Evaluation of Current Alternatives and Estimated Cost Curves for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water

Prepared for
Minnesota Pollution Control Agency

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Prepared by:
Barr Engineering Co., Hazen and Sawyer

4300 MarketPointe Drive, Suite 200
Minneapolis, MN 55435
952.832.2600
www.barr.com

Certifications

I hereby certify that this report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Minnesota.

Alison Ling
PE #: 54858
Date: May 10, 2023

Responsible for Sections 1, 2, 3, 4, 10 (except 10.5), and 11; Appendices A, B, C, and D

I hereby certify that this report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Minnesota.

Kathryn Wolohan
PE #: 54881
Date: May 10, 2023

Responsible for Sections 5, 6, 8, and 9; Appendix E

I hereby certify that this report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Minnesota.

Anna J Munson

Anna Munson
PE #: 51711
Date: May 10, 2023

Responsible for Sections 7 and 10.5

Contributors

This report was developed by Barr Engineering Co. and Hazen and Sawyer in collaboration with the Minnesota Pollution Control Agency.

Barr Engineering Co.
Katie Wolohan, PE
Ali Ling, PhD, PE
Andy McCabe, PhD
Becca Vermace, PE
Don Richard, PhD, PE
Charles Gantzer, PhD, PE
Sorel Nelson

Hazen and Sawyer
Anna Munson, PE
Derya Dursun, PhD, PE
Micah Blate, PE
Mohammed Abu-Orf, PhD

Minnesota Pollution Control Agency
Scott Kyser, PE

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- 374Water (supercritical water oxidation)
- ECT2 (foam fractionation and anion exchange)
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- Tim Sperfslage, Barr Engineering Co.

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Abbreviations

ADONA	8-dioxa-3H-perfluorononanoate
AFFF	aqueous film-forming foam
AIX	anion exchange
Barr	Barr Engineering Co.
BOD_5	five-day biochemical oxygen demand
CAA	Clean Air Act
$CaCO_3$	calcium carbonate
CCI	Construction Cost Index
CEPCI	Chemical Engineering Plant Cost Index
CO_2	carbon dioxide
COD	chemical oxygen demand
DOC	dissolved organic carbon
dtpd	dry tons of wastewater solids per day
EBCT	empty bed contact time
EIS	Environmental Impact Statement
ENR	Engineering News Record
FASA	perfluoroalkane sulfonamide
FTE	full-time employees
FTOH	fluorotelomer alcohol
FTS	fluorotelomer sulfonate
GAC	granular activated carbon
GHG	greenhouse gas
gpd	gallons per day
gpm	gallons per minute
HALT	high-temperature alkaline treatment
Hazen	Hazen and Sawyer
HBV	Health-Based Value
HF	hydrofluoric acid
HFPO-DA	propanoate
HRL	Health Risk Limit
HLR	hydraulic loading rate
HSDM	homogenous surface diffusion model
HWI	hazardous waste incinerator
ITRC	interstate technology regulatory council
kSCF	thousand standard cubic feet
lb	pound
MBR	membrane bioreactor
MC	modified clay
MF	microfiltration

mg/L	milligrams per liter
MGD	million gallons per day
min	minute
MPCA	Minnesota Pollution Control Agency
MSW	municipal solid waste
N-EtFOSA	N-ethyl perfluorooctane sulfonamide
N-EtFOSAA	N-ethyl perfluorooctane sulfonamido acetic acid
N-EtFOSE	N-ethyl perfluorooctane sulfonamidoethanol
NF	nanofiltration
ng/L	nanogram per liter
N-MeFOSAA	N-methyl perfluorooctanesulfonamido-acetic acid
NPDES	National Pollutant Discharge Elimination System
NPV	net present value
O&M	operations and maintenance
PASF	perfluoroalkane sulfonamido substance
PFAA	perfluoroalkyl acid
PFAS	per- and polyfluoroalkyl substances
PFBA	perfluorobutanoic acid
PFBS	perfluorobutane sulfonic acid
PFCA	perfluoroalkyl carboxylate
PFHpA	perfluoroheptanoate, perfluoroheptanoic acid
PFHxA	perfluorohexanoate, perfluorohexanoic acid
PFHxS	perfluorohexanesulfonic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonic acid
PFSA	perfluoroalkane sulfonate
PICs	products of incomplete combustion
Report	*Evaluation of Current Alternatives and Estimated Cost Curves for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water*
RO	reverse osmosis
SCWO	supercritical water oxidation
sq. ft.	square feet
SSI	sewage sludge incineration
SSOM	source-separated organic material
STU	standard treatment units
TDS	total dissolved solids
TOC	total organic carbon
TOP	total oxidizable precursors
TS	total solids
TSS	total suspended solids

UF	ultrafiltration
USD	United States Dollars
U.S. DOD	United States Department of Defense
U.S. EPA	United States Environmental Protection Agency
WRRF	water resource recovery facility

Executive Summary

This study develops alternatives to remove and destroy per- and polyfluoroalkyl substances (PFAS) from water resource recovery facility (WRRF) effluent, biosolids, mixed municipal solid waste (MSW) landfill leachate, and compost contact water (waste streams) using currently feasible technologies (i.e., could be built today). Barr Engineering Co. (Barr) and Hazen and Sawyer (Hazen) screened over 50 PFAS separation and destruction technologies for their ability to remove and destroy select PFAS to below current analytical reporting limits (a non-regulatory target established by the Minnesota Pollution Control Agency [MPCA] specifically for this study) and for their demonstrated commercial status. Thirteen technologies were retained for detailed consideration and assembled into alternatives, including destroying PFAS in final waste products. Assembled alternatives were ranked for criteria related to technical feasibility, economic feasibility, and byproducts management. Barr and Hazen retained two-to-four alternatives for each waste stream for preliminary design and cost estimating.

Currently, feasible technologies to separate PFAS from liquid waste streams are limited to sorption processes in pressure vessels (including granular activated carbon [GAC], anion exchange [AIX], and modified clay), reverse osmosis (RO) membrane separation, and foam fractionation. Feasible technologies to destroy PFAS from liquid media are currently limited to high-temperature incineration, thermal oxidation, and supercritical water oxidation (SCWO). Management of PFAS in biosolids remains a developing field with significant public and regulatory interest. Technologies selected as feasible at this time include SCWO, pyrolysis followed by thermal oxidation, and gasification followed by thermal oxidation.

Table ES-1 summarizes estimated capital and operations and maintenance (O&M) cost ranges for the two highest-ranking PFAS management alternatives for each waste stream for illustrative purposes. These estimates do not include pretreatment costs to achieve specified PFAS treatment process requirements. Pretreatment costs can, in some cases, be more expensive than PFAS removal and destruction. Requirements for both pretreatment and PFAS removal will vary significantly among sites and will need site-specific evaluations. Site-specific goals, conditions, and limitations may impact technology selection and implementation costs. Detailed PFAS removal cost estimates and cost curves for three facility sizes are included in this report. Based on our analyses, capital costs for removing PFAS from WRRF effluent and biosolids are similar, but O&M costs are significantly lower for biosolids treatment.

Table ES-1 Select capital and O&M cost ranges for highest-ranking alternatives

Waste Stream	Facility Size	Highest-Ranking Alternatives	Capital Cost Range (by facility)	Annual O&M Cost Range (by facility)	Relative Confidence in Ability to Reliably Meet PFAS Targets[2]
Municipal WRRF effluent	10 million gallons per day (MGD) (6,940 gpm) (similar to Mankato or Moorhead with a population of 45,000)	GAC with reactivation (Alt 1a)[1]	$41M–$88M	$4.5M–$9.6M	Medium-high (breakthrough of short-chain PFAS may limit reliability)
		GAC, single-use AIX with GAC reactivation and AIX high-temperature incineration (Alt 6a)[1]	$80M–$170M	$6.1M–$13M	High (two processes provide more controlled breakthrough)
Municipal WRRF biosolids	10 dry tons per day (estimated for 10 MGD WRRF)	SCWO[3]	$40M–$85M	$0.47M–$0.99M	Medium-high (limited testing at full-scale)
		Pyrolysis or gasification with thermal oxidation of pyrogas[1,3]	$53M–$110M	$0.55M–$1.2M	Medium-high high (limited testing at full scale)
Mixed MSW landfill leachate	0.014 MGD (10 gpm)	GAC with high-temperature incineration (Alt 1a)[1]	$0.30M–$0.60M	$0.23M–$0.48M	Medium (breakthrough of short-chain PFAS may limit reliability)
		Foam fractionation with high-temperature incineration of foamate (Alt 8a)	$5.0M–$11M	$0.20M–$0.42M	Low (limited removal of short-chain PFAS)
Compost contact water	0.014 MGD (10 gpm)	GAC with high-temperature incineration (Alt 1a)[1]	$0.30M–$0.60M	$0.21M–$0.44M	Medium (breakthrough of short-chain PFAS may limit reliability)
		Foam fractionation with high-temperature incineration of foamate (Alt 8a)	$5.0M–$11M	$0.20M–$0.42M	Low (limited removal of short-chain PFAS)

[1] Alternatives indicated likely need pretreatment processes to operate PFAS separation and destruction technologies. Pretreatment costs are not included in this table but are discussed in report sections for each waste stream.

[2] Relative ability to reliably meet PFAS targets reflects a combination of technology performance and reliability. For example, foam fractionation alternatives receive a “low” score because they are not expected to meet short-chain PFAS treatment targets. Alternately, single-process media filtration is expected to meet targets most of the time, except when a breakthrough event occurs. Hence, it receives a “medium” to “medium-high” score for reduced reliability. Breakthrough can be monitored and managed to limit PFAS reporting to effluent; however, targeting levels below analytical reporting limits for PFBA in high-concentration waste streams like landfill leachate could require media changeout every 2–4 weeks, which is on a similar time frame as analytical turnaround time for PFAS. Thus, PFAS breakthrough may not be detected in time for changeout, resulting in a lower reliability score for single-process media filtration for high PFAS concentration waste streams. Compared to single-process media filtration, dual-process media filtration receives a score of “high” because it is expected to allow for more time for monitoring breakthrough across four vessels instead of two and thus to more reliably meet PFAS targets.

[3] Biosolids costs are extrapolated from cost curves developed for this study.

Capital costs are driven by the recalcitrant and water-soluble nature of PFAS, which requires multiple additional processes, including pretreatment ahead of designated PFAS separation and destruction alternatives. Most currently available PFAS removal systems are modular, with limited economy-of-scale benefits for large facilities. O&M costs are driven by operational labor, energy use of high-temperature destruction technologies, and frequent sorption media changeout needed to achieve concentrations of short-chain PFAS below current method reporting limits (for alternatives with sorption media).

Costs were also evaluated with a lens on the cost per benefit provided by comparing the cost per mass of target PFAS removed between different waste streams and technologies over 20 years (detailed in Table 11-1). Treating wastewater biosolids or landfill leachate had the lowest cost per mass of target PFAS removed over 20 years (approximately $0.7 million to $4.0 million per pound of PFAS removed from biosolids and $0.2 million to $18 million per pound of PFAS removed from leachate). These costs are further described in Section 11.2. This cost range reflects the range of facility sizes analyzed here and the design basis influent PFAS concentrations established for this study.

When costs for individual facilities were extrapolated to the estimated number of WRRFs in Minnesota accepting greater than 0.05 MGD and mixed MSW landfills and composting sites, estimated costs for Minnesota could be at least $14 billion for removing and destroying PFAS from WRRF effluent and biosolids, and at least $105 million for removing and destroying PFAS from mixed MSW landfill leachate and compost contact water. These estimates, which include pretreatment, are summarized in Table ES-2 and further discussed in Section 11.3.

Table ES-2 Summary of estimated 20-year costs for managing PFAS in targeted waste streams in Minnesota[1]

Waste Stream	Estimated Number of Facilities	Range of Flows	Estimated 20-year costs for Minnesota (Millions of USD)[2]
Municipal WRRF effluent[3]	283	0.1–300 MGD	$12,000–$25,000
Municipal WRRF biosolids[4]	1 regional facility, plus 50 on-site facilities	50 dry tons of wastewater solids per day (dtpd) regional facility, on-site for 1–10 dtpd	$1,600–$3,300
Mixed MSW landfill leachate[5]	24	1–100 gpm	$77–$160
Compost contact water[6]	9	1–100 gpm	$28–$60

[1] This statewide evaluation carries additional uncertainty related to approximations for facility sizing, number of facilities, and degree of pretreatment needed. Costs are rounded to two significant figures. Costs are based on design basis concentrations selected to be typical of those reported in WRRF effluent (Helmer, Reeves, and Cassidy 2022; Coggan et al. 2019; Thompson et al. 2022), biosolids (Venkatesan and Halden 2013; Helmer, Reeves, and Cassidy 2022), landfill leachate (Lang et al. 2017), and compost contact water (Wood Environment & Infrastructure Solutions Inc. 2019).

[2] Twenty-year costs reflect net present value calculations using an interest rate of 7%.

[3] WRRF upgrade costs for effluent treatment are for PFAS separation and destruction using GAC adsorption with high-temperature incineration of media at flow rates below 1.1 MGD and GAC reactivation at higher flow rates. These include approximate costs for tertiary treatment retrofits (at WRRFs) or pretreatment processes (at landfill leachate and composting sites) likely needed at most facilities to provide the water quality required for GAC or RO feed. This analysis excludes WRRFs below 0.05 MGD.

[4] WRRF upgrade costs are for PFAS destruction in biosolids using pyrolysis or gasification with thermal oxidation of produced gasses. Costs include centrifuge dewatering to provide 25% solids material for process feed for each facility. These assume that WRRFs treating more than 0.1 MGD but producing less than 1 dtpd biosolids would ship to one regional, 50-dtpd pyrolysis facility. The costs shown here do not include transporting biosolids to that facility. These costs also do not include a pyrolysis/gasification facility with thermal oxidation for Minnesota's largest WRRF because costs for a facility of this size are not available.

[5] Costs are presented for 24 landfills, but the total number of landfills accepting mixed MSW in Minnesota is difficult to estimate due to mixed-use. Assumed equalization is present to limit peak leachate flows to twice the annual average leachate flow. Facility sizes are estimated based on publicly available data.

[6] Costs are presented for nine composting sites, but the total number of source-separated organic material (SSOM) composting sites is difficult to estimate due to mixed-use. Facility sizes are estimated based on publicly available data.

Most currently available PFAS destruction technologies are designed to treat concentrated waste streams rather than WRRF effluent water and are unlikely to be economically viable for most individual facilities. Regionalization of PFAS destruction may make financial sense for managing concentrated PFAS waste streams such as biosolids, foam fractionation foamate, GAC, and AIX resin. It may also be beneficial for treating high-concentration waste streams like landfill leachate, compost contact water, and biosolids from smaller facilities where on-site destruction is not economically viable. Evaluation of a regional high-temperature incineration facility for sorption media and a regional biosolids pyrolysis or gasification facility suggests that such facilities could potentially be economically viable when the fee structure is set appropriately to benefit the individual utilities and the regional facility. Other regionalization options that may become feasible include regional disposal of smaller volumes of foamate from foam fractionation using emerging destruction technologies such as SCWO, high-temperature alkaline treatment (HALT), or electrochemical oxidation.

Except for foam fractionation, liquid treatment technologies currently available at commercial scales are conventional water treatment technologies used in the water treatment industry for many years to treat other substances. While these technologies have been adapted at the commercial scale for PFAS treatment, many were not specifically designed for PFAS removal. New, targeted technologies to concentrate and destroy PFAS exist and have been demonstrated at bench- and pilot-scale. These newer technologies have the potential to reduce future capital and operating costs. However, these technologies are currently applied at small scales; for many of these newer technologies, performance and long-term maintenance needs have not been proven in full-scale implementations. In the future, these technologies may potentially be implemented at individual facilities rather than relying on regional or out-of-state high-temperature incineration facilities.

1 Introduction

Evaluation of Current Alternatives and Estimated Cost Curves for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water (Report) has been prepared for the MPCA by Barr, pursuant to a 2020 grant from the Legislative-Citizen Commission on Minnesota Resources. The objectives for this Report and the scope of work followed are summarized in this introductory section.

1.1 Background

Many studies and technologies investigated to-date have focused on the removal of PFAS from environmental media (Jin, Peydayesh, and Mezzenga 2021; Liu and Sun 2021; Berg et al. 2022). These often focus on waste streams with high concentrations of PFAS, including waste streams from primary and secondary manufacturers that produce or directly use PFAS-containing products and groundwater contaminated with aqueous film-forming foam (AFFF). The general management strategy for PFAS discharges has been industrial source-zone reduction and pretreatment.

While industrial sources reflect a significant input of PFAS to the environment, PFAS are also widely used in everyday consumer products and present in municipal wastewater, solid waste, and organic waste (Thompson et al. 2022; Roy et al. 2018; Hamid, Li, and Grace 2018; Choi et al. 2019). Thus, municipal waste streams act as a secondary avenue by which PFAS in consumer and industrial products enter the environment. Municipal WRRFs, in conjunction with municipal drinking water treatment and distribution, contribute to the recycling of PFAS in groundwater and surface drinking water supplies back into the environment.

Municipal and non-municipal solid and organic wastes are routed to landfills and commercial composting facilities, where PFAS in the wastes enter landfill leachate and compost contact water. Municipal WRRFs receive these streams along with municipal wastewater and industrial discharges. While these facilities are effective barriers for removing nutrients and organic matter, they are not designed or operated to remove PFAS, which report to both treated effluent (discharged to surface water) and the solid material removed from the wastewater. When these solids are stabilized through additional treatment, they are called "biosolids." Twenty-two percent of biosolids in Minnesota are applied to agricultural land for reuse of their nutrient value (from 171 WRRFs), 62% of biosolids are incinerated (from three WRRFs), and approximately 16% of biosolids are landfilled (from 27 WRRFs). This cycle is illustrated in Figure 1-1. This study targets the removal and destruction of PFAS from four waste streams, as illustrated by green circles.

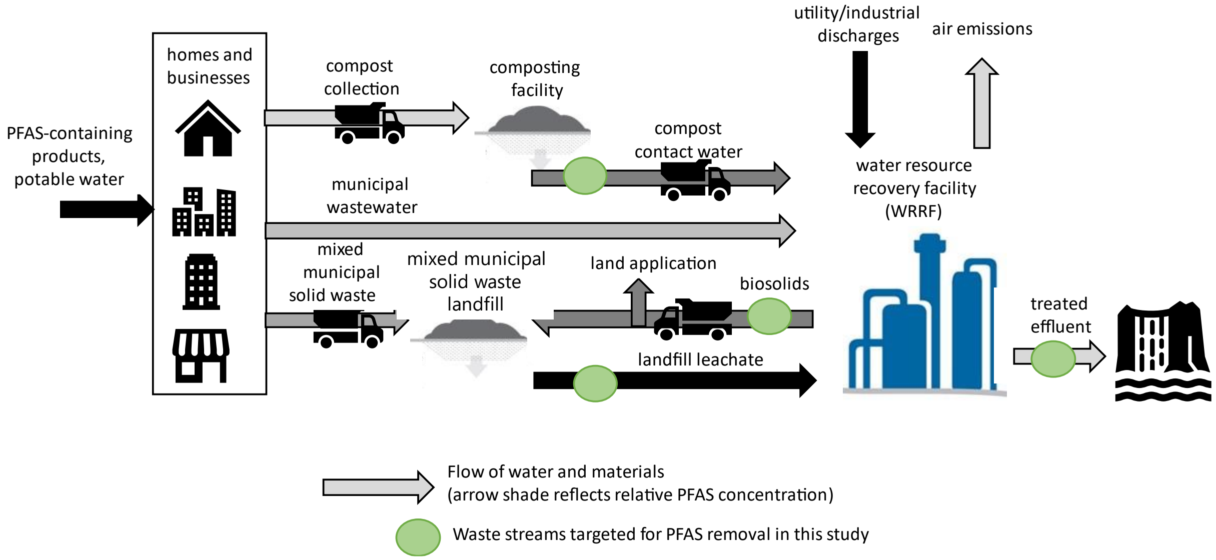


Figure 1-1 **PFAS use and disposal and target waste streams in this Report**

1.2 Study Objectives

The objective of this Report is to provide a conceptual understanding and costs for currently available approaches to **manage and destroy** per- and poly-fluoroalkyl substances (PFAS) down **to below current analytical reporting limits** in four waste streams:

- Municipal WRRF effluent
- Municipal WRRF biosolids
- Mixed MSW landfill leachate
- Compost contact water (also known as compost leachate)

Results may be used to inform future PFAS water quality standards and regulatory requirements associated with the four waste streams.

Manage and destroy: PFAS management has increasingly focused on the final fate of PFAS and the destruction (mineralization) of these chemicals to avoid potential re-release to the environment. This study aims to develop PFAS management strategies that mineralize PFAS to non-fluorinated end products. Management options that recycle PFAS to wastewater treatment plants, landfills, or other temporary reservoirs were not considered.

Below analytical reporting limits: PFAS guidelines for human and environmental health are rapidly evolving, and toxicity thresholds vary by compound. The MPCA set treatment targets for this study at current analytical reporting limits (5 ng/L for aqueous streams or 5 ng/g for biosolids) to reflect the target of complete PFAS removal (to the extent it can currently be measured) and destruction from both the targeted waste streams and other media that take on PFAS mass during treatment processes. Targeting analytical reporting limits for removal in this Report is aggressive, especially for short-chain PFAS with limited regulatory guidance. Many beneficial projects may target the mass removal of total PFAS or long-chain PFAS instead of a specific target concentration. However, evolving regulations around PFAS risk-based limits make it challenging to select alternative treatment targets.

Source-reduction strategies are not included as treatment options because the study evaluates end-of-pipe treatment options for PFAS. However, source-reduction strategies can potentially decrease source loads of PFAS routed to the waste streams under consideration, reducing the need to rely on end-of-pipe treatment. Source-reduction strategies may include phasing out PFAS use (Cousins et al. 2019) and continued treatment of concentrated point sources. As the cost of removing PFAS from the water phase is more related to the volume of water treated than to the mass of PFAS present, removal of PFAS from concentrated sources is more cost-effective than downstream treatment of lower-concentration WRRF flows.

The primary focus of the work completed for this Report was to use existing data sources to analyze the engineering feasibility and cost of current PFAS separation and destruction strategies to understand the management methods that could be employed at full-scale today to address PFAS in the waste streams considered. The alternatives evaluation did not include ongoing or future research and development activities to address PFAS. However, because PFAS treatment is a relatively new technical issue and a focus of significant current research, future treatment alternatives may significantly alter potential methods and costs for managing PFAS. A brief summary of ongoing and potential future research opportunities is discussed in Section 11.8.

The intent of this study is not to conduct a full life-cycle analysis of the treatment approaches identified. However, each treatment technology includes potential secondary effects (such as greenhouse gas emissions) associated with producing, transporting, reactivating, regenerating, and disposing of the treatment media and byproducts. These effects, which potentially negatively impact the sustainability of PFAS treatment, are discussed briefly in Section 11.4. It is recommended that facilities and sites seeking to implement PFAS management alternatives consider these sustainability effects and the full life-cycle impact of the technologies under consideration.

1.3 Use of Report

The purpose of this study is to provide a conceptual understanding and estimated costs for currently available approaches to **manage and destroy** per- and poly-fluoroalkyl substances (PFAS) in select waste streams outlined in this Report. Identification of possible treatment endpoints related to current PFAS analytical method detection limits and references to regulatory guidance/values existing at the time this study was completed are used to provide reference points and allow for cost calculations but are not intended to indicate the need for specific additional actions at specific facilities. That is beyond the scope of this study and should involve a wider consideration of each facility’s unique conditions and setting.

The capital and O&M cost estimates developed for this Report represent the best judgment of the experienced and qualified professionals familiar with this project. The estimated capital and O&M costs developed for preliminary PFAS management alternatives in this Report are intended to compare alternatives rather than represent estimates for specific projects. These cost estimates should not be directly applied in applications with different water or solids quality, operational constraints, or site-specific conditions. Barr has no control over the cost of labor, materials, equipment, or services furnished by others, any contractor's methods of determining prices, or competitive bidding or market conditions. Barr expects that costs for a specific site will vary from the opinions of probable capital and O&M costs for preliminary PFAS management alternatives developed for this Report. If managers of specific sites wish greater assurance as to probable costs, they should conduct a site-specific feasibility evaluation, including pilot testing, to characterize site-specific considerations and needs and to more accurately estimate PFAS management costs.

1.4 Report Structure and Study Scope

This Report is structured to address each of the four waste streams in separate sections to streamline use by readers primarily interested in one or two specific waste streams.

- Section 6 addresses municipal WRRF effluent.
- Section 7 addresses municipal WRRF biosolids.
- Section 8 addresses landfill leachate from mixed MSW landfills.
- Section 9 addresses compost contact water.

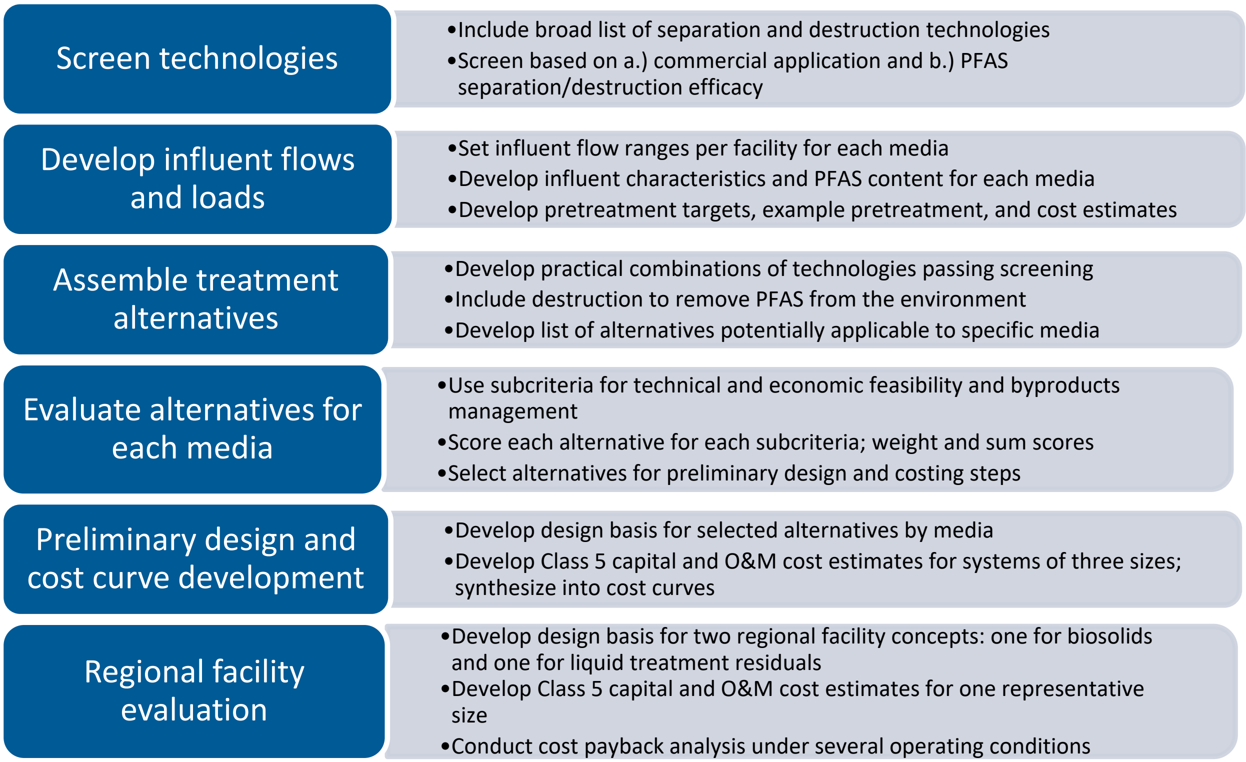
Key steps in the project and relevant sections for each are discussed below and summarized in Figure 1-2:

- **Selection of currently feasible PFAS separation and destruction technologies:** This task included reviewing and summarizing relevant peer-reviewed literature and vendor/owner data documenting the performance of currently available PFAS treatment and destruction systems (Section 3). Technology screening was used to evaluate the ability of individual technologies to separate or destroy PFAS. Technologies passing the screening phase were combined with others to develop a list of potential "treatment alternatives" for each waste stream.
- **Influent flow and load development for each waste stream**: Ranges of typical waste stream inflow rates per facility for each type of waste stream were developed to guide cost estimating. Typical water quality, biosolids characteristics, and PFAS content were also developed based on literature studies and MPCA-provided data (Sections 6.1, 7.1, 8.1, and 9.1). Many PFAS separation technologies require pretreatment to limit sorption media or membrane fouling, so pretreatment targets were also developed and used as assumed influent characteristics for those technologies. Example pretreatment trains with the potential to achieve influent water quality targets upstream were also developed (Sections 6.2, 7.2, 8.2, and 9.2); however, pretreatment requirements and costs are expected to vary significantly among facilities.
- **Assembly and evaluation of PFAS treatment alternatives:** Using currently feasible technologies, potentially viable treatment alternatives were assembled for each waste stream. These consist of multiple treatment technologies that, when employed together, could result in

complete or near-complete destruction of measurable PFAS (Section 4). Using previously developed influent flows and loads, assembled treatment alternatives were evaluated based on technical feasibility, economic feasibility, and byproducts management (Sections 6.2, 7.2, 8.2, and 9.2). The highest-ranking alternatives for each waste stream were carried forward to preliminary design and costing.

- **PFAS treatment design, costing, and cost curve development:** Preliminary designs were developed for selected PFAS treatment alternatives based on industry design standards and feedback from vendors. Vendor budgetary estimates and previous project costs were then used to develop cost curves for the influent flow ranges identified for each waste stream (within a margin of +50/-30%) (Sections 6.3, 7.3, 8.3, and 9.3).

- **Evaluation of regional PFAS destruction facility feasibility:** The feasibility, costs, and benefits of regionalized PFAS-destruction facilities (Section 10) were evaluated. Specific options evaluated in detail were a new, high-temperature incineration facility designed to handle sorption media from liquid treatment processes and a new pyrolysis facility designed to handle municipal wastewater biosolids from nearby WRRFs. Regional facility evaluations included consideration for economic viability, secondary impacts (externalities), and permitting and siting considerations.



Screen technologies	•Include broad list of separation and destruction technologies •Screen based on a.) commercial application and b.) PFAS separation/destruction efficacy
Develop influent flows and loads	•Set influent flow ranges per facility for each media •Develop influent characteristics and PFAS content for each media •Develop pretreatment targets, example pretreatment, and cost estimates
Assemble treatment alternatives	•Develop practical combinations of technologies passing screening •Include destruction to remove PFAS from the environment •Develop list of alternatives potentially applicable to specific media
Evaluate alternatives for each media	•Use subcriteria for technical and economic feasibility and byproducts management •Score each alternative for each subcriteria; weight and sum scores •Select alternatives for preliminary design and costing steps
Preliminary design and cost curve development	•Develop design basis for selected alternatives by media •Develop Class 5 capital and O&M cost estimates for systems of three sizes; synthesize into cost curves
Regional facility evaluation	•Develop design basis for two regional facility concepts: one for biosolids and one for liquid treatment residuals •Develop Class 5 capital and O&M cost estimates for one representative size •Conduct cost payback analysis under several operating conditions

Figure 1-2 Summary of steps used to develop treatment alternatives and cost analyses

1.5 Definitions

1.5.1 Waste Streams

Below are the definitions of the waste streams considered in this report.

- **Municipal wastewater or WRRF effluent:** Effluent from either conventional activated sludge WRRFs or stabilization pond WRRFs. Conventional activated sludge facilities were assumed to include primary treatment with physical screening, sedimentation, and/or floatation, followed by secondary treatment with mechanical aeration and clarification.

- **Municipal wastewater or WRRF biosolids:** For conventional activated sludge WRRFs, biosolids refer to a mixture of wastewater and solid materials separated from the wastewater during treatment (including microorganisms grown within the WRRF) and stabilized in an additional process, such as anaerobic digestion. For stabilization pond WRRFs, biosolids are the solids that accumulate and are naturally digested over time within the stabilization ponds.

- **Mixed MSW landfill leachate:** Liquid that drains from solid waste in a landfill, including water sourced from precipitation or originating in the landfilled material. Leachate available for treatment is assumed to be collected at a central location.

- **Compost contact water:** Water that has come into contact with source-separated organic material in the tipping area, material in the mixing area, rejects, residuals, or active compost at a commercial composting facility. The water originates from precipitation or moisture associated with compostable materials. Water originating from curing or finished storage areas at composting facilities is considered stormwater and managed separately from compost contact water.

1.5.2 Treatment and Destruction

Due to the evolving nature of PFAS regulation and treatment, semantics surrounding PFAS management can vary by application and location. The following definitions were developed for this study to support consistency and clarity:

- **Water treatment or biosolids treatment:** Technology or combination of technologies that alter the composition of water or biosolids to make it ready for another use.

- **PFAS removal:** The process of removing target PFAS from a specific waste stream of interest. This term can be applied to both separation and destruction technologies (Figure 1-3).

    - **PFAS separation:** Treatment technology or process that moves PFAS from one phase, waste stream, or media to another but does not destroy PFAS.

    - **PFAS destruction:** Treatment technology or process that destroys PFAS. For this Report, two categories of PFAS destruction were defined, as described below.

- **PFAS transformation or conversion:** The processes of transforming or converting PFAS to PFAS-reaction byproducts, which typically have a lower molecular weight and still include one or more carbon-fluorine bonds. These processes often apply to PFAS precursors converted or transformed into terminal perfluoroalkyl carboxylates (PFCAs).

- **PFAS mineralization:** The processes whereby PFAS are mineralized to carbon dioxide (CO_2), hydrofluoric acid (HF), and water. Defluorination, or the process of breaking the C-F bond, is a key step in PFAS mineralization processes because of the relatively high energy requirement. This definition is intended to be consistent with the United States Environmental Protection Agency's (U.S. EPA) definition of PFAS destruction as provided in the *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances* (U.S. EPA 2020).

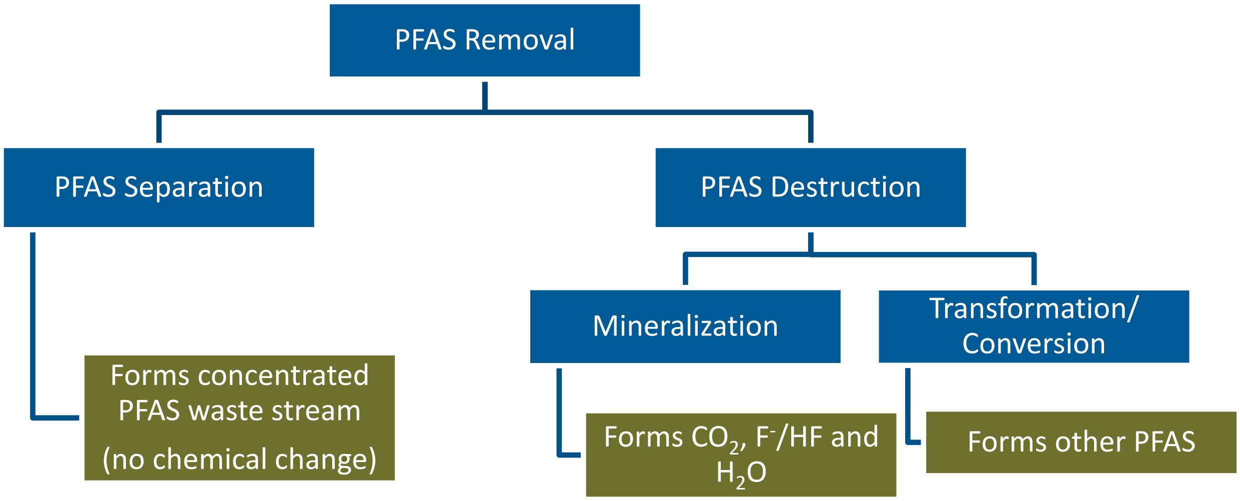


Figure 1-3 Distinction between PFAS separation and PFAS destruction mechanisms

2 PFAS Chemistry and Selection of PFAS Considered in this Study

2.1 PFAS Classes and Chemical Characteristics

Thousands of individual PFAS have been produced on a commercial scale, with newer chemicals replacing older ones as toxicology data and regulations evolve (U.S. EPA 2021a). Scientists are still learning about the chemical nature and health impacts of newer classes of PFAS (Evich et al. 2022). PFAS differ from each other based on various chemical characteristics, including carbon-chain length, the number of fluorinated carbon atoms, the inclusion of various functional groups, and per- versus polyfluorinated carbon chains (i.e., in perfluorinated compounds, all carbons are fully fluorinated while in polyfluorinated compounds, one or more carbon atom is not fully fluorinated). Major PFAS classifications for non-polymer PFAS are summarized below. These classifications are based on information from the *Naming Conventions Fact Sheet* from the Interstate Technology Regulatory Council (ITRC 2020).

- **Perfluoroalkyl acids (PFAAs):** This class includes perfluoroalkyl substances that have been most extensively studied, including perfluoroalkane carboxylates (PFCAs), such as perfluorooctanoic acid (PFOA) and perfluorobutanoic acid (PFBA), and perfluoroalkane sulfonates (PFSAs), such as perfluorooctane sulfonic acid (PFOS) and perfluorobutane sulfonic acid (PFBS).

- **Perfluoroalkane sulfonamides (FASAs):** This class includes perfluoroalkyl substances used as surfactants and in surface protection products. They can also be intermediate environmental transformation products. Representative compounds include perfluorooctane sulfonamide (PFOSA or FOSA) and N-ethyl perfluorooctane sulfonamide (N-EtFOSA).

- **Fluorotelomer substances:** This class includes polyfluorinated substances created via fluorotelomerization and used as major raw materials. This class also includes fluorotelomers, environmental transformation products and intermediates; they are also potential PFCA precursors. Representative compounds include 8:2 fluorotelomer sulfonate (8:2 FTS) and 10:2 fluorotelomer alcohol (10:2 FTOH).

- **Perfluoroalkane sulfonamido substances (PASFs):** This class includes polyfluorinated substances used as major raw materials. This class also includes PFAS which are environmental transformation intermediates and potential PFSA precursors. The carbon chains of these PFAS are perfluorinated (as suggested by the class name); however, they are considered polyfluorinated because the head group (defined below) of these PFAS contains carbon atoms bonded to hydrogen atoms. Thus, the alkyl carbons are not fully fluorinated. Representative compounds include N-ethyl perfluorooctane sulfonamidoethanol (N-EtFOSE) and N-ethyl perfluorooctane sulfonamido acetic acid (N-EtFOSAA).

- **Per- and polyfluoroalkyl ether carboxylates:** This class includes replacement chemistries for legacy C8 compounds, which are used as fluoropolymer processing aids. Two representative examples include ammonium 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy) propanoate (HFPO-DA) and ammonium 4,8-dioxa-3H-perfluorononanoate (ADONA).

Differences in PFAS chemistries dictate how they partition between air, water, and soil/sediment phases as well as whether they are amenable to transformation processes. Fluorine characteristics and the strength of the carbon-fluorine bond contribute to PFAS being resistant to biodegradation, adsorption, oxidation, and other common treatment processes (ITRC 2022). The potential effects of these variable characteristics on PFAS media partitioning and behavior during treatment are summarized below.

- **Number of carbons:** Long-chain (PFCAs with eight or more carbon atoms or PFSAs with six or more carbon atoms) PFAS are easier to remove from the aqueous phase using sorption media technologies (i.e., GAC and AIX) than short-chain compounds (e.g., PFOA versus PFBA), due to their higher tendency to partition to solid surfaces and hydrophobic phases. Because long-chain PFAS tend to partition to solid phases, typically, they are preferentially found in biosolids relative to short-chain PFAS.

- **Proportion of fluorinated carbons:** The C-F bond is a strong covalent bond and difficult to cleave. Thus, many PFAS and associated terminal degradation products are thermally and chemically stable. As the proportion of fluorinated carbons increases, PFAS tend to be more difficult to completely degrade and more hydrophobic. PFAS with non-fluorinated carbon atoms (i.e., polyfluorinated, many of which may be referred to as precursors or intermediates) are susceptible to oxidative degradation, forming stable PFAA products.

- **Head (or functional) groups:** The head group (also known as the functional group) of PFAS can influence their physical and chemical properties. The head group also helps dictate which of the PFAS classes defined above apply. Examples of functional groups include carboxylates, sulfonates, phosphates, and amines. For treatment with GAC and AIX resin, sulfonates tend to be more readily absorbed than carboxylates with comparable chain-lengths.

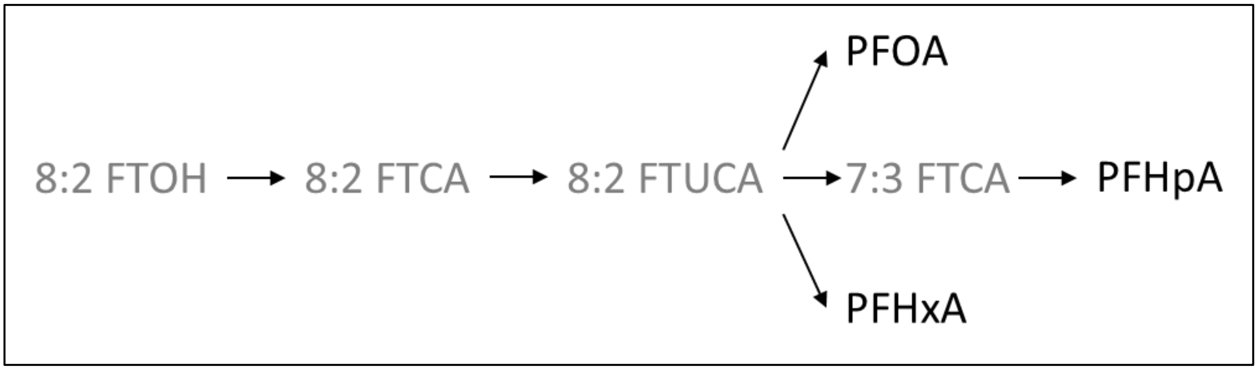
- **Acid versus base/anionic form:** Head groups of PFAS (e.g., carboxylates and sulfonates) can be protonated or deprotonated, which can impart either an uncharged form or a charged form (typically anionic) to the PFAS, respectively. The anionic form is more soluble in water and less likely to volatilize into the air phase than the uncharged, acid form. Based on typical acid dissociation constants (i.e., pK_a values) for PFAS and typical environmental pH conditions, most PFAS exist in the deprotonated, anionic form. Although, whether a PFAS is present in the environment in an uncharged or charged form depends on the chemistry of the specific PFAS and solution pH (ITRC 2021). For consistency throughout this report, the acid form will be used when referencing specific PFAS names (e.g., perfluorooctanoic acid rather than perfluorooctanoate).

2.2 PFAS Precursors and Transformations

PFAS precursors include several classes of PFAS, some of which were described in Section 2.1 (e.g., FASAs, fluorotelomer substances, PASFs, and polyfluoroalkyl ether acids). These PFAS typically contain non-fluorinated alkyl carbons that are amenable to microbial transformation processes, the products of which are typically terminal PFAAs.

Several WRRFs have reported an increase in total PFAS in the effluent compared to influent (Thompson et al. 2022; Houtz et al. 2016; Helmer, Reeves, and Cassidy 2022). Helmer et al. (2022) showed that effluent PFAS concentrations in 10 WRRFs were as much as 19 times greater than influent concentrations. Thus, WRRFs effectively transform polyfluorinated precursors into measurable, terminal degradation products, and long-chain PFAS preferentially adsorb to the biosolids during treatment (Helmer, Reeves, and Cassidy 2022).

The transformation of precursor or intermediate compounds to stable, measurable PFAS also occurs in land application of biosolids. The *U.S. EPA Land Application Field Study II* in October 2020 showed that on day one of land application, the PFAS in biosolids were dominated by intermediates and accounted for 95% of PFAS mass in the C8 path, as represented in Figure 2-1 (Herrmann et al. 2020). However, the ratio was reversed after 371 days of land application, where stable PFAS (i.e., PFOA, perfluoroheptanoate, perfluoroheptanoic acid (PFHpA), and perfluorohexanoate, perfluorohexanoic acid (PFHxA)) were dominant and accounted for 83% of the PFAS mass in the C8 path. The stable PFAS increased by 10 times for PFOA, 17 times for PFHpA, and 21 times for PFHxA over one year of land application. The transformation oxidative pathways are shown in Figure 2-1 (Herrmann et al. 2020).



8:2 FTOH is 8:2 fluorotelomer alcohol, 8:2 FTCA is 8:2 fluorotelomer carboxylic acid, 8:2 FTUCA is 8:2 fluorotelomer unsaturated carboxylic acid, 7:3 FTCA is 7:3 fluorotelomer carboxylic acid. (Herrmann et al. 2020).

