# Best Available Technologies and Small System Compliance Technologies for Per- and Polyfluoroalkyl Substances (PFAS) in Drinking Water

**Best Available Technologies and Small System Compliance Technologies for Per- and Polyfluoroalkyl Substances (PFAS) in Drinking Water**

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EPA Document Number: 815R24011

March 2024

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# Acronyms and Abbreviations

| | |
|---|---|
| ANSI | American National Standards Institute |
| BAT | best available technology |
| EBCT | empty bed contact time |
| EPA | Environmental Protection Agency |
| GAC | granular activated carbon |
| IX | ion exchange |
| MCL | maximum contaminant level |
| MHI | median household income |
| MGD | million gallons per day |
| mg/L | milligrams per liter |
| NF | nanofiltration |
| ng/L | nanograms per liter |
| NSF | NSF International, The Public Health and Safety Company[1] |
| O&M | operating and maintenance |
| PFAS | per- and polyfluoroalkyl substances |
| POU | point-of-use |
| RCRA | Resource Conservation and Recovery Act |
| RO | reverse osmosis |
| RSSCT | rapid small-scale column test |
| SDWA | Safe Drinking Water Act |
| SSCT | small system compliance technology |
| TOC | total organic carbon |
| WBS | Work Breakdown Structure |

See also Table 2 for abbreviations for individual PFAS compounds.

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[1] Formerly National Sanitation Foundation

# 1.0 Introduction

The U.S. Environmental Protection Agency (EPA) finalized a regulation for certain per- and polyfluoroalkyl substances (PFAS) under the Safe Drinking Water Act (SDWA). This document addresses treatment technologies that drinking water systems could use to meet the requirements of the regulation. Specifically, it provides an evaluation of several technologies against predefined criteria to determine whether they might be considered best available technologies (BATs). In addition, it provides an evaluation of technologies for small systems against criteria to determine whether they can be designated small system compliance technologies (SSCT).

The three technologies included in the BAT evaluation are: granular activated carbon (GAC), PFAS-selective ion exchange (IX), and reverse osmosis (RO) or nanofiltration (NF). Table 1 provides a list of the six major criteria considered for the BAT evaluation, along with specific evaluation questions. Sections 2.0 through 4.0 provide a discussion of the extent to which each technology meets the BAT criteria. Section 5.0 provides a summary of the BAT evaluation results. The detailed discussion is based primarily on literature search information and technical analysis conducted during development of the document, *Technologies and Costs for Removing Per- and Polyfluoroalkyl Substances from Drinking Water* (USEPA, 2024a). That document contains a more complete description of each technology and the state of science regarding their use for PFAS treatment.

The SDWA, as amended in 1996, requires that EPA list technologies for small systems [Section 1412(b)(4)(E)(ii)]:

> The Administrator shall include in the list any technology, treatment technique, or other means that is affordable, as determined by the Administrator in consultation with the States, for small public water systems serving -
>> (I) a population of 10,000 or fewer but more than 3,300;
>> (II) a population of 3,300 or fewer but more than 500; and
>> (III) a population of 500 or fewer but more than 25;
> and that achieves compliance with the maximum contaminant level (MCL) or treatment technique, including packaged or modular systems and point-of-entry or point-of-use treatment units (POU).

Section 6.0 of this document provides EPA's analysis to identify SSCTs for the rule. Specifically, it evaluates the three technologies against the affordability and compliance effectiveness criteria for SSCTs. It also presents preliminary results on the affordability of POU devices. POU devices are not currently listed as a compliance option because the rule requires treatment to concentrations below the current NSF International[2]/American National Standards Institute (NSF/ANSI) certification standard for POU device removal of PFAS. However, POU treatments are reasonably anticipated to become a compliance option for small systems in the future if NSF/ANSI develop a new certification standard that mirrors *or is more stringent* than the regulatory standard. As of the writing of this document, NSF/ANSI is considering lowering its current standard to the regulatory standard.  Based on efficacy of reverse osmosis technology, RO POU devices can be reasonably anticipated to remove the majority of PFAS when they are

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[2] Formerly National Sanitation Foundation

properly designed and maintained.  Other POU devices (e.g., activated carbon) may also meet EPA PFAS regulatory limits. These devices would also need third-party testing and certification against the regulatory limits.

EPA's affordability criterion uses an affordability threshold of 2.5 percent of the median household income (MHI) of the median water system (as ranked by MHI) in each small system size category (i.e., systems serving populations of (1) 25 – 500; (2) 501 – 3,300; and (3) 3,301 – 10,000 people). As long as the sum of baseline expenditures on water (i.e., current costs excluding PFAS treatment costs) and the incremental expenditures associated with a particular PFAS treatment technology do not exceed 2.5 percent of MHI, then that technology meets the affordability criterion.

## Table 1. BAT Criteria for PFAS Technologies Evaluation

| CRITERION |
| --- |
| **1. High Removal Efficiency** |
| 1.1. Have high removal efficiencies that achieve potential MCLs been documented? <br> 1.2. Are the effects of water quality parameters on treatment effectiveness and reliability well-known? <br> 1.3. Is the technology reliable enough to continuously meet a drinking water MCL? <br> 1.4. Is additional research needed? |
| **2. History of Full-Scale Operation** |
| 2.1. Do existing studies include full-scale operations at drinking water treatment facilities? <br> 2.2. Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options? <br> 2.3. Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling? <br> 2.4. Is additional research needed? |
| **3. General Geographic Applicability** |
| 3.1. What regions do the existing research studies represent? <br> 3.2. Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas? <br> 3.3. Are there any regional issues with respect to residuals handling or water resource use? <br> 3.4. Is additional research needed? |
| **4. Compatibility with Other Treatment Processes** |
| 4.1. Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated? <br> 4.2. Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train? <br> 4.3. Is additional research needed? |
| **5. Ability to Bring All of the Water System into Compliance** |
| 5.1. Will the treatment process adversely affect the distribution system or water resource decisions? <br> 5.2. Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns? <br> 5.3. Is additional research needed? |
| **6. Reasonable Cost Basis for Large and Medium Systems** |
| 6.1. Is the technology currently used by medium and large systems (including uses for other treatment purposes)? <br> 6.2. Do the treatment studies provide sufficient information on design assumptions to allow cost modeling? <br> 6.3. Is additional research needed? |

## 1.1  PFAS Background

Per- and polyfluoroalkyl substances (PFAS) are a broad class of approximately 10,000 synthetic chemicals (Rogers et al., 2021; Weaver, 2020; USEPA, 2021d). As a result of their water-resistant, stain-resistant, and non-stick properties, they are incorporated in or used as coatings for many products. Household and industrial PFAS applications include use in carpeting, clothing, cookware, cosmetics, electronics, fire-fighting foam, glass, and packaging. The manufacture of PFAS and PFAS-containing products, along with the use and disposal of these products, have resulted in releases to air, soil, and water (ATSDR, 2021; Rogers et al., 2021; Weaver, 2020). The same properties that make PFAS useful in industry and commerce also make them stable and persistent in the environment (ATSDR, 2021).

Table 2 lists PFAS for which treatability data are available in the literature included in EPA's Drinking Water Treatability Database (USEPA, 2021a; 2021b; 2021c). The two most frequently studied PFAS are PFOA, which refers to perfluorooctanoic acid or perfluorooctane carboxylate, and PFOS, which refers to perfluorooctane sulfonic acid or perfluorooctane sulfonate.[3] Figure 1 shows the chemical structure of these two PFAS. Both molecules incorporate a chain of fully fluorinated (perfluorinated) carbon atoms but differ in the functional group attached at the end of the chain. In PFOA, the terminal functional group is carboxylic acid ($CO_2H$) or carboxylate ($CO_2^-$) in the anionic form. In PFOS, the terminal functional group is sulfonic acid ($SO_3H$) or sulfonate ($SO_3^-$) in the anionic form.

Both PFOA and PFOS include a total of eight carbon atoms in their molecular chain. Other perfluorinated PFAS incorporate the same terminal functional groups but have a different number of carbon atoms in the chain. For example, PFHxA refers to a perfluorinated six-carbon compound with a carboxylic acid or carboxylate functional group. PFHxS refers to a perfluorinated six-carbon compound with a sulfonic acid or sulfonate functional group. In general, degree of fluorination, functional group, and chain length provide a means of classifying PFAS compounds, as shown in Table 3. Buck et al. (2011) and ITRC (2020) provide a more detailed and nuanced categorization of PFAS, but for purposes of discussing treatment technologies and costs this simplified categorization is useful.

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[3] Although different sources within the literature may use the names for the acid and anion forms of PFOA, PFOS, and other perfluorinated PFAS interchangeably, they most frequently occur in the environment in their anion form (ITRC, 2020).

**Table 2. PFAS with Treatability Data**

| Abbreviation | Full Name | Chemical Abstract Service (CAS) Number |
|---|---|---|
| ADONA | Ammonium 4,8-dioxa-3H-perfluorononanoate | 958445-44-8 or 919005-14-4 (as acid) |
| F-53B | A combination of 9-chlorohexadecafluoro-3-oxanone-1-sulfonic acid and 11-chloroeicosafluoro-3-oxaundecane-1-sulfonic acid | 756426-58-1 and 763051-92-9 (respectively) |
| FtS 4:2 | Fluorotelomer sulfonate 4:2 | 414911-30-1 |
| FtS 6:2 | Fluorotelomer sulfonate 6:2 | 27619-97-2 |
| FtS 8:2 | Fluorotelomer sulfonate 8:2 | 39108-34-4 |
| HFPO-DA[*] | Ammonium perfluoro-2-methyl-3-oxahexanoate, Perfluoro(2-methyl-3-oxahexanoic) acid | 62037-80-3 (as ammonium salt), 13252-13-6 (as acid) |
| Nafion BP2 | Perfluoro-2-{[perfluoro-3-(perfluoroethoxy)-2-propanyl]oxy}ethanesulfonic acid | 749836-20-2 |
| N-EtFOSAA | 2-(N-Ethyl-perfluorooctanesulfonamido)acetate | 2991-50-6 |
| N-MeFOSAA | 2-(N-Methylperfluorooctanesulfonamido)acetate | 909405-48-7 or 2355-31-9 (as acid) |
| PFBA | Perfluorobutanoic acid | 375-22-4 |
| PFBS | Perfluorobutyl sulfonic acid | 375-73-5 |
| PFBSA | Perfluorobutylsulfonamide | 30334-69-1 |
| PFDA | Perfluorodecanoic acid | 335-76-2 |
| PFDoA | Perfluorododecanoic acid | 307-55-1 |
| PFDS | Perfluorodecyl sulfonic acid | 335-77-3 |
| PFECHS | Perfluoro-4-(perfluoroethyl)cyclohexylsulfonate | 80988-54-1 |
| PFHpA | Perfluoroheptanoic acid | 375-85-9 |
| PFHpS | Perfluoroheptyl sulfonic acid | 375-92-8 |
| PFHxA | Perfluorohexanoic acid | 307-24-4 |
| PFHxS | Perfluorohexyl sulfonic acid | 355-46-4 |
| PFHxSA | Perfluorohexanesulfonamide | 41997-13-1 |
| PFMOAA | Difluoro(perfluoromethoxy)acetic acid, also known as perfluoro-2-methoxyacetic acid | 674-13-5 |
| PFMOBA | Perfluoro-4-methoxybutanoic acid | 863090-89-5 |
| PFMOPrA | Perfluoro-3-methoxypropanoic acid | 377-73-1 |
| PFNA | Perfluorononanoic acid | 375-95-1 |
| PFNS | Perfluorononane sulfonic acid | 68259-12-1 |
| PFO2HxA | Perfluoro-3,5-dioxahexanoic acid | 39492-88-1 |
| PFO3OA | Perfluoro-3,5,7-trioxaoctanoic acid | 39492-89-2 |
| PFO4DA | Perfluoro-3,5,7,9-butaoxadecanoic acid | 39492-90-5 |
| PFOA | Perfluorooctanoic acid | 335-67-1 |
| PFOS | Perfluorooctane sulfonic acid | 1763-23-1 |
| PFOSA | Perfluorooctanesulfonamide | 754-91-6 |
| PFPeA | Perfluoropentanoic acid | 2706-90-3 |
| PFPrS | Perfluoropropane sulfonate | 110676-15-8 |
| PFTriA | Perfluorotridecanoic acid | 72629-94-8 |
| PFUnA | Perfluoroundecanoic acid | 2058-94-8 |

[*] HFPO-DA is used in a processing aid technology developed by DuPont to make fluoropolymers without using PFOA. The chemicals associated with this process are commonly known as GenX Chemicals and the term is often used interchangeably for HFPO-DA along with its ammonium salt.
Sources: USEPA, 2021a; 2021b; 2021c
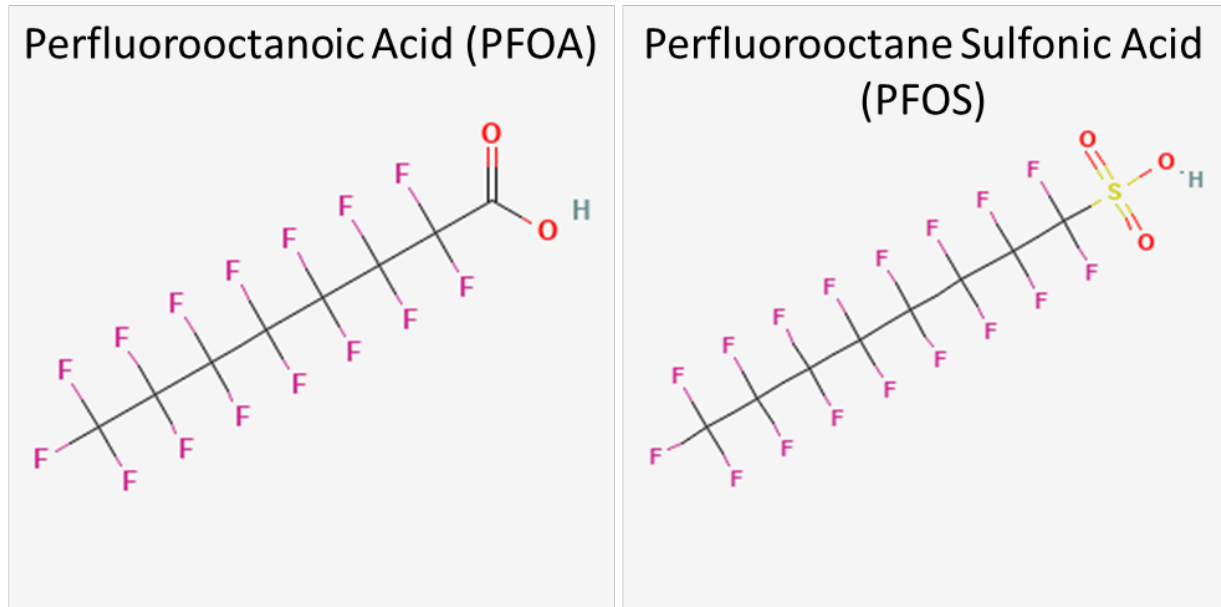


**Figure 1. Chemical Structure of PFOA and PFOS**

Sources: NCBI, 2021a; 2021b

## Table 3. PFAS Classified by Functional Group and Chain Length

| Number of Carbons | Perfluorinated Carboxylic Acids/Carboxylates | Perfluorinated Sulfonic Acids/Sulfonates | Other Perfluorinated | Polyfluorinated |
|---|---|---|---|---|
| 3 | | PFPrS | | PFMOAA |
| 4 | PFBA | PFBS | PFBSA | FtS 4:2, PFO2HxA, PFMOPrA |
| 5 | PFPeA | PFPeS | | PFO3OA, PFMOBA |
| 6 | PFHxA | PFHxS | HFPO-DA, PFHxSA | FtS 6:2, PFO4DA |
| 7 | PFHpA | PFHpS | | ADONA, Nafion BP2 |
| 8 | PFOA | PFOS | PFOSA, PFECHS | FtS 8:2, 9Cl-PF3ONS |
| 9 | PFNA | PFNS | | |
| 10 | PFDA | PFDS | | 11Cl-PF3OUdS |
| 11 | PFUnA | PFUnS | | N-MeFOSAA |

| Number of Carbons | Perfluorinated Carboxylic Acids/Carboxylates | Perfluorinated Sulfonic Acids/Sulfonates | Other Perfluorinated | Polyfluorinated |
|---|---|---|---|---|
| 12 | PFDoA | PFDoS | | N-EtFOSAA |
| 13 | PFTriA | PFTriS | | |

Sources: ITRC, 2020; USEPA, 2021a; 2021b; 2021c

# 2.0 Best Available Technology Evaluation for GAC

GAC is a porous adsorptive media with extremely high internal surface area. GAC is manufactured from a variety of raw materials with porous structures including bituminous coal, lignite coal, peat, wood, coconut shells, and others. Physical and/or chemical manufacturing processes are applied to these raw materials to create and/or enlarge pores, resulting in a porous structure with a large surface area per unit mass.

