PFAS Treatment Evaluation

Framework for Approaching Permit/Plan Approval

American Water Works Association

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Abbreviations, Acronyms, and Units

AIX	anion exchange
ASDWA	Association of State Drinking Water Administrators
AWWA	American Water Works Association
BAT	best available technology
BV	bed volume
C	effluent concentration
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CI	common influent
C_o	influent concentration
CSMR	chloride to sulfate mass ratio
CWS	community water system
Da	Dalton
DBP	disinfection byproduct
DOC	dissolved organic carbon
EBCT	empty bed contact time
EQ	equalization
ft^2	square foot
GAC	granular activated carbon
GBM	gradient boosting machine
gpm	gallons per minute
HI	hazard index
HASP	health and safety plan
HLR	hydraulic loading rate
ICE	individual column effluent
IEX-CM	ion exchange column model
IST	intermediate sampling tap
KPI	key performance indicator
lb	pound
LSI	langelier saturation index
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
µg/L	micrograms per liter
mg/L	milligrams per liter
MGD	million gallons per day
MIB	methyl-isoborneol
min	minute
MTZ	mass transfer zone
MWCO	molecular weight cutoff

ND	non-detect
NDMA	N-nitrosodimethylamine
NF	nanofiltration
ng/L	nanograms per liter
NOM	natural organic matter
NPDWR	National Primary Drinking Water Regulation
NSF	National Sanitation Foundation
NTNCWS	non-transient non-community water system
NTU	nephelometric turbidity units
O&M	operation and maintenance
PAC	powdered activated carbon
PFAS	per- and polyfluoroalkyl substances
PQL	practical quantification limit
PSDM	pore surface diffusion model
PTFE	polytetrafluoroethylene
PVDF	polyvinylidene fluoride
PWS	public water system
QA/QC	quality assurance and quality control
RAA	running annual average
RO	reverse osmosis
RSSCT	rapid small-scale column test
SDS	safety data sheet
SDWA	Safe Drinking Water Act
SMCL	Secondary Maximum Contaminant Level
SOP	standard operating procedure
SRF	state revolving fund
T&O	taste and odor
TAW	technical advisory workgroup
TCLP	toxicity characteristic leaching procedure
TOC	total organic carbon
TSS	total suspended solids
UCMR 5	fifth Unregulated Contaminant Monitoring Rule
US EPA	United States Environmental Protection Agency
VOC	volatile organic carbon
WBS	work breakdown structure
WITAF	Water Industry Technical Action Fund
WTP	water treatment plant

Executive Summary

On April 26, 2024, the United States Environmental Protection Agency (US EPA) promulgated a National Primary Drinking Water Regulation (NPDWR) which established maximum contaminant levels (MCLs) and MCL goals (MCLGs) for five (5) individual per- and polyfluoroalkyl substances (PFAS) and one (1) mixture of four (4) PFAS. Federal compliance with the MCLs is based on a running annual average (RAA) calculated based on observations from samples collected at the entry points to the distribution systems (EPTDSs). Compliance monitoring at EPTDSs begins April 26, 2027, with results published in the 2027 consumer confidence reports and annually thereafter. The calculated RAA from four quarters of monitoring at the EPTDS(s) prior to April 26, 2029 will determine initial compliance and public notification requirements. After the compliance deadline, any MCL violations require a Tier 2 public notification, or notification as soon as practicable but no later than 30 days after violation is identified.

Many water systems with PFAS levels exceeding the MCLs will need to install additional treatment, which typically requires a minimum of three (3) years for detailed design, bidding, and construction, though additional time is required on the front end for treatment alternative evaluations and selection. While specific requirements for permitting and approval vary by primacy agency, the primary intent of permitting is to ensure the proposed treatment approach will meet treatment objectives while avoiding potential pitfalls associated with treatment technologies for specific design criteria, water quality, and operations.

Treatment alternative evaluation methods include desktop evaluations, bench-scale testing, and/or pilot testing. Given the short timeframe for water systems to implement additional treatment if required to achieve regulatory compliance, all aspects of project development have little margin for schedule overruns. Given the relatively low PFAS concentrations in source water supplies and capacity of sorptive media, pilot studies can extend for several years before PFAS is detected in the column effluent. Thus, when applicable, other, less time-consuming treatment evaluation methods may be appropriate if they can achieve the site-specific target objectives.

The framework presented here allows water system managers and primacy agency staff to identify sources of uncertainty in PFAS treatment selection and design relevant to individual installations and organize data collection to efficiently address key data gaps. The tight compliance schedules in the PFAS NPDWR necessitate efficient decision-making to achieve desired PFAS treatment solution implementation. Efficient data collection, including pilot studies (when appropriate), will facilitate timely PFAS treatment system approval. Constructing a uniform framework can also have benefits for both water systems and state primacy agencies broadly by reducing the cumulative monetary and time investments associated with treatment system approval. For circumstances that require piloting, minimum piloting objectives are defined for site specific conditions for permitting purposes. In all instances, early involvement with state regulators is critical to ensure alignment and minimize time delays/rework.

PFAS Treatment Evaluation Approaches

The Best Available Technologies (BATs) for PFAS treatment include adsorptive technologies such as granular activated carbon (GAC) and anion exchange (AIX), as well as high pressure membrane technologies such as reverse osmosis (RO), and nanofiltration (NF). Other treatment approaches include powder activated carbon (PAC) adsorption or novel sorbent media in fixed bed contacts. Treatment evaluation methods for permitting of a PFAS treatment system design include:

- **Desktop evaluations** include analysis of operating data collected from representative pilot or full-scale operations from a similar site or literature. This approach provides a general comparative performance of different alternatives, but its accuracy is dependent upon the similarity to a given source water and quality of the data from the similar site. This approach is more widely accepted for groundwater sources due to the more stable nature of the physiochemical water quality relative to surface water sources. Empirical models that predict PFAS removal performance are available as well, although they provide the lowest confidence of all evaluation methods.

- **Bench-scale testing** involves small scale testing in a laboratory environment, using water collected from the source. Relevant considerations for each technology include:
  - Sorptive media bench-scale tests can be accomplished through rapid small scale column tests (RSSCTs). RSSCTs can expedite comparison of alternative media products for generation of life cycle cost estimates, but do not incorporate seasonal variability in water quality and are not well equipped to evaluate operational modes of failure such as fouling. RSSCTs were initially developed for predicting sorbate breakthrough of GAC media but have recently been expanded to AIX resins for PFAS removal evaluations.
  - If a novel media is approved by a primacy agency as an acceptable alternative to GAC or AIX and the novel media supplier provides accuracy data that supports scale-up from RSSCTs to pilot- or full-scale performance, bench scale testing through RSSCTs may be appropriate. Until that time, piloting of novel media will be needed to assure risk mitigation of unknown ancillary impacts.
  - PAC bench scale testing can be accomplished through jar testing for product selection and to establish the basis of design (e.g., design dose, mixing conditions, and contact time). The AWWA Standard B600-24 includes an example jar testing procedure for PAC for MIB and Geosmin treatment evaluation. This document provides guidance for adapting that procedure for PFAS treatment.
  - NF/RO bench-scale testing allows for the evaluation and development of PFAS rejection rates for a specific membrane product and may be valuable for estimating performance of a specific membrane under intended operating conditions.
- **Pilot testing** includes many benefits. This framework focuses on situations that justify pilot testing for permitting of full-scale facilities. Piloting is generally appropriate for conditions where the basis of design parameters fall outside of recommended design ranges, water quality exceeds recommended thresholds, there are unavoidable chemical additives in the influent that could compromise performance, simultaneous compliance considerations apply, or there is a desire to develop accurate operational costs. Relevant considerations for each technology include:
  - For GAC and AIX, there are several well-known water quality impacts during startup and operation that are documented herein and do not require piloting. While novel sorbents may demonstrate performance comparable to GAC and AIX, piloting is employed unless the local primacy agency approves the media as an acceptable alternative to a BAT. Circumstances that may justify piloting are presented within Table 3-4.
  - Evaluation of PAC is more appropriately conducted at the bench-scale than in a pilot test.
  - Performance of NF/RO is well documented for PFAS with typical rejection rates greater than 90 percent for NF and greater than 95 percent for RO. Pilot testing of NF/RO is necessary to determine pretreatment requirements and design criteria. Piloting of NF/RO is especially important for surface water sources due to potential impacts of organic fouling. There are a variety of piloting guidance materials available for membrane technologies, which are referenced herein.

The appropriate treatment evaluation method to select which technology to install is dependent upon the treatment technology, local primacy agency requirements, site-specific objectives, and water quality considerations. A combination of approaches may be most beneficial to selecting a treatment alternative and optimized design. A comprehensive list of objectives that can be accomplished by each treatment evaluation method is presented in Table 3-1.

Existing State Permitting Approaches

At the time of publication of this framework, four states have implemented PFAS piloting guidance for adsorptive piloting design, operation, and evaluation. The contents of these guidance documents are summarized herein. Black & Veatch and ASDWA completed two surveys to collect additional feedback on the treatment evaluation approaches required by various primacy agencies for permitting the design of new PFAS treatment systems. The results are summarized on Figure ES-1. Most states confirmed piloting would be the required treatment evaluation method. However, many states requiring piloting lack formal piloting guidance, highlighting the utility of this document. Most states confirmed their approach is expected to become less dependent on piloting over time as more data becomes available for treatment efficacy of these treatment technologies. In consideration of the compliance timeline, the US EPA has acknowledged the criticality in permitting to allow for construction to begin without knowing details of operation that may be determined through piloting while confirmatory evidence is obtained.

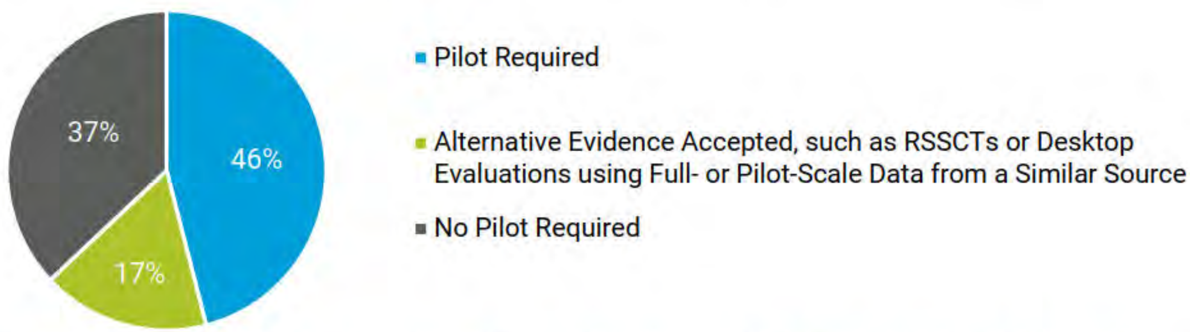

Figure ES-1 Primacy Agency Treatment Evaluation Test Requirements for Permitting Design of a New PFAS Treatment Facility as of December 2024

Sorptive Media Pilot Testing Recommendations

If a pilot test is required for adsorption technologies, suggested elements are presented herein to support development of a successful pilot program. The following are limited to piloting for GAC and AIX. However, piloting guidelines can be adapted to novel sorbents with product-specific considerations.

- A pilot protocol fully describing the pilot program must be prepared. Engaging the primacy agency at the start of a pilot program can help avoid delays and support successful pilot planning and execution. The extent of primacy agency reviews of the test protocol, periodic updates, and final findings will vary from agency-to-agency.
- Some primacy agencies will require pilot columns to be operated at the intended full-scale design hydraulic loading rate (HLR), because this will be the most conservative representation of media performance. The design empty bed contact time (EBCT) can be scaled at a consistent HLR, providing flexibility in pilot design and duration, particularly when using data from intermediate sample ports.
- A functioning pilot skid contains a variety of components that are summarized herein. Proper material selection is necessary to avoid unintended sample contamination.

- Pilot programs are designed to be representative of ultimate full-scale design. This includes utilizing source water in the pilot that is representative of the water to be treated in the full-scale treatment installation. Siting the pilot skid adjacent to the influent water collection location on the water treatment plant (WTP) site and incorporating intended full-scale pretreatment technologies, potentially including but not limited to cartridge filters and chemical feed systems facilitates achieving this objective.
- Loading and conditioning media in the individual columns per manufacturer recommendations is necessary to accurately reflect media performance.
- A sampling plan is used to execute appropriate sampling for initial startup, ongoing operation, and collection of ancillary data (e.g., data relevant to simultaneous compliance). A minimum sampling plan is presented herein, as well as methods that can be employed to decrease analytical sampling costs. By including sampling plans in pilot protocols systems can ensure proper budget is allocated.
- Regular pilot skid operational check-ins are necessary to ensure continuous operation of all pilot skid components, collect samples, confirm flow ranges, and perform as-needed backwashes.
- The piloting duration varies based on the site-specific piloting objectives. Considering the compliance timeline for the PFAS NPDWR, contaminant breakthrough at column outlets will not be the default objective for every pilot.
- There are opportunities to accelerate piloting schedules, including pore surface diffusion modeling (PSDM), scaling breakthrough data at one EBCT to another (through intermediate sample ports), emerging modeling techniques if approved by the local primacy agency, and influent PFAS spiking.
- Data obtained throughout piloting must be monitored, analyzed and tracked against the piloting objectives to assess performance and identify when the pilot columns have met their objectives and shutdown can occur. Data can be analyzed through software such as Excel and PowerBI. If breakthrough is achieved during piloting, life cycle cost projections can be developed and considered alongside non-financial factors such as simultaneous compliance and operability.
- Once the pilot is decommissioned, spent media is disposed in compliance with applicable state and federal regulations. Postmortem testing of media can be considered, as it can be informative.

1.0 Introduction

With the recent promulgation of drinking water regulations for per- and polyfluoroalkyl substances (PFAS), drinking water systems are faced with new compliance requirements for monitoring and treatment. For some WTPs, additional treatment processes will be required, while for others with PFAS removal capabilities, operational changes may be necessary to maintain compliance.

This document includes a summary of available PFAS treatment evaluation methods, including desktop evaluations, bench-scale testing, and pilot testing for various treatment technologies, and their applicability based on site-specific conditions. A summary of compiled feedback from primacy agencies nationwide has been included to document what treatment evaluation methods have been approved to-date for permitting of new PFAS treatment systems. A science-backed, expert consensus approach was used to craft the framework described. For situations that require a pilot test, key considerations for successful design and execution are presented. This framework can serve as a reference for water systems and primacy agencies nationwide.

The framework presented here allows water systems managers and primacy agency staff to identify sources of uncertainty in PFAS treatment selection and design relevant to individual installations and organize data collection to efficiently address key data gaps. The tight compliance schedules in the PFAS NPDWR necessitate efficient decision-making to achieve desired PFAS treatment solution implementation. Efficient data collection, including, when appropriate, pilot studies will facilitate timely PFAS treatment system approval. Constructing a uniform framework can also have benefits for both water systems and state primacy agencies broadly by reducing the cumulative monetary and time investments associated with treatment system approval. For circumstances that require piloting, piloting objectives are defined for site specific conditions for permitting purposes. In all instances, early involvement with state regulators is critical to ensure alignment and minimize time delays/rework.

1.1 Regulated Maximum Contaminant Levels

On April 26, 2024, the US EPA promulgated a National Primary Drinking Water Regulation (NPDWR), including maximum contaminant levels (MCLs) for five (5) individual PFAS and one (1) mixture of four PFAS, as summarized in Table 1-1 (2024).

Table 1-1 National Primary Drinking Water Regulation for PFAS

PFAS	Name	MCL (Note 1)	MCLG (Note 2)	PQL (Note 3)
PFOA (Note 4)	Perfluorooctanoic acid	4.0 ng/L (also expressed as ppt)	0 ng/L	4 ng/L
PFOS (Note 4)	Perfluorooctane sulfonic acid	4.0 ng/L	0 ng/L	4 ng/L
PFHxS (Note 5)	Perfluorohexane sulfonic acid	10 ng/L	10 ng/L	3 ng/L
GenX Chemicals (Note 5)	Hexafluoropropylene oxide dimer acid (HFPO-DA)	10 ng/L	10 ng/L	5 ng/L
PFNA (Note 4)	Perfluorononanoic acid	10 ng/L	10 ng/L	4 ng/L
PFHxS, GenX, PFNA, and PFBS (Note 5)	Perfluorohexane sulfonic acid, Hexafluoropropylene oxide dimer acid (HFPO-DA), Perfluorononanoic acid, and Perfluorobutane sulfonic acid	Hazard Index (HI) = 1 (Note 6)	HI = 1	3 ng/L 5 ng/L 4 ng/L 3 ng/L

PFAS	Name	MCL (Note 1)	MCLG (Note 2)	PQL (Note 3)
1. MCLs contain two (2) significant figures for PFOA and PFOS and one (1) significant figure for PFHxS, GenX, PFNA, and the HI.				
2. Due to carcinogenic determination for PFOA and PFOS, the MCL goals (MCLGs) were set at 0 ng/L.				
3. The practical quantitation limit (PQL) is the lowest concentration that can be reliably measured in US EPA-approved laboratories nationwide.				
4. Long-chain classification (perfluoroalkyl sulfonic acids containing ≥ 6 carbons, perfluoroalkyl carboxylic acids containing ≥ 7 carbons).				
5. Short-chain classification.				
6. The HI approach limits the combined concentration of four PFAS and is only applicable when at least two of the four PFAS are simultaneously detected. The HI is calculated using the following formula: HI = (GenX)/(10 ng/L) + (PFBS)/(2,000 ng/L) + (PFNA)/(10 ng/L) + [PFHxS]/(10 ng/L)				
Where (x) = concentration in water sample in ng/L and the denominator is a health-based water concentration for each PFAS				

Federal compliance with the MCLs is based on a running annual average (RAA) calculated using observations from samples collected at EPTDSs. Compliance monitoring at EPTDSs begins April 26, 2027, with results published in the 2027 consumer confidence reports and annually thereafter. The calculated RAA from four quarters of monitoring at EPTDSs prior to April 2029 will determine initial compliance and public notification requirements, as indicated by the following formula. Any results below the PQL will be counted as zero (0) in the RAA calculation.

$$\text{April 2029 RAA (Initial Compliance)} = \frac{\text{Q3 2028} + \text{Q4 2028} + \text{Q1 2029} + \text{Q2 2029}}{4}$$

After the compliance deadline, any MCL violations require a Tier 2 public notification, or notification as soon as practicable but no later than 30 days after violation is identified. The regulated entities are community water systems (CWS) and non-transient non-community water systems (NTNCWS). Some primacy agency requirements may differ from the NPDWR. In that case, the more stringent requirement will take precedence.

Systems using a BAT may seek a variance under the Safe Drinking Water Act (SDWA) section 1415(a)(1)(A) if that system fails to meet an MCL by the compliance deadline. Similarly, a PWS that cannot install a BAT due to inability to obtain financing and instead justifies and installs an alternative technology may seek an exemption under SDWA section 1416. More typical practice for systems exceeding MCLs after the compliance date is for those systems to be in violation and subject to state direction with specific timelines for remedying the violation.

1.2 Compliance Timelines

Many public water systems (PWSs) with PFAS levels exceeding the MCLs will need to install additional treatment, which typically requires a minimum of three (3) years for detailed design, bidding, and construction, though additional time is required on the front end for treatment alternative evaluations and selection. Treatment alternative evaluation methods include desktop evaluations, bench-scale testing, and/or pilot testing. Few primacy agencies have published guidance on PFAS pilot testing required for permitting approvals, as further detailed in Section 4.1. Given the short timeframe for water systems to implement additional treatment if required to achieve regulatory compliance, all aspects of project development have little margin for schedule overruns. Given the relatively low PFAS concentrations in source water supplies and capacity of sorptive media, pilot studies can extend for several years before PFAS is detected in the column effluent (also referred to as breakthrough).

An example schedule is presented on Figure 1-1, which displays the planning window afforded by the PFAS NPDWR for a PWS with finished water PFAS concentrations greater than or equal to four (4) times their respective MCLs. Since the RAA must be below the MCL by April 2029, PFAS removal treatment would need to be installed nine (9) months prior to the deadline. This assumes the first compliance sample is collected in July 2028, which may vary between PWSs. Depending on the starting concentrations and compliance sampling schedule, construction timelines may be less rigorous than this example. Additionally, design and construction durations will vary from the example presented due to a number of factors, including facility size.

