Rodriguez-Freire, L., R. Balachandran, R. Sierra-Alvarez, and M. Keswani. 2015. “Effect of Sound Frequency and Initial Concentration on the Sonochemical Degradation of PFOS,” *Journal of Hazardous Materials*, 300, 662–669.

Rodriguez-Freire, L., N. Abad-Fernandez, R. Sierra-Alvarez, C. Hoppe-Jones, H. Peng, J. Giesy, and M. Keswani. 2016. "Sonochemical Degradation of Perfluorinated Chemicals in Aqueous Film-Forming Foams," *Journal of Hazardous Materials*, 317, 275–283.

Ross, I., J. McDonough, J. Miles, P. Storch, P. T. Kochunarayanan, E. Kalve, J. Hurst, S. Dasgupta, and J. Burdick. 2018. "A Review of Emerging Technologies for Remediation of PFASs," *Remediation*, 28:2, 101-126.

Saleem, M., O. Biondo, G. Sretenović, G. Tomei, M. Magarotto, D. Pavarin, E. Marotta, and C. Paradisi. 2020. "Comparative Performance Assessment of Plasma Reactors for the Treatment of PFOA; Reactor Design, Kinetics, Mineralization and Energy Yield," *Chemical Engineering Journal*, 1385-8947: 382, 123031.

Sales, C. 2018. Application of Non-Thermal Plasma Technology for the Removal of Per- and Polyfluorinated Substances from Investigation-Derived Wastes. ER18-1570.

Schultz, M., D. Barofsky, and J. Field. 2003. "Fluorinated Alkyl Surfactants," *Environ. Eng. Sci*. 20:5, 487-501.

Singh, R., N. Multari, C. Nau-Hiz, R. Anderson, S. Richardson, and T. Holsen. 2019. "Rapid Removal of Poly-and Perfluorinated Compounds from Investigation Derived Waster in a Pilot-Scale Plasma Reactor," *Environ. Sci. Technol*. 53:19, 11375-11382.

Sörengårda, M., D. Klejab, and L. Ahrens. 2019. "Stabilization and Solidification Remediation of Soil Contaminated with Poly and Perfluoroalkyl Substances (PFASs)," *Journal of Hazardous Materials*, 367, 639–646.

Steinle-Darling, E. and M. Reinhard. 2008. "Nanofiltration for Trace Organic Contaminant Removal: Structure, Solution, and Membrane Fouling Effects on the Rejection of Perfluorochemicals," *Environmental Science and Technology*, 42, 5292-5297.

Tang, C., Q. Fu, A. Robertson, C. Criddle, and J. Leckie. 2006. "Use of Reverse Osmosis Membranes to Remove Perfluorooctane Sulfonate (PFOS) from Semiconductor Wastewater," *Environmental Science and Technology*, 40, 7343-7349.

Tang, C., Q. Fu, C. Criddle, and J. Leckie. 2007. "Effect of Flux (Transmembrane Pressure) and Membrane Properties on Fouling and Rejection of Reverse Osmosis and Nanofiltration Membranes Treating Perfluorooctane Sulfonate Containing Wastewater," *Environ. Sci. Technol*. 41, 2008-2014.

Taniyasu, S., N. Yamashita, E. Yamazaki, G. Petrick, and K. Kannan. 2013. "The Environmental Photolysis of Perfluorooctanesulfonate, Perfluorooctanoate, and Related Fluorochemicals," *Chemosphere*, 90, 1686-1692.

Vaalgamaa, S., A. Vähätalo, N. Perkola, and S. Huhtala. 2011. "Photochemical Reactivity of Perfluorooctanoic Acid (PFOA) in Conditions Representing Surface Water," *Science of the Total Environment*, 409, 3043-3048.

Van Vinkle, J. 2019. Air Force Tests Plasma Reactor to Degrade, Destroy PFOS and PFOA. 88th Air Base Wing Public Affairs News Release. Available at: https://www.wpafb.af.mil/News/Article-Display/Article/2007997/air-force-tests-plasma-reactor-to-degrade-destroy-pfos-pfoa/

Vecitis, C., H. Park, J. Cheng, B. Mader, and M. Hoffmann. 2008. "Kinetics and Mechanism of the Sonolytic Conversion of the Aqueous Perfluorinated Surfactants, PFOA, and PFOS into Inorganic Products," *The Journal of Physical Chemistry A*, 112:18, 4261-4270.

Vecitis, C. D., H. Park, J. Cheng, B. T. Mader and M. R. Hoffmann (2009). "Treatment technologies for aqueous perfluorooctanesulfonate (pfos) and perfluorooctanoate (pfoa)." Frontiers of Environmental Science & Engineering in China **3**(2): 129-151.

Yamada, T. and P. Taylor. 2003. Laboratory Scale Thermal Degradation of Perfluoro-Octanyl Sulfonate and Related Precursors. Final Report, 3M Company.

Yamada, T., P. Taylor, R. Buck, M. Kaiser, and R. Giraud. 2005. "Thermal Degradation of Fluorotelomer Treated Articles and Related Materials," *Chemosphere*, 61, 974-984.