When water is treated with GAC, it passes through treatment columns or beds containing GAC. The process separates dissolved contaminants from the water through adsorption to the surfaces in the pores of the GAC. In the case of PFAS, the literature suggests that the primary mechanisms of adsorption include both hydrophobic and electrostatic interactions (Ateia et al., 2019). In addition to removing PFAS, GAC can remove contaminants including taste and odor compounds, natural organic matter, volatile organic compounds, synthetic organic compounds, disinfection byproduct precursors, and radon. Organic compounds with high molecular weights are also readily adsorbable.

The contaminants are adsorbed by GAC until the carbon is no longer able to adsorb additional molecules at the influent feed concentration. At this point, the result is reduced removal of the contaminant, referred to as "breakthrough." Figure 2 is a conceptual diagram of the GAC treatment process, from initial adsorption to breakthrough. Once the contaminant concentration in the treated water reaches an unacceptable level, the carbon is considered "spent" and must be replaced by virgin or reactivated GAC. The length of time between GAC replacement events is known as "bed life" and is often quantified in "bed volumes," which are a measure of throughput. Reactivation[4] is a process that removes organic compounds from adsorption sites on GAC so that it can be reused. Although different methods are available for GAC reactivation, the process most commonly involves high temperature thermal treatment in a specialized facility such as a multiple hearth furnace or rotary kiln (Matthis and Carr, 2018; USEPA, 2022b).

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[4] The terms "reactivation" and "regeneration" are sometimes used interchangeably in the drinking water industry. GAC vendors, however, make a distinction between the two processes. The appropriate term for the process used on spent GAC containing adsorbed PFAS is reactivation (Matthis and Carr, 2018).
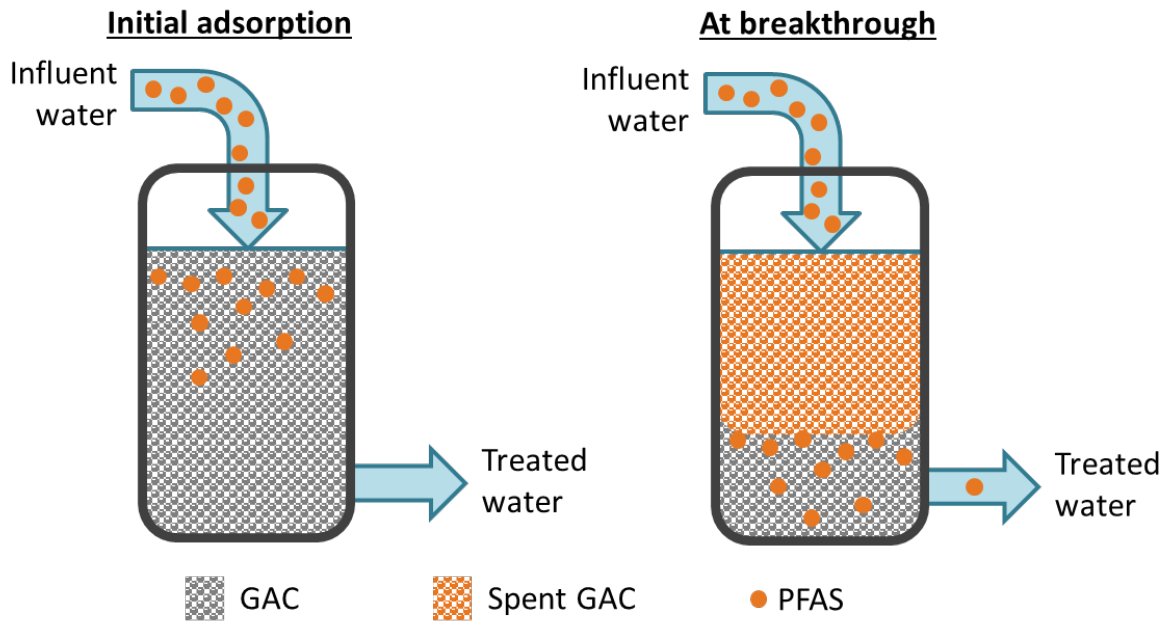
**Figure 2. Conceptual Diagram of the GAC Treatment Process**

## 2.1  High Removal Efficiency

### 2.1.1  *Have high removal efficiencies that achieve potential MCLs been documented?*

Yes. EPA's Drinking Water Treatability Database (USEPA, 2021a; 2021b; 2021c) includes extensive data from the literature on PFAS removal by GAC. Results are available from studies conducted in the laboratory, in the field at pilot scale, and in full-scale application, as shown in Table 4, Table 5, and Table 6. The literature demonstrates PFAS removal efficiencies for many PFAS compounds in the high 90 percent range and to levels below analytical detection limits. For PFOA and PFOS, maximum removal efficiencies are greater than 99 percent, also to below analytical detection limits[5] and lower than the regulatory thresholds currently under consideration.

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[5] The analytical detection limit is the lowest amount of a substance whose presence or absence can be determined; this is strictly lower than the quantification limit which is the lowest concentration that can be determined with acceptable precision and accuracy. These are also different than the minimum reporting limit which is a combination minimum quantification limits from different EPA validated laboratories.

**Table 4. Studies of GAC Treatment for Carboxylate PFAS**

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum Removal Efficiency | Source(s) for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|
| PFBA | 4 | 8 | 5 | 5 | 99.5 | Westreich et al. 2018 |
| PFPeA | 5 | 7 | 5 | 5 | 90 | Appleman et al. 2013; McCleaf et al. 2017; Park et al. 2017; Lombardo et al. 2018; Kempisty et al. 2019; Liu et al. 2019; Park et al. 2020 |
| PFHxA | 6 | 12 | 6 | 6 | 99.5 | Westreich et al. 2019 |
| PFHpA | 7 | 9 | 5 | 7 | >99 | Zeng et al 2020 |
| PFOA | 8 | 23 | 9 | 17 | >99.8 | Forrester and Bostardi 2019 |
| PFNA | 9 | 6 | 3 | 8 | >99 | Zeng et al 2020 |
| PFDA | 10 | 6 | 1 | 4 | 97 | Appleman et al. 2013 |
| PFUnA | 11 | 1 | 0 | 1 | 90 | McCleaf et al. 2017 |
| PFDoA | 12 | 3 | 0 | 0 | 90 | McCleaf et al. 2017; Park et al. 2017 |
| PFTriA | 13 | 1 | 0 | 0 | 90 | McCleaf et al. 2017 |

Sources: USEPA, 2021a; 2021c

**Table 5. Studies of GAC Treatment for Sulfonate PFAS**

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum Removal Efficiency | Source for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|
| PFPrS | 3 | 0 | 1 | 0 | 90 | Liu et al. 2019 |
| PFBS | 4 | 13 | 7 | 8 | 99.5 | Westreich et al. 2018 |
| PFPeS | 5 | 2 | 2 | 0 | 90 | Liu et al. 2019 |
| PFHxS | 6 | 13 | 7 | 11 | 99.5 | Westreich et al. 2018 |
| PFHpS | 7 | 2 | 4 | 1 | >99 | Belkouteb et al. 2020 |
| PFOS | 8 | 24 | 10 | 15 | 99.7 | Woodard et al. 2017 |
| PFNS | 9 | 1 | 0 | 0 | 95.82 | Wang et al. 2020 |

Sources: USEPA, 2021b; 2021c

**Table 6. Studies of GAC Treatment for Other PFAS**

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum Removal Efficiency | Source for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|
| PFMOAA | 3 | 0 | 0 | 1 | 70 | Hopkins et al. 2018 |
| FtS 4:2 | 4 | 0 | 1 | 0 | Not reported | |
| PFBSA | 4 | 1 | 0 | 0 | 56 | Yan et al. 2020 |
| PFO2HxA | 4 | 0 | 0 | 1 | 90 | Hopkins et al. 2018 |
| PFO3OA | 5 | 0 | 0 | 1 | 90 | Hopkins et al. 2018 |
| FtS 6:2 | 6 | 1 | 3 | 0 | 88 | Casey et al. 2018 |
| HFPO-DA | 6 | 1 | 1 | 1 | 93 | Hopkins et al. 2018 |
| PFHxSA | 6 | 1 | 1 | 0 | 80 | Rodowa et al. 2020 |
| PFO4DA | 6 | 0 | 0 | 1 | 90 | Hopkins et al. 2018 |
| Nafion BP2 | 7 | 0 | 1 | 1 | >99 | Hopkins et al. 2018 |
| FtS 8:2 | 8 | 1 | 3 | 0 | 88 | Woodard et al. 2017 |
| PFOSA | 8 | 3 | 1 | 0 | 95 | Kothawala et al. 2017 |
| PFECHS | 8 | 1 | 0 | 0 | 65 | Yan et al. 2020 |

Source: USEPA, 2021c

## 2.1.2 Are the effects of water quality parameters on treatment effectiveness and reliability well-known?

Yes. Natural organic matter, often measured as dissolved organic carbon or total organic carbon (TOC), can interfere with GAC's capacity to adsorb PFAS (Appleman et al., 2013; Ateia et al., 2019; Berretta et al., 2021; Gagliano et al., 2020; Kothawala et al., 2017). The significance of this interference may depend on the specific type of natural organic matter present (Gagliano et al., 2020; Kothawala et al., 2017). However, in general, it does not necessarily reduce the maximum removal effectiveness of GAC. Instead, it shortens the time to breakthrough, meaning more frequent GAC replacement can be required at higher TOC concentrations, all other factors being equal. Therefore, it should be possible to reliably manage the impact of natural organic matter through piloting, selection of design parameters, and operational monitoring.

## 2.1.3 Is the technology reliable enough to continuously meet a drinking water MCL?

Yes. Numerous full-scale drinking water facilities are using GAC to meet current state drinking water requirements for PFAS (see Question 2.2.1, below). In general, GAC is an established, reliable technology that has been used successfully to meet other MCLs.

## 2.1.4   Is additional research needed?

No. Additional research is not required.

## 2.2 History of Full-Scale Operation

## 2.2.1   Do existing studies include full-scale operations at drinking water treatment facilities?

Yes. As indicated under Question 2.1.1, there are numerous studies of GAC performance for PFAS removal at full-scale facilities. These effectiveness studies include results for GAC facilities designed specifically to target PFAS, in addition to facilities originally designed for other contaminants. In total, the literature identifies 34 full-scale GAC facilities removing PFAS from drinking water, as listed in Table 7.

**Table 7. Full-scale GAC Systems Removing PFAS from Drinking Water**

| Location | Flow rate (MGD) | Groundwater or Surface Water | Year of Startup | Sources |
|---|---|---|---|---|
| Moose Creek, Fairbanks North Star Borough, Alaska | 2.2 | Groundwater | 2016 | Alaska Community Action on Toxics 2019; Forrester 2019 |
| Gustavus, Alaska | Not reported | Groundwater | 2018-2019 | Alaska Community Action on Toxics 2019 |
| Airline/Lambert Water Treatment Campus, Marana, Pima County, Arizona | Not reported | Groundwater | Not reported | Marana Water 2019 |
| Picture Rocks Water Treatment Campus, Marana, Pima County, Arizona | Not reported | Groundwater | Not reported | Marana Water 2019 |
| Municipal Services Commission of the City of New Castle, New Castle, Delaware | 0.50 | Groundwater | 2015 | Mordock 2016; Forrester 2019 |
| Emerald Coast Utilities Authority, Pensacola, Escambia County, Florida | 1.44 | Groundwater | 2017 | Robinson 2018; Forrester 2019 |
| Kennebunk, Kennebunkport & Wells Water District, Kennebunk, Maine | 2.90 | Groundwater | 2020 | Berretta et al. 2021; Business Wire 2018 |
| Mary Dunn Water Supply Wells, Hyannis & Town of Barnstable, Massachusetts | 1.44 | Groundwater | 2015 | Gallagher 2017; Forrester 2019 |
| City of Westfield Department of Public Works, Westfield, Massachusetts | Not reported | Groundwater | 2018 | Westfield 2019 |
| Plainfield Township, Kent County, Michigan | 9 | Groundwater | 2018 | Biolchini 2018 |
| Ann Arbor Water Treatment Plant, Ann Arbor, Michigan | 50 | Surface Water | 2018 | Stanton 2019; Page 2020 |
| Oakdale Public Works, Oakdale, Minnesota | 3.6 | Groundwater | 2006 | MDH 2010; ATSDR 2008 |