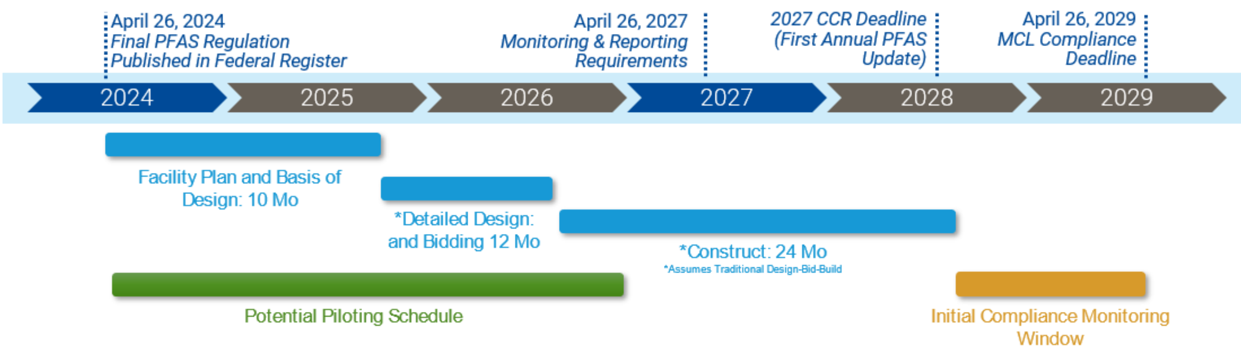

Figure 1-1 Example Compliance Timeline for New PFAS NPDWR for PWS with PFAS >4x MCL

This example provided in Figure 1-1 highlights the criticality of optimizing piloting efforts within the compliance timeline. Refinement of piloting objectives is necessary to streamline the schedule. Sufficient data must be gleaned early on to minimize rework during detailed design that could delay the project schedule and minimize risk of change orders during construction. This example also highlights the criticality of flexibility in permitting that allow for construction to begin without knowing details of operation that may be determined through piloting. Section 5.0 provides details on pilot objective identification and opportunities to streamline piloting durations to allow PWSs to meet the compliance timeline and reduce risk of change orders during construction.

1.3 Pilot Testing

Most existing state regulatory frameworks and guidance for pilot testing is not applicable to PFAS treatment. Thus, PFAS piloting objectives need to be established early in the process to avoid unnecessary delays. For permitting purposes, regulators typically focus on understanding and mitigating unintended treatment impacts in a pilot test.

In the absence of guidance to define clear pilot objectives for a new adsorptive media PFAS treatment system, the evaluation of target contaminant breakthrough can become the default objective of piloting. Although piloting to determine media life can provide valuable information for life cycle cost evaluations, accurate life cycle cost projections of a preferred solution is not a fundamental element of the permitting process. Treatment efficacy for PFAS reduction using the BATs identified in the NPDWR has been demonstrated in many studies. Treatment alternative evaluations and cost comparisons can be assessed through desktop evaluations or bench-scale tests (less time-consuming methods than piloting) in instances where there is high certainty in technology performance efficacy.

Objectives that can be accomplished through each treatment evaluation method, including pilot testing, are summarized in Table 3-1, and considerations that may prompt the need for a pilot test are covered in Table 3-4. If a system is driven to pilot for various reasons, there are many supplementary benefits from the data collected, such as more accurate life cycle cost predictions, design optimization, and operator training, but treatment evaluation method selection for permitting purposes is not based on these criteria.

2.0 Technologies and Approaches to Achieve Compliance

The path for compliance with the PFAS NPDWR for water systems that exceed regulatory limits may include:

- Remediating the contamination
- Avoiding the use of contaminated water sources
- Switching to or developing new water sources that meet the regulatory limits
- Implementing PFAS treatment to meet regulatory limits
- Some combination of the above strategies

The strategy that each PWS employs must be based on a site-specific evaluation that considers economic and non-economic factors. An exhaustive accounting of all aspects of these strategies is out of the scope of this document. A variety of references are available to support source water evaluations and technology selection, as listed below.

- Best Available Technologies and Small System Compliance Technologies for Per- and Polyfluoroalkyl Substances (PFAS) in Drinking Water, US EPA, March 2024
- Treatment Options for Removing PFAS from Drinking Water, US EPA, April 2024
- Source Water Evaluation Guide for PFAS, AWWA, 2020
- Drinking Water Treatment for PFAS Selection Guide, AWWA and HDR, 2020
- Ion Exchange for Drinking Water Treatment; AWWA, 2021
- Activated Carbon: Solutions for Improving Water Quality, AWWA, 2013
- Powdered Activated Carbon; ANSI/AWWA Standard B600-24; AWWA, 2024
- Granular Activated Carbon; ANSI/AWWA Standard B604-18; AWWA, 2018
- Reactivation of Granular Activated Carbon; ANSI/AWWA Standard B605-18; AWWA, 2018
- Single-Use Ion Exchange Treatment for Trace Contaminant Removal; ANSI/AWWA Standard B104-24, AWWA, 2025

2.1 Best Available Technologies (BATs)

US EPA identified granular activated carbon (GAC), anion exchange (AIX), and high-pressure membranes such as reverse osmosis (RO) and nanofiltration (NF) as the BATs for meeting the PFAS NPDWR. BATs were established based on PFAS removal efficiency, historical full-scale operation, geographic applicability, compatibility with other treatment processes, and the ability to bring PWSs into compliance.

2.1.1 Granular Activated Carbon

GAC media is a well-known adsorbent for organics and has been widely applied in water treatment. GAC is produced from carbon-based materials such as coal, coconut shells, peat, or wood that has been "activated" to produce a highly porous media with adsorptive properties. The pores contain sites on which organic compounds become attached and are adsorbed onto the activated carbon matrix. GAC treatment applications include removal of organics, color, disinfection byproducts (DBP) and their precursors, taste and odor (T&O) causing compounds, industrial chemicals, emerging contaminants such as PFAS, endocrine disrupting compounds, and pharmaceuticals and personal care products. Current research indicates greater PFAS removal using bituminous coal-based media than non- and sub-bituminous media

(Pannu, et al., 2023), (Medina, et al., 2022), though alternative GAC products can still provide PFAS treatment and may be preferred based on other site-specific conditions.

Various influent water quality constituents, particularly natural organic matter (NOM) as a component of total organic carbon (TOC), compete with PFAS for adsorption sites on GAC media. TOC is widely recognized as a primary limiting factor for PFAS adsorption on GAC due to its typically higher concentrations (milligram per liter) compared to PFAS (nanogram per liter) and its strong affinity for GAC, as evidenced by competitive adsorption effects observed in several studies (Gagliano, et al., 2020; Du, et al., 2014). GAC performance for TOC removal varies based on the site-specific TOC characterization, with humic and fulvic acids having high affinity to GAC sorption and hydrophilic organics generally not adsorbing to GAC (Pannu, et al., 2023). In some cases, co-adsorption can be viewed as a benefit for using GAC as the co-contaminants are simultaneously removed; in other cases, co-removal is a disadvantage because it works to decrease the adsorptive capacity for target compounds.

Adsorptive media, such as GAC and AIX, demonstrates greater efficacy in removing long-chain PFAS compared to short-chain PFAS and is more effective at adsorbing sulfonic acids (e.g., PFOS, PFBS, PFHxS) than their carboxylic acid counterparts (e.g., PFOA, PFNA) (Chow, et al., 2022). Due to the finite number of adsorption sites in adsorptive media, there is a potential for chromatographic peaking, where stronger adsorbing constituents outcompete weaker ones, thereby displacing the weaker-adsorbing contaminants into the effluent. Also, when the influent concentration of a contaminant drops, the contaminant can be released as it begins to reach its solid/liquid phase equilibrium point at lower liquid-phase concentrations. Longer design empty bed contact time (EBCT), including that for lead/lag pressure vessel arrangements, can provide additional adsorption sites, thereby delaying this effect. Alternatively, increased media changeout frequencies may be required.

2.1.1.1 Design Considerations for GAC

Typical design criteria for each contactor arrangement are summarized in Table 2-1.

Table 2-1 Typical Design Criteria for GAC Treatment of PFAS

Design Criteria	Value/Range	
Contactor Arrangement	**Gravity Basin**	**Pressure Vessel**
Maximum Hydraulic Loading Rate (HLR) at Design Flow	6 gpm/ft^2	8 gpm/ft^2
EBCT at Design Flow	10 to 20 min	10 to 20 min
Operation	Parallel	Parallel (single stage) or Series (lead-lag; dual stage)
Influent Water Quality Considerations to avoid Fouling	TOC < 4 mg/L (Note 1) Fe < 0.3 mg/L (Note 2) Mn < 0.05 mg/L (Note 2) Cl_2 < 4 mg/L Langelier saturation index (LSI) < 1 (Note 3)	

Notes:
1. GAC will perform best for PFAS treatment at lower TOC levels than presented herein due to competitive adsorption. Risk of fouling from TOC is largely dependent upon the nature of the compounds comprised in those organics. Risk of fouling may vary based on TOC composition. Biofouling concerns can be mitigated through increased grain sizing in GAC, though grain sizing may impact PFAS adsorption performance.
2. See further context in Section 2.1.1.2.
3. One GAC manufacturer suggested an LSI below 1 to avoid issues with excessive scale accumulation onto the media, which could negatively impact performance.

GAC contactors include backwash provisions. Backwashing to achieve approximately 25 to 30 percent bed expansion (per the manufacturer recommendations) is required at start up. During normal operation, periodic backwashing at a rate that does not fluidize the bed has been beneficial to mitigate head loss. Subfluidization backwash is also recommended before placing a contactor online after sitting idle to displace any stagnant water. Subfluidization backwash rates will minimize disturbance of the mass transfer zone (MTZ). If subfluidization backwash rates do not mitigate head loss, fluidized backwash rates may be necessary. The frequency and duration of the subfluidization and normal backwashes are minimized to the degree possible. These operational practices are typically defined and optimized during full-scale operation. However, there are design implications, for example high turbidity influent water that may require excessive backwashing, such as raw water treatment of a surface water source, requires treatment prior to GAC. Treating filtered surface water or raw groundwater is not expected to cause issues with head loss unless there are other unmitigated water quality issues such as presence of high iron or manganese concentrations, as summarized further in Section 2.1.1.2.

Filter-to-waste is an important element of GAC design. Filter-to-waste will be necessary during GAC contactor startup but can be accomplished through alternative, temporary means. Depending on the number of contactors included in the design, additional filter-to-waste provisions may be necessary following reactivation if blending is insufficient to meet finished water quality goals. Post-backwash filter-to-waste can also remove fines developed during backwash, optimizing finished water quality sent to the distribution system.

Another design consideration for GAC systems is the impact of GAC treatment on primary disinfection. When chlorine is applied to GAC, a rapid surface-catalyzed reaction occurs that reduces free chlorine to chloride at the GAC surface, but has negligible impact to the meso- and micro-pores within the media and therefore its adsorptive capacity. Chemicals used to achieve primary disinfection credits will need to be re-applied downstream of the GAC system. Optimizing pre-oxidant dosages avoids unnecessary carry-over from previous treatment processes and excessive chemical use. Pre-oxidation processes such as pre-chlorination may oxidize NOM into lower molecular weight compounds that compete for GAC adsorption sites (Chen, et al., 2022), but the impact of pre-oxidation is expected to be limited when GAC is implemented after filtration.

The Langelier Saturation Index (LSI) is a widely used parameter to characterize saturation and solubility with respect to calcium carbonate, which can precipitate out of solution and accumulate scale onto treatment equipment. The LSI is the difference between the actual water pH and the saturation pH for calcium carbonate. As summarized in Table 2-1, LSI values greater than 1 indicate a potential for excessive scale accumulation, which could negatively impact GAC performance.

2.1.1.1.1 Contactor Arrangement

GAC treatment for PFAS is commonly implemented employing a dedicated contactor downstream of conventional filters. Conventional filtration using GAC media for particle removal and PFAS adsorption can be very cost-effective, but involves the following considerations:

- HLR will be limited to state-approved level (typically 4.0 gpm/ft^2).
- Conventional granular media filters are typically not deep enough to achieve recommended GAC empty bed contact times (EBCTs) for PFAS treatment. This can be overcome by more frequent media changeouts if target facility production capacity can be maintained.

- Conventional filters require backwashing at a rate that fluidizes and vigorously mixes the entire bed for removal of particulate material that is retained in the media, which can disrupt the MTZ of PFAS within the media and cause premature breakthrough, as compared to the subfluidization backwash rates for adsorption applications as summarized in Section 2.1.1.1. Additionally, backwash fluidization rates required for conventional filtration may result in GAC abrasion, releasing GAC fines and causing material degradation.

GAC adsorbers can be implemented as either gravity basins or pressure vessels, where selection of contactor configuration is often driven by the treatment capacity required. Pressure vessels are more appropriate at smaller design capacities due to the offset of costs for pressure vessels in comparison to concrete costs. Gravity basins are typically designed for parallel operation, whereas pressure vessels can be designed to operate in parallel or series. The following considerations are true for each orientation:

- Parallel
  - For a pressure vessel design, EBCT in an individual vessel is typically limited to 10-15 minutes at the peak HLR due to media volume limitations in a standard pressure vessel size. For parallel operation, total EBCT is therefore typically limited to 10-15 minutes at peak design HLR. Lower design HLRs are necessary to achieve peak design EBCTs.
  - Primacy agency approval of parallel operation for pressure vessels currently varies nationally.
  - The level of redundancy required for parallel operation varies based on potential primacy agency requirements, number of contactors, contactor unit sizing, and operational factors (frequency of media changes, outage duration, ability to time based on off-peak periods, etc.). Redundancy will be considered on a case-by-case basis. Any variations to primacy agency requirements can be validated through piloting, as summarized in Table 3-4.
- Series
  - For operation in series, the design EBCT can be achieved by the cumulative EBCT of the lead and lag vessels, although this may be limited in practice by specific primacy agency guidelines. EBCT is oftentimes maximized using allowable media depths within the two series vessels. When additional, redundant EBCT is provided in lead-lag orientation, improved media utilization with less frequent change-outs is likely to be observed because additional polishing in the lag vessel allows operation of the lead vessel past finished water quality objectives.
  - Pressure vessels in series afford redundancy in the lag vessel for continued production when one of the vessels in series is taken offline for media changeout; however, additional redundancy may still be required by some primacy agencies to meet firm capacity requirements.

2.1.1.2 Iron and Manganese Considerations for GAC

The available manufacturer recommendation for total iron in the influent placed onto GAC media is the secondary MCL (SMCL) of 0.3 mg/L. If particulate iron is applied to GAC, it most likely will be filtered out and backwashed once head loss accumulation occurs. If there is any chlorine applied upstream of contactors, iron will tend to be present as particulate due to the fast kinetics of iron and free chlorine.

The available manufacturer recommendation for total manganese in the influent placed onto GAC media is the SMCL of 0.05 mg/L. If particulate manganese is present in GAC influent, it will likely pass through due to its small size. Dissolved manganese (i.e., occurring in the absence of a chlorine residual in the influent water) will likewise pass through the GAC media.

If dissolved manganese is present in influent water for GAC with a chlorine residual, a manganese oxide (MnOx) coating will develop on the top few inches of media, resulting in adsorption and chemical oxidation of soluble manganese onto the oxide surface. To address this effect, filter design can incorporate 6-8 inches of additional media in the contactor to bolster the EBCT and overcome the loss in GAC performance.

If treatment is not provided to these levels, an increased head loss accumulation rate and associated backwash frequency is expected.

2.1.1.3 Start Up Considerations for GAC Contactors

Initial startup of GAC contactors (including startup following reactivation) is known to result in increased pH, total suspended solids (TSS), and metals. Of the various metals, arsenic is the most impactful due to the 10 µg/L drinking water MCL. In a case study for Cape Fear Public Utility Authority in Wilmington, NC, virgin GAC reached an arsenic concentration less than 10 µg/L (i.e., the NPDWR MCL) after approximately 20 bed volumes (BVs) were treated during initial startup. After approximately 150 to 200 BVs, the virgin GAC achieved non-detectable (ND) levels of arsenic. This rinsing also lowered the pH and TSS concentration to normal levels. Rinsing and blending strategies can be employed to manage pH and TSS impacts.

Provisions for filter-to-waste are typically recommended to mitigate ancillary water quality impacts during startup of virgin or reactivated GAC contactors. Acid-washed GAC and low-arsenic GAC products are also available to minimize these impacts but may be more costly and may not fully resolve arsenic-leaching issues. The filter-to-waste volumes required to return to normal operating conditions for arsenic, pH, and TSS for virgin and reactivated GAC varies depending on influent water quality characteristics (including background arsenic concentrations) and may vary with each media delivery. The rinse water requirements can be significant and require strategic planning for contactor start-up, including rinse water disposal. Desktop studies can be performed to calculate rinse water usage (with safety factors to account for carbon variability) and blending ratios and to identify discharge options.

2.1.1.4 Spent GAC Media Considerations

GAC can be reactivated by the media supplier through thermal treatment at high temperatures (up to 1800˚ F) to remove and destroy adsorbed contaminants (DiStefano, et al., 2022). This reactivation process restores the media's adsorptive capacity, allowing the media to be returned for reuse, with a small percentage (approximately 10 percent) of virgin GAC makeup due to loss of GAC during reactivation. The GAC supplier will check media characteristics, such as iodine number, during reactivation and may issue a full virgin replacement after multiple reactivation cycles if it falls outside of recommended threshold tolerances.

Reactivation is one of three methods for handling of spent PFAS residuals, despite analytical limitations to be able to close the mass balance on destruction (EPA, 2024). GAC is sometimes regenerated by heating the media to temperatures typically less than 400˚ F to remove a portion of the adsorbed contaminants. However, this process will not remove all the PFAS or destroy any PFAS; therefore, reactivation is required for GAC utilized for PFAS removal. Approval for the use of reactivated GAC in drinking water treatment varies from state to state. Virgin and reactivated GAC and must follow the appropriate National Sanitation Foundation (NSF) International (NSF/ANSI/CAN 61) and AWWA Carbon standards.

The anticipated difference in performance when using virgin media (only used at the first application), compared to reactivated media (every application thereafter) has been studied and documented in various literature sources. Available data have documented that there is not a significant impact of reactivated GAC on the contactors' performance for PFAS removal (Medina, et al., 2022); (Pannu, et al., 2023), (McNamara, et al., 2018); thus, for demonstration tests, testing with only virgin media is acceptable. The performance of reactivated media from the same facility is expected to provide nearly equivalent removal to virgin media.

Alternatives to reactivation for exhausted GAC are incineration or landfilling. Virgin media replacement with incineration or landfill disposal of spent media may be preferable to reactivation for simplicity in smaller-scale systems or where contactor media volumes are too small to accommodate reactivation.

Current regulations for PFAS-laden treatment residuals are limited to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) regulations for PFOA and PFOS (EPA, 2024), which designates these two PFAS as hazardous substances. The PFOA/PFOS CERCLA regulations include a reporting requirement for environmental releases above a threshold defined as 1 pound within a 24-hour period. The US EPA has proposed a rule to list nine (9) PFAS (PFOA, PFOS, PFBS, GenX, PFNA, PFHxS, PFDA, PFHxA, PFBA) as hazardous constituents under the Resource Conservation and Recovery Act (RCRA) (EPA, 2024). Future RCRA regulations could impact treatment, storage, and disposal of treatment residuals contaminated with PFAS.

2.1.1.5 Key Performance Indicator (KPI) for Adsorptive Media Contactors

They key performance indicators (KPIs) for adsorptive media contactors (including GAC, AIX, and novel sorbents) include treatment efficacy of the target water quality constituent and head loss accumulation. Efficacy of adsorptive media for the removal of different water quality constituents is analyzed by monitoring a breakthrough curve of the contaminant being detected in the outlet of the media column. The concentration of contaminant is monitored as C, for effluent concentration, while C_0 represents the feed water, or initial concentration. The breakthrough curve is developed by plotting the C/C_0 versus bed volumes (BVs) treated (based on the flow rate, which is assumed to remain consistent through the entire breakthrough time period). In a breakthrough curve, the removal is represented as C/C_0, and a C/C_0 of 0.7 correlates to 70 percent breakthrough, or 30 percent removal of the water quality constituent. Each media product will have different breakthrough curve for each water quality constituent. Curves created at conservative conditions (higher HLR and lower EBCT) can generally be representative of curves at a range of anticipated operational conditions.