Figure 2-1 Example PFAS precursor breakdown pathway to perfluoroalkyl end products

The TOP assay measures the total target PFAS and PFAS formation potential in wastewater and biosolids treatment processing. This assay involves oxidative treatment of a sample prior to PFAS measurement so that measured PFAS more closely reflect the end products of potential oxidative transformations. The influent TOP minus the sum of target PFAS in effluent and biosolids indicates residual target PFAS formation potential. In their Phase I Study, the California State Water Resources Control Board required PFAS sampling and analysis using the TOP assay for both influent and biosolids. The results presented to the Bay Area Clean Water Agencies Board meeting in August 2021 indicated the significant presence of PFAS precursors from the results of TOP (Lin, Mendez, and Sutton 2021).

Due to the transformation of precursors in wastewater influent to terminal PFAS in wastewater effluent and biosolids sources, the total oxidizable precursors (TOP) assay is strongly recommended to serve as a quantification method for precursor PFAS and suggested as a future “target” for wastewater and biosolids treatment in this study, along with selected measurable PFAS. However, studies reporting complete TOP results are limited. As a result, separation and destruction efficiencies for TOP precursors are not well defined, and TOP measurements were not included as a specific target in this study.

2.3 Selection of PFAS Considered for this Study

Due to the challenges of evaluating a large list of potentially relevant PFAS, target PFAS were selected for each waste stream to reflect a range of characteristics. This section presents the selected PFAS and the criteria and methodology used for their selection.

The following criteria were developed by MPCA and used in this Report to select the target PFAS:

- They are well described in the PFAS treatment literature.
- They have a diversity of functional groups (sulfonates and carboxylates).
- They have variable carbon chain lengths (four to eight).
- It is likely that treatment systems designed to treat these PFAS would also treat the majority of other PFAS that may also be present.
- Preliminary regulatory and/or guidance values have been established.

With these criteria in mind, Barr and Hazen reviewed the PFAS determined to be relevant to each waste stream at this time and either a) mapped them as being similar to an existing target PFAS or b) made it a new target PFAS. Table 2-1 lists target PFAS for each waste stream and typical concentrations assumed for this study. Appendix A outlines this process, along with chemical data for each of the 40 PFAS in U.S. EPA draft Method 1633 (US Environmental Protection Agency 2022). This list of commonly analyzed PFAS is a small fraction of the thousands of PFAS in use today, and has limited representation of replacement PFAS chemistries, many of which were not analyzed or not detected in available data sets.

The selected target PFAS include members from each class of PFAS presented in the ITRC guidance (ITRC 2021), with target PFAS for this study listed in bold:

- Perfluoroalkyl acids (PFAAs): **PFBA, PFBS, PFHxA, PFOA, and PFOS** reflect compounds with Minnesota Health Risk Limits (HRLs) or Health-Based Values (HBVs) and are included as target PFAS for all waste streams. These are sufficient to reflect the diversity in chemical characteristics in this class.
- Perfluoroalkane sulfonamides: **PFOSA** (perfluorooctanesulfonamide) was selected as a target PFAS for biosolids based on observed occurrence and concentrations.

- Fluorotelomer substances: **6:2 FTS** (6:2 fluorotelomer sulfonate) was selected because it is of moderate size, is in the MPCA 2020 guidance (MPCA 2020) and U.S. EPA Method 1633 (U.S. EPA 2021b) lists, and was relevant to multiple targeted waste streams.

- Perfluoroalkane sulfonamido substances: **N-MeFOSAA** (N-methyl perfluorooctanesulfonamido-acetic acid) was selected for biosolids because it is of moderate size and is in the MPCA 2020 guidance and U.S. EPA Method 1633 lists. **N-EtFOSAA** (N-ethyl perfluorooctane sulfonamidoacetic acid) was selected as a target PFAS for mixed MSW landfill leachate for similar reasons. In addition, more data are available for this parameter in leachate than N-MeFOSAA.

- Per- and polyfluoroalkyl ether carboxylic acids (replacement chemistries): No PFAS were selected from this class because, based on the current datasets available, no representative PFAS were detected in most samples reviewed for the four targeted waste streams despite these chemistries being increasingly used to replace other PFAS.

While replacement compounds are in development and active production to replace longer-chain PFAS, legacy compounds like PFOA and PFOS remain in widespread environmental circulation because no environmental mechanism exists to destroy them (Stoiber, Evans, and Naidenko 2020). Short-chain, replacement compounds have been less studied but have similar chemistry and potential human health impacts (Nian et al. 2020). As a result, target compounds include both legacy and replacement compounds.

Table 2-1 Summary of target PFAS and representative concentrations for this study

	Municipal WRRF Effluent[1]		Mixed MSW Landfill Leachate[2]		Compost Contact Water[3]		Municipal WRRF Biosolids[4]	
Basis	**2009/2010 MPCA Data Helmer et al. (2022) Coggan et al. (2019)**		**Lang et al. (2017)**		**Wood (2019)**		**Venkatesan and Halden (2013) Helmer et al. (2022)**	
Value Type	**Typical (ng/L)**	**High (ng/L)**	**Typical (ng/L)**	**High (ng/L)**	**Typical (ng/L)**	**High (ng/L)**	**Typical (ng/g)**	**High (ng/g)**
PFBA	**15**	**200**	**950**	**2,600**	**450**	**1,500**	**2**	**5**
PFBS	**15**	**50**	**250**	**650**	**10**	**25**	**20**	**40**
PFHxA	**30**	**60**	**1,500**	**4,000**	**500**	**2,000**	**5**	**15**
PFHxS	**5**	**15**	**350**	**750**	**10**	**100**	**15**	**30**
PFOA	**40**	**80**	**900**	**1,900**	**30**	**100**	**60**	**200**
PFOS	**5**	**30**	**150**	**300**	**20**	**1,500**	**400**	**600**
PFOSA	<2	<2	NA	NA	<10	<10	**20**	**70**
6:2 FTS	**5**	**150**	**150**	**350**	<20	<20	30	--[5]
N-EtFOSAA	ND	ND	**150**	**450**	<5	<5	**30**	**60**
N-MeFOSAA	ND	ND	NA	NA	<5	<5	**100**	**200**
Types of PFAS that are relevant	Short-chain PFCAs, long-chain legacy PFCAs and PFSAs, and fluorotelomers		Short and long-chain PFAAs, fluorotelomers, and precursors		PFCAs and PFSAs associated with composted items		Long-chain PFAAs that partition to biosolids, precursors	
Other characteristics of PFAS for each waste stream	Variable and reflective of consumer and industry changes		Variable and dependent on waste source, landfill age, and landfill type		High organic content and reduced; may have metals, other co-contaminants, and nutrients		High organic and nutrient content	

Bold and highlighted grey = target PFAS for each waste stream; ND=not detected, the detection or reporting limit was not specified in the referenced datasets; NA=not analyzed in source dataset; PFAA=perfluoroalkyl acids; PFCA=perfluoroalkyl carboxylates; PFSA=perfluoroalkane sulfonates

[1] Data reflect aqueous concentrations in treated effluent from municipal WRRFs.

[2] Data reflect aqueous concentrations in leachate from mixed MSW landfills.

[3] Data reflect aqueous concentrations in surface water that have come in contact with waste materials at commercial composting facilities.

[4] Data reflect concentrations in biosolids material as it leaves the municipal WRRF before any off-site processing or storage.

[5] Based on one data point from one study, so no "high" value developed.

2.4 Treatment Target Selection

For this Report, MPCA selected "non-detectable" concentrations of target PFAS as a treatment goal to guide the alternative evaluation. This stance of targeting analytical reporting limits is aggressive, especially for short-chain PFAS with limited regulatory guidance; many beneficial projects may instead target mass removal or percent removal of total PFAS or long-chain PFAS instead of a specific concentration target.

However, evolving regulations around PFAS risk-based limits make it challenging to select alternative treatment targets.

Targeting "non-detectable" effluent concentrations may also be moving target over time, as analytical methods with the ability to measure lower and lower concentrations are developed. For this study, treatment targets were set by MPCA as current analytical reporting limits. MPCA's document "Guidance for Per- and Polyfluoroalkyl Substances: Analytical" is intended for use starting in 2023 (MPCA 2020) and includes reporting limit goals of approximately 5 ng/L for aqueous and 5 ng/g for solid matrices. Current analytical reporting limits for both aqueous and solids materials are in that range. **This study uses 5 ng/L and 5 ng/g as treatment targets.** While some labs are achieving lower reporting limits, differences within approximately one lower order of magnitude would not necessarily affect technology selection for this study.

3 Selection of Currently Feasible Treatment Technologies for PFAS Removal

This section describes the individual technologies considered for this study and the screening approach used to identify currently feasible treatment technologies for PFAS removal. Currently feasible treatment technologies are defined here as technologies that have been implemented at scales similar to those considered in this study and demonstrated to be effective for PFAS removal and/or destruction (i.e., there is a publicly available body of work demonstrating technology effectiveness).

3.1 Technology Screening Approach

A comprehensive list of potential treatment technologies for PFAS, considerations for their full-scale implementation, and their technology readiness level are in Appendix B. Each technology was screened against two threshold criteria, as described below.

- <u>Demonstrated treatment scale</u>: Technologies passing this screening criterion must have been "field-implemented" and commercially available for liquid technologies or implemented at the pilot-scale for biosolids. Two different standards were used here for liquid streams and biosolids. This is because established technologies have been widely applied at full scale for liquid-phase PFAS treatment, while biosolids have only been treated at the demonstration or pilot scale.
- <u>Demonstrated PFAS removal</u>: Technologies passing this screening criterion must have publicly available data demonstrating at least 90% separation or destruction of at least one selected PFAS (or removal to below method-reporting limits for that study).

The ability of each technology to meet the two screening criteria is described and rated in Appendix B. The appendix table includes a "yes" or "no" assessment of whether a technology meets each criterion. Technologies that were assigned a "yes" for both screening criteria are described in more detail in the following subsections. These technologies were carried forward for assembly into a PFAS management alternative, as described in Section 4, and further evaluated for inclusion in preliminary design and cost-estimating efforts.

The field of PFAS separation and destruction technologies is rapidly evolving. The results of this technology screening exercise reflect publicly available information in December 2022. Barr and Hazen acknowledge that some of the technologies included on the initial compiled list have demonstrated PFAS removal but are not yet commercially available or may become available in the near future. Despite being promising, these technologies are outside the scope of this study and, thus, were not carried forward. Section 11.7 further discusses technology readiness and the future of PFAS management technologies.

3.2 Technology Screening Results—PFAS Liquid-Liquid Separation

The following liquid-liquid PFAS separation technologies passed the threshold screening process and were considered currently feasible PFAS management alternatives. These technologies produce two separate liquid streams: a treated water stream (large volume with lower concentrations of PFAS than the feed water) and a waste stream (small volume with higher concentrations of PFAS than the feed water). These technologies are commonly used to concentrate PFAS into a smaller volume of water prior to further treatment with other PFAS separation or destruction technologies. These technologies include nanofiltration/RO (NF/RO) membrane separation and foam fractionation.

3.2.1 NF/RO Membrane Separation

NF/RO membrane separation concentrates PFAS in the feed stream into a lower volume concentrate stream by physical separation via high-pressure membranes. NF membranes typically have higher water recovery or operate at lower pressures than RO due to larger membrane pore sizes. RO membranes have proven more effective at PFAS separation because of their more dense construction and smaller effective pore size (Jin, Peydayesh, and Mezzenga 2021). Operation of an NF/RO membrane system typically requires, at minimum, pretreatment with micro- or ultrafiltration (MF and UF, respectively) to protect the NF/RO membranes from suspended solids fouling. Additional pretreatment may be required depending on the specific water quality conditions of the waste stream. MF and UF water recoveries depend on the feed water quality and the frequency of backwashes and chemical cleanings but are typically on the order of 80–98%. NF/RO recovery depends on the influent concentrations of potentially scale-forming parameters, operating conditions, and membrane construction. Recoveries range from 50–80% for conventional RO to 90% for high-recovery RO technologies (Crittenden et al. 2012). The waste stream generated by membrane systems for PFAS treatment can be as large as 5–30% of the treated flow rate (AWWA 2019; NGWA 2017).

Specialty RO membrane systems also exist that may limit the pretreatment required for liquid waste streams with high fouling potential (due to organics and/or mineral concentrations) compared to conventional RO. These systems are typically constructed with wider feed spacers than conventional RO, which improves the flow distribution of the feed, limits the pressure drop across the membrane in streams with high fouling potential, and allows suspended solids to flow between membrane layers more easily (Bates, Bartels, and Franks 2008). The wide spacers also allow for more effective chemical cleaning of the membranes to remove foulants during routine clean-in-place procedures. Specialty RO membrane systems are most applicable for sites with low-to-moderate flow (e.g., landfill leachate). They are not expected to be cost-competitive with conventional RO for high-flow systems like WRRF effluent. Common approaches for management of wide-spaced RO concentrate are (1) solidification and solids disposal in the landfill, (2) reuse as a wetting and compaction agent in the landfill, or (3) deep well injection, none of which destroy PFAS as targeted in this study.

PFAS removal or “rejection” across membranes depends on influent pH (Steinle-Darling and Reinhard 2008), transmembrane pressure, the characteristics of other ions in solution (Zhao et al. 2013), and the concentration, size, and hydrophobicity of each specific PFAS compound (Wang et al. 2018). Higher operating pressures and associated recovery typically correlate to higher rejection rates for PFAS because they result in increased water flux with limited change in PFAS transfer (Jin, Peydayesh, and Mezzenga 2021; Bellona et al. 2004; Tang et al. 2007). Demonstrated PFOS separation (membrane rejection) is over 99% for RO membranes and 90–99% for NF membranes (ITRC 2022). One study found over 93% rejection of PFAA as small as PFBA using a cross-flow NF membrane (Appleman et al. 2013), but other studies report much lower rejection rates for short-chain PFOS, down to 20% for PFBS (Wang et al. 2018). While data are more limited, specialty wide-spaced RO systems have also demonstrated high rejection of PFAS in landfill leachate. PFOS, PFOA, PFHxS, PFHxA, PFBS, and PFBA have all shown >99% rejection based on the data available (Stanford 2019). Appendix C compares NF and RO rejection for different PFAS across multiple studies.

The removal of dissolved minerals by RO systems may increase the corrosivity of the treated water (low pH, hardness, and alkalinity), and post-treatment mineral addition may be required (ITRC 2018; NGWA 2017). NF has lower rejection rates for monovalent anions, like chloride or sodium, and thus may require less post-treatment than RO (ITRC 2018). Thermal evaporation and crystallization are thermal processes that evaporate water, leaving a concentrated solid residual and reducing the concentrated RO/NF brine volume. Thermal evaporation and crystallization were not considered in this study for brine management due to the potential for PFAS partitioning from the aqueous brine to the vapor or gaseous stream. If PFAS do partition to the vapor/gaseous stream, removing PFAS from that stream could require a thermal oxidizer. Ultimately, the combination of evaporation/crystallization with thermal oxidation of the gas stream resembles direct incineration of the brine, assuming the solid residual would be managed by incineration.

3.2.2 Foam Fractionation

Foam fractionation is a separation technology that concentrates PFAS from a water phase into a smaller volume foam phase using fine air bubbles. This technology takes advantage of the surfactant properties of PFAS, enabling PFAS to partition to the surface of rising air bubbles (Smith et al. 2022). The resulting foam is collected and collapsed (referred to as the foamate) for further treatment or management off-site or, in the future, could be managed by an on-site destruction technique (Buckley et al. 2022). Foam fractionation can be an advantageous treatment alternative for PFAS because treatment systems are relatively simple and have relatively low capital costs, energy requirements, and operational costs (Buckley et al. 2022). In addition, produced foamate volumes are significantly lower than RO/NF concentrate volumes with concentration factors up to one million (Burns, Stevenson, and Murphy 2021), much higher than RO/NF concentration of approximately two times (50% recovery) to 10 times (90% recovery). Conventional aeration basins could potentially be retrofitted as a foam fractionation system (Smith et al. 2022).

Commercial foam fractionation systems are typically operated in continuous batches (i.e., batches are sequenced and run in parallel). PFAS removal depends on several operational parameters such as contact time, air ratio, air flow rate, and foam fraction (Dai et al. 2019; Smith et al. 2022). Removal efficiencies for long-chain PFAS are typically greater than 90% (Meng et al. 2018; Robey et al. 2020; Burns et al. 2022). Removal of short-chain PFAS is typically 50% or less. For example, PFBA and PFBS tend to have removals of less than 10% (Smith et al. 2022). The use of foaming agents, such as cationic surfactants, can improve short-chain PFAS removal, but overall removal is still relatively low (Beattie, Salvetti, and Macbeth 2022; Vo et al. 2023). Vacuum pumps on the foam collection system may also improve short-chain removal. Smith et al. (2022) also observed that mass balances for long-chain PFAS did not close through the foam fractionation system, potentially suggesting that mass is lost as aerosol. Foam fractionation removal efficiency for different PFAS is compared across multiple studies in Appendix C.

Ozone may be used instead of air and may improve separation efficiencies due to a relatively higher affinity of the PFAS head group to ozone than air. However, this chemistry is somewhat uncertain (Buckley et al. 2022). Ozone may also degrade PFAS precursors into terminal PFCAs. Dai et al. (2019) demonstrated up to 80% PFAS removal without ozone and up to 95% PFAS removal when combined with ozone, with both having relatively low removal for short-chain PFAS.

Based on vendor-provided information, current full-scale foam fractionation installations can treat flows of 26,000–132,000 gallons per day (gpd) or approximately 20–100 gallons per minute (gpm), including one 60 gpm field trial (Burns et al. 2022).

3.2.3 Comparison of PFAS Liquid Separation Technologies

NF/RO membrane separation is a well-developed technology deployed across multiple industries and able to treat water flow rates from several gallons per minute to several MGD. While foam fractionation is an effective technology for PFAS, the size of demonstrated applications is lower, on the order of 20–100 gpm. It is not currently feasible as a primary separation technology for large municipal WRRFs, but it may be feasible for small WRRFs, mixed MSW landfill leachate, and compost contact water installations. Foam fractionation is a more specific treatment option for PFAS than NF/RO. It has the potential for lower operational costs, fewer pretreatment requirements, and higher recovery of treated water than NF/RO but is not very effective at separating short-chain PFAS. In contrast, RO/NF can reject multiple potential contaminants of concern providing benefits for potential future contaminants of interest.

3.3 Technology Screening Results—PFAS Liquid-Solid Separation

The following liquid-solid PFAS separation technologies passed the threshold screening process and were considered currently feasible PFAS management alternatives. These technologies transfer PFAS from liquid to solid media producing a treated water stream with low concentrations of PFAS and a solid media phase requiring further treatment (destruction, regeneration, or reactivation) or disposal.

3.3.1 Granular Activated Carbon Adsorption

GAC adsorption is a separation technology that removes PFAS from the liquid stream through adsorption to the solid surface of the GAC media. GAC is one of the most common treatment technologies for removing PFAS from water (Darlington, Barth, and McKernan 2018), can be rapidly deployed, and typically requires modest operator involvement (NGWA 2017). Virgin bituminous coal-based GACs are typically used for PFAS removal due to their higher removal performance. However, enhanced virgin coconut-based GACs may be applicable in some installations as well as reactivated GAC (see Section 3.3.2).

PFAS removal occurs via a physical mass transfer process (ITRC 2018) between the non-polar functional groups on the GAC and the hydrophobic tail of the PFAS (Darlington, Barth, and McKernan 2018). Due to the adsorption mechanism, GAC can remove PFAS to below detection limits until breakthrough occurs.

PFAS removal efficiencies can be higher than 99%, with effluent concentrations near or below analytical detection limits (AWWA 2019).

However, GAC does not adsorb all PFAS equally. GAC has higher removal capacities for long-chain PFAS and sulfonates than short-chain PFAS and carboxylates (ITRC 2018). Because the GAC media has a finite number of adsorption sites, readily sorbed, long-chain PFAS can displace the short-chain PFAS on the GAC surface, leading to faster breakthrough times for short-chain carboxylates, such as PFBA.

While short-chain PFAS have lower GAC loading capacities and faster breakthrough times than long-chain PFAS, they can be effectively removed if the GAC media is replaced at higher frequencies. The required GAC changeout frequency and associated operational cost depend on the effluent targets, influent PFAS concentrations, influent concentrations of other compounds adsorbing to GAC, and the vessel configuration. The effluent PFAS concentration is dependent on the empty bed contact time (EBCT) of the GAC reactor (commonly between 10 and 20 minutes (AWWA 2019)), how frequently the GAC is replaced, influent PFAS concentrations, and the general feed water quality. The difference in duration between the time to breakthrough of PFBA and a long-chain PFAS like PFOA varies by water quality and influent concentrations but has been observed to be between two and 10 times more rapid for four-carbon PFAS than for the most similar eight-carbon PFAS (Westreich et al. 2018; J. Burkhardt et al. 2019; Franke et al. 2021). This suggests that the frequency of GAC changeout when targeting PFBA rather than PFOA would need to occur much more frequently. Bed volumes to the first breakthrough are compared for different PFAS across multiple studies in Appendix D.

The efficacy of PFAS removal by GAC can be inhibited by competitive adsorption (NGWA 2017). High concentrations of total organic carbon (TOC) and other hydrophobic compounds (such as volatile organic compounds) in the water can compete for GAC adsorption sites, which reduces PFAS adsorption capacity and may increase changeout frequency (AWWA 2019; Darlington, Barth, and McKernan 2018). Bench-scale accelerated column testing or pilot testing using site-specific water is recommended to estimate the expected GAC changeout frequency. High concentrations of iron, manganese, or particulates can also foul GAC media and cause short-circuiting in the GAC bed (AWWA 2019) or pressure increases that trigger GAC replacement. Bacterial growth can also occur in the presence of sufficient nutrients and cause pressure increases that trigger backwashing, disinfection, or GAC replacement.

GAC systems for PFAS are commonly operated as pressure vessels in series, using a lead-lag configuration that enables improved treatment efficiency and PFAS breakthrough monitoring PFAS between the lead and lag vessels. Vessels are operated in a downflow configuration under pressure, with adsorption occurring at the top of the bed and gradually moving down the bed as the adsorption sites on the GAC are filled. The area of the GAC bed where active adsorption occurs is known as the mass transfer zone. The depth of the mass transfer zone and the rate at which the mass transfer zone travels through the GAC bed differs for different PFAS. Typically, the concentrations of PFAS are monitored between the lead and lag vessels, and when the mass transfer zones of PFAS reach the bottom of the lead bed, PFAS are detected in the effluent of the lead vessel. Once a treatment threshold has been reached, the GAC media in the lead vessel is replaced, and the locations of the lead and lag vessels are switched such that the former lag vessel becomes the new lead, and the former lead vessel becomes the new lag. Monitoring frequency depends on estimated changeout frequency and PFAS treatment targets.

Current options for spent media disposal include thermal reactivation, incineration, or landfilling. Thermal reactivation and incineration are discussed in more detail in Section 3.4.

3.3.2 Reactivated Granular Activated Carbon

Reactivated GAC is GAC that has undergone a thermal reactivation process to restore its sorption capacity after being used. The GAC reactivation process and PFAS destruction efficiency are discussed further in Section 3.4.2.

Thermal GAC *reactivation* occurs at 980°C and differs from thermal GAC *regeneration,* which is conducted at 200°C using either steam or nitrogen gas (DiStefano et al. 2022). GAC *regeneration* can also be completed using a solvent/brine (Siriwardena et al. 2021). These GAC regeneration options remove sorbents from the GAC surfaces, but for PFAS destruction, additional treatment would be needed.

Thermally reactivated GAC can generally be categorized into two types:

1. General pool reactivated GAC: This is GAC that is pooled from multiple sources after use, thermally reactivated, and resold for reuse. The grade and quality of this material can be variable. It is not typically used for PFAS treatment, although it can be used as part of the treatment train to sorb background organics.

2. Site-dedicated reactivated GAC: This is GAC that is segregated by site during the reactivation process. By segregating the GAC, the grade and quality of the GAC can be better controlled. Time to PFAS breakthrough is similar between virgin GAC and site-dedicated, reactivated GAC but lower for general pool, reactivated GAC (McNamara et al. 2018; Westreich et al. 2018). Due to the size of commercial reactivation facilities, site-dedicated reactivation is limited to facilities that produce approximately 80,000 pounds of GAC or more per media changeout event.

The benefit of thermal reactivation of GAC is that the GAC media can be reused, reducing ongoing operational costs associated with a GAC treatment system. Based on vendor-provided information, after the initial purchase of GAC media, ongoing GAC replacement costs can be up to 50% lower for reactivation and reuse of GAC compared to costs to dispose of spent media and purchase new media for single-use GAC. For this study, site-dedicated, reactivated GAC is considered for facilities expected to generate 80,000 pounds of GAC or more per media changeout event. General pool reactivated GAC is not considered a PFAS separation technology due to the expected rapid PFAS breakthrough.

3.3.3 Single-Use Anion Exchange Resin

Single-use AIX resins for PFAS removal are typically positively charged polystyrene beads with tertiary amine, quaternary amine, or complex amino functional groups (Boyer, Fang, et al. 2021). AIX resins remove PFAS from the liquid stream via two primary mechanisms:

- Electrostatic interactions between the negatively charged head groups of PFAS and AIX resin cationic functional groups, and
- Hydrophobic interactions between the fluorinated alkyl chain of PFAS and the AIX resin structural polymer backbone (Boyer, Fang, et al. 2021).

Single-use ion exchange refers to using AIX resin once, then replacing the AIX resin and disposing of it via landfill or high-temperature incineration.

Like GAC, AIX resin is typically applied in lead-lag pressure vessels. AIX can remove many PFAS to below detection limits until breakthrough occurs. Also similar to GAC, long-chain PFAS within each PFAS subgroup (ITRC 2022) are more readily removed and thus have a longer treatment time or volume of water treated before breakthrough occurs. PFAS removal efficiencies with AIX can be upwards of 99% with new resin (AWWA 2019) but change as the resin is used and the PFAS sorptive and exchange capacity is exhausted. Boyer et al. (2021) summarized bed volumes treated to 10% breakthrough as reported in the literature for various water matrices and individual PFAS. Time to breakthrough depended on several variables, including the type of AIX resin used, EBCT, initial PFAS concentrations, concentrations of major anions (such as sulfate), and concentration of natural organic matter. The kinetics of PFAS uptake by AIX resins is typically faster than GAC (ITRC 2022), which results in shorter design EBCTs on the order of two to five minutes (AWWA 2019). Generally, the breakthrough of PFSAs with AIX resins occurs after 10,000–100,000 bed volumes or more, whereas the breakthrough of PFCAs with AIX resins occurs after 1,000–100,000 bed volumes (Boyer, Fang, et al. 2021). Bed volumes to first breakthrough are compared for different PFAS across multiple studies in Appendix D.

Anions can inhibit AIX media effectiveness; for example, nitrate, sulfate, and perchlorate can compete with PFAS for the AIX sites and should be removed from the water before PFAS treatment using AIX (NGWA 2017). In addition, iron and manganese can foul AIX resin, similar to GAC, and cause short-circuiting (AWWA 2019). Organics and minerals can also block pore spaces in the resin. Pretreatment is required for waters with these co-contaminants. In particular, removing negatively charged ions can be expensive, often requiring targeted ion exchange media or membrane treatment as a pretreatment.

3.3.4 Regenerable Anion Exchange Resin and Solvent Regeneration

Regenerable AIX operates the same way as single-use AIX, but once exhausted, the AIX resin is regenerated using a brine/solvent mixture and returned to service. The regeneration efficiency depends on the specific resin used and the regeneration solution used (Boyer, Fang, et al. 2021). Regeneration efficiency can be as high as 90% or more for PFOS and PFOA (Boyer, Fang, et al. 2021). The removal capacity of regenerable AIX resin is generally less than single-use AIX resin (ITRC 2022), requiring regeneration more frequently than single-use AIX changeout. The lifespan and long-term performance of regenerable resin for PFAS management is uncertain because the first publicly known regenerable AIX system was installed in 2018 (ITRC 2022). If the resin is not rinsed properly before being put back into service, it can cause corrosion issues downstream (ITRC 2018).

The benefits of being able to regenerate the resin can offset the costs of purchasing single-use resin, especially for larger systems. Based on vendor-provided information, typical costs to regenerate AIX resin are $5–$100 per cubic foot of resin (compared to $300–$400 per cubic foot for new resin purchase). Regeneration of AIX resin will save on media costs but requires larger vessels than single-use AIX (although still smaller than GAC vessels for comparable flows). The typical EBCT for regenerable AIX is 5–6 minutes, slightly longer than single-use resin, because regenerable AIX resins have approximately one-third the sorptive capacity of single-use resins. Smaller sites using off-site regeneration will have slightly higher transportation costs for the higher media volume required compared to disposal of single-use resin (assuming similar travel distances). Some facilities may be large enough and have enough media to warrant the additional cost of constructing an on-site AIX resin regeneration facility to reduce long-term operating costs. The cost-benefit of off-site versus on-site media regeneration is site-specific.

Regeneration can be completed on-site or in a regional facility. AIX regeneration involves a solvent brine solution that helps desorb PFAS from the resin. This brine can be thermally distilled, with PFAS routed to a small volume of still bottoms or loaded onto a small volume of GAC at very long EBCT. Resulting still bottoms or GAC can be subjected to destruction using any of the technologies outlined in Section 3.4.

3.3.5 Modified Clay Adsorption

Modified clays have a high surface area and small uniform pore size (ITRC 2022). They are typically produced from smectite clays treated with quaternary ammonium surfactants (Yan et al. 2020; Jiang et al. 2022). They remove PFAS using the dual mechanism of adsorption and ion exchange, similar to AIX media. Modified clays can be naturally occurring or made with surface modifications that incorporate electrostatic and hydrophobic moieties specific to PFAS treatment (ITRC 2022). Modified clay media is used in a fixed bed pressure vessel and can be operated in lead-lag arrangement, similar to GAC and AIX operations. Once exhausted, the clay media is removed and disposed of through landfilling or high-temperature incineration.

Modified clay media have been used to demonstrate removal of PFAS to non-detect concentrations, but adsorption performance varies by clay media type and surface treatments (Pannu and Plumlee 2021). Modified clay adsorption treatment has been used to treat groundwater AFFF contamination in pump-and-treat systems. A study using modified clays to remove AFFF from groundwater found PFAS removal efficiencies of 95–99% (Yan et al. 2020). Modified clay absorbents have also been used for landfill leachate, groundwater, stormwater, and drinking water treatment (Goldenberg 2022). Modified clay media have demonstrated longer bed life than GAC for short-chain PFAS, which are typically enriched in landfill leachate (Donovan 2022). In the Orange County Water District pilot test, a modified clay adsorbent had the longest life of any of the sorption media tested, which also included GAC and AIX (Pannu and Plumlee 2021).

Salts can precipitate on the clay media and effectively blind it from the PFAS. Based on vendor-provided information, modified clay media can foul with concentrations of salts above 5,000 mg/L TDS but will continue to remove PFAS until concentrations reach 16,000 mg/L TDS. Laboratory studies have shown high PFAS removals with TOC concentrations of up to 1,300 mg/L (Goldenberg 2022), suggesting PFAS removal by modified clay is less subject to competition with background organic material than removal by

AIX or GAC. However, modified clays are still a filtration media in a pressure vessel. They are expected to have similar pretreatment requirements for solids and metal foulants to prevent increased operating pressure due to pore space blockage.

3.3.6 Comparison of PFAS Phase Separation Technologies for Liquid Streams

Each of the five sorption media passing the technology screening effectively removes PFAS from liquid waste streams. Sorption media should be selected based on influent water quality, pretreatment requirement, short-chain PFAS removal needs, treatment goals, and cost. GAC and AIX are both widely used for PFAS removal, and modified clay has been applied to a lesser degree. GAC is often used instead of AIX because less pretreatment is required. With the information available, modified clay media requires even less pretreatment than GAC. GAC is not very effective for short-chain carboxylic acid PFAS such as PFBA and requires frequent changeout to remove them consistently. AIX is sometimes selected due to its higher sorption capacity, especially for shorter PFAS, so AIX systems are expected to have a lower media use rate than GAC systems. The limited data for modified clay applications suggests that their sorption capacity is more similar to AIX than GAC. Generally, on a per unit volume basis, AIX resin is more expensive than modified clay, and modified clay is more expensive than GAC media.

Regenerable AIX is typically selected over single-use AIX when PFAS concentrations and predicted changeout frequencies are high. Regenerable AIX has a lower sorption capacity than single-pass AIX but can be regenerated on-site at a specialized regeneration facility and reused, which reduces the cost of operation compared to single use AIX resins (Bolea 2022).

Reactivated GAC is typically selected over GAC when a large volume of GAC is required, making it possible to maintain dedicated, site-specific regeneration. Using current vendors, a site would need approximately 80,000 pounds of GAC in circulation for dedicated reactivation, which correlates to a WRRF over 1 MGD in size based on conceptual equipment sizing and estimated changeout frequency.

3.4 Technology Screening Results—PFAS Destruction

The technologies described in this section are intended to mineralize PFAS to non-fluorinated products, requiring the breakage of carbon-fluorine bonds. These technologies rely on high temperature or a combination of high temperature and pressure to mineralize PFAS. They include thermal reactivation of GAC, high-temperature incineration (also known as hazardous waste incineration), SCWO, pyrolysis with thermal oxidation, and gasification with thermal oxidation.

The first two listed, as well as thermal oxidation, were detailed as potential thermal treatment options in the U.S. EPA's *Interim Guidance on Destroying and Disposing of Certain PFAS and PFAS-Containing Materials* (U.S. EPA 2020). SCWO, pyrolysis, and gasification are less developed but were in this study as the most developed biosolids management options capable of achieving near-complete PFAS destruction.

Regulatory and scientific information on the efficacy of PFAS destruction in high-temperature incinerators and other thermal, non-hazardous waste combustors remains uncertain. Areas of uncertainty include the potential formation of products of incomplete combustion (PICs); unknown occurrence of PFAS or PICs in emission control devices; lack of standardized methods to monitor potential gaseous PFAS emissions, especially for less common PFAS; and variability in destruction efficiency due to different incinerator designs, waste feed approaches, and operational conditions (temperatures, residence times, and turbulence) (U.S. EPA 2020).

The U.S. EPA recently evaluated the efficacy and technology readiness of non-combustion-based technologies potentially capable of mineralizing PFAS associated with spent GAC and AIX media, soils, biosolids, AFFF, and landfill leachate (Berg et al. 2022). This study identified limited technological readiness outside of high-temperature incineration, except potentially for applying SCWO for AFFF destruction and pyrolysis for biosolids treatment (Berg et al. 2022). Limited data are currently available to assess the applicability of PFAS destruction technologies for the waste streams considered, largely due to the areas of uncertainty identified above.

Furthermore, on April 26, 2022, the U.S. Department of Defense (U.S. DOD) issued a temporary prohibition on the incineration of U.S. DOD PFAS waste streams, including AFFF and water treatment media. Some states, including Illinois and New York, have also placed a moratorium on the incineration of PFAS-containing waste streams.

3.4.1 High-Temperature Incineration (retained for disposal of Sorption Media and Concentrates)

Incineration is combustion in the presence of excess air. Two common incinerators are sewage sludge incinerators (SSIs) and hazardous waste incinerators (HWIs). To achieve thermal decomposition and destruction of PFAS exceeding 99.9%, temperatures exceeding at least approximately 500–700°C are required (Xiao et al. 2020). These temperatures are above the typical operational range of SSIs (L. J. Winchell et al. 2021a). PFAS incineration at lower temperatures might be possible with longer residence time, mixing, and favorable stoichiometry, but much work is still needed to understand the conditions for complete combustion (Lewis 2008; Niessen 2002; L. J. Winchell et al. 2021a).

In contrast to SSIs, HWIs are typically operated at higher temperatures (650–1,650°C) and longer solids residence times (0.5–1.5 hours) (U.S. EPA 2020). Currently, approximately 10 HWI facilities are operating in the United States (U.S. EPA 2020). HWIs typically accept solid or liquid wastes and consist of a rotary kiln with an afterburner for further gas phase thermal destruction, along with ancillary equipment for air pollution control, influent gas conditioning, ash treatment, scrubber blowdown, management, and boilers. Afterburners are typically operated at 1,100–1,370°C with a gas phase residence time of one to three seconds (U.S. EPA 2020). Afterburners at this temperature can control PFAS at an efficiency greater than 99% (Barranco, Caprio, and Hay 2020).

Commercial incineration of sorption media, such as GAC and AIX, is a common practice, though limited research has been published on its performance. Available research suggests efficient thermal decomposition of many target PFAS sorbed to GAC (Xiao et al. 2020). Additional research is needed to verify PFAS destruction and evaluate the formation of PICs, including other PFAS not commonly measured (U.S. EPA 2020).

3.4.2 Thermal Reactivation of Granular Activated Carbon (retained for disposal of Sorption Media)

PFAS can be desorbed from GAC and destroyed using thermal GAC reactivation. The process restores most of the sorptive capacity of the media. The process of thermal GAC reactivation includes:

- Exposing GAC to temperatures up to 980°C in a multiple hearth furnace or rotary kiln furnace under low oxygen conditions. PFAS and other sorbents are volatilized and partially destroyed in the furnace.
- Volatilized PFAS and other sorbents not completely combusted in the furnace are drawn into an abatement system consisting of a thermal oxidizer (afterburner), a scrubber, and a baghouse.

PFAS separation during GAC reactivation is PFAS- and temperature-specific. Decomposition of 80–100% of PFCAs and PFSAs occurs at 500°C, and up to 80–100% defluorination of both PFCAs and PFSAs has been observed at 1,000°C (Sonmez Baghirzade et al. 2021). One test evaluating PFAS sorbed to GAC before and after thermal reactivation found that of 21 PFAS detected on the spent media, all PFAS, except for PFDA, were below analytical detection limits (0.5–2.9 ng PFAS/g GAC) after reactivation (DiStefano et al. 2022). In the stack emissions, 23 of 36 target PFAS were detected. On a mass-basis, a 99.99% removal efficiency was observed between the mass of PFAS entering the reactivation furnace and the mass of PFAS leaving through the stack emissions (DiStefano et al. 2022). The performance of reactivated GAC for removal of PFAS via adsorption was previously described in Section 3.3.2.

3.4.3 Supercritical Water Oxidation (retained for disposal of Biosolids)

Any material containing water subjected simultaneously to high temperature and pressure (374°C and pressure of 250 bar, respectively) will reach the supercritical state for water, where most organic material dissolves. Organic material is then oxidized through the addition of air, resulting in byproducts of CO_2, minerals, water, and energy (if the feedstock supports it). This process can be economical for the disposal of biosolids, sorption media, or any organic waste (e.g., AFFF), but fuel costs make direct SCWO of dilute liquid waste streams impractical. SCWO has been successfully implemented commercially for hazardous materials and is currently undergoing demonstration pilots for PFAS-specific applications (Krause et al. 2022). Figure 3-1 shows an example process flow diagram of an SCWO system.

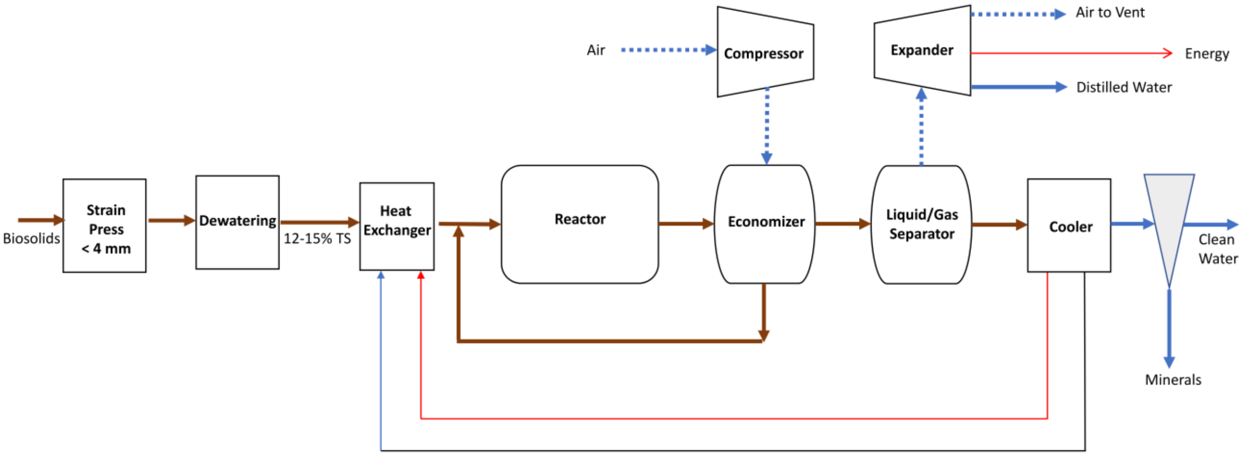


Figure 3-1 Example SCWO process flow diagram

PFAS removal and transformation in SCWO reactors depend on the design and operational parameters such as batch or continuous flow, excess oxygen, and reaction time. Research to date has established the successful destruction of PFAS using SCWO. For example, in one study, the destruction of up to 70% PFOS was observed in a batch reactor (Pinkard et al. 2021), but the same group saw 99.999% PFOS destruction in a continuous reactor (J. Li et al. 2023). In another study, 99% or greater destruction of PFOS and PFOA was observed using diluted AFFF samples (initial concentrations on the order of mg/L to final concentrations on the order of μg/L) (Krause et al. 2022).

Based on vendor-provided feedback, SCWO can be operated as a self-sustaining reaction with a minimum influent energy content of 2–3 MJ/kg (1,000 BTU/lb) and can produce electricity with some feedstocks, including biosolids and possibly GAC or AIX media slurries. This minimum self-sustaining energy requirement translates to approximately 100,000 mg/L of chemical oxygen demand (COD) in water phase wastes. Feedstocks with lower energy content would require a co-fuel, such as diesel or isopropanol, which quickly makes the treatment of many water streams uneconomical.

3.4.4 Pyrolysis with Thermal Oxidation (retained for disposal of Biosolids)

Pyrolysis is the thermo-chemical decomposition of organic matter at high temperatures without oxygen. Pyrolysis of biosolids is achieved by heating the material to 500–800°C in a reactor purged with nitrogen gas to remove oxygen. The biosolids are the fuel for the thermal decomposition reaction and must be dewatered to contain less than 25% moisture before pyrolysis. During pyrolysis, the solid molecules vibrate rapidly and break apart into lighter volatile molecules and fixed carbon, producing pyrogas, tars, oils, and biochar (Paz-Ferreiro et al. 2018). Figure 3-2 shows an example flow diagram for a pyrolysis unit.

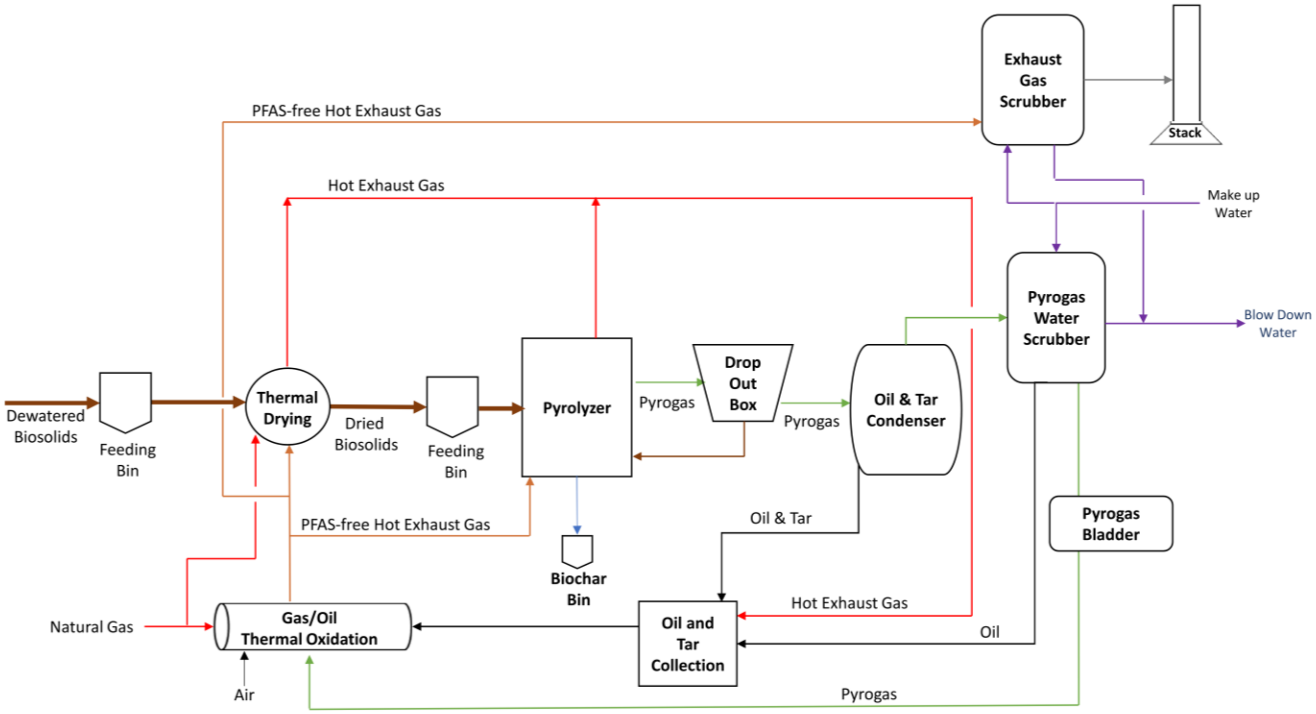


Figure 3-2 **Example pyrolysis process flow diagram**

The exhaust gas from pyrolysis (pyrogas) will contain high concentrations of PFAS. Current pyrolysis systems direct primary pyrolysis byproducts, including oil, tar, pyrogas, and exhaust gas, from the thermal dryer to a thermal oxidation unit for PFAS destruction. Natural gas burners supply additional heat to the thermal oxidation unit to raise the gas temperature to more than 1,100°C. Temperatures greater than 1,100°C are required for the defluorination of PFAS.