Yu, H. 2018. Destruction of PFAS and Organic Co-Contaminants in Water and Soil Present in Investigation-Derived Waste at DoD Sites Using Novel Adsorbent and Ultrasound. ER18-1652.

Xiao, X., B. Ulrich, B. Chen, and C. Higgins. 2017. "Sorption of PFASs Relevant to Aqueous Film Forming Foam (AFFF)-Impacted Groundwater by Biochars and Activated Carbon," *Environmental Science & Technology*, 51:11, 6342–6351.

Zaggia, A., L. Conte, L. Falletti, M. Fant, and A. Chiorboli. 2016. "Use of Strong Anion Exchange Resins for the Removal of Perfluoroalkylated Substances from Contaminated Drinking Water in Batch and Continuous Pilot Plants," *Water Research*, 91, 137–146.

Zhao, D. 2018. Cost-effective Destruction of Per- and Polyfluoroalkyl Substances from DoD Subsurface Investigation-derived Wastes Using a New Class of Adsorptive Photocatalysts. ER18-1515.

APPENDIX A
TECHNOLOGIES CURRENTLY UNDER RESEARCH

Multiple DoD Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) projects are ongoing with the goal to develop more cost effective and efficient technologies for treatment of IDW from PFAS investigations. Table A-1 provides the technology descriptions and the project objective for a selection of these emerging PFAS IDW treatment research projects. Some of these technologies demonstrate treatment of PFAS-impacted IDW containing a mixture of both liquids and solids and/or including multiple unit processes in a treatment train. The projects include emerging technologies such as: advanced oxidation-reduction with membrane treatment, chemical decomposition combined with adsorption, chitosan-modified montmorillonite, electron-beam technology, infrared thermal treatment, novel adsorbents, hydrothermal technologies, persulfate (peroxone-activated), photocatalysts (Si-C based, titanate nanotubes, $BiPO_4$), photo/electrochemical treatment, plasma-based treatment, reactive electrochemical membrane reactors, smoldering combustion, thermal desorption coupled with thermal oxidation, thermal treatment (small-scale and on-site), and ultrasound/sonic treatment for regenerant solutions. More information can be found here, which provides a comprehensive table of DoD SERDP-ESTCP projects completed and ongoing related to PFAS IDW research.

In addition to those technologies being studied by SERDP-ESTCP above, a range of PFAS treatment technologies are undergoing bench-scale testing to further gauge their feasibility. As summarized in Table A-2, these technologies for liquid treatment include biochar adsorption, physical, separation, flocculation/coagulation, nanofiltration, redox manipulation, sonic treatment, plasma, and solar ponding.

Table A-1. Select DoD SERDP-ESTCP Research Projects for IDW

Technology	Description	Objective	Source
Adsorption and Ultrasound	Overall, the technology uses a three-step approach for PFAS and co-contaminant destruction for soil and water in IDW (Yu, 2018): (i) Removal of PFAS and co-contaminants from impacted groundwater using a novel, low cost adsorbent, (ii) Desorb the chemicals from the adsorbent with a chemical (regenerant) solution, and (iii) Destroy PFAS and other co-contaminants in the regenerant solution and those sorbed on soil using ultrasound in one reactor. The novel adsorbent will be mixed in the IDW tank to remove PFAS and co-contaminants. The adsorbent and soil will be filtered out and the treated water will be discharged. The chemicals sorbed on the adsorbent and soil will be desorbed and destroyed using ultrasound in one reactor. The iron-based adsorbent is separated from the slurry using magnets and reused (Yu, 2018).	This proof of concept project will lead to the development of a very simple, low cost, small footprint, easy to operate treatment system having primarily a polyvinyl chloride tank for IDW, small filter, magnet, pH controller, and a small ultrasound reactor. It will be applicable to all DoD sites where PFAS related IDW is generated (Yu, 2018).	Yu, H. (2018). Destruction of PFAS and Organic Co-Contaminants in Water and Soil Present in Investigation-Derived Waste at DoD Sites Using Novel Adsorbent and Ultrasound. ER18-1652.
Adsorption/Waste Reduction	This technology adds GAC and IX resins packaged in polypropylene mesh pouches to liquid PFAS IDW with circulation. The circulation causes the PFAS in the water to be adsorbed and concentrated on the GAC and IX resin. In bench-scale tests, up to 97% and 96.4% PFOS and PFOA respectively was removed from PFAS IDW by GAC. IX showed up to 99.4% and 96.7% removal of PFOS and PFOA, respectively, from PFAS containing liquid waste. The technology was tested on high total dissolved solids water containing chloride and sulfate.	The objective of the study was to reduce the volume of PFAS waste by concentrating the PFAS onto GAC and IX resins.	Popovic, J., Thorn, J., Jones, A., and J. Kornuc. 2020. Evaluation of a Drop-in Waste Volume Reduction Method for Liquid Investigation Derived Waste Containing Per-and Polyfluoroalkyl Substances. *Journal of Environmental Management*.