| Location | Flow rate (MGD) | Groundwater or Surface Water | Year of Startup | Sources |
|---|---|---|---|---|
| Merrimack Village District Water Works, Merrimack, Hillsborough County, New Hampshire | Not reported | Groundwater | 2020 | Cronin 2020 |
| Pease International Tradeport Drinking Water System, Portsmouth, New Hampshire | 0.72 | Groundwater | 2019 | City of Portsmouth 2020; Forrester 2019 |
| Town of Petersburgh Water District, Petersburgh/Rensselaer County, New York | 0.07 | Not reported | 2017 | Forrester 2019; NYS DEC 2020a |
| Hampton Bays Water District, Suffolk County, New York | 9 | Groundwater | 2018 | Gordon 2018 |
| Wright-Patterson Air Force Base, Dayton, Ohio | 2.74 | Groundwater | 2017 | Barber 2017; Forrester 2019 |
| Horsham Water and Sewer Authority, Horsham, Montgomery County, Pennsylvania | 1.44 | Groundwater | 2017 | Boodoo et al. 2019; Montgomery News 2017; Forrester 2019 |
| Village of Hoosick Falls, New York | 1.01 | Groundwater | Not reported | Forrester 2019; NYS DEC 2021 |
| City of El Campo Water Department, El Campo, Texas | Not reported | Groundwater | 2017 | Sullivan 2018 |
| Issaquah, Washington | 4.32 | Groundwater | 2016 | Issaquah 2020; Mende 2019; Kwan and York 2017 |
| Airway Heights Water System, City of Airway Heights, Washington | Not reported | Groundwater | 2018 | ATSDR 2020 |
| Joint Base Lewis-McChord, Washington | Not reported | Groundwater | Not reported | Sullivan 2018 |
| Little Hocking Water Association, Little Hocking, Ohio | Not reported | Groundwater | 2007 | Cummings et al 2015 |
| Former Naval Air Station, Brunswick, Maine | Not reported | Not reported | 2011 | Danko 2018 |
| Washington Lake Filtration Plant, Newburgh, New York | 8.86 | Groundwater | 2017 | Forrester 2019; NYS DEC 2020b |
| Liberty Utilities, Litchfield Park, Arizona | 1.58 | Groundwater | 2017 | ADEQ 2021; Forrester 2019 |
| Passaic Valley Water Commission, Garfield, New Jersey | 0.5 | Groundwater | Not reported | Forrester 2019; Sobko 2021 |
| Aqua Pennsylvania, Chalfont Borough, Pennsylvania | 0.58 | Groundwater | Not reported | Forrester 2019; Chalfont Borough 2021 |
| Montclair Water Bureau, Montclair, New Jersey | 0.72 | Groundwater | Not reported | Forrester 2019; PFAS Project Lab 2021 |
| Warrington Township Water and Sewer Department, Warrington, Pennsylvania | 0.58 | Groundwater | Not reported | Forrester 2019; Warrington Township 2017 |

| Location | Flow rate (MGD) | Groundwater or Surface Water | Year of Startup | Sources |
|---|---|---|---|---|
| Rome Water and Sewer Division, Rome, Georgia | 9 | Groundwater | Not reported | Forrester 2019; City of Rome 2019 |
| Sweeny Water Treatment Plant, Cape Fear Public Utilities Authority, North Carolina | 44 | Surface Water | 2022 | Vandermeyden and Hagerty 2020 |
| Parkersburg Utility Board, Parkersburg, West Virginia | Not reported | Not reported | Not reported | USEPA 2009 |

MGD = million gallons per day

## 2.2.2 Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options?

The most likely management option for spent GAC containing adsorbed PFAS is reactivation. There are a number GAC vendor-operated reactivation facilities available, including some that hold Resource Conservation and Recovery Act (RCRA) permits to treat spent GAC that is classified as hazardous waste (USEPA, 2020; Matthis and Carr, 2021). Matthis and Carr (2021) report results from leaching tests on GAC used to remove PFAS from drinking water at full-scale after reactivation, also in a full-scale facility. They found that 15 of the 16 PFAS compounds analyzed were below analytical limits in the leachate. PFBA was present, but only at 1.9 parts per trillion. These results suggest that reactivated GAC should be suitable for reuse.

The full-scale study in Mathis and Carr (2021), however, did not fully address the fate of PFAS in the GAC reactivation process. There are a limited number of smaller scale studies that examine whether PFAS compounds are transformed, volatilized, or destroyed/defluorinated during the process (e.g., Watanabe et al., 2016; Watanabe et al., 2018; Xiao, 2020). These studies suggest that the fate of PFAS in GAC reactivation depends on factors including PFAS chain length, reactivation temperature, and combustion atmosphere (Baghirzade et al., 2021). DiStefano et al., (2022) showed >99.99 percent destruction of PFAS at a full-scale commercial reactivation facility with a large percentage of the PFAS destruction occurring in the furnace. The fluoride mass balance was reported to be 61.4 percent. In the future, additional full-scale research might be needed to better understand and manage PFAS air emissions from GAC reactivation facilities. The results of this research might necessitate changes to spent GAC management practices. Approximately 10-30 percent of GAC may be lost during the reactivation process and new GAC must be added to replace the lost GAC. There are also circumstances when reactivating spent GAC may not make economic sense. In these circumstances, GAC may be disposed of after use, such as in a landfill, and then replaced with completely new GAC. Future RCRA hazardous waste regulations could also limit the available management options.

## 2.2.3 Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling?

For PFAS removal, there is no consensus in the literature regarding methods to scale up GAC from bench-scale tests, specifically rapid small-scale column tests (RSSCTs), to full-scale (Hopkins, 2021; Kempisty et al., 2019; Meng et al., 2021; Redding et al., 2019). However, as a mature and established technology, the scale-up of GAC from pilot- to full-scale is well understood and has been implemented at full-scale facilities treating PFAS (e.g., Vandermeyden and Hagerty, 2019).

## 2.2.4 Is additional research needed?

In general, additional research is not required. However, in the future, additional full-scale research might be needed to better understand and manage PFAS air emissions from GAC reactivation facilities.

## 2.3 General Geographic Applicability

## 2.3.1 What regions do the existing research studies represent?

EPA's Drinking Water Treatability Database (USEPA, 2021a; 2021b; 2021c) includes effectiveness data for PFAS removal by GAC in waters from 12 geographically dispersed U.S. states (Arizona, Colorado, Illinois, Maine, Michigan, Minnesota, New Hampshire, New Jersey, North Carolina, Ohio, Pennsylvania, Washington, and West Virginia), as well as from countries overseas. The full-scale facilities listed under Question 2.2.1 are distributed across the U.S. from Alaska to Florida and Maine to Arizona.

## 2.3.2 Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas?

No. Although there may be regional variations in natural organic matter, these variations are likely to be less significant than variation among individual water sources within a region. Furthermore, as discussed under Question 2.1.2, it should be possible to reliably manage the impact of water quality variations through piloting, design parameter selection, and operational monitoring.

## 2.3.3 Are there any regional issues with respect to residuals handling or water resource use?

Under current state regulations, there no known regional barriers with respect to spent GAC reactivation or disposal.

## 2.3.4 Is additional research needed?

No. Additional research is not required.

## 2.4  Compatibility with Other Treatment Processes

### 2.4.1  Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated?

Yes. GAC can have a beneficial effect by removing natural organic matter (see Question 2.1.2) and trace contaminants other than PFAS (e.g., volatile organic compounds) from treated water. Removal of natural organic matter (as measured by total organic carbon) results in meaningful co-benefits, including reducing disinfection byproduct formation. In general, GAC does not have significant negative effects on other treatment processes.

### 2.4.2  Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train?

No. In general, GAC integrates easily with traditional treatment trains.

### 2.4.3  Is additional research needed?

No. Additional research is not required.

## 2.5  Ability to Bring All of the Water System into Compliance

### 2.5.1  Will the treatment process adversely affect the distribution system or water resource decisions?

No. Although there can in some cases be temporary water chemistry changes immediately following GAC changeout, these effects are readily managed by diverting the first few bed volumes of treated water to waste. In general, GAC does not have adverse distribution system or water resource effects.

### 2.5.2  Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns?

Possibly. As discussed under Question 2.2.2, uncertainty exists about the fate of PFAS in GAC reactivation. For example, unregulated air emissions from reactivation may result in secondary environmental impacts.

### 2.5.3  Is additional research needed?

Additional research might be needed to better understand and manage PFAS emissions from GAC reactivation facilities.

## 2.6 Reasonable Cost Basis for Large and Medium Systems

### 2.6.1 Is the technology currently used by medium and large systems (including uses for other treatment purposes)?

Yes. The 34 full-scale PFAS GAC systems identified in the literature include medium and large systems: 16 are larger than 1 million gallons per day (MGD) and two are larger than 10 MGD, with the largest being 50 MGD.

### 2.6.2 Do the treatment studies provide sufficient information on design assumptions to allow cost modeling?

Detailed data are available from the treatment studies for all the relevant design parameters, including:

- Vessel configuration (i.e., number of vessels in series)
- Empty bed contact time (EBCT)
- GAC bed life
- Loading rate
- Residuals management options.

### 2.6.3 Is additional research needed?

No. Additional research is not required.

# 3.0  Best Available Technology Evaluation for IX

IX is a physical/chemical separation process in which ions such as per- and polyfluoroalkyl substances (PFAS) in the feed water are exchanged for an ion (typically chloride) on a resin generally made of synthetic beads or gel. In application, feed water passes through a bed of resin in a vessel or column. For PFAS compounds, vendors generally recommend using PFAS-selective resins (Boodoo, 2018a; Boodoo et al., 2019; Lombardo et al., 2018; Woodard et al., 2017).

The IX process continues until the resin does not have sufficient exchange sites available for the target PFAS compounds. At this point, the result is reduced removal of the contaminant, referred to as "breakthrough." Figure 3 is a conceptual diagram of the IX treatment process, from initial adsorption to breakthrough. Once the contaminant concentration in the treated water reaches an unacceptable level, the resin is considered "spent." In IX processes removing more traditional contaminants (e.g., nitrate), the capacity of the spent resin is often restored by rinsing the media with a concentrated chloride solution. However, conventional regeneration solutions are not effective for restoring the capacity of PFAS-selective resins (Liu and Sun, 2021). Regeneration of selective resins may be possible using organic solvents (Boodoo, 2018a; Zaggia et al., 2016) or proprietary methods (Woodard et al., 2017). These alternative regeneration practices are generally practical or cost-effective only with very high influent concentrations, such as in remediation settings. Therefore, in drinking water applications using PFAS-selective resin, vendors recommend a single-use approach where the spent resin is disposed and replaced with fresh resin (Boodoo, 2018a; Lombardo et al., 2018). The length of time between resin replacement events is known as "bed life" and is often quantified in "bed volumes," which are a measure of throughput.
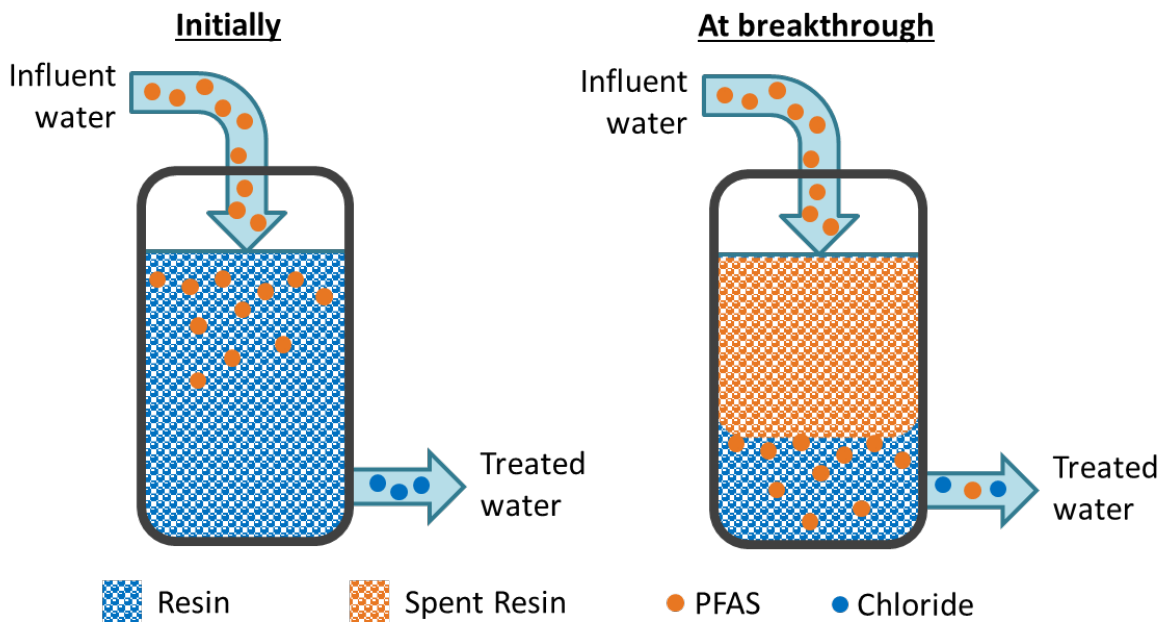


**Figure 3. Conceptual Diagram of the IX Treatment Process**

## 3.1 High Removal Efficiency

### 3.1.1 Have high removal efficiencies that achieve potential MCLs been documented?

Yes. EPA's Drinking Water Treatability Database (USEPA, 2021a; 2021b; 2021c) includes extensive data from the literature on PFAS removal by IX. Results are available from studies conducted in the laboratory, in the field at pilot scale, and in full-scale application, as shown in Table 7, Table 8, and Table 9. The literature demonstrates PFAS removal efficiencies for many PFAS compounds in the high 90 percent range and to levels below analytical detection limits. For PFOA and PFOS, maximum removal efficiencies are greater than 99 percent, also to below analytical detection limits and lower than the regulatory thresholds currently under consideration.