An example PFOA breakthrough curve is plotted in Figure 2-1, which compares the performance of three different media products. This curve was generated using data from a Black & Veatch-performed rapid small scale column test (RSSCT) for a PWS in the northeast, using three different types of GAC, a HLR that would be representative of 6 gpm/ft^2 in a full scale contactor and pore surface diffusion modeling to fit the curves.

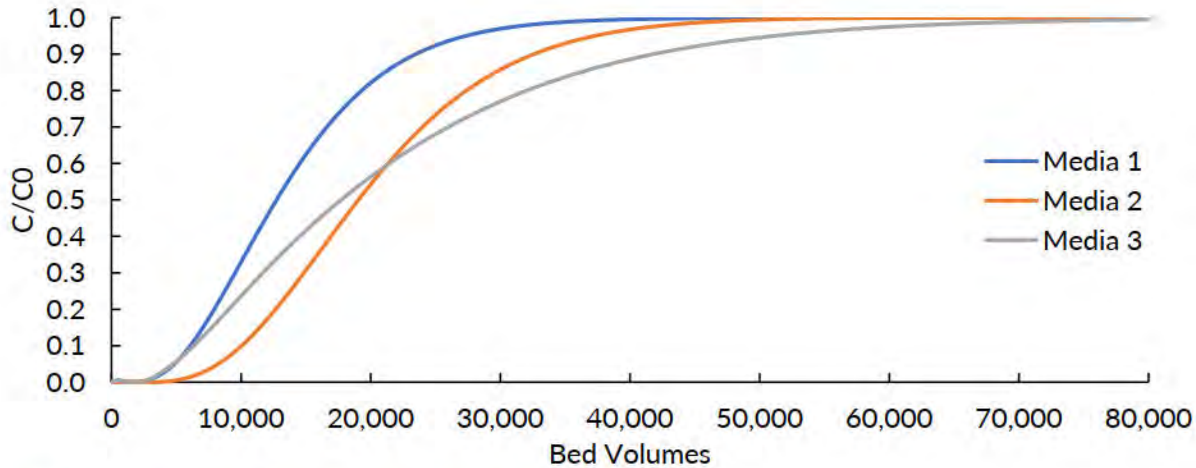

Figure 2-1 Example Breakthrough Curve for PFOA

As the adsorptive sites in the media are consumed, concentrations in the effluent begin to increase over time until full breakthrough occurs where $C/C_0 = 1$. Two exceptions to this are as follows:

- TOC in GAC media may not achieve $C/C_0 = 1$ due to biological removal after the adsorptive capacity is exhausted (e.g., C/C_0 reaches its asymptote under a value of 1.0, with continuous and sustained 10-25 percent TOC removal through biological filtration). This is observed in full-scale and pilot-scale contactors yet is not often observed in RSSCTs.
- Chromatographic peaking may cause C/C_0 to exceed 1, where the concentration of a certain water quality constituent in the finished water exceeds that in the raw water, as described in Section 2.1.1. This is observed in full-and pilot-scale contactors and RSSCTs, with illustrations in various publications (Chow, et al., 2022).

2.1.2 Anion Exchange Resin

AIX is an adsorptive water treatment process that involves the selective exchange of anions in solution with ions that are bound to a resin matrix. AIX has a long history in water treatment, and resins are manufactured for a variety of contaminants, including PFAS. Some AIX resins are designed to be selective for PFAS while others have demonstrated incidental high affinity for PFAS (e.g., AIX resins designed for perchlorate adsorption).

AIX resins contain varying affinities based on PFAS type and influent concentration. This is also demonstrated in Figure 2-1, where Media 2 out-performed Media 3 until a C/C_0 of approximately 0.6, after which the reverse was true.

As described in Section 2.1.1, GAC and AIX both contain higher selectivity for long-chain PFAS than short-chain PFAS and demonstrate higher affinity for sulfonic acids than carboxylic acids. However, PFAS-selective AIX resins generally exhibit higher selectivity for anionic PFAS compared to GAC (Chow, et al., 2022; Boyer, et al., 2021).

AIX resin adsorptive capacity for PFAS is impacted to a smaller degree by competing water quality constituents than GAC because AIX resins are more selective; however, anions such as perchlorate, nitrate, sulfate, chloride, and bicarbonate/alkalinity (listed in order of affinity from strongest to weakest for PFAS-selective AIX resins) are also removed. PFAS-selective AIX resins can also remove contaminants such as uranium. The presence of these compounds increases the rate of breakthrough for PFAS.

The affinity order of anions mentioned above generally applies to PFAS-selective resins, which are typically functionalized with tributylamines or complex amino groups. These groups have greater hydrophobicity and wider site spacing, reducing their affinity for divalent anions like sulfate. In contrast, resins functionalized with trimethylamines, which feature closer site spacing and lower hydrophobicity, exhibit a stronger affinity for sulfate adsorption compared to PFAS-selective resins (Hu, et al., 2016; Kassar, et al., 2022).

As described in Section 2.1.1, chromatographic peaking can also occur in AIX resins, where constituents with lower selectivity can be released more readily to those with higher selectivity, however, the risk of PFAS release in PFAS-selective AIX resins is lower in comparison to GAC. Influent concentration fluctuations can lead to desorption as well, even for higher affinity ions. Due to high selectivity in PFAS-selective AIX resins for nitrate and perchlorate, chromatographic peaking risks are less anticipated. However, data has shown chromatographic peaking impacts following initial equilibrium (as discussed further in Section 2.1.2.3) for bicarbonate, sulfate, and chloride, depending on the resin structure (Smith, et al., 2023).

Having chemical residuals (e.g., chlorine) in the influent to the AIX resin beds is generally discouraged by the resin suppliers, but it is sometimes unavoidable due to ancillary treatment requirements. Chlorine residual limits are shown in Table 2-2 and considerations are discussed in Section 2.1.2.4. Polyphosphate competitively adsorbs to AIX resins. Impacts to PFAS adsorption efficacy from polyphosphate in the influent may vary, though one study documented a 15 to 25 percent reduction in PFAS adsorption efficacy when concentrations of a poly/ortho phosphate blend are in the range of 0.2-0.4 mg/L as PO_4 (Haupert, et al., 2023). Additionally, there have been occurrences of polyphosphate residuals, when added to water containing high levels of dissolved manganese, causing solidification issues in AIX resins.

Currently, AIX resins for PFAS removal in drinking applications are typically single-use media, as removing adsorbed PFAS from the resin requires solutions that are typically explosive/flammable, requiring class 1, division 1 facilities, and disposal options for the highly concentrated PFAS brine stream would be limited. However, development of regenerable AIX resins is ongoing and some are entering the drinking water market.

The utility of single use AIX resins has led to a newly developed and published AWWA Standard B104-24, Single-Use Ion Exchange Treatment for Trace Contaminant Removal. This standard is AWWA's primary reference for use of AIX media for PFAS treatment.

2.1.2.1 Design Considerations for AIX

Typical design criteria for AIX pressure vessels are presented in Table 2-2.

Table 2-2 Typical Design Parameters for AIX Treatment of PFAS

Design Criteria	Value/Range
Contactor Arrangement	**Pressure Vessel**
Maximum HLR at Design Flow	16 gpm/ft^2 (Note 1)
Minimum EBCT at Design Flow	1.5 to 3 minutes (2 minutes is common) per pressure vessel
Minimum Media Depth	3.0 ft for HLR < 12 gpm/ft^2 3.7 ft for HLR > 12 gpm/ft^2 (Note 1)

Design Criteria Contractor Arrangement	Value/Range Pressure Vessel
Design Criteria **Contactor Arrangement**	**Value/Range** **Pressure Vessel**
Operation	Parallel (single stage) or Series (lead-lag; dual stage)
Influent Water Quality Considerations to Avoid Fouling or Head Loss Issues	Solids loading < 5 µm (Note 2) TOC < 4 mg/L (Note 3) Fe < 0.3 mg/L (Note 4) Mn < 0.02 mg/L (Note 4) Periodic Cl_2 residual (none for gel-based resins, < 1.0 mg/L for macroporous-based resins) (Note 5) Continuous Cl_2 residual (none for gel- and macroporous-based resins) (Note 5) LSI < 1

Notes:

1. The Single-Use Ion Exchange Treatment for Trace Contaminant Removal AWWA standard recommends up to 18 gpm/ft^2 for strong based anion exchange resins, with varying minimum bed depth requirements based on design HLR (AWWA, 2025). AIX manufacturers of PFAS-selective resins suggest varying upper limits for HLR, currently ranging from 16-18 gpm/ft^2. The most conservative recommended threshold from the various manufacturers is listed here.
2. Prefiltration with a 5 µm filter is recommended to avoid head loss issues due to backwashing limitations in AIX resin (AWWA, 2025).
3. AIX manufacturer has indicated a 4 mg/L TOC threshold for AIX resin, though fouling could be a risk in AIX resin at values below this threshold. Risk of fouling may vary based on TOC composition, particularly highly bioactive TOC downstream of advanced oxidation processes such as ozone.
4. See further context in Section 2.1.2.2.
5. Chlorine quenching is recommended for continuous influent chlorine residuals due to risk of nitrosamine formation and damage of gel-based resins. See Section 2.1.2.4 for additional detail.

As noted in Table 2-2, minimum resin depth requirements vary based on HLR (AWWA, 2025). Depending on design flows, design HLR, and pressure vessel sizing, additional EBCT may be required to meet the minimum bed depth requirements.

Pre-filtration using a 5-micron filter before the resin is recommended for single-use AIX systems, even if downstream of another form of filtration due to risk of solids loading and head loss repercussions (AWWA, 2025).

Proper prefiltration is important for sustained operation with minimal interventions. Backwashing AIX resin is generally not recommended due to potential disruptions to the MTZ. Depending on expected suspended solids concentrations in the influent water, pretreatment is instead recommended to avoid disturbances to the resin bed once placed into service. Manufacturer instructions are followed when there are instances of significant head loss in an AIX contactor when significant PFAS adsorption capacity remains. Individual AIX manufacturer direction may include

- Subfluidization wash provisions at a rate less than 1 gpm/ft2 which can release particles from the top of the bed without resin disruption and fluidization that disrupts the MTZ. Backwash has been incorporated into full-scale designs for AIX applications in some installations.

- Removing (or skimming) the top few inches of resin to mitigate any accumulation of solids that are creating head loss. This process is labor-intensive, particularly if frequent head loss accumulation is expected, and may require confined space entry.

Filter-to-waste provisions are necessary for the initial startup and rinsing of new AIX media, as well as for periodic rinsing when contactors have remained stagnant for an extended period before being brought back online. Although AIX resins are generally less prone to biogrowth compared to GAC, the duration during which AIX media can remain stagnant before biogrowth occurs typically ranges from one to a few days, depending on external factors such as temperature (e.g., cooler temperatures slow the onset of biogrowth). As a conservative estimate, biogrowth can be expected to start after a 24-hours stagnation period.

The same considerations exist for LSI in AIX resin as in GAC media. As summarized in Table 2-2, a LSI less than 1 is recommended to avoid excessive scale formation and compromised resin performance.

2.1.2.1.1 Contactor Arrangement

To date, AIX resins for PFAS removal have been applied in fixed-bed pressure vessel contactors. Media required to achieve an EBCT of 1.5-3 minutes at peak design HLRs is achievable in standard pressure vessel sizing, although at lower design HLRs, additional EBCT may be necessary to achieve the minimum resin depth recommendations as summarized in Table 2-2. Pressure vessels can be designed to operate in parallel or series, where the following considerations apply:

- Parallel
  - The level of redundancy required for parallel operation varies based on primacy agency requirements, contactor number/sizing, and operational factors (i.e., the frequency of media changes, outage duration, ability to time based on off-peak periods, etc.). Redundancy will be considered on a case-by-case basis. Any variations to the primacy agency requirements can be validated through piloting, as summarized in Table 3-4.
  - Primacy agency approval of parallel operation for pressure vessels may vary nationwide.
- Series
  - The design EBCT is typically provided by each pressure vessel, even for lead-lag arrangement, due to operational benefits as described in this section. In other words, for a design EBCT of 2 minutes, a parallel contactor arrangement would contain 2 minutes and a series contactor arrangement would contain 4 minutes (2 per contactor).
  - Pressure vessels in series contain redundancy in the lag vessel for continued production when one is taken offline for media changeout; however, additional redundancy may still be required by individual primacy agencies to meet firm water treatment facility capacity requirements.
  - Operation in series offers improved media utilization with less frequent change-outs. This is because additional polishing provided in the lag vessel allows the lead vessel to be operated with effluent concentrations of the contaminant compound in excess of the target finished water quality objectives.
  - The capital cost to install two vessels per train is nearly double that of one vessel and two vessels in series means more components to maintain. A lead-lag configuration may be cost prohibitive at higher design capacities.

2.1.2.2 Iron and Manganese Considerations for AIX

Reduce levels of total iron in influent placed onto AIX resin to as low as possible, with the SMCL of 0.3 mg/L being an upper threshold. This is also true for total manganese in influent placed onto AIX resin, with 0.02 mg/L being an upper threshold (below the SMCL). Soluble iron and manganese may precipitate on the resin bed. Particulate iron and manganese will likely be filtered out within the AIX. Both of these occurrences would cause increased head loss within the contactor.

If treatment is not provided to these levels of influent iron and manganese, an increased head loss accumulation rate is expected, requiring premature resin changeouts or regular media skimming, as summarized in Section 2.1.2.1.

2.1.2.3 Start Up Considerations for AIX

During startup of a system with AIX resin, for the first approximately 1,000 to 2,000 bed volumes of treatment, which is typically equivalent to 1.5 to 4 days of continuous operation, resins tend to adsorb sulfates and release chlorides. This leads to an imbalance in the chloride-to-sulfate mass ratio (CSMR), which affects the corrosivity of the water (Smith, et al., 2023), (AWWA, 2025). Additionally, due to the initial bicarbonate adsorption, a drop in pH occurs, which is expected to last up to 200 BVs.

During initial startup, it may be necessary to dispose of or re-route some water to avoid having corrosive water entering the distribution system or stagger contactor startup to minimize CSMR impacts in the blended finished water. After each resin changeout, water from the newly changed media vessel is then blended with effluent from older media to avoid experiencing large change in CSMR. If these options are not feasible, and evaluation of the PWS's corrosion control treatment indicates the risk of lead or copper release is high, buffered resins can be considered. This evaluation and any plans to mitigate corrosion via altering corrosion control treatment will need to be approved by the primacy agency.

In order to prevent resin damage, particularly for gel-based resins, it is not recommended for any water used for fluidization of virgin media for filling empty contactors to contain a chlorine residual. Likewise, if backwashing capabilities are installed, it is recommended to use backwash water that has not sat stagnant, with a reductant chemical used to quench chlorine residual prior to resin contact as required.

2.1.2.4 Long-term Water Quality Considerations for AIX

The presence of chlorine residual in the influent to the AIX resin bed can cause degradation of the resin functional groups (i.e., adsorption sites) and potential release of byproducts such as nitrosamines (e.g., N-Nitrosodimethylamine (NDMA) or N-Nitrosodibutylamine (NDBA)). It is best practice to ensure that any chlorine residual is quenched before entering the AIX bed. One macroporous AIX resin supplier has suggested that these resins are resistant to intermittent applications of a low chlorine residual (i.e., <1 mg/L) without damage due to the macroporous resin structure, however it is recommended to avoid continuous influent chlorine residuals due to the risk of nitrosamine formation. Ancillary supplier-provided performance guarantees and relevant evidence of no water quality implications in a similar source can validate the approach. EPA Method 521 can be used to quantify nitrosamine formation if chlorine residuals are present in the influent to AIX resins.

Common chlorine quenching agents, such as sodium bisulfite, contain anions that will competitively adsorb to AIX resin. If chlorine residuals are quenched upstream of AIX contactors, only a minor impact to PFAS performance will be observed due to the low doses used for quenching. For example, if a WTP contains a filter effluent chlorine residual of 0.5 mg/L as Cl_2, which is a common operational concentration for maintaining a manganese oxide coating on filter media for manganese removal, a sodium bisulfite dose of 0.7 mg/L as $NaHSO_3$ would be required, contributing approximately 0.7 mg SO_4/L to the influent water sulfate concentration via the reaction with free chlorine. Background sulfate levels are typically between 50 and 100 mg/L (and sometimes higher), so the contribution of sulfate by the quenching agent is negligible.

2.1.2.5 Spent AIX Media Considerations

Exhausted single-use AIX resin is landfilled or incinerated. Regulatory considerations for handling PFAS-laden waste streams are summarized in Section 2.1.1.4.

2.1.2.6 KPIs for AIX

See Section 2.1.1.5.

2.1.3 High Pressure Membranes (Reverse Osmosis and Nanofiltration)

NF and RO are two high pressure membrane-based treatment processes that utilize a semi-permeable membrane to reject dissolved inorganic and organic substances from water. The membrane recovery rate is defined as the percentage of feed water that passes through the membrane as permeate. For example, if an RO system has a recovery rate of 85 percent, 85 percent of the feed water is collected as permeate, while the remaining 15 percent is rejected as concentrate. The recovery rate is limited by the concentration of sparingly soluble cations, (e.g., barium strontium, and calcium), anions (e.g., sulfate, sulfide, and bicarbonate), and silica in the concentrate and their solubility products or metal complexes. NF and RO recoveries for surface water and groundwater applications typically range from 80 to 90 percent depending on the specific feed water quality conditions.

NF and RO membranes typically reject 95 to 99 percent of dissolved inorganic and organic compounds; however, rejection rates vary by constituent and are influenced by water quality conditions, membrane type, and membrane age. For example, salt passage increases with increasing water temperature and with increasing membrane age.

RO membrane rejection rates vary by membrane product and are typically characterized by rejection of NaCl under standard testing conditions. NF membranes are characterized by rejection of divalent ions such $MgSO_4$ under standard testing conditions. Some NF membranes may also be characterized by the MWCO. The removal mechanisms are dependent on the membrane properties and the constituent characteristics (molecular weight, charge density, functional group, polarity, etc.). NF/RO systems are highly effective for PFAS treatment with NF membranes typically providing a minimum PFAS rejection of 90 percent, and RO membranes typically providing a minimum PFAS rejection of 95 percent. There is usually higher rejection of long chain PFAS like PFOA and PFOS and lower rejection of short chain PFAS (Liu, et al., 2022).

There are many NF/RO membrane products on the market ranging from “loose” to “tight” membranes within each category. Selection of “loose” or “tight” membranes will depend on the level of removal required, with “loose” membranes typically having the benefit of reduced energy consumption. It is important to note that NF and RO are exactly the same technology, with the primary distinction that NF membranes are notable “looser” for ions with small charge and/or organics with lower MWCO.

Depending on the influent PFAS concentrations and treatment objectives, it may be possible to treat a portion of the total plant flow through NF/RO with a bypass for blending to meet PFAS treatment goals if acceptable by the primacy agency. Additionally, blending is often beneficial for NF/RO permeate stabilization and corrosion control.

2.1.3.1 Design Considerations for NF/RO

NF/RO applications for groundwater and surface water systems typically consist of a single pass consisting of two or three stages. In a multi-stage NF/RO unit, concentrate from the first stage becomes the feed water to the second stage. The NF/RO membranes consist of semi-permeable polyamide sheets spiral-wound around a permeate collection tube. Typically, six (6) to seven (7) membrane elements are installed inside an individual pressure vessel, and pressure vessels are arranged in stages to make up an individual NF/RO rack. Conventional NF/RO systems operate with continuous, single-pass flow, whereas high recovery alternatives such as closed-circuit RO (CCRO) and flow reversal RO (FR-RO) utilize a modified operational strategy. For example, in a CCRO system, the concentrate is blended with the feed such that the RO influent becomes more concentrated over time and feed pressure is adjusted to accommodate to maintain permeate production. This process operates in a semi-batch mode based on scale formation. Similarly, FR-RO seeks to increase recovery and minimize scale formation by periodically reversing the flow of concentrate in blocks of pressure vessels.

The design and implementation of NF/RO systems requires several pretreatment, post-treatment, and ancillary equipment systems. Specifically, NF/RO system design typically includes chemical pretreatment (e.g., antiscalant and/or acid for pH adjustment), cartridge filters, feed pumps, NF/RO racks, clean-in-place system, flushing system, neutralization system, post-treatment chemical addition (e.g., sodium hydroxide or lime), and concentrate disposal. NF/RO systems are operationally very complex and are highly sensitive to inorganic and organic fouling and cannot tolerate exposure to free chlorine. To prevent precipitation of sparingly soluble compounds like calcium carbonate and silica, sulfuric acid and antiscalant are often applied for pH suppression and for control of sparingly soluble compounds.