A portion of the hot exhaust gas is returned to the thermal drying process and to the pyrolysis reactor to recover heat and maintain treatment temperatures. The remaining exhaust gas passes through an exhaust gas scrubber before being released into the atmosphere. A typical thermal oxidizer is depicted in Figure 3-3.

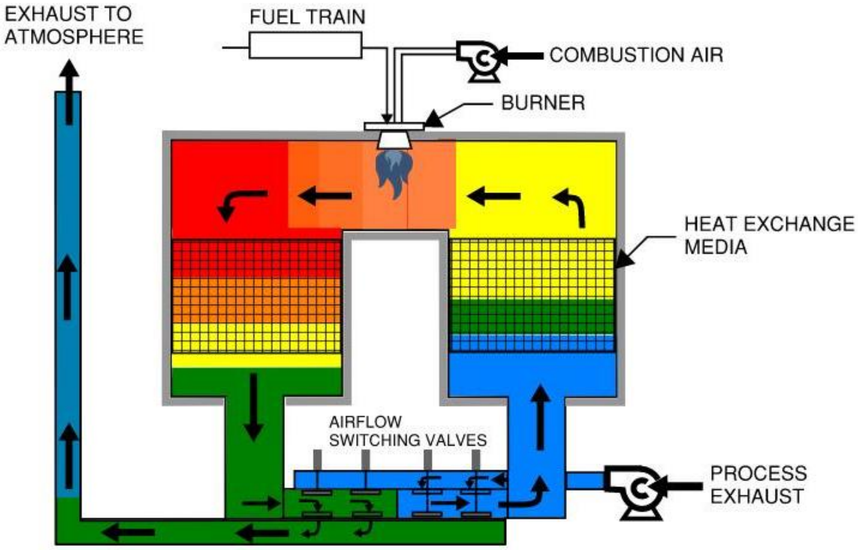


Figure 3-3 **Example thermal oxidizer process flow diagram**

Thermal oxidation of the gas destroys the PFAS at an efficiency greater than 99% at 1,100°C (Barranco, Caprio, and Hay 2020; Focus Environmental Inc. 2020). A recent pilot study evaluated pyrolysis and subsequent thermal oxidation of pyrogas for the destruction of 41 PFAS and found removal efficiencies between >81.3% and >99.9% (Thoma et al. 2022). However, additional studies are required to determine the PFAS concentration in any solid residuals from high-temperature oxidation of the tars and oils.

Research is ongoing to understand all potential opportunities to use biochar material. Use as a soil amendment, coal substitute in power plants, filtration media, and industrial additive are known opportunities. The biochar may be landfilled if no outlets are identified within a reasonable hauling distance.

3.4.5 Gasification with Thermal Oxidation (retained for disposal of Biosolids)

Gasification is a thermochemical process where pre-dried (<75% moisture) biosolids are heated in a reactor, typically from 675ºC to 815ºC. In gasification systems, a controlled amount of air, oxygen, or steam is added to the reactor to make it an "oxygen-starved," reducing environment, with oxygen levels near 30% of those required for complete oxidation. The gasifier produces PFAS-laden syngas and low-carbon biochar. The temperature conditions and processing time of the biosolids can be controlled to maximize the caloric (heating) value of the syngas. The syngas is then fully oxidized in a separate chamber with excess air for complete combustion (thermal oxidation). Figure 3-4 depicts an example process flow diagram for a gasification system.

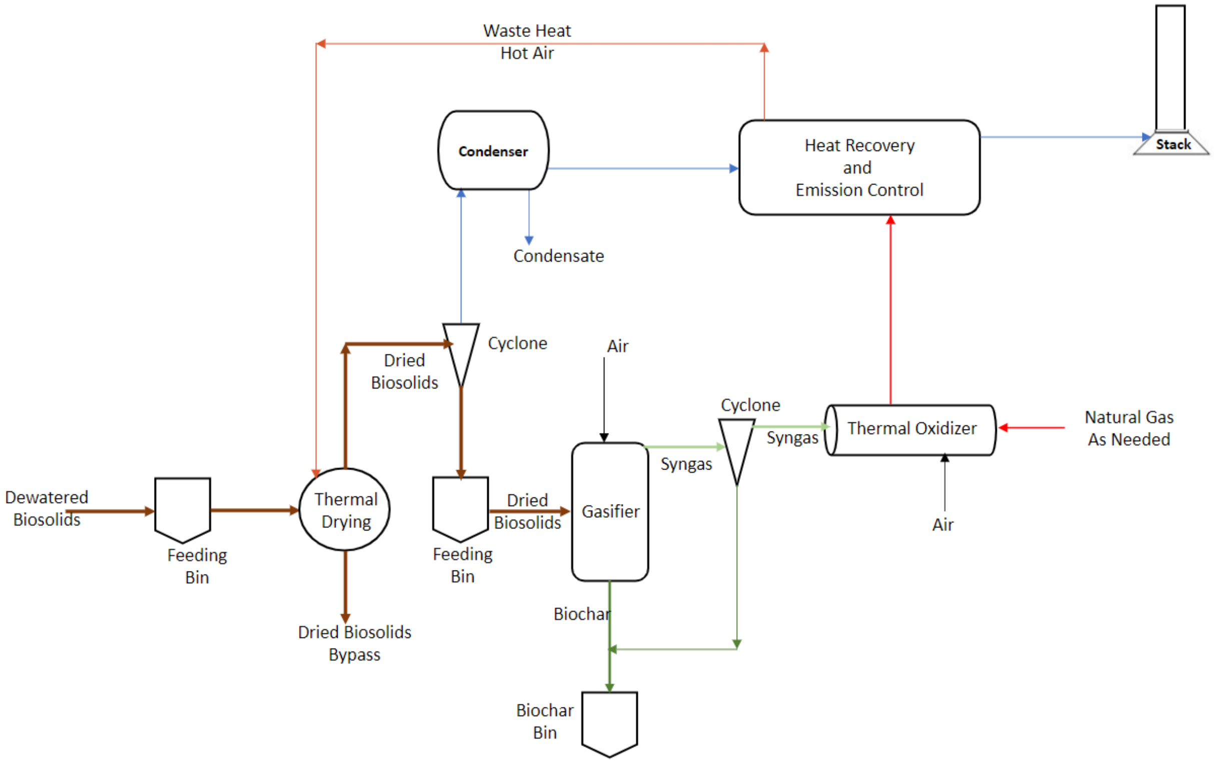


Figure 3-4 **Example gasification process flow diagram**

Gasification is anticipated to effectively destroy many, but not all, PFAS. Some research indicated limited removal from gasification alone, but 99.9% of the sum of analyzed PFAS was removed between the feed and the resulting char when coupled with thermal oxidation (Davis 2020). Results provided by vendors of full-scale systems showed PFAS removal from waste streams and air phases with the coupled processes. Thermal oxidation is described in more detail in the pyrolysis with the thermal oxidation section, Section 3.4.4.

4 Assembly of Currently Feasible Management Alternatives for PFAS Removal

PFAS management alternatives in this study were compiled from currently feasible treatment technologies identified as effective and scalable when this Report was written (see technology screening described in Section 3). Compiled alternatives were developed using process understanding and previous project experience with the goal of including a range of options likely to perform well in the detailed alternative screening evaluation. In assembling currently feasible PFAS management alternatives, this study included final PFAS destruction options in each alternative. These alternatives are meant to address comprehensive PFAS management at specific facilities. Consideration of regional solutions is included later in Section 10.

4.1 Liquid Waste Streams (Municipal WRRF Effluent, Mixed MSW Landfill Leachate, and Compost Contact Water)

Assembled liquid management alternatives were evaluated for relevance to each liquid waste stream (municipal WRRF effluent, mixed MSW landfill leachate, and compost contact water), as described below. Four to 12 management alternatives were considered and screened for the three liquid waste streams, as summarized in Table 4-1 and further described below.

Technologies selected for **municipal WRRF effluent** needed to be demonstrated at a similar scale to be considered.

- Foam fractionation has not been applied at the 0.1–10 MGD scale assumed here for municipal WRRF effluent, so those alternatives were not considered.
- Modified clay media, specialty wide-spaced RO, and SCWO have also not been applied at a scale relevant to primary treatment without preconcentration using RO but were included in alternatives where those technologies are applied to RO concentrate.
- Alternatives with RO as a pre-concentration step were included (see options with a “b”). This lowers the required size of downstream treatment processes. An added benefit of using RO pre-concentration before GAC adsorption of RO concentrate is a lower GAC media usage rate. This is related to a higher mass of PFAS sorbed per mass of GAC media when fed with higher PFAS concentrations (Franke et al. 2019).

Alternatives selection for **mixed MSW landfill leachate** needed to be suitable for use in liquids with high organics and salt content, even after pretreatment (refer to Section 6.5 for more information).

- Alternatives, including single-use and regenerable AIX, were not evaluated; these are expected to incur significant fouling from salt and organic concentrations expected in mixed MSW landfill leachate.
- Specialty wide-spaced RO has been used to treat landfill leachate and has demonstrated high rejection of PFAS with lower pretreatment requirements than conventional RO. However, this

technology was not incorporated into alternatives because concentrated brine would still require PFAS destruction to meet the goals of this study. RO concentrate water requires additional treatment to remove organics and total suspended solids (TSS) before other separation technologies (GAC and modified clay), so it is not expected to provide an advantage over conventional RO.

For **compost contact water**, the water flow rate was expected to be low, and the overall treatment system complexity will need to align with the ability of the composting facility to construct, operate, and maintain a PFAS water treatment system.

- Alternatives with an RO concentration step (using either conventional RO or specialty wide-spaced RO) were not considered for compost contact water treatment because they were considered too operationally complex for implementation at a compost site.
- Due to the high salt and organic content and potential resin fouling, single-use and regenerable AIX were also not considered for compost contact water.

Table 4-1 Summary of liquid phase PFAS management alternatives

	PFAS Management Alternative (assembled from technologies passing threshold screening and described in Section 3)	Selected for WRRF Effluent Evaluation?	Selected for Mixed MSW Landfill Leachate Evaluation?	Selected for Compost Contact Evaluation?
1a	GAC, high-temperature incineration	X	X	X
1b	RO, GAC, high-temperature incineration	X	X	
2a	Single-use AIX, high-temperature incineration	X		
2b	RO, single-use AIX, high-temperature incineration	X		
3a	Regenerable AIX, AIX regeneration, GAC, high-temperature incineration	X		
3b	RO, regenerable AIX, AIX regeneration, GAC, high-temperature incineration	X		
4a	Regenerable AIX, AIX regeneration, SCWO	X		
4b	RO, regenerable AIX, AIX regeneration, SCWO	X		
5a	Modified clay media, high-temperature incineration		X	X
5b	RO, modified clay media, high-temperature incineration	X	X	
6a	GAC, single-use AIX, high-temperature incineration	X		
6b	RO, GAC, single-use AIX, high-temperature incineration	X		
7b	RO, SCWO[1]	X	X	
8a	Foam fractionation, high-temperature incineration		X	X
8b	Foam fractionation, SCWO		X	X

[1] This alternative is labeled as a "b" option to match with other options, including RO. There is no alternative 7a evaluated because SCWO is likely not economically viable for direct liquid treatment at these scales due to high co-fuel requirements.

4.2 Biosolids

Based on the technology screening, three PFAS management alternatives were identified for municipal WRRF biosolids. Biosolids treatment technologies for PFAS that passed the initial technology screening destroy PFAS as part of the normal operation of the technology. The same process that pyrolyzes or oxidizes the biosolids acts simultaneously to destroy the PFAS compounds. Table 4-2 includes a summary description of the PFAS management alternatives assembled for treating biosolids.

Table 4-2 Summary of PFAS management alternatives for biosolids

	PFAS Management Alternative	Benefit
1	Pyrolysis, thermal oxidation of pyrogas	Produces more biochar, which may be used in a granular media application. Can reuse energy from thermal treatment for thermal drying.
2	Gasification, thermal oxidation of syngas	Produces less biochar, leaving less post-processing material to manage. Can reuse energy from thermal treatment for thermal drying.
3	SCWO	Flexibility to process biosolids with higher water content than pyrolysis or gasification; requires less pre-processing. Can be energy-producing if feed streams have high heating value.

5 PFAS Management Alternatives Evaluation and Cost Curve Methods

5.1 Goals and Approach to Alternative Evaluation Criteria Development and Weighting

The combined PFAS management alternatives identified in Section 4 were scored using a detailed screening matrix of criteria and sub-criteria outlined in Section 5.1.1. Criteria and sub-criteria were assigned numeric weights to reflect their relative importance to each waste stream. The numeric weights were multiplied by the individual scores, and the resulting values for all criteria were summed for each alternative. Higher overall scores correspond to more viable alternatives.

The influent water or biosolids quality and other project assumptions considered for each waste stream are described in Sections 6.1, 7.1, 8.1, and 9.1.

5.1.1 Technical Feasibility

5.1.1.1 PFAS Separation Efficiency (Ability to Meet 5 ng/L or 5 ng/g)

This screening criterion was intended to evaluate each alternative by the ability to meet the PFAS targets in any residual liquid that would subsequently be discharged to the environment, sanitary sewer, or reused (treated water). The ability of an alternative to separate PFAS was based on the potential to achieve the treated water quality targets provided by the MPCA based on published results from similar applications. Alternatives that received the highest scores have PFAS concentrations in treated liquid streams below 5 ng/L for liquids and 5 ng/g for biosolids for all target PFAS listed in Table 2-1. Treated liquid streams comprise sorption media vessel effluent for alternatives using media sorption, blended RO permeate and media vessel effluent for alternatives using both, and RO permeate for alternatives where RO is the only separation technology.

- Scores correspond with the following separation abilities:
    - 1 - <= Treated water <5 ng/L for one or two target PFAS
    - 2 - <= Treated water <5 ng/L for over half of target PFAS
    - 3 - <= Treated water <5 ng/L for all target PFAS

While some technologies report a percent separation or percent destruction, others evaluated in this study separate or destroy nearly all PFAS present—at least for a defined operating period. For example, GAC adsorption can achieve near-complete separation of PFAS until sorption media is saturated or sorption kinetics results in desorption of previously sorbed PFAS. As another example, pyrolysis of biosolids coupled with thermal oxidation achieves near-complete destruction of PFAS.

For media-based separation, scoring considered treated effluent assuming consistent changeout frequency and equipment sizing for typical hydraulic loading rates and empty-bed contact times (e.g., 10–

20 minutes per bed for GAC, 2–10 minutes per bed for modified clay media, and 2–6 minutes per bed for AIX resin). This was intended to capture differences in breakthrough periods and sorption media use rates for different media types. This criterion is not applicable to biosolids.

5.1.1.2 PFAS Destruction Efficiency

This screening criterion was intended to evaluate the PFAS destruction efficiency of each alternative. The ability of an alternative to destroy PFAS was based on the reported removal of target PFAS provided by the MPCA. Alternatives that received the highest scores have demonstrated PFAS mineralization across the process for target PFAS. All destruction technologies that passed the threshold screening can potentially create additional PFAS as byproducts, with more information needed on total organic fluorine mass balances. Thus, the scoring for this criterion was differentiated by measured removal of target PFAS only.

- Scores correspond with the following destruction abilities:
    - 1 - >= 90% reported removal of target PFAS
    - 2 - >= 99% reported removal of target PFAS
    - 3 - >= 99.9% reported removal of target PFAS

5.1.1.3 Degree of Commercialization

Alternatives that include PFAS separation and destruction technologies with a range of commercialization were evaluated using multiple feasible configurations. Alternatives containing technologies with a higher composite degree of commercialization were ranked higher for this criterion.

- Scores correspond with the following degrees of commercialization for the primary separation or destruction technology for liquid waste streams:
    - 1 - Commercial application of the primary separation and destruction technology in one industry each
    - 2 - Commercial application of the primary separation and destruction technology in two-to-three industries each
    - 3 - Commercial application of the primary separation or destruction technology in more than three industries each, including municipal wastewater treatment and/or landfill leachate treatment
- Scores correspond with the following degrees of commercialization for biosolids technologies:
    - 1 - Pilot study of the destruction technology for biosolids
    - 2 – Two commercial applications of the destruction technology for non-biosolids applications with a pilot study in progress or completed for biosolids

    - 3 – Three or more commercial applications of the destruction technology for biosolids

5.1.1.4 Reliability of Performance

Reliability of performance applies to the overall ability of a PFAS management alternative to produce treated effluent or biosolids that consistently meet the PFAS treatment targets given variable influent liquid or biosolids quality, variable flows or loading rates, or variable environmental conditions.

- Scores correspond with the following qualitative level of performance reliability for the alternative as a whole:
    - 1 - Reliability may be inconsistent or unknown
    - 2 – Intermediate reliability
    - 3 - Most reliable

5.1.1.5 Simplicity of Operation and Maintenance

The relative simplicity of operation and maintenance requirements for each alternative was evaluated based on the number of process steps, pre- and post-primary separation or destruction technology requirements, level of operator attention required, level of operator certification/training required, and the anticipated number of operational changes required under normal operating conditions.

- Scores correspond with the following level of complexity for the alternative as a whole:
    - 1 - Most complex
    - 2 - Average complexity
    - 3 - Most simple

5.1.1.6 Operator and Public Health

The operator and public health criterion refers to known health risks to the individual operators and the general public associated with the operation of each alternative. This includes direct and indirect exposure risks attributable to PFAS and other potentially harmful substances. It also includes more general safety risks associated with equipment operation and effluent and byproducts management.

- Scores correspond with the following level of complexity for the alternative as a whole:
    - 1 - Moderate additional health risk
    - 2 - Some additional health risk
    - 3 - Limited additional health risk

5.1.2 Economic Feasibility

Five unique economic criteria were used to compare the anticipated costs of each alternative based on available information from existing applications and technology vendors. Economic feasibility criteria included the following.

5.1.2.1 Relative Capital Costs

Under this criterion, lower rankings were given to the most expensive alternatives and higher rankings to relatively low-cost alternatives. Alternatives incorporating fewer unit processes and less mechanical equipment generally had lower capital costs. Capital cost screening was based on relative costs within the four specific waste streams targeted in this study.

- Scores correspond with the following for the alternative as a whole:
    - 1 - High relative capital cost
    - 2 - Average relative capital cost
    - 3 - Low relative capital cost

5.1.2.2 Relative Operation and Maintenance Costs (Not Including Energy Costs)

O&M costs include labor, parts and maintenance, chemicals for operations and cleaning processes, consumables, and byproducts management. Energy usage (power) was considered separately from other O&M costs. Lower rankings were given to the alternatives with the highest relative O&M requirements/costs and higher rankings to relatively low O&M demand alternatives. O&M cost screening was based on relative costs within the four specific waste streams targeted in this study.

- Scores correspond with the following for the alternative as a whole:
    - 1 - High relative O&M cost
    - 2 - Average relative O&M cost
    - 3 - Low relative O&M cost

5.1.2.3 Relative Energy Consumption

Under this criterion, lower rankings were given to the alternatives with the highest energy consumption and higher rankings to relatively low-energy demand alternatives. Alternatives incorporating unit processes with high-temperature requirements for PFAS destruction had the highest energy consumption.

- Scores correspond with the following for the alternative as a whole:
    - 1 - High relative energy consumption
    - 2 - Average relative energy consumption

    - 3 - Low relative energy consumption

5.1.2.4 Relative Complexity and Cost of Pretreatment

Under this criterion, lower rankings were given to the alternatives requiring pretreatment ahead of PFAS treatment. This includes alternatives with sorption media and RO membrane separation technologies. Liquid waste stream alternatives that use foam fractionation were not expected to require pretreatment beyond a simple particulate filter, thus simplifying implementation.

- Scores correspond with the following for the alternative as a whole:
    - 1 - High relative pretreatment complexity
    - 2 - Average relative pretreatment complexity
    - 3 - Low relative pretreatment complexity

5.1.2.5 Relative Energy Recovery from Biosolids Alternatives

The thermal technologies used to desorb and destroy PFAS from biosolids can recover energy from the heat remaining in the process after meeting the energy demand of the process itself. Heat energy can be used to supplement building or process heating systems or to generate electric power. This criterion is separated from energy consumption in this evaluation because energy recovery can potentially affect the favorability of some alternatives. Under this criterion, the lowest rankings were given to the alternatives with no recoverable energy. Alternatives that incorporated unit processes with ample recoverable energy were scored the highest.

- Scores correspond with the following for the alternative as a whole:
    - 1 - No recoverable energy from biosolids process
    - 2 - Low relative recoverable energy from biosolids process
    - 3 - High relative recoverable energy from biosolids process

5.1.2.6 Applicability at Scale

This criterion refers to the scale at which alternatives have been implemented in field and full-scale applications, as well as considerations for the commercial availability of equipment and supplies. It also considers economies of scale at the design basis sizing for each waste stream. While primary separation or destruction technologies may be commercialized, these applications may be at a scale much smaller than required for a specific waste stream in this study.

- Scores correspond with the following for the alternative as a whole:
    - 1 – Minimal commercial application at a relevant scale (0–2 applications)
    - 2 – Limited commercial application at a relevant scale (2–10 applications)

    - 3 – Significant commercial application at a relevant scale (>10 applications)

Other considerations that affect applicability at different scales include the availability of sorption media, chemicals, and other materials needed for treatment. These were not considered in this evaluation.

5.1.3 Byproducts Management

Byproducts include treated water (post-primary separation or destruction), spent sorption media, waste streams, combustion-related solids/ash, etc. Consideration of byproducts management is divided into two criteria to evaluate the potential for byproduct reuse after PFAS have been removed or destroyed as well as the potential for air emissions of PFAS or other air pollutants not currently measured.

5.1.3.1 Beneficial Reuse Opportunity for Water or Byproducts

This criterion applies to the potential use of PFAS separation and destruction byproducts, such as water reuse instead of discharge and GAC reactivation. Beneficial reuse of treated water or solid byproducts may offset PFAS separation and destruction costs, though this is site-specific. In addition, high-quality treated water could be used for irrigation, industrial reuse, and indirect potable reuse applications, potentially offsetting water treatment costs in the region.

- Scores correspond with the following for the alternative as a whole:
    - 1 – No beneficial reuse of water or solid byproducts
    - 2 – Potential beneficial reuse of water or solid byproducts
    - 3 – Established beneficial reuse of water or solid byproducts

5.1.3.2 Potential for Media Shifting of PFAS Pollutants

The potential for media shifting of PFAS refers to the composition and disposition of residual materials and how likely remaining PFAS are to partition into another phase (pathways such as air, ash, etc.) during management, reuse, destruction, or disposal. Significant uncertainty remains regarding the loss of PFAS, including compounds not included in current analytical methods that could be volatilized or formed during existing and developing thermal destruction processes.

- Scores regarding qualitative byproduct transformation potential correspond with the following for the alternative as a whole:
    - 1 – High media shifting potential, likely development of PFAS byproducts of incomplete combustion
    - 2 – Possible media shifting potential; unknown possibility of development of PFAS byproducts of incomplete combustion
    - 3 – Low media shifting potential, unlikely development of PFAS byproducts of incomplete combustion

5.1.4 Evaluation Criteria Selection and Weighting by Waste Stream

Criteria weighting differed by waste stream depending on specific priorities for each industry. Scoring of each alternative for each criterion also varied among media depending on the scale, pretreated water quality, and other site considerations associated with each waste stream evaluated.

Table 5-1 summarizes the criteria weighting used for different waste streams. Each criterion was given a weight of one through five, which was multiplied by the one-to-three score for each alternative for a weighted score. Some of the considerations used in the development of criteria weighting included the following:

- Municipal WRRF effluent and biosolids treatment alternatives require more commercialization and reliability than alternatives applied to landfill leachate and compost contact water, partly due to the larger volume of material requiring management and partly due to the importance of consistent wastewater treatment to society.
- Beneficial reuse opportunities for biosolids treatment alternatives are important to decrease or eliminate the need for landfill disposal of the residuals.
- Pretreatment complexity is more important for lower-quality liquid streams like mixed MSW landfill leachate and compost contact water than municipal WRRF effluent. The lack of existing treatment translates to a higher operational burden imposed by extra treatment processes. All biosolids management options require pretreatment via dewatering, so there was no difference in complexity and cost among alternatives.

Table 5-1 Evaluation criteria weightings by waste stream

Category	Municipal WRRF Effluent	Biosolids	Mixed MSW Landfill Leachate	Compost Contact Water
Technical Feasibility				
PFAS separation efficiency	5	N/A	5	5
PFAS destruction efficiency	5	5	5	5
Degree of commercialization	4	4	3	3
Reliability of performance	3	4	2	2
Simplicity of operation/maintenance	3	2	4	4
Operator and public health	2	2	2	2
Economic Feasibility				
Relative capital costs	4	4	4	4
Relative operation and maintenance costs	3	3	3	3
Relative energy consumption	2	2	2	2
Relative complexity and cost of pretreatment	2	1	4	4
Energy recovery options (applicable for biosolids technologies only)	N/A	2	N/A	N/A
Applicability at scale	5	5	5	5
Byproducts Management				
Beneficial reuse opportunity for water or byproducts	1	3	1	1
Potential for media shifting of PFAS	2	2	2	2
Minimum score achievable[1]	**41**	**39**	**42**	**42**
Maximum score achievable[1]	**123**	**117**	**126**	**126**

[1] The minimum score achievable by a given alternative is the sum of criteria weights multiplied by one (the lowest allowable score for each criterion). The maximum score achievable is the sum of criteria weights multiplied by three (the highest allowable score for each criterion).

5.2 Goals and Approach for Preliminary Design and Costing of Example Pretreatment Facilities

Some PFAS management alternatives require the pretreatment of municipal wastewater, landfill leachate, or compost contact water before entering PFAS separation processes. Alternatives that require pretreatment include RO membrane separation or sorption media pressure vessels (with GAC, AIX, or modified clay media). Other alternatives for liquid waste streams that rely on foam fractionation for PFAS separation or destruction were not expected to require pretreatment.

Pretreatment requirements and design basis for liquid waste streams are expected to vary considerably among specific sites. This study outlines pretreatment water quality requirements for liquid waste streams and anticipated influent water quality for PFAS management alternatives. It then outlines an example pretreatment process flow that could meet pretreatment water quality requirements in some instances and associated costs, as provided in Sections 6.5, 8.5, and 9.5. These evaluations were meant to provide an approximate order-of-magnitude cost estimate for pretreatment and should not replace site-specific treatability evaluations for select pretreatment processes. Because the focus of this study is PFAS separation and destruction and pretreatment requirements were expected to vary significantly by site, pretreatment cost estimates were developed in less detail, with greater uncertainty (at +100%/-50%) than PFAS separation and destruction cost estimates (at +50%/-30%).

To optimize the treatment efficacy of the PFAS management alternatives, it is recommended that the influent water quality for the aqueous waste streams meet the pretreated concentrations outlined in Table 5-2. These pretreatment concentrations are based on vendor-recommended influent water quality for RO membrane separation, GAC sorption, and AIX technologies.

Table 5-2 Targeted pretreated water quality for PFAS management alternatives with RO or sorption media vessels

Parameter[1]	Units	GAC Influent Targets	AIX Influent Targets	RO Influent Targets	Rationale
TOC[2]	mg/L	20	2	2	Membrane and sorption media foulant
TSS	mg/L	1	1	1	Membrane and sorption media foulant
TDS	mg/L	NA	500	NA	AIX foulant; affects RO recovery
Iron	mg/L	0.5	0.1	0.1	Limits fouling
Manganese	mg/L	0.5	0.1	0.1	Limits fouling

[1] Pretreatment thresholds for these parameters were not established for modified clay media. However, it is assumed that modified clay media must achieve similar pretreatment targets as GAC to avoid media fouling and pore blockage issues.

[2] Dissolved organic carbon (DOC) is the parameter directly affecting fouling. However, TOC is used here because it is more commonly monitored and because the low TSS means that DOC and TOC concentrations are very similar. TOC is listed as the primary organic bulk parameter, but if not measured, BOD_5 should be less than 60 mg/L.

PFAS destruction alternatives for biosolids require pretreatment to remove material that could damage the destruction equipment and dewater the biosolids enough to meet SCWO, pyrolysis, or gasification feed requirements. The PFAS destruction alternatives' solids concentration requirements for biosolids are outlined with associated costs in Section 7.5.

5.3 Goals and Approach for Preliminary Design and Costing of Site-Specific Facilities

Alternatives that scored the highest in the detailed screening for each waste stream were carried forward for preliminary design and cost-curve development. This includes four alternatives for municipal WRRF effluent, two for municipal WRRF biosolids, four for mixed MSW landfill leachate, and three for compost contact water.

The following components for each site-specific PFAS management alternative can be found in Sections 6 through 9:

- Process flow diagram
- Design basis summary table
- Class 5—Association for the Advancement of Cost Engineering International Recommended Practice No. 17R-97 (AACE International 2020) capital cost table and scalable cost curve
- O&M cost table and scalable cost curve
- Narrative summarizing any relevant implementation concerns related to design, construction, operation, or maintenance for each alternative developed

5.3.1 Preliminary Design

Preliminary design basis summary tables in subsequent sections summarize key design parameters selected for each unit process comprising a single alternative.

The purpose of the preliminary design was to develop equipment needs and implementation considerations and support Class 5 (AACE) cost estimating. These preliminary designs were developed based on conversations with vendors, as well as relevant project experience and professional judgment. Preliminary designs were developed to address the design basis, including PFAS management alternative influent water and biosolids quality. These are outlined in subsequent sections for each targeted waste stream and are not intended to be applied to facilities with different conditions. The actual feasibility and effectiveness of any technology can vary from that assumed for a variety of site-specific reasons. Bench-scale or pilot-scale testing (or further testing, etc.) will be needed if more certainty as to the effectiveness of the technology based on site-specific conditions is required.

Specific design basis decisions that affect multiple waste streams include the following:

- 15-minute EBCT for GAC sorption media, reflecting a value slightly higher than the industry standard of 10 minutes for PFAS removal due to relatively low PFAS treatment targets.
- 4-minute EBCT for AIX sorption media, reflecting a value slightly higher than the industry standard of 2 minutes for PFAS removal due to relatively low PFAS treatment targets.

- 10-minute EBCT for modified clay sorption media, based on vendor feedback that EBCT should be higher than for AIX for high-PFAS waste streams like mixed MSW landfill leachate and compost contact water.

- Target hydraulic loading rate of 1–10 gpm/ft^2 for GAC vessels and 5–18 gpm/ft^2 for AIX and modified clay vessels.

- RO flux of 16 gallons per square foot per day.

- RO recovery of 85% for tertiary wastewater effluent and 65% for pretreated mixed MSW landfill leachate.

5.3.2 Cost Estimate Approach and Limitations

A Class 5 (AACE) capital cost estimate was developed for each PFAS management alternative carried forward to a preliminary design. Each cost estimate was then scaled to flows within the design basis flow range for each waste stream to develop cost curves. Capital costs are presented in summary tables for three flow rates (low, middle, and high) for each waste stream and management alternative, with cost curves spanning the design basis flow range. Each capital cost curve has an estimated accuracy within a margin of +50%/-30%, consistent with less than 2% maturity of project design deliverables (AACE International 2020).

Sources used in the development of the capital cost curves included existing cost estimates prepared by Barr and Hazen as part of recent economic evaluations for multiple PFAS treatment and destruction alternatives, Barr's cost estimate repository, Minnesota project experience, conversations and budgetary estimates from vendors, and resources available through Barr's membership and involvement with the Interstate Technology Regulatory Council PFAS Team.

O&M costs were also developed based on the preliminary designs for the PFAS management alternatives and capital cost estimates. O&M costs also relied on vendor input, relevant project experience, and current industry rates for labor, electrical, sorption media, transportation, and disposal. The O&M costs are assumed to have the same level of accuracy (+50%/-30%) as the capital cost estimates.

The capital and O&M cost estimates developed for this Report represent the best judgment of the experienced and qualified professionals familiar with this project. Using the above sources, the estimated capital and O&M costs developed for preliminary PFAS management alternatives in this Report are intended to compare alternatives rather than represent estimates for specific projects. These cost estimates should not be directly applied in situations with different water or solids quality, operational constraints, or site-specific conditions. Barr has no control over the cost of labor, materials, equipment, or services furnished by others, over any contractor's methods of determining prices, or over competitive bidding or market conditions. Barr expects that costs for a specific site will vary from the opinions of probable capital and O&M costs for preliminary PFAS management alternatives developed for this Report. If managers of specific sites wish greater assurance as to probable costs, they should conduct a site-specific feasibility evaluation, including pilot testing, to characterize site-specific considerations and needs and to more accurately estimate PFAS management costs.

5.3.3 Capital Cost Support

PFAS separation and destruction equipment costs were solicited from multiple vendors who were presented with representative pretreated liquid waste stream or biosolids quality and characteristics and flow rates. Vendors were asked to assemble equipment options, footprints and dimensional diagrams, and capital costs. The information received from vendors was evaluated and compared for selecting representative equipment capital costs for inclusion in the preliminary cost estimates for each alternative at each flow rate evaluated. Specific vendor equipment models and the breakdown of equipment costs between unit processes, where an alternative includes multiple units, are not reported in the design basis or capital cost estimate tables. For most alternatives, the most conservative equipment costs were selected for inclusion at this preliminary design stage.

Equipment sizing for sorption vessels treating RO concentrate was accomplished by estimating achievable RO recovery. Lower recovery rates reduce energy use and fouling rate but lower permeate flux. The water quality and the required percentage removal of some of the water constituents also affect potential operating conditions and target recovery of RO membranes. For the current work, the recovery rate for the RO membranes treating municipal WRRF effluent and mixed MSW landfill leachate was set at 85% and 65%, respectively, based on literature and water quality.

For alternatives that include multiple unit processes, the total equipment cost was reported as a single line item in the capital cost estimates. Equipment costs were marked up by 28% to account for the estimated contractor markup (20%), and the average Minnesota sales tax was rounded up to the nearest percentage point (8%).

Most of the remaining capital-cost estimate line items were calculated as percentages of equipment, building, and/or construction costs based on relevant project experience and considering the level of preliminary design, except for treatment building costs. The percentages and line-item inclusions were as follows:

- General conditions: 15% of construction and equipment subtotal
    - Includes: Contractor mobilization and demobilization and site and project management
- Piping and appurtenances: 50% of total equipment cost
    - Includes: Separation and destruction equipment interconnected piping, piping supports, valves, and fittings
- Electrical and instrumentation/controls: 20% of total equipment cost
    - Includes: Controllers, valves, switches, indicators, transmitters, converters, instruments, conduits, and supports
- Site work: 10% of building cost
    - Includes: Yard piping and utilities

- Installation (equipment and piping): 50% of the total equipment and piping and appurtenances costs
    - Includes: Contractor installation of separation and destruction equipment, process piping and appurtenances, and yard piping and utilities

A treatment building cost of $500 per square foot was assumed, which includes subgrade excavation and preparation, a concrete pad, building materials, heat, power and electrical, mechanical/HVAC/plumbing, and appurtenances. Separation and destruction equipment footprints were estimated with vendor-provided information and dimensional diagrams and rounded to the nearest 10 or 100 square feet, depending on the size of the facility. For alternatives that include media sorption processes, a footprint for a driving lane for media changeout and a pipe gallery were included for liquid waste stream flow rates greater than or equal to 100 gpm (0.14 MGD). For all alternatives, a footprint for a lab and bathroom was included for liquid waste stream flow rates greater than or equal to 500 gpm (0.72 MGD).

With the framework described in this section, capital cost estimate tables were developed for three flow values for each waste stream, targeting each order of magnitude. Where appropriate, cost curves were developed by fitting a power formula to the three costs and flows. In some cases (the very low flow range used for mixed MSW landfill leachate and compost contact water and alternatives with significant modular equipment costs), a linear formula was used to fit the cost curves.

5.3.4 Operation and Maintenance Cost Support

Operation and maintenance cost estimates were developed with the following line items (as applicable):

- Utilities (including energy use for process and non-process loads)
- Sorption media replacement (including media purchase and trucking)
- Sorption media disposal (including spent media disposal and trucking)
- GAC reactivation (applicable to systems with 80,000 pounds or more of spent GAC per changeout event)
- Concentrate disposal (including concentrate disposal and trucking)
- Chemical usage (including flocculants, caustic, antiscalants, and clean-in-place chemicals, as needed)
- Maintenance (including process equipment and general building maintenance)
- Monitoring (including shipping and analytical fees for PFAS monitoring)
- Labor (including payroll and benefits for full-time equivalents for operation and maintenance staff)

For alternatives that include GAC adsorption, thermal reactivation was expected to be more cost-effective than single-use GAC. However, this technology has only been demonstrated as effective for PFAS removal when a facility can designate dedicated (site-dedicated) carbon to be reused only at that site (Westreich et al. 2018). Vendors have advised that the GAC use rates of smaller facilities (e.g., less than 80,000 pounds total per changeout event) are likely too small to enroll in site-dedicated reactivation programs, largely due to constraints on reactivation facility sizes. As a result, alternatives with GAC adsorption were assumed to use thermal reactivation for sites with over 80,000 pounds of GAC per changeout, which only applies to municipal WRRF effluent greater than 1.0 MGD. Other waste streams and smaller WRRF sizes with GAC adsorption were assumed to use single-use GAC with off-site high-temperature incineration. Disposal of GAC via general pool reactivation through a GAC vendor could be a cost-saving option over high-temperature incineration. However, the availability of this option is subject to media acceptance into the general pool reactivation program by the GAC vendor based on the media characteristics. Because of the uncertainty of the availability of this disposal option, it was not considered in the O&M estimates prepared for this study.

Utility use estimates were based on guidelines from the Electric Power Research Institute (Electric Power Research Institute 2013), assuming electrical costs of $0.13/kW-hr based on commercial pricing in Minnesota in 2022 (U.S. EIA 2022a). The natural gas estimate of $15.91/kSCF (kSCF=1,000 standard cubic feet) was based on reported commercial pricing in Minnesota in 2022 (U.S. EIA 2022b).

GAC media replacement frequencies were approximated by modeling the estimated bed volumes treated to breakthrough at 5 ng/L. Bed volumes treated to breakthrough using GAC (Calgon F400) were estimated using an advection-dispersion model coupled with a homogenous surface diffusion model (HSDM) (Crittenden et al. 1986). Freundlich isotherm parameters for specific PFAS were taken from Burkhardt et al. (2022). Water-film mass transfer coefficients and surface diffusivities of PFAS on GAC were taken from Jarvie et al. (2005), and water-phase diffusion coefficients for individual PFAS were taken from Schaefer et al. (2019). This modeling exercise assumed influent PFAS concentrations matching those typical for each waste stream: municipal WRRF effluent, mixed MSW landfill leachate, compost contact water, and concentrate from RO treatment of municipal WRRF effluent and mixed MSW landfill leachate. These influent concentrations are presented in waste stream-specific sections in Table 6-1, Table 7-1, Table 8-1, and Table 9-1. PFAS concentrations in RO concentrate were estimated assuming 100% PFAS rejection and 85% water recovery for wastewater effluent and 65% recovery for mixed MSW landfill leachate. Additional details are included in Appendix D.

Mechanistic modeling was not completed for media replacement frequencies of AIX resin and modified clay due to limited data and information available in peer-reviewed literature to enable the development and implementation of mechanistic breakthrough models for these media. Instead, media replacement frequencies were estimated, assuming both AIX resin and modified clay media would have the same volume throughput of treated water (in gallons) as estimated for GAC using the HSDM model. For this study, breakthrough of the short-chain PFAS, PFBA, and PFBS dictated media exchange frequencies for GAC. Thus, for AIX resin beds and modified clay media beds designed to typical industry EBCTs (e.g., 4 minutes and 10 minutes, respectively), it was assumed that each media (GAC, AIX, and modified clay) would achieve the same volume throughput based on the breakthrough of the short-chain PFAS, PFBA or

PFBS. This assumption was supported by similar ranges in the bed volumes to breakthrough for each media for these PFAS as summarized in Appendix C.

Due to the uncertainties in the estimated media replacement frequencies used in this study, Barr recommends that sites seeking to implement media sorption for PFAS removal conduct pilot studies to accurately predict media replacement frequencies based on site-specific water quality and PFAS removal goals.

Costs for sorption media replacement were based on vendor feedback and pricing estimates for the selected sorption media. Costs for high-temperature incineration (for sorption media and foam fractionation foamate) were based on vendor discussions and data summarized in U.S. EPA (2020). GAC reactivation costs were based on vendor discussions. Disposal fees will vary depending on the specific characteristics of the waste and the waste manager. Therefore, the costs presented in this study may not reflect actual costs for the disposal of PFAS wastes, byproducts, or concentrates.

Trucking costs to incineration and reactivation facilities assumed $3/mile (assuming the PFAS-containing wastes are considered non-hazardous), 760 miles to a commercial incinerator that accepts PFAS waste, and 900 miles to a commercial GAC reactivation facility. Mileage was based on approximate distances between the Minneapolis-Saint Paul metro area of Minnesota and a conceptual commercial facility for each type.

Other line items included chemical usage for foam fractionation (cationic surfactant) and SCWO (caustic), antiscalant and clean-in-place chemicals for RO membrane separation, bag filter replacement for foam fractionation, and monthly PFAS sample collection and analysis.

Annual process equipment maintenance costs were assumed to be 3% of the purchase price of the process equipment. Annual general building maintenance was assumed to be $2.50/sq ft.

Labor (operator and maintenance staff time) was adjusted based on the facility size and complexity of the unit processes.

5.4 Goals and Approach for Regional Facility Evaluation

In addition to the site-specific alternatives evaluated, the feasibility and cost-effectiveness of regional PFAS destruction technologies were evaluated. This included a concept-level design for two regional PFAS destruction facilities and capital and O&M cost estimates for each. Operating costs (or savings) unique to regional facilities were developed to establish a potential payback period compared to discrete treatment systems.

The following components, outlined in Section 10, were developed for each regional PFAS destruction facility:

- Process flow diagrams
- Capital cost estimates

- O&M cost estimates and payback evaluation
- Narrative summarizing any relevant implementation concerns related to design, construction, operation, or maintenance for each alternative developed

The limitations of the PFAS management cost estimates outlined in Section 5.3 also apply to cost estimates for regional PFAS destruction facilities described in Section 10. Capital costs were based on a combination of vendor quotes for available equipment (for a regional biosolids pyrolysis facility) and scaling from recent reports of costs of facility expansions (for a regional high-temperature sorption media incineration facility).

Net present value (NPV) and payback period were used to evaluate the potential economic feasibility of new regional facilities. NPV reflects the current value of the net return at the end of the planning period relative to what might have been gained by investing elsewhere. The interest rate was assumed to be 2–6% (achievable market rate interest less inflation). This reflects the minimum attractive rate of return that could be achieved by investing capital elsewhere. A range was used to reflect a high degree of future uncertainty due to currently high inflation rates. The payback period is the time the capital expense can be repaid from the project benefits, not considering interest.

The effects of secondary environmental impacts (externalities) were also estimated for each regional facility based on literature regarding the cost of these impacts.

6 Municipal Wastewater

6.1 Project Assumptions for Municipal Wastewater

6.1.1 Description and Scale of Required Treatment

In the United States, centralized municipal WRRFs are the primary means by which wastewater is treated to remove biochemical oxygen demand, nutrients, and pathogens prior to discharge back to the environment. The majority of water treated comes from municipal sources, which contain PFAS due to their wide use in everyday consumer products (Thompson et al. 2022; Roy et al. 2018; Hamid, Li, and Grace 2018; Choi et al. 2019). Many WRRFs also accept industrial wastewater discharges under pretreatment agreements, which have the potential to contribute additional PFAS loading to WRRFs (Thompson et al. 2022). Some WRRFs serve communities with PFAS-contaminated potable water above the treatment targets identified in this study, and could thus exceed the treatment targets without additional PFAS loading from municipal or industrial sources (McNamara et al. 2018; Appleman et al. 2014; Pan, Liu, and Ying 2016). For this study, high industrial loads of PFAS were assumed to be managed via industrial pretreatment agreements, whereby PFAS are removed from industrial discharges before entering a WRRF. The concentrations assumed as design basis reflect typical values for Minnesota facilities without significant industrial PFAS loading. While this assumption is not realistic for every Minnesota WRRF, given current source management practices, it enables the development of baseline treatment needs and costs that can be increased, if needed, for facilities with significant industrial PFAS inputs.