Table A-1. Select DoD SERDP-ESTCP Research Projects for IDW

Technology	Description	Objective	Source
Adsorption, Plasma, and Soil Washing	The reactor will employ a sorbent (IX resin) to remove PFAS from solution. After adequate amounts of PFAS are sorbed, the feed stream will be turned off and a desorption solution added to the reactor to initiate PFAS desorption. Plasma will then be used to treat the desorbed PFAS. As destruction continues, additional PFAS will be desorbed and destruction will continue. The regenerated sorbent will then be re-exposed to PFAS to determine how many cycles it can be used for. Removal of PFAS from soil IDW using soil washing will also be evaluated. A variety of solutions including water alone, water plus methanol and water plus methanol and salt will be evaluated (Halsen, 2018).	On-site options that treat the waste and destroy the PFAS will result in significant cost reductions compared to off-site disposal and incineration (Halsen, 2018).	Halsen, T. (2018). Plasma Based Treatment Processes for PFAS Investigation Derived Waste. ER18-1624.
eBeam	Testing will be conducted using field IDW samples obtained from representative DoD sites impacted by a range of AFFF-derived PFAS. Samples will be analyzed before and after eBeam treatment for soil parameters (pH, alkalinity, % moisture content,) and co-contaminants to identify factors that may influence treatment efficiency of PFAS in IDW.	eBeam technology has the potential to be implemented in a mobile treatment unit, it offers significant advantages in cost and coordination over off-site high temperature incineration.	Pillai, S.D. (2018). Ex Situ Remediation of Investigation-Derived Wastes containing PFAS by Electron Beam Technology. ER18-1620.
Non-Thermal Plasma	Lab study to demonstrate the feasibility of applying dielectric barrier discharge to enhance the use of cold plasma to degrade PFAS in IDW (Sales, 2018).	Development of a treatment technology that can degrade PFAS in a wide variety of matrices, including IDW, soil, sediments, and groundwater (Sales, 2018).	Sales, C. (2018). Application of Non-Thermal Plasma Technology for the Removal of Per- and Polyfluorinated Substances from Investigation-Derived Wastes. ER18-1570.
Thermal Decomposition	A lab project focused on evaluating thermal decomposition of PFAS in IDW materials, and utilizing $Ca(OH)_2$ amendments to lower energy use and reduce volatile organic fluorine gases produced during such decomposition (Koster van Groos, 2018).	Provide the data necessary to design a robust and mobile system for on-site treatment of IDW (Koster van Groos, 2018).	Koster van Groos, P. (2018). Small-Scale Thermal Treatment of Investigation-Derived Wastes (IDW) Containing Per- and Polyfluoroalkyl Substances (PFAS). ER18-1556.

Table A-1. Select DoD SERDP-ESTCP Research Projects for IDW

Technology	Description	Objective	Source
	Two furnaces will be placed in series, with aqueous solutions capable of trapping mineralized fluorine species located after each furnace (Koster van Groos, 2018).		
Adsorption and Photocatalysts	Lab testing of a photo-regenerable composite material composed of can activated carbon core that adsorbs and concentrates PFAS from water onto the reactive surfaces of the material, whereas the photocatalyst facilitates subsequent destruction of the chemicals under ultraviolet or solar light, which also regenerates the saturated material (Zhao, 2018).	Develop an innovative, cost-effective, and green technology for destruction of PFAS from DoD subsurface IDWs (Zhao, 2018).	Zhao, D. (2018). Cost-effective Destruction of Per- and Polyfluoroalkyl Substances from DoD Subsurface Investigation-derived Wastes using a New Class of Adsorptive Photocatalysts. ER18-1515.
Oxidation-Reduction and Membrane Concentration	A lab study for IDW treatment via advanced oxidation, hydrated electron defluorination, and membrane-based concentration (Liu, 2018). The treatment train contains four modules: (i) oxidation pretreatment, (ii) nanofiltration-based concentration, (iii) defluorination using hydrated electrons in an ultraviolet-sulfite system, and (iv) further oxidation with residual sulfite (Liu, 2018).	Develop an effective and practical treatment train for intensive destruction of PFAS and organic co-contaminant in liquid IDW at DoD sites (Liu, 2018).	Liu, J. (2018). High-Performance Treatment of PFAS from Investigation-derived Waste: Integrating Advanced Oxidation-Reduction and Membrane Concentration. ER18-1497.
Adsorption and Oxidation/Reduction	A bench-scale study incorporating zerovalent iron with common oxidants such as hydrogen peroxide, persulfate, and peroxymonosulfate, where electrons, hydrogens, and superoxide radical anions generated in situ function as strong reducing species while simultaneously hydroxyl radicals and sulfate radicals serve as strong oxidizing species to degrade PFAS in IDW (Choi, 2018).	The overall objective of this project is to integrate various effective treatment technologies, including physical adsorption, advanced oxidation, and reductive defluorination, into one engineered system to synergistically remove and degrade PFAS in IDW under ambient conditions (Choi, 2018).	Choi, H. (2018). Chemical Decomposition Combined with Physical Adsorption for the Treatment of Investigation-Derived Waste Containing PFAS. ER18-1482.