2.1.3.2 Start-up Considerations for NF/RO

Manufacturers and RO system suppliers provide system-specific recommendations for startup and commissioning activities. After completing general startup and commissioning steps and putting the NF/RO system into operation.

The NF/RO permeate water quality must be stabilized (i.e., noncorrosive). Focusing on stabilization and post-treatment chemical addition during startup is necessary to ensure distribution system compatibility. Because of the potential to impact the corrosivity of finished water, state primacy agencies may require a corrosion control evaluation prior to start up. This evaluation and any plans to mitigate corrosion via altering corrosion control treatment will need to be approved by the primacy agency.

2.1.3.3 Operating Considerations for NF/RO

Implementation of NF/RO may have significant impacts on chemical treatment. At a minimum, the system would require new chemical storage and feed systems for antiscalant, acid, and sodium hydroxide. Additional pretreatment may also be required to improve the RO feed water quality to minimize the risk of fouling and scaling from colloidal solids and precipitates. Additional chemical treatment would increase the frequency of chemical deliveries and annual operation and maintenance (O&M) costs.

NF/RO permeate typically has a pH ranging from 5.5 to 6.5 and is stripped of alkalinity. As such, NF/RO permeate is corrosive and requires post-treatment stabilization to minimize distribution system impacts. Thus, stabilization is often required to ensure compatibility with historical water quality conditions. Stabilization can be accomplished by chemical addition, aeration, blending, or a combination of these methods. Desktop evaluations, bench-top testing, and/or pipe rig testing may be necessary to assure finished water stability in the distribution system.

NF/RO processes are highly energy-intensive and would significantly increase energy consumption and annual O&M costs. Additional O&M expenses include replacement of cartridge filter elements four times per year and replacement of the membrane elements every five to seven years. Depending on the state, implementation of NF/RO may also impact on the system classification and operator licensing requirements.

NF/RO systems generate a concentrated waste stream where the concentration of constituents in the NF/RO concentrate is a function of the recovery rate and rejection of a given constituent. Options for disposal of NF/RO concentrate must be carefully considered in conjunction with regulatory considerations for handling PFAS-laden waste streams summarized in Section 2.1.1.4.

2.2 Other Treatment Technologies

Technologies that are not BATs are available for PFAS treatment and these include powdered activated carbon (PAC) and novel adsorbents. Considerations for those treatment technologies are discussed herein.

2.2.1 Powdered Activated Carbon

PAC is finely ground carbon which adsorbs contaminants in water. PAC is commonly used in many WTPs for seasonal treatment of organics, taste and odor causing compounds, pesticides, and/or color-causing compounds. PAC is delivered as a dry product and batched into a slurry solution. PAC is often applied to the raw water and allowed to settle during sedimentation prior to the filters to avoid filter productivity impacts.

The efficacy of PAC for removal of target contaminants is determined by the type of PAC, dose, dosing location, contact time, mixing conditions, target compound for removal, and the presence of other water quality constituents that may compete for adsorption sites. PAC is moderately effective at removing long-chain PFAS and is less effective at removing short-chain PFAS (Gagliano, et al., 2020; Son, et al., 2020). The removal capacity of PAC is less than that of GAC due to the relative mass of media per gallon of water treated. Superfine PAC (effective size of approximately 1 μm) is more effective than conventional PAC products (effective size <0.1 mm), though commercial availability of these products may be limited. The same competing constituents that negatively impact GAC adsorption impact PAC; however, recommended thresholds of competing contaminants for PAC use are not established due to limited data available.

While PAC is not recognized as a BAT by US EPA, it may be a viable treatment strategy for PWSs with PFAS concentrations at or near the MCL and can be used to meet treatment objectives. If PAC is implemented for PFAS treatment, adjustments in the required dose and application approach will impact solids handing (while seasonal PAC usage may have historically been necessary, continuous usage may be necessary for PFAS, depending on influent PFAS conditions, resulting in year-round PAC residuals). Additionally, product selection may change based on optimized performance for multiple treatment purposes. Additionally, infrastructure considerations include the potential for addition of PAC storage and feed equipment if the WTP does not have an existing PAC system or if the existing PAC system is undersized relative to the PAC dose required for PFAS treatment.

Additionally, since PFAS-contaminated PAC solids will accumulate in the sedimentation basin residuals, the fate of PFAS in the waste stream must be considered. Regulatory considerations for handling PFAS-laden waste streams are summarized in Section 2.1.1.4.

2.2.2 Novel Media

Due to the emerging nature of PFAS treatment and the new regulation, there are several novel adsorbents that have been specifically formulated for PFAS removal, some of which have achieved NSF-certification. Each media has unique properties and differentiators for water treatment applications. There are various approaches to defining novel adsorbents and determining whether they would be acceptable to primacy agencies. Some primacy agencies may define novel adsorbents as anything that is not listed by US EPA as a BAT or as not being promulgated in their regulatory code with accepted design parameters. Thus, it is anticipated that the list of adsorbents classified as novel media will change over time.

At present, there are few documented full-scale applications utilizing media other than GAC and AIX in drinking water applications, leading to more uncertainty regarding long-term performance, interactions with background water quality constituents, backwash compatibility, etc. As such, recommended design parameters, water quality boundary conditions, and material testing methodologies are not broadly established.

Some states have begun permitting novel sorbent products for full scale implementation. The Association of State Drinking Water Administrators (ASDWA) is developing a novel media database, which includes compiled novel media testing and implementation data that is intended to be regularly updated. This database is intended to reduce uncertainty in novel media products and inform primacy agency determinations of products that may be deemed as acceptable alternatives to established media alternatives.

3.0 Treatment Evaluation Approaches for Permitting / Plan Approval

Primacy agencies must review and approve plans for modifications to existing WTP processes or additions of new WTP processes prior to construction. While specific requirements for permitting and approval vary by primacy agency, the primary intent of permitting is to ensure the proposed treatment approach will meet treatment objectives while avoiding potential pitfalls associated with treatment technologies for specific design criteria, water quality, and operational approaches. Permitting does not apply to technology selection; instead, it applies to the approval of design criteria and facility plans. New technologies or proven treatment technologies that are planned to be operated outside established design criteria must generally be accompanied by sufficient data to demonstrate that satisfactory results can be achieved.

The technologies that require additional demonstration including site-specific pilot tests depends on how the primacy agency rules are documented. For instance, while GAC and AIX are BATs for PFAS treatment with established recommended design parameters, if recommended design parameters are not promulgated in the administrative code for an individual primacy agency, they may still be categorized as technologies that require pilot testing.

Primacy agencies that do not have such restrictions in their regulatory compliance structure may consider proposals for technology implementation and treatment evaluation requirements on a case-by-case basis. This structure allows the agency to respond to advances in the state-of-the-science and to recommended best practices as they are developed without having to revise existing rules or promulgate new regulations; however, it also places the burden of acceptance of the advances on the primacy agency reviewers. Primacy agencies that do not have this flexibility, however, may still be able to consider alternative means of testing without requiring a site-specific pilot for PFAS treatment. Additionally, if state revolving fund (SRF) loans are utilized, the level of evidence required by the primacy agency may become more stringent. Early coordination with the primacy agency is critical to ensure alignment around treatment evaluation requirements to avoid delays or rework.

Situations that may preclude the need for site-specific pilot testing include primacy agency acceptance of:

- Design within established design guidelines or recommendations
- Desktop analyses, including:
    - Validation from similar systems with comparable or worse source water quality and operational approaches; validation could be full-scale implementation data, pilot-tests, or bench-scale tests (e.g. RSSCTs for sorbents and jar tests for PAC)
    - Modeling approaches that conservatively estimate anticipated performance
- Site-specific bench-scale testing results to validate performance

Each alternative treatment evaluation testing approach has unique time and cost requirements, as well as relative advantages and disadvantages, as summarized on Figure 3-1.

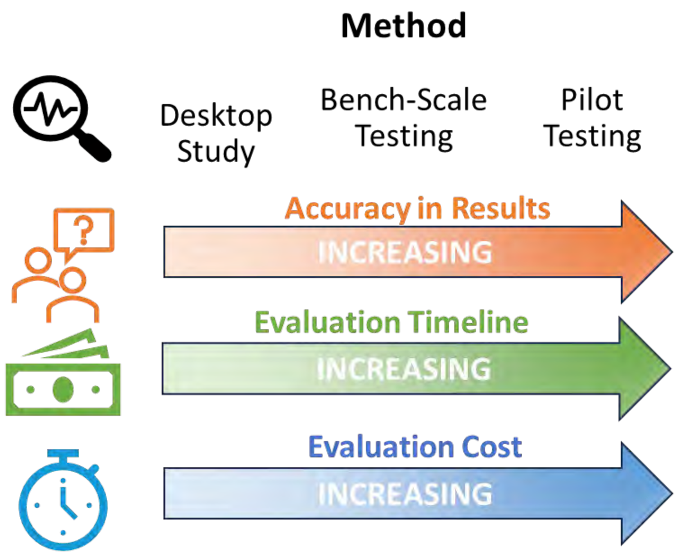

Figure 3-1 Relative Accuracy, Cost, and Duration of Various Treatment Evaluation Methods

In general, documented evidence from full-scale operations is more robust than pilot-scale, which is more robust than bench-scale or desktop evaluations. Similarly, site-specific information is more reliable for anticipating full-scale performance than documentation from a site that is of similar or worse water quality and PFAS contamination level. Data from a similar site that provides a conservative estimate of performance may be adequate to validate whether the treatment technology will perform as intended. Alternative approaches may suffice for documenting performance for permitting and plan approval. The analyses used to support treatment facility permitting is at the discretion of the primacy agency, and more flexibility may exist for some types of systems than others. Alternative treatment evaluation methods may be easier to approve for groundwaters, which are generally more seasonally stable and geographically uniform in water quality than surface water sources.

It is important to select the treatment evaluation method(s) that achieves the information objectives appropriate to the installation being evaluated. For example, if a PWS needs to compare the performance of different media suppliers, RSSCTs or piloting are both sufficient. Having data about the performance of each media will allow the PWS to collect competitive bids from the suppliers. If testing with media from different suppliers has not been performed, it may be difficult for a PWS to change media suppliers when operating at full-scale.

Ancillary treatment impacts for each technology are summarized throughout Section 2.0. Simultaneous compliance considerations will inform the treatment evaluation method utilized. If the technology is selected to treat two regulated contaminants below their respective MCLs, sufficient evidence must be provided in the approved treatment evaluation method. For ancillary water quality impacts, such as the initial water quality impacts documented in Sections 2.1.1.3 and 2.1.2.3, coordination with the primacy agency may be required to evaluate corrosion control implications or develop a treatment evaluation approach.

Achievable objectives for various treatment evaluation methods are summarized in Table 3-1. The only method not summarized is full-scale demonstration testing, which can achieve all objectives listed. Additional detail on this technique is summarized in Section 3.4.

Table 3-1 Objectives that can be Accomplished by Various Treatment Evaluation Methods

Treatment Technology	Treatment Evaluation Objective	Desktop Study (Note 1)	Bench-Scale Testing (Note 2)	Pilot Testing (Note 3)
Adsorptive Media in fixed contactors (GAC, AIX, Novel Sorbents)	PFAS removal efficacy	Yes *Using similar site results is dependent on similarity of water quality and operational approach;* *Modeling approaches depend on robustness of model and predicting fouling potential may be limited (See Table 3-2)*	Yes *Breakthrough curves are generated, which can be supplemented with modeling. There are scale-up methods for GAC and AIX with varying degrees of maturity; however, there are limited data sets available for scale-up of novel adsorbents*	Yes *Breakthrough curve resolution may be limited by low PFAS concentration*
	Comparative media performance evaluation			Yes
	Fouling potential		No	Yes *Captures seasonal fluctuations that are more impactful for surface water sources; Pretreatment requirements can be established*
	Characterize water quality impacts (i.e., competitive adsorption)		Yes *Based on a snapshot of time during the water collection event;* *Can simulate alternative pretreatment impacts such as chemical dosages/chemistry, addition of quench chemical, polyphosphate*	Yes *Captures seasonal fluctuations that are more impactful for surface water sources*
	Design criteria optimization		Yes	Yes
	Quantify operational considerations		Yes *Modeling allows for simulation of contactor staging/arrangement*	Yes *Modeling allows for simulation of contactor staging/arrangement*
	Characterize performance with alternative influent water conditions (e.g., upstream TOC removal optimization; new source blending)		Yes *Can cover a wider range of conditions than in a pilot*	Limited *Simulating different pretreatments are labor-intensive*
	Validate contactor operational strategy and media changeout triggers for permitting		Yes	Yes
	Simultaneous compliance (e.g., VOC, DBP, corrosivity) and aesthetic treatment goals (e.g., MIB, Geosmin)		Limited *Must carefully consider influent water conditions to account for seasonal fluctuations in water quality or parallel testing to address other contaminants*	Yes *Captures seasonal fluctuations that are more impactful for surface water sources*
PAC	PFAS removal efficacy	Yes	Yes *Can easily simulate alternative conditions*	Often not practical *Achieves similar results as jar testing evaluating alternatives but is more difficult and labor intensive*
	Comparative media performance evaluation			
	Design criteria optimization (i.e., PAC characteristics, dosing location, and concentration)			
	Characterization of water quality impacts (i.e., competitive adsorption)			
NF/RO	PFAS rejection rates	*Yes* *Peer-reviewed literature characterizes PFAS rejection; Proprietary software to establish design criteria is available, permeate water quality, chemical pretreatment, and post-treatment chemical addition*	*Bench-scale testing can be used to assess PFAS rejection at known operating conditions (flux and feed pressure) for a given water matrix.* *Can be used to assess membrane fouling potential but results will not be representative of anticipated permeate and concentrate water quality and cannot be used to estimate CIP cleaning frequency*	Yes *Alternative pretreatments are resource intensive to simulate*
	Design criteria selection			
	Pre-qualify membrane element for selection			
	Characterization of permeate and concentrate water quality			
	Optimization of pretreatment systems, RO design, and post-treatment systems and estimate of CIP cleaning frequency	No		

Notes:
1. Applicability is limited by available data; more detail is likely to be available in the coming years that may make desktop studies of adsorptive media performance more reliable.
2. Standardized processes for AIX RSSCTs are being developed and showing promising results, as described in Section 3.2.1. In order to use RSSCTs for AIX, the primacy agency must provide approval and the manufacturers of the resins to be considered must have evidence of suitability of scale-up from RSSCTs to full-scale for their products to confirm that it is acceptable.
3. Additional benefits from piloting include operational practice for a new full-scale unit process and the ability to retain the pilot skid for continued future testing.

3.1 Desktop Evaluations

Desktop evaluations can provide conceptual confirmation that proposed designs will meet treatment goals using conservative assumptions and projections.

For sorptive media, desktop evaluations include the following:

- Similar site results. Making conservative performance assumptions based on adsorptive media performance from sites with a representative source and quality (e.g., full-scale or pilot-scale data, literature, or other sources of performance data of similar source water quality). While this approach is widely used, finding comparable sites can be challenging to locate and document adequately.
- Performance models. Any desktop model contains a degree of uncertainty. The significance of that uncertainty will vary from model to model with the embedded assumptions in the model and the attributes of the site being evaluated. The use of different models to simulate comparative performance of different treatment technologies at an individual site contains risk due to inherent disparities in modeling approaches. Effective use of performance models entails analysis by an expert with experience using the model as well as experience with equipment selection, design, and implementation of similar treatment systems. Publicly available models are summarized in Table 3-2. Media manufacturer performance models are also available. Manufacturer models are typically proprietary and developed with data that are not publicly available.

Table 3-2 Publicly Available Desktop Evaluation Performance Models

Model	Media Type	Creator	Purpose	Required Inputs
Work Breakdown Structure (WBS) Model	GAC and AIX	US EPA (referenced document : Technical Support Document)	AIX (pg 41 of referenced document) and GAC (pg 22) bed life estimates central tendency cost for PFAS performance.	For performance prediction: TOC concentration, PFAS concentrations, target PFAS removal goal
Ion Exchange Column Model (IEX-CM)	AIX (Note 5)	US EPA (IonExchangeModel)	Simulate column effluent inorganic anions and PFAS concentrations using combination of sub-models, including Homogenous Surface Diffusion Model (HSDM)	PFAS properties and concentration, inorganic anions concentrations (i.e., chloride, sulfate, bicarbonate, and nitrate), AIX properties, and column design parameters
Gradient boosting machine (GBM) Model	GAC (Note 3)	North Carolina State University (NCSU) – (BV10 Estimation)	Use of machine learning to estimate pilot/full scale BV to 10 percent breakthrough (Note 6)	Water quality parameters (e.g., pH, DOC, UV254), GAC properties, PFAS concentrations, and design EBCT
Pseudo-single Solute Model	AIX (Note 4)	NCSU	Estimates PFAS breakthrough curves using influent water quality parameters. (Note 7)	PFAS properties and concentration, TOC, and nitrate concentrations, and AIX type (applicable for CalRes 2301 and PFA694E).

Model	Media Type	Creator	Purpose	Required Inputs
Pore Surface Diffusion Model (PSDM) – AdDesignS	GAC (Note 1), AIX (Note 2)	National Center for Clean Industrial and Treatment Technologies (CenCITT) (AdDesignS Software model)	Predict breakthrough curves, but must have data to fit curve (e.g., from similar site). Completes PFAS breakthrough curves using initial testing data	PFAS properties and concentration, media properties, column design parameters. Typically parameters are adjusted to fit breakthrough data (up to a C/C_0 of 0.3-0.5, or 30-50 percent, is recommended). There is limited applicability to producing breakthrough curves based on only PFAS isotherm data without experimental data.
Membrane projection software	NF/RO	Various proprietary software developed by membrane suppliers (available for free download)	Establish design criteria for NF/RO systems, range of anticipated operating conditions, range of anticipated permeate and concentrate water quality characteristics	Source water type, individual anion and cation concentrations, water temperature, feed water pH, RO design parameters, membrane selection Does not provide information specific to PFAS removal.
Antiscalant modeling software	NF/RO	Various software developed by antiscalant chemical suppliers (free, publicly available software)	Determine chemical pretreatment and NF/RO recovery based on feed water quality characteristics, antiscalant selection and dosing, and pH adjustment	Individual anion and cation concentrations, source water temperature and pH, general RO design parameters Does not provide information specific to PFAS removal.

Notes:

1. This model is demonstrated in (Burkhardt, et al., 2021) and (Hopkins, et al., 2024)
2. AdDesignS developed for GAC but can be applied to AIX. This model is demonstrated in (Cheng, et al., 2024)
3. This model is demonstrated in (Koyama, et al., 2024)
4. This model is demonstrated in (Cheng, et al., 2025).
5. This model is demonstrated in (Smith, et al., 2023) and (Wahman, et al., 2023) for gel-type resins.
6. GBM model predictions for BV to 10 percent breakthrough show an error margin of ± 24 to 32 percent, based on water quality and media inputs.
7. The Pseudo-single Solute model predictions indicate over 83 percent accuracy for AIX capacity and 67 percent accuracy for BV to 10 percent breakthrough, within a 30 percent variance from observed data.

3.2 Bench-Scale Testing

Bench-scale testing offers a rapid, site-specific evaluation of technology performance for sorptive technologies at a fraction of the cost of piloting. For PAC, jar testing is used; for fixed bed media, RSSCTs are used. These evaluations are useful for documenting the expected relative performance between treatment alternatives and providing an estimate of life cycle costs. Another benefit of bench-scale testing is that this testing can be performed on site, or water can be sent to a testing laboratory. PFAS can be added to the water if necessary to generate meaningful results. Bench-scale tests, however, have the inherent limitation that they will not aid in identifying operational challenges such as fouling. These tests also only capture the feed water quality at the time of water collection for the bench-scale test. See Table 3-1 for an overview of testing capabilities. Below, rapid small-scale column tests and jar testing approaches for adsorptive media are discussed.

3.2.1 Rapid Small-Scale Column Tests (RSSCTs)

RSSCTs are bench-scale tests that can be used to develop breakthrough curves to evaluate treatment efficacy of various adsorptive media. RSSCT were initially developed for predicting sorbate breakthrough of GAC media (Crittenden, et al., 1986; Crittenden, et al., 1987), but have recently been expanded to AIX resins to evaluate PFAS removal (Schaefer, et al., 2020; Zeng, et al., 2020). Standard D6586-14 includes RSSCT experimental procedures that are recommended for these tests.