Characteristics for two different types of existing, conventional treatment were used to reflect the majority of WRRFs in Minnesota:

- Conventional activated sludge treatment, including grit removal, primary sedimentation, secondary activated sludge with nitrification, and disinfection
- Stabilization pond treatment, including treatment in unaerated stabilization ponds, followed by disinfection

PFAS treatment of WRRF effluent would be applied downstream of existing treatment (end-of-pipe) to provide high-quality water that reduces fouling and maintenance costs associated with removing PFAS. This study addressed and produced cost curves for removing and destroying PFAS from WRRFs with influent flows ranging from 0.1 to 10 MGD and, as noted, assumes no significant industrial contributions of PFAS.

While the primary goal of the study was to evaluate PFAS treatment alternatives for their ability to separate and mineralize PFAS, WRRFs may be interested in the ability of retrofit equipment to meet other water quality goals, including removing the following:

- Total nitrogen to less than 7 mg/L
- Total phosphorus to less than 0.5 mg/L

- Total mercury to less than 6.9 ng/L

Pretreatment retrofits achieving tertiary treatment are expected to be needed for all PFAS management alternatives evaluated in detail and are described in more detail in Section 6.5. This tertiary treatment is expected to meet the above water quality goals, so the ability of PFAS management alternatives to do so was not evaluated. An added benefit of tertiary treatment is the potential for beneficial reuse, including possibly industrial and irrigation uses as well as indirect potable reuse.

6.1.2 PFAS Influent Concentrations and Treatment Targets

The presence and abundance of specific PFAS in WRRF influent are variable and reflective of ongoing consumer and industry changes. The PFAS most relevant in municipal wastewaters include short-chain PFCAs, long-chain legacy PFCAs and PFSAs, and fluorotelomers, with target PFAS selected as previously described in Section 2.3. Of the PFAS mass entering a WRRF, long-chain PFAS preferentially sorb to biosolids, and short-chain PFAS preferentially remains in the liquid phase (Guo et al. 2010; Pan, Liu, and Ying 2016). However, the transformation of PFAS precursors within the WRRF can lead to an increase in PFAA concentrations between WRRF influent and WRRF effluent (Thompson et al. 2022; Houtz et al. 2016).

Assumed typical and high WRRF effluent PFAS concentrations for use in this study were developed based on MPCA data for Minnesota WRRFs and are summarized in Table 6-1. Typical and high values were selected to reflect approximate median and 90th percentile concentrations observed in the source data and serve as a basis for developing design basis and cost estimates in this study. These values are not intended to reflect the full range of PFAS concentrations that may be present at WRRFs.

Table 6-1 Assumed influent concentrations and treatment goals for target PFAS in municipal WRRF effluent (all units in ng/L)

PFAS[1]	Typical Concentrations[2]	High Concentrations[2]	Treatment Target
PFBA	15	200	5
PFBS	15	50	5
PFHxA	30	60	5
PFHxS	5	15	5
PFOA	40	80	5
PFOS	5	30	5
6:2 FTS	5	150	5

[1] Total oxidizable precursor assay is identified as an important analysis for municipal wastewater, but representative typical and high numerical concentrations were not available from the referenced datasets.

[2] Typical concentrations were selected to be in the range observed in three main sources: 2009–2010 MPCA-supplied data; Helmer, Reeves, and Cassidy (2022); and Coggan et al. (2019). Data reflect aqueous concentrations in treated effluent from municipal WRRFs.

6.1.3 Water Quality Assumptions for Pretreated WRRF Effluent

Non-PFAS water quality parameters have significant implications for currently available PFAS removal technologies. This section describes general water quality assumptions for municipal WRRF effluent. Representative influent and effluent water quality reflecting a typical WRRF in Minnesota was developed for non-PFAS parameters and listed in Table 6-2. This water quality includes moderate-to-high hardness of 511 mg/L as $CaCO_3$ and high alkalinity of 410 mg/L as $CaCO_3$. While this water quality will not be accurate for any one facility, it serves as a starting point to enable preliminary design and cost estimating for Minnesota WRRFs.

Effluent from conventional activated sludge or stabilization pond WRRFs is expected to contain concentrations of suspended solids and organic matter that would cause operational issues with primary PFAS separation technologies (e.g., GAC adsorption, AIX, and RO membrane separation). As a result, pretreatment consistent with tertiary treatment technologies is needed. Table 6-2 also includes tertiary-treated water quality used as the design basis for preliminary design and cost estimates. This water quality is assumed to be the influent to PFAS separation technologies and was based on WRRF effluent water quality and pretreatment targets for media sorption (GAC and AIX) and RO processes discussed in Section 5.2. Examples of WRRF retrofits and potential costs to provide this water quality prior to PFAS separation are further discussed in Section 6.5.

Table 6-2 Assumed initial and pretreated municipal wastewater quality

Parameter	Units	Municipal WRRF Influent[1]	Concentration in Mechanical Secondary Effluent[1,2]	Assumed Concentration in Pretreated Water (Influent for PFAS Management Alts)
pH	SU	Not reported	Not reported	7[3]
TDS	mg/L	Not reported	Not reported	500[3]
TSS	mg/L	200	5	1[4]
BOD_5	mg/L	200	8	2
TOC	mg/L	Not reported	Not reported	2[4]
Alkalinity	mg/L as $CaCO_3$	410	410	410
Chloride	mg/L	560	560	560
Sulfate	mg/L as SO_4	100	100	100
Sodium	mg/L	320	320	320
Potassium	mg/L	27	27	27
Calcium	mg/L	120	120	120
Magnesium	mg/L	52	52	52
Ammonia	mg/L as N	30	0.25	0.25
Phosphorus	mg/L	14	0.8	0.3
Iron	mg/L	Not reported	Not reported	0.1[4]
Manganese	mg/L	Not reported	Not reported	0.1[4]

[1] WRRF influent and effluent concentrations compiled by MPCA for municipal WRRFs in Minnesota.

[2] Conventional activated sludge with nitrification, secondary clarification, and no coagulation or tertiary treatment, compiled by MPCA for municipal WRRFs in Minnesota without significant industrial PFAS inputs.

[3] pH assumed to be neutral, and TDS assumed to be in typical range for WRRF effluent from regions sourcing drinking water from groundwater sources.

[4] Based on the pretreatment discussion in Section 5.2. Refer to Section 6.5 for more guidance on potential retrofit options to achieve this water quality prior to PFAS separation technologies.

6.2 PFAS Management Alternatives Evaluation Results

Each PFAS management alternative identified for liquid-phase PFAS separation and destruction in Section 4.1 was scored for each evaluation criterion described in Section 5.1.1 for municipal WRRF effluent.

6.2.1 Evaluation Scoring Results

Alternatives evaluated for municipal WRRF effluent, as described in Section 4.1, were:

- Alternative 1a: GAC sorption followed by off-site, high-temperature incineration of GAC

- Alternative 1b: RO membrane separation followed by GAC sorption of concentrate and off-site, high-temperature incineration of GAC
- Alternative 2a: single-use AIX followed by off-site, high-temperature incineration of resin
- Alternative 2b: RO membrane separation followed by single-use AIX of concentrate and off-site, high-temperature incineration of AIX resin
- Alternative 3a: regenerable AIX followed by on-site brine regeneration of resin and off-site, high-temperature incineration of spent regenerant residuals
- Alternative 3b: RO membrane separation followed by regenerable AIX sorption of concentrate and on-site brine regeneration of resin and off-site, high-temperature incineration of spent regenerant residuals
- Alternative 4a: regenerable AIX followed by on-site brine regeneration of resin and SCWO of still bottoms
- Alternative 4b: RO membrane separation followed by regenerable AIX sorption of concentrate and on-site brine regeneration of resin and SCWO of still bottoms
- Alternative 5b: RO membrane separation followed by modified clay media sorption of concentrate and off-site, high-temperature incineration of clay media
- Alternative 6a: GAC sorption followed by single-use AIX with off-site, high-temperature incineration of sorption media
- Alternative 6b: RO membrane separation with concentrate treated by GAC sorption followed by single-use AIX with off-site, high-temperature incineration of sorption media
- Alternative 7b: RO membrane separation followed by SCWO of concentrate

Evaluation results are summarized in Table 6-3 and described in subsequent sections. Specific criteria and subcriteria were defined in Section 5.1. Based on the screening, Alternatives 1a, 2a, 6a, and 6b were retained for preliminary design and cost curve development.

Table 6-3 Alternatives evaluation results for municipal WRRF effluent

Alternative Number		**1a**	**1b**	**2a**	**2b**	**3a**	**3b**	**4a**	**4b**	**5b**	**6a**	**6b**	**7b**
Membrane separation technology		-	RO	-	RO	-	RO	-	RO	RO	-	RO	RO
First PFAS sorption technology		GAC	GAC	AIX	AIX	RA	RA	RA	RA	MC	GAC	GAC	-
Second PFAS sorption technology		-	-	-	-	-	-	-	-	-	AIX	AIX	-
PFAS destruction technology		Inc	Inc	Inc	Inc	Inc	Inc	SC	SC	Inc	Inc	Inc	SC
Technical Feasibility	wt	60	55	60	55	52	49	48	45	51	66	61	*48*
PFAS separation efficiency	5	3	3	3	3	3	3	3	3	3	3	3	3
PFAS destruction efficiency	5	3	3	3	3	3	3	3	3	3	3	3	3
Degree of commercialization	4	3	3	3	3	2	2	1	1	2	3	3	1
Reliability of performance	3	1	1	1	1	3	2	3	2	1	3	3	3
Simplicity of operation/maintenance	3	3	2	3	2	1	1	1	1	2	3	2	1
Operator and public health	2	3	2	3	2	1	1	1	1	2	3	2	1
Economic Feasibility	**wt**	**44**	**39**	**44**	**39**	**33**	**26**	**21**	**21**	**30**	**37**	**32**	***16***
Relative capital costs	4	3	3	3	3	2	1	1	1	2	2	2	1
Relative operation and maintenance costs	3	3	2	3	2	3	2	2	2	2	2	1	1
Relative energy consumption	2	3	2	3	2	2	2	2	2	2	3	2	1
Relative complexity and cost of pretreatment	2	1	1	1	1	1	1	1	1	1	1	1	1
Applicability at scale	5	3	3	3	3	2	2	1	1	2	3	3	1
Byproducts Management	**wt**	**3**	**4**	**3**	**4**	**4**	**5**	**6**	**7**	**4**	**3**	**4**	***6***
Beneficial reuse opportunity for water or byproducts	1	1	2	1	2	2	3	2	3	2	1	2	2
Potential for media shifting of PFAS	2	1	1	1	1	1	1	2	2	1	1	1	2
Total Score		**107**	**98**	**107**	**98**	**89**	**80**	**75**	**73**	**85**	**106**	**97**	**70**
Retained?		**x**		**x**							**x**	**x**	

wt = criteria weight, as defined previously in Section 5.1.4, RO = RO membrane separation, GAC = granular activated carbon, AIX = anion exchange, RA = regenerable anion exchange, MC = modified clay, Inc = high-temperature incineration, SC = supercritical water oxidation (SCWO)

6.2.2 Technical Feasibility

All alternatives evaluated receive a score of 3 for **PFAS separation efficiency** because they were selected to be able to remove all target PFAS under selected operating conditions. While short-chain PFAS, such as PFBA, may break through quickly in alternatives that include media sorption technologies, treated water could potentially be kept below treatment targets given frequent monitoring and proactive changeout.

All alternatives evaluated received a score of 3 for **PFAS destruction efficiency** because both high-temperature incineration and SCWO mineralize 99% or more of target PFAS. However, both have the potential for additional PFAS formation (Krause et al. 2022; L. Winchell et al. 2022). Additional research is needed for both these technologies to demonstrate the degree of mineralization achievable and the nature of byproducts formed.

Alternatives with combinations of RO membrane separation, GAC, single-use AIX, and high-temperature incineration received a score of 3 for **degree of commercialization**, because all of these technologies have been widely applied in multiple industries for PFAS removal. AIX regeneration and modified clay sorption have been demonstrated in fewer industries and applications, so alternatives that included those technologies received a score of 2. Of the technologies included for consideration, SCWO is the least applied for PFAS management (limited to pilot-scale application for liquid treatment), so alternatives with SCWO scored a 1.

Short-chain PFAS have the potential to break through sorption media vessels between monitoring events, resulting in detectable effluent concentrations until a monitoring event and subsequent sorption media changeout can be completed. AIX resin and modified clay are more effective at removing short-chain PFAS than GAC but are also more susceptible to fouling, so all technologies using one lead-lag sorption process scored a 1 for **reliability of performance**. Regenerable AIX scored higher for reliability because on-site regeneration could provide the ability to regenerate once breakthrough is observed more quickly than single-use sorption media could be changed out. However, using regenerable AIX to treat RO concentrate scored a 2 because it is sensitive to the higher salt content in concentrate. Alternatives with both GAC and AIX scored a 3 because this multiple barrier approach provides more opportunity to capture breakthrough before it reaches final effluent. RO with SCWO of concentrate scored a 3, reflecting the high expected reliability of both these processes.

Alternatives with GAC, modified clay, or single-use AIX media and off-site high-temperature incineration scored a 3 for **simplicity of operation/maintenance** because, other than sorption media changeout events, they have only one on-site process that is relatively simple to operate. Alternatives with RO followed by sorption media all scored a 2 because RO membrane operation can be complex, requiring considerations for membrane fouling and cleaning. Regenerable AIX, with and without RO pre-concentration, scored a 1 because the regenerable AIX process includes high temperatures and chemical management. RO with SCWO of concentrate scored a 1 because of RO operational complexity and high temperature and pressure conditions associated with SCWO.

Sorption media alternatives with high-temperature incineration received a score of 3 because minimal **operator and public health** risks are associated with these types of treatment and destruction technologies. Alternatives with regenerable AIX or SCWO scored a 1 due to high-temperature on-site processes. Alternatives with RO and other media received a score of 2 because, though commonly used in the industry, they have increased risk to operators and public health due to one or more of the following: addition of chemicals, high operating temperatures, or high operating pressures.

6.2.3 Economic Feasibility

Alternatives using single-use sorption media have the lowest **relative capital cost** and received a score of 3. Adding RO as a pre-concentration step increases the capital cost for RO, but that additional cost is similar to savings resulting from smaller media filtration, leaving these scores at 3. Installation of on-site AIX regeneration equipment is expected to have a large capital cost, so alternatives with regenerable AIX technology received a lower score (by 1) than single-use AIX. Alternatives with both GAC and single-use AIX also scored 1 point lower than alternatives with just one of those technologies, resulting in a score of 2 both with or without RO. SCWO is expected to be relatively high in capital cost, so alternatives including SCWO scored a 1.

Alternatives with single-use sorption media disposed of via high-temperature incineration are expected to have the lowest **relative O&M cost (without energy)**, with primary costs associated with sorption media changeout and high-temperature incineration of media. The score for sorption media alternatives with RO upstream of the media was 1 point lower than the score without RO due to increased O&M costs associated with RO operation and maintenance. SCWO paired with regenerable AIX is expected to treat a very small waste stream consisting of AIX still bottoms, so O&M costs are ranked a 2, while RO/SCWO will send a larger flow rate to SCWO and was ranked a 1.

Alternatives with media sorption without RO concentration were the alternatives with the lowest **relative energy consumption** and had a score of 3, as energy costs would be associated with off-site high-temperature incineration of a concentrated media volume. The remaining alternatives were scored relative to these alternatives. Each alternative with RO lost a point due to the high pressures and resultant high energy needed to operate RO. Regenerable AIX would use more energy on-site for the regeneration process but less energy for residual destruction due to the low volume of residual still bottoms. These alternatives were ranked a 2. RO/SCWO ranked the lowest due to the high energy cost of applying SCWO to the full volume of RO concentrate.

All alternatives evaluated for municipal WRRF effluent were scored a 1 for **relative complexity and cost of pretreatment** because all would require pretreatment, as described in Section 6.5.

GAC, single-use AIX, and RO membrane separation have been widely **applied at scale** for municipal wastewater treatment (over 1 MGD), so alternatives including only these technologies received a score of 3. Regenerable AIX and modified clay media have limited applications at this flow rate, and alternatives including them received a score of 2. SCWO applications are very limited in size, so alternatives with SCWO were scored as 1.

6.2.4 Byproducts Management

Alternatives with two opportunities for **beneficial reuse** of byproducts received a score of 3—for example, RO permeate for water reuse in the plant and reuse of resin through regeneration in the alternative combining RO, regenerable AIX, and SCWO of still bottoms. Alternatives with one form of beneficial reuse received a score of 2. Alternatives with no potential beneficial reuse of byproducts received a score of 1.

All alternatives with high-temperature incineration received a score of 1. This is due to the current uncertainty and ongoing industry research to investigate PFAS transformations and emissions associated with high-temperature incineration. Alternatives with SCWO destruction received a score of 2 because the possibility of **PFAS media shifting** is unknown. The potential for PFAS aerosolization to occur in WRRF aeration basins should be evaluated as a phase transfer mechanism for WRRFs under all scenarios.

6.2.5 PFAS Management Alternatives for Preliminary Design

Based on the screening described in Section 6.2, four PFAS management alternatives were carried forward to preliminary design and cost analysis for municipal WRRF effluent:

- Alternative 1a: GAC sorption followed by off-site, high-temperature incineration of GAC (or GAC reactivation for WRRFs larger than 1 MGD)
- Alternative 2a: single-use AIX followed by off-site, high-temperature incineration of resin
- Alternative 6a: GAC sorption followed by single-use AIX with off-site, high-temperature incineration of sorption media (and GAC reactivation for WRRFs larger than 1 MGD)
- Alternative 6b: RO membrane separation with concentrate treated by GAC sorption followed by single-use AIX with off-site, high-temperature incineration of sorption media

While Alternatives 1b and 2b both scored 1 point higher than 6b, they were not included here, as the additive cost of RO preconcentration and cost savings on smaller media vessels will be similar for all three alternatives, and 6b reflects a moderate scenario due to its inclusion of both GAC and AIX processes. Costs for 1b and 2b could be estimated by subtracting 6a costs from 6b to get added RO costs and adding them to either 1a or 2a.

6.3 Alternative Preliminary Design and Cost Curve Development

6.3.1 Alternative 1a (Municipal Wastewater)

For Alternative 1a, pretreated WRRF effluent meeting the water quality listed in Table 6-2 flows directly to lead-lag GAC adsorption pressure vessels. For facilities with less than 80,000 pounds of GAC per changeout event, once GAC media is exhausted with respect to target PFAS (limited by PFBA and PFBS in this case), it would be sent to high-temperature incineration. Larger facilities, including the 10 MGD basis used here, are expected to use enough GAC to merit dedicated reactivation of GAC for reuse at that site only. This GAC reactivation process is expected to decrease O&M costs related to the purchase of new carbon. This process flow is summarized in Figure 6-1.

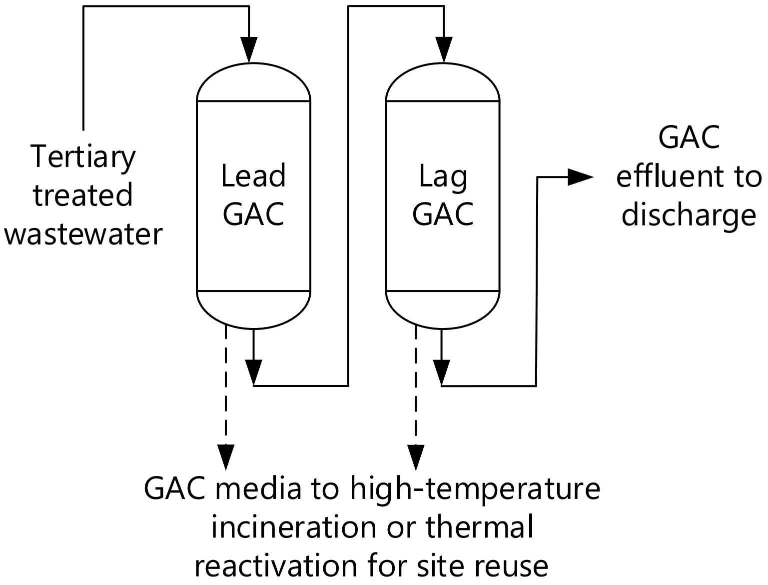


Figure 6-1 Conceptual process flow diagram for Alternative 1a for municipal wastewater

Key design basis assumptions for Alternative 1a are listed in Table 6-4, with a detailed design basis in Appendix E.

Table 6-4 Summary of design basis assumptions for Alternative 1a for municipal wastewater

Design Parameter	Basis		
	0.1 MGD/70 gpm	1 MGD/700 gpm	10 MGD/7,000 gpm
Vessel capacity (lb)	6,000	20,000	60,000
Number of trains	1	3	9
Number of vessels	2	6	18
EBCT per vessel (min)	15	15	15
HLR (gpm/sq. ft)	2.5	2.1	5.1
Estimated bed volumes to breakthrough[1]	10,000	10,000	10,000
GAC disposal route	High-temperature incineration	High-temperature incineration	Dedicated reactivation

[1] Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L. Described further in Section 5.3.4 and Appendix D.

Figure 6-2 and Figure 6-3 illustrate estimated capital and annual O&M costs for a range of influent flow rates. These costs do not include pretreatment costs described in Section 6.5. Detailed capital and O&M cost estimates are in Appendix E.

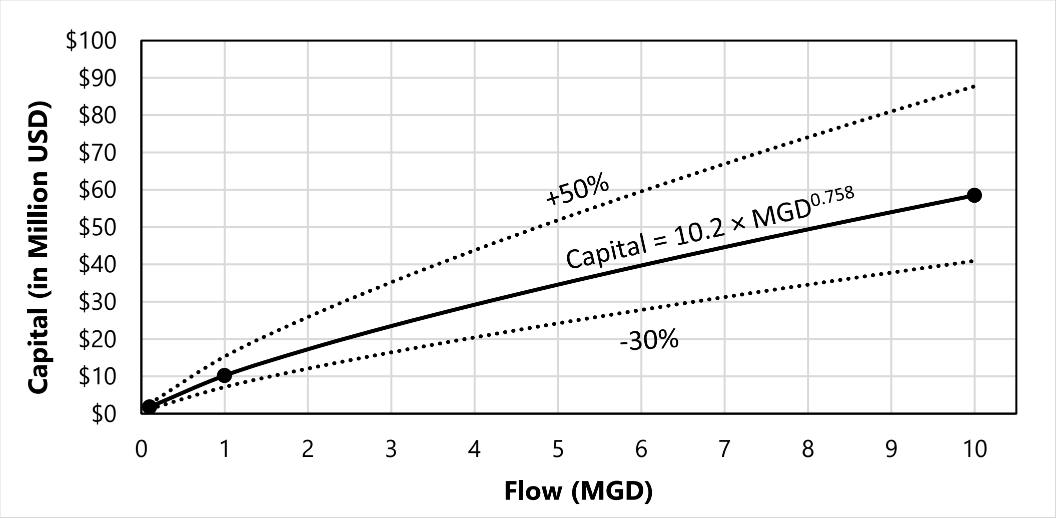


Figure 6-2 Capital cost curve for Alternative 1a for municipal wastewater

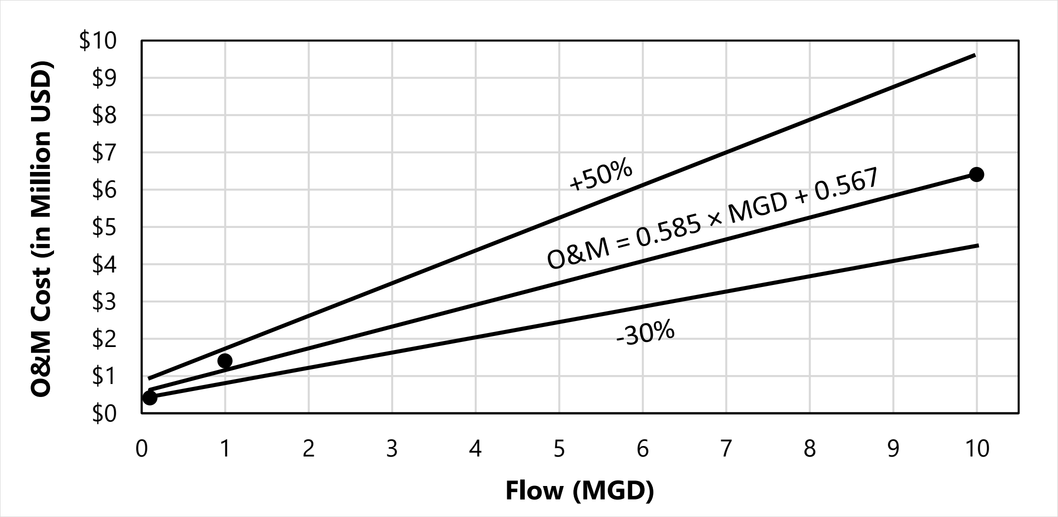


Figure 6-3 O&M curve for Alternative 1a for municipal wastewater

The highest operating costs are associated with labor and sorption media replacement and disposal. Primary uncertainties for Alternative 1a for municipal wastewater treatment include the following:

- Pretreatment processes needed and the ability to meet pretreatment targets
- Actual GAC breakthrough timing and requirements, depending on actual pretreated water quality
- Potential for GAC fouling limiting bed life over PFAS breakthrough
- Location and incineration fees of a selected high-temperature incineration facility

6.3.2 Alternative 2a (Municipal Wastewater)

For Alternative 2a, pretreated WRRF effluent meeting the water quality listed in Table 6-2 flows directly to lead-lag AIX pressure vessels. Once single-use AIX media is exhausted with respect to target PFAS (limited by PFBA and PFBS in this case), it would be sent to high-temperature incineration. This process flow is summarized in Figure 6-4.

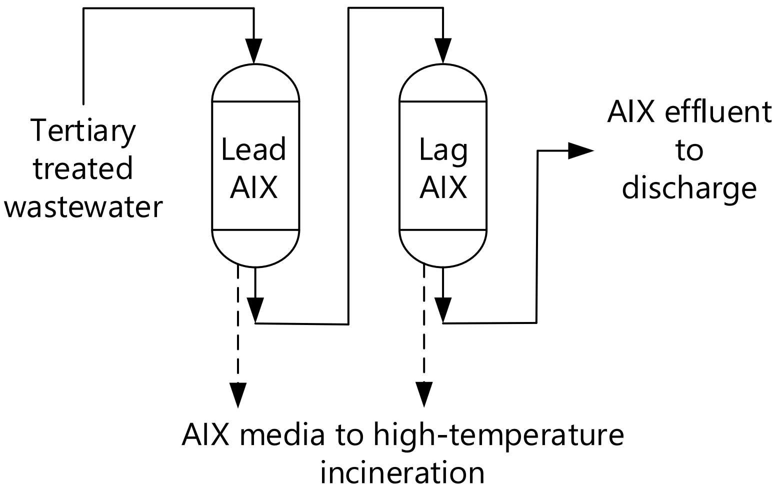


Figure 6-4 Conceptual process flow diagram for Alternative 2a for municipal wastewater

Key design basis assumptions for Alternative 2a are listed in Table 6-5, with a detailed design basis in Appendix E.

Table 6-5 Summary of design basis assumptions for Alternative 2a for municipal wastewater

Design Parameter	Basis		
	0.1 MGD/70 gpm	1 MGD/700 gpm	10 MGD/7,000 gpm
Vessel capacity (cu. ft)	40	200	450
Number of trains	2	2	9
Number of vessels	4	4	18
EBCT per vessel (min)	4	4	4
HLR (gpm/sq. ft)	5.0	7.0	6.9
Estimated bed volumes to breakthrough[1]	20,000	20,000	20,000
AIX disposal route	High-temperature incineration	High-temperature incineration	High-temperature incineration

[1] Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L. Described further in Section 5.3.4 and Appendix D.

Figure 6-5 and Figure 6-6 illustrate estimated capital and annual O&M costs for a range of influent flow rates. These costs do not include pretreatment costs described in Section 6.5. Detailed capital and O&M cost estimates are in Appendix E.

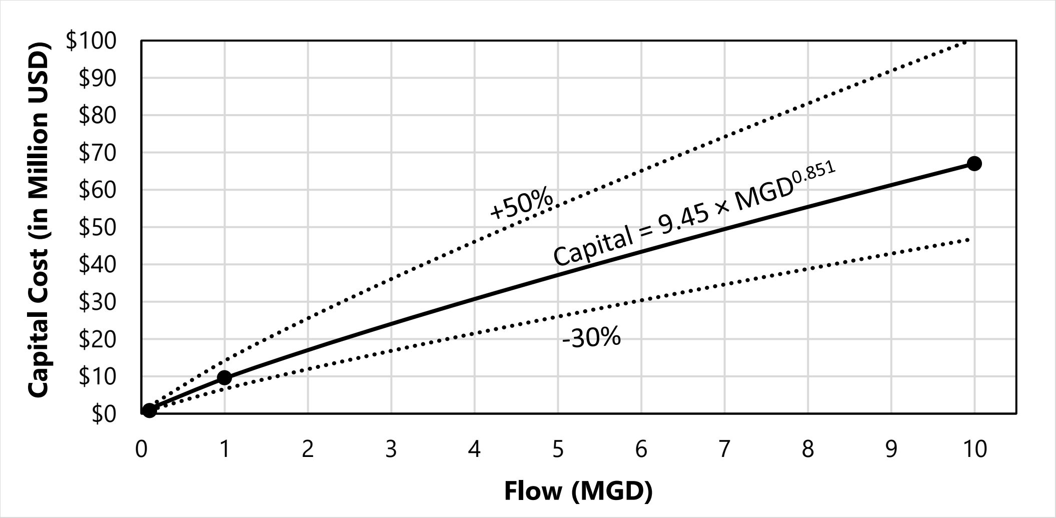


Figure 6-5 **Capital cost curve for Alternative 2a for municipal wastewater**

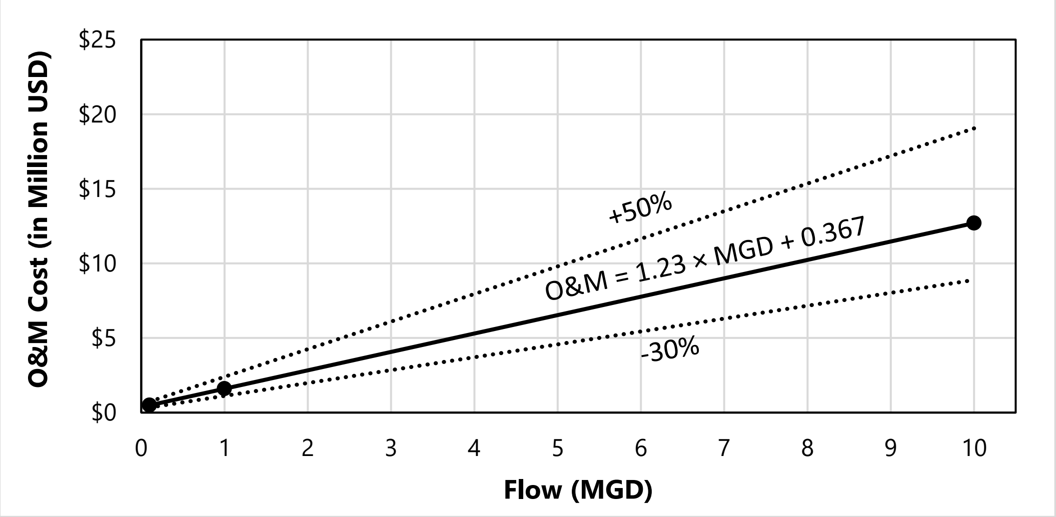


Figure 6-6 **O&M cost curve for Alternative 2a for municipal wastewater**

Estimated capital costs for single-use AIX (Alternative 2a) are similar to those estimated for GAC sorption (Alternative 1a). O&M cost estimates are similar between Alternatives 2a and 1a at low flows but diverge at higher flows because in Alternative 1a spent GAC is assumed to be reactivated rather than incinerated in the 10 MGD cost estimate, which substantially decreases the O&M costs.

Primary uncertainties for Alternative 2a for municipal wastewater treatment include the following:

- Pretreatment processes needed and the ability to meet pretreatment targets
- Actual AIX breakthrough timing and requirements, depending on actual pretreated water quality
- Potential for AIX fouling limiting bed life over PFAS breakthrough
- Location and incineration fees of the selected high-temperature incineration facility

6.3.3 Alternative 6a (Municipal Wastewater)

For Alternative 6a, pretreated WRRF effluent meeting the water quality listed in Table 6-2 flows directly to lead-lag GAC adsorption pressure vessels. GAC effluent would be routed to AIX pressure vessels. For facilities with less than 80,000 pounds of GAC per changeout, once GAC media is exhausted with respect to target PFAS (limited by PFBA and PFBS in this case), it would be sent to high-temperature incineration. Larger facilities are expected to use enough GAC to merit dedicated GAC reactivation, which enables GAC reactivation and reuse for that site only. This GAC reactivation process is expected to decrease O&M costs related to the purchase of new carbon. The single-use AIX process would primarily be present to limit the risk of breakthrough to treated effluent; GAC would be changed out frequently enough to target no breakthrough. Single-use AIX resin changeout is expected to be infrequent. Spent AIX resin would be sent to high-temperature incineration. This process flow is summarized in Figure 6-7.

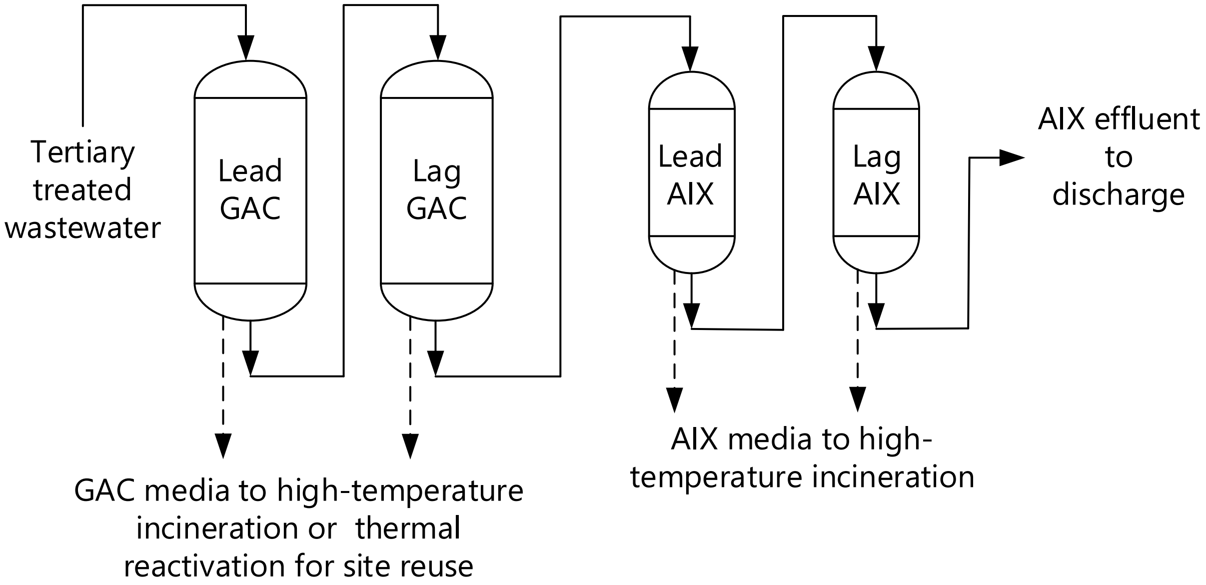


Figure 6-7 **Conceptual process flow diagram for Alternative 6a for municipal wastewater**

Key design basis assumptions for Alternative 6a are listed in Table 6-6, with a detailed design basis in Appendix E.

Table 6-6 Summary of design basis assumptions for Alternative 6a for municipal wastewater

Design Parameter	Basis		
	0.1 MGD/70 gpm	1 MGD/700 gpm	10 MGD/7,000 gpm
GAC			
Vessel capacity (lb)	6,000	20,000	60,000
Number of trains	1	3	9
Number of vessels	2	6	18
EBCT per vessel (min)	15	15	15
HLR (gpm/sq. ft)	2.5	4.6	5.1
Estimated bed volumes to breakthrough[1]	10,000	10,000	10,000
GAC disposal route	High-temperature incineration	High-temperature incineration	Dedicated reactivation
AIX			
Vessel capacity (cu. ft)	40	200	450
Number of trains	2	2	9
Number of vessels	4	4	18
EBCT (min)	4	4	4
HLR (gpm/sq. ft)	5.0	7.0	6.9
Estimated bed volumes to breakthrough[2]	140,000	140,000	140,000
AIX disposal route	High-temperature incineration	High-temperature incineration	High-temperature incineration

[1] Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L. Described further in Section 5.3.4 and Appendix D.

[2] Bed volumes to breakthrough shown assume one media bed replacement per year. Described further in Appendix D.

Figure 6-8 and Figure 6-9 illustrate estimated capital and annual O&M costs for a range of influent flow rates. These costs do not include pretreatment costs described in Section 6.5. Detailed capital and O&M cost estimates are in Appendix E.

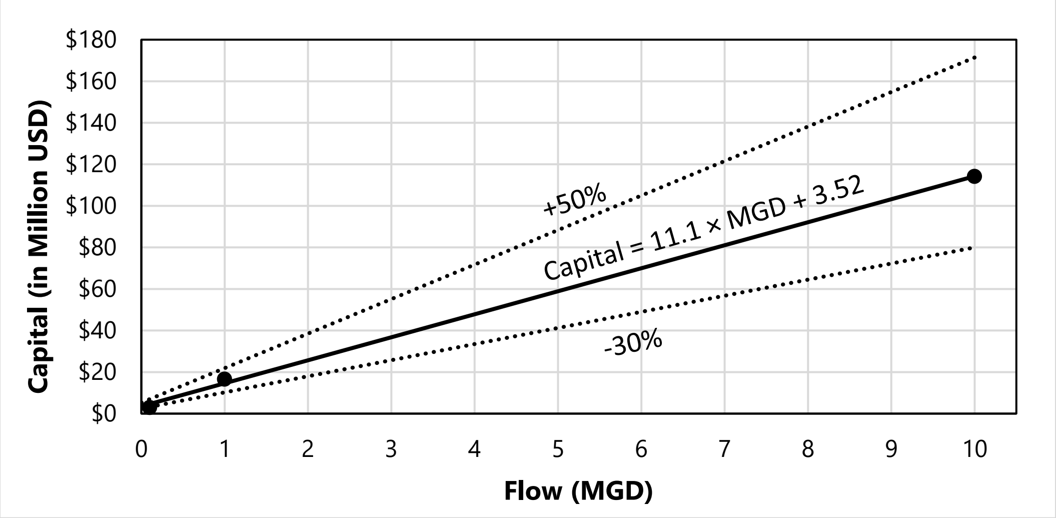


Figure 6-8 **Capital cost curve for Alternative 6a for municipal wastewater**

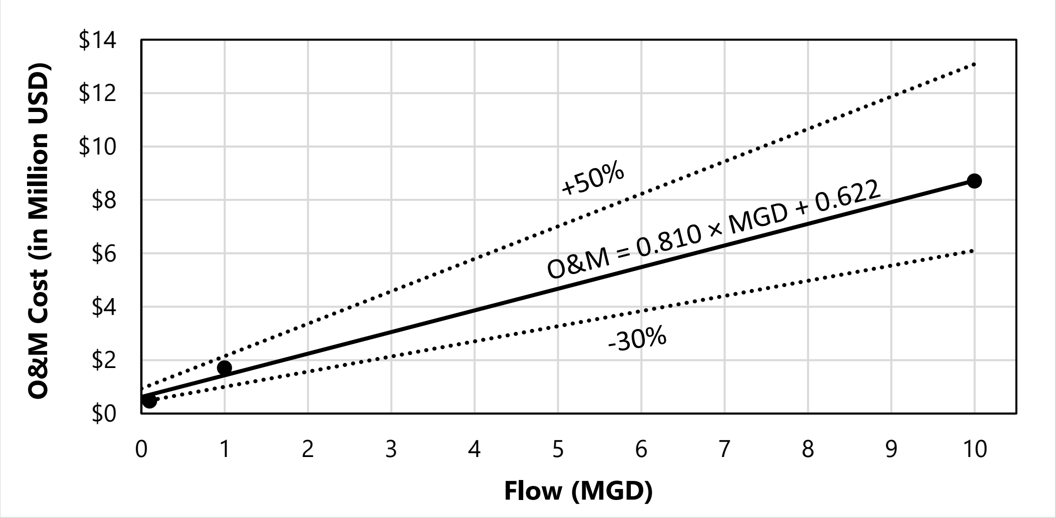


Figure 6-9 **O&M cost curve for Alternative 6a for municipal wastewater**

Estimated capital costs for the two-media sorption system, including both GAC and AIX (Alternative 6a), are approximately double those estimated for either sorption media alone (Alternatives 1a and 2a) due to the need for twice as many vessels. However, O&M costs are only slightly higher than those presented for GAC only because AIX resin changeout is expected to be infrequent.

Primary uncertainties for Alternative 6a for municipal wastewater treatment include the following:

- Actual GAC breakthrough timing and requirements, depending on actual pretreated water quality
- Actual AIX breakthrough timing and requirements, depending on actual GAC effluent water quality
- Potential for GAC fouling, limiting bed life over PFAS breakthrough
- Relative balancing of changeout priority for GAC versus AIX media

- Pretreatment processes needed and an ability to meet pretreatment targets
- Location and incineration fees of a selected high-temperature incineration facility

6.3.4 Alternative 6b (Municipal Wastewater)

Alternative 6b includes both GAC and AIX sorption processes, as previously described for Alternative 6a, with the addition of an RO membrane pre-concentration step. Tertiary treated water would route through an RO membrane separation process, with membrane concentrate routed to the lead-lag GAC adsorption pressure vessels followed by AIX pressure vessels. Membrane permeate would be blended with AIX effluent for discharge. This process flow is summarized in Figure 6-10.

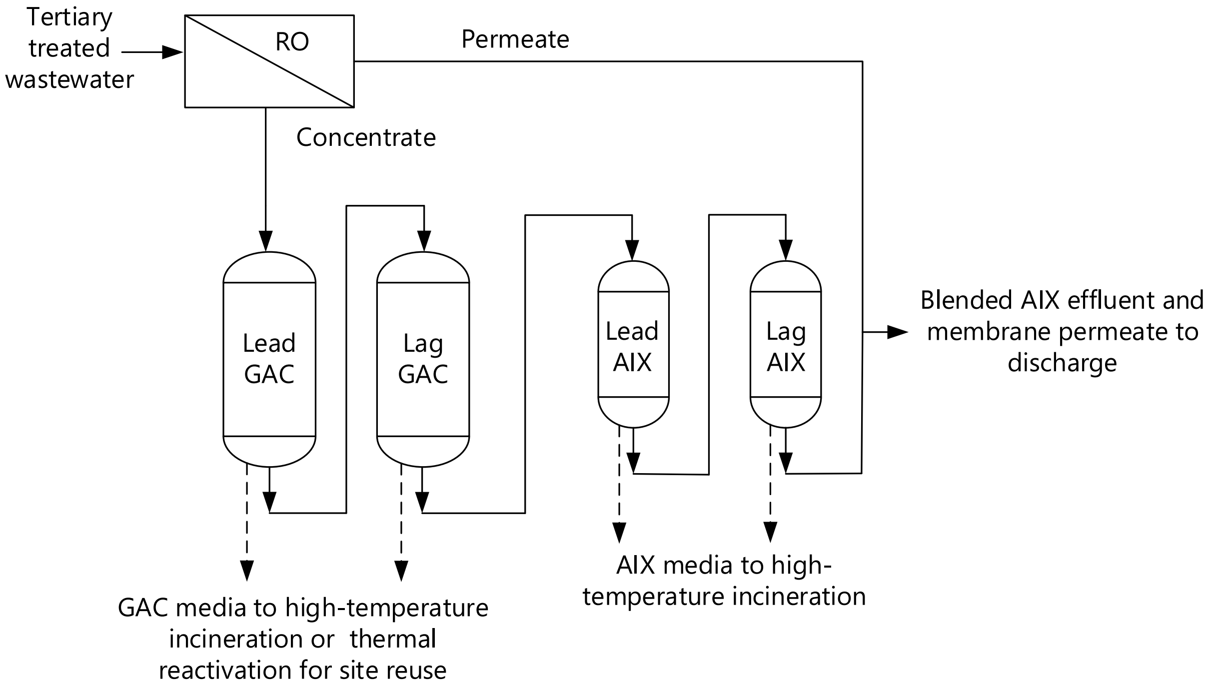


Figure 6-10 Conceptual process flow diagram for Alternative 6b for municipal wastewater

Key design basis assumptions for Alternative 6b are listed in Table 6-7, with a detailed design basis in Appendix E.