**Table 8. Studies of IX Treatment for Carboxylate PFAS**

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum Removal Efficiency | Source(s) for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|
| PFBA | 4 | 11 | 5 | 2 | 99.3 | Dixit et al. 2020; Dixit et al. 2021 |
| PFPeA | 5 | 7 | 3 | 2 | 95.5 | Schaefer et al. 2019 |
| PFHxA | 6 | 11 | 4 | 3 | >97 | Liu 2017 |
| PFHpA | 7 | 9 | 6 | 4 | >99 | Zeng et al. 2020 |
| PFOA | 8 | 15 | 7 | 4 | 99.3 | Dixit et al. 2019; Dixit et al. 2020; Dixit et al. 2021 |
| PFNA | 9 | 6 | 3 | 2 | >99 | Zeng et al. 2020; Kumarasamy et al. 2020 |
| PFDA | 10 | 7 | 0 | 0 | >99 | Kumarasamy et al. 2020 |
| PFUnA | 11 | 1 | 0 | 0 | 90 | McCleaf et al. 2017 |
| PFDoA | 12 | 2 | 0 | 0 | 99.3 | Dixit et al. 2021 |
| PFTriA | 13 | 1 | 0 | 0 | 90 | McCleaf et al. 2017 |

Sources: USEPA, 2021a; 2021c

**Table 9. Studies of IX Treatment for Sulfonate PFAS**

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum Removal Efficiency | Source(s) for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|
| PFBS | 4 | 12 | 8 | 4 | 99.3 | Dixit et al. 2020; Dixit et al. 2021 |
| PFPeS | 5 | 2 | 0 | 0 | 74 | Yan et al. 2020 |

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum Removal Efficiency | Source(s) for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|
| PFHxS | 6 | 11 | 7 | 4 | >99 | Zeng et al. 2020; Boodoo 2018a; Arevalo et al. 2014; Kumarasamy et al. 2020 |
| PFHpS | 7 | 2 | 3 | 0 | 93 | Yan et al. 2020 |
| PFOS | 8 | 16 | 8 | 4 | 99.7 | Woodard et al. 2017 |
| PFNS | 9 | 1 | 0 | 0 | 54.9 | Wang et al. 2020 |

Sources: USEPA, 2021b; 2021c

**Table 10. Studies of IX Treatment for Other PFAS**

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum Removal Efficiency | Source(s) for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|
| PFBSA | 4 | 1 | 0 | 0 | 98 | Yan et al. 2020 |
| PFMOPrA | 4 | 1 | 0 | 0 | 99.3 | Dixit et al. 2021 |
| PFMOBA | 5 | 1 | 0 | 0 | 99.3 | Dixit et al. 2021 |
| FtS 6:2 | 6 | 2 | 2 | 0 | 99.3 | Dixit et al. 2021 |
| HFPO-DA | 6 | 4 | 1 | 0 | 99.3 | Dixit et al. 2020; Dixit et al. 2021 |
| PFHxSA | 6 | 1 | 0 | 0 | 99 | Yan et al. 2020 |
| FtS 8:2 | 8 | 2 | 2 | 0 | 99.3 | Dixit et al. 2021 |
| PFOSA | 8 | 3 | 0 | 1 | 98 | Yan et al. 2020 |
| PFECHS | 8 | 1 | 0 | 0 | 97 | Yan et al. 2020 |

Source: USEPA, 2021c

## 3.1.2  Are the effects of water quality parameters on treatment effectiveness and reliability well-known?

Yes. PFAS-selective resins are designed to have higher affinity for PFAS than other anions, such as nitrate, sulfate, bicarbonate, and chloride. However, these anions can be present in drinking water at concentrations many orders of magnitude higher than PFAS. Therefore, they can compete with PFAS for available exchange sites on the resin (Ateia et al., 2019; Berretta et al., 2021; Boodoo, 2021). Data are not available to precisely quantify the effect of competing anions under a wide range of water quality conditions. However, in general, competition does not necessarily reduce the maximum removal effectiveness of the resin for PFAS. Instead, it shortens the time to breakthrough, meaning more frequent resin replacement may be required in the

presence of competing anions, all other factors being equal. Therefore, it should be possible to reliably manage the impact of competition through piloting, selection of design parameters, and operational monitoring.

### 3.1.3  Is the technology reliable enough to continuously meet a drinking water MCL?

Yes. Several full-scale drinking water facilities are using IX to meet current state drinking water requirements for PFAS (see Question 2.2.1, below). In general, IX is an established, reliable technology that has been used successfully to meet other MCLs.

### 3.1.4  Is additional research needed?

No. Additional research is not needed.

## 3.2  History of Full-Scale Operation

### 3.2.1  Do existing studies include full-scale operations at drinking water treatment facilities?

Yes. The first full-scale system treating drinking water using PFAS-selective IX commenced operation in 2017 (WWSD, 2018). Since that time, several additional full-scale facilities have begun using the technology, as listed in Table 11. The effectiveness studies enumerated under Question 3.1.1 include results for some of these facilities.

**Table 11. Full-scale IX Systems Removing PFAS from Drinking Water**

| Location | Flow rate (MGD) | Groundwater or Surface Water | Year of Startup | Sources |
|---|---|---|---|---|
| Pease International Tradeport Drinking Water System, Portsmouth, New Hampshire | Not reported | Groundwater | 2019 | City of Portsmouth 2020 |
| Horsham Water and Sewer Authority, Horsham, Montgomery County, Pennsylvania | 0.14 | Groundwater | 2021 | Boodoo 2018a; Boodoo et al. 2019; HWSA 2021 |
| Security Water and Sanitation Districts, Security, Colorado | 9 | Groundwater | 2019 | Jent 2020 |
| Stratmoor Hills Water District, Stratmoor Hills, El Paso County, Colorado | 1 | Groundwater | Not reported | Berretta et al. 2021 |
| City of Stuart, Florida | 4 | Groundwater | 2018 | Aqueous Vets 2019 |
| Warminster Municipal Authority, Warminster, Pennsylvania | Not reported | Not reported | Not reported | Boodoo 2018a; Boodoo 2018b |
| Widefield Water and Sanitation District, Widefield, Colorado | Not reported | Groundwater | 2017 | WWSD 2018 |

MGD = million gallons per day

### 3.2.2 Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options?

There are no known full-scale studies of spent resin from IX facilities specifically for the removal of PFAS. In general, however, the characteristics and quantities of spent resin are predictable. This waste stream contains the PFAS compounds and other anions removed from the treated water. The generation rate is a function of bed volume and replacement frequency.

Under current regulations, spent resin is typically incinerated (Boodoo, 2018b). The literature is inconclusive regarding the fate of PFAS during incineration in general (USEPA, 2020) and there are no studies specific to incineration of IX resin. Additional full-scale research might be needed to better understand and manage PFAS air emissions from incineration facilities. The results of this research might necessitate changes to spent resin management practices. Similar to GAC, IX resins may also be landfilled. Future RCRA hazardous waste regulations could also limit the available management options.

### 3.2.3 Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling?

The use of RSSCTs to predict IX performance for PFAS removal is a recent development (Najm et al., 2021; Schaefer et al., 2019; Zeng et al., 2020), so there are no validated methods to scale up from these bench-scale results. However, as a mature and established technology, the scale-up of IX from pilot- to full-scale is well understood and has been implemented at full-scale facilities treating PFAS (e.g., WWSD, 2018).

### 3.2.4 Is additional research needed?

In general, additional research is not required. However, additional full-scale research might be needed to better understand and manage PFAS air emissions from incineration facilities.

## 3.3 General Geographic Applicability

### 3.3.1 What regions do the existing research studies represent?

EPA's Drinking Water Treatability Database (USEPA, 2021a; 2021b; 2021c) includes effectiveness data for PFAS removal by IX in waters from four geographically dispersed U.S. states (Alabama, Colorado, New Jersey, and Pennsylvania). The full-scale facilities listed under Question 3.2.1 are located in Colorado, New Hampshire, and Pennsylvania.

### 3.3.2 Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas?

No. Although there may be regional variations in competing anions, these variations are likely to be less significant than variation among individual water sources within a region. Furthermore, as discussed under Question 3.1.2, it should be possible to reliably manage the impact of water quality variations through piloting, selection of design parameters, and operational monitoring.

### 3.3.3  Are there any regional issues with respect to residuals handling or water resource use?

Under current state regulations, there no known regional barriers with respect to spent resin disposal.

### 3.3.4  Is additional research needed?

No. Additional research is not required.

## 3.4 Compatibility with Other Treatment Processes

### 3.4.1  Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated?

Yes. In general, IX can have an adverse effect on treated water chemistry by increasing corrosivity. One vendor suggests this issue may be limited in the case of PFAS-selective resin (Boodoo, 2018b, see Question 3.5.1). In cases where this impact does occur, it can be managed through post-treatment corrosion control or alterations to existing corrosion control. The technology can also have a beneficial effect by removing other undesirable anions from the treated water (e.g., nitrate, sulfate), even when using PFAS-selective resin (see Question 3.1.2).

### 3.4.2  Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train?

Possibly. The treated water chemistry changes resulting from IX might require post-treatment corrosion control or alterations to existing corrosion control.

### 3.4.3  Is additional research needed?

No. Additional research is not required.

## 3.5 Ability to Bring All of the Water System into Compliance

### 3.5.1  Will the treatment process adversely affect the distribution system or water resource decisions?

In general, IX treatment can increase treated water corrosivity because of chloride ion addition and/or carbonate along with bicarbonate removal. For example, Berlien (2003) reported increased corrosivity with a full-scale application of IX for perchlorate treatment. One vendor of PFAS-selected resin reports that this effect is limited to the first 200 bed volumes of treatment for their product. During this initial period, pH in treated water will decrease by 1 to 1.5 units; then the alkalinity and pH of the treated water returns to normal (Boodoo, 2018b). In cases where increased corrosivity occurs, distribution system effects can be managed by adjusting corrosion control programs.

### 3.5.2   Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns?

Possibly. As discussed under Question 3.2.2, uncertainty exists about the fate of PFAS during the incineration of spent resin. For example, unregulated air emissions from reactivation may result in secondary environmental impacts.   In addition, the corrosivity impacts discussed above under Question 3.5.1, if not adequately managed through post-treatment, could create new environmental quality concerns in the distribution system.

### 3.5.3   Is additional research needed?

Additional research might be needed to better understand and manage address PFAS air emissions from incineration facilities.

## 3.6  Reasonable Cost Basis for Large and Medium Systems

### 3.6.1   Is the technology currently used by medium and large systems (including uses for other treatment purposes)?

Yes. The full-scale PFAS IX facilities identified in the literature include two medium systems (larger than 1 MGD). There are many medium and large systems that use selective IX for other contaminants (e.g., perchlorate).

### 3.6.2   Do the treatment studies provide sufficient information on design assumptions to allow cost modeling?

Detailed data are available from the treatment studies for all the relevant design parameters, including:

- Vessel configuration (i.e., number of vessels in series)
- EBCT
- Resin bed life
- Loading rate
- Residuals management options.

### 3.6.3   Is additional research needed?

No. Additional research is not required.

# 4.0 Best Available Technology Evaluation for RO/NF

RO and NF are membrane separation processes that physically remove contaminants from drinking water. These processes separate solutes such as PFAS compounds from solution by forcing the solvent to flow through a membrane at a pressure greater than the normal osmotic pressure. In drinking water treatment, these membranes are most often used in a spiral-wound configuration that consists of several membrane envelopes, layered with feed spacers and rolled together in around a central collection tube.

The membrane is semi-permeable, transporting different molecular species at different rates. The application of pressure splits the influent water passing over the membrane into two streams:

- Treated water or "permeate" that passes through the membrane layers along with solutes of lower molecular weight into the central collection tube
- Water containing higher molecular weight solutes that remains outside the membrane layers, called "reject," "concentrate," or "brine."

"Recovery rate" and "rejection rate" are the percentages of influent water that are recovered as permeate and lost as reject, respectively.[6] Figure 4 is a conceptual diagram of this process as applied to water containing PFAS. Specific membranes differ in terms of the size of dissolved contaminants they can remove. Membranes that remove smaller contaminants require higher feed pressure. Feed pressures for NF membranes are typically in the range of 50 to 150 pounds per square inch (psi). Feed pressures for RO membranes are in the range of 125 to 300 psi in low pressure applications (such as PFAS removal) but can be as high as 1,200 psi in applications such as seawater desalination (USEPA, 2022c). As discussed under Question 4.1.1, both RO and NF membranes have the capacity to remove PFAS.
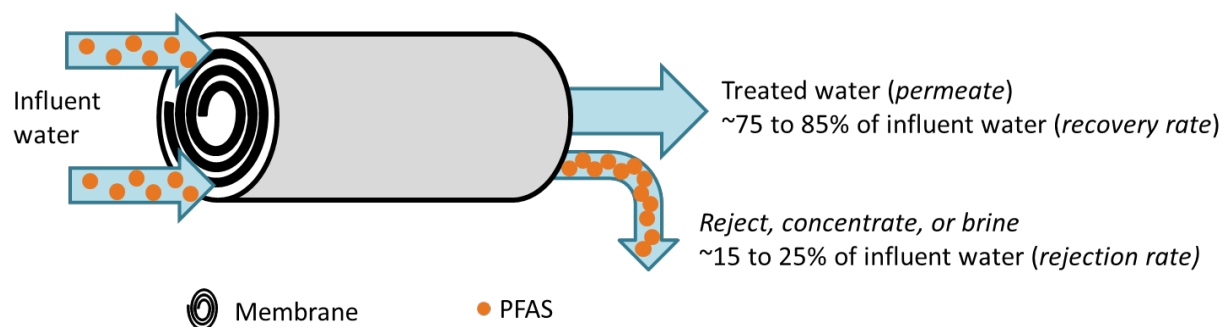


**Figure 4. Conceptual Diagram of the RO Treatment Process**

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[6] Note that recovery and rejection rates are not directly related to removal efficiency, which is the percentage of influent PFAS removed from the treated water.

## 4.1 High Removal Efficiency

### 4.1.1 Have high removal efficiencies that achieve potential MCLs been documented?

Yes. EPA's Drinking Water Treatability Database (USEPA, 2021a; 2021b; 2021c) includes extensive data from the literature on PFAS removal by RO and NF. Results are available from studies conducted in the laboratory, in the field at pilot scale, and in full-scale application, as shown in Table 10, Table 11, and Table 12. The literature demonstrates PFAS removal efficiencies for many PFAS compounds in the high 90 percent range and to levels below analytical detection limits. For PFOA and PFOS, maximum removal efficiencies are greater than 99 percent, also to below analytical detection limits and lower than the regulatory thresholds currently under consideration.