RSSCTs take advantage of using a much smaller size media in a test column relative to full-scale application to reduce the amount of time and volume of water required to observe significant breakthrough of target contaminants. Water is passed through a small column that contains crushed media, and influent and effluent samples are collected over the duration of the experiment to determine the fraction of target contaminant that passes through the media as a function of the volume of water treated. The results of the RSSCT are then used to develop design conditions (i.e., flow rate and media replacement frequency) for full-scale media contactors. Media-specific manufacturer input is necessary to assure scale-up following crushing media for RSSCT analysis is appropriate prior to conducting an RSSCT. Not all media may be suitable to this technique.

RSSCTs are a cost-effective testing method to generate representative data that can be used to select the best performing media for a specific water matrix and provide insight into optimization of design parameters. RSSCT sizing and scale-up approaches have been developed for GAC and AIX media such that RSSCT results can be used to directly predict full-scale performance up to approximately 70 percent breakthrough (e.g., Hopkins and Knappe, 2024; Cheng and Knappe, 2024). PSDM modeling can be calibrated with RSSCT data and used to provide a higher resolution of data analysis than discreet RSSCT datapoints alone (Burkhardt et al., 2022).

Besides obtaining results at a fraction of the time and cost relative to a pilot, RSSCTs are also more easily conducted, so various source waters and conditions can be tested in rapid succession to narrow design options quickly. They also provide the advantage of being able to be conducted using source water that is spiked with PFAS to concentrations that are more readily measurable at low levels of breakthrough. This provides more confidence in the estimate of the breakthrough curve. A photo of the RSSCT experimental setup is provided on Figure 3-2. Spiking PFAS into the source water does not impact adsorptive performance below a total mass of PFAS of approximately 0.3 μg/L (Cheng et al., 2024). When spiking PFAS, it is important to minimize organic carbon contributions from solvents that are used to dissolve stock PFAS (e.g., methanol by evaporating the methanol and then reconstituting the PFAS in water).

If column hydraulics force premature shutdown before target contaminant breakthrough occurs, predictive modeling techniques are available to predict breakthrough of the target compound using available breakthrough data from other compounds. Use of these modeling techniques require primacy agency approval and use by a qualified expert, experienced in using the technique.

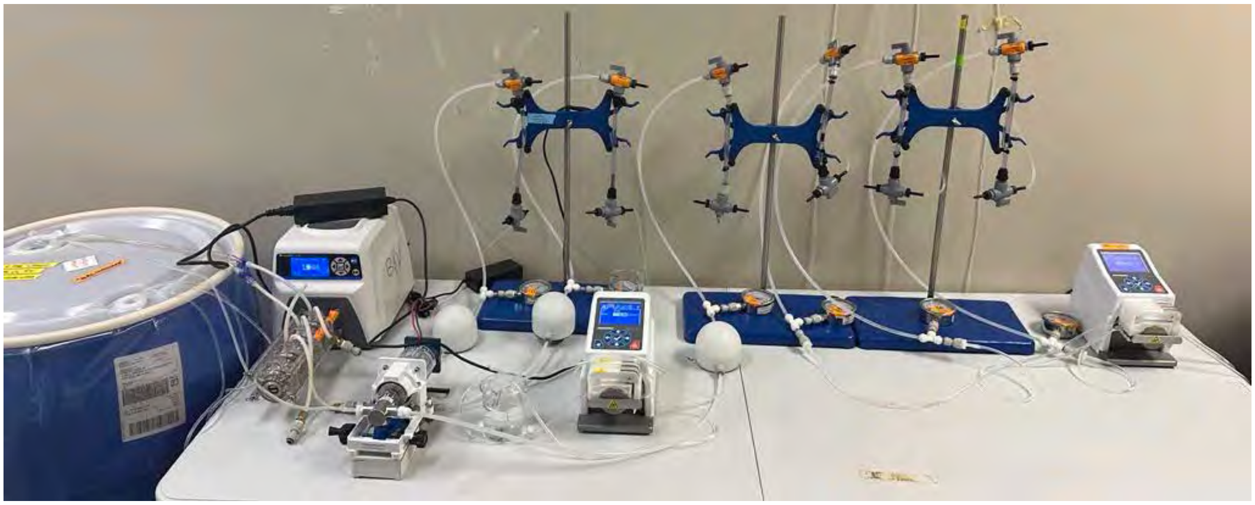

Figure 3-2 RSSCT Bench-Scale Testing Experimental Setup (55-gallon drum of feed water on left, pumps, and RSSCT columns mounted on stands with valves and flow measurement)

3.2.2 PAC Jar Testing

PAC bench-scale testing is conducted using a jar-testing apparatus. The target concentration of PAC media is dosed to the jar stirrer, and the stirrer is operated to simulate the treatment processes (e.g., mixing energy, contact time, and settling time) experienced at the plant. Full treatment can be simulated, to observe the impacts of the contact times at different plant flows as well as the impacts of other treatment chemicals such as coagulant and polymer. At the specified contact time, PAC must be removed from the water sample via filtration or centrifugation to stop the adsorption process in order to represent the desired contact time. A photo of the PAC jar testing experimental setup is provided on Figure 3-3.

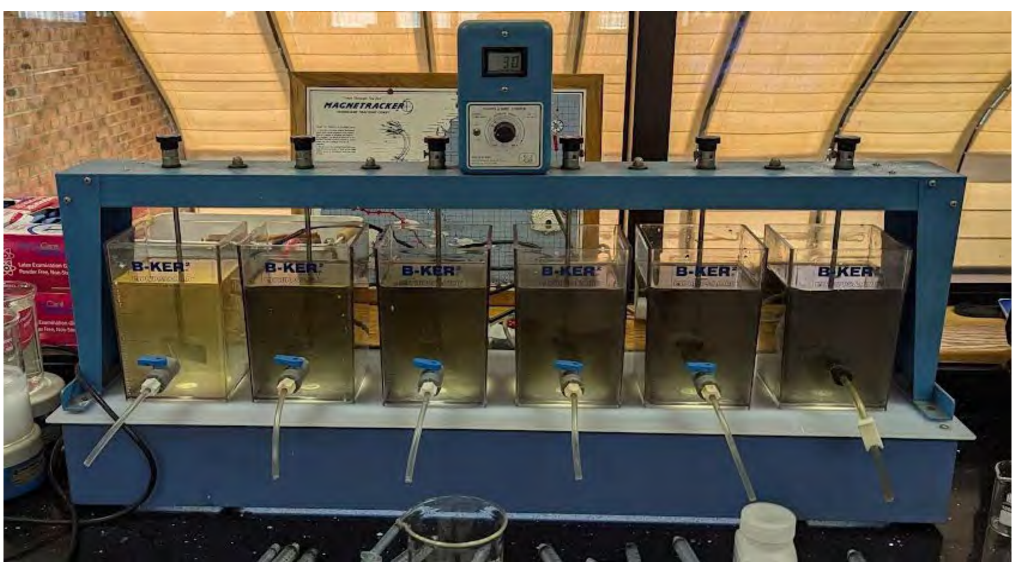

Figure 3-3 PAC Bench-Scale Testing Experimental Setup

A reference PAC bench-scale testing procedure is available in Appendix B of AWWA Standard B600-24, though this procedure is specific to taste-and-odor causing compounds (AWWA, 2016). Modifications to tailor this procedure to PFAS include:

- Item 2 in Section B.1.2.1 (Reagents). The stock solution would need to be prepared for relevant PFAS in the water supply. Due to PFAS analytical method detection limits, spike with relevant PFAS up to 100 ng/L to obtain dose-response curves with useful resolution. When spiking PFAS, it is important to minimize organic carbon contributions from solvents that are used to dissolve stock PFAS (e.g., methanol).
- Item 4 in Section B.1.3.1 (Performance Test Procedure Preparation). The full-scale treatment objectives must be defined for the relevant PFAS at the facility in question.
- Item 1 in Section B.1.3.2 (Procedure). Transfer volume of PFAS stock solution that is representative of the intended starting dose.
- B.1.3.3 (Calculations). Calculation and analysis methodology remains unchanged but are performed for PFAS instead of MIB and Geosmin.
- Sections B.2 and B.3. Not applicable. PFAS concentrations are quantified using a US EPA-approved method such as EPA Method 533 or 537.1, however this non-compliance sampling does not need to be conducted by a certified lab unless required by primacy agency. If an uncertified lab (e.g., university) is used, periodic duplicate samples by a certified lab will increase confidence in the results.

3.2.3 NF/RO Bench-Scale Testing

Bench-scale testing of NF/RO allows for the evaluation and development of PFAS rejection rates for a specific membrane product. Characterizing PFAS rejection is critical for accurately predicting system performance as existing data may be limited to peer-reviewed journal publications since membrane projection software currently does not evaluate PFAS. Operating conditions such as permeate flux, applied pressure, and water quality can vary significantly across different sites, leading to considerable deviation in PFAS rejection, particularly for “loose” membrane products designed for lower energy use and reduced fouling. Bench-scale evaluations may be valuable for estimating the performance of a specific membrane under intended operating conditions.

3.3 Pilot Testing

While there are many benefits of pilot testing, this guidance manual focuses on situations that justify pilot testing for permitting of full-scale facilities. The intended purposes of PFAS piloting for permit approval include treatment efficacy and to establish operational parameters and identify and mitigate potential failures (e.g., biological or inorganic fouling), and not performance / life cycle cost determination. Bed life determination by piloting is possible, but these estimates can be made using other methods, such as bench-scale testing or modeling. Piloting requires more equipment, set-up, personnel, monitoring, and time to get results than bench-scale tests. Thus, it is important for piloting objectives to justify the relative cost.

3.3.1 Cost Considerations for Piloting

The cost to construct and operate a pilot may not yield enough design optimization benefit to justify the resource expense. A simplified cost-benefit analysis for piloting of two adsorptive media is presented in Table 3-3. This shows how many media replacements would be made at the same cost as a pilot study for treatment capacities of 1, 4, and 10 MGD. The analysis is limited to GAC and AIX because small systems serving 3,300 or fewer people comprise most of the systems that are anticipated to require PFAS treatment (approximately 69 percent of distribution system entry points) and small systems are most likely to install GAC or AIX (Black & Veatch, Corona Environmental Consulting, 2024).

For smaller facilities, where the cost of piloting significantly exceeds the cost of multiple media changeouts, the benefit of piloting diminishes. If a water system has already decided on a technology (i.e., decided to a specific type of media: GAC or AIX), full-scale media trials may be more practical and cost-effective, especially because it is a BAT (i.e. if the media does not last as long as the PWS hoped, the product can be replaced with another on the full scale treatment system, resulting in less costs than would have been incurred for pilot-scale product comparisons). Conversely, for larger facilities, piloting becomes more justifiable due to the higher relative cost impact of media changeouts. Flexibility to utilize full-scale trials when appropriate offer significant cost and time savings for both systems and primacy agency oversight.

Table 3-3 Cost-Benefit Analysis for Piloting One Technology Based on Treatment Capacity

Treatment Capacity, MGD	Number of Media Replacements that Would Offset Piloting Costs (Note 1)	
	GAC (Note 2)	AIX (Note 3)
1	3.0 - 8.9	2.8 – 8.4
4	0.7 – 2.2	0.7 – 2.1
10	0.3 – 0.9	0.3 – 0.8

Notes:

1. Range of media replacements are representative of piloting costs ranging from $250,000 to $750,000 (in 2024). Cost may vary based on a number of factors, such as piloting complexity, pilot skid rental vs. purchase methods, duration, and analytical costs. Costs for disposal are not included. Costs for hazardous waste classification of spent media disposal would increase the number of media replacements required to offset pilot costs.
2. GAC assumptions include 20-minute EBCT and spent media reactivation at $1.35/lb (2024 pricing).
3. AIX assumptions include 2-minute EBCT, virgin resin costs of $9.16/lb, and spent resin incineration at $2.12/lb (2024 pricing).

3.3.2 Pilot Objective Considerations

As stated previously, the primary objectives for piloting are to obtain permit approval and identify and mitigate potential failure mechanisms such as establishing pretreatment requirements to avoid potential fouling issues. The relative impacts of certain issues for each technology have been established and do not necessitate a pilot. These include:

- **GAC.** For GAC, impacts from an influent chlorine residual and virgin vs. reactivated media are known to be negligible for PFAS removal performance. Additionally, the impact to effluent water pH and leaching of arsenic are known and mitigation options are available through strategic startup phasing, using acid-washed GAC, or flushing to waste.
- **AIX.** For AIX, performance impacts based on a quench chemical upstream are known, as well as initial CSMR impacts. Disinfectant residual byproducts are possible and deserve consideration of piloting if the influent disinfectant residual cannot be removed (see additional detail in Section 2.1.2.4). For intermittent influent chlorine residuals, if the AIX manufacturer provides ancillary performance guarantees and sufficient evidence exists for no water quality implications in a similar source, then pilot testing is also not deemed necessary if accepted by the primacy agency.
- **Novel Media.** If a novel media product is approved by the primacy agency, piloting considerations would match those for AIX or GAC and be focused on situations where operational conditions

exceed manufacturer recommendations or validating known potential ancillary water quality impacts (e.g., impact of chlorine exposure on the media performance, generation of undesirable byproducts, or leaching of heavy metals).

- **PAC.** PAC testing is typically performed on the bench-scale to aid with selecting the best-performing PAC, the range of dosages, and contact time required to achieve treatment objectives.

  Other operational impacts of a new PAC feed system, PAC product, or PAC dose on solids loading and handling can be considered through desktop evaluations. Similarly, fluid dynamics impacts can be assessed via desktop evaluations (e.g., computational fluid dynamics modeling) and refined during full-scale start up.

- **NF/RO.** Piloting is typically not required to establish basic design parameters, including NF/RO flux, recovery, rejection, pretreatment chemical dosing, and post-treatment chemical dosing. However, piloting is generally recommended to confirm effectiveness of pretreatment conditions and validate NF/RO design criteria and performance.

Capabilities of the various testing techniques are summarized in Table 3-1. Checklists are provided in Table 3-4 that identify conditions for which a pilot is recommended, including source water type (i.e., surface water or ground water), ancillary treatment technologies, and implications to other treatment processes.

3.3.3 Evaluation Checklist for Sorptive Technologies

Conditions for GAC, AIX, and novel media that include risks or unknowns that would necessitate a pilot are summarized in a checklist format in Table 3-4. Note that identifying one or more applicable risks or unknowns does not automatically necessitate a pilot. The risks or unknowns associated with a treatment option are evaluated in the context of a PFAS treatment and compliance risk assessment for a site. Design or operational practice can also be used to mitigate risks and the delays associated with piloting can be avoided. This checklist can inform planning at the PWS or coordination between a PWS and the primacy agency.

For projects where sorptive media designs deviate from standard design criteria or that have water quality that pose a risk of treatment failure (i.e., channeling, biological or inorganic fouling), pilot testing is generally necessary.

The water quality parameters listed in Table 3-4 include concentration limits that help to avoid fouling of the media due to iron, manganese, precipitated or particulate solids, biological growth, and/or organics. Conditions are also included in the table when water quality has the potential to promote chromatographic peaking, or the desorption of contaminants, including PFAS. For surface waters or groundwaters under influence of surface waters that contain historical levels that reach these thresholds, pilot studies would be designed to capture the range of water quality experienced in different seasons.

It may be beneficial for a PWS to conduct pilot testing to obtain a more representative estimate of media life, but media life estimates can be achieved through techniques other than pilot testing if accepted by the primacy agency.

Table 3-4 **Checklist for Determining if Adsorptive Media Pilot is Recommended**

Media	Applicable?	Water Quality Parameter or Guidance Consideration
GAC		Required by primacy agency
		Design EBCT is less than 10 min (Note 6)
		Design HLR greater than 8 gpm/ft^2
		95th percentile feed water iron exceeds 0.3 mg/L (Note 1)
		95th percentile feed water manganese exceeds 0.05 mg/L (Note 1)
		Proposed treatment location downstream of conventional softening processes with an LSI that exceeds 1 without stabilization provided in proposed design or existing operations
		95th percentile feed water TOC >4 mg/L (Note 4)
		Intending to use as a substitution for conventional filter media for simultaneous compliance of turbidity/pathogens and PFAS (Note 3)
		Intending to use for simultaneous compliance of another NPDWR, either through substitution of another unit process or due to an existing MCL violation
	Additional Considerations for Surface Waters or Groundwaters Under Influence of Surface Waters	
		Treating a raw water (i.e., before clarification and filtration)
AIX		Required by primacy agency
		Design EBCT is less than 1.5 minutes
		Design HLR greater than 16 gpm/ft^2 or manufacturer-recommended upper limit with approval from local primacy agency
		Pre-filters are not included in the design
		95th percentile feed water iron exceeds 0.3 mg/L (Note 2)
		95th percentile feed water manganese exceeds 0.02 mg/L (Note 2)
		Influent water with polyphosphate residual and manganese > 0.02 mg/L
		95th percentile feed water TOC >4 mg/L (Note 4)
		95th percentile feed water sulfate exceeds 250 mg/L (Notes 1, 5)
		95th percentile feed water chloride exceeds 250 mg/L (Notes 1, 5)
		Proposed treatment location downstream of conventional softening processes with an LSI that exceeds 1 without stabilization provided in proposed design or existing operations
		Continuous feed water chlorine residual concentration in influent stream, or instantaneous chlorine residuals that are outside of AIX manufacturer recommended range, without a plan to quench. For intermittent influent chlorine residuals, if the AIX manufacturer provides ancillary performance guarantees and sufficient evidence exists for no water quality implications in a similar source, piloting may not be required.
		Intending to use for simultaneous compliance of another NPDWR, either through substitution of another unit process or due to an existing MCL violation
	Additional Considerations for Surface Waters or Groundwaters Under Influence of Surface Waters	
		Treating a raw water (i.e., before clarification and filtration)

Media	Applicable?	Water Quality Parameter or Guidance Consideration
Novel Sorbent		Not approved by the primacy agency as an acceptable alternative to a BAT
		Required by primacy agency
		Design EBCT is less than manufacturer recommendations
		Design HLR range outside of media manufacture recommended range
		If backwash is not allowable and pre-filters are not included in the design
		95th percentile feed water TOC >4 mg/L
		Water quality (including potential treatment chemical residuals) falls outside of manufacturer recommended thresholds
		Proposed treatment location downstream of conventional softening processes with an LSI that exceeds 1 without stabilization provided in proposed design or existing operations
		Intermittent or continuous feed water chlorine concentration in influent stream that is outside of media manufacturer recommended range without a plan to quench.
		Intending to use as a substitution for conventional filter media for simultaneous compliance of turbidity/pathogens and PFAS (Note 3)
		Intending to use for simultaneous compliance of another NPDWR, either through substitution of another unit process or due to an existing MCL violation
	Additional Considerations for Surface Waters or Groundwaters Under Influence of Surface Waters	
		Treating a raw water (i.e., before clarification and filtration)

Notes:

1. Level referenced is the contaminant SMCL.
2. SMCL limit recommended for iron for AIX. Manganese limit for AIX aligns with limitation established by various suppliers to avoid excess precipitation on the media/resin, decreasing adsorptive capacity.
3. Full-scale pilot is also appropriate for GAC replacement for conventional filters. See additional detail in Section 3.4. The same would be true for a novel adsorbent if approved by the primacy agency as an acceptable alternative to GAC.
4. GAC manufacturers indicate a up to TOC of 2 mg/L has minimal impact on GAC performance for PFAS removal. The TOC level that may impact PFAS adsorption efficacy in AIX resin is higher than for GAC. The primary driver for piloting would be risk of fouling. A TOC of 4 mg/L was selected as the threshold in which risk of fouling is increased, resulting in greater justification for piloting. 4 mg/L of TOC matches AIX resin manufacturer recommended limits, though fouling could be a risk at values below this threshold. Risk of fouling may vary based on TOC composition. Biofouling concerns can be mitigated through increased grain sizing in GAC.
5. This limit was selected in consideration of the risk of chromatographic peaking to avoid SMCL exceedances after initial equilibrium occurs, as summarized in Section 2.1.2.3.
6. Design EBCT applies to the design EBCT of the lead + lag vessel is operated in series or a single contactor if operated in parallel.