Table A-2. Innovative PFAS Liquid Treatment Technologies Demonstrated at the Bench-Scale

Technology	Description	Advantages	Limitations	Source
Biochar	Biochar is a carbon-rich, porous solid synthesized from biomass, such as wood or manure, through "pyrolysis" (Ahmad et al., 2014). Key factors controlling the properties of biochar (for example, pore size, chemical composition, and hydrophobicity) include the temperature of pyrolysis and biomass feedstock (ITRC, 2021).	• Laboratory studies have demonstrated that biochar is potentially viable for treatment of PFAS, but additional research is needed to fully establish viability and costs (ITRC, 2021). • Based on batch studies, biochars with large surface areas could be an alternative to GAC, although variability in biochar properties relative to GAC may affect reliability (Xiao et al., 2017). • The use of waste material as a starting feedstock results in a lower overall carbon footprint (ITRC, 2021).	• Various laboratory experiments have evaluated the efficacy of biochar, but no full-scale treatment systems are in place for the removal of PFAS (ITRC, 2021). • While biochar removal is effective in ultrapure water, when used to treat river water (with more complicated water chemistry), biochar is ineffective compared to IX and GAC and exhibited significantly slower adsorption kinetics (Rahman, 2014). • Reactivation of biochar is not currently feasible and energy-intensive incineration or landfilling is required, which offsets some of the sustainability benefits (ITRC, 2021).	ITRC. (2018). Remediation Technologies and Methods for Per- and Polyfluoroalkyl Substances (PFAS). March. https://pfas-1.itrcweb.org/wp-content/uploads/2018/03/pfas_fact_sheet_remediation_3_15_18.pdf
Flocculation/ Coagulation	Flocculation/coagulation is typically conducted by adding a soluble polymer (for example, aluminum or ferric salts and proprietary chemical coagulants or electrocoagulation) and slowly mixing to allow the particles to agglomerate and grow. PFAS can be physically incorporated into, or sorbed onto, the flocculated particulate. The precipitated solids are then separated from the water by sedimentation, filtration, or a combination of both processes (ITRC, 2021).	• Recent studies have found that PFAAs, such as PFOA and PFOS, can be quickly sorbed on the surface of zinc hydroxide particulates generated by electrocoagulation (Lin et al., 2015). • One study has proposed using electrocoagulation combined with chemical oxidation and electrochemically activated persulfate to remove PFAS (Christenson, 2020)	• The solid material containing the PFAS requires disposal (ITRC, 2021). • Pilot- and full-scale applications have not been documented in the United States (Birk and Alden, 2017). • PFAS precipitation by flocculation/coagulation has shown limited applicability for complete treatment of PFAS; therefore, it could be considered mainly as a pretreatment technology (ITRC, 2021).	Birk, G. and D. Alden. (2017). Ex Situ Treatments of Aqueous Film-Forming Foam Impacted Water, Presented at the Fourth International Symposium on Bioremediation and Sustainable Environmental Technologies. Christenson. 2020. Removing PFAS in Investigation Derived Wastes (IDW) with Electrocoagulation and Electrochemically Activated Persulfate | Research Project Database | Grantee Research Project | ORD | US EPA. Small Business Innovation Research (SBIR) Grant No. 68HERC20C0033. ITRC. (2018). Remediation Technologies and Methods for Per- and Polyfluoroalkyl Substances (PFAS). March. https://pfas-1.itrcweb.org/wp-content/uploads/2018/03/pfas_fact_sheet_remediation_3_15_18.pdf Lin, H., Y. Wang, J. Niu, Z. Yue, and Q. Huang. (2015). Efficient Sorption and Removal of Perfluoroalkyl Acids (PFAAs) from Aqueous Solution by Metal Hydroxides Generated in situ by Electrocoagulation. *Environmental Science and Technology* 49 (17): 10562-9.
Nanofiltration	Nanofiltration is a form of membrane technology that is pressure-driven and shown to be effective in the removal of PFAS (Tang et al., 2007). This method provides high water flux at low operating pressure (Izadpanah and Javidnia, 2012).	• Reported rejections were generally > 95% for PFAS with molecular weights ranging from 214 g/mol to 713 g/mol (Steinle-Darling and Reinhard, 2008; Appleman et al., 2013). • Salt passage for PFOS was reported to range from < 1% for the tighter NF-90 membrane to about 6% for the looser NF-270 and DK membranes (Tang et al., 2007).	• Nanofiltration is considered a partially developed technology as available data on the removal of PFAS are limited to laboratory-scale tests (ITRC, 2021). • Lower rejections were observed for PFPeA and FOSA—about 70 and 90%, respectively (Steinle-Darling and Reinhard, 2008). • Appropriate disposal or treatment of the membrane concentrate stream is another design factor. • Nanofiltration membrane fouling mechanisms are poorly understood, and further research is needed to develop cost-effective cleaning methods to restore membrane performance (Al-Amoudi and Lovitt, 2007).	Al-Amoudi, A. and R.W. Lovitt. (2007). Fouling Strategies and the Cleaning System of NF Membranes and Factors Affecting Cleaning Efficiency. *Journal of Membrane Science* 303: 4-28. Appleman, T.D., E. Dickenson, C. Bellona, and C.P. Higgins. (2013). Nanofiltration and Granular Activated Carbon Treatment of Perfluoroalkyl Acids. *Journal of Hazardous Materials* 260: 740-746. ITRC. (2018). Remediation Technologies and Methods for Per- and Polyfluoroalkyl Substances (PFAS). March. https://pfas-1.itrcweb.org/wp-content/uploads/2018/03/pfas_fact_sheet_remediation_3_15_18.pdf Izadpanah, A.A. and A. Javidnia. (2012). The Ability of a Nanofiltration Membrane to Remove Hardness and Ions from Diluted Seawater. *Water* 4: 283-294. Steinle-Darling, E. and M. Reinhard. (2008). Nanofiltration for Trace Organic Contaminant Removal: Structure, Solution, and Membrane Fouling Effects on the Rejection of Perfluorochemicals. *Environmental Science and Technology* 42: 5292-5297.