**Table 12. Studies of RO/NF Treatment for Carboxylate PFAS**

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum NF Removal Efficiency | Maximum RO Removal Efficiency | Source(s) for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|---|
| PFBA | 4 | 2 | 1 | 2 | 99 | 99.9 | Lipp et al. 2010 |
| PFPeA | 5 | 2 | 3 | 2 | >99 | >99 | Horst et al. 2018; Liu et al. 2021; Dickenson and Higgins 2016 |
| PFHxA | 6 | 3 | 4 | 4 | >98 | 99.2 | Liu et al. 2021 |
| PFHpA | 7 | 1 | 2 | 3 | 99 | >99 | Steinle-Darling et al. 2008; Liu et al. 2021 |
| PFOA | 8 | 4 | 4 | 5 | 99.9 | 99.9 | Boonya-Atichart et al. 2016; Lipp et al. 2010 |
| PFNA | 9 | 2 | 1 | 4 | 99 | >98 | Steinle-Darling et al. 2008; Dickenson and Higgins 2016; Appleman et al. 2014 |
| PFDA | 10 | 2 | 0 | 4 | 99 | >99 | Steinle-Darling et al. 2008; Dickenson and Higgins 2016; Appleman et al. 2014 |
| PFUnA | 11 | 1 | 0 | 2 | 99 | >77 | Steinle-Darling et al. 2008; Dickenson and Higgins 2016; Appleman et al. 2014 |
| PFDoA | 12 | 0 | 0 | 2 | - | >87 | Dickenson and Higgins 2016; Appleman et al. 2014 |

- = no data; NF = nanofiltration; RO = reverse osmosis
Sources: USEPA, 2021a; 2021c

**Table 13. Studies of RO/NF Treatment for Sulfonate PFAS**

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum NF Removal Efficiency | Maximum RO Removal Efficiency | Source(s) for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|---|
| PFPrS | 3 | 0 | 1 | 0 | >98 | >99 | Liu et al. 2021 |
| PFBS | 4 | 3 | 4 | 3 | 99.8 | 99.8 | Lipp et al. 2010 |
| PFPeS | 5 | 0 | 1 | 0 | >98 | >99 | Liu et al. 2021 |
| PFHxS | 6 | 2 | 4 | 4 | >99 | >99 | Appleman et al. 2013; Thompson et al. 2011; Liu et al. 2021 |
| PFHpS | 7 | 0 | 1 | 0 | >98 | >99 | Liu et al. 2021 |
| PFOS | 8 | 6 | 4 | 5 | >99.9 | 99.9 | Lipp et al. 2010; 2163 |
| PFDS | 10 | 1 | 0 | 0 | 99 | - | Steinle-Darling et al. 2008 |

- = no data; NF = nanofiltration; RO = reverse osmosis
Sources: USEPA, 2021b; 2021c

**Table 14. Studies of RO/NF Treatment for Other PFAS**

| PFAS Compound | Number of Carbons | Number of Bench Studies | Number of Pilot Studies | Number of Full-scale Studies | Maximum NF Removal Efficiency | Maximum RO Removal Efficiency | Source(s) for Maximum Removal Efficiency |
|---|---|---|---|---|---|---|---|
| PFMOAA | 3 | 0 | 1 | 0 | - | >98.5 | CDM Smith 2018 |
| PFO2HxA | 4 | 0 | 1 | 0 | - | >80.8 | CDM Smith 2018 |
| PFO3OA | 5 | 0 | 1 | 0 | - | >67.2 | CDM Smith 2018 |
| FtS 6:2 | 6 | 1 | 2 | 1 | 99.5 | >65.5 | Steinle-Darling et al. 2008; CDM Smith 2018 |
| HFPO-DA | 6 | 0 | 1 | 0 | - | >64.2 | CDM Smith 2018 |
| PFOSA | 8 | 2 | 0 | 1 | 98.5 | >13 | Steinle-Darling et al. 2008; Dickenson and Higgins 2016 |
| N-MeFOSAA | 11 | 0 | 0 | 2 | - | >84 | Dickenson and Higgins 2016 |
| N-EtFOSAA | 12 | 0 | 0 | 2 | - | >58 | Dickenson and Higgins 2016 |

- = no data; NF = nanofiltration; RO = reverse osmosis
Source: USEPA, 2021c

### 4.1.2   Are the effects of water quality parameters on treatment effectiveness and reliability well-known?

Yes. In general, water quality affects the design (e.g., concentrate volume, cleaning frequency, antiscalant selection) of RO and NF systems, but not removal efficiency. The literature specifically for PFAS removal by membranes supports this conclusion. For example, Appleman et al. (2013) found that the effectiveness of NF for PFAS removal was not impaired by the presence of humic acid. Similarly, Steinle-Darling and Reinhard (2008) found that ionic strength did not have a significant effect on removal performance. Although these authors noted a significant effect from pH, this effect was observed at pH 2.8, substantially lower than typical drinking water influent. Boonya-Atichart et al. (2016) found no significant effect within a more typical range of pH (5.5 to 10). Although they observed a slight decrease in effectiveness with increasing total dissolved solids, this effect was not significant.

### 4.1.3   Is the technology reliable enough to continuously meet a drinking water MCL?

Yes. In general, RO and NF are established, reliable technology that has been used successfully to meet other MCLs. As discussed under Question 4.2.1, full-scale plants recently began operation using low-pressure RO designed to meet state drinking water requirements for PFAS.

### 4.1.4   Is additional research needed?

No. Additional research is not needed.

## 4.2 History of Full-Scale Operation

### 4.2.1   Do existing studies include full-scale operations at drinking water treatment facilities?

Yes. Two drinking water systems, in North Carolina (Dowbiggin et al., 2021) and Alabama (Wetzel, 2021; WHNT News, 2019), recently constructed full-scale treatment plants using low-pressure RO. These are the first two treatment plants utilizing membrane technology specifically targeted at PFAS removal from drinking water. Although performance data are not yet available from these facilities, the effectiveness studies enumerated under Question 4.1.1 include results from full-scale facilities using membrane separation to treat other contaminants.

### 4.2.2   Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options?

There are no full-scale studies of residuals from RO or NF facilities specifically for the removal of PFAS. In general, however, the characteristics of membrane concentrates are predictable and handling and treatment options are well understood. This waste stream contains the PFAS compounds and other dissolved solids removed from the treated water. The two full-scale facilities identified under Question 4.2.1 are designed for recovery rates of 85 to 92 percent (Dowbiggin et al., 2021; Wetzel, 2021; WHNT News, 2019), which means that concentrate

flows at these facilities would account for 8 to 15 percent of influent (i.e., 100 percent minus the recovery rate). Assuming these facilities achieve 95 percent removal efficiency, PFAS concentrations in this waste stream would be approximately 6 to 12 times the concentration in influent water.[7]

For disposal of membrane concentrate, most systems use surface water discharge or discharge to sanitary sewer. Deep well injection is common in Florida. A small percentage of systems use land application, evaporation ponds, or recycling (Mickley, 2018). The large volume of residuals is a well-known obstacle to adoption of membrane separation technology, in general. In the case of PFAS removal, the high PFAS concentration in the residuals might limit the disposal options or require additional treatment prior to disposal, depending on state and local discharge regulations. Concentrate treatment is not common in other applications (Mickley, 2018). Studies specific to treatment of concentrate containing PFAS currently are limited to lab- or pilot-scale (Tow et al., 2021). The Alabama facility identified under Question 4.2.1 initially planned to treat membrane concentrate through its existing granular activated carbon (GAC) filters prior to discharge (WHNT News, 2019). More recent reports (Wetzel, 2021) do not address concentrate treatment at this facility. The North Carolina facility includes the construction of a discharge pipeline to a point "several miles" away, downstream of any drinking water intakes (Dowbiggin et al., 2021).

### 4.2.3   Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling?

Yes. As a mature and established technology, the scale-up of RO, in general, from bench- to pilot- to full-scale is well understood and has been implemented at full-scale facilities treating PFAS (e.g., Dowbiggin et al., 2021).

### 4.2.4   Is additional research needed?

In general, additional research is not required. In cases where regional or system-specific conditions associated with PFAS-bearing residuals management present a significant barrier, however, additional research on residuals treatment prior to disposal would be useful.

## 4.3 General Geographic Applicability

### 4.3.1   What regions do the existing research studies represent?

EPA's Drinking Water Treatability Database (USEPA, 2021a; 2021b; 2021c) includes effectiveness data for PFAS removal by membrane separation in waters from three geographically dispersed U.S. states (California, Illinois, and North Carolina), as well as from countries overseas. The full-scale facilities listed under Question 4.2.1 are located in Alabama and North Carolina.

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[7] The concentration in the reject stream can be calculated as the concentration in influent times the removal efficiency, divided by the rejection rate. In this example, 0.95 / 0.15 = 6.33 and 0.95 / 0.08 = 11.88.

## 4.3.2   Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas?

No. There are no data indicating that regional water quality variations will limit effectiveness or reliability. As discussed under Question 4.1.2 water quality affects the design (e.g., concentrate volume, cleaning frequency, antiscalant selection, temperature) of a RO and NF systems, but not their effectiveness or reliability.

## 4.3.3   Are there any regional issues with respect to residuals handling or water resource use?

The large volume of reject water "lost" from membrane separation can be an issue in regions where water scarcity is a concern. The Small Business Advocacy Review Panel (1999) pointed out that a water rejection rate of 20 to 25 percent can present a problem where water is scarce, such as in the western states. The availability of discharge options for residuals is also a region- and system-specific issue, depending on location, climate, and state and local regulations. The technology is more likely to be feasible when ocean or estuarine discharge is an option.

## 4.3.4   Is additional research needed?

No. Additional research is not required.

## 4.4  Compatibility with Other Treatment Processes

## 4.4.1   Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated?

Yes. Adverse effects are unlikely. Membrane separation might have some effect on treated water chemistry (see Question 4.5.1), which might alter corrosion control or blending requirements. Generally, however, these effluent chemistry changes should not require significant adjustments to downstream treatment processes. Regarding beneficial effects, RO and NF membranes can remove a wide range of contaminants, including inorganic ions, total dissolved solids, nitrate, radionuclides, some disinfection byproduct precursors, and synthetic organic chemicals. Since membrane permeate has a reduced chlorine demand, its finished water requires a low dose of disinfectant.

## 4.4.2   Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train?

Possibly. Post-treatment can be required to control corrosion impacts (Lipp et al., 2010), particularly in instances where blending is not possible (see Question 4.5.1).

## 4.4.3   Is additional research needed?

No. Additional research is not required.

## 4.5 Ability to Bring All of the Water System into Compliance

### 4.5.1 Will the treatment process adversely affect the distribution system or water resource decisions?

Yes, if not properly managed. The permeate from RO and, in some cases, NF can be corrosive. The extent of this impact is site-specific (Bergman et al., 2012). In other drinking water treatment applications, the permeate is often blended with untreated water to produce a less corrosive finished water (Mickley, 2018). If the source water has a sufficiently low concentration of PFAS and other contaminants, blending may reduce post-treatment requirements. Thus, distribution system effects can be managed by adjusting corrosion control programs or blending practices.

As discussed under Question 4.3.3, the large volume of membrane concentrate might have an impact on water resource decisions in regions where water scarcity is a concern.

### 4.5.2 Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns?

Yes. The disposal of large membrane concentrate volumes, containing high PFAS concentrations, could create an environmental quality concern. As discussed under Question 4.3.3, discharge concerns are region- and system-specific. In addition, the corrosivity impacts discussed above under Question 4.5.1, if not adequately managed through post-treatment, could create new environmental quality concerns.

### 4.5.3 Is additional research needed?

No. Additional research is not required.

## 4.6 Reasonable Cost Basis for Large and Medium Systems

### 4.6.1 Is the technology currently used by medium and large systems (including uses for other treatment purposes)?

Yes. Both full-scale PFAS RO facilities identified in the literature are large (10 and 48 MGD). There are many medium and large systems that use RO or NF for other contaminants.

### 4.6.2 Do the treatment studies provide sufficient information on design assumptions to allow cost modeling?

Detailed data are available from the treatment studies for the following design parameters:

- Membrane type
- Flux rate
- Recovery rate
- Residuals management options.

Assumptions about pretreatment requirements and cleaning procedures, in general, are determined based on major water quality parameters, such as hardness parameters, chloride, sulfate, silica, pH, silt density index, and total dissolved solids. They typically are not affected by trace contaminant influent concentrations or removal requirements. There is nothing unique about PFAS removal by membrane separation that suggests a different relationship between the major water quality parameters and typical pretreatment and cleaning requirements.

## 4.6.3   Is additional research needed?

No. Additional research is not required.

# 5.0  Summary of Best Available Technology Evaluation

Table 15 provides a summary of the evaluation results for the three technologies against each of the criteria. Based on this evaluation, the overall conclusions are:

- GAC is a potential BAT. It has been shown to achieve high removal efficiency for PFAS. It is a mature and established technology in general and has been used for full-scale treatment of PFAS at many facilities. Changes in air quality regulations might necessitate changes to spent GAC management practices. Research on the fate of PFAS during GAC reactivation would provide additional clarity on the significance of this issue. Future RCRA hazardous waste regulations could also limit the available management options.

- IX is a potential BAT. PFAS-selective resin has been shown to achieve high removal efficiency for PFAS. IX is a mature and established technology in general and PFAS-selective resin has been used for full-scale treatment at several facilities. Changes in air quality regulations might necessitate changes to typical spent resin management practices. Research on the fate of PFAS during spent resin incineration would provide additional clarity on the significance of this issue. Future RCRA hazardous waste regulations could also limit the available management options.

- Membrane separation using RO or NF is a potential BAT. It has been shown to achieve high removal efficiency for PFAS, including at full-scale facilities designed for other contaminants. Two drinking water systems recently constructed full-scale treatment plants specifically targeting PFAS using low-pressure RO. Large volumes of residual concentrate, however, will likely restrict the technology's applicability on a system-specific basis. Additional research on treatment of PFAS-bearing membrane concentration could help mitigate this issue in some cases.

**Table 15. PFAS Removal Technologies Evaluated Against BAT Criteria**

| Criterion | GAC | IX | RO/NF |
|---|---|---|---|
| **1. High Removal Efficiency** | | | |
| 1.1. Have high removal efficiencies that achieve potential MCLs been documented? | Yes | Yes | Yes |
| 1.2. Are the effects of water quality parameters on treatment effectiveness and reliability well-known? | Yes | Yes | Yes |
| 1.3. Is the technology reliable enough to continuously meet a drinking water MCL? | Yes | Yes | Yes |
| 1.4. Is additional research needed? | No | No | No |
| **2. History of Full-Scale Operation** | | | |
| 2.1. Do existing studies include full-scale operations at drinking water treatment facilities? | Yes | Yes | Yes |
| 2.2. Are there studies of full-scale treatment of residuals that fully characterize residual waste streams and disposal options? | Yes (given current regulations) | Yes (for other treatment purposes) | Yes (for other treatment purposes) |
| 2.3. Can the bench or pilot studies be scaled up to represent full-scale treatment, including residuals generation and handling? | Yes | Yes | Yes |
| 2.4. Is additional research needed? | Maybe | Maybe | Maybe |
| **3. General Geographic Applicability** | | | |
| 3.1. What regions do the existing research studies represent? | Nationwide | Nationwide | Nationwide |
| 3.2. Is it known that regional water quality variations will limit treatment effectiveness or reliability in some areas? | No | No | No |
| 3.3. Are there any regional issues with respect to residuals handling or water resource use? | Not currently | Not currently | Yes |
| 3.4. Is additional research needed? | No | No | No |
| **4. Compatibility with Other Treatment Processes** | | | |
| 4.1. Have the effects (adverse or beneficial) of the treatment process on other processes likely to be present at existing plants been evaluated? | Yes | Yes | Yes |
| 4.2. Will additional pre- or post-treatment be required for integration into an existing (or planned) treatment train? | No | Possibly | Possibly |
| 4.3. Is additional research needed? | No | No | No |
| **5. Ability to Bring All of the Water System into Compliance** | | | |
| 5.1. Will the treatment process adversely affect the distribution system or water resource decisions? | No | Possibly | Possibly |
| 5.2. Might the treatment process, residuals handling, or pre- or post-treatment requirements raise new environmental quality concerns? | Possibly | Possibly | Yes |
| 5.3. Is additional research needed? | Maybe | Maybe | No |
| **6. Reasonable Cost Basis for Large and Medium Systems** | | | |
| 6.1. Is the technology currently used by medium and large systems (including uses for other treatment purposes)? | Yes | Yes | Yes |
| 6.2. Do the treatment studies provide sufficient information on design assumptions to allow cost modeling? | Yes | Yes | Yes |
| 6.3. Is additional research needed? | No | No | No |

# 6.0 Small System Compliance Technology Evaluation

## 6.1 SSCT Analysis Method

A technology must be both effective and affordable to be designated as an SSCT. Technologies that meet the effectiveness criterion include those designated as BATs for the rule: GAC, PFAS-selective IX, and RO. This section also presents preliminary affordability results for POU RO. POU RO is not currently a compliance option because the regulatory options under consideration require treatment to concentrations below 70 ng/L total of PFOA and PFOS, the current certification standard for POU devices. However, POU treatment is reasonably anticipated to become a compliance option for small systems in the future should NSF/ANSI develop a new certification standard that mirrors EPA's regulatory standard.