3.3.4 Reverse Osmosis and Nanofiltration Piloting Considerations

Performance of NF/RO with respect to PFAS removal is well documented. However, specific rejection rates vary depending on the membrane product and its MWCO as well as the constituent characteristics (molecular weight, charge density, etc.). Pilot testing may be desirable to validate performance of specific membranes, confirm design parameters (flux, recovery), and characterize pretreatment conditions/requirements, permeate water quality, and concentrate water quality. For these reasons, if NF/RO is selected as the PFAS removal process, piloting is typically employed unless vendor models can confidently set pretreatment requirements or in cases where NF/RO is widely implemented on the same source water. The following considerations may be included in NF/RO piloting objectives:

- Determining the rejection rate of PFAS that can be achieved at the design recovery rate and flux.
- Confirming design flux and recovery.
- Assessing the level of pretreatment required for reliable and sustained operation of NF/RO. Depending on the source water, pretreatment can include coagulation, flocculation, and filtration, cartridge filtration, antiscalant or acid addition.
- Determining cleaning frequency and chemicals for cleaning.
- Confirming post-treatment requirements for permeate stabilization (i.e., corrosion control).
- Evaluating the feasibility of meeting PFAS treatment objectives with a portion of the feed water bypassing NF/RO.
- Evaluating performance of different membrane elements.
- Characterization of concentrate water quality, evaluation of disposal options, and potential need for treatment of PFAS in the concentrate prior to discharge.

Piloting of NF/RO is recommended for surface water supplies where pretreatment conditions are critical to mitigate the risk of organic fouling. Piloting is also recommended when groundwater under the influence of a surface water is being treated. In cases where there are several existing NF/RO installations (e.g., neighboring water systems with NF/RO drawing from the same aquifer with similar water quality and pretreatment), it is possible that their operational data can be examined in lieu of conducting a pilot study. Bench-scale testing and/or pipe rig testing may also be warranted in when stabilizing NF/RO permeate for introduction to a distribution system. In this situation, it will be necessary to evaluate what blending with other sources and corrosion control treatment is required to maintain stable distribution system water quality.

Additional references for NF/RO pilot testing objectives and criteria are summarized in Table 3-5.

Table 3-5 Resources for NF/RO Pilot Criteria

Reference	Content
AWWA Water Quality & Treatment, A Handbook on Water Treatment, 6th Edition, Chapter 11	• Reasons for performing pilot testing • Considerations for testing duration and timing to demonstrate NF/RO performance and fouling potential under seasonal water quality conditions • Membrane element specifications for pilots • Considerations for instrumentation and controls
AWWA Water Treatment Plant Design, 5th Edition, Chapter 19	• Overview of NF/RO pilot system components and pilot design considerations • Typical pilot testing objectives • Considerations for testing duration and timing to demonstrate NF/RO performance and fouling potential under seasonal water quality conditions • Considerations for characterizing performance and membrane fouling • Overview of commercially available pilot skids
Industrial Water Reclamation and Reuse to Minimize Liquid Discharge, 1st Edition	• General guidance for pilot system design, duration of testing, operations and maintenance, and safety considerations for industrial applications • General guidance for analytical testing and data analysis

3.4 Full-Scale Demonstration Testing

A full-scale demonstration test is when a unit process is demonstrated in bulk flow at a WTP. When treated water from a demonstration test is conveyed into the distribution system, permitting will require all risks to be thoroughly documented and assessed. It may be possible to waste effluent water from a demonstration-scale test, but this depends on the available infrastructure on site. To formulate successful conclusions from a full-scale demonstration test, the source water tested will need to contain intended influent PFAS levels. In practice, it can be challenging to conduct full-scale demonstration where contaminated source water supplies are isolated.

The feasibility of a full-scale demonstration test must be determined on a case-by-case basis and will require approval by the primacy agency in advance. Examples of full-scale demonstration tests include the following:

- Conventional filter media replacement in an individual filter if sufficient redundancy exists to achieve filtered water quality and quantity goals in the remaining filters.
- A small system with a lead/lag pressure vessel orientation may test with an alternative media type in the lead vessel location, because the proven media will provide an additional barrier in the lag position downstream.
- Replacement PAC product dose response curves and product efficacy achieving desired ancillary water quality goals (e.g., taste and odor removal).
- NF/RO demonstration facilities, which are common in water reuse applications to demonstrate permeate and concentrate water quality.
- If the site already has NF/RO to achieve other water quality benefits, the primacy agency can review existing full-scale data to ascertain if any additional testing is required.

4.0 Available State Regulatory PFAS Permitting Criteria

This section provides context for this framework by describing the PFAS piloting guidance materials that are available at the time of publication. The following summary reflects permitting philosophies that are used for PFAS treatment systems nationwide, as gathered from surveys prepared from Black & Veatch and ASDWA are also presented.

Membrane technologies were excluded from this summary because, in cases where pilot testing is likely to be conducted (i.e., for surface water sources), the primary objective of the pilot would be to define full-scale operating parameters. States that specify pilot testing for membrane treatment typically set durations at 2 to 6 months of operation.

4.1 States with Specific Piloting Guidelines for PFAS Treatment

Table 4-1 summarizes the pilot requirements for GAC and AIX for PFAS treatment from four states: Ohio, Maryland, Pennsylvania, and Wisconsin. At the time of this publication, these states had developed detailed frameworks to guide the design, operation, and evaluation of pilot studies for PFAS treatment systems. The table categorizes the requirements into key areas such as pilot objectives, water quality monitoring, pilot design, and operational considerations.

- **Maryland:** *Pending official publication*
- **Ohio:** PFAS Treatment Guidance
- **Pennsylvania:** PFAS Piloting and Design Standards
- **Wisconsin:** Final PFAS Treatment Submittal and Pilot Study Guidance

Table 4-1 Summary of Existing State PFAS Piloting Requirements for Adsorptive Media Note 1

Category	PFAS Piloting Requirement
Pilot Objectives and Planning	
Purpose	• Ensure compliance with state/federal standards. • Optimize full-scale design (develop cost-effective treatment) • Identify impact on existing processes (avoid simultaneous compliance issues)
Application Requirements	• **Majority of States:** Pilot applications to be signed by licensed professional engineer (P.E.) • **Most Conservative State Requirement:** Timeframe of pilot, monitoring, analysis methods, pilot design parameters, and fees. Submit RSSCT data, if available.
Pilot Duration	• **Majority of States:** 6 weeks of operation • **Most Conservative State Requirement:** Duration that must account for two full cycles of media exhaustion or at least three seasons (e.g., winter, summer, and spring/fall) to account for variability in water quality.

Category	PFAS Piloting Requirement
Water Quality and Monitoring	
Historical Water Quality Data	• **Majority of States:** One year of quarterly pilot feed water quality, including PFAS, pH, TOC/DOC, total alkalinity, temperature, total hardness, certain inorganic anions and metals, turbidity, radiologicals, and technology-specific competing contaminants (Note 2). • **Most Conservative State Requirement:** Up to 5 years of historical data where available including additional regulated contaminants such as perchlorate, bromate, arsenic, 1,4 Dioxane etc.
Monitoring Frequency	• **Majority of States:** Bi-weekly PFAS for the first three months and monthly thereafter. Quarterly for additional parameters • **Most Conservative State Requirement:** Weekly PFAS sampling throughout the duration of the pilot. Daily/weekly sampling for additional parameters. Monitoring influent, midpoint, and pilot effluent required.
Simultaneous Compliance	• **Majority of States:** Ensure lead and copper corrosion control concerns are addressed. • **Most Conservative State Requirement:** Ensure impacts on disinfection byproducts, microbial quality, downstream disinfection efficacy, and the oxidation of iron and manganese are evaluated.
Pilot Design	
Column Configuration	• **Majority of States:** Single-column setup • **Most Conservative State Requirement:** Columns in series, lead and lag
Column Diameter	• **Majority of States:** 1-inch columns • **Most Conservative State Requirement:** At least 3 inches to avoid sidewall effects
Media Depth	• **Majority of States:** AIX: 3 feet; GAC: 5 to 6 feet • **Remaining State Requirements:** Not determined
Empty Bed Contact Time	• **Majority of States:** AIX ≥1.5 min; GAC ≥10 min at design capacity • **Most Conservative State Requirement:** AIX ≥2.5 min; GAC ≥10 min at design capacity
Hydraulic Loading Rate	• **Majority of States:** AIX ≤12 gpm/ft^2; GAC ≤6 gpm/ft^2 • **Remaining State Requirements:** Not determined
Backwash Requirement	• **Majority of States:** AIX: not determined; GAC: backwashing to remove solids/fines. Managing backwash waste stream must be addressed. • **Remaining State Requirements:** Not determined

Category	PFAS Piloting Requirement
Pretreatment and Operational Considerations	
Pretreatment Requirements	• **Majority of States:** Pretreat to address fouling concerns, residual oxidants, and competing contaminants • **Most Conservative State Requirement:** Pretreatment required when AIX feed contains chloride > 250 mg/L, nitrate > 10 mg/L as N, TDS > 500 mg/L, sulfate > 50 mg/L, or when GAC/AIX feed contains TOC/NOM > 1 mg/L, iron > 0.3 mg/L, manganese > 0.05 mg/L, or turbidity > 0.3 NTU. Phosphates, fluoride, and polymers must not be injected prior to AIX. For surface water sources, it is recommended to locate AIX contactors downstream of conventional filters.
Chemical Addition	• **Majority of States:** Document usage of all chemicals on pilot logs • **Guidance-specific:** All chemicals used, their injection points, and dosages must be clearly recorded in pilot logs. Information on residuals and impacts of chemicals must also be provided, including corrosion control measures, feed source chemical quenching, etc.
Waste Management	• **Majority of States:** Spent media and backwash waste must be properly disposed of in compliance with environmental regulations. • **Most Conservative State Requirement:** Permits must be secured for disposal. Backwash water must be treated, with backflow prevention in place for tanks holding backwash waste.
Documentation and Reporting	
Record-keeping	• **Majority of States:** Records must include sample collection, PFAS breakthrough data points, flow rates, and chemical usage. • **Most Conservative State Requirement:** Must document operational problems, corrective measures, media changeout, disposal measures, and any deviations from expected outcomes.
Final Report	• **Majority of States:** Summary of study providing recommendations and findings including all water quality and performance data. • **Most Conservative State Requirement:** Include compliance and scalability recommendations.

Notes:

1. Guidance is a summary from four states that currently have PFAS piloting document requirements: Ohio, Maryland, Pennsylvania, and Wisconsin.
2. The reported data consists of historical data that would be analyzed to inform pilot design. This does not imply that water systems are required to initiate data collection and delay pilot deployment. Competing contaminants vary with each adsorptive technology considered. Refer to Table 3-3 for additional detail.

4.2 Survey of Nationwide PFAS Pilot Test Requirements by Primacy Agencies

Primacy agencies have been surveyed to gain a perspective on the current requirements for pilot testing of PFAS treatment. Two separate state surveys were conducted to gather insights from state primacy agencies: an independent survey conducted by ASDWA and a survey conducted specifically for this project by Black & Veatch. These surveys canvassed primacy agencies to gather information on their current approaches to reviewing and approving PFAS treatment technologies. They addressed key factors in PFAS treatment system approval, including the types of evidence that may be a substitute for pilot testing and current guidance or references that are recommended for PWSs implementing new PFAS treatment systems. The ASDWA survey was distributed in the first quarter of 2024, and the Black & Veatch survey was distributed in the fourth quarter of 2024.

These surveys provided a nationwide assessment of the current pilot requirements, with 38 state agencies responding to the combination of the two surveys. Figure 4-1 provides a map that illustrates PFAS detections along with states that did or did not respond to the surveys. State primacy agencies that did not respond to the survey are outlined in red. PFAS detection data are from the Unregulated Contaminant Monitoring Rule 5 (UCMR 5) as of Q4 2024. These data were gathered using the US EPA's Unregulated Contaminant Monitoring Rule Data Finder. The map shows the PFAS detection levels for PWSs, defined as the percentage of PWSs serving more than 3,300 individuals that have at least one or more of the six regulated PFAS detected above the reporting limit, relative to the total number of such PWSs in each state. Darker green states indicate a higher percentage of detections, while lighter green states indicate a lower percentage of detections.

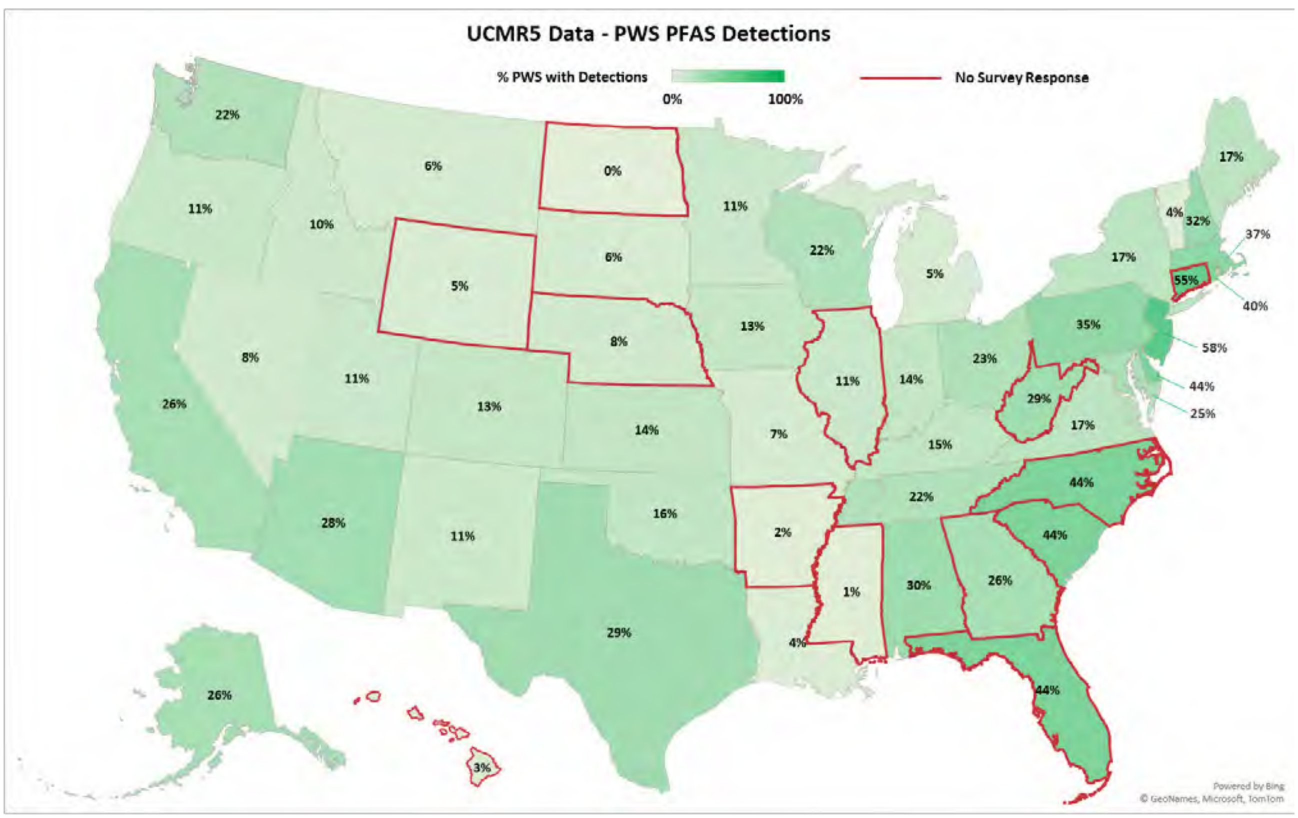

Figure 4-1 UCMR 5 PFAS Detection Data and States which Participated in Surveys about their Requirements to Pilot Test Adsorptive Media for PFAS Removal

One of the main questions in the survey was about understanding the types of testing that states currently require, or plan to require, for specific technologies before approving full-scale treatment installation permits. The survey results are summarized on Figure 4-2.

The responses fall into four categories, reflecting each state's current stance on pilot testing requirements for systems using AIX or GAC media that adhere to the design guidelines outlined in Section 2.0. As policies and practices continue to evolve and more data become available after implementation of PFAS treatment systems nationwide, these trends may shift and become less conservative. In fact, many states noted that likely outcome as part of the survey.

The color-coded states that are displayed on the map in Figure 4-2 represent the following state responses:

- **Yes:** Indicates that pilot testing is strictly required for AIX or GAC systems for PFAS applications. Among the states with an established permitting process, 46 percent responded "yes," suggesting that while AIX and GAC are established processes, there remains uncertainty related to full-scale implementation.
- **Yes, but alternative evidence may be acceptable:** Indicates a preference for pilot testing; however, in cases of time constraints or other circumstances, alternative testing methods (e.g., RSSCTs), combined evidence as described in Section 5.7.2 (e.g., accelerated piloting combined with modeling), or performance data from similar water sources may be sufficient for approving AIX or GAC systems. This category represented 17 percent of responses.
- **No:** Indicates that pilot testing is not required for GAC or AIX systems when operating within standard design ranges. Notably, several states indicated a "no" for piloting requirements on groundwater sources but a "yes" for surface water sources, due to considerations discussed in Section 3.0. This response accounted for 37 percent of replies, indicating an increasing familiarity and comfort with implementing AIX and GAC systems. Some of these states have indicated piloting would not be required for GAC but would for AIX.

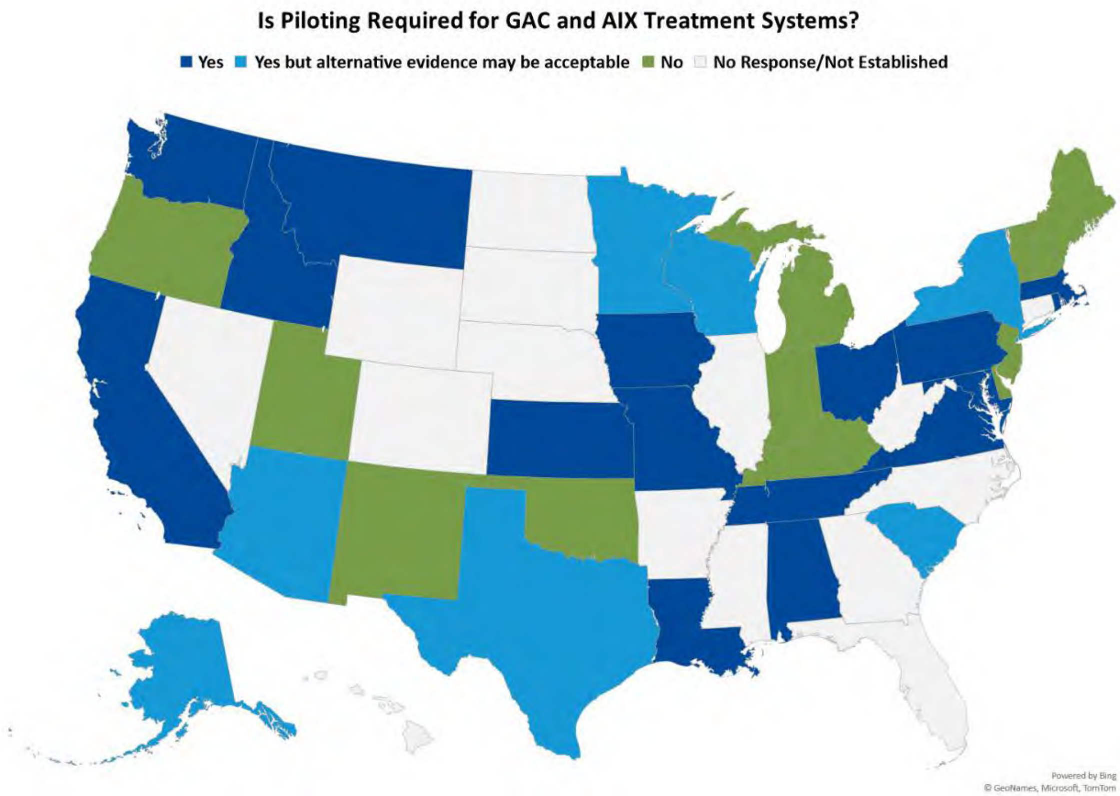

Figure 4-2 Survey Results Showing Which States Require Piloting of GAC and AIX Treatment Systems for Full-Scale Treatment Installation (data from Black & Veatch, 2024 and ASDWA, 2024)

Figure 4-3 presents the results of an ASDWA subset survey, summarizing 29 responses received as of the first quarter of 2024, and shows the states that have already permitted design of a PFAS treatment systems. These data show permitting for groundwater systems is more common at this time than for surface water systems, and most states with surface water permitted systems also have ground water permitted systems. States that have previously permitted PFAS treatment systems tend to have more flexible requirements, often allowing for other types of evidence as an alternative for pilot testing, which aligns with future expected trends for treatment evaluation methodologies as more data becomes available.