Table A-2. Innovative PFAS Liquid Treatment Technologies Demonstrated at the Bench-Scale

Technology	Description	Advantages	Limitations	Source
				Tang, C.Y., Q.S. Fu, C.S. Criddle, and J.O. Leckie. (2007). Effect of Flux (Transmembrane Pressure) and Membrane Properties on Fouling and Rejection of Reverse Osmosis and Nanofiltration Membranes Treating Perfluorooctane Sulfonate Containing Wastewater. *Environ. Sci. Techno*l. 41: 2008-2014.
		Data on nanofiltration performance are more limited, but positive bench-scale test results have been reported for removal of PFAS with a range of molecular weights.		CDM Smith. (2018). Advanced Treatment Options for the Northwest Water Treatment Plant. https://www.cdmsmith.com/-/media/Insights/PFAS-Treatment-Options/PFAS-March-Newsletterdocx.pdf
Sonic Treatment	Cavitation is the creation of microbubbles in a fluid due to negative pressures, which creates heat (Ross et al., 2018).	• Sonolysis appears to destroy a wide range of PFAS (long chain and short chain), with consistent observations of pseudo-first order rate kinetics and faster kinetics for larger PFAS with more fluorination (perfluorinated > polyfluorinated) (Fernandez et al., 2016). • The operational energy costs are moderate (in the range of 0.1 to 0.3-kilowatt hour per liter of water treated) (Ross et al., 2018).	• One limitation of the available sonolysis data for PFAS is that the focus is on viability and, therefore, high concentrations of PFAS are used (greater than 10,000 ng/L) (Ross et al., 2018). • Sonolysis is only applicable to the liquid phase and, therefore, PFAS adsorbed to solids will require leaching with extractants to enable sonochemical degradation in the liquid phase (Ross et al., 2018). • Sonolysis has been demonstrated at laboratory scale for PFAS but not scaled up for commercial use. Scale-up likely involves significant design challenges as propagation of cavitation bubbles from transducers has limited zones of efficacy (Ross et al., 2018). • Larger scale sonolytic reactors can suffer from dead zones (Gole et al., 2017). • Cheng et al. (2009) evaluated the effects of several inorganic species on sonochemical kinetics. It showed that the rate of reduction in the groundwater was primarily due to the presence of bicarbonate. Common cations had negligible effects (Cheng et al., 2009). • In landfill groundwater with the application of sonolysis the degradation rate was reduced by 61% and 56% for PFOS and PFOA, respectively, due to the presence of other organic constituents (Cheng et al., 2008). The lower degradation rate was caused by other organic chemicals, rather than dissolved organic matter. A combined process of ozonation and sonolysis has shown to recover the rate loss for PFOS and PFOA (Arcadis, 2016).	Arcadis. (2016). Environmental fate and effects of poly and perfluoroalkyl substances (PFAS). June. https://www.Arcadis.eu/wp-content/uploads/2016/06/Rpt_16-8.pdf Cheng, J.C, D. Vecitis, H. Park, B.T. Mader, and M.R. Hoffmann. (2008). Sonochemical Degradation of Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoate (PFOA) in Landfill Groundwater: Environmental Matrix Effects. *Environmental Science and Technology*, 42:21, 8057-8063. Cheng, J.C., D. Vecitis, H. Park, B.T. Mader, and M.R. Hoffmann. (2009). Sonochemical Degradation of Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoate (PFOA) in Groundwater: Kinetic Effects of Matrix Inorganics. *Environmental Science and Technology*, 44:1, 445-450. Fernandez, N.A., L. Rodriguez-Freire, M. Keswani, and R. Sierra-Alvarez. (2016). Effect of Chemical Structure on the Sonochemical Degradation of Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS). *The Royal Society of Chemistry, Environmental Science: Water Research and Technology*, 2, 975-983. https://doi.org/10.1039/c6ew00150e Gole, V.L., A. Fishgold, R. Sierra-Alvarez, P. Deymier, and M. Keswani. (2017). Treatment of (per) Fluorooctanesulfonic Acid (PFOS) Using a Large-Scale Sonochemical Reactor. *Separation and Purification Technology*, 194, 104– 110. https://doi.org/10.1016/j.seppur.2017.11.009 Moriwaki, H., Y. Takagi, M. Tanaka, K. Tsuruho, K. Okitsu, and Y. Maeda. (2005). *Environmental Science & Technology*, 39(9), 3388-3392. Rodriguez-Freire, L., R. Balachandran, R. Sierra-Alvarez, and M. Keswani. (2015). Effect of Sound Frequency and Initial Concentration on the Sonochemical Degradation of Perfluorooctane Sulfonate (PFOS). *Journal of Hazardous Materials*, 300, 662–669. https://doi.org/10.1016/j.jhazmat.2015.07.077 Rodriguez-Freire, L., N. Abad-Fernandez, R. Sierra-Alvarez, C. Hoppe-Jones, H. Peng, J.P. Giesy, and M. Keswani. (2016). Sonochemical degradation of perfluorinated chemicals in aqueous film-forming foams. *Journal of Hazardous Materials*, 317, 275–283. https://doi.org/10.1016/j.jhazmat.2016.05.078 Ross, I., J. McDonough, J. Miles, P. Storch, Thelakkat P. Kochunarayanan, E., Kalve, J. Hurst, S. Dasgupta, and Burdick. (2018). A review of emerging technologies for remediation of PFAS. *Remediation*, 28(2), 101-126. https://onlinelibrary.wiley.com/doi/pdf/10.1002/rem.21553