To evaluate affordability, EPA compared incremental costs per household for each technology against an *expenditure margin*. Table 16 shows the expenditure margins for each system size category. It also shows how EPA derived the expenditure margins, beginning with estimates of MHI, which vary by system size category. The annual affordability threshold for household expenditures on drinking water is 2.5 percent of MHI. EPA deducted estimates of baseline or current water bills from the affordability threshold to obtain the expenditure margin estimates.

**Table 16. Expenditure Margins for SSCT Affordability Analysis**

| System Size (Population Served) | Median Household Income[1] | Affordability Threshold[2] | Baseline Water Cost[3] | Expenditure Margin |
|---|---|---|---|---|
|  | A | B = 2.5% x A | C | D = B - C |
| 25-500 | $62,950 | $1,574 | $551 | $1,022 |
| 501-3,300 | $60,926 | $1,523 | $638 | $885 |
| 3,301-10,000 | $66,746 | $1,669 | $666 | $1,002 |

Notes:
[1] MHI based on U.S. Census 2010 American Community Survey 5-year estimates (U.S. Census Bureau, 2010) stated in 2010 dollars, adjusted to 2022 dollars using the CPI (for all items) for areas under 2.5 million persons.
[2] Affordability threshold equals 2.5 percent of MHI.
[3] Household water costs derived from 2006 Community Water System Survey (USEPA, 2009), based on residential revenue per connection within each size category, adjusted to 2020 dollars based on the Consumer Price Index (for all items) for areas under 2.5 million persons.

The cost per household varies by technology and by system size category. EPA used the following method to estimate per-household costs using EPA's work breakdown structure (WBS) drinking water treatment cost models:

- Estimate system-level daily design and average flow based on median population
- Estimate entry point design and average flow by dividing system-level flow by the average number of entry points[8]

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[8] Except for POU RO. The analysis here assumes POU devices must be installed at all households regardless of entry point. Therefore, costs are estimated based on the total system-level flow.

- Estimate capital costs using a technology-specific WBS cost curve and design flow
- Estimate O&M costs using a technology-specific WBS cost curve and average flow
- Annualize capital costs at 7 percent over the expected useful life of the treatment process
- Calculate total annual costs (annualized capital costs plus O&M costs)
- Multiply total annual costs by the average number of entry points,[9] conservatively assuming systems must install treatment at all entry points (erring on the side of higher costs)
- Divide total annual costs by the median number of households served
- Assess affordability by comparing these values with the expenditure margins.

Table 17 shows median population served, number of households, number of entry points, and resulting design and average flows used in these calculations. EPA generated costs assuming systems must meet MCLs for PFOA and PFOS of 4 nanograms per liter (ng/L) each, with initial influent concentrations of 70 ng/L and 264 ng/L, respectively. These influent concentrations correspond to the 90th percentile for each contaminant, considering detected values only.

**Table 17. Design and Average Flow Estimates and Service Estimates for the 50th Percentile or Median System**

| Parameter | | System Size (Population Served) | | |
|---|---|---|---|---|
| | | 25-500 | 501-3,300 | 3,301-10,000 |
| System Population[1] | **A** | 110 | 1,140 | 5,476 |
| System Households[2] | **B = A/2.53** | 43 | 451 | 2,164 |
| | | Groundwater | | |
| System Design Flow[3] (MGD) | **C** | 0.049 | 0.458 | 2.051 |
| System Average Flow[3] (MGD) | **D** | 0.012 | 0.147 | 0.776 |
| Entry Points[4] | **E** | 1 | 2 | 2 |
| Entry Point Design Flow (MGD) | **F = C/E** | 0.049 | 0.229 | 1.025 |
| Entry Point Average Flow (MGD) | **G = D/E** | 0.012 | 0.074 | 0.388 |
| | | Surface Water | | |
| System Design Flow[3] (MGD) | **H** | 0.050 | 0.459 | 2.026 |
| System Average Flow[3] (MGD) | **I** | 0.015 | 0.156 | 0.748 |
| Entry Points[4] | **J** | 1 | 1 | 1 |
| Entry Point Design Flow (MGD) | **K = H/J** | 0.050 | 0.459 | 2.026 |
| Entry Point Average Flow (MGD) | **L = I/J** | 0.015 | 0.156 | 0.748 |

Notes:
[1] Median system populations are from USEPA Safe Drinking Water Information System Federal (SDWIS/Fed) fourth quarter 2021 "frozen" dataset that contains information reported through January 14, 2022
[2] Median system household estimates equal median populations divided by 2.53 persons per household, based on 2020 Census data (Table AVG1. Average Number of People per Household, by Race and Hispanic Origin/1, Marital Status, Age, and Education of Householder: 2020).
[3] Flow estimates are based on regression equations that relate population and design or average flows, derived in USEPA (2000).
[4] Entry point data from 2006 Community Water System Survey (USEPA, 2009), Table 13, values rounded to nearest whole number.

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[9] Except for POU RO, as discussed in the previous footnote.

EPA generated costs for each system size category for 22 treatment technology scenarios. There are eight scenarios for GAC comprising all combinations of two source waters (ground and surface), two cost levels (low and high), and two bed life scenarios. The bed life scenarios reflect results from linear equations derived as described in USEPA (2024a) and correspond to a range of influent TOC from 0.5 mg/L and 2 mg/L (discussed further in Section 6.2). There are eight scenarios for IX that are combinations of two source waters, two cost levels, and two bed life scenarios. The bed life scenarios for IX also result from equations presented in USEPA (2024a). For IX, they correspond to a range of total influent PFAS from 334 ng/L to approximately 7,000 ng/L (discussed further in Section 6.2). There are four scenarios for RO to account for two source waters, and two cost levels. There are two scenarios for POU RO to account for two source waters. Costs for POU RO do not vary by cost level input (high, mid, low). USEPA (2024a) contains the cost curve parameters for all the treatment technology scenarios. There are separate parameter sets for capital costs and O&M costs and for small, medium, and large entry point sizes (corresponding to design flow ranges of less than 1 MGD, 1 MGD to less than 10 MGD, and greater than or equal to 10 MGD).

## 6.2 Results

Table 18 provides ranges of per-household costs for each technology and system size category. The ranges indicate minimum and maximum costs across the scenarios noted in the previous section.

**Table 18. Total Annual Cost per Household for Candidate Technologies**

| System Size (Population Served) | GAC | IX | RO | POU[1] |
|---|---|---|---|---|
| 25-500 | $607 to $1,241 | $563 to $990 | $4,332 to $5,224 | $345 to $357 |
| 501-3,300 | $203 to $484 | $171 to $351 | $721 to $1,324 | $327 to $327 |
| 3,301-10,000 | $178 to $417 | $145 to $284 | $388 to $544 | Unavaliable[2] |

Notes:
1. POU is not currently a compliance option because the regulatory options under consideration require treatment to concentrations below the current certification standard for POU devices. However, POU treatment is anticipated to become a compliance option for small systems in the future should NSF/ANSI develop a new certification standard that mirrors (or is demonstrated to treat to concentrations lower than) EPA's regulatory standard. The affordability conclusions presented here should be considered preliminary estimates because they reflect the costs of devices certified under the current testing standard, not a future standard.
2. For evaluating costs for the PFAS rulemaking, EPA's WBS model for POU treatment does not cover systems larger than 3,300 people (greater than 1 MGD design flow).

For each system size category, the per-household cost range for GAC is lower than the corresponding expenditure margin in Table 16. The lower end of the cost range reflects a bed life corresponding to an influent TOC of 0.5 mg/L, which is a typical detection limit for TOC. The upper end of the range corresponds to an influent TOC of 2 mg/L, which is approximately the median for surface water systems and the 85th percentile for groundwater systems.

Based on the linear equations from USEPA (2024a), TOC influent concentrations above 3.2 mg/L may sufficiently reduce GAC bed life such that regulated utilities may choose other treatment options. The maximum influent TOC value of 3.2 mg/L used in this analysis should not be regarded as a strict limit on the practicality or affordability of GAC. EPA is aware that systems may use GAC with TOC influent concentrations above 3.2 mg/L. The bed life equations

are based on pooled data from a limited number of studies and reflect central tendency results under varying water quality conditions. They should not be used in lieu of site-specific engineering analyses or pilot studies to estimate bed life or treatment costs for specific individual treatment systems. Individual systems might achieve longer GAC bed lives and lower treatment costs at higher influent TOC concentrations, particularly if their influent concentrations of PFAS are lower than the 90th percentile values used in this analysis.

For IX, the per-household cost range for each system size category also is lower than the corresponding expenditure margin in Table 16. The lower end of the cost range reflects a bed life corresponding to a total influent PFAS concentration of 334 ng/L, the sum of the initial influent concentrations of PFOS and PFOA, assuming that no other PFAS compounds are present. The upper end of the range assumes additional PFAS compounds are present such that total influent PFAS is approximately 7,000 ng/L. Data are not available to estimate bed life for higher influent concentrations using the linear equations from USEPA (2024a). IX costs are uncertain beyond this value, but it should not be regarded as a strict limit on the feasibility or affordability of the technology.

For RO, the results are mixed. The cost range is lower than the expenditure margin for the largest size category but higher than the margin for the smallest size category. The upper bound of the cost range is also higher than the margin for the middle size category. Therefore, RO meets the SSCT criteria only for the largest system size category.

Table 18 includes preliminary results for POU RO. As discussed above, POU RO is not a compliance option under current certification standards but is expected to become an option in the future should NSF/ANSI develop a new certification standard that mirrors or is more stringent than EPA's regulatory standard. The results for POU RO reflect the costs of devices certified under the current testing standard, which might differ from the costs of devices certified under a future standard. Therefore, the POU RO costs should be considered preliminary estimates. Based on the preliminary estimates, POU RO would meet the affordability criteria for the two smaller size categories. For evaluating costs for the PFAS rulemaking, EPA's WBS model for POU treatment does not cover systems serving greater than 3,300 people (greater than 1 MGD design flow).

The results discussed above assume management of spent GAC and spent IX resin using current typical management practices (reactivation for GAC and incineration for resin) and do not acknowledge all possible management scenarios such as landfilling which may be more appropriate for select entities. Future changes to regulations might result in classification of spent GAC or spent IX resin as hazardous waste. Table 19 shows the resulting cost per household if systems are required to dispose of these residuals as hazardous waste. Although costs increase in this scenario, the increases are not significant enough to change the conclusions about affordability.

**Table 19. Total Annual Cost per Household Assuming Hazardous Waste Disposal for Spent GAC and Resin**

| System Size (Population Served) | GAC | IX |
|---|---|---|

| | | |
|---|---|---|
| 25-500 | $630 to $1,369 | $586 to $1,027 |
| 501-3,300 | $211 to $520 | $176 to $360 |
| 3,301-10,000 | $185 to $438 | $148 to $289 |

Table 20 provides a summary of which technologies meet SSCT criteria for the three system size categories. As discussed above, the affordability conclusions do not change under hazardous waste regulations.

**Table 20. SSCT Affordability Analysis Results – Technologies that Meet Effectiveness and Affordability Criteria**

| System Size (Population Served) | GAC | Ion Exchange | RO | POU[1] |
|---|---|---|---|---|
| 25-500 | In some cases[2] | Yes | No | Yes |
| 501-3,300 | Yes | Yes | No | Yes |
| 3,301-10,000 | Yes | Yes | Yes | Unavaliable[3] |

Notes:
1. POU is not currently a compliance option because the regulatory options under consideration require treatment to concentrations below the current certification standard for POU devices. However, POU treatment is anticipated to become a compliance option for small systems in the future should NSF/ANSI develop a new certification standard that mirrors (or is demonstrated to treat to concentrations lower than) EPA's regulatory standard. The affordability conclusions presented here should be considered preliminary estimates because they reflect the costs of devices certified under the current testing standard, not a future standard.
2. Upper bound estimated annual household treatment costs exceed expenditure margin. Lower bound estimated annual household treatment costs do not exceed the expenditure margin. This exceedance is primarily driven by capital costs and attributable to the use of high-cost materials (e.g., stainless steel) in the upper bound estimates. Systems using low-cost materials, but with source water characteristics otherwise set to the upper bound (e.g., influent PFAS at approximately 7,000 ng/L, influent TOC at 2 mg/L), would fall below the expenditure margin.
3. For evaluating costs for the PFAS rulemaking, EPA's WBS model for POU treatment does not cover systems larger than 3,300 people (greater than 1 MGD design flow.

## 6.3 Small System Affordability Analysis with Potential Additional Expenditure Margins and when Accounting for Financial Assistance

As part of EPA's consideration of potential additional annual expenditure margins to improve the assessment of affordability impacts to low income and disadvantaged communities, EPA considered two incremental cost analyses are conducted utilizing alternative potential expenditure margins. The first expenditure margin threshold is based on 1.0 percent of annual MHI based on a recommendation from EPA's National Drinking Water Advisory Council (NDWAC). The second expenditure margin threshold is set equal to 2.5 percent of the lowest quintile of annual household income and is based on an AWWA 2021 expert panel report. These expenditure margins are estimated for each of the small system size categories: 25 to 500, 501 to 3,300, and 3,301 to 10,000 people served. Additionally, EPA's Science Advisory Board (SAB) and the NDWAC recommended to EPA that the national level affordability analysis should include the impact of financial assistance if the financial support is generally available to all

systems (nationwide). EPA is also considering including this recommendation in the national affordability calculations. For further discussion, please see section 9.13.2 of EPA's Economic Analysis for the Per- and Polyfluoroalkyl Substances National Primary Drinking Water Regulation (EPA, 2024b).