Table 6-7 Summary of design basis assumptions for Alternative 6b for municipal wastewater

Design Parameter	Basis		
	0.1 MGD/70 gpm	1 MGD/700 gpm	10 MGD/7,000 gpm
RO			
Recovery (%)	85	85	85
Flux (gal./sq. ft/day)	16	16	16
GAC			
Vessel capacity (lb)	800	6,000	20,000
Number of trains	2	2	4
Number of vessels	4	4	8
EBCT per vessel (min)	15	15	15
HLR (gpm/sq. ft)	3.2	1.9	2.4
Estimated bed volumes to breakthrough[1]	8,100	8,100	8,100
GAC disposal route	High-temperature incineration	Dedicated reactivation	Dedicated reactivation
AIX			
Vessel capacity (cu. ft)	5	40	200
Number of trains	3	2	3
Number of vessels	6	4	6
EBCT per vessel (min)	4	4	4
HLR (gpm/sq. ft)	3.8	7.8	7.3
Estimated bed volumes to breakthrough[2]	140,000	140,000	140,000
AIX disposal route	High-temperature incineration	High-temperature incineration	High-temperature incineration

[1] Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L. Described further in Section 5.3.4 and Appendix D.

[2] Bed volumes to breakthrough shown assume one media bed replacement per year.

Figure 6-11 and Figure 6-12 illustrate estimated capital and annual O&M costs for a range of influent flow rates. These costs do not include pretreatment costs described in Section 6.5. Detailed capital and O&M cost estimates are in Appendix E.

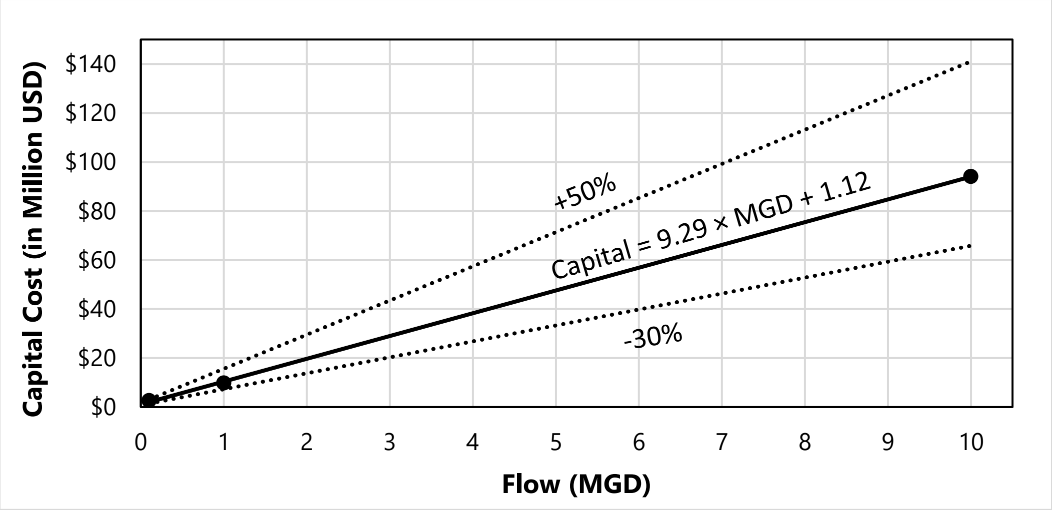


Figure 6-11 Capital cost curve for Alternative 6b for municipal wastewater

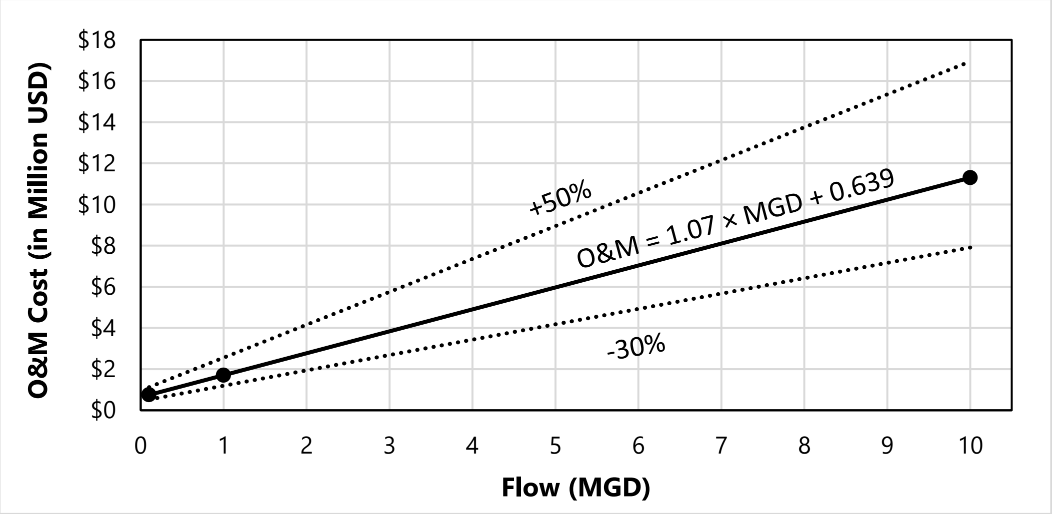


Figure 6-12 O&M cost curve for Alternative 6b for municipal wastewater

Estimated capital costs for the RO plus a two-media adsorption system, including both GAC and AIX (Alternative 6b), are lower than those estimates for the two-media system without RO (Alternative 6a). While the RO membrane equipment adds additional costs, the sorption media vessel sizing can be much smaller because the media influent flow is the membrane concentrate, which is lower than the total treated effluent flow routed to sorption media for Alternative 6a. O&M costs for the system with RO are higher than Alternative 6a due to similar media use rates but added O&M costs for RO operation.

Primary uncertainties for Alternative 6a for municipal wastewater treatment include the following:

- Achievable recovery of RO membranes and associated energy usage
- Fouling potential of RO membranes, depending on actual pretreated water quality

- Fouling potential of GAC and AIX media treating RO concentrate as a result of concentrated salts and metals
- Potential for GAC fouling limiting bed life over PFAS breakthrough
- Actual GAC breakthrough timing and requirements, depending on actual pretreated water quality
- Actual AIX breakthrough timing and requirements, depending on actual GAC effluent water quality
- Relative balancing of changeout priority for GAC versus AIX media
- Pretreatment processes needed and ability to meet pretreatment targets
- Location and incineration fees of selected high-temperature incineration facility

6.4 PFAS Removal Performance and Reliability

The relative ability of each alternative to meet treatment goals of <5 ng/L for target PFAS is summarized in Table 6-8. The single GAC or AIX sorption process included with Alternative 1a or 2a is expected to meet limits the majority of the time, with some risk for breakthrough of short-chain PFAS between monitoring events. Including both GAC and AIX processes in series increases the reliability of consistent removal by providing an additional treatment buffer before discharge. Including RO (Alternative 6b versus 6a) has limited effect on PFAS removal because the PFAS removal mechanism is the same GAC sorption process. Specific references for PFAS removal efficiency are detailed further in Appendix C.

Table 6-8 PFAS removal performance and reliability for municipal WRRF effluent treatment alternatives

Target PFAS	Assumed Influent Concentration (ng/L)	Percent Removal to Achieve <5 ng/L	Relative Ability to Consistently Meet Targets			
			1a: GAC	2a: AIX	6a: GAC/AIX	6b: RO with GAC/AIX
PFBA	15	67%	Moderate	Moderate	High	High
PFBS	15	67%	Moderate	Moderate	High	High
PFHxA	30	83%	Moderate	Moderate	High	High
PFHxS	5	0%	High	High	High	High
PFOA	40	88%	High	High	High	High
PFOS	5	0%	High	High	High	High
6:2 FTS	5	0%	High	High	High	High

6.5 Example Pretreatment and Retrofit Options for PFAS Separation Technologies Applied to WRRF Effluent

As described in Section 6.1.2, the effluent water from WRRFs used in this study will need to be pretreated with tertiary treatment (filtration) to achieve pretreatment targets that will limit the fouling of downstream PFAS removal processes. Due to the inclusion of RO membrane separation or sorption media pressure vessels, all PFAS management alternatives evaluated for municipal WRRF effluents are expected to require pretreatment, either in the form of a process upgrade or a new treatment process.

One example of a tertiary treatment upgrade that could meet pretreated water quality parameters is a membrane bioreactor (MBR). The MBR process is similar to a conventional activated sludge system, but active biomass is retained using microfiltration membranes rather than a separate secondary clarifier (settling tank). The MBR configuration permits the operation of the activated sludge process with a higher biomass concentration, which reduces footprint needs. A microfiltration membrane also provides high-quality effluent with lower concentrations of suspended solids and organic material than conventional activated sludge with settling. Only eight WRRFs in Minnesota have MBR processes installed, and only four of those treat their entire flows with MBR.

This section summarizes estimated costs to achieve pretreatment needs using MBR when starting with municipal wastewater treated with activated sludge or by stabilization ponds. Retrofitting a WRRF using conventional activated sludge to include tertiary filtration, potentially with coagulation and flocculation, also has the potential to meet pretreatment targets, depending on site-specific conditions. MBRs were chosen over adding a tertiary media filtration process to a conventional activated sludge facility because the costs are expected to be similar, especially when nutrient removal is also required, and MBR provides higher quality effluent with respect to solids concentrations (Brepols, Schäfer, and Engelhardt 2010; Young et al. 2014).

The conceptual pretreatment cost estimates did not include a detailed feasibility study or any design for site-specific requirements. Pretreatment needs are expected to vary by facility due to differences in existing infrastructure, water quality, space availability, and other site-specific constraints. Thus, the degree of detail included in this Report for pretreatment is less than that provided for PFAS treatment alternatives in subsequent sections. The conceptual pretreatment costs shown are intended to provide an order-of-magnitude estimate for potential pretreatment costs. **Facilities looking to implement PFAS treatment should conduct site-specific treatment evaluations prior to capital planning or implementation.**

While existing PFAS separation technologies commercially available at the scale of WRRF effluent treatment require tertiary treatment quality upstream of PFAS separation, future and developing PFAS removal technologies may have lower pretreatment requirements. These technologies may be able to treat WRRF secondary effluent without additional tertiary treatment or could potentially augment PFAS removal during secondary treatment.

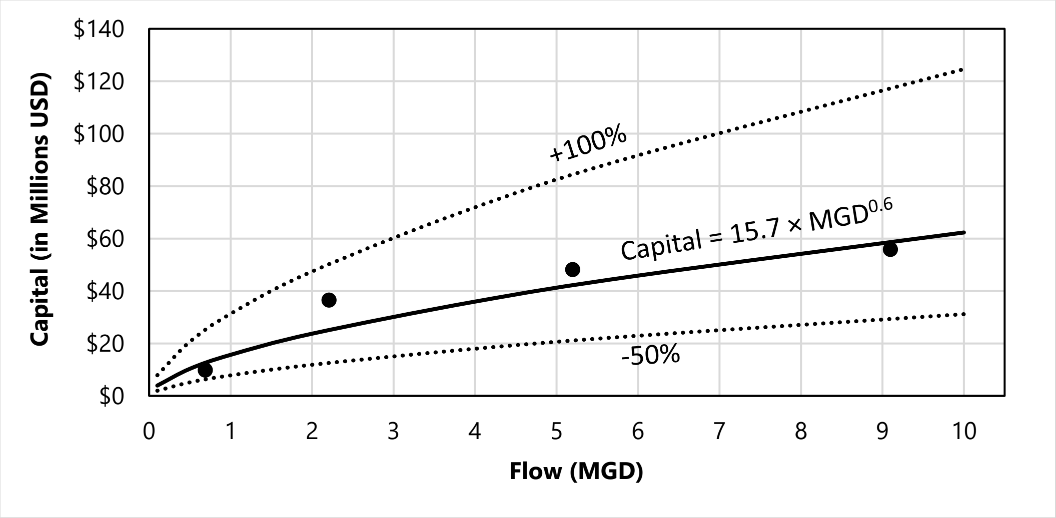
6.5.1 Example Pretreatment Retrofit for Existing Activated Sludge Treatment

Minnesota has over 300 activated sludge municipal WRRFs continuously treating wastewater. Retrofitting one of these plants with MBR technology could be done by using existing aeration basins and equipment, with membranes added directly to the existing aeration tanks, within the existing clarifier, or in separate new tanks. An MBR retrofit may also simultaneously increase treatment capacity while improving treatment performance. The approach and costs described below describe the retrofit of a typical activated sludge system to include an MBR. However, this approach will not be appropriate for all systems. The evaluation and selection of pretreatment and retrofit processes should be undertaken specifically for each facility seeking to implement a PFAS management approach.

The cost estimates developed for this Report include the following changes and additions for retrofitting an activated sludge WRRF to an MBR operation:

- Retrofit of existing aeration basins to fit membranes
- Purchase and installation of membranes
- Decommissioning or conversion of secondary clarifiers
- Installation of additional blower capacity for air scour and increased process aeration

While retrofit costs will vary significantly among WRRFs, converting an existing activated sludge facility with secondary clarification to MBR could range from 50% to 75% of the cost of a new MBR facility for a given flow capacity. Figure 6-13 presents a Class 5 (AACE) cost curve (+100%/-50%) for capital costs to retrofit a conventional activated sludge treatment facility to MBR treatment as described above. These costs are based on four MBR retrofits reported in Minnesota between 2016 and 2022 (Kyser 2022) and adjusted to November 2022 costs using the Engineering News Record (ENR) Construction Cost Index (CCI). The modeled cost curve was forced to a power factor of 0.6, consistent with the conventional 0.6 power factor for Class 5 (AACE) wastewater cost estimating (Tribe and Alpine 1986) and similar to the empirical power factor observed (0.67).



Black dots reflect actual costs for retrofit installations in Minnesota. The dashed line reflects the estimated cost curve. Black lines reflect +100%/-50% cost range. All costs scaled to November 2022 using ENR CCI.

Figure 6-13 Capital cost curve for retrofitting conventional activated sludge to MBR

Additional considerations for retrofitting a conventional activated sludge WRRF to MBR are listed below (Bagg 2009; Brepols et al. 2008):

- Flat-sheet or hollow fiber membranes—hollow fiber at lower depths
- Existing tank sizing and configuration—put membranes in or add separate membrane tank
- Upgraded screening to remove particles (from 3–12 mm to <0.5–3 mm screens) and associated headloss
- Hydraulic profile updates with membrane and screening addition and removal of clarifiers
- Energy demand of membrane air scour and increased process aeration needs for higher MLVSS concentration
- Higher RAS flow rates needed for MBRs than conventional activated sludge
- Foam management
- Nutrient removal processes and requirement
- Access for installation, maintenance, and operation

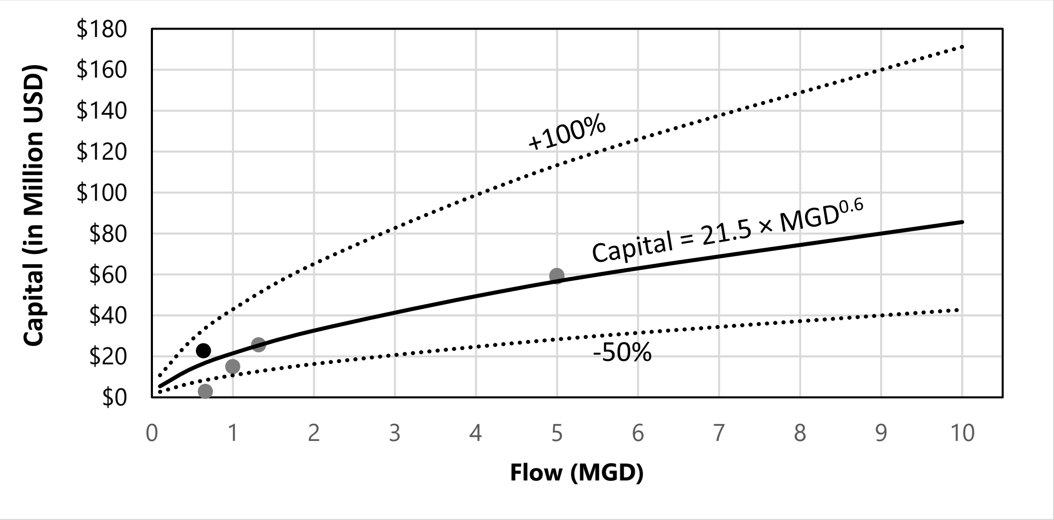
6.5.2 Example Pretreatment Retrofit for Existing Stabilization Ponds

Retrofitting an existing stabilization pond WRRF to include tertiary filtration would require significantly more investment and expansion than retrofitting an activated sludge WRRF and could be more similar to a greenfield installation than a retrofit. More WRRFs in Minnesota have stabilization ponds than activated sludge, especially in greater Minnesota, due to lower wastewater production rates and higher land availability in small communities.

The cost estimates developed in this Report assume that upgrading a stabilization pond facility includes the following changes and additions to accommodate an MBR system:

- Primary treatment, including screening, grit removal, and primary clarification (potentially could repurpose stabilization ponds)
- Aeration basins and diffusers
- Blowers and aeration control equipment
- MBR membranes
- Operational control system with an operator interface and associated measurement devices
- Pond decommissioning

For this study, converting a stabilization pond WRRF to an MBR system was assumed to require 90%–100% of the full cost of a new MBR facility for a given flow capacity. Figure 6-14 shows a Class 5 (AACE) cost curve (+100%/-50%) for capital costs to retrofit a stabilization pond WRRF to MBR treatment as described above. These estimates were based on reported MBR capital costs for one installation in Minnesota (Kyser 2022) and literature reports of MBR costs (Young et al. 2014; DeCarolis et al. 2007; Lo, McAdam, and Judd 2015; Brepols, Schäfer, and Engelhardt 2010). All were adjusted to November 2022 costs using the ENR CCI and standardized to include allowances for mechanical, electrical, piping, site work, and contractor overhead; profit, contingency, and engineering; and legal and administration fees.



Black dot reflects the actual cost for one new MBR installation in Minnesota. Grey dots reflect costs from Young et al. 2014; DeCarolis et al. 2007; Lo, McAdam, and Judd 2015; Brepols, Schäfer, and Engelhardt 2010. The solid line reflects the estimated cost curve. Dashed lines reflect +100%/-50% cost range. All costs scaled to November 2022 using ENR CCI.

Figure 6-14 Capital cost curve for new MBR installation for a stabilization pond system, including the cost to replace stabilization ponds

Other potential considerations for retrofit of a stabilization pond WRRF to an MBR system would include the activated sludge retrofit considerations listed in Section 6.5.1 as well as the following:

- Depending on the preferences of the WRRF, the existing stabilization ponds or a smaller pond footprint could be used for primary treatment and/or equalization ahead of the MBR instead of the mechanical primary treatment included above.

6.6 Other Considerations for Municipal WRRF Effluent

Which PFAS management alternative is most economically feasible for specific WRRFs will depend upon site-specific capacity, treatment goals, space availability, and operational preferences.

- Activated sludge WRRFs with flows higher than 1 MGD are likely to see the economic benefit of including an RO concentration step upstream of media sorption or AIX, as proposed in Alternative 6b. The payback period for RO will be less favorable for smaller facilities.
- Specific treatment targets will also affect technology selection, with facilities targeting primarily long-chain compounds more able to rely upon one media sorption process. Facilities targeting short-chain compounds at low concentrations or with strict permit limits disallowing daily exceedances may benefit from multiple media sorption processes in series, as proposed in Alternatives 6a and 6b.
- The decision to select one of these PFAS management alternatives and implement it at a WRRF will vary site by site based on the PFAS management strategy, existing infrastructure, existing effluent water quality, and actual treatment targets. Another consideration is that municipal WRRF effluent has a larger volume and lower PFAS concentrations than other liquid municipal waste streams evaluated in this study. The Metro Plant WRRF in Saint Paul, Minnesota, produces over 300 MGD of treated effluent. This relatively large flow with dilute PFAS concentrations highlights the challenges of downstream PFAS management. Future evaluation of PFAS management in WRRF effluent should consider further concentration processes, especially those with limited pretreatment needs. For example, foam fractionation presents a potentially appealing alternative because the volume of concentrated PFAS waste produced could be as low as a millionth of the initial water volume. However, additional studies to improve short-chain PFAS removal and equipment scale-up concerns limit current applications of foam fractionation for treating WRRF effluent.
- Large WRRFs implementing PFAS removal from effluent may be justified in building on-site destruction facilities for sorption media, foam fractionation foamate, or RO concentrate. Smaller WRRFs will need to use either existing or future regional facilities developed for that purpose.

7 Municipal Wastewater Biosolids

Management of municipal WRRF biosolids in Minnesota is currently accomplished using a combination of land application, landfilling, reed bed disposal, and sewage sludge incineration (SSI) (Beecher et al. 2022). While SSI has demonstrated the capability to destroy PFAS in some studies, depending on the design and operating conditions (L. J. Winchell et al. 2021b), the SSIs in Minnesota do not operate at the temperatures required for PFAS destruction. To date, none of the biosolids management techniques practiced in Minnesota destroy PFAS. Technologies that could be added to existing WRRFs to destroy PFAS in solids are discussed in this section.

7.1 Project Assumptions for Municipal Wastewater Biosolids

7.1.1 Description and Scale of Required Treatment

Biosolids are the byproducts of wastewater treatment (including microorganisms grown within the WRRF and solid materials) that have been stabilized in an additional process, such as anaerobic digestion. Wastewater solids treatment techniques vary depending on WRRF treatment processes and the solids end-use plan. The majority of WRRFs in Minnesota use one of the following wastewater treatment processes:

- Conventional activated sludge treatment, including grit removal, aeration, sludge settling, disinfection, and solids stabilization via anaerobic digestion. Some WRRFs include primary clarification, which produces primary sludge. Conventional activated sludge treatment results in the continuous production of solids from wasted activated sludge.

- Stabilization pond treatment, including treatment in unaerated stabilization ponds, disinfection, and in-situ anaerobic digestion of solids that have settled to the bottom of the ponds. Solids in stabilization ponds digest naturally, decreasing in volume over time. Stabilization pond treatment systems are typically designed to accumulate solids for up to five years. When the solids blanket in the pond reaches the cleanout level, biosolids are either pumped from the pond or dredged from the dewatered pond using front-end loaders.

Both treatment processes typically result in biosolids with 3–5% solids (by volume). Biosolids treatment for PFAS removal considered in this study was assumed to begin at the point of biosolids discharge from the stabilization process (i.e., anaerobic digester) at a conventional activated sludge WRRF or the stabilization pond.

Biosolids production is dependent on each WRRF’s unique influent loading and operating conditions. Each WRRF has a unique influent solids flow rate, activated sludge production rate, and volatile solids reduction rate. A WRRF with an influent flow of 1 MGD could produce approximately 0.08 to 1.0 dry tons of wastewater solids per day (dtpd) based on Minnesota-specific data. A general rule of thumb used in the remainder of this Report is to assume that a 1 MGD WRRF produces approximately 1 dtpd of biosolids.

7.1.2 Biosolids PFAS Concentrations and Treatment Targets

Target PFAS selection by waste stream was detailed previously in Section 2.3. The PFAS identified as most relevant in biosolids include long-chain PFAAs and PFAS precursors that partition to biosolids. PFAS presence within a WRRF and associated biosolids are variable and reflective of ongoing consumer and industry changes (EGLE 2020). Typical and high concentrations of PFAS in biosolids used to support the design basis and cost estimates for this study are summarized in Table 7-1. These values are not intended to reflect the full range of PFAS concentrations that can be present in WRRF biosolids. The treatment target for the selected PFAS compounds is 5 ng/g, as described in Section 2.4, which is the detection limit for PFAS in biosolids at the time of this study.

Table 7-1 Assumed influent concentrations and treatment goals for target PFAS for municipal WRRF biosolids (all units in ng/g)

Value Type	Typical [1]	High [1]	Treatment Target
PFBA	2	5	5
PFBS	20	40	5
PFHxA	5	15	5
PFHxS	15	30	5
PFOA	60	200	5
PFOS	400	600	5
PFOSA	20	70	5
N-EtFOSAA	30	60	5
N-MeFOSAA	100	200	5

[1] Data from Venkatesan and Halden (2013) and Helmer et al. (2022).

This study does not include specific treatment targets for the non-PFAS compounds in biosolids. However, the treatment methods for PFAS in biosolids will decrease both the volatile solids and water content in the biosolids.

7.1.3 Biosolids Composition and Characteristics

Table 7-2 summarizes the assumed characteristics of biosolids entering the PFAS management strategy. These characteristics were selected to represent typical municipal WRRF biosolids after anaerobic digestion. Example technologies and costs to achieve targeted solids content for pyrolysis or gasification and SCWO are discussed in Section 7.4. Biosolids have a higher concentration of organic material and nutrients than wastewater due to the higher solids content. The biosolids production rate was selected with the following considerations:

- This study's municipal WRRF influent rate was 0.1 to 10 MGD, corresponding to roughly 0.1 to 10 dtpd. Actual biosolids production rates by facility may vary significantly from this range based on processes used for wastewater treatment and solids management as well as incoming wastewater characteristics.

- The minimum solids feed rate for PFAS destruction technologies is 1 dtpd, so the range evaluated for on-site biosolids management was 1 to 10 dtpd.
- WRRFs producing less than 1 dtpd of solids could partner with other local WRRFs to accumulate enough biosolids to meet the minimum PFAS destruction process feed rate.

Table 7-2 Assumed composition and characteristics of municipal WRRF biosolids feed to PFAS destruction technologies

Parameter	Unit	Characteristics of WRRF Biosolids
Biosolids to dewatering process following anaerobic digestion or lagoon treatment process	dtpd	1–10
Total solids, pre-dewatering	%	2–4
pH	Standard Units	7–8
Total solids, dewatered for drying [1]	%	25
Total solids, dried for pyrolysis or gasification	%	90
Total solids, dewatered for SCWO	%	15

[1] Pyrolysis/gasification vendors supply the solids dryer(s) and pyrolysis/gasification unit(s) as a system package.

7.2 PFAS Management Alternatives Evaluation Results

Each PFAS management alternative identified for biosolids PFAS separation and destruction in Section 4.2 was scored for each evaluation criterion described in Section 5.1.1 for municipal WRRF biosolids. The highest individual and weighted scores indicate the most favorable alternative.

Two evaluation criteria were different for biosolids treatment than for liquid-phase treatment. PFAS separation efficiency does not apply to biosolids treatment technologies. All treatment technologies evaluated for biosolids destroy the compounds rather than separating the compounds from the biosolids. In addition, pyrolysis, gasification, and SCWO systems have opportunities to recover heat energy from the process to reduce the energy input requirements or generate electricity, so energy recovery was included as a sub-criterion.

7.2.1 Evaluation Scoring Results

Evaluation results are summarized in Table 7-3 and described in subsequent sections. Specific criteria and sub-criteria were previously defined in Section 5.1. Based on the screening, pyrolysis/gasification with thermal oxidation and SCWO were retained for preliminary design and cost curve development. The rationale for considering pyrolysis and gasification as a single technology is described in Section 7.2.5.

Table 7-3 Alternatives evaluation results for municipal WRRF biosolids

Alternative Number		**1**	**2**	**3**
PFAS separation technology		N/A	N/A	N/A
PFAS destruction technology		Pyrolysis / Thermal oxidation	Gasification / Thermal oxidation	SCWO
Technical Feasibility	**weight**	**41**	**41**	**35**
PFAS separation efficiency	N/A	N/A	N/A	N/A
PFAS destruction efficiency	5	3	3	3
Degree of commercialization	4	3	3	1
Reliability of performance	4	2	2	2
Simplicity of operation/maintenance	2	1	1	2
Operator and public health	2	2	2	2
Economic Feasibility	**weight**	**32**	**32**	**40**
Relative capital costs	4	1	1	3
Relative operation and maintenance costs	3	2	2	3
Relative energy consumption	2	2	2	3
Relative complexity and cost of pretreatment	1	2	2	2
Energy recovery options	2	3	3	3
Applicability at scale	5	2	2	1
Byproduct Management	**weight**	**13**	**13**	**13**
Beneficial reuse opportunity for water or byproducts	3	3	3	3
Potential for media shifting of PFAS	2	2	2	2
	Total Score	**86**	**86**	**88**
	Retained?	**x**[1]	**x**[1]	**x**[1]

[1] Pyrolysis and gasification with thermal oxidation are similar processes and use the same equipment. The project team determined that they could be considered together as a single technology. Additional details follow in this section.

7.2.2 Technical Feasibility

While pyrolysis, gasification, and SCWO are established technologies for treating other waste materials, using these technologies to destroy PFAS in biosolids is relatively new. Many studies are underway to improve our understanding of how to apply these technologies for PFAS in biosolids and the fate and transport of PFAS during treatment. This study evaluated the technical feasibility of treating biosolids for

PFAS using currently available data. As more research is completed, it is anticipated that future scores may be different.

All three technologies received high scores for **PFAS destruction efficiency**, with over 99% reduction in concentrations of measured PFAS compounds in treated biosolids (Thoma et al. 2022; Davis 2020; Krause et al. 2022).

Pyrolysis and gasification systems are **commercially available** and currently operating to treat municipal WRRF biosolids. They were assigned an individual score of 3. SCWO was not commercially available for biosolids treatment at the time of this study and was scored lower than the other two technologies. However, demonstration testing of a commercial prototype is expected to begin at Orange County Sanitation District in California in 2023.

All three technologies scored a 2 for **reliability of performance**. They work well within their design conditions, but variability in influent biosolids, flow rate, organics concentration, or moisture content may impact performance. In addition, the high capital cost of these systems makes it unlikely that utilities will have a duplicate standby system. If a critical component of a PFAS destruction system is inoperable, the entire process will need to stop and biosolids would need to be stored.

Pyrolysis and gasification scored lowest for **simplicity of operation/maintenance**. The technologies include thermal drying and pyrolysis/gasification, which require operator training and attention at a higher level than for a typical biosolids treatment process. SCWO requires less specialized training and was scored as a 2.

All three technologies scored a 2 for **operator and public health**, indicating they have a moderate additional health risk beyond a typical biosolids treatment process. The systems include very hot unit processes, posing increased risk to operators. In addition, thermal drying can produce dust and create an explosion hazard. SCWO systems operate at high temperatures and pressure, increasing the risk to plant staff.

The complete, weighted scoring for the three technologies resulted in pyrolysis and gasification having the same technical feasibility score of 41, while SCWO scored 35. The primary reason for the low SCWO score was its low score for commercial availability, which is highly weighted to reflect the importance of currently feasible technologies.

7.2.3 Economic Feasibility

In the categories of **relative capital cost, relative O&M costs, and relative energy consumption**, SCWO scored higher than pyrolysis and gasification. Recent vendor cost estimates per wet ton for SCWO are lower than for the other technologies. Operation and maintenance costs are also expected to be lower for SCWO due to lower energy requirements.

Pyrolysis, gasification, and SCWO all scored 2 for **relative complexity and cost of pretreatment**. All require dewatering as pretreatment prior to PFAS destruction, which is a common biosolids process but requires added equipment, operator time, and maintenance attention.

All three technologies scored high for **energy recovery**. The systems are designed to transfer heat from the treatment process exhaust gases to the initial portion of the treatment process, reducing the demand for external energy.

Currently, none of the technologies are commonly used or **available at scale** to treat PFAS in biosolids. However, pyrolysis and gasification systems are used at a few facilities, with several vendors supplying full-scale systems. Pyrolysis and gasification scored a 2 for this category to reflect a minimal commercial application of these technologies for PFAS treatment in biosolids. SCWO has no commercially available systems at this time and scored lowest in the category.

Despite the low score for SCWO's applicability at scale, the combined weighted score for economic feasibility was higher than pyrolysis or gasification, reflecting the relative importance of capital and O&M costs in the scoring for this category.

7.2.4 Byproducts Management

All three technologies scored a 3 for the **beneficial reuse of water or byproducts**. Pyrolysis and gasification produce biochar, which has multiple uses and returns heat to the process. The temperature of the operation dictates the amount of biochar produced and the energy recovered. SCWO produces clean water, inert gases, and mineral salts.

All three technologies received a score of 2 for **potential media shifting of PFAS**. The possibility of PFAS media shifting is unknown and an area of ongoing research.

7.2.5 PFAS Management Alternatives for Preliminary Design

SCWO had the highest combined weighted score (88) of the PFAS destruction technologies for biosolids. SCWO was carried forward to preliminary design and cost analysis for municipal WRRF biosolids.

The combined weighted scores for pyrolysis with thermal oxidation and gasification with thermal oxidation were the same: 86. Pyrolysis and gasification were considered similar enough in equipment, solids and energy inputs, and biochar production to be evaluated as a single alternative for preliminary design. Based on the screening, pyrolysis/gasification with thermal oxidation and SCWO were retained for preliminary design and cost curve development.

7.3 Alternative Preliminary Design and Cost Curve Development

7.3.1 Supercritical Water Oxidation (Wastewater Biosolids)

In this treatment alternative, dewatered biosolids at 15% of total solids are conveyed to the SCWO process inlet. The first component is a heat exchanger used to raise the temperature of the biosolids before SCWO. SWCO reactor effluent is routed through an economizer and liquid/gas separator.

Separated gas is used to produce energy and is vented to the atmosphere, with condensate available for discharge or reuse. Solids leaving the liquid/gas separator enter a cooler, and recovered heat is used to preheat incoming biosolids. Water is separated from resulting solids in a clarifier, with cooled solids routed to disposal or beneficial reuse. This process flow is summarized in Figure 7-1.

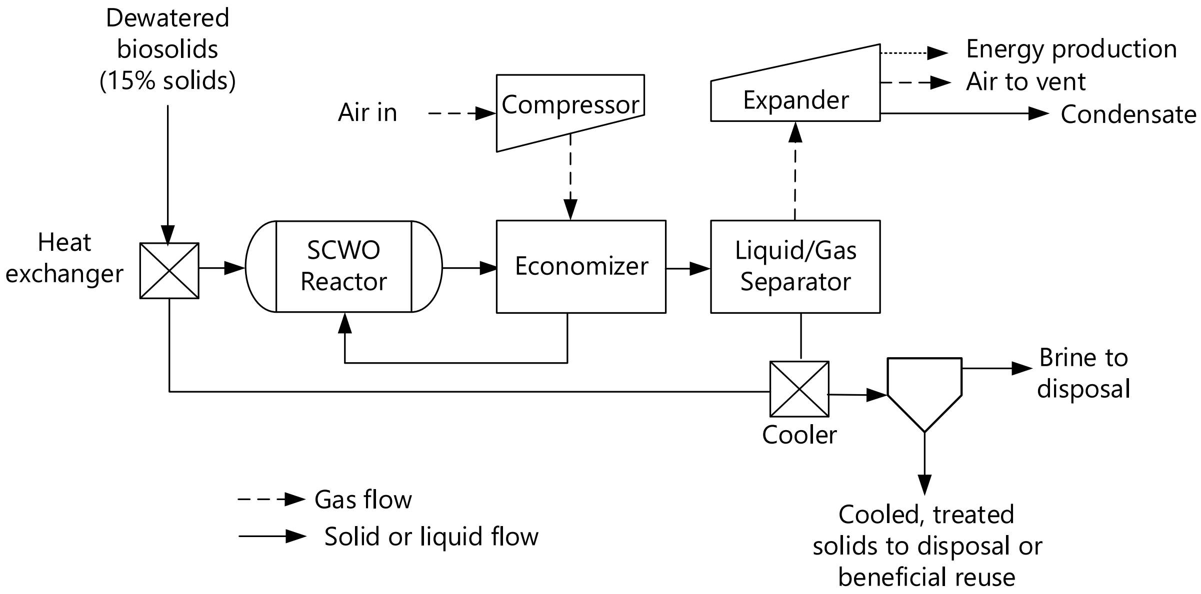


Figure 7-1 Conceptual process flow diagram for biosolids supercritical water oxidation

Currently, a single manufacturer is marketing SCWO systems for destroying PFAS in biosolids in the United States. The systems are sold as an equipment package and include all the unit processes shown in Figure 7-1. The manufacturer sizes the unit processes based on the rated treatment system capacity. The system sizes currently available are shown in Table 7-4.

Table 7-4 SCWO system sizing

Available SCWO System Sizes	Treatment Capacity, Wet Metric Tons per Day (15% total solids)	Treatment Capacity (dtpd)
SCWO 6	6	1.0
SCWO 30	30	5.0
SCWO 200	200	33

The selection of the SCWO system size for a given facility is based on the dewatered biosolids feed rate, with proposed pricing and sizing for systems between six and 200 wet tons per day (1 to 33 dtpd). The system is a continuous treatment process. External fuel is needed to bring the treatment process to operating temperature. Once at temperature, SCWO systems require minimal external fuel. Thus, running periodic treatment campaigns is not a recommended operating strategy. Facilities treating less than 1 dtpd may not be good candidates for an individual SCWO system. SCWO units can be operated in parallel to treat flow rates of biosolids that fall between the individual treatment unit capacities.

The SCWO system is provided within containerized modular units (smaller units) or on a series of skids (large unit). A contractor will connect the biosolids feed piping, electrical and controls wiring, natural gas, and water to the package treatment units. In cold-weather areas like Minnesota, the SCWO system will be enclosed within a climate-controlled building. In temperate climates, the system may be installed in a covered area but does not require a full enclosure.

The development of the cost curve for SCWO was based on the selection of the size and number of units to meet an incremental solids load increase. The SCWO system design basis and assumptions are listed in Table 7-5 and reflect manufacturer recommendations for feedstock total solids and minimum heating value.

Table 7-5 Summary of design basis assumptions for supercritical water oxidation for biosolids

Design Parameter	Low Loading	High Loading
Dewatered biosolids load (dtpd)	0.99–4.0	5.0–10
Total solids (%TS)	15%	15%
Minimum heating value (BTU/dry lb)	5,000	5,000
Treatment capacity (dry ton/treatment unit)	0.99	5.0
Number of treatment units	1–4	1–6
Operating schedule	24 hours, 7 days/week	
PFAS removal estimate for target PFAS	99% (Krause et al. 2022)	

Figure 7-2 illustrates estimated capital costs for a range of solids loading rates. These costs do not include pretreatment costs described in Section 7.5. Detailed capital cost estimates are in Appendix E.

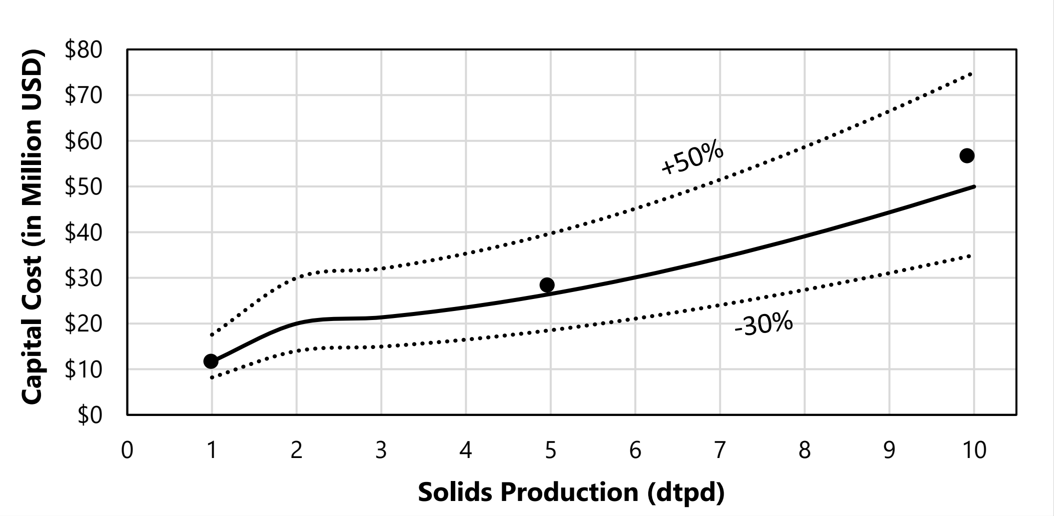


Figure 7-2 Capital cost curve for biosolids SCWO

The demonstration project for full-scale SCWO systems for biosolids is currently in construction, so minimal information is available on operation and maintenance costs for the full-scale operations. The SCWO manufacturer provided the predicted energy use for each unit size. The smallest SCWO systems are expected to consume 300 kWh of electricity per day. Larger SCWO systems that process over five dtpd or more are expected to produce electricity if paired with a generator. The annual O&M costs shown in Figure 7-3 include the electricity costs and savings, natural gas for startup, maintenance, materials, and labor.

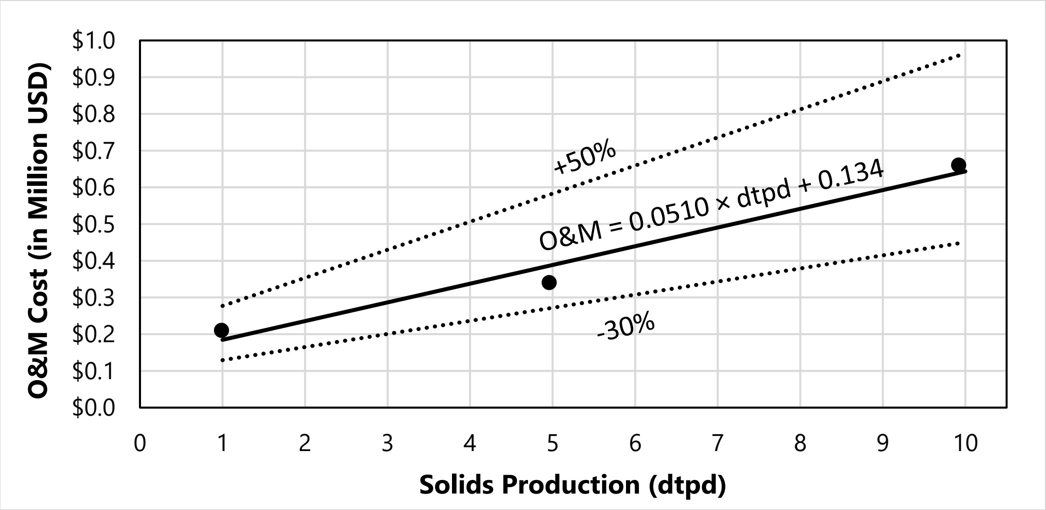


Figure 7-3 O&M cost curve for biosolids SCWO

Factors that influence the O&M costs include the heating value of the biosolids, oxidation potential, and savings from eliminating biosolids disposal costs. SCWO systems that run continuously offer energy savings by avoiding natural gas use for repeated startups; some have the potential to be energy-positive and electricity-producing.

Primary uncertainties for SCWO treatment of biosolids include the following:

- Documented commercial prototype performance with processing biosolids
- Reliability of continuous operation
- Technology robustness at a commercial scale
- Required maintenance and frequency of parts replacement
- Robustness against corrosion, plugging, and deposition of salts in the system components
- Performance of PFAS destruction at commercial scale
- Limited data available for comparing costs with conventional technologies

7.3.2 Pyrolysis/Gasification with Thermal Oxidation (Wastewater Biosolids)

As noted previously, gasification and pyrolysis are similar processes. They use similar equipment and process strategies, resulting in similar process outputs, and the costs for construction and operation are similar. Thus, both processes were evaluated as a single alternative for this study.

Pyrolysis or gasification of biosolids is a two-step process. First, dewatered biosolids at roughly 25% solids are dried to 75–90% solids in a biodryer or thermal dryer. The dried biosolids are then processed in the pyrolysis or gasification reactor unit. Literature indicates that gasification and pyrolysis reactors are operated at different temperatures. However, in practice, they are both operated at a wide range of temperatures that overlap. Gasification uses limited oxygen during operation, while pyrolysis uses no oxygen. Biochar from the pyrolyzer/gasifier is collected for beneficial use or disposal at a landfill and is documented to have non-detect PFAS. Biochar could potentially be used as a sorbent for PFAS in other waste streams, though full-scale application is limited. as discussed in more detail in Appendix B.

Pyrogas or syngas is generated from the process and contains PFAS compounds. If the gas is to be used for electricity production, it is routed to an oil/tar condenser to remove oil, tar, and other impurities. Oil and tar are routed directly to the thermal oxidizer, while the gas continues on to a scrubber before being used as generator fuel. Exhaust from the generator is returned to the thermal oxidizer and processed through the exhaust gas scrubber. If the gas is to be thermally oxidized for recoverable heat generation, oil/tar condensing and gas scrubbing upstream of the thermal oxidizer are unnecessary. Research to date has shown that PFAS are destroyed when the thermal oxidation temperature is above 1,000°C. Thermal oxidizer exhaust is processed through an additional exhaust scrubber before venting to the atmosphere. This process flow is summarized in Figure 7-4.