Table A-2. Innovative PFAS Liquid Treatment Technologies Demonstrated at the Bench-Scale

Technology	Description	Advantages	Limitations	Source
	There are several factors related to the design of large-scale sonochemical reactors. Designs vary in numbers and locations of transducers, frequency of operation, geometries of reactors, power dissipation per unit volume and cavitational yield.	• Results of several investigations have demonstrated that sonochemical degradation of PFAS is effective for reducing lengths of fluorocarbon chains and decreasing concentrations of PFAS from initial concentrations of mM to nM (Gole et al., 2018). • A laboratory study tested a sonochemical reactor of volume 91 L to degrade two commercially available AFFFs. The reactor consisted of 12 transducers with operating frequencies of 1 MHz or 500 kHz and total input power of 12 kW (Gole et al., 2018). • Approximately 90.5% and 26.6% reduction of perfluoroalkyl sulfonate (PFSA) and PFCA, respectively, and 38.4% reduction were achieved in 13 hours. Estimated costs of energy for the treatment of the two AFFFs at a 500× dilution were $0.015 ± 0.0001/L and $0.019 ± 0.0002/L, respectively (Gole et al., 2018).	• Due to issues of scalability, studies conducted using large-scale sonochemical reactors have been very limited (Gole et al., 2018).	Gole, V.L., R. Sierra-Alvarez, H. Pengc, J.P. Giesyc, P. Deymiera, and M. Keswania. (2018). Sonochemical Treatment of Per- and Poly-Fluoroalkyl Compounds in Aqueous Film-Forming Foams by Use of a Large-Scale Multi-Transducer Dual-Frequency Based Acoustic Reactor. *Ultrasonics - Sonochemistry*, 45 213-222. doi:10.1016/j.ultsonch.2018.02.014
Vapor Energy Generator (VEG)	The VEG process uses steam at 1,100 ºC to destroy PFAS from impacted soils in an ex situ treatment chamber (Ross et al., 2018).	• This technology has multiple perceived benefits including lower energy costs, a relatively small operating footprint, and, thus, a lower mobilization cost than large-scale TD systems (Ross et al., 2018). • Using steam at 1,100 ºC should destroy all PFAS (polyfluorinated precursors and long- and short-chain PFAAs) (Ross et al., 2018). • The VEG technology has been used for enhanced oil recovery (both in situ and ex situ remediation) for a range of recalcitrant chemicals, with approximately 45 full-scale projects completed in the United States (Ross et al., 2018). • Regarding implementation, the VEG technology can be deployed via a mobile system which will be more easily mobilized at sites than TD units with even smaller batch systems available, if required (Ross et al., 2018).	• No full-scale application of VEG specifically to address PFAS has been implemented (Ross et al., 2018). • The method may disturb the soil and may harm the ecosystem. • To date, thermal technologies have not been a good strategy for in situ treatment because of the high temperature required.	Ross, I., J. McDonough, J. Miles, P. Storch, P. Thelakkat Kochunarayanan, E. Kalve, J. Hurst, S. Dasgupta, and J. Burdick. (2018). A Review of Emerging Technologies for Remediation of PFAS. *Remediation*, 28(2), 101-126. https://onlinelibrary.wiley.com/doi/pdf/10.1002/rem.21553
	The VEG system is a patented, mobile in situ and ex situ technology used to remediate soils for unrestricted reuse (Javaherian, 2018). A patented, mobile, vapor generator, the ex situ component of the technology thermally treats soils within a fully enclosed chamber, while eliminating emissions through the use of a closed-loop filtration system. The filtration process incorporates a combination of chemical reduction, thermal oxidation, carbon dioxide reduction, acid gas scrubbing, and transformation of chemicals	• Eliminates off-site transport, disposal, and waste generator liability (Javaherian, 2018). • Results in unrestricted onsite reuse of soils, eliminating land use controls (Javaherian, 2018). • In situ source removal and light nonaqueous phase liquid recovery • Patented closed-loop design and patented filters eliminate air emissions. • Entirely sustainable system, transforming chemicals into syngas to fuel system operations. • Typical cost savings greater than 50% relative to landfill disposal. • Typical carbon footprint reductions greater than 80%. • No incineration process involved. • Pre-VEG 87 mg/kg, Post-VEG treatment greater than 0.0001 mg/kg of PFAS. • The bench-scale study was performed using site soil spiked with AFFF. The results of the testing suggest that measurable reduction (i.e., greater than 60%) in		Javaherian, M. (2016). Bench-Scale VEG Research & Development Study: Implementation Memorandum for Ex-Situ Thermal Desorption of Perfluoroalkyl Compounds (PFCs) in Soils. https://www.endpoint-inc.com/wp-content/uploads/2016/05/VEG-Bench-Scale-PFCs-Soil.pdf Javaherian, M. Endpoint. (2018). VEG Technology In-Situ and Ex-Situ Treatment of Soils Enhanced Oil & NAPL Recovery. http://www.endpoint-inc.com/wp-content/uploads/2017/02/VEG-Technology-2018.pdf