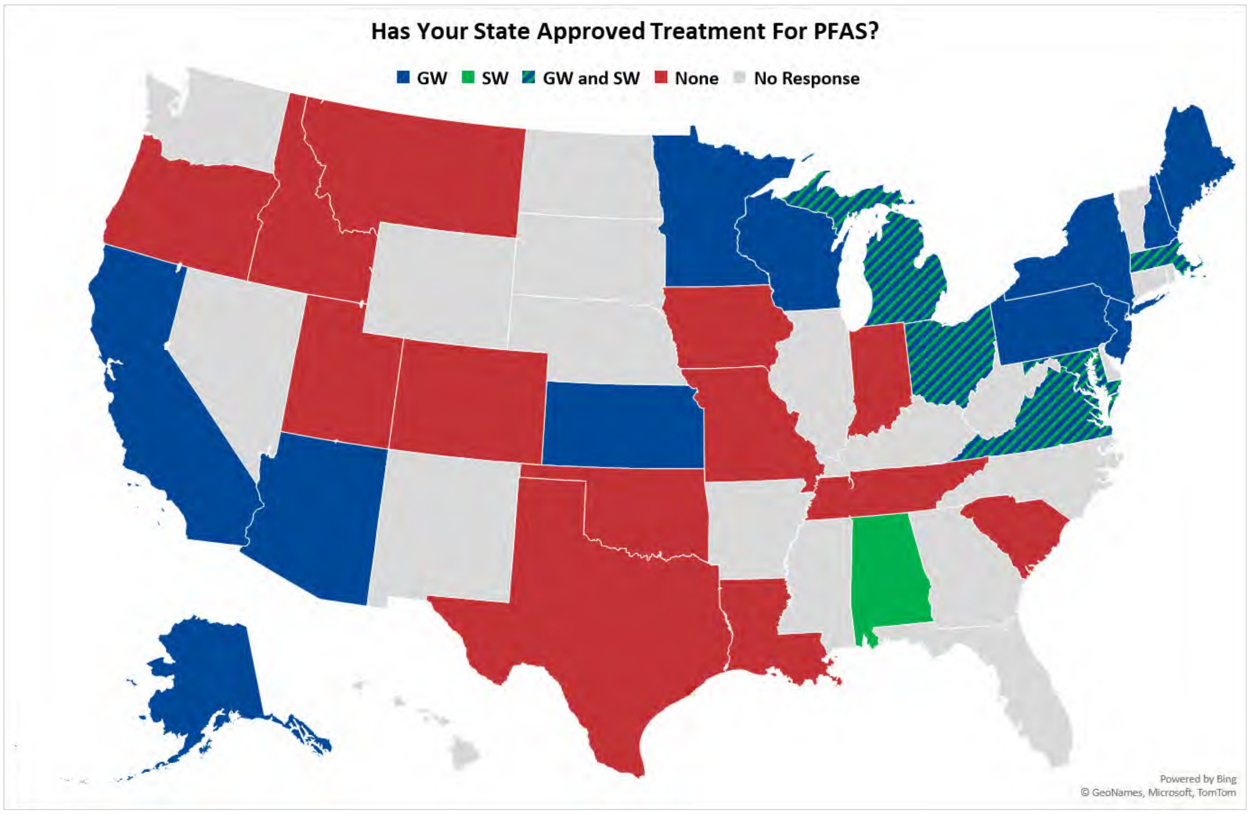

Figure 4-3 **States that have Previously Approved a PFAS Treatment System Design for Groundwater and/or Surface Water Sources (ASDWA 2024)**

Figure 4-4 shows the percentage of state agency responses that accept different types of evidence for permitting purposes, based on a subset of 30 responses. As expected, trust in the data used to permit treatment systems decreases when it is less specific to the site's actual water quality or does not closely simulate full-scale performance. Trust in models as a substitute for real-world data is currently low, as practical testing data provides more confidence than desktop studies.

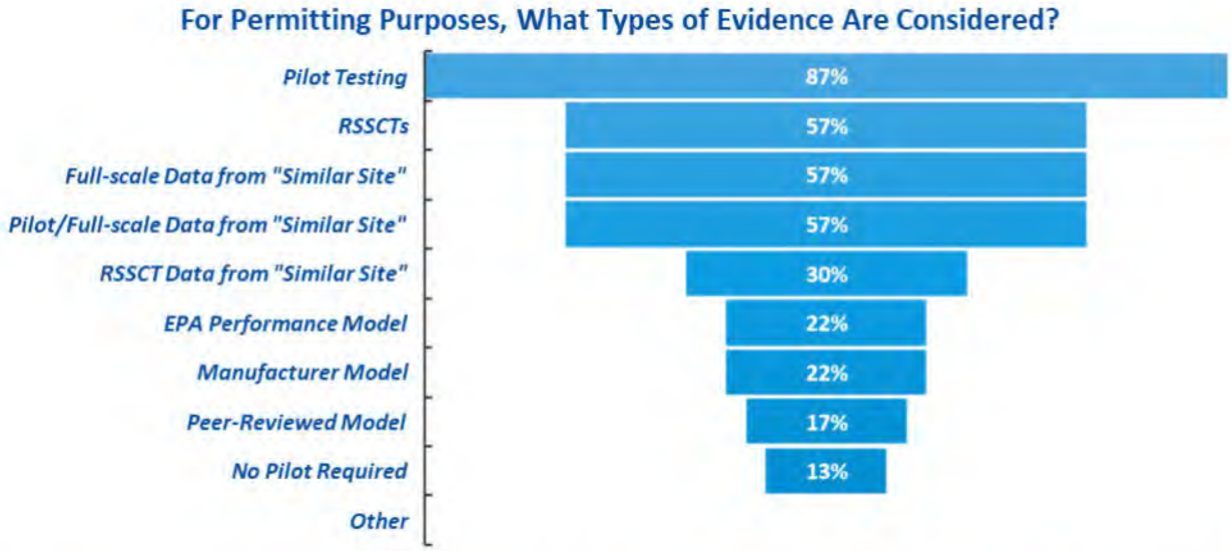

Figure 4-4 **Survey Responses about the Types of Evidence Considered for Permitting (data from Black & Veatch / AWWA, 2024 and ASDWA, 2024)**

Figure 4-5 summarizes the types of documents, including standard operating procedures (SOPs) and guidance materials, that state agencies recommend as useful resources for approving typical PFAS treatment systems.

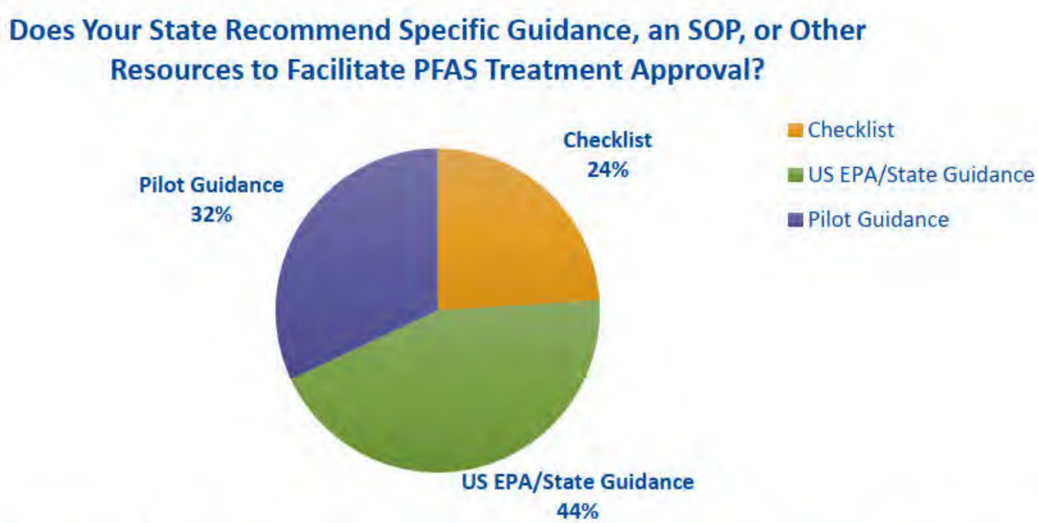

Figure 4-5 **Summary of State-Recommended SOPs and Guidance Documents for PFAS Treatment System Approval (data from Black & Veatch / AWWA, 2024 and ASDWA, 2024)**

The recommended documents are summarized into the following categories:

1. **Checklist:** 24 percent of states have recommended checklists, such as the one used in Georgia, to guide the submission of pilot or treatability study plans for new or modified surface water systems. These concise documents provide a structured framework, outlining essential requirements for pilot studies and full-scale system designs using PFAS-specific treatment technologies. Example documents: Georgia surface water checklist 3 submission pilot studies (Georgia); Alaska Plan Review Checklist (Alaska).

2. **Pilot Guidance:** 32 percent of states have recommended the PFAS-specific pilot guidance material listed in Section 4.1 or general pilot testing guidelines that PWSs are required to follow. Example documents: Hawaii DoH General Guidance (Hawaii); Texas (TCEQ) Request for Exception to Provide Innovative/Alternate Treatment (Texas); Massachusetts Pilot Study Requirements (Massachusetts).

3. **US EPA/State Guidance:** 44 percent of states have suggested using guidance documents such as the US EPA's BAT and State-specific design standards as a starting point. These resources offer comprehensive design standards and best practices for implementing PFAS treatment technologies at full-scale level. Example documents: US EPA BAT and Small System Compliance Technologies for PFAS in Drinking Water (EPA); Arizona PFAS Decision Tree (Arizona); Minimum Design Standards for Missouri Community Water Systems (Missouri); Interim Recommendations for Granular Activated Carbon (GAC) (New York); and the PFAS Treatment Engineering Document (Vermont).

4. **Ten State Standards:** *In addition to recommending other guidance documents*, 20 percent of states have also referenced the Ten State Standards as a valuable resource. This widely recognized standard outlines best practices and technical specifications for designing and approving PFAS treatment systems. Example document: Recommended Standards for Water Works (Ten States).

5.0 Recommended PFAS Piloting Criteria

Pilot testing in order to permit a new PFAS treatment system is anticipated when the installation meets criteria in Section 3.3.3 for sorptive media. This section summarizes the basic elements of the protocol or execution plan for a pilot intended to support the implementation of a new PFAS treatment system. This section is limited to piloting for GAC and AIX. However, piloting guidelines can be adapted to novel sorbents with product-specific considerations. Piloting recommendations for NF/RO are covered in Section 3.3.4.

5.1 Pilot Test Protocol for GAC or AIX PFAS Treatment

All pilot protocols must contain enough supplementary information to document the goals of the pilot study and demonstrate how those goals will be achieved. This section outlines the recommended information to include in a pilot protocol. Conceptually, these sections apply to any technology that will be piloted and are informed by adsorptive technology characteristics, as documented throughout this framework, and publicly available published state guidance or requirements, as summarized in Section 4.1. The intent is to document a recommended level of information to be included; specific requirements of primacy agencies must be deferred to, to the extent expectations differ.

The content to include in a pilot testing protocol for GAC or AIX PFAS treatment systems are summarized in Table 5-1.

Table 5-1 Information Recommended to be Included in an Adsorptive Media Pilot Testing Protocol

Section	Recommendation
Introduction, Background, Objectives	
Existing Conditions / Description of the Water System	• Public water system name and ID number • Description of water source and existing treatment processes • Process flow diagram with location of proposed PFAS treatment • Summary of PFAS occurrence • Water quality and production data at the location where PFAS treatment will be installed
Treatment Goals	• Existing goals and KPIs • New goals and KPIs • Simultaneous compliance (e.g. corrosion control)
Overview of the Study to be Performed	• Objectives • Technologies to be evaluated • Rationale for selection • Expected duration and intended installation date to confirm ability to meet compliance deadlines
Pilot System Design	
Preliminary Full-scale Design (required to document pilot represents full-scale conditions)	• Table comparing full-scale design criteria compared to piloting criteria to validate piloting design criteria and facilitate future permitting approvals • Design criteria (e.g., EBCT, HLR) at design and average flow • Description of orientation (e.g., lead-lag, parallel) • Description of operation (e.g., continuous, intermittent)

Section	Recommendation
Pilot Design Overview	• Design criteria • Description of orientation (e.g., lead-lag, parallel) • Process flow diagram (including pretreatment, source water and disposal) • Pilot schematic and summary of conditions to be tested
Pilot System Operation	• Continuity of service (e.g., continuous, intermittent) • Periodic changes to HLR/EBCT to validate intended operation (verify redundancy strategy, etc.)
Pilot system installation	• Description of equipment • Photos/diagrams of pilot equipment location(s) • Description feed water and modifications required (including chemical pretreatment) • Description of effluent/disposal • Description of monitoring locations (i.e., influent, effluent, intermediate sampling ports) and their interpretation/purpose
Pilot Startup	• Description of startup parameters of concern • Commissioning requirements (e.g., media loading, backwash, filter-to-waste) • Start-up monitoring parameters (constituents, location, frequency)
Pilot Monitoring	• Routine monitoring parameters (constituents, location, frequency), including flows and pressures, chemical feed system operation • Decommissioning decision making (e.g., duration, breakthrough, fouling failure)
Data Management	• Description of data storage and back up
Residuals/Waste Management	• Identification of all residual and waste streams, (i.e., spent media, treated effluent, equalization overflow, etc.) and designation of how they will be disposed of • Identification of permits required to address these streams, such as, but not limited to sewer discharge or National Pollution Discharge Elimination System (NPDES) permit
QA/QC Plan	
Sampling	• Sampling protocol (See example in Appendix A) • Description of positive/negative controls • Data collection templates
Critical Control Point Analysis	• Summary of critical parameters to be routinely checked to ensure basic operation of pilot (e.g., flow rates)
Safety Plan	• Summary of risks and mitigation (e.g., Health and Safety Plan) • Safety Data Sheet (SDS) for all chemicals used
Data Analysis	
Analysis	• Regulatory reporting/update frequencies • Internal PWS update frequencies • Data analysis software description

If the pilot finished water is discharged to an existing WTP process (further details presented in Section 5.2), the primacy agency may require the protocol to be signed off by a licensed operator.

5.2 Pilot Plant Design for GAC or AIX for PFAS Treatment

This section summarizes adsorptive media pilot column design considerations and pilot skid components to facilitate success and subsequent permitting of the full-scale system.

5.2.1 Hydraulic Loading Rate and Empty Bed Contact Time

Breakthrough curves are fairly uniform at different EBCTs when the HLR is held constant. Intermediate sample taps can be used to model performance at various EBCTs at a single loading rate without requiring duplicate columns with varying media depths. Since short-chain PFAS tend to have a deeper MTZ than long-chain PFAS, the scale-up accuracy can be compromised for those short-chain PFAS since the MTZ must be contained within the bed depth in order to accurately predict breakthrough at one EBCT from another. These concepts are evidenced by the following two studies:

- In a pilot study conducted on a PFAS-contaminated groundwater system in Minnesota with GAC and AIX, it was observed that the bed volumes to 50 percent breakthrough (BV_{50}) closely overlapped at the various sample taps (EBCTs of 3.6, 6.9, and 10.3 minutes for GAC and 0.8, 1.4, and 2.7 minutes for AIX). The bed volumes to 10 percent breakthrough (BV_{10}) varied from earlier EBCTs to higher EBCTs, with a larger difference observed at the earlier sample taps. However, results were conservative, meaning that if early breakthrough data is used to project performance of design EBCTs, BV_{10} estimates will be conservative whereas BV_{50} estimates will be more representative (Chow, et al., 2022).
- Another pilot study conducted on a groundwater well in California had similar findings, where breakthrough data at shorter EBCTs (1 minute) was representative of that at higher EBCTs (2 minutes) for the two PFAS that experienced sufficient breakthrough (PFOA and PFBS) within AIX resins and a novel sorbent. For each media, the predicted data was consistently conservative in comparison to actual data, with the higher EBCT overperforming predictions by approximately 20 to 30 percent throughout the experiment (up to 500,000 BVs). The predicted vs. actual performance diverged for the novel sorbent after BV_{50} for the tested PFAS. These findings further corroborate the limited risk in scale-up data from early sample taps to later sample taps to accelerate piloting conclusions (Pannu, et al., 2024).

Some primacy agencies will require pilot columns to be operated at the intended full-scale design HLR, because this will be the most conservative representation of media performance. If the PWS wants more information on O&M cost, a duplicate column operated to represent average conditions can be used, though this information may be more cost-effectively estimated through a desktop evaluation or RSSCT.

The overall intended EBCT may be split between multiple columns in series, which may be the only option available to test extended EBCT for GAC due to common height limitations to media columns in the piloting space. Scaling results from 10 minutes of EBCT to a higher EBCT results in more conservative performance estimates due to the larger impact of MTZ at lower EBCTs. Effective conclusions for full-scale design EBCTs above 10 minutes may be drawn from a pilot with EBCTs less than or equal to 10 minutes. However, a PWS can perform piloting at higher EBCTs if higher resolution data is desired.

5.2.2 Pilot Skid Components

An image of an adsorptive media pilot skid and list of pilot materials is presented on Figure 5-1.

Pilot Equipment

1- 4-6 in diameter columns

2- Pressure gauges (useful before pretreatment, before column, and at column effluent)

3- Rotameters (one per column)

4- Flow totalizers (one per column)

5- Plenums (one per column)

6- Underdrain plate (one per column)

7- Intermediate sample taps with media screens (multiple per column)

8- Air relief valves (one per column)

9- Pressure relief valves (not shown)

10- Equalization (EQ) tank

11- Feed pump(s)

12- Backwash tank

13- Backwash pump

14- Piping, valves, fittings

15- Light shade for algal prevention

16- Cartridge filters (if applicable, not shown)

17-Chemical metering pumps and storage (if applicable, not shown)

Figure 5-1 Typical Components of Adsorptive Media Pilot Testing Skid (example shown includes two GAC columns on left and two AIX columns on right)

Some key recommendations for pilot design considerations include the following:

- The pilot skid components be representative of features to be included in the full-scale design, including media support provisions.
- Sufficient intermediate sample taps to track mass transfer zone through column depth over time and potentially accelerate pilot duration, as described further in Section 5.7.2 If intermediate sample taps are used, a minimum of two intermediate sample taps are recommended. Design of the sample tap depths account for the expected time to achieve breakthrough data at the representative depth in comparison to project schedule and account for expected media depth changes during pilot operation (e.g. AIX media depths will compress during operation). AIX manufacturers offer media-specific recommendations for column construction, such as media retention screens above each sample tap to maintain the corresponding EBCT. Alternatively, multiple columns could be used.
- Sample ports extend at least ½-inch into the pilot column to avoid potential wall effects that could impact sample accuracy, and media retention screens be included to avoid media loss during sample collection.
- Columns are transparent to allow for media observation. Columns are shaded from light in foil or cloth in their entirety to prevent algal growth (Figure 5-1 does show full column wrap), which can be easily removed for visual inspections.
- Cartridge filters anticipated in an AIX design are included in a pilot, including site-specific size exclusion requirements.
- Pilot skids are designed to convey treated water to a pilot backwash holding tank that overflows to the intended location (i.e., pilot effluent water can be returned to the process or to a WTP drain with applicable backflow prevention and/or air gap devices to prevent cross contamination).
    - When discharging pilot skid effluent back to the full-scale treatment facility, all materials must meet Primacy Agency and NSF 60/61 standards, otherwise discharge of the pilot effluent water to a WTP drain will likely be required. NSF 42 may be an acceptable substitute for smaller systems per the primacy agency's discretion.
    - The pilot's backwash holding tank will then be the source of backwash water for the pilot skid as needed, because it will be representative of future full-scale backwash water quality. Backwash water not treated for PFAS may negatively impact PFAS breakthrough results.
- Flush the pilot system with water prior to loading media. Whether constructing a skid or purchasing a prefabricated pilot skid, it is important to understand the materials being used. Several states have published guidance describing PFAS containing materials as it relates to sampling procedures. It is also important to ensure that PFAS contamination is minimized. For example, fluorinated materials such as PTFE (including Teflon tape that is commonly used for pipe threads) and PVDF are made from PFAS or PFAS containing materials and can impart PFAS contamination in pilot evaluations. To validate that the materials of construction are not contributing a measurable amount of PFAS, samples of the influent and effluent streams prior to column loading can be collected and compared. Similar considerations made for volatile organic carbon (VOC) contamination are also valuable, because VOCs may impact GAC performance. Use of VOC-containing glues is not recommended. If glue to control pipe leaks are needed, apply glue as far from the wetted surface of the pipe as possible.