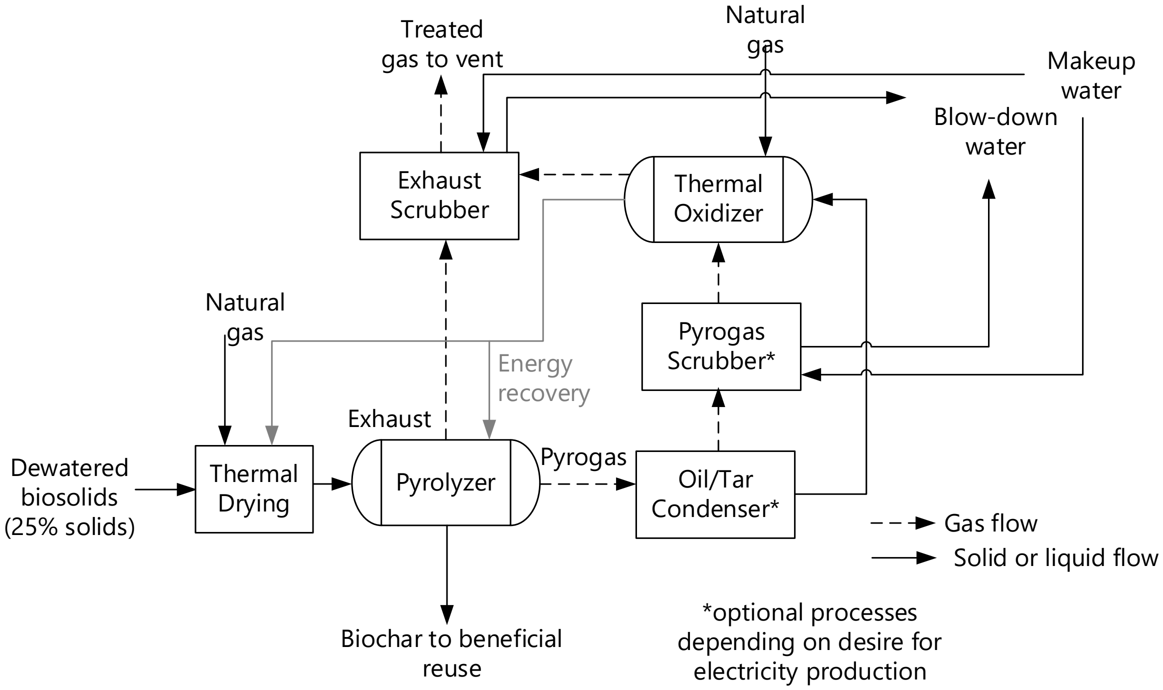


Figure 7-4 **Conceptual process flow diagram for biosolids pyrolysis/gasification with thermal oxidation**

The dryer and pyrolysis/gasification system can be provided as a complete equipment package by a single vendor. Alternatively, the pyrolysis/gasification unit can be supplied separately from the dryer if the WRRF already has a biosolids dryer. For this study, WRRFs were assumed to not have an existing biosolids dryer.

Selection of the pyrolysis/gasification system size is based on the dewatered biosolids feed rate. Continuous dryer and pyrolysis/gasification unit operation is recommended to minimize the demand for natural gas during the treatment startup process. Once the process reaches operating temperature, the energy in the biosolids may be sufficient to fuel the process without natural gas input. The minimum biosolids feed rate for autogenous (self-fueling) pyrolysis/gasification system operation is approximately 1 dtpd.

The dryer and pyrolysis/gasification units are typically separate unit processes connected by process piping. The vendor provides the connections for smaller systems. The system owner typically must provide the connections for the larger systems and the connection to the thermal oxidizer system. For all system sizes, a contractor will connect the biosolids feed piping, electrical and controls wiring, natural gas, and water to the treatment units. In cold-weather areas, the dryer and pyrolysis/gasification system would be enclosed within a climate-controlled building. In temperate climates, the system may be installed in a covered area but does not require full enclosure.

Development of the cost curve for biosolids pyrolysis/gasification systems was based on three recent pyrolysis/gasification system designs prepared for WRRFs producing 10 dtpd of biosolids or less. The primary design parameters are summarized in Table 7-6.

Table 7-6 Summary of design basis assumptions pyrolysis/gasification with thermal oxidation for biosolids

Design Parameter	Low	Mid	High
Dewatered biosolids load (dtpd)	2	6	10
Total solids (%TS)	25%	25%	25%
Evaporation rate (lb water/hour)	560	1,400	2,400
Number of dryers	1	1	1
Type of thermal dryer	Paddle	Paddle	Belt
Total solids of dried product (%TS)	90%	90%	90%
Pyrolysis/gasification unit capacity (dtpd each)	3	3	10
Number of pyrolysis/gasification units	1	2	1
Operating schedule	24 hours, 7 days/week		
Removal estimate for target PFAS	99.5%		

The resulting construction costs were plotted against the associated biosolids feed rate in dry tons per day, resulting in the cost curve shown in Figure 7-5. These costs do not include the pretreatment costs described in Section 7.5. Detailed cost tables are in Appendix E.

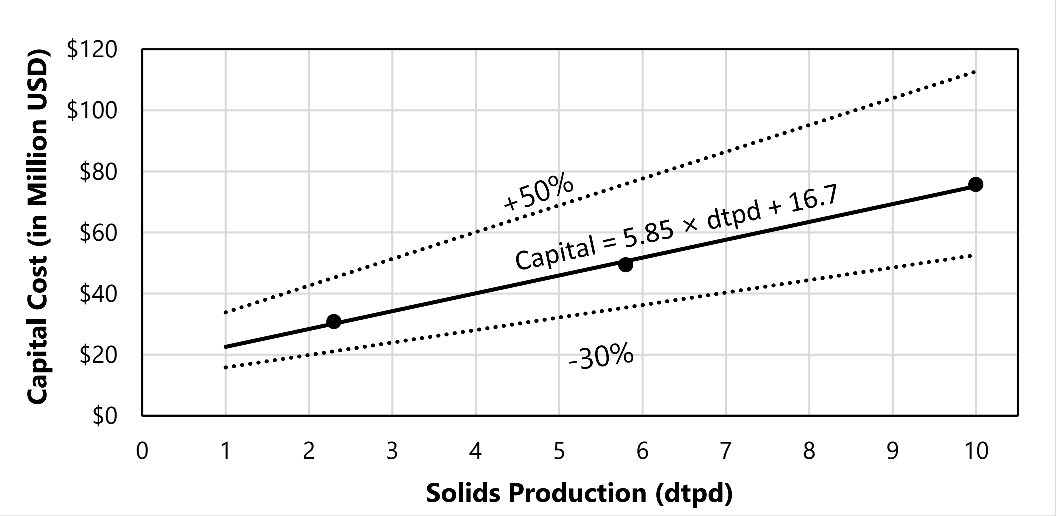


Figure 7-5 Capital cost curve for biosolids pyrolysis/gasification with thermal oxidation

Operation and maintenance costs for dryer and pyrolysis/gasification systems will vary depending on the type of dryer and pyrolysis/gasification unit selected. Recent O&M estimates prepared for pyrolysis/gasification system design projects were studied to develop a range of costs based on the dry tons per day of system capacity. The O&M costs included electricity, natural gas for startup, chemicals, operation labor, and maintenance materials. The annual O&M costs for small systems (up to 10 dtpd) are shown in Figure 7-6.

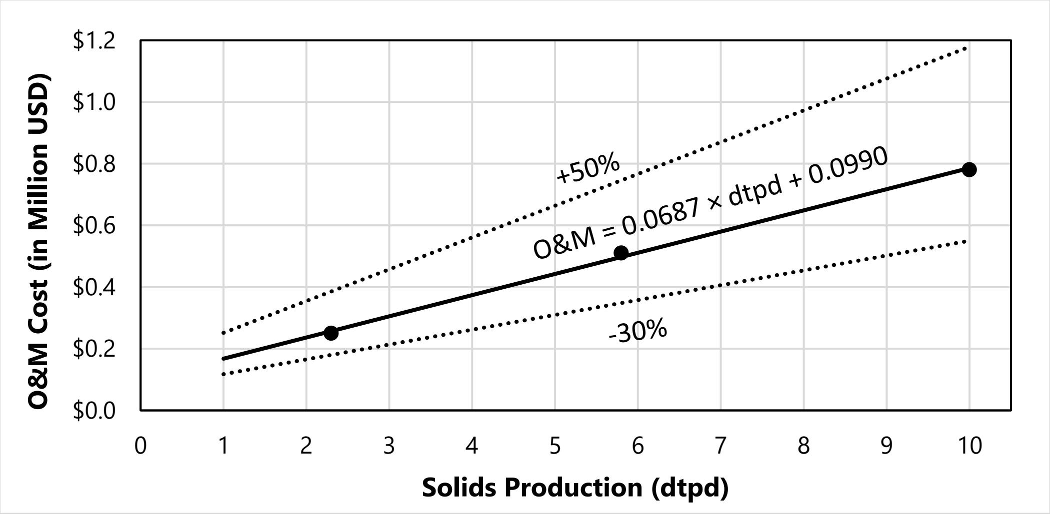


Figure 7-6 **O&M costs for biosolids pyrolysis/gasification with thermal oxidation**

Gasification and pyrolysis are well-established technologies for biowaste conversion to energy. However, using them for biosolids processing is emerging. There are several vendors commercially marketing various configurations of each process. The main obstacle these technologies need to overcome is the lack of a long-term, sustainable operation record. Other primary uncertainties for pyrolysis/gasification with thermal oxidation for biosolids include the following:

- Energy efficiency and balance, which is vendor-specific
- Documented destruction of PFAS during the process, mainly documenting PFAS destruction in the syngas at full-scale biosolids processing operations
- Required maintenance due to lack of long-term operating history of these systems
- Use and value of end products; the biochar market is not yet well developed

7.4 PFAS Removal Performance and Reliability

Both pyrolysis/gasification and SCWO are maturing processes with limited full-scale operations. However, various studies of PFAS in pyrolysis/gasification products (biochar) have shown non-detect PFAS concentrations (Davis 2020, Thoma et al. 2022). Limited data are available for the air phase from the pyrolysis/gasification; however, the process would be coupled with thermal oxidation, which has been shown to destroy PFAS at temperatures greater than 1,000°C. SCWO has been shown to destroy PFAS at a lab scale but does not have full-scale operational data (at the time this study was produced).

7.5 Example Pretreatment for PFAS Destruction Technologies Applied to Biosolids

The water content of stabilized biosolids must be reduced prior to any PFAS destruction alternatives for biosolids. The target solids percentage is dictated by the specific destruction technology. Water removed from the biosolids in dewatering and any equipment wash water would be collected and returned to the liquid wastewater treatment process.

7.5.1 Example Pretreatment for SCWO

Biosolids fed to a SCWO system must be dewatered to 12–15% total solids. Biosolids would also need to pass through a strain press upstream of dewatering to protect the SCWO unit from damage by grit, rags, or other non-sludge materials. Dewatering to this range could be achieved by any of several commercially available sludge dewatering technologies. For this study, a screw press was used to achieve a sludge concentration of 15% total solids.

The cost estimates developed in this Report for dewatering of anaerobically digested biosolids to produce 15% solids material for SCWO included the following additions:

- Biosolids storage and equalization tank
- Strain press feed pumps
- Strain press
- Screw press feed pumps
- Screw press(es)
- Dewatered biosolids pump or conveyor
- Polymer blending and feed system
- Ancillary systems, including:
    - Wash water supply
    - Ventilation for heating, cooling, and odor control
    - Supporting electrical, instrumentation, and controls
- Enclosed building
- Sitework

The number and size of major process equipment items needed will depend on the volume of biosolids produced at the WRRF and the frequency of biosolids processing. Some facilities may process biosolids on weekdays and only during a dayshift, whereas others may operate constantly. Redundancy requirements of major equipment items will depend on the facility's operating strategy. For this study, it was assumed that the pretreatment facility would constantly operate, with storage and equipment redundancy to support that operation. One spare strain press, screw press, dewatered biosolids conveyor, and polymer blending unit are included in the cost estimate. The Class 5 (AACE) cost curve (+100%/-50%) for capital costs for the dewatering system is provided in Figure 7-7.

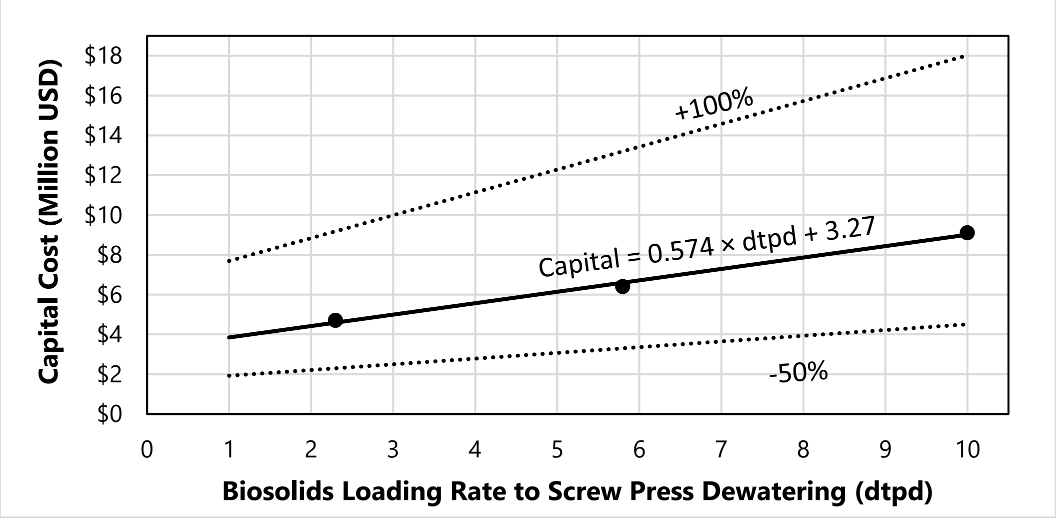


Figure 7-7 Capital cost curve for screw press dewatering to 15% solids for SCWO

7.5.2 Example Pretreatment for Pyrolysis/Gasification

Wastewater solids must be dried to reduce the water content prior to thermal drying and subsequent pyrolysis/gasification. Then the dried product is fed to the pyrolysis/gasification unit. Biosolids fed to a pyrolysis/gasification system should be dewatered as much as possible. Dewatering centrifuges are used to produce the driest dewatered biosolids compared to other biosolids dewatering technologies. Centrifuges can produce dewatered biosolids of 22%–30% total solids by mass, depending on the biosolids' characteristics and the polymer dose. For this study, dewatered biosolids were assumed to have 25% total solids.

The cost estimate of biosolids dewatering to 25% of total solids developed for this Report included the following additions:

- Dewatering feed pumps
- Dewatering centrifuge(s)
- Dewatered biosolids hopper
- Polymer blending and feed system
- Dewatered biosolids pump or conveyor
- Ancillary systems, including:
    - Wash water supply
    - Ventilation for heating, cooling, and odor control
    - Supporting electrical, instrumentation, and controls
- Enclosed building

- Sitework

The number and size of major process equipment items needed will depend on the mass and volume of biosolids produced at the WRRF and the frequency of biosolids processing. Some facilities may process biosolids on weekdays and only during a dayshift, whereas others may operate constantly. Redundancy requirements of major equipment items will depend on the facility's operating strategy. For this study, it was assumed that the pretreatment facility would constantly operate, with storage and equipment redundancy to support that operation. One spare dewatering centrifuge, dewatered biosolids conveyor, and polymer blending and feed unit are included in the cost estimate. The Class 5 (AACE) cost curve (+100%/-50%) for capital costs for the centrifuge dewatering system is provided in Figure 7-8.

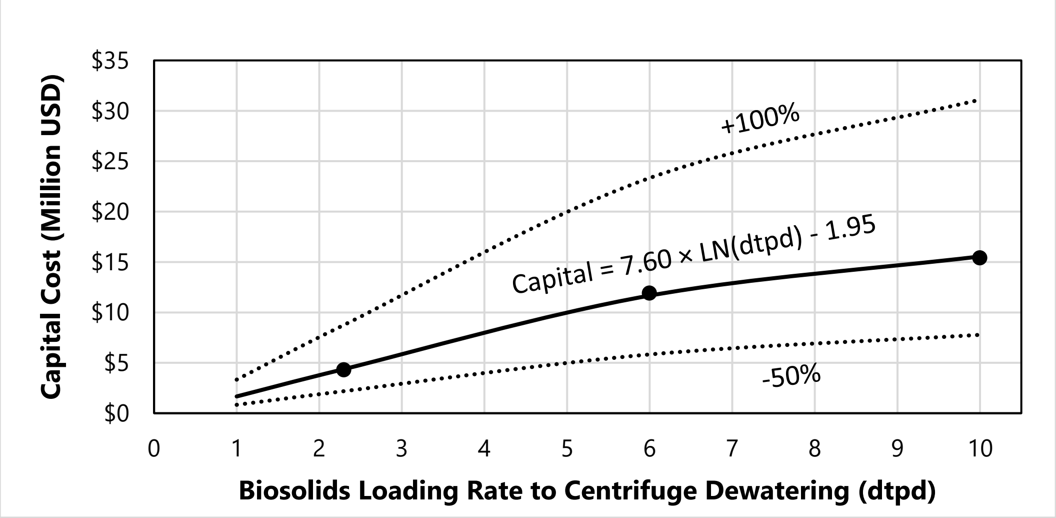


Figure 7-8 **Capital cost curve for dewatering to 25% solids for pyrolysis/gasification**

7.6 Other Considerations for Municipal Wastewater Biosolids

Treating biosolids with pyrolysis/gasification or SCWO would be a major shift away from the typical processing practices in Minnesota. Land application of Class B biosolids has been the common method of biosolids management for decades. Pyrolysis/gasification and SCWO produce a product of higher value than a Class B product. The solids drying step in the pyrolysis/gasification system produces a Class A product. Any biochar produced in the process could be land-applied as a Class A material. Operating a complex pyrolysis/gasification or SCWO system may be very challenging for some utilities. Utilities may also be concerned about the safety of these high-temperature and high-pressure systems, which may also require different operator training. Other considerations for destroying PFAS in biosolids include the following:

- The beneficial use of minerals remaining after SCWO or other management of resulting brine has not been determined. More work is needed to guide utilities to select end uses for the products of these treatment processes.

- Pyrolysis/gasification relies on intensive heat energy and does not require the presence of oxygen to "crack" or chemically decompose organic materials. Through heat application, pyrolysis/gasification disintegrates the long hydrocarbon bonds of the incoming feed materials. Pyrolysis/gasification generates not only tars, oils, and particulate matter but also reduced sulfur and nitrogen compounds and hazardous air pollutants, including polycyclic aromatic hydrocarbons. Hence, pyrolysis/gasification technologies are both subject to rules and regulations. The U.S. EPA is actively developing regulations under the Clean Air Act Section 129 pertaining to pyrolysis and gasification units used to convert solid and semi-solid feedstocks, including municipal sludge, to make useful products such as energy, fuels, and chemical commodities. The permitting of a new facility could take significant time; time frames can vary depending on the site.

8 Mixed MSW Landfill Leachate

8.1 Project Assumptions for Mixed MSW Landfill Leachate

8.1.1 Description and Scale of Required Treatment

Most MSW is managed in landfills (Kjeldsen et al. 2002). As of 2018, 63% of MSW was sent to landfills in the United States (U.S. EPA 2022b). Landfills generate leachate mainly from rainwater percolating through the waste layers in the landfill, both during operations and after closure. This leachate is generally collected for management, which can include recirculation for moisture compaction at the working face or within the waste mass, direct discharge to a WRRF, pretreatment with discharge to a WRRF, or land application. In Minnesota, mixed MSW landfills primarily discharge collected leachate to centralized municipal WRRFs for treatment or other waste management. Treatment options and cost curves for mixed MSW landfill leachate will be evaluated for facilities ranging from 1 gpm to 100 gpm, approximately 1/100th of the scale for municipal WRRF effluent considered in this study.

For this Report, the primary goal was to evaluate PFAS treatment alternatives for their ability to separate and mineralize PFAS from mixed MSW landfill leachate. The treated landfill leachate could still be sent to a WRRF for final treatment and disposal before discharging to surface water. However, in some cases, the treatment alternatives considered in this Report may sufficiently treat the landfill leachate to allow discharge to surface water instead of continuing to discharge to a WRRF. This should be evaluated on a site-specific basis.

8.1.2 PFAS Influent Concentrations and Treatment Targets

PFAS-containing products, like food packaging, clothing, and non-stick cookware, are the source of the PFAS in landfill leachate (Berg et al. 2022). Longer-chain PFAS commonly remain attached to solids within the landfill, while short-chain PFAS mobilize to the liquid leachate phase. As a result, landfill leachate is frequently enriched in short-chain PFCAs (Wei, Xu, and Zhao 2019). Other types of PFAS most relevant in mixed MSW landfill leachate are long-chain PFAAs, fluorotelomers, and precursors. Target PFAS selection was detailed in Section 2.3. Typical and high concentrations assumed as a design basis were developed from available literature and are shown in Table 8-1. These values are not intended to reflect the entire range of PFAS concentrations that may be present in all landfill leachates.

Table 8-1 Assumed influent concentrations and treatment goals for target PFAS for mixed MSW landfill leachate (all units in ng/L)

PFAS	Typical Concentrations[1]	High Concentrations[1]	Treatment Target
PFBA	950	2,600	5
PFBS	250	650	5
PFHxA	1,500	4,000	5
PFHxS	350	750	5
PFOA	900	1,900	5
PFOS	150	300	5
6:2 FTS	150	350	5
N-EtFOSAA	150	450	5

[1] Data from Lang et al.; 2017 data on 87 samples from 18 landfills across the U.S. Typical concentrations reflect the mean of 87 samples, and high concentrations reflect the 90th percentile of 87 samples. These target PFAS generally represented between 60% and 85% of the sum of PFAS analyzed. Values were rounded to the nearest 50 ng/L and two significant digits.

8.1.3 Water Quality Assumptions for Pretreated Mixed MSW Landfill Leachate Quality

Non-PFAS water quality parameters have significant implications for PFAS pretreatment and treatment of landfill leachate. The impacts of these water quality parameters are typically magnified in landfill leachate, considering its complexity and elevated concentrations, compared to WRRFs. For the pretreatment and cost analysis, it is essential to define non-PFAS parameters for landfill leachate.

Landfill leachate quality is highly variable and dependent on waste source, landfill age, and landfill type (Kjeldsen et al. 2002). In general, landfill leachate is a high-strength waste, with 20 to 57,000 mg/L of BOD_5 and 2,000 to 60,000 mg/L total solids (TS) (Kjeldsen et al. 2002). It also typically has higher concentrations of ammonia, salts, and organic carbon than municipal wastewater. Landfill leachate has a very low oxidation state, reflecting anaerobic conditions within the landfill. As a result, metals and nutrients are expected to be present in their most reduced forms (e.g., nitrogen present as ammonia and metals as dissolved metals).

Typical mixed MSW landfill leachate concentrations are listed in Table 8-2. This study chose two landfill leachate qualities for non-PFAS-related parameters meant to be representative of typical mixed MSW landfill leachate quality in Minnesota. The first landfill leachate quality is intended to represent raw mixed MSW landfill leachate for the alternatives not requiring pretreatment (Alternatives 8a and 8b). The second is for alternatives requiring pretreatment before PFAS removal (Alternatives 1a, 1b, 5a, 5b, and 7b). It reflects assumed water quality before PFAS separation technologies based on equipment fouling potential outlined previously in Section 5.2. One example of a pretreatment train and potential costs to provide this water quality at a landfill site is discussed in Section 8.5.

Table 8-2 Assumed initial and pretreated mixed MSW landfill leachate quality

Parameter	Units	Assumed Water Quality in Untreated Mixed MSW Landfill Leachate			Assumed Concentration in Pretreated Water (Influent for all Other PFAS Management Alts Evaluated)
		Typical Value (Assumed Influent Water Quality for Alt 8a and 8b)	Minimum Value[1]	Maximum Value[1]	
pH	SU	8[1]	4.5	9	8
TDS	mg/L	6,300[2]	Not reported	Not reported	6,300
TSS	mg/L	3,000[2]	2,000[3]	60,000[3]	1[4]
COD	mg/L	3,100[5]	140	152,000	90[6]
BOD$_5$	mg/L	850[5]	20	57,000	60[4]
TOC	mg/L	Not reported	30	29,000	2[4]
Alkalinity	mg/L as $CaCO_3$	6,900[2]	Not reported	Not reported	6,900
Chloride	mg/L	1,800[5]	150	4,500	1,800
Sulfate	mg/L	200[1]	Not reported	Not reported	200
Sodium	mg/L	1,600[5]	Not reported	Not reported	1,600
Potassium	mg/L	1,100[1]	Not reported	Not reported	1,100
Calcium	mg/L	110[1]	10	72,000	110
Magnesium	mg/L	150[1]	30	15,000	150
Ammonia	mg/L as N	1,200[1]	50	2,200	1,100[7]
Phosphorus	mg/L	10[1]	0.1	23	5[8]
Iron	µg/L	22,000[5]	3,000	5,500,000	0.1[4]
Manganese	µg/L	1,800[5]	30	1,400,000	0.1[4]

[1] Based on a landfill leachate review article (Kjeldsen et al. 2002).

[2] Provided by the MPCA.

[3] Kjeldsen et al. provides minimum and maximum concentrations for total solids, not TSS. The range of total solids is shown here.

[4] Based on the pretreatment discussion in Section 5.2.

[5] Based on Vermont landfill leachate study (Brown & Caldwell 2019).

[6] Based on expected BOD$_5$ reduction due to pretreatment.

[7] Ammonia is expected to decrease through biological pretreatment, however, a majority of the ammonia would remain due to the pH adjustment to prevent toxicity.

[8] Phosphorus is expected to decrease due to biological uptake.

8.2 PFAS Management Alternatives Evaluation Results

Each PFAS management alternative identified for water-phase PFAS separation and destruction in Section 4.1 was scored for each evaluation criterion described in Section 5.1 for mixed MSW landfill leachate.

8.2.1 Evaluation Scoring Results

Alternatives evaluated for mixed MSW landfill leachate, as described in Section 4.1, were:

- Alternative 1a: GAC sorption followed by off-site, high-temperature incineration of GAC

- Alternative 1b: RO membrane separation followed by GAC sorption of concentrate and off-site, high-temperature incineration of GAC
- Alternative 5a: modified clay media sorption followed by off-site, high-temperature incineration of modified clay
- Alternative 5b: RO membrane separation followed by modified clay media sorption of concentrate and off-site, high-temperature incineration of modified clay
- Alternative 7b: RO membrane separation followed by SCWO of concentrate
- Alternative 8a: foam fractionation followed by off-site, high-temperature incineration of foamate
- Alternative 8b: foam fractionation followed by SCWO of foamate

Evaluation results are summarized in Table 8-3 and described in subsequent sections. Specific criteria and subcriteria were previously defined in Section 5.1. Based on the screening, Alternatives 1a, 1b, 5a, and 8a were retained for preliminary design and cost curve development.

Table 8-3 Alternatives evaluation results for mixed MSW landfill leachate

Alternative Number		**1a**	**1b**	**5a**	**5b**	**7b**	**8a**	**8b**
Membrane separation technology		-	RO	-	RO	RO	FF	FF
PFAS sorption technology		GAC	GAC	MC	MC	-	-	-
PFAS destruction technology		**Inc**	**Inc**	**Inc**	**Inc**	**SCWO**	**Inc**	**SCWO**
Technical Feasibility	weight	*59*	*53*	*56*	*50*	*45*	*47*	*38*
PFAS separation efficiency	5	3	3	3	3	3	2	2
PFAS destruction efficiency	5	3	3	3	3	3	3	3
Degree of commercialization	3	3	3	2	2	1	2	1
Reliability of performance	2	1	1	1	1	3	2	2
Simplicity of operation/maintenance	4	3	2	3	2	1	2	1
Operator and public health	2	3	2	3	2	1	2	1
Economic Feasibility	**weight**	***46***	***41***	***41***	***36***	***26***	***40***	***34***
Relative capital costs	4	3	3	3	3	1	2	1
Relative operation and maintenance costs	3	3	2	3	2	1	2	3
Relative energy consumption	2	3	2	3	2	1	2	2
Relative complexity and cost of pretreatment	4	1	1	1	1	3	3	3
Applicability at scale	5	3	3	2	2	1	2	1
Byproducts Management	**weight**	***3***	***4***	***3***	***4***	***6***	***3***	***5***
Beneficial reuse opportunity for water or byproducts	1	1	2	1	2	2	1	1
Potential for media shifting of PFAS	2	1	1	1	1	2	1	2
Total Score		**108**	**98**	**100**	**90**	**77**	**93**	**74**
Retained?		**x**	**x**	**x**			**x**	

RO = RO membrane separation, GAC = granular activated carbon, MC = modified clay, Inc = high-temperature incineration, SCWO = supercritical water oxidation, FF = foam fractionation

8.2.2 Technical Feasibility

All sorption media alternatives evaluated received a score of 3 for **PFAS separation efficiency** because they were chosen to remove all target PFAS under selected operating conditions. While short-chain PFAS such as PFBA may break through quickly in these systems, treated water could potentially be kept below treatment targets given frequent monitoring and proactive changeout. RO/SCWO also received a score of 3 in this category because RO permeate and SCWO condensate routed to effluent are both expected to contain very low concentrations of PFAS. Alternatives with foam fractionation as the primary technology scored a 2 because foam fractionation is not currently effective at removing short-chain PFAS.

All alternatives received a score of 3 for **PFAS destruction efficiency** because both high-temperature incineration and SCWO remove 99% or more of PFAS. However, both have the potential for additional PFAS formation (Krause et al. 2022; L. Winchell et al. 2022). Additional research is needed for both these technologies to demonstrate the degree of mineralization achievable and the nature of byproducts formed.

Alternatives including combinations of RO membrane separation, GAC, and high-temperature incineration received a score of 3 for **degree of commercialization**. All of these technologies have been widely applied in multiple industries for PFAS removal. Alternatives including modified clay and foam fractionation received a score of 2 because they are commercially applied but in fewer industries. Alternatives including SCWO received a score of 1 because the technology is still developing for PFAS removal, especially in the water phase. It is currently limited to pilot-scale installations.

Sorption media received a score of 1 for **reliability of performance** because rapid breakthrough of short-chain PFAS could result in detectable concentrations in treated effluent, depending on monitoring frequency and mobilization time for changeout. Flow-rate variation in media vessel influent can also adversely affect the EBCT and associated mass transfer zone in sorption reactors, which can cause premature breakthrough. Alternatives with foam fractionation received a 2, with higher reliability for long-chain PFAS but low reliability for short-chain PFAS. RO/SCWO received a score of 3 because treatment efficiency is not impacted by changing water quality, flows, or environmental conditions.

Alternatives with sorption media combined with high-temperature incineration received the highest score of 3 for **simplicity of operation**. Alternatives with RO and media received a score of 2 due to the operational complexity of running an RO system, including system monitoring and membrane cleaning and replacement. Foam fractionation with high-temperature incineration received a score of 2 because it is expected that foam fractionation systems are more complex to operate than sorption media systems. Foam fractionation combined with SCWO received a score of 1 due to the complexity of operating both technologies.

Sorption media alternatives with high-temperature incineration received a score of 3 for **operator and public health** because there are minimal risks associated with these types of treatment and destruction technologies. Alternatives with RO/SCWO and foam fractionation with SCWO were scored a 1 due to the combined risks of high-temperature SCWO, high-pressure RO, and the PFAS volatilization potential associated with foam fractionation. All other alternatives received a score of 2 because although they are used in the industry, there is an increased risk to operators and public health due to one or more of the following: addition of chemicals, high operating temperatures, or high operating pressures.

8.2.3 Economic Feasibility

Alternatives that combine two high-energy technologies, like RO/SCWO and foam fractionation with SCWO have the highest **relative capital cost** and therefore received a score of 1. Foam fractionation with off-site, high-temperature incineration received a score of 2 due to lower on-site capital expenses. Alternatives with sorption media received a score of 3, reflecting the lowest relative capital cost. While using RO as a pre-concentration step adds capital costs, these are expected to be offset by the lower capital cost of media vessels treating only concentrate relative to alternatives with media vessels treating the full leachate flow.

When considering **relative O&M costs (without energy)**, alternatives with single-use media disposed of via high-temperature incineration received a score of 3, with primary O&M costs associated with transport and off-site incineration of sorption media. Sorption media alternatives with RO upstream received a score of 2 due to increased operational and maintenance costs of the added RO process. Foam fractionation is less expensive than RO and produces a lower volume of foamate than RO concentrate (higher recovery), resulting in lowered O&M costs and a score of 3 when paired with high-temperature incineration destruction and 2 with SCWO destruction. RO/SCWO is expected to have the highest operational costs and received a score of 1.

Sorption media without RO pre-concentration is expected to have the lowest **relative energy consumption**, with a score of 3. Each alternative with RO and sorption media for concentrate treatment and high-temperature incineration of the media scored a 2. RO/SCWO received a score of 1 due to the high energy required for the high temperatures and pressure needed to treat the full RO concentrate stream. Foam fractionation with SCWO scored a 2 due to the smaller waste stream routed to the SCWO feed. Foam fractionation with off-site high-temperature incineration also scored a 2, assuming similar energy use for SCWO and incineration of the same volume of liquid.

Alternatives using GAC, modified clay, or RO scored a 1 for **relative complexity and cost of pretreatment** because all would require pretreatment, as described in Section 8.1.38.5. Foam fractionation alternatives scored a 3 because they do not require complex pretreatment. RO/SCWO also scored a 3, assuming that specialty wide-spaced RO could be applied without pretreatment.

Applicability at scale was somewhat pre-screened as part of technology screening. GAC and RO membrane separation have been widely applied at the scale for landfill leachate treatment (1–100 gpm), so alternatives including only these separation technologies received a score of 3. Modified clay media sorption and foam fractionation have limited applications at this flow rate, and alternatives including these technologies received a score of 2. Alternatives with SCWO scored a 1 due to limited commercial application for PFAS management.

8.2.4 Byproducts Management

Alternatives with two opportunities for **beneficial reuse** of the treated waste stream or byproducts received a score of 3. Alternatives with one form of beneficial reuse received a score of 2. Alternatives with no potential beneficial reuse received a score of 1. For mixed MSW landfill leachate, no alternatives included two opportunities for reuse, and the highest score was a 2. The one example of reuse was for alternatives with RO, which produces RO permeate that could be reused on-site at the landfill (i.e., for dust control or compaction).

All alternatives with high-temperature incineration received a score of 1 for **potential media shifting of PFAS.** This is due to the current uncertainty and ongoing industry research investigating PFAS transformations and emissions associated with high-temperature incineration. Alternatives with SCWO destruction received a score of 2 because the possibility of PFAS media shifting is unknown.

8.2.5 PFAS Management Alternatives for Preliminary Design

Based on the screening described in Section 8.2, four PFAS management alternatives were carried forward to preliminary design and cost analysis for mixed MSW landfill leachate:

- Alternative 1a: GAC sorption followed by off-site, high-temperature incineration of GAC
- Alternative 1b: RO membrane separation followed by GAC sorption of concentrate and off-site, high-temperature incineration of GAC
- Alternative 5a: modified clay media sorption followed by off-site, high-temperature incineration of modified clay
- Alternative 8a: foam fractionation followed by off-site, high-temperature incineration of foamate

8.3 Alternative Preliminary Design and Cost Curve Development

8.3.1 Alternative 1a (Landfill Leachate)

For Alternative 1a, pretreated mixed MSW landfill leachate meeting the water quality listed in Table 8-2 flows directly to lead-lag GAC adsorption pressure vessels. Once GAC media is exhausted with respect to target PFAS (limited by PFBA and PFBS in this case), it would be sent to high-temperature incineration because the flows of landfill leachate considered in this Report would not meet the GAC volume required for site-specific reactivation. This process flow is summarized in Figure 8-1.

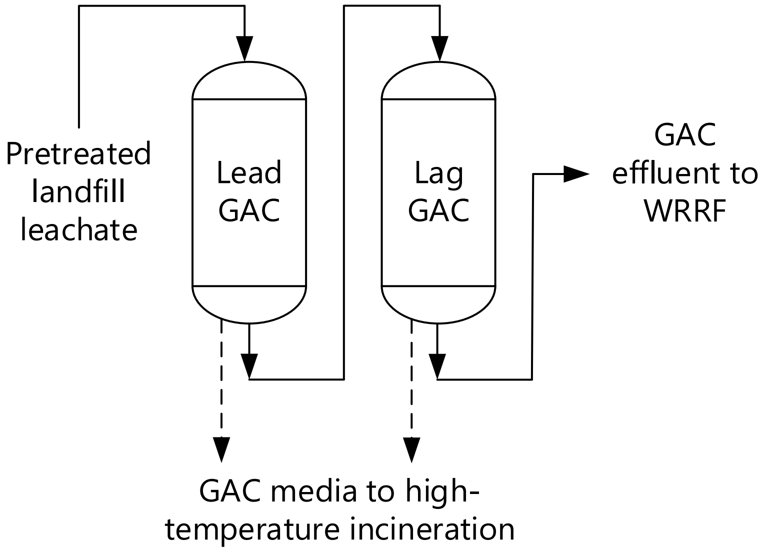


Figure 8-1 Conceptual process flow diagram for Alternative 1a for landfill leachate

Key design basis assumptions for Alternative 1a are listed in Table 8-4, with a detailed design basis in Appendix E.

Table 8-4 Summary of design basis assumptions for Alternative 1a for landfill leachate

Design Parameter	Basis		
	0.0014 MGD/1 gpm	0.014 MGD/10 gpm	0.14 MGD/100 gpm
Vessel capacity (lb GAC)	90	750	10,000
Number of trains	2	1	1
Number of vessels	4	2	2
EBCT per vessel (min)	15	15	15
HLR (gpm/sq. ft)	0.5	3.2	2.0
Estimated bed volumes to breakthrough[1]	5,100	5,100	5,100
GAC disposal route	High-temperature incineration	High-temperature incineration	High-temperature incineration

[1] Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L. Described further in Section 5.3.4 and Appendix D.

Figure 8-2 and Figure 8-3 illustrate estimated capital and annual O&M costs for a range of influent flow rates. These costs do not include pretreatment costs described in Section 8.5. Detailed capital and O&M cost estimates are in Appendix E.

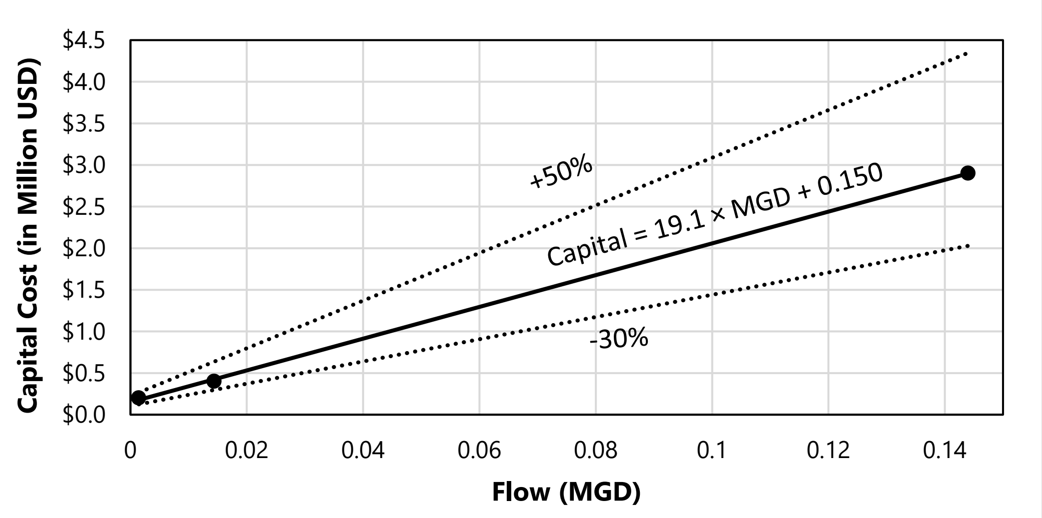


Figure 8-2 Capital cost curve for Alternative 1a for landfill leachate

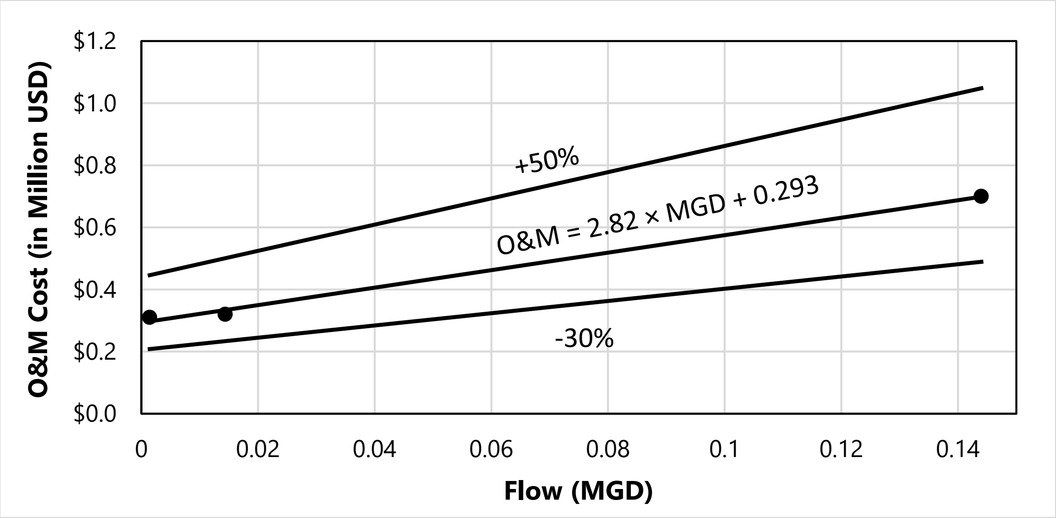


Figure 8-3 **O&M cost curve for Alternative 1a for landfill leachate**

Estimated annual O&M costs are similar to estimated capital costs at low flows but approximately one-quarter of estimated capital costs at higher flows. The highest operating costs are associated with labor and sorption media replacement and incineration.

Primary uncertainties for Alternative 1a for landfill leachate treatment include the following:

- Actual GAC breakthrough timing and requirements, depending on actual pretreated water quality
- Potential for GAC fouling limiting bed life over PFAS breakthrough
- Pretreatment processes needed and ability to meet pretreatment targets
- Location and incineration fees of a selected high-temperature incineration facility
- The capital costs for the lowest flow rates may change depending on facility preference for operational flexibility. The vessels included in this analysis are relatively small such that a typical valve tree included with larger vessels is not standard and was not included.

8.3.2 Alternative 1b (Landfill Leachate)

Alternative 1b includes GAC sorption, as previously described for Alternative 1a, with the addition of an RO membrane pre-concentration step. Pretreated mixed MSW landfill leachate meeting the water quality listed in Table 8-2 is routed directly to RO membranes. The RO concentrate flows to lead-lag GAC adsorption pressure vessels. RO permeate and GAC effluent would be combined and sent to a WRRF. Once GAC media is exhausted with respect to target PFAS (limited by PFBA and PFBS in this case), it would be sent to high-temperature incineration. This process flow is summarized in Figure 8-4.

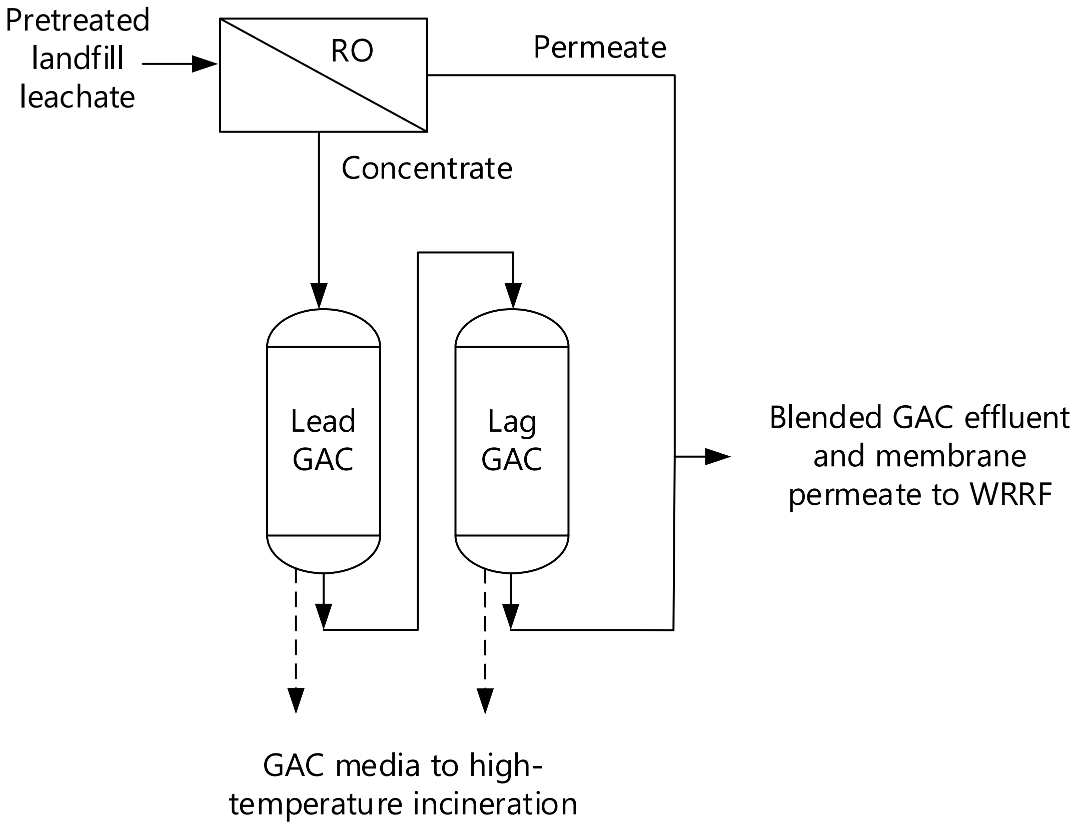


Figure 8-4 **Conceptual process flow diagram for Alternative 1b for landfill leachate**

Key design basis assumptions for Alternative 1b are listed in Table 8-5, with a detailed design basis in Appendix E.