Table A-2. Innovative PFAS Liquid Treatment Technologies Demonstrated at the Bench-Scale

Technology	Description	Advantages	Limitations	Source
	removed into a fuel (Javaherian, 2016).	total PFC concentrations in soil are achievable under soil treatment temperatures upwards of 1,100 °F and treatment periods on the order of 15 minutes (Javaherian, 2016).		
Plasma	Plasma-based water treatment (gas stream and electricity) converts water into reactive oxidative species and generates reductive species (aqueous electrons), which degrade PFAA (Singh et al., 2019).	• In pilot-scale testing, a plasma reactor treated IDW to reduce PFAAs concentrations below the EPA's lifetime health advisory level. Can be operated in continuous mode (pilot-scale testing up to 2 gpm) (Singh et al., 2019). • Electrical discharge plasma appears to be one of the most efficient technologies for the removal of PFOA and PFOS (Singh et al., 2019). • The energy efficiency of a self-pulsing streamer discharge reactor improved when argon was used instead of air as the plasma feed gas and water with higher conductivity was tested (Saleem et al., 2020). • At Wright-Patterson Air Force Base the technology was deployed as part of a field demonstration.	• Additional field testing of the technology needs to be performed. A field test was performed on September 25, 2020. Results are pending. • Reactive species generated by the reaction can react with other constituents in the groundwater. • Co-chemicals can have an impact on the process. • The process can create toxic and mobile byproducts.	Singh, R.K., N. Multari, C. Nau-Hiz, R.H. Anderson, S.D. Richardson, T.M. Holsen. (2019). Rapid Removal of Poly-and Perfluorinated Compounds from Investigation Derived Waster (IDW) in a Pilot-Scale Plasma Reactor. *Environ. Sci. Technol.* 53, 19, 11375-11382. September. https://pubs.acs.org/doi/pdf/10.1021/acs.est.9b02964 Saleem, M., O. Biondo, G. Sretenović, G. Tomei, M. Magarotto, D. Pavarin, E. Marotta, and C. Paradisi. (2020). Comparative performance assessment of plasma reactors for the treatment of PFOA; reactor design, kinetics, mineralization, and energy yield. *Chemical Engineering Journal*, ISSN: 1385-8947, Vol: 382, Page: 123031.https://doi.org/10.1016/j.cej.2019.123031 Van Vinkle, John (2019). Air Force Tests Plasma Reactor to Degrade, Destroy PFOS, PFOA.88th Air Base Wing Public Affairs .https://www.wpafb.af.mil/News/Article-Display/Article/2007997/air-force-tests-plasma-reactor-to-degrade-destroy-pfos-pfoa/
Smoldering	Smoldering combustion is a flameless, self-sustaining process that occurs on the surface of a condensed fuel, converting organic material into primarily heat, carbon dioxide, and water (Major, 2019).	• A laboratory study was performed. GAC was found to be the best fuel surrogate and produced temperatures greater than 900 ºC when mixed with sand or a surrogate soil mixture between 40 and 60 g/kg soil. The successful treatment of PFAS by smoldering was demonstrated (Major, 2019). • In laboratory tests, prior to smoldering, the calculated concentration in the GAC/sand mixture for PFOA, PFOS, and PFHxS ranged from 140 to 590 mg/kg. After smoldering all compounds were non-detect at a detection limit of 0.4 µg/kg (Major, 2019).	• Mixing of the fuel (GAC) required in soil. In situ mixing of fuel may be difficult and may result in non-uniform combustion. • A uniform smoldering front needs to be maintained to destroy chemicals. • Incomplete combustion byproducts can be created.	Major, D. (2019). Demonstration of Smoldering Combustion Treatment of PFAS-impacted Investigation-Derived Waste. SERDP Project ER18-1593. https://www.serdp-estcp.org/content/download/48955/466822/file/ER18-1593%20Final%20Report.pdf
Solar Ponding	Using solar energy to concentrate the volume of liquid wastewater.	• The photodegradation process of PFOA/PFOS is an attractive technology due to its operational simplicity and the potential to directly utilize the inexhaustible solar energy (Lyu et al., 2015a). • A laboratory study was performed on ultraviolet photodecomposition of PFOA in water found that photodecomposition was enhanced with utilization of vacuum ultraviolet (185 nm). The presence of abundant dissolved oxygen in solution was detrimental for PFOA mineralization. Mineralization of PFOA was enhanced more at pH 3 than at higher pH values. Higher concentrations of organic constituents and bicarbonates in water led to a decrease in PFOA photo-mineralization (Giri et al., 2011). • A laboratory study on ultraviolet (medium pressure lamp) photodegradation of PFOS in catalyst-free aqueous solution. Under appropriate pH (11.8) and temperature conditions (100 ºC), PFOS degradation was reported at a rate constant of 0.91 hr^{-1} (Lyu et al., 2015a). Photodegradation of PFOS was significantly enhanced under boiling conditions. The defluorination	• No information on pilot- or full-scale solar ponding studies found. Only bench-scale laboratory studies on PFOA/PFOS photodegradation found during a literature search. • According to the detection limit of the products and typical solar radiation at the surface of the ocean, photochemical half-life for PFOA was estimated to be at least 256 years at the depth of 0 m, >5000 years in the mixing layer of open ocean and >25,000 years in coastal ocean (Vaalgamaa et al., 2011). • Direct photolysis of PFOA does not occur under natural solar radiation due to the lack of overlap in the absorption spectrum of PFOA and solar radiation. • PFCAs and PFSAs have shown to be very persistent in the environment, there is no solid evidence that these compounds degrade photolytically under natural light conditions. There are references present that show that PFOS, PFOA and PFDA can degrade in the laboratory under circumstances in the ultraviolet-C range (Tang et al., 2015). The adsorption is weak up to 220 nm and even lower from 220 to 600 nm (Arcadis, 2016).	Arcadis. (2016). Environmental fate and effects of poly and perfluoroalkyl substances (PFAS). June. https://www.Arcadis.eu/wp-content/uploads/2016/06/Rpt_16-8.pdf Giri, R.R. (2011). Factors Influencing UV Photodecomposition of Perfluorooctanoic Acid in Water. *Chemical Engineering Journal*, 180 197-203. Jin, L., P. Zhang, T. Shao, and S. Zhao. (2014). Ferric Ion Mediated Photodecomposition of Aqueous Perfluorooctane Sulfonate (PFOS) Under UV Irradiation and its Mechanism. *Journal of Hazardous Materials*, 271: 9-15. Lyu, X., W. Li, P.K.S. Lam, and H.Q. Yul. (2015a). Insights into Perfluorooctane Sulfonate Photodegradation in a Catalyst-Free Aqueous Solution. *Scientific Reports*, 5: 9353. Lyu, X.J., W.W. Li, P.K. Lam, and H.Q. Yu. (2015b). Boiling Significantly Promotes Photodegradation of Perfluorooctane Sulfonate. Chemosphere, 138 (2015) 324-327. Taniyasu, S., N. Yamashita, E. Yamazaki, G. Petrick, and K. Kannan. (2013). The Environmental Photolysis of Perfluorooctanesulfonate,