- General practice is to pilot a single column per test variable. Duplication is unnecessary, but optional.

5.3 Source Water Considerations

Multiple aspects of source water may influence optimal pilot design and utility of pilot study results, including how representative the pilot source is of the anticipated full-scale influent, and the water quality characteristics that may necessitate pretreatment.

5.3.1 Representativeness of Pilot Influent

To have utility, the representativeness of the pilot study to full-scale design extends to the water the full-scale facility will treat. Preparing representative influent water supply for a pilot study can become a complex challenge. For example, there are instances when different wells contain different concentrations of constituents that could impact treatment performance, such as TOC, iron, manganese, VOCs, and anions. If raw water treatment is proposed, source water blending or pilot treatment of the most contaminated source may be considered. If filtered water treatment is proposed, the existing WTP filtered water would be the most appropriate piloting source to avoid adding significant complexity to the pilot. If existing filtered effluent is low in PFAS due to contaminated sources being offline, or interim PFAS treatment measures, spiking of PFAS to the pilot influent is more representative of actual treatment conditions than attempting to replicate existing treatment on a contaminated source. When spiking PFAS into a pilot, provisions are included in the pilot's design and operating protocols to ensure PFAS is not released into finished water or waste streams. Media life is estimated by applying normalized breakthrough curves, as summarized in Section 2.1.1.5, with the expected influent concentration (C_0) and the removal percentage needed to achieve the effluent water treatment PFAS goal.

5.3.2 Pretreatment Requirements

Pretreatment considerations include the following:

- Confirmation of pre-filtration recommendation upstream of AIX. In that case, a dedicated filter upstream of an individual column could be compared to the performance of an un-filtered column, or a pre-filter upstream of a column could ultimately be deemed unnecessary based on a complete absence of particulate accumulation, or valuable based on frequent clogging
- If chlorine or other oxidants are present in the sample stream in excess of the resin manufacturer recommended range, quench the residual chlorine to prevent media degradation or potential risk of byproduct formation. Nitrosamine formation potential can be piloted for confirmation of the quench chemical requirement.
- If full-scale treatment improvements to provide additional TOC removal prior to GAC or AIX for PFAS removal is being considered, investigating the associated benefits and costs would necessitate the production of TOC-reduced water for the pilot influent. If feasible, TOC reduction modifications could potentially be evaluated at full-scale. Otherwise, the modifications would be incorporated as an additional unit process in the pilot design.

5.4 Pilot Plant Startup Considerations

Media is installed and conditioned in the test columns per media manufacturer recommendations. This can include rinsing, fluidization, and water quality monitoring. Monitoring spent backwash and rinse water quality may be performed to inform full-scale startup planning.

Refer to Table 5-2 for initial sampling requirements during startup.

5.5 Sampling Throughout the Pilot Study

A sampling plan for initial startup monitoring and ongoing monitoring is presented in Table 5-2.

Table 5-2 Adsorptive Media Pilot Study Sampling Recommendations

Classification	GAC		AIX		Sample Location (Notes 2, 3)
	Parameter	Frequency (Note 7)	Parameter	Frequency (Note 7)	
Initial (Startup) Monitoring (Note 1)	pH	Increased frequency (every 25-20 BVs) until levels stabilize (Influent = Effluent) (Notes 1, 2)	pH	Increased frequency until levels stabilize (Influent = Effluent) (Note 1)	CI, ICE
	Turbidity		Sulfate		
	Arsenic		Chloride		
	TOC	Weekly	TOC		
	Iron, µg/L		Perchlorate		
			Nitrate, as N		
	Manganese		Alkalinity, as $CaCO_3$		
			Iron	Weekly	
			Manganese		
			Turbidity	Daily (Note 3)	
	PFAS	Once (Notes 4, 5)	PFAS	Once (Notes 4, 5)	CI, ICE, IST
Ongoing Monitoring (Note 1)	pH	During operational check-ins	pH	During operational check-ins	CI, ICE
	Turbidity		Turbidity		
	TOC	Monthly	TOC	Monthly	
	Iron		Iron		
	Manganese		Manganese		
			Sulfate		
			Chloride		
			Perchlorate		
			Nitrate, as N		
			Alkalinity, as $CaCO_3$		
	PFAS	Monthly (Notes 5, 6)	PFAS	Monthly (Notes 5, 6)	CI, ICE, IST

Notes:

1. Initial startup monitoring is conducted until the listed parameters reach equilibrium, which is expected to take approximately one week, though analytical results will take additional time to receive and analyze. Ongoing monitoring will commence after that.
2. Initial arsenic monitoring recommended to inform startup requirements for new GAC contactors.
3. CI = Common Pilot Skid Influent, ICE = Individual Column Effluent, IST = Intermediate Sample Tap.
4. It is recommended to monitor influent turbidity during startup to ensure it aligns with expectations and inform pretreatment modifications.
5. For PFAS, begin sampling at the top-most sample tap. Once the relevant PFAS is detected at the top sample tap, move to the next location for the following sample.
6. Once the relevant PFAS is detected at the bottom sample tap, increase frequency of monitoring at the last sample tap and relevant ICE tap appropriately.
7. If the relevant PFAS is short-chain and expected to break through rapidly, monitoring frequencies may increase from those listed herein.
8. Frequencies are site specific and may deviate from those listed herein.

In addition to the parameters specified in Table 5-2, parameters relevant to simultaneous compliance are also included in sampling plan. That may include the following:

- Data for supplemental corrosion control evaluations, as summarized in Section 2.1.2.2.
- Data to quantify ancillary water quality benefits, as summarized in Sections 2.1.1 and 2.1.2.
- If chlorine is not quenched prior to contact with a macroporous-based resin, analyze samples from the relevant column effluent samples for formation of relevant byproduct(s) using US EPA approved methods (e.g., EPA Method 521 for nitrosamines).
- Spent backwash water quality may be monitored to inform residuals handling approaches.

Piloting samples are analyzed using US EPA approved methods 533 and 537.1. Samples can be analyzed by a lab that is not certified for regulatory compliance, such as those employed by universities; however, periodic analysis of duplicate samples using a US EPA-certified lab will provide a higher level of comfort with the results. To serve this purpose, duplicate samples need to have measurable concentrations above applicable analytical method detection limits (i.e., from the pilot skid influent water). Proper quality assurance / quality control (QA/QC) procedures including chain of custody reporting are important for analytical samples. For PFAS in particular, it is important to include negative controls to detect potential cross-contamination.

Samples are collected using appropriate practices to minimize the potential for sample contamination to be best extent possible. It is also important to collect samples in a manner that does not harm the pilot or alter observed concentrations. For examples samples from test columns are drawn slowly by cracking the sample line valve instead of opening it fully to avoid disrupting column hydraulics, causing channeling and associated misrepresentation of sample results.

5.6 Pilot Operation

Key considerations for successful operation of a PFAS pilot include:

- Pilot operational QA/QC checks to confirm the pilot is operating as intended are necessary to ensure that the data that are collected are useful and accurate. The frequency of checks and parameters to monitor are pilot-specific. Routine checks are initially conducted three times weekly and more in-depth checks are conducted bi-weekly. Frequency and thoroughness of routine checks can be reduced as familiarity with the pilot and its operations develop. Log sheets are used to identify items to check, data to record, and actions to take if issues are observed. Separate log sheets might be considered for items requiring observations at different frequencies (weekly, monthly, etc.). It is critical to check essential operational data such as flow rates while onsite to ensure they are within acceptable limits and make required adjustments. Operational checks are summarized in Table 5-3.

Table 5-3 Recommended Operational Checks for QA/QC

Frequency	Data to log (as applicable)	Specific Equipment or Operation to Check (as applicable)
Every time operator is onsite (e.g., 3X/week)	• Flow • Differential pressures • Any analog or digital measurement output • Water quality parameters measured on site (e.g., pH or temperature) • Relevant WTP operational changes per discussions with WTP operators (chemical usage, etc.)	• Check for leaks • Feed pump operation • Equalization tank level
Weekly	• Chemical feed dose rate • Discoloration of pilot media	• Check chemical feed stock tank levels • Ensure suction tubing is submerged
Monthly	• Chemical feed tubing	• Check for wear on peristaltic tubing and replace

- It is possible that the useful life of some equipment will be shorter than the pilot duration. Periodically monitor the pilot equipment for signs of wear or degradation, such as increased noise, decreased flow, increased pressure, leaks, etc., and take a proactive approach to rehabilitate and/or replace equipment.
- Pilot equipment is operated in a way that will mimic full-scale operations. For surface water plants, continuous operation may be desired, whereas for small groundwater systems, intermittent operation may be more appropriate. When the pilot equipment is at an existing WTP engage the WTP operators to support maintaining intended pilot production throughout the course of the test.
- Brief outages may be unavoidable but can be mitigated through proper pilot SOPs and use of an equalization tank to support continued pilot influent water supply during brief disruptions to pilot influent such as filter backwashes.
- For GAC, as in full-scale operation, subfluidization backwashing is used during piloting when flowrates (and therefore HLR) decline. If head loss it not mitigated at subfluidization backwash rates, higher backwash rates may be needed to remove additional particles. Pilot operations follow backwash procedures provided in manufacturer recommendations to the extent feasible.
- For AIX, it is generally not recommended to backwash the media to maintain the MTZ. Subfluidization wash at a rate less than 1 gpm/ft^2 has been used to release particles from the top of the bed without disrupting the resin to extend media lifespan of AIX pilot columns and full-scale installations. If backwash alleviates differential pressure across the pilot column, this is an indicator that particle buildup is occurring and installation of a cartridge filter (or modification of existing cartridge filter size exclusion) at the column inlet can prevent future particle buildup. Alternatively, if acceptable pressures are not restored through subfluidization backwashing, the resin may have experienced fouling and may have to be taken offline. When fouling issues occur during pilot testing, incorporate lessons learned into full-scale design and operational plans.
- Operations personnel at WTPs where pilot studies are ongoing can be trained in the basic safety and operation of the pilot system, including what issues to monitor for and how the pilot can be safely shut down if needed. Providing in-person training and placing quick reference resources with key action items on the pilot site facilitates timely, effective action. Readily available information

includes a contact list including at least an emergency contact. Periodic reminders to staff that do not interact with the pilot frequently are helpful. Cross training one or more persons in the day-to-day operations of the pilot can facilitate seamless management of planned and unplanned absences.

5.7 Duration for GAC and AIX Adsorptive Media Pilots

The intended duration of a pilot study is aligned with the stated pilot study objectives. If operational constraints are the focus of the pilot, extending pilot operation through periods the most challenging source water conditions can be informative. If observation of breakthrough is a stated goal of the pilot, plan and budget for piloting durations that are consistent with duration of other pilots with similar water qualities and media being tested or through estimates provided by media manufacturers. In the event that the time anticipated to observe breakthrough of target contaminants during a pilot is not compatible with a water system's budget or schedule constraints, techniques to accelerate acquisition of pilot results may be employed.

5.7.1 Duration Commensurate with Objectives

The pilot duration, or threshold at which the pilot can be terminated, is defined with the piloting objectives in mind. Examples can include:

- A PWS may determine that high spring TOC levels and winter manganese turnover present the most challenging water quality characteristics for treatment, and these events may occur within a six-month seasonal window. If a PWS decides that a six-month operation is acceptable/affordable, the pilot duration can be capped at that duration
- A small system may need to achieve 80 percent removal of PFOA to meet its treatment target, allowing the pilot to be stopped once a PFOA C/C_0 of 20 percent is achieved.
- A water system decides that a preferred media will be sufficiently cost-effective if it can sustain effective treatment at least one year between changeout events. In this instance, the pilot could be discontinued either as soon as breakthrough is observed, or at one year of operation if the media is still meeting the treatment goals at that time.

5.7.2 Pilot Schedule Acceleration Techniques

Based on the piloting objectives as defined in Section 3.3.3, there may be opportunities to reduce piloting durations once initial water quality data are collected. Those include:

- Using PSDM or other curve fitting models (such as manufacturer models) to predict breakthrough at all bed volumes treated. A minimum of 10 percent breakthrough has been used as a threshold for PSDM in some research (Cheng and Knappe, 2024) and accuracy increases with additional breakthrough (typical recommendation is 30-50 percent breakthrough before). The data can be used to project the rest of the curve to full breakthrough. Additional detail is provided in Table 3-2.
- Utilizing breakthrough data from intermediate sample ports at lower EBCTs to extrapolate breakthrough data at the column effluent at higher EBCTs, as discussed in Section 5.2.1. It is also possible to design the pilot with shorter duration EBCTs if only column effluent sample ports are provided; but this approach has the limitation that the projections of the acceleration could not be confirmed unless multiple columns are tested in series.
- Using a different emerging technique, if it is approved as equal to other modeling methods by the primacy agency and if the engineer has demonstrated experience successfully using the model or technique. For example, observing breakthrough of weaker adsorbing constituents and then

modeling the stronger adsorbing constituents (e.g., regulated PFAS) that may not have broken through to avoid having to run the columns for years to observe target constituent breakthrough.

- Spiking PFAS into the influent of the pilot to decrease the duration of the pilot until quantifiable breakthrough results are obtained. Spiking of weaker adsorbing constituents may also facilitate use of emerging modeling techniques previously mentioned. Comprehensive design and safety provisions are included in pilot design to avoid release of PFAS into the finished water or waste streams.

For site-specific conditions with high risk of fouling, these techniques may not fully represent all potential impairments to media life since the rate of fouling cannot be simultaneously accelerated. Applicability of these techniques are evaluated on a case-by-case basis. When risk of fouling is a concern, initial conclusions can be drawn using these acceleration techniques to allow detailed design and construction phase services to progress in parallel with confirmatory piloting, as acknowledged in Section 1.2.

5.8 Pilot Data Analysis and Interpretation

Data collection and analysis throughout pilot evaluations allows for pilot progress performance monitoring in comparison with the target piloting objectives. Maintaining records of date and time, instantaneous flow rates, totalized flows, influent PFAS concentration, and effluent PFAS concentration are critical for data analysis. Check with your primacy agency at the onset of the pilot evaluation to understand project specific reporting requirements.

Breakthrough curves, as described in Section 2.1.1.5, can be developed early on to assist in identifying the pilot duration to achieve significant breakthrough of the PFAS of concern. This can be done in a simple spreadsheet software such as Microsoft Excel. Other software, such as Microsoft PowerBI, can be used to create dashboards displaying breakthrough curves for a wide range of project stakeholders to view throughout the pilot evaluation. An example dashboard is shown on Figure 5-2.

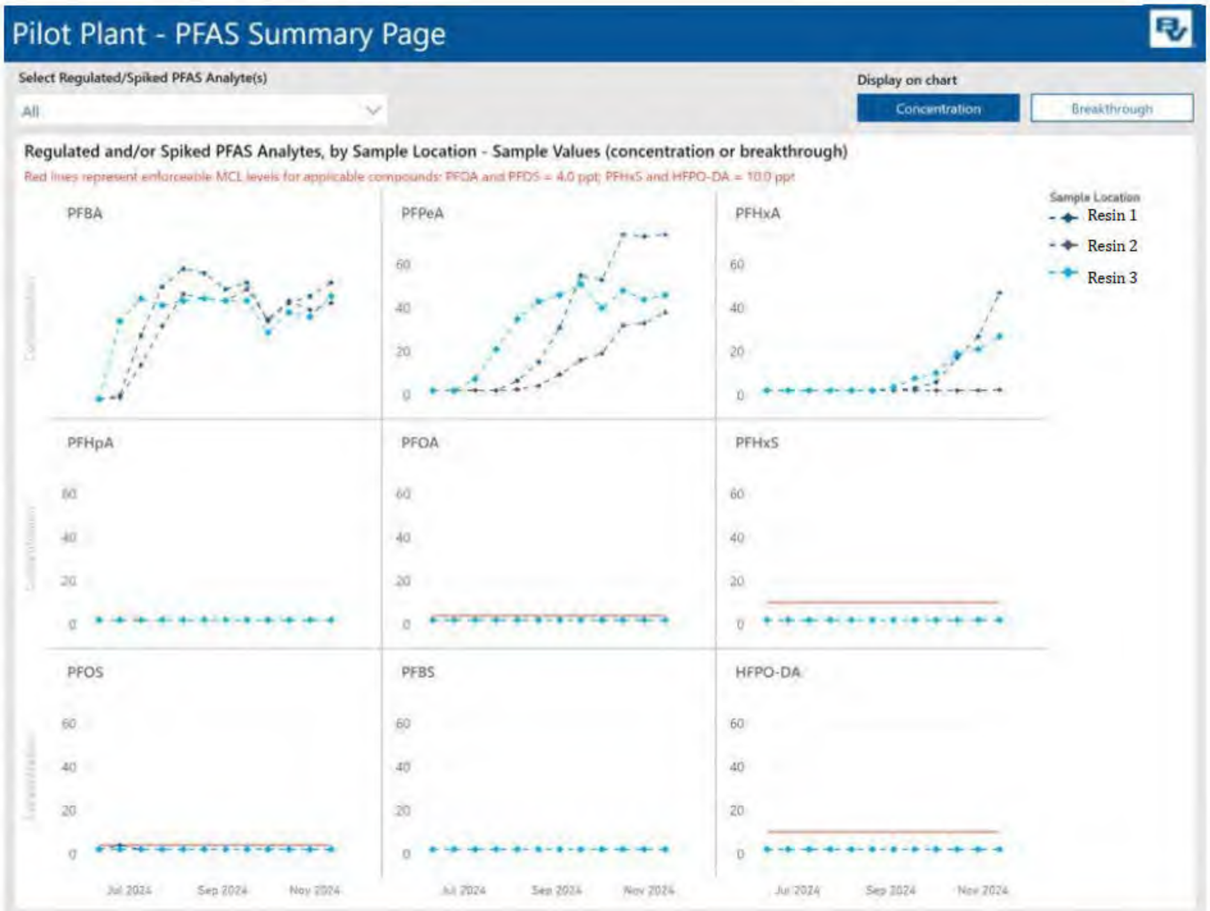

Figure 5-2 **Example Dashboard using PowerBI showing the Breakthrough of Contaminant Over Time During Piloting**

Depending on the starting concentration of relevant PFAS, breakthrough data may be limited at the bottom of the breakthrough curve due to detection limits. For example, if PFOS is present at a concentration of 8.0 ng/L, reliable data will not be available until nearly 50% breakthrough (associated with the PQL of 4.0 ng/L) is achieved.

After plotting breakthrough data, continuous breakthrough curves can be developed using non-linear regression techniques or by utilizing US EPA models such as PSDM and HSDM as described in Section 3.1.

Continuous breakthrough curves can be used to estimate the media change out frequency. Simulation of the planned operation of full-scale contactors is important to maximize calculation accuracy since these variables impact the amount of adsorption capacity used prior to change out (e.g., lead-lag or parallel flow, staggered contactor operation).

After quantifying the media changeout frequency based on intended full-scale operation, life-cycle costs can be developed, accounting for both capital costs (such as cost of equipment, infrastructure, etc.) and O&M costs (such as cost of media replacement, residuals management, chemicals, electricity, etc.). While life-cycle costs are an important consideration when selecting an appropriate technology, non-financial factors such as co-beneficial removal of contaminants, and ease of operation, environmental fate of PFAS, among others, are important to consider on a case-by-case basis.

In addition to development of breakthrough curves and life-cycle costs, additional data collected during the pilot evaluation can be analyzed as summarized in Section 5.5, to inform simultaneous compliance evaluations if applicable, in addition to full-scale operations and startup planning.

5.9 Pilot Decommissioning Considerations for GAC and AIX Adsorptive Media

Once the pilot is decommissioned, spent media is disposed in compliance with relevant federal and state regulations. At the time of publication of this guidance manual, disposal in a US EPA-compliant landfill would be acceptable. The spent media can be combined with other WTP residuals that are transported to a landfill.

Postmortem testing can be completed to identify the degree of fouling in media beyond that which is quantified through head loss accumulation in the respective pilot columns. Additionally, Toxicity Characteristic Leaching Procedure (TCLP) testing can be performed to understand any risks associated with landfill disposal, such as that from uranium.

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