Table 8-5 **Summary of design basis assumptions for Alternative 1b for landfill leachate**

Design Parameter	Basis		
	0.0014 MGD/1 gpm	0.014 MGD/10 gpm	0.14 MGD/100 gpm
	RO		
Recovery (%)	65	65	65
Flux (gal./sq. ft/day)	16	16	16
	GAC		
Vessel capacity (lb GAC)	90	250	2,000
Number of trains	2	2	2
Number of vessels	4	4	4
EBCT per vessel (min)	15	15	15
HLR (gpm/sq. ft)	0.5	0.6	1.0
Estimated bed volumes to breakthrough[1]	3,600	3,600	3,600
GAC disposal route	High-temperature incineration	High-temperature incineration	High-temperature incineration

[1] Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L. Described further in Section 5.3.4 and Appendix D.

Figure 8-5 and Figure 8-6 illustrate estimated capital and annual O&M costs for a range of influent flow rates. These costs do not include pretreatment costs described in Section 8.5. Detailed capital and O&M cost estimates are in Appendix E.

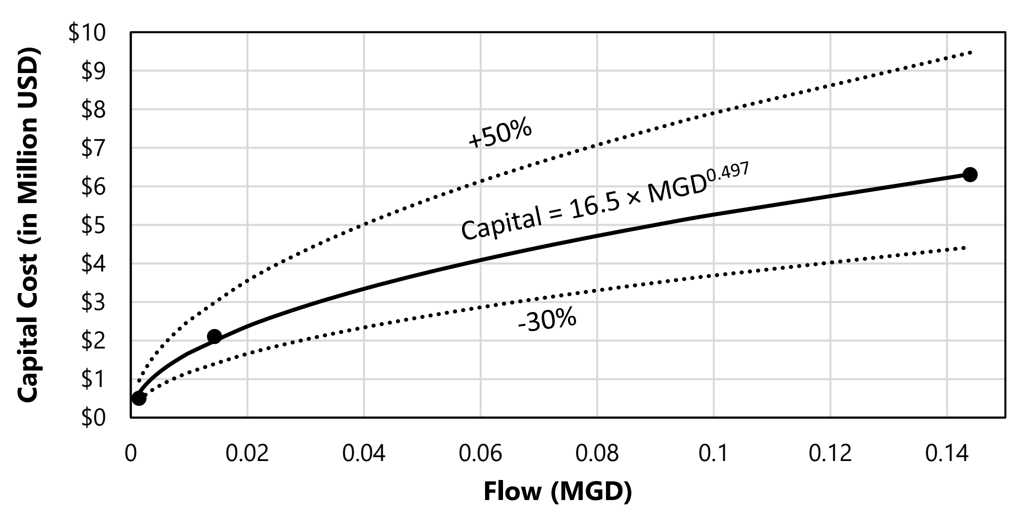


Figure 8-5 **Capital cost curve for Alternative 1b for landfill leachate**

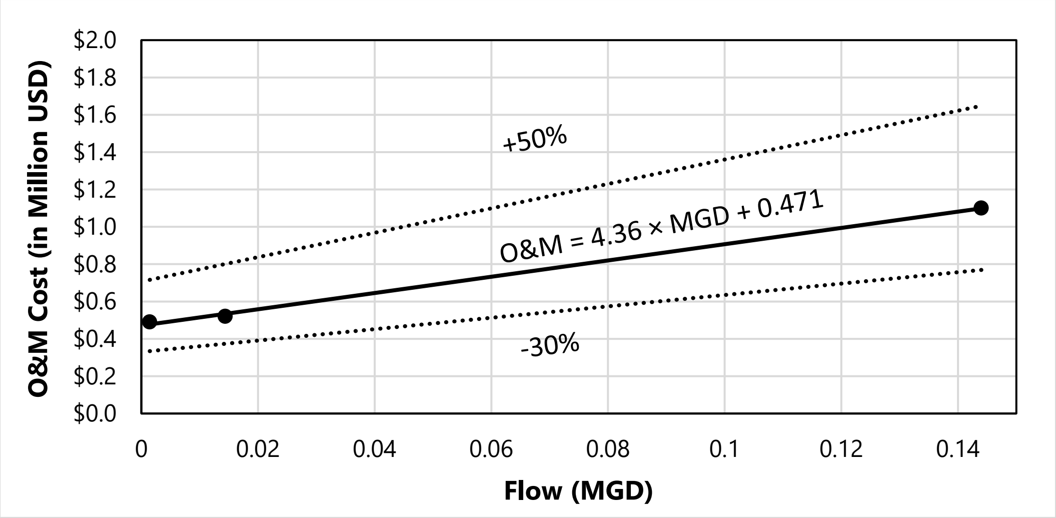


Figure 8-6 O&M cost curve for Alternative 1b for landfill leachate

Estimated capital costs are approximately twice those for Alternative 1a, and O&M costs are approximately one-and-a-half times those for Alternative 1a. The highest operating costs are associated with utilities, labor, and sorption media replacement and incineration.

Primary uncertainties for Alternative 1b for landfill leachate treatment include the following:

- Achievable recovery of RO membranes and associated energy usage
- Fouling potential of RO membranes, depending on actual pretreated water quality
- Actual GAC breakthrough timing and requirements, depending on actual pretreated water quality
- Potential for GAC fouling limiting bed life over PFAS breakthrough
- Pretreatment processes needed and ability to meet pretreatment targets
- Location and incineration fees of selected high-temperature incineration facility
- The capital costs for the lowest flow rates may change depending on facility preference for operational flexibility. The vessels included in this analysis are relatively small such that a typical valve tree included with larger vessels is not standard and was not included.

8.3.3 Alternative 5a (Landfill Leachate)

For Alternative 5a, pretreated mixed MSW landfill leachate meeting the water quality listed in Table 8-2 flows directly to lead-lag modified clay adsorption pressure vessels. Once modified clay media is exhausted with respect to the target PFAS (likely limited by breakthrough of short-chain PFAS), the spent media is sent to high-temperature incineration. This process flow is summarized in Figure 8-7.

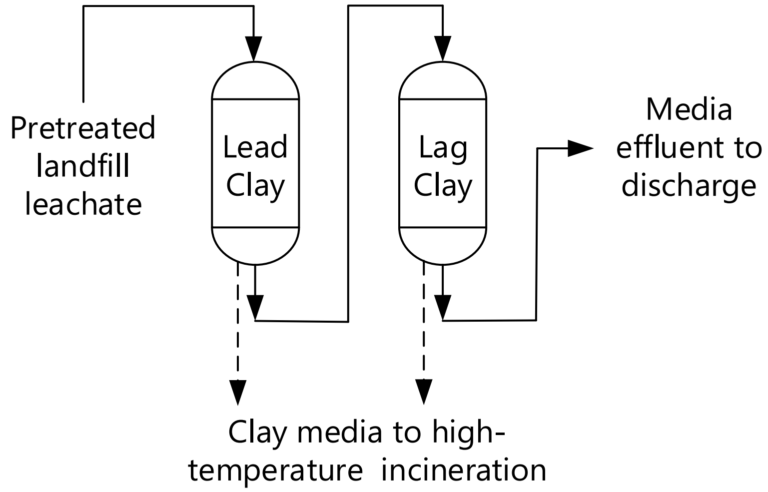


Figure 8-7 **Conceptual process flow diagram for Alternative 5a for landfill leachate**

Key design basis assumptions for Alternative 5a are listed in Table 8-6, with a detailed design basis in Appendix E.

Table 8-6 **Summary of design basis assumptions for Alternative 5a for landfill leachate**

Design Parameter	Basis		
	0.0014 MGD/1 gpm	0.014 MGD/10 gpm	0.14 MGD/100 gpm
Vessel capacity (cu. ft media)	3	5	40
Number of trains	1	3	4
Number of vessels	2	6	8
EBCT per vessel (min)	10	10	10
HLR (gpm/sq. ft)	0.9	1.9	3.5
Estimated bed volumes to breakthrough[1]	5,000	5,000	5,000
Media disposal route	High-temperature incineration	High-temperature incineration	High-temperature incineration

[1] Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L. Described further in Section 5.3.4 and Appendix D.

Figure 8-8 and Figure 8-9 illustrate estimated capital and annual O&M costs for a range of influent flow rates. These costs do not include pretreatment costs described in Section 8.5. Detailed capital and O&M cost estimates are in Appendix E.

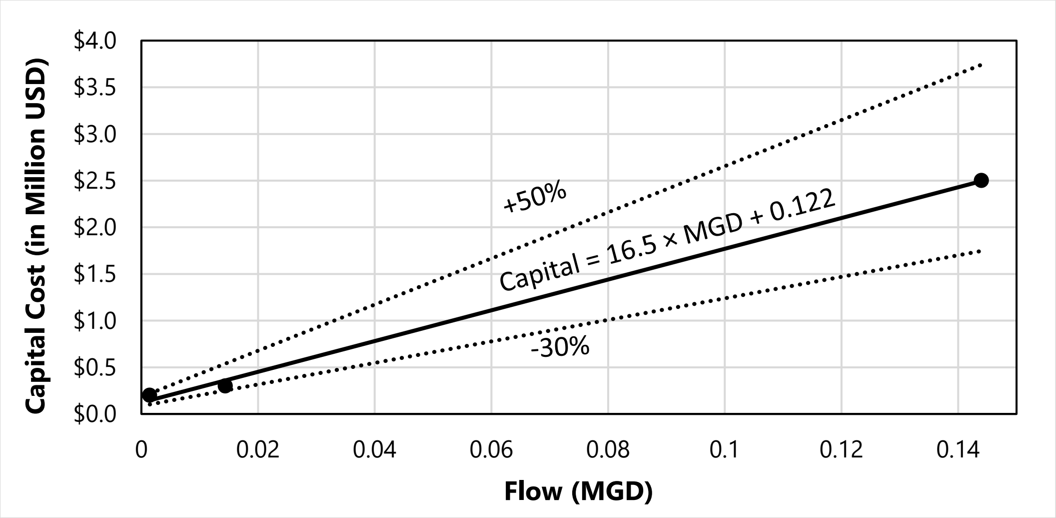


Figure 8-8 **Capital cost curve for Alternative 5a for landfill leachate**

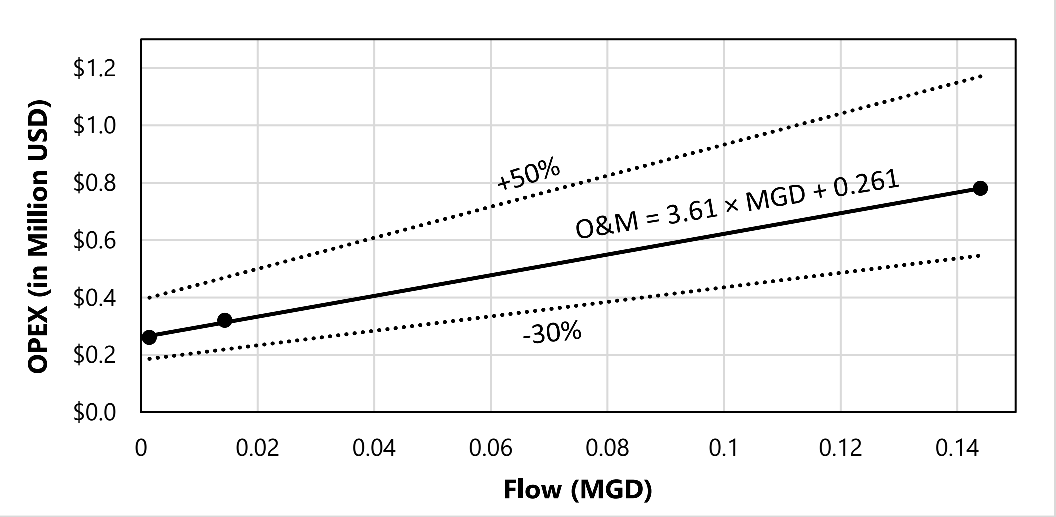


Figure 8-9 **O&M cost curve for Alternative 5a for landfill leachate**

Estimated annual O&M costs and estimated capital costs for Alternative 5a are similar to estimated costs for Alternative 1a. The highest operating costs for 5a are associated with labor and sorption media replacement and incineration.

Primary uncertainties for Alternative 5a for landfill leachate treatment include the following:

- Actual PFAS breakthrough timing through modified clay media, depending on media performance and actual pretreated water quality
- Potential for modified clay fouling to limit bed life over PFAS breakthrough
- Pretreatment processes needed and ability to meet pretreatment targets
- Location and incineration fees of a selected high-temperature incineration facility

- The capital costs for the lowest flow rates may change depending on facility preference for operational flexibility. The vessels in this analysis are relatively small such that a typical valve tree included with larger vessels is not standard and was not included.

8.3.4 Alternative 8a (Landfill Leachate)

For Alternative 8a, mixed MSW landfill leachate would be pumped to a series of foam fractionation vessels. The contact water initially goes through a bag filter to remove suspended solids, avoiding solids buildup in the foam fractionation vessels. The foam generated from the primary foam fractionation vessel is further enriched in a secondary foam fractionation vessel. The air that generates the foam in the closed foam fractionation vessel is discharged to carbon canisters to capture volatile organics. The resulting foam is collected and transported to a high-temperature incineration facility for destruction. This process flow is summarized in Figure 8-10.

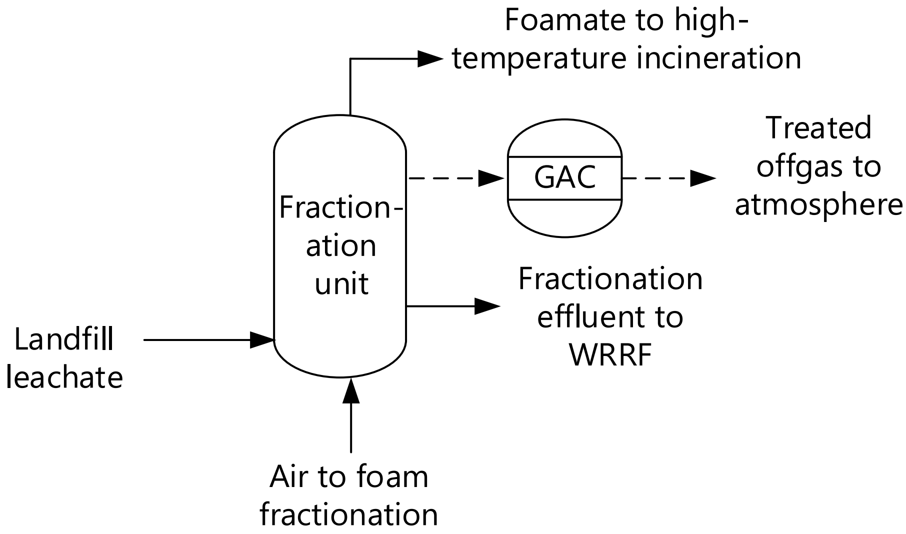


Figure 8-10 **Conceptual process flow diagram for Alternative 8a for landfill leachate**

Key design basis assumptions for Alternative 8a are listed in Table 8-7, with a detailed design basis in Appendix E.

Table 8-7 Summary of design basis assumptions for Alternative 8a for landfill leachate

Design Parameter	Basis		
	0.0014 MGD/1 gpm	0.014 MGD/10 gpm	0.14 MGD/100 gpm
Number of primary vessels	2	2	4
Number of secondary vessels	1	1	2
Assumed concentration factor[1]	1,000,000	1,000,000	1,000,000
Expected foamate flow rate (gpd)	0.0014	0.014	0.14

[1] Based on vendor input.

Figure 8-11 and Figure 8-12 illustrate estimated capital and annual O&M costs for a range of influent flow rates. Detailed capital and O&M cost estimates are in Appendix E.

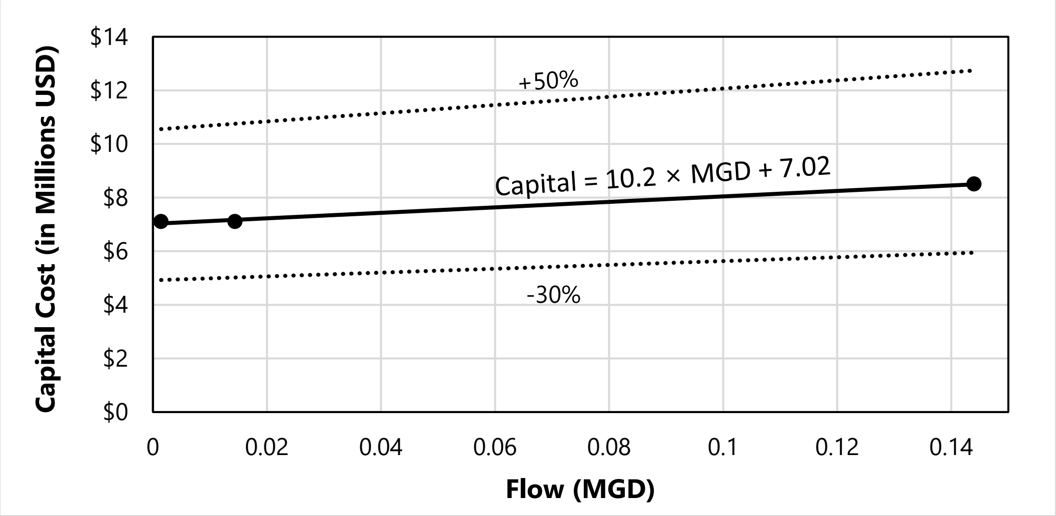


Figure 8-11 Capital cost curve for Alternative 8a for landfill leachate

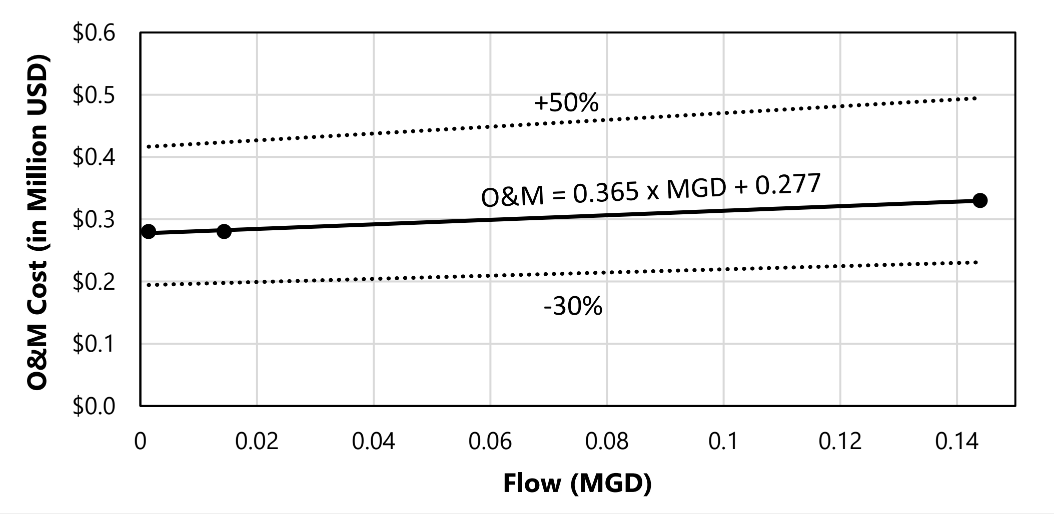


Figure 8-12 **O&M cost curve for Alternative 8a for landfill leachate**

Estimated annual O&M costs are approximately one order of magnitude lower than the estimated capital costs. The highest operating costs are associated with utilities, maintenance, and labor. The capital costs are an order of magnitude higher than Alternative 1a for the low and middle flow rates but the same order of magnitude for the high flow rate. The O&M costs are similar to those for Alternative 1a. However, unlike Alternative 1a, there are no O&M costs associated with pretreatment for Alternative 8a. Although pretreatment O&M costs were not considered in this report, long-term O&M may cost less for Alternative 8a and should be evaluated on a site-specific basis.

Primary uncertainties for Alternative 8a for landfill leachate treatment include the following:

- Actual concentrating factor of the foam (assumed to be 1,000,000)
- The removal efficiency of short-chain PFAS (such as PFBA) and the potential usage rate of cationic surfactants or enhancements to improve the removal efficiency. Polishing treatment (such as media sorption) on the treated water stream from foam fractionation may be needed to achieve the PFAS performance targets of this study. This would increase the capital and O&M cost estimates provided above.
- Location and incineration fees of a selected high-temperature incineration facility

8.4 PFAS Removal Performance and Reliability

The relative ability of each alternative to meet treatment goals of <5 ng/L for target PFAS is summarized in Table 8-8. Including RO with GAC (Alternative 1a versus 1b) has limited effect on PFAS removal because the PFAS removal mechanism is the same GAC adsorption process. Currently, it is uncertain if foam fractionation (Alternative 8a) can remove 90% of short-chain PFAS. If not, this would result in pass-through of PFAS such as PFBA, PFBS, PFHxA, and possibly others into the treated water phase at concentrations higher than the 5 ng/L target. Specific references for PFAS removal efficiency are detailed further in Appendix C.

Table 8-8 PFAS removal performance and reliability for mixed MSW landfill leachate alternatives

Target PFAS	Assumed Influent Concentration (ng/L)	Percent Removal to Achieve <5 ng/L	Relative Ability to Consistently Meet Targets			
			1a: GAC	1b: RO/GAC	5a: Modified Clay	8a: Foam Fractionation with Incineration
PFBA	950	>99%	Moderate	Moderate	Moderate	Low
PFBS	250	98%	Moderate	Moderate	Moderate	Low
PFHxA	1,500	>99%	Moderate	High	Moderate	Moderate
PFHxS	350	99%	High	High	High	High
PFOA	900	>99%	High	High	High	High
PFOS	150	97%	High	High	High	High
6:2 FTS	150	97%	High	High	High	High
N-EtFOSAA	150	97%	High	High	High	High

8.5 Example Pretreatment for PFAS Separation Technologies Applied to Mixed MSW Landfill Leachate

Minnesota currently has no landfills with permanent, full-scale leachate treatment beyond settling and equalization. Therefore, we expect most landfills implementing PFAS management alternatives will require significant pretreatment prior to PFAS separation and destruction.

Biological and filtration processes are required to achieve the TOC and TSS pretreatment goals required for Alternatives 1a and 1b to limit the fouling of downstream processes, as described in Section 5.2. One challenge with biological treatment in the case of landfill leachate is the potential for ammonia toxicity. For a biological process to effectively remove the BOD_5 in landfill leachate, the free ammonia concentration in the leachate needs to be lower than 30–50 mg NH_3-N/L through ammonia removal or acidification to convert all ammonia to the less toxic ionized form (Kim et al. 2008). At raw landfill leachate concentrations and pH (8 STU), free ammonia would be toxic to the aerobic treatment microbes. As a result, acid can be added to reduce pH and associated toxicity or raise the pH and strip out the ammonia ahead of biological treatment.

One potential pretreatment train for landfill leachate would include aeration for iron oxidation to the particulate form followed by a clarifier to remove oxidized iron and TSS. After settling, the pH would be adjusted down to drive the ammonia speciation to ammonium and prevent toxicity but not low enough to prevent pH inhibition. After pH adjustment, the water would flow through an MBR for TOC, BOD_5, and TSS removal.

MBR systems require consistent flows to maintain healthy biomass. Because landfill leachate flows are variable and dependent on precipitation, the treatment system will need sufficient flow equalization to maintain continuous flow during dry periods (e.g., summer and winter). It is assumed that existing landfill infrastructure could be used for flow equalization, with minor modifications as necessary. Thus, construction costs for equalization basins are not included in the capital costs shown below. If sufficient flow equalization is not practical for a specific facility, alternative treatment could be evaluated instead of MBR treatment that could be operated as needed (i.e., batch-wise).

The example conceptual process flow and capital cost estimates for mixed MSW landfill leachate pretreatment for PFAS removal are assumed to include the following:

- Aeration—to oxidize iron
- Chemical precipitation and sedimentation—to remove oxidized iron, a fraction of the TOC, and fine suspended solids
- Acid addition—to lower pH and prevent unionized ammonia toxicity during biological treatment
- MBR—to remove BOD_5, TOC, and residual suspended solids

The conceptual pretreatment process flow is shown in Figure 8-13.

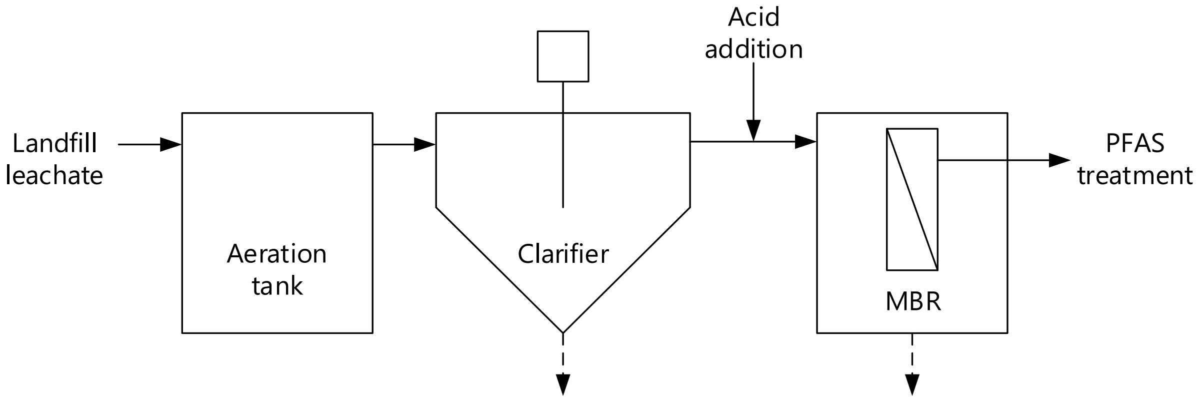
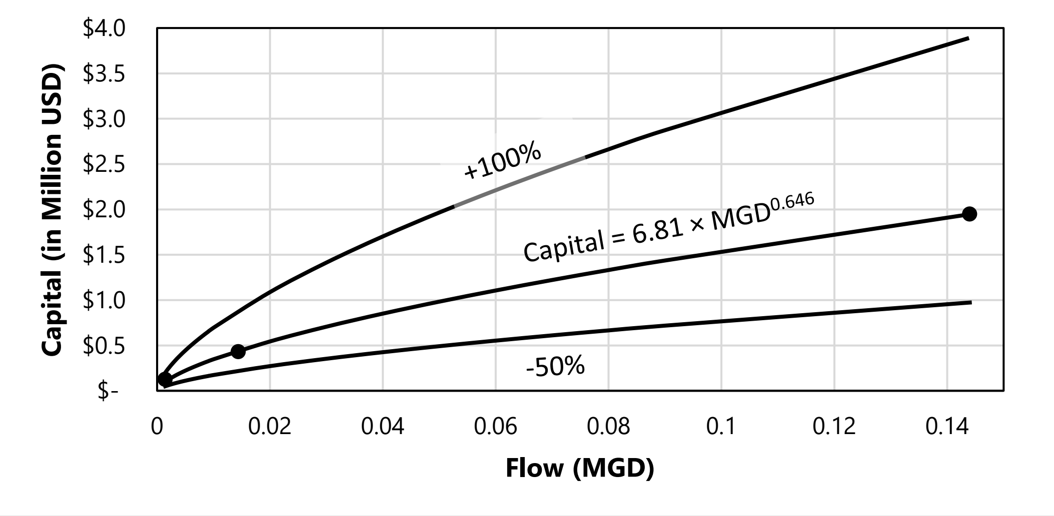


Figure 8-13 Conceptual process flow diagram for landfill leachate pretreatment

The pretreatment approach and estimated costs are meant to reflect one example but will not be appropriate for all systems. The evaluation and selection of a pretreatment system should be completed specifically for each individual site looking to implement a PFAS management approach. For example, this pretreatment example assumes relatively constant leachate flow, which might not be the case for each site. This Report evaluates the use of a clarifier for particulate iron and solids removal instead of a pond. This enables estimation of a conservative pretreatment cost due to the clarifier and associated equipment costs and the increased building footprint. If a pond exists on site that could be repurposed for solids removal, the pretreatment cost could be lower than estimated here. An additional consideration not included in this evaluation is air controls for potential volatilization of PFAS in the pretreatment units.

Capital cost estimates for this pretreatment train are shown in MBR costs from Lo, McAdam, and Judd (2015). Other equipment costs estimated from CapdetWorks (Hydromantis, v4.0). The solid line reflects the estimated cost curve. The dashed lines reflect the
+100%/-50% accuracy range. All costs scaled to November 2022 using ENR CCI (13175).

Figure 8-14. Costs are Class 5 (AACE) cost estimates with an accuracy range of +100%/-50%. This cost curve should only be used for the flow range shown (1–100 gpm; 0.0014–0.14 MGD).



MBR costs from Lo, McAdam, and Judd (2015). Other equipment costs estimated from CapdetWorks (Hydromantis, v4.0). The solid line reflects the estimated cost curve. The dashed lines reflect the +100%/-50% accuracy range. All costs scaled to November 2022 using ENR CCI (13175).

Figure 8-14 Capital cost curve for new MBR installations with pre-aeration, sedimentation, and chemical addition for landfill leachate pretreatment

The conceptual pretreatment cost estimates did not include a detailed feasibility study or any design for site-specific requirements. Pretreatment needs are expected to vary by facility due to differences in existing infrastructure, water quality, space availability, and other site-specific constraints. Thus, the degree of detail included in this Report for pretreatment is less than that provided for PFAS treatment alternatives in subsequent sections. The conceptual pretreatment costs shown are intended to provide an order-of-magnitude estimate for potential pretreatment costs. **Facilities looking to implement PFAS treatment should conduct site-specific treatment evaluations prior to capital planning or implementation.**

8.6 Other Considerations for Mixed MSW Landfill Leachate

The PFAS management alternative most appropriate for a given site will depend on space constraints, initial water quality, operational and treatment targets, and permit conditions. Sites targeting only long-chain PFAS will likely find foam fractionation (as included in Alternative 8a) the most cost-effective separation technology because it does not require pretreatment. However, foam fractionation’s efficacy for separating short-chain PFAS remains limited at this time. Large landfills with short-chain removal requirements and space constraints may benefit from using conventional RO (with appropriate pretreatment) or specialty wide-spaced RO (as included in Alternative 1b) as a pre-concentration step before media sorption vessels for concentrate management. Modified clay media (Alternative 5a) are still being vetted as a sorption media for PFAS separation and may have specific advantages over GAC (Alternative 1a), such as lower capital cost and footprint.

The decision to select one of these alternatives and implement them on-site will vary site by site and based on the PFAS management strategy of the WRRF receiving the mixed MSW landfill leachate discharge. PFAS management strategies for landfill leachate should consider if on-site treatment is necessary. For example, if a downstream WRRF is implementing PFAS treatment, it may not make sense to also implement PFAS treatment at a landfill. Other considerations for removing and destroying PFAS from landfill leachate include the following:

- Off-site treatment at a regional facility may be the preferred alternative, depending on the flow and the proximity to a regional facility. If on-site treatment is selected, the feasibility of treatment to surface water standards with direct discharge should also be considered.
- Depending on the landfill leachate strength, leachate treatment with SCWO could be more favorable than for the design landfill leachate considered in this Report. Landfill leachate containing higher-strength organics may require less co-fuel when using SCWO, which could lower the operating costs for this technology. Additionally, landfill gas could be captured and cleaned to use as a co-fuel source if compressed to a liquid to potentially reduce operating costs.
- Media shifting should be evaluated, particularly when using pretreatment with aeration. Aeration may cause PFAS volatilization and result in surface deposition of PFAS. Any treatment, including aeration, should consider air pollution control strategies to prevent media shifting and contamination due to airborne PFAS.
- In addition to the technologies included in this alternatives analysis, there are a few technologies currently available at the pilot scale that might be amenable to PFAS treatment without pretreatment. Advanced electrochemical oxidation and HALT treatment, depending on performance in pilot-scale tests and ultimate costs, may be other beneficial technologies to consider for treatment of landfill leachate.

9 Compost Contact Water

9.1 Project Assumptions for Compost Contact Water

9.1.1 Description and Scale of Required Treatment

Compost contact water (also known as compost leachate) originates from precipitation runoff from active compost areas, moisture associated with source compost materials, and water added to maintain specific moisture contents during the composting process (Krogmann and Woyczechowski 2000). Minnesota administrative rules part 7035.2836 defines contact water from commercial composting facilities as:

> *[W]ater that has come into contact with source-separated organic material in the tipping area, source-separated organic material in the mixing area, rejects, residuals, or active compost.*

Water originating from curing or finished storage areas at composting facilities is considered stormwater (different from the definition of contact water) under Minnesota rules. It is managed with other site stormwater under industrial stormwater permits.

Compost contact water must be collected in lined ponds and managed according to Minnesota administrative rules part 7035.2815, subpart 9, which defines design and construction criteria for solid waste leachate collection systems.

This study addresses compost contact water from source-separated organic material (SSOM) facilities that accept both food and yard waste, including compostable packaging. Nine commercial SSOM composting facilities are permitted to accept food waste in Minnesota (Minnesota Pollution Control Agency 2022). Currently, no commercial composting facilities in Minnesota have active treatment systems for contact water. Instead, contact water is transported to local WRRFs for treatment on an as-needed basis, depending on the capacity of the on-site collection ponds.

Because compost contact water is partly dependent on precipitation, water generation is seasonal and depends on the size of a facility and the volume of precipitation received. Alternatives developed in this study for compost contact water treatment assume that generation for a given facility varies between 1–100 gpm (0.0014–0.14 MGD) based on typical compost contact water generation rates reported in Roy et al. (2018). This flow range estimate is not specific to Minnesota commercial composting facilities due to limited available data.

For this Report, the primary goal was to evaluate PFAS treatment alternatives for their ability to separate and mineralize PFAS from compost contact water. The treatment evaluated is based on water quality criteria required for effective PFAS treatment, not necessarily surface water discharge criteria. The recommended level of treatment for PFAS may provide sufficient water quality for surface water discharge in specific instances but should be evaluated in individual, site-specific studies.

9.1.2 PFAS Influent Concentrations and Treatment Targets

The MPCA and Wood Environmental & Infrastructure Solutions completed a study of PFAS concentrations in compost contact water in 2018 and 2019 (Wood Environment & Infrastructure Solutions Inc. 2019). The scope of that study was to collect samples from ponds at five SSOM facilities and two yard waste facilities over three sampling events. The study concluded that PFAS are prevalent in compost contact water at concentrations higher than in Minnesota's ambient groundwater.

The types of PFAS most relevant in compost contact water are terminal PFCAs, such as PFHxA, and PFSAs, such as PFOS, associated with composted items (Choi et al. 2019; Wood Environment & Infrastructure Solutions Inc. 2019). The selection of target PFAS for consideration in this study was detailed in Section 2.3, and concentrations of the target PFAS assumed to be present in compost contact water are summarized in Table 9-1. These values were developed to support preliminary design and cost estimating and are not intended to reflect the full range of PFAS concentrations potentially present in compost contact water.

Table 9-1 Assumed influent concentrations and treatment goals for target PFAS for compost contact water (all units in ng/L)

PFAS	Unit	Typical Concentrations[1]	High Concentrations[1]	Treatment Target
PFBA	ng/L	450	1,500	5
PFBS	ng/L	10	25	5
PFHxA	ng/L	500	2,000	5
PFHxS	ng/L	10	100	5
PFOA	ng/L	30	100	5
PFOS	ng/L	20	1,500	5

[1] Data summarized from Wood Environment & Infrastructure Solutions Inc. (2019).

9.1.3 Water Quality Assumptions for Pretreated Compost Contact Water

Compost contact water quality can vary significantly depending on specific feedstocks, the phase of composting, and specific operations of individual facilities.

Compost contact water typically has high nitrogen concentrations and high organic content with relatively low bioavailability (BOD_5:COD ratios are on the order of 0.1 to 0.5) because readily biodegradable organics are largely removed in the composting process. Other potential contaminants associated with compost contact water include heavy metals, suspended solids, chloride and other dissolved solids, and emerging organic contaminants, such as plasticizers (Roy et al. 2018).

Non-PFAS water quality parameters have significant implications for PFAS treatment. The water quality assumed for this study as initial untreated and pretreated water ahead of PFAS treatment is shown in Table 9-2. A range of concentrations is shown, reflecting the expected variability in water quality. This study assumes most facilities accept both food waste and yard waste as feedstocks, although water quality represented in Table 9-2 is based on compost contact water from a variety of facilities. Alternatives that do not require pretreatment (Alternatives 8a and 8b) are assumed to accept water with concentrations typical of raw compost contact water. Water quality targets for PFAS separation technologies requiring pretreatment (Alternatives 1a and 5a) are also shown. They reflect assumed water quality entering the PFAS management process based on equipment fouling potential outlined in Section 5.2. One example of a pretreatment train and costs that may be able to provide this water quality at commercial composting facilities is discussed in Section 9.4.

Table 9-2 Assumed initial and pretreated compost contact water quality

Parameter	Units	Assumed Water Quality in Untreated Compost Contact Water			Assumed Concentration in Pretreated Water (Influent for all Other PFAS Management Alts Evaluated)
		Typical Value (Assumed Influent Water Quality for Alts 8a and 8b)	Minimum Value	Maximum Value	
pH[1]	s.u.	7.5	4.0	8.0	7.5
TDS[2]	mg/L	6,000	Not reported	Not reported	6,000
TSS[1]	mg/L	1,000	10	34,000	1[3]
COD[1,4]	mg/L	25,000	400	185,000	90[5]
BOD_5[1,4]	mg/L	6,000	20	90,000	60[3]
TOC[4]	mg/L	750	<50	18,000	20[3]
Conductivity[1,4]	mS/cm	20	1.0	80	20
Hardness, as $CaCO_3$[4]	mg/L	1,800	1,100	2,400	1,800
Alkalinity[2]	mg/L as $CaCO_3$	1,800	Not reported	Not reported	1,800
Chloride[1]	mg/L	2,000	30	8,700	2,000
Sulfate	mg/L	Not reported	Not reported	Not reported	--
Sodium	mg/L	Not reported	Not reported	Not reported	--
Potassium	mg/L	Not reported	Not reported	Not reported	--
Calcium[4]	mg/L	360	280	460	360
Magnesium[4]	mg/L	210	100	300	210
Ammonia-N[1]	mg/L	800	5	2,300	800[6]
Phosphorus[1]	mg/L	30	0.5	500	30[6]
Iron[3]	mg/L	30	20	50	0.5[3]
Manganese	mg/L	Not reported	Not reported	Not reported	0.5[3]

[1] Concentrations shown are based on values in Tables 1, 2, and 3 of Roy et al. (2018).

[2] A typical value could not be established for TDS or alkalinity from referenced literature. The values shown were calculated based on the typical concentrations shown for the other constituents. The value shown for total dissolved solids only includes inorganic constituents; thus, it likely represents a low estimate.

[3] Based on the pretreatment discussion in Section 5.2.

[4] Concentrations shown are based on values provided in Table 7 of Krogmann and Woyczechowski (2000). Hardness was calculated based on reported concentrations of calcium and magnesium.

[5] The concentration of COD is assumed to decrease based on removal of BOD_5 during biological pretreatment (e.g., MBR). It is assumed that $COD=1.5\times BOD_5$.

[6] Concentrations of ammonia and phosphorus are both expected to decrease through biological pretreatment (e.g., MBR), but the level of removal is uncertain.

9.2 PFAS Management Alternatives Evaluation Results

Each PFAS management alternative identified for water-phase PFAS separation and destruction in Section 4.1 was scored for each evaluation criterion described in Section 5.1 for compost contact water.

9.2.1 Evaluation Scoring Results

Alternatives evaluated for compost contact water, as described in Section 4.1, were as follows:

- Alternative 1a: GAC sorption followed by off-site, high-temperature incineration of GAC
- Alternative 5a: modified clay media sorption followed by off-site, high-temperature incineration of modified clay
- Alternative 8a: Foam fractionation followed by off-site, high-temperature incineration of foamate
- Alternative 8b: Foam fractionation followed by SCWO of foamate

Evaluation results are summarized in Table 9-3 and described in subsequent sections. Specific criteria and subcriteria are defined in Section 5.1. Based on the screening, Alternatives 1a, 5a, and 8a were retained for preliminary design and cost curve development.

Table 9-3 Alternatives evaluation results for compost contact water

Alternative Number		1a	5a	8a	8b
PFAS separation technology		GAC	MC	FF	FF
PFAS destruction technology		Inc	Inc	Inc	SCWO
Technical Feasibility	**weight**	***59***	***56***	***47***	***40***
PFAS separation efficiency	5	3	3	2	2
PFAS destruction efficiency	5	3	3	3	3
Degree of commercialization	3	3	2	2	1
Reliability of performance	2	1	1	2	2
Simplicity of operation/maintenance	4	3	3	2	1
Operator and public health	2	3	3	2	2
Economic Feasibility	**weight**	***44***	***39***	***40***	***34***
Relative capital costs	4	3	3	2	1
Relative operation and maintenance costs	3	3	3	2	3
Relative energy consumption	2	2	2	2	2
Relative complexity and cost of pretreatment	4	1	1	3	3
Applicability at scale	5	3	2	2	1
Byproducts Management	**weight**	**3**	**3**	**3**	**5**
Beneficial reuse opportunity for water or byproducts	1	1	1	1	1
Potential for media shifting of PFAS	2	1	1	1	2
Total Score		**106**	**98**	**90**	**79**
Retained?		**x**	**x**	**x**	

GAC = granular activated carbon, MC = modified clay, Inc = high-temperature incineration, SCWO = supercritical water oxidation, FF = foam fractionation

9.2.2 Technical Feasibility

GAC and modified clay media scored highest for **PFAS separation efficiency** relative to foam fractionation due to the limited ability of foam fractionation to separate short-chain PFAS into foamate. Both GAC and modified clay are adsorption processes with effluent water quality dependent on media breakthrough status for specific PFAS. The score of 3 assigned here reflects the assumption that breakthrough could be detected in lead vessel effluent and media changed out before PFAS reports to the lag vessel effluent.

All alternatives received a score of 3 for **PFAS destruction efficiency** because both high-temperature incineration and SCWO remove 99.9% or more of PFAS. However, both have the potential for additional PFAS formation (Krause et al. 2022; L. Winchell et al. 2022). Additional research is needed for both these technologies to demonstrate the degree of mineralization achievable and the nature of byproducts formed.

GAC media with high-temperature incineration received a score of 3 for **degree of commercialization** because these technologies have been widely applied in multiple industries for PFAS removal. Alternatives including modified clay media and foam fractionation received a score of 2 because they are commercially applied but in fewer industries. The alternative including SCWO received a score of 1 because the technology is still developing for PFAS removal, especially in the water phase. It is currently limited to pilot-scale installations.

Sorption media received a score of 1 for **reliability of performance** because flow rate variation can adversely affect the EBCT and associated mass transfer zone in sorption vessels, which can cause premature breakthrough. In addition, rapid breakthrough of short-chain PFAS could result in detectable concentrations in treated effluent, depending on monitoring frequency and mobilization time for changeout. Foam fractionation with high-temperature incineration and with SCWO both received a score of 2 because treatment efficiency is expected to be unaffected by changing water quality, flows, or environmental conditions, but some uncertainty remains due to limited commercial application.

Alternatives with sorption media (GAC and modified clay) combined with high-temperature incineration received the highest score for **simplicity of operation**. These alternatives would have one on-site treatment process for PFAS and low operational complexity, except for sorption media changeout events. Foam fractionation with high-temperature incineration received a score of 2 because it is expected to be more complex to operate than single-use sorption media and only uses one on-site process. Foam fractionation combined with SCWO received a score of 1 due to the complexity of operating both technologies on-site.