Table A-2. Innovative PFAS Liquid Treatment Technologies Demonstrated at the Bench-Scale

Technology	Description	Advantages	Limitations	Source
		ratios were 0.79 to 0.97 and the desulfonation ratios were 0.80 to 0.93 (Lyu et al., 2015b). • A laboratory study was performed with reaction solutions containing purified water, fulvic acid (representing dissolved organic matter), nitrate, ferric iron or sea water from the Baltic Sea spiked with PFOA and irradiated with an artificial sun (290–800 nm). The samples irradiated with an artificial sun contained no decomposition products and no decrease in PFOA concentration was observed. In comparison similar samples were also irradiated under ultraviolet radiation at 254 nm in order to study the direct photolysis. Ultraviolet radiation at 254 nm decomposed PFOA to perfluoroheptanoic-, perfluorohexanoic- and perfluoropentanoic acids (Vaalgamma et al., 2011). • The lab test was carried out in Mt. Mauna Kea at an altitude of 4,200 m, for 106 days. Strong solar radiation coupled with better air quality at this high altitude offered favorable environmental conditions for photodegradation of PFAS. It is worth noting that long-chain PFAS degraded at higher proportions than shorter-chain PFSAs and PFCAs (Taniyasu et al., 2013). • Adding $FeCl_3$ increases the applicable absorption region (Jin et al., 2014). In this research, PFOS concentrations decreased below the detection limit within 48 hours. A reaction mechanism was proposed, with intermediates of mainly C2-C8 PFCAs. After 72 hours, 74% of the fluorine could be accounted for, with 58% as free fluoride (Arcadis, 2016).		Perfluorooctanoate, and Related Fluorochemicals. *Chemosphere*, 90 1686-1692. Vaalgamaa, S., A.V. Vähätalo, N. Perkola, and S. Huhtala S. (2011). Photochemical Reactivity of Perfluorooctanoic Acid (PFOA) in Conditions Representing Surface Water. *Science of the Total Environment*, 409 3043-3048.