# 7.0 References

Alaska Community Action on Toxics. DeFazio, D. and Tynan, T. 2019. *Threats To Drinking Water and Public Health in Alaska: The Scope of The PFAS Problem, Consequences Of Regulatory Inaction, And Recommendations.* Retrieved from https://www.akaction.org/wp-content/uploads/Report-Threats-to-Drinking-Water-and-Public-Health-in-Alaska-FINAL-web-version-9-24-19.pdf

Agency for Toxic Substances and Disease Registry (ATSDR). 2008. *Perfluorochemical Contamination in Lake Elmo Final Release and Oakdale, Washington County, Minnesota.* Retrieved from https://www.atsdr.cdc.gov/HAC/pha/PFCsLakeElmo/PFCs_in_Lake_Elmo_PHA_8-29-2008_508.pdf

ATSDR. 2020. *PFAS Exposure Assessment Airway Heights, Spokane County, WA*. Retrieved from https://www.atsdr.cdc.gov/pfas/docs/factsheet/Spokane-Factsheet-508.pdf

ATSDR. 2021. *Toxicological Profile for Perfluoroalkyls*. U.S. Department of Health and Human Services. Retrieved from https://www.atsdr.cdc.gov/toxprofiles/tp200.pdf

Appleman, T.D., Higgins, C.P., Quinones, Q., Vanderford, B.J., Kolstad, C., Zeigler-Holady, J.C., and Dickenson, E.R.V. 2014. Treatment of poly- and perfluoroalkyl substances in U.S. full-scale water treatment systems. *Water Research*, 51(2014), 246-255. http://dx.doi.org/10.1016/j.watres.2013.10.067

Appleman, T.D., Dickenson, E.R.V., Bellona, C., and Higgins, C.P. 2013. Nanofiltration and granular activated carbon treatment of perfluoroalkyl acids. *Journal of Hazardous Materials*, 260(2013), 740-746. http://dx.doi.org/10.1016/j.jhazmat.2013.06.033

Aqueous Vets. 2019. The City of Stuart, Florida Installs 4 MGD Ion Exchange System to Address PFAS Contamination. AVP-0016 Rev.2 9/19/2019. Retrieved from http://www.aqueousvets.com/uploads/9/8/8/7/98870448/avp-0016_pfas_treatment_system_-_stuart_fl_-_09.19.19.pdf

Arevalo, E., Strynar, M., Lindstorm, A., McMillan, L., and Knappe, D. 2014. Removal of Perfluorinated Compounds by Anion Exchange Resins: Identifying Effective Resin Regeneration Strategies. AWWA Annual Conference and Exposition. Boston, MA.

Ateia, M., Maroli, A., Tharayil, N., and Karanfil, T. 2019. The overlooked short- and ultrashort-chain poly- and perfluorinated substances: A review. *Chemosphere,* 220(2019), 866-882. https://doi.org/10.1016/j.chemosphere.2018.12.186

Baghirzade, B.S., Zhang, Y., Reuther, J. F., Saleh, N. B., Venkatesan, A. K., and Apul, O. G. 2021. Thermal Regeneration of Spent Granular Activated Carbon Presents an Opportunity to Break the Forever PFAS Cycle. *Environmental Science & Technology*, 2021, 55, 5608−5619. https://doi.org/10.1021/acs.est.0c08224

Barber, B. 2017. *Wright-Patt treating tainted water in contaminated drinking wells*. Dayton Daily News. Retrieved from https://www.daytondailynews.com/news/local/wright-patt-treating-tainted-water-contaminated-drinking-wells/WigOWMcSdQHNMYYE2bHCOK/

Belkouteb, N., Franke, V., McCleaf, P., Kohler, S., and Ahrens, L. 2020. Removal of per- and polyfluoroalkyl substances (PFASs) in a full-scale drinking water treatment plant: Long-term performance of granular activated carbon (GAC) and influence of flow-rate. *Water Research*, 182(2020), 115913. https://doi.org/10.1016/j.watres.2020.115913

Bergman, R.A., Garcia-Aleman, J., Morgan, R. 2012. Membrane Processes. In Randtke, S.J. and Horsely, M.B. (Eds.), *Water Treatment Plant Design, Fifth Edition* (pp. 15.01-15.62). McGraw Hill.

Berlien, M. J. 2003. *La Puente Valley County Water District's Experience with ISEP* Presentation of Carollo Engineers, Inc. and Association of California Water Agencies.

Berretta, C., Mallmann, T., Trewitz, K., and Kempisty, D.M. 2021. Removing PFAS from Water: From Start to Finish. In Kempisty, D.M. and Racz, L. (Eds.), *Forever Chemicals: Environmental, Economic, and Social Equity Concerns with PFAS in the Environment* (pp. 235-253). Taylor & Francis. https://doi.org/10.1201/9781003024521

Biolchini, A. 2018. *First PFAS filters in place at Plainfield Township water plant.* MLive. Retrieved from https://www.mlive.com/news/grand-rapids/2018/06/first_pfas_filters_in_place_at.html

Boodoo, F. 2018a. *Short & Long Chain PFAS Removal to Non-Detect Level with Single-Use PFA694E Resin*. Presentation by Purolite Corporation. Retrieved from https://docs.house.gov/meetings/IF/IF18/20180906/108649/HHRG-115-IF18-20180906-SD027.pdf

Boodoo, F. 2018b. Personal Communication (E-mail). July 12, 2018.

Boodoo, F. 2021. Personal Communication (E-mail). June 7, 2021.

Boodoo, F., Begg, T., Funk, T., Kessler, T., Shaw, E., and Pickel, M. 2019. "Polishing PFAS to Non-Detect Levels Using PFAS-Selective Resin." Water Online, February 13. Retrieved from https://www.wateronline.com/doc/polishing-pfas-to-non-detect-levels-using-pfas-selective-resin-0001

Boonya-Atichart, A., Boontanon, S. K., and Boontanon, N. 2016. Removal of perfluorooctanoic acid (PFOA) in groundwater by nanofiltration membrane. *Water Science and Technology*, 74 (11), 2627–2633. https://doi.org/10.2166/wst.2016.434

Buck, R.C., Franklin, J., Berger, U., Conder, J.M., Cousins, I.T., de Voogt, P., Jensen, A.A., Kurunthachalam, K., Mabury, S.S., and van Leeuwen, S.P. 2011. Perfluoroalkyl and polyfluoroalkyl substances in the environment: terminology, classification, and origins. *Integr Environ Assess Manag*, 7(4), 513-541. https://doi.org/10.1002/ieam.258

Business Wire. 2018. *Kennebunkport and Wells Water District to Remove PFAS with Evoqua's Granular Activated Carbon (GAC) System.* Business Wire. Retrieved from

https://www.businesswire.com/news/home/20180521005092/en/Kennebunkport-Wells-Water-District-Remove-PFAS-Evoqua%E2%80%99s

Casey, D., Goetz, B., Martin, B. 2018. *Case Study: Moving Beyond Carbon for More Effective PFAS Removal*. AWWA Water Quality Technology Conference. Toronto, ON.

CDM Smith. 2018. *Advanced Treatment Options for the Northwest Water Treatment Plant*. Final Report. Prepared for Brunswick County Public Utilities.

Chalfont Borough. 2021. *Public Water Quality*. Borough Services for Chalfont Borough. Retrieved from https://www.chalfontborough.com/information/public-water-quality/

City of Issaquah. 2020. *PFAS*. Retrieved from https://www.issaquahwa.gov/1742/PFAS

City of Portsmouth – Department of Public Works. 2019. *Portsmouth Water System PFAS Update*. Retrieved from https://www.cityofportsmouth.com/publicworks/water/portsmouth-water-system-pfas-update

City of Rome. 2019. *ROME WATER AND SEWER DIVISION – EPA UPDATE BRIEF (PFOA / PFOS)*. Retrieved from https://www.romega.us/DocumentCenter/View/204/PFAS-Update-2019-PDF

City of Westfield Department of Public Works Water Division. 2019. *DRINKING WATER HEALTH ADVISORY UPDATE: Westfield Public Drinking Water System*. Retrieved from https://westfielddevelopment.com/DocumentCenter/View/8884/Drinking-Water-Health-Advisory---October-2019

Cronin, M. 2020. *Water filtration facility under construction to filter PFAS from Merrimack water*. WMUR9. Retrieved from https://www.wmur.com/article/water-filtration-facility-under-construction-to-filter-pfas-from-merrimack-water/30616073#

Cummings, L., Matarazzo, A., Nelson, N., Sickels, F., and Storms, C. 2015. *Recommendation on Perfluorinated Compound Treatment Options for Drinking Water*. New Jersey Drinking Water Quality Institute Treatment Subcommittee. Retrieved from https://www.nj.gov/dep/watersupply/pdf/pfna-pfc-treatment.pdf

Danko, A. 2018. *Treatment Technologies for PFAS Site Management*. Retrieved from https://frtr.gov/pdf/meetings/nov18/presentations/handouts/danko-handout.pdf

Dickenson, E.R.V. and Higgins, C. 2016. *Treatment Mitigation Strategies for Poly- and Perfluoroalkyl Substances*. Web Report #4322. Water Research Foundation.

DiStefano, R., Feliciano, T., Mimna, R., Redding, A., and Matthis J. (2022) Thermal destruction of PFAS during full-scale reactivation of PFAS-laden granular activated carbon, Remediation, 2022;32:231-238., https:/doi.org/10.1002/rem.21735.

Dixit, F., Barbeau, B., Mostafavi, S.G., and Mohseni, M. 2021. PFAS and DOM removal using an organic scavenger and PFAS-specific resin: Trade-off between regeneration and faster kinetics. *Science of the Total Environment*, 754(2021), 142107. https://doi.org/10.1016/j.scitotenv.2020.142107

Dixit, F., Barbeau, B., Mostafavi, S.G., and Madjid, M. 2020. Removal of legacy PFAS and other fluorotelomers: Optimized regeneration strategies in DOM-rich waters. *Water Research*, 183(2020), 116098. https://doi.org/10.1016/j.watres.2020.116098

Dixit, F., Barbeau, B. and Mohseni, M., 2019. Optimized regeneration strategies for ion exchange resins during PFCs removal from natural waters.

Dowbiggin, B., Treadway, J., Nichols, J. and Walker G. 2021. Exploring Treatment Options for PFAS Removal in Brunswick County, North Carolina. *Journal AWWA,* 113(4), 10-19. https://doi.org/10.1002/awwa.1705

Forrester, E. 2019. *Calgon Carbon PFAS Experience.* Calgon Carbon.

Forrester, E. and Bostardi, C. 2019. *PFAS Removal: GAC & IX.* Calgon Carbon Corporation. Webinar. April 23, 2019.

Gagliano, E., Sgroi, M., Falciglia, P.P., Vagliasindi, F.G.A., and Roccaro, P. 2020. Removal of poly- and perfluoroalkyl substances (PFAS) from water by adsorption: Role of PFAS chain length, effect of organic matter and challenges in adsorbent regeneration. *Water Research,* 171(2020), 115381. https://doi.org/10.1016/j.watres.2019.115381

Gallagher, A. 2017. *NEWMOA Workshop: PFAS in the Northeast: State of Practice & Regulatory Perspectives.* Retrieved from www.newmoa.org/events/docs/259_227/GallagherMA_May2017_final.pdf

Gordon, V. 2018. *Hampton Bays Water District Gets Green Light to Turn On Two Of Three Wells.* The Southampton Press. Retrieved from https://www.27east.com/southampton-press/southampton-news/hampton-bays-water-district-gets-green-light-to-turn-on-two-of-three-wells-1568745/

Hopkins, Z.R. 2021. *Granular Activated Carbon Adsorption of Per- and Polyfluoroalkyl Substances - from Scale-Up to Factors Affecting Performance.* Doctoral Dissertation, North Carolina State University. ProQuest Dissertations Publishing. 29004569.

Hopkins, Z.R., Sun, M., DeWitt, J.C., and Knappe, D.R.U. 2018. Recently Detected Drinking Water Contaminants: GenX and Other Per- and Polyfluoroalkyl Ether Acids. *Journal AWWA,* 110(7), 13-28. https://doi.org/10.1002/awwa.1073

Horsham Water and Sewer Authority (HWSA). 2021. *PFAS Summary.* Retrieved from https://www.horshamwater-sewer.com/pfas-summary

Horst, J., McDonough, J., Ross, I., Dickson, M., Miles, J., Hurst, J., and Storch, P. 2018. Water Treatment Technologies for PFAS: The Next Generation. *Groundwater Monitoring & Remediation*, 38(2), 13-23. https://doi.org/10.1111/gwmr.12281

Interstate Technology Regulatory Council (ITRC). 2020. Naming Conventions and Physical and Chemical Properties of Per- and Polyfluoroalkyl Substances (PFAS). Retrieved from https://pfas-1.itrcweb.org/fact_sheets_page/PFAS_Fact_Sheet_Naming_Conventions_April2020.pdf

Jent, H. 2020. *Crews near completion on new ion-exchange treatment plant to purify water in Security.* The Gazette. Retrieved from https://gazette.com/news/crews-near-completion-on-new-ion-exchange-treatment-plant-to-purify-water-in-security/article_2bf7d0ce-0410-11eb-8776-8306994433b3.html

Kempisty, D.M., Arevalo, E., Reinert, A., Edeback, V., Dickenson, E., Husted, C. Higgins, C.P., Summers, R.S., and Knappe, D.R.U. 2019. *Adsorption of per and polyfluoroalkyl acids from ground and surface water by granular activated carbon.* AWWA Water Quality Technology Conference, Dallas, TX.

Kothawala, D.N., Kohler, S.J., Ostlund, A., Wiberg, K., and Ahrens, L. 2017. Influence of dissolved organic matter concentration and composition on the removal efficiency of perfluoroalkyl substances (PFASs) during drinking water treatment. *Water Research,* 121(2017), 320-328. http://dx.doi.org/10.1016/j.watres.2017.05.047

Kumarasamy, E., Manning, I. M., Collins, L. B., Coronell, O., and Leibfarth, F. A. 2020. Ionic Fluorogels for Remediation of Per-and Polyfluorinated Alkyl Substances from Water. *ACS Central Science*, 2020(6), 487−492. https://doi.org/10.1021/acscentsci.9b01224

Kwan, P., and York, B. 2017. *City of Issaquah's Treatment Response after Detecting Perfluorinated Compounds.* AWWA Water Quality Technology Conference, Portland, OR.

Lipp, P., Sacher, F., and Baldauf, G. 2010. Removal of organic micro-pollutants during drinking water treatment by nanofiltration and reverse osmosis. *Desalination and Water Treatment*, 13(2010), 226-237. http://doi.org/10.5004/dwt.2010.1063

Liu, C. 2017. *Removal of Perfluorinated Compounds in Drinking Water Treatment: A Study of Ion Exchange Resins and Magnetic Nanoparticles*. Doctoral Dissertation, University of Waterloo. Retrieved from http://hdl.handle.net/10012/12660

Liu, C.J., Strathmann, T.J. and Bellona, C. 2021. Rejection of per- and polyfluoroalkyl substances (PFASs) in aqueous film-forming foam by high-pressure membranes. *Water Research*, 188(2021), 116546. https://doi.org/10.1016/j.watres.2020.116546

Liu, C., Werner, D., and Bellona, C. 2019. Removal of per- and polyfluoroalkyl substances (PFASs) from contaminated groundwater using granular activated carbon: a pilot-scale study with breakthrough modeling. *Environ. Sci.: Water Res. Technol.,* 2019(11). https://doi.org/10.1039/c9ew00349e

Liu, Y.-L. and Sun, M. 2021. Ion exchange removal and resin regeneration to treat per- and polyfluoroalkyl ether acids and other emerging PFAS in drinking water. *Water Research*, 207(2021), 117781. https://doi.org/10.1016/j.watres.2021.117781

Lombardo, J., Berretta, C., Redding, A., Swanson, C., and Mallmann, T. 2018. Carbon and Resin Solutions for PFAS Removal. Evoqua Water Technologies Webinar. March 6.

Marana Water. 2019. *Updates: April/May 2019.* Retrieved from https://www.maranaaz.gov/water-project-water

Matthis, J. and Carr, S. 2018. Reactivation of Spent Activated Carbon Used for PFAS Adsorption. In Kempisty, D.M, Xing, Y., and Racz, L. (Eds.), *Perfluoroalkyl Substances in the Environment: Theory, Practice, and Innovation* (pp. 303-323). Taylor & Francis. https://doi.org/10.1201/9780429487125

McCleaf, P., Englund, S., Ostlund, A., Lindegren, K., Wiberg, K., and Ahrens, L. 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. http://dx.doi.org/10.1016/j.watres.2017.04.057

Mende, B. 2019. *Acting Fast to Remove PFAS.* AWWA Water Quality Technology Conference, Dallas, TX.

Meng, P., Hopkins, Z., Tang, T., Liu, C., Bellona, C., and Knappe, D.R.U. 2021. *PFAS removal by GAC: What are drivers for GAC use rate?* AWWA Water Quality Technology Conference, Tacoma, WA.

Mickley, M. 2018. *Updated and Extended Survey of U.S. Municipal Desalination Plants*. Desalination and Water Purification Research and Development Program Report No. 207. U.S. Department of the Interior, Bureau of Reclamation.

Minnesota Department of Health (MDH). 2010. *Oakdale and 3M Work Together to Remove Perfluorochemicals.* Waterline. Retrieved from https://www.health.state.mn.us/communities/environment/water/waterline/featurestories/oakdale.html

Montgomery News. 2017. *Horsham Township Council members inspect new water filter.* The Reporter. Retrieved from https://www.thereporteronline.com/news/times-chronicle-public-spirit/

Mordock, J. 2016. *In Delaware, C8 contamination blamed on firefighting foam.* The News Journal. Retrieved from https://www.delawareonline.com/story/money/2016/04/01/delaware-c8-contamination-blamed-firefighting-foam/81538418/

National Center for Biotechnology Information (NCBI). 2021a. *PubChem Compound Summary for CID 9554, Perfluorooctanoic acid*. Retrieved from https://pubchem.ncbi.nlm.nih.gov/compound/9554#section=2D-Structure

NCBI. 2021b. *PubChem Compound Summary for CID 74483, Perfluorooctanesulfonic acid*. Retrieved from https://pubchem.ncbi.nlm.nih.gov/compound/Perfluorooctanesulfonic-acid#section=2D-Structure

New York State Department of Environmental Conservation (NYS DEC). 2021. *Hoosick Falls Area Information for Communities Impacted by Per- and Poly-fluorinated Aklyl Substances (PFAS).* Retrieved from https://www.dec.ny.gov/chemical/108791.html

NYS DEC. 2020a. *Newburgh Information for Communities Impacted by Per- and Polyfluoroalkyl Substances (PFAS).* Retrieved from https://www.dec.ny.gov/chemical/108825.html

NYS DEC. 2020b. *Petersburgh Information for Communities Impacted by Perfluorinated Compounds (PFCs)*. Retrieved from https://www.dec.ny.gov/chemical/108820.html

Najm, I., Gallagher, B., Vishwanath, N., Blute, N., Gorzalski, A., Feffer, A., and Richardson, S. 2021. Per- and polyfluoroalkyl substances removal with granular activated carbon and a specialty adsorbent: A case study. *AWWA Water Science*, 3(5), e1245. https://doi.org/10.1002/aws2.1245

Page, S. 2020. *Quantifying GAC Performance for PFAS Removal at a Surface Water Treatment Plant.* Retrieved from https://cdn.ymaws.com/mi-water.site-ym.com/resource/resmgr/docs/borchardt_2020_presentations/07_-_borchardtconf-quantgacp.pdf

Park, M., Wu, S., Lopez, I.J., Chang, J.Y., Karanfil, T., and Snyder, S.A. 2020. Adsorption of perfluoroalkyl substances (PFAS) in groundwater by granular activated carbons: Roles of hydrophobicity of PFAS and carbon characteristics. *Water Research*, 170(2020), 115364. https://doi.org/10.1016/j.watres.2019.115364

Park, M., Wu, S., Lopez, I., and Snyder, S. 2017. *Granular activated carbon (GAC) adsorption for perfluorinated alkylsubstances (PFASs) attenuation in groundwater*. AWWA Water Quality Technology Conference. Portland, OR.

PFAS Project Lab. 2021. *Montclair, New Jersey.* Retrieved from https://pfasproject.com/montclair-new-jersey/

Redding, A., Grieco, S., Roth, J., and Forrester, E. 2019. *Validation of Rapid Small-Scale Column Tests (RSSCTs) to Replicate Large Scale Systems for PFAS*. AWWA Water Quality Technology Conference, Dallas, TX.

Robinson, K. 2018. *ECUA sues national manufacturers over contamination of Escambia water wells.* Pensacola News Journal. Retrieved from https://www.pnj.com/story/news/2018/06/26/ecua-sues-over-contaminated-water-wells/731268002/

Rodowa, A. E., Knappe, D. R., Chiang, S. Y. D., Pohlmann, D., Varley, C., Bodour, A., and Field, J. A. 2020. Pilot scale removal of per-and polyfluoroalkyl substances and precursors from AFFF-impacted groundwater by granular activated carbon. *Environmental Science: Water Research & Technology*, 2020(6), 1083. https://doi.org/10.1039/c9ew00936a

Rogers, R.D., Reh, C.M., and Breysse, P. 2021. Advancing per- and polyfluoroalkyl substances (PFAS) research: an overview of ATSDR and NCEH activities and recommendations. *J Expo Sci Environ Epidemiol*, 31(6), 961-971. https://doi.org/10.1038/s41370-021-00316-6

Schaefer, C.E., Nguyen, D., Ho, P., Im, J., and LeBlanc, A. 2019. Assessing Rapid Small-Scale Column Tests for Treatment of Perfluoroalkyl Acids by Anion Exchange Resin. *Ind. Eng. Chem. Res.*, 2019(58), 9701−9706. https://doi.org/10.1021/acs.iecr.9b00858

Small Business Advocacy Review Panel. 1999. *Report of the Small Business Advocacy Review Panel on EPA's Planned Proposal of the National Primary Drinking Water Regulation for Arsenic*. Retrieved from

https://www.sba.gov/sites/default/files/files/Report_Drinking_Water_Regulation_Aresnic_06-04-1999.pdf

Sobko, K. 2021. *Garfield faces $2M tab after contamination of water supply exceeds standards.* North Jersey. Retrieved from https://www.northjersey.com/story/news/bergen/garfield/2021/07/22/garfield-nj-water-contamination-cleanup-chemicals/8046381002/

Stanton, R. 2019. *Ann Arbor spending another $950K on PFAS filters for water plant*. MLive. Retrieved from https://www.mlive.com/news/ann-arbor/2019/06/ann-arbor-spending-another-950k-on-pfas-filters-for-water-plant.html

Steinle-Darling, E., and Reinhard, M. 2008. Nanofiltration for Trace Organic Contaminant Removal: Structure, Solution, and Membrane Fouling Effects on the Rejection of Perfluorochemicals. *J. Environ. Sciences,* 42, 5292–5297. https://doi.org/10.1021/es703207s

Sullivan, M. 2018. *Addressing Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoic Acid (PFOA)*. U.S. Department of Defense. Retrieved from https://denix.osd.mil/derp/home/documents/pfos-pfoa-briefing-to-the-hasc/

Thompson, J., Eaglesham, G., Reungoat, J., Poussade, Y., Bartkowf, M., Lawrence, M. and Mueller, J.F. 2011. Removal of PFOS, PFOA and other perfluoroalkyl acids at water reclamation plants in South East Queensland Australia. *Chemosphere*, 82(2011), 9-17. https://doi.org/10.1016/j.chemosphere.2010.10.040

Tow, E.W., Ersan, M.S., Kum, S., Lee, T., Speth, T.F., Owen, C. Bellona, C., Nadagouda, M.N., Mikelonis, A.M., Westerhoff, P., Mysore, C., Frenkel, V.S., DeSilva, V., Walker, S.W., Safulko, A.K., and Ladner, D.A. 2021. Managing and treating per- and polyfluoroalkyl substances (PFAS) in membrane concentrates. *AWWA Water Science,* 3(5), e1233. https://doi.org/10.1002/aws2.1233

U.S. Census Bureau. 2010. *American Community Survey, 5-year Estimates (2006-2010)*.

U.S. Environmental Protection Agency (USEPA). 2000. *Geometries and Characteristics of Public Water Systems*. EPA 815-R-00-24.

USEPA. 2009. *2006 Community Water System Survey*. Volume II: Detailed Tables and Survey Methodology. EPA 815-R-09-002.

USEPA. 2020. *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances*. EPA-HQ-OLEM-2020-0527-0002.

USEPA. 2021a. *Drinking Water Treatability Database: Per- and Polyfluoroalkyl Substances*. Retrieved from https://tdb.epa.gov/tdb/contaminant?id=11020

USEPA. 2021b. *Drinking Water Treatability Database: Perfluorooctane Sulfonate*. Retrieved from https://tdb.epa.gov/tdb/contaminant?id=10940

USEPA. 2021c. *Drinking Water Treatability Database: Perfluorooctanoic Acid*. Retrieved from https://tdb.epa.gov/tdb/contaminant?id=10520

USEPA. 2021d. *CompTox Chemicals Dashboard: PFAS structures in DSSTox (update August 2021).* Retrieved from https://comptox.epa.gov/dashboard/chemical-lists/PFASSTRUCTv4

USEPA. 2022b. *Drinking Water Treatability Database: Granular Activated Carbon*. Retrieved from https://tdb.epa.gov/tdb/treatmentprocess?treatmentProcessId=2074826383

USEPA. 2022c. *Drinking Water Treatability Database: Membrane Separation*. Retrieved from https://tdb.epa.gov/tdb/treatmentprocess?treatmentProcessId=-2103528007

USEPA. 2024a. *Technologies and Costs for Removing Per- and Polyfluoroalkyl Substances from Drinking Water*. 815R24012.

USEPA. 2024b. *Economic Analysis for the Final Per- and Polyfluoroalkyl Substances National Primary Drinking Water Regulation.* 815R24001.

Vandermeyden, C. and Hagerty, V. 2020. Managing PFAS: A North Carolina Utility Story. *Journal AWWA*, 112(10), 10-18. https://doi.org/10.1002/awwa.1590

Warrington Township. 2017. *Water Contamination Information.* Retrieved from https://www.warringtontownship.org/departments/water-sewer/water-contamination-info/

Wang, R., Ching, C., Dichtel, W.R., and Helbling, D.E. 2020. Evaluating the Removal of Per- and Polyfluoroalkyl Substances from Contaminated Groundwater with Different Adsorbents Using a Suspect Screening Approach. *Environmental Science and Technology Letters*, 2020(7), 954-960. https://doi.org/10.1021/acs.estlett.0c00736

Watanabe, N., Takata, M., Takemine, S., and Yamamoto, K. 2018. Thermal mineralization behavior of PFOA, PFHxA, and PFOS during reactivation of granular activated carbon (GAC) in nitrogen atmosphere. *Environmental Science and Pollution Research*, 25, 7200–7205. https://doi.org/10.1007/s11356-015-5353-2

Watanabe, N., Takemine, S., Yamamoto, K., Haga, Y., and Takata, M. 2016. Residual organic fluorinated compounds from thermal treatment of PFOA, PFHxA and PFOS adsorbed onto granular activated carbon (GAC). *Journal of Material Cycles & Waste Management,* 18, 625–630. https://doi.org/10.1007/s10163-016-0532-x

Weaver, J. 2020. PFAS should be managed as a single class of chemicals, experts say. *Environmental Factor: Your Online Source for NIEHS News*. Retrieved from: https://factor.niehs.nih.gov/2020/8/papers/pfas/index.htm

Westreich, P., Mimna, R., Brewer, J., and Forrester, F. 2018. The removal of short-chain and long-chain perfluoroalkyl acids and sulfonates via granular activated carbons: A comparative column study. *Remediation*, 29(1), 19-26. https://doi.org/10.1002/rem.21579

Wetzel, M. 2021. *Reverse osmosis filtration facility near completion.* The Moulton Advertiser. Retrieved from https://www.moultonadvertiser.com/news/article_dd221c14-fabf-11eb-801f-c3b7ff0b4dc4.html

WHNT News. 2019. *WMEL water authority approves $30.5 million contract for Reverse Osmosis treatment system*. Nexstar Media Inc. Retrieved from https://whnt.com/news/wmel-water-authority-approves-30-5-million-contract-for-reverse-osmosis-treatment-system/

Widefield Water and Sanitation District (WWSD). 2018. From Pilot to Full-Scale: A Case Study for the Treatment of Perfluorinated Compounds (PFCs) with Ion Exchange. AWWA Water Quality Technology Conference, Toronto, ON, Canada.

Woodard, S., Berry, J., and Newman, B. 2017. Ion exchange resin for PFAS removal and pilot test comparison to GAC. *Remediation*, 27, 19-27. https://doi.org/10.1002/rem.21515

Xiao, F., Sasi, P.C., Yao, B., Kubatova, A., Golovko, S.A., Golovko, M.Y., and Soli, D. 2020. Thermal Stability and Decomposition of Perfluoroalkyl Substances on Spent Granular Activated Carbon. *Environmental Science and Technology Letters*, 2020, 7, 343−350. https://dx.doi.org/10.1021/acs.estlett.0c00114

Yan, B., Munoz, G., Sauvé, S., and Liu, J. 2020. Molecular mechanisms of per- and polyfluoroalkyl substances on a modified clay: a combined experimental and molecular simulation study. *Water Research*, 184(2020), 116166. https://doi.org/10.1016/j.watres.2020.116166

Zaggia, A., Conte, L., Falletti, L., Fant, M., and Chiorboli, A. 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(2016), 137-146. http://dx.doi.org/10.1016/j.watres.2015.12.039

Zeng, C., Atkinson, A., Sharma, N., Ashani, H., Hjelmstad, A., Venkatesh, K., and Westerhoff, P. 2020. Removing per-and polyfluoroalkyl substances from groundwaters using activated carbon and ion exchange resin packed columns. *AWWA Water Science*, 2(1), e1172. https://doi.org/10.1002/aws2.1172