Sorption media (GAC and modified clay) alternatives with high-temperature incineration received a score of 3 for **operator and public health** because there are minimal risks associated with these types of treatment and destruction technologies. All other alternatives received a score of 2 because there is an increased risk to operators and public health due to one or more of the following: the addition of chemicals, high operating temperatures, or high operating pressures.

9.2.3 Economic Feasibility

The alternative with the highest **relative capital cost** is foam fractionation with on-site SCWO destruction because it requires two on-site processes and therefore received a score of 1. Foam fractionation with off-site, high-temperature incineration received a score of 2 due to lower on-site capital expenses. Media sorption with off-site, high-temperature incineration scored a 3 because the vessels and ancillary equipment needed are relatively inexpensive.

When considering **relative O&M costs (without energy)**, alternatives with single-use media disposed of via high-temperature incineration received a score of 3, with primary O&M costs associated with transport and off-site incineration of a small volume of sorption media. Foam fractionation with high-temperature incineration scored a 2 due to the aeration costs of foam fractionation and the cost of off-site, high-temperature incineration of foamate. Foam fractionation with SCWO treatment of the foamate received a score of 3 because it does not incur fees associated with off-site, high-temperature incineration.

Alternatives with high-temperature incineration or sorption media or foam fractionation foamate received a score of 2 for **relative energy consumption** because they require thermal incineration of waste materials. Foam fractionation followed by SCWO also received a score of 2, assuming that the energy required for SCWO treatment of foamate is similar to that required for high-temperature incineration of the same volume. SCWO of foamate is expected to require a co-fuel, such as diesel, to be self-sustaining. However, an on-site material, such as reject material or residuals, could potentially be used as a co-fuel source to reduce the purchase of external fuels.

GAC and modified clay sorption scored a 1 for **relative complexity and cost of pretreatment** because it would require pretreatment, as described in Section 9.5. Alternatives with foam fractionation scored a 3 because they do not require complex pretreatment.

GAC sorption with high-temperature incineration received a score of 3 for **applicability at scale**. Modified clay sorption and foam fractionation with high-temperature incineration each received a score of 2 because applications using these technologies are more limited. Foam fractionation with SCWO received a score of 1 because it includes two technologies with limited applications at this scale.

9.2.4 Byproducts Management

All four alternatives received a score of 1 for **beneficial reuse** because the water or solid byproducts produced are not expected to have valuable reuse opportunities.

All alternatives with high-temperature incineration received a score of 1 for **potential media shifting of PFAS.** This is due to the current uncertainty and ongoing industry research to investigate PFAS transformations and emissions associated with high-temperature incineration. Alternatives with SCWO destruction received a score of 2 because there are still unknowns regarding the mass balance of fluorine through SCWO reactors.

9.2.5 PFAS Management Alternatives for Preliminary Design

Based on the screening described in Section 9.2, three PFAS management alternatives were carried forward to preliminary design and cost analysis for compost contact water:

- Alternative 1a: GAC sorption followed by off-site, high-temperature incineration of GAC
- Alternative 5a: modified clay media sorption followed by off-site, high-temperature incineration of modified clay
- Alternative 8a: foam fractionation followed by off-site, high-temperature incineration of foamate

9.3 Alternative Preliminary Design and Cost Curve Development

9.3.1 Alternative 1a (Compost Contact Water)

For Alternative 1a, pretreated compost contact water meeting the water quality listed in Table 9-2 flows directly to lead-lag GAC adsorption pressure vessels. Once GAC media is exhausted with respect to the target PFAS (limited by PFAS breakthrough in this case), it would be sent to high-temperature incineration for destruction. This process flow is summarized in Figure 9-1.

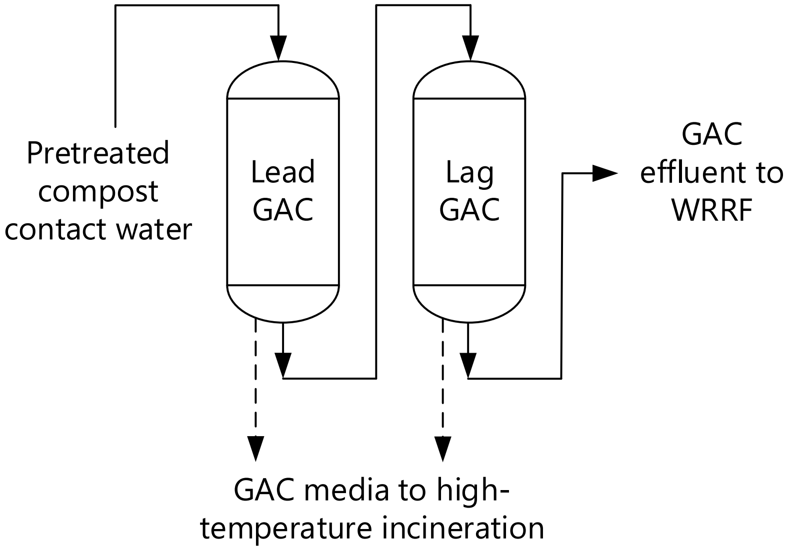


Figure 9-1 **Conceptual process flow diagram for Alternative 1a for compost contact water**

Key design basis assumptions for Alternative 1a are listed in Table 9-4, with additional details in Appendix E.

Table 9-4 Summary of design basis assumptions for Alternative 1a for compost contact water

Design Parameter	Basis		
	0.0014 MGD/ 1 gpm	0.014 MGD/ 10 gpm	0.14 MGD/ 100 gpm
Vessel capacity (lb)	90	750	10,000
Number of trains	2	1	1
Number of vessels per train	4	2	2
EBCT per vessel (min)	15	15	15
HLR (gpm/sq. ft)	0.5	3.2	2.0
Estimated bed volumes to breakthrough[1]	6,400	6,400	6,400
GAC disposal route	High-temperature incineration	High-temperature incineration	High-temperature incineration

[1] Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L. Described further in Section 5.3.4 and Appendix D.

Figure 9-2 and Figure 9-3 show the estimated capital and annual O&M costs for the range of influent flow rates considered for compost contact water. These costs do not include the pretreatment costs summarized in Section 9.5. Detailed tables with supporting data for the cost curves are included Appendix E.

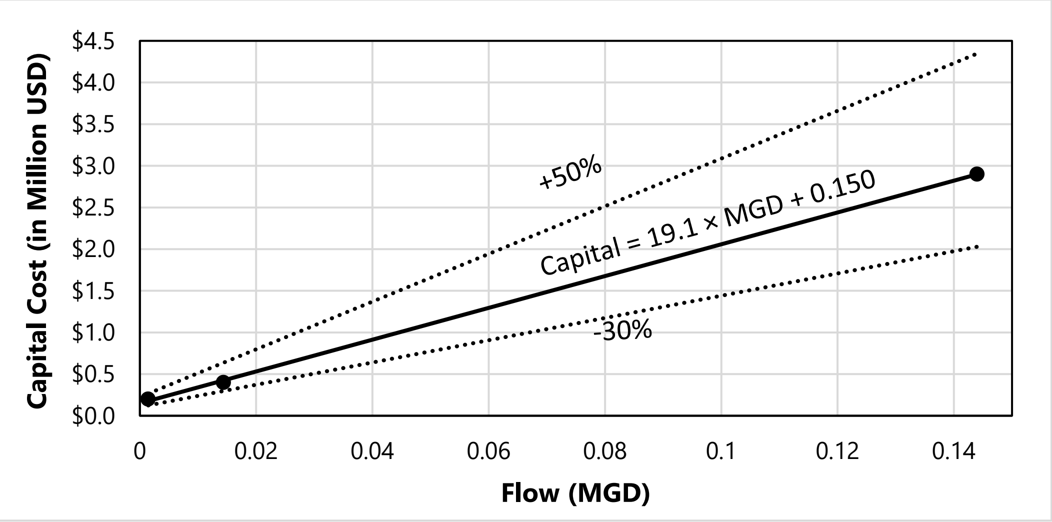


Figure 9-2 Capital cost curve for Alternative 1a for compost contact water

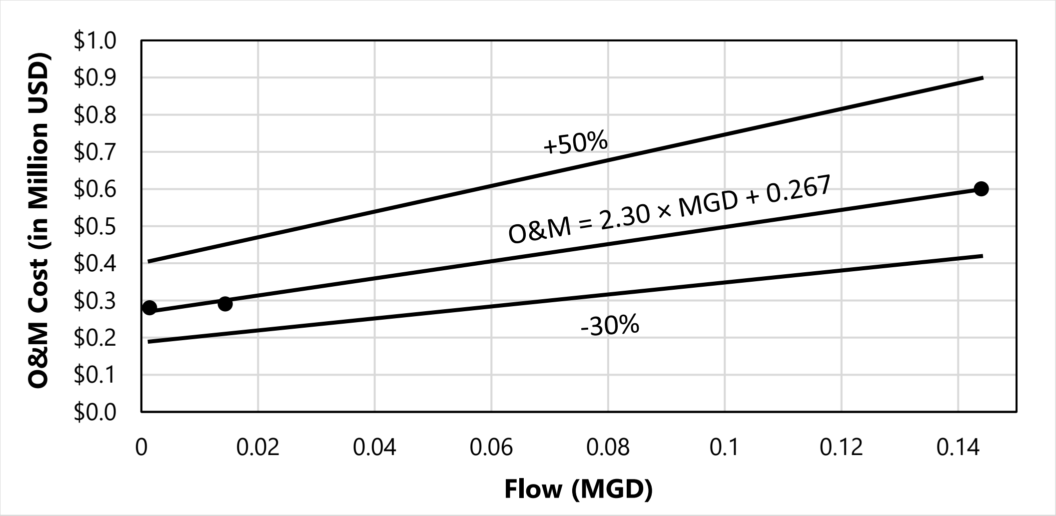


Figure 9-3 O&M cost curve for Alternative 1a for compost contact water

Estimated annual O&M costs are approximately 40% over the estimated capital costs at the lowest flow rate. Estimated annual O&M costs are similar to estimated capital costs at 10 gpm. The highest operating costs are associated with operation and maintenance labor and sorption media replacement.

Primary uncertainties for Alternative 1a for compost contact water include the following:

- Actual GAC breakthrough timing and requirements, depending on actual pretreated water quality
- Potential for GAC fouling limiting bed life over PFAS breakthrough
- Pretreatment processes needed and ability to meet pretreatment targets
- Location and incineration fees of a selected high-temperature incineration facility
- The capital costs for the lowest flow rates may change depending on facility preference for operational flexibility. The vessels included in this analysis are relatively small such that a typical valve tree included with larger vessels is not standard and was not included.

9.3.2 Alternative 5a (Compost Contact Water)

For Alternative 5a, pretreated compost contact water meeting the water quality listed in Table 9-2 flows directly to lead-lag modified clay adsorption pressure vessels. Once modified clay media is exhausted with respect to the target PFAS (limited by breakthrough of short-chain PFAS), the spent sorption media would be sent to high-temperature incineration for destruction. This process flow is summarized in Figure 9-4.

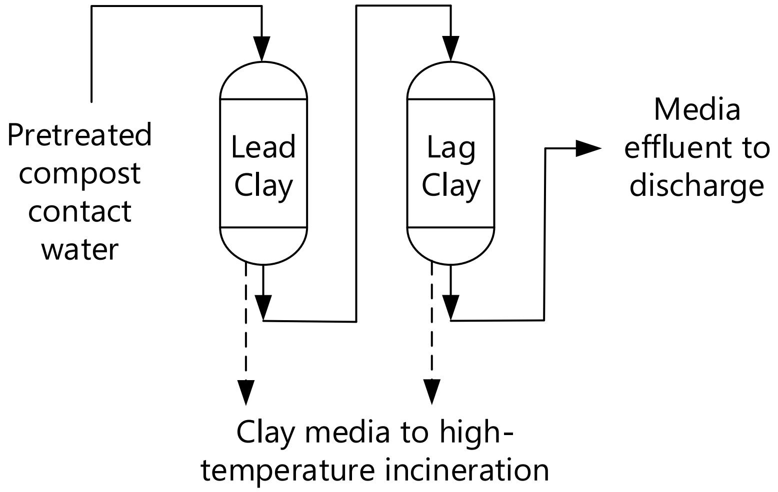


Figure 9-4 **Conceptual process flow diagram for Alternative 5a for compost contact water**

Key design basis assumptions for Alternative 5a are listed in Table 9-5, with a detailed design basis in Appendix E.

Table 9-5 **Summary of design basis assumptions for Alternative 5a for compost contact water**

Design Parameter	Basis		
	0.0014 MGD/1 gpm	0.014 MGD/10 gpm	0.14 MGD/100 gpm
Vessel capacity (cu. ft)	3	5	40
Number of trains	1	3	4
Number of vessels	2	6	8
EBCT per vessel (min)	10	10	10
HLR (gpm/sq. ft)	0.9	1.9	3.5
Estimated bed volumes to breakthrough[1]	10,000	10,000	10,000
Media disposal route	High-temperature incineration	High-temperature incineration	High-temperature incineration

[1] Defined as the estimated volume of water treated through the lead media vessel until the first detection of PFAS at 5 ng/L. Described further in Section 5.3.4 and Appendix D.

Figure 9-5 and Figure 9-6 illustrate estimated capital and annual O&M costs for a range of influent flow rates. These costs do not include pretreatment costs described in Section 9.5. Detailed capital and O&M cost estimates are in Appendix E.

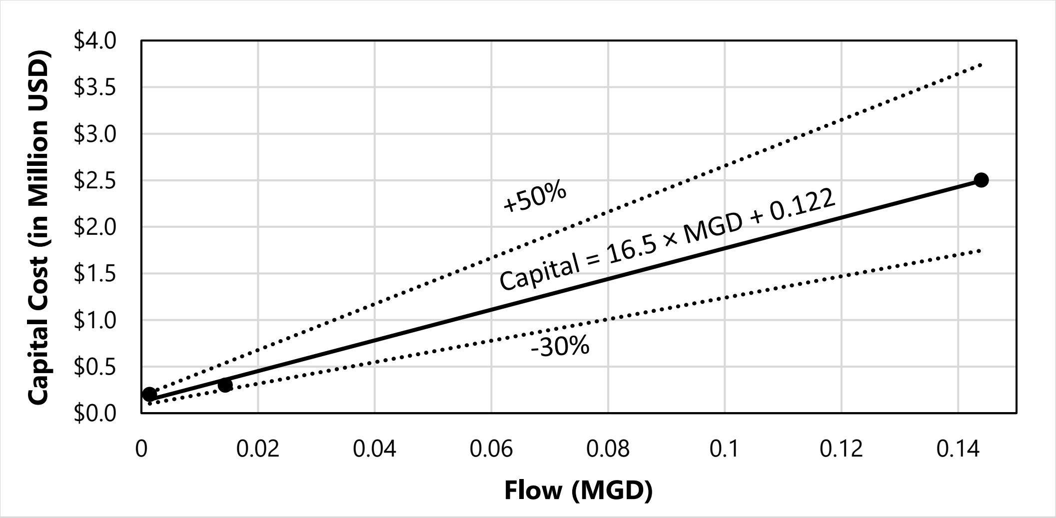


Figure 9-5 Capital cost curve for Alternative 5a for compost contact water

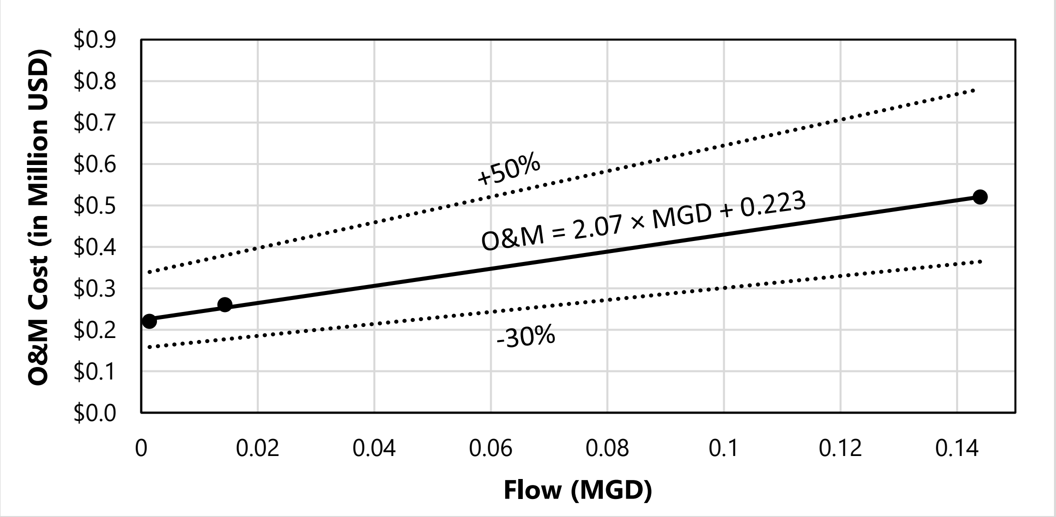


Figure 9-6 O&M cost curve for Alternative 5a for compost contact water

Estimated annual O&M costs and estimated capital costs for Alternative 5a are similar to estimated costs for Alternative 1a. The highest operating costs are associated with labor and sorption media replacement and incineration.

Primary uncertainties for Alternative 5a for compost contact water treatment include the following:

- Actual PFAS breakthrough timing through modified clay media, depending on media performance and actual pretreated water quality
- Potential for modified clay fouling to limit bed life over PFAS breakthrough
- Pretreatment processes needed and ability to meet pretreatment targets
- Location and incineration fees of a selected high-temperature incineration facility

- The capital costs for the lowest flow rates may change depending on facility preference for operational flexibility. The vessels in this analysis are relatively small such that a typical valve tree included with larger vessels is not standard and was not included.

9.3.3 Alternative 8a (Compost Contact Water)

For Alternative 8a, compost contact water would be pumped to a series of foam fractionation vessels. The contact water initially goes through a bag filter to remove suspended solids, avoiding solids buildup in the foam fractionation vessels. The foam generated from the primary foam fractionation vessel is further enriched in a secondary foam fractionation vessel. The air that generates the foam in the closed foam fractionation vessel is discharged to carbon canisters to capture volatile organics. The resulting foam is collected and transported to a high-temperature incineration facility for destruction. This process flow is summarized in Figure 9-7.

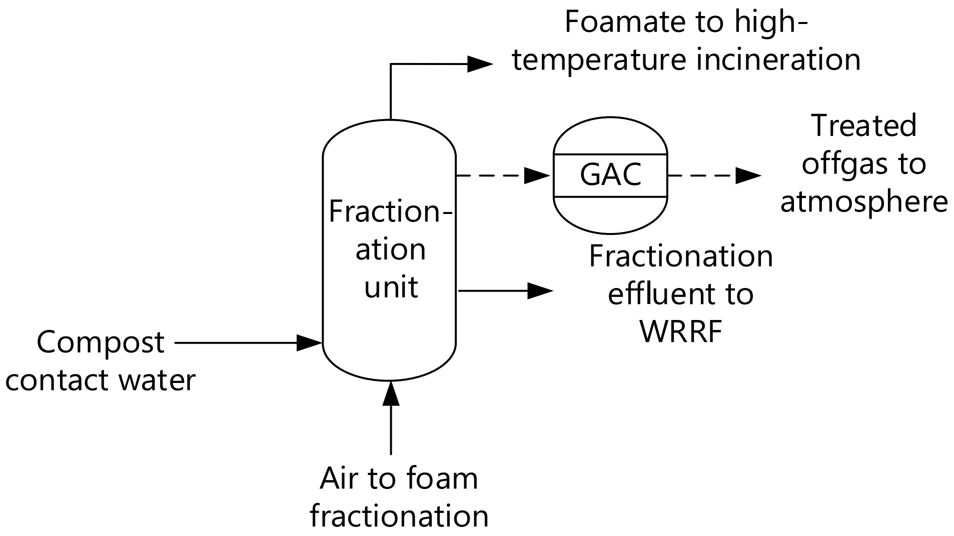


Figure 9-7 **Conceptual process flow diagram for alternative 8a for compost contact water**

Key design assumptions for Alternative 8a are listed in Table 9-6, with an additional detailed design basis in Appendix E.

Table 9-6 **Summary of design basis assumptions for Alternative 8a for compost contact water**

Design Parameter	Basis		
	0.0014 MGD/1 gpm	0.014 MGD/10 gpm	0.14 MGD/100 gpm
Number of primary vessels	2	2	4
Number of secondary vessels	1	1	2
Assumed concentration factor[1]	1,000,000	1,000,000	1,000,000
Expected foamate flow rate (gpd)	0.0014	0.014	0.14

[1] Based on vendor input.

Figure 9-8 and Figure 9-9 show estimated capital and annual O&M costs, respectively, for the range of influent flow rates considered for compost contact water. Detailed tables with supporting data for the cost curves are in Appendix E.

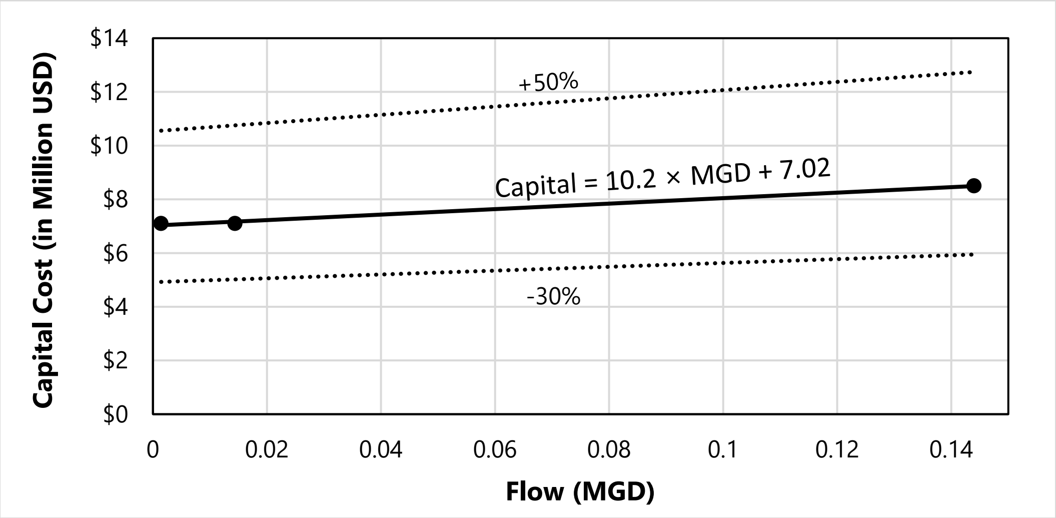


Figure 9-8 **Capital cost curve for Alternative 8a for compost contact water**

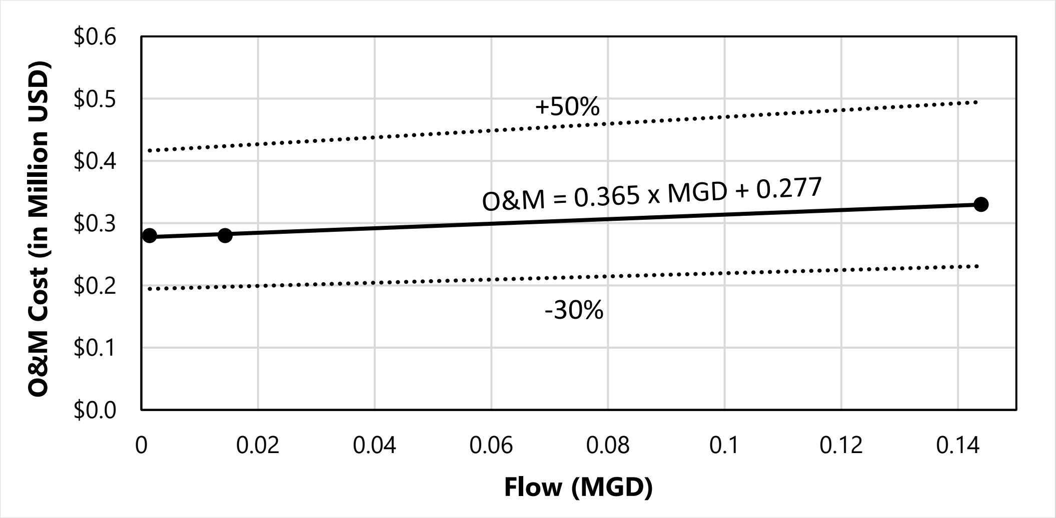


Figure 9-9 **O&M cost curve for Alternative 8a for compost contact water**

Estimated capital and O&M costs for compost contact water are relatively independent of flow rate due to the modular nature of foam fractionation equipment and current vendor offerings. Capital costs for foam fractionation are approximately 3–40 times higher than GAC adsorption (Alternative 1a), and O&M costs are comparable between these two alternatives. The highest operating costs are associated with utilities, maintenance, and labor.

Primary uncertainties for Alternative 8a for compost contact water include the following:

- Actual concentrating factor of the foam (assumed to be 1,000,000)

- The removal efficiency of short-chain PFAS (such as PFBA) and the potential usage rate of cationic surfactants or enhancements to improve the removal efficiency. Polishing treatment (such as media sorption) on the treated water stream from foam fractionation may be needed to achieve the PFAS performance targets of this study. This would increase the capital and O&M cost estimates provided above.
- Location and incineration fees of a selected high-temperature incineration facility

9.4 PFAS Removal Performance and Reliability

The relative ability of each alternative to meet treatment goals of <5 ng/L for target PFAS is summarized in Table 9-7. Alternatives 1a and 5a are expected to meet the PFAS treatment targets most of the time, with some risk of rapid breakthrough of short-chain PFAS and frequent media changeout required. Currently, it is uncertain if foam fractionation (Alternative 8a) can remove 90% of short-chain PFAS. If not, this would result in pass-through of PFAS such as PFBA, PFBS, PFHxA, and possibly others into the treated water phase at concentrations higher than the 5 ng/L target. Specific references for PFAS removal efficiency are detailed further in Appendix C.

Table 9-7 PFAS removal performance and reliability for compost contact water treatment alternatives

Target PFAS	Assumed Influent Concentration (ng/L)	Percent Removal to Achieve <5 ng/L	Relative Ability to Consistently Meet Targets		
			1a: GAC	5a: Modified Clay	8a: Foam Fractionation with Incineration
PFBA	450	99%	Moderate	Moderate	Low
PFBS	10	50%	Moderate	Moderate	Low
PFHxA	500	99%	Moderate	Moderate	Moderate
PFHxS	10	50%	High	High	High
PFOA	30	83%	High	High	High
PFOS	20	75%	High	High	High

9.5 Example Pretreatment for PFAS Separation Technologies Applied to Compost Contact Water

This section summarizes the conceptual design and capital costs for the pretreatment of compost contact water to limit the fouling of pressure vessel media sorption for PFAS treatment (Alternatives 1a and 5a). Other alternatives considered applicable for compost contact water (Alternative 8a and 8b—foam fractionation) are not expected to require pretreatment aside from filtration for TSS reduction. Currently, no commercial composting facilities in Minnesota have active treatment for contact water. Thus, implementing PFAS water treatment at composting facilities would require significant site upgrades and equipment installation.

Based on the assumed water quality in Table 9-2, contact water would need to be treated for TSS, TOC, and iron removal ahead of sorption media pressure vessels (Alternatives 1a and 5a) for PFAS treatment.

The conceptual pretreatment system for compost contact water is assumed to include the following:

- Aeration—to oxidize iron
- Chemical precipitation and sedimentation—to remove oxidized iron, a fraction of the TOC, and fine suspended solids
- Acid addition—to lower pH and prevent unionized ammonia toxicity during biological treatment (discussed in detail in Section 8.5)
- MBR—to remove BOD_5, TOC, and residual suspended solids

The conceptual pretreatment process flow is shown in Figure 9-10.

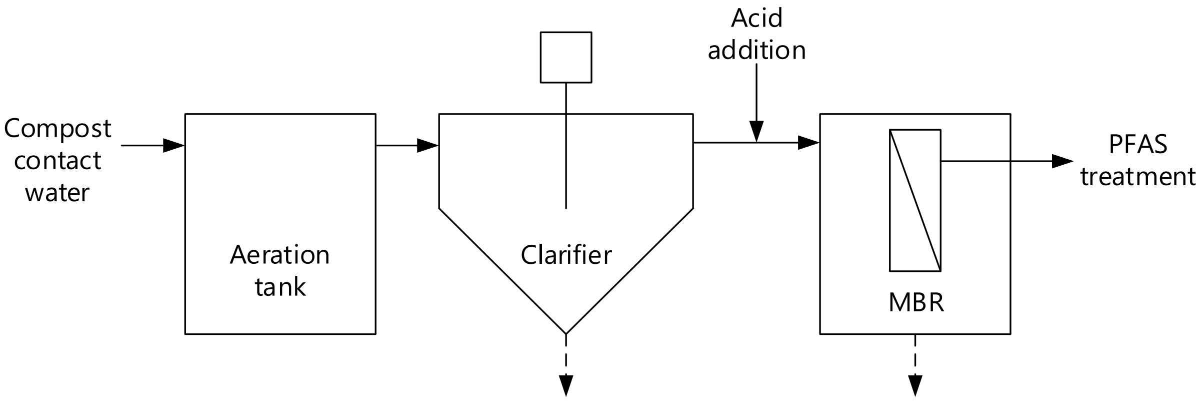
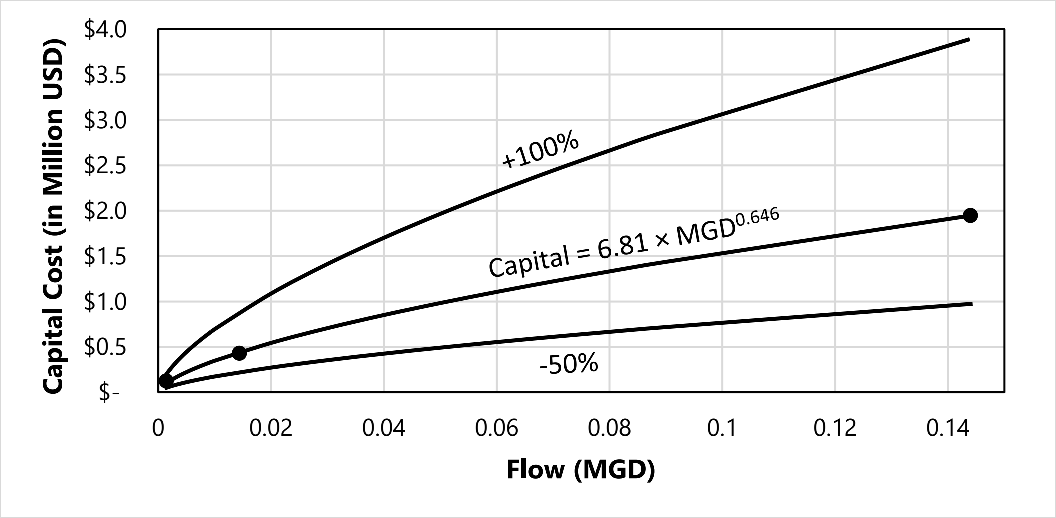


Figure 9-10 Conceptual pretreatment process flow diagram for compost contact water

MBR systems require consistent flows to maintain healthy biomass. Because compost contact water flows are variable and dependent on precipitation, the treatment system will need sufficient flow equalization to maintain continuous flow during dry periods (e.g., summer and winter). It is assumed that existing contact water collection ponds could be used for flow equalization, with minor modifications as necessary. Thus, construction costs for equalization basins are not included in the capital costs shown below. If sufficient flow equalization is not practical for a specific facility, alternative pretreatment other than MBR could be evaluated to allow pretreatment on an as-needed basis (i.e., batch-wise) instead of MBR pretreatment, which requires continuous flow. For example, greensand filtration could be used for iron and TSS removal with GAC adsorption for TOC removal. An individual, site-specific feasibility study should be completed to evaluate the appropriateness of the conceptual pretreatment presented here, or alternative pretreatment strategies should be identified.

High salts and metals, low biodegradability, and variable flow rates make compost contact water challenging to treat using conventional treatment methods. Depending on water quality and site-specific conditions, pretreatment using an MBR followed by GAC adsorption for PFAS removal may not be effective. First, the low biodegradability of the organic matter present means that the pretreatment target for TOC may not be met. This could result in high concentrations of TOC in sorption vessel influent, using up sorption sites and requiring significantly faster changeout frequencies than anticipated to maintain effluent PFAS concentrations below detection limits. Second, iron may not be removed to the pretreatment targets through coagulation and settling and could precipitate on the sorption media, ultimately blocking pore spaces and requiring backwashing or frequent media changeouts.

Capital cost estimates for this pretreatment train are shown in Figure 9-11. Costs are Class 5 (AACE) cost estimates with an accuracy range of +100%/-50%. This cost curve should only be used for the flow range shown (1–100 gpm; 0.0014–0.14 MGD).



MBR costs from Lo, McAdam, and Judd (2015). Other equipment costs estimated from CapdetWorks (Hydromantis, v4.0). The solid line reflects the estimated cost curve. The dashed lines reflect +100%/-50% accuracy range. All costs scaled to November 2022 using ENR CCI (13175).

Figure 9-11 Capital cost curve for new MBR installations with pre-aeration, sedimentation, and chemical addition for compost contact water pretreatment

The conceptual pretreatment cost estimates did not include a detailed feasibility study or any design for site-specific requirements. Pretreatment needs are expected to vary by facility due to differences in existing infrastructure, water quality, space availability, and other site-specific constraints. Thus, the degree of detail included in this Report for pretreatment is less than that provided for PFAS treatment alternatives in subsequent sections. The conceptual pretreatment costs shown are intended to provide an order-of-magnitude estimate for potential pretreatment costs. **Facilities looking to implement PFAS treatment should conduct site-specific treatment evaluations prior to capital planning or implementation.**

9.6 Other Considerations for Compost Contact Water

The PFAS management alternative most appropriate for a given site will depend on space constraints, initial water quality, operational and treatment targets, and permit conditions. Sites targeting only long-chain PFAS will likely find foam fractionation (as included in Alternative 8a) the most cost-effective separation technology because it does not require pretreatment. However, foam fractionation's efficacy for separating short-chain compounds remains limited at this time. Modified clay (Alternative 5a) is still being vetted as a sorption media for PFAS separation but may have specific advantages over GAC (Alternative 1a), such as lower capital cost and footprint.

The decision to select one of these alternatives and implement them on-site will vary site by site and be based on the PFAS management strategy of the WRRF receiving the discharge. PFAS management strategies should consider if an on-site treatment is necessary. For example, if a downstream WRRF is implementing PFAS treatment or is willing to accept compost contact water as is, PFAS management may not be needed at the composting site. Other considerations for removing and destroying PFAS from compost contact water include the following:

- Commercial SSOM composting facilities offer a critical means to reduce organic waste going to landfills and produce a saleable product (Minnesota Pollution Control Agency 2022). However, compost facilities have a very low-cost margin and limited ability to implement costly treatment of PFAS in contact water. Any level of on-site treatment of PFAS in contact water will likely require increasing the costs to dispose of organic materials at composing facilities or require external funding to keep these facilities operational.
- While this Report identifies potential options for active treatment of PFAS in compost contact water, reducing PFAS loads in compost feedstocks in parallel with active water treatment would be a complementary way to reduce PFAS in compost contact water. Possible ways to reduce PFAS in compost feedstocks include (U.S. EPA 2021c):
    - Feedstock restrictions—identify PFAS loads in compost feedstock materials (e.g., food contact materials) and implement outreach programs to limit the input of these materials.
    - Phase-outs and bans on the use of fluorinated chemicals in compostable food materials, for example, refer to the standard for fluorinated chemicals from the Biodegradable Products Institute (Biodegradable Products Institute 2020).
- Reducing the volume of contact water is another strategy that could be implemented in conjunction with active water treatment to reduce the overall size of the treatment system. Volume reduction could be accomplished by converting an open compost facility to an enclosed facility to limit water contributions from precipitation. A site-specific feasibility study would likely be needed to evaluate the costs and benefits of operating an enclosed composting facility versus an open composting facility and the expected impact on treatment system sizing.
- High salt and metal concentrations, expected low biodegradability of organics, and variable flow rates of compost contact water make it challenging to treat using conventional treatment methods like GAC adsorption for PFAS removal. Future management of PFAS at composting facilities should target low-energy, low-complexity treatment that can handle variable flows, variable water qualities, and treatment options that can be operated as needed to manage periods of limited or no contact water generation.

- GAC treatment (Alternative 1a) was identified as the likely lowest-cost option, even when considering the inclusion of pretreatment unit operations. However, long-term GAC performance is uncertain, especially the feasibility of treating short-chain, terminal PFAS like PFBA with a relatively high load of background organics.

- Modified clay (Alternative 5a) has slightly higher capital costs than Alternative 1a. The benefit of Alternative 5a over Alternative 1a may be higher water throughput before breakthrough of target PFAS. However, on-site testing would be required to determine the most effective sorption media.

- Foam fractionation (Alternative 8a) with off-site disposal of the foamate is a promising alternative with similar estimated ongoing O&M costs as GAC but would likely require a higher upfront capital cost. Foam fractionation would also likely require on-site feasibility testing to demonstrate whether it can meet PFAS treatment targets, especially for short-chain PFCAs.

- Other on-site destruction strategies for PFAS management will likely become more cost-effective as these technologies are further vetted and implemented. Future technology development for PFAS treatment is discussed further in Section 11.8.

10 Regional PFAS Management Facility Evaluation

Regional management of the waste streams containing PFAS described in the prior sections of this Report is considered here as a potential option to provide cost savings to multiple customers by centralizing PFAS destruction in one or several large, centralized locations rather than having on-site destruction technologies installed at individual sites. Here a "regional" facility is any facility that treats concentrated PFAS waste streams from multiple sites, as compared to the previous sections of this study, which addressed PFAS wastes from a single WRRF, landfill, or composting facility.

Existing WRRFs currently serve as regional collection facilities for PFAS-impacted municipal and industrial streams, as well as direct-piped or hauled landfill leachate and compost contact water, However, these facilities were not designed to remove or destroy PFAS. If PFAS treatment needs to be implemented at WRRFs, they could also serve as regional facilities for PFAS management and destruction, provided they have available space for expansion.

10.1 Products for Regional Facility PFAS Destruction by Waste Stream

The products that could potentially be managed at a regional facility include solids or concentrated liquids. From WRRFs, this would include spent sorption media or concentrated liquids such as foam fractionation foamate or AIX regeneration still bottoms. Biosolids would likely be dewatered prior to management at a regional facility. Landfill leachate and compost contact water could potentially be sent to a regional facility without concentration, depending on the flow requiring treatment. Some of these facilities effectively practice regional management already by sending or trucking their effluents to a central WRRF. More practically, spent sorption media or concentrated liquids could be sent to a regional PFAS destruction facility.

10.2 Technologies for Regional Facility PFAS Destruction

The commercially available technologies known to destroy PFAS (high-temperature incineration, GAC reactivation, pyrolysis/gasification with thermal oxidation, and SCWO) are much more complex than typical waste management techniques in the state of Minnesota, requiring specialized training for operators. A regional PFAS residuals management facility could lower the number of PFAS destruction systems for biosolids and the number of specialized operators required within a certain geographic area.

PFAS destruction facilities currently at scale are all high-temperature processes located outside the State of Minnesota. Potential economies of scale may be realized for these facilities due to their high capital costs as well as the associated potential for heat retention and energy recovery inherent in larger facilities. Regional savings would also be realized by reduced transportation costs for destruction of these materials outside Minnesota. For this study, regional destruction resources are evaluated for the final destruction of PFAS-containing waste streams using off-site high-temperature incineration or GAC reactivation (Alternatives 1a, 2a, 2b, 5a, 6a, 6b, and 8a developed for design and cost estimating).

Other regionalization options that may become feasible in the future include regional disposal of smaller volumes of foam fractionation foamate or AIX regeneration still bottoms using emerging destruction technologies such as SCWO, HALT, or electrochemical oxidation.

10.3 Specific Considerations for Regional Facilities

Regional facilities can be economically feasible and would provide resilience to individual facilities as current hauling and disposal rates for PFAS-laden waste streams increase. Prioritizing proximity to individual facilities in selection regional facility locations to reduce material hauling costs are likely to be critical for financial viability.

The operation and management of regional facilities would be challenging and may require establishment of a specific entity/partnership to finance and operate the facility. Various management strategies and financial approaches can be developed. In one option (fee-based), costs incurred by the facility (capital, operation, and maintenance) could be recovered by tipping or disposal fees collected from individual facilities. This model may require higher fees and would not guarantee long-term collaboration with individual facilities. An alternative would separate the design and construction costs of the regional facilities in an up-front fee to WRRF partners (ownership). This would guarantee the participating individual facilities access to a portion of the regional facility capacity. The participating utilities typically contract with the regional facility owner to provide a portion of the funding for construction, maintenance, and facility operation. Contract terms vary widely but typically include fixed annual fees, periodic equipment replacement fees, and fees per unit of biosolids delivered to the regional facility. An example of this economic framework is detailed in Section 10.5.3.

10.3.1 Summary of Existing Regional Facility Networks

An existing network of high-temperature incineration facilities for hazardous waste currently accepts GAC and other sorption media containing PFAS. This network comprises about 10 facilities in the country, including those operated by Clean Harbors Environmental Services and Veolia North America, with none in Minnesota.

Regional GAC reactivation facilities are operated by GAC vendors, with approximately 17 facilities in the country (U.S. EPA 2020), with none in Minnesota. These facilities have processes for GAC receiving and reactivation, followed by thermal oxidation of released gasses, as described in Section 3.4.2.

10.3.2 Potential New Regional Facility Concepts

Four types of regional PFAS destruction facilities were considered for evaluation in this report:

- High-temperature incineration facility for sorption media, AIX resins, and other wastes,
- Pyrolysis/gasification facility with thermal oxidation for WRRF biosolids,
- AIX regeneration facility for spent, regenerable AIX resins, and

- SCWO facility accepting a variety of wastes, including biosolids, sorption media, AIX resin, and concentrated liquid waste streams.

Given that high-temperature incineration is currently the most widely used destruction alternative for PFAS, **potential cost scenarios and other considerations were developed for a hypothetical Minnesota high-temperature incineration facility.** A new regional high-temperature incineration facility could incinerate sorption media, such as GAC, AIX resin, or modified clay media at high temperatures above 1,000°C, as described in Section 3.4.1. This facility could also potentially accept other PFAS-containing wastes such as biosolids, RO concentrate, foam fractionation foamate, or AFFF, though these feeds are not considered in this cost evaluation for simplicity. Considerations and costs for a potential new regional high-temperature incineration facility are likely similar to a new regional GAC reactivation facility, as the processes and temperatures required are relatively similar.

A pyrolysis/gasification system with thermal oxidation was chosen for the development of cost scenarios and considerations for a regional PFAS destruction facility for biosolids. Pyrolysis/gasification systems with thermal oxidation are commercially available at full-scale. A regional pyrolysis/gasification facility would accept dewatered biosolids from municipal WRRFs rather than receiving liquid biosolids. Despite being dewatered, the biosolids would still contain more than 70% water, making the hauling distance to a regional facility and associated costs an important consideration. Receiving schedules and feed rates would need to be considered in planning a regional pyrolysis/gasification facility.

A regional AIX regeneration facility would use organic solvent and brine mixtures to regenerate AIX resin for reuse, as described in Section 3.3.4. This is not a destruction technology but produces a brine with high concentrations of PFAS. This technology has been implemented at selected sites with AIX resin use rates large enough to merit the capital expense of a regeneration facility. However, this option was not considered for a potential regional facility due to the limited application of AIX regeneration and the fact that it is not a destruction technology. This option could be considered in the future as the number of AIX regeneration applications continue to be developed.

A regional SCWO facility could potentially accept a combination of wastes, including biosolids, spent sorption media and AIX resins, and concentrated waste streams from liquid waste facilities. SCWO was previously detailed in Section 3.4.3. Specific wastes could include RO concentrate, foam fractionation foamate, and sorption media from WRRFs, landfills, and composting facilities. Planning and designing a multi-media SCWO facility would need to consider the range of waste mixtures that would make the facility economically viable. This option was not considered for detailed evaluation at this time because current SCWO applications are currently limited to small and pilot scale.

10.4 Sorption Media High-Temperature Incineration Facility Concept-Level Design

10.4.1 Design Basis and Equipment Needs

A new high-temperature incinerator targeted for sorption media is expected to require the following components:

- Rotary kiln (1,000°C)
- Secondary combustion chamber (1,100°C)
- Spray dryer
- Acid gas scrubbers to neutralize HF and other acids
- Particulate baghouse filtration
- Liquid scrubber to remove sulfur and NO_x
- Waste receiving equipment and storage tanks
- Ash treatment process and metal recovery process
- Residual solids load-off facility
- Wastewater neutralization and treatment
- Boilers to provide heat

Specific unit sizes and requirements were not estimated because costs are scaled from reported expenses for a similar facility. The conceptual high-temperature incineration process is illustrated in Figure 10-1. Mineralization of PFAS is expected to produce significant quantities of corrosive hydrofluoric acid, which requires high-level alloys to sustain long-term operation at the high operating temperatures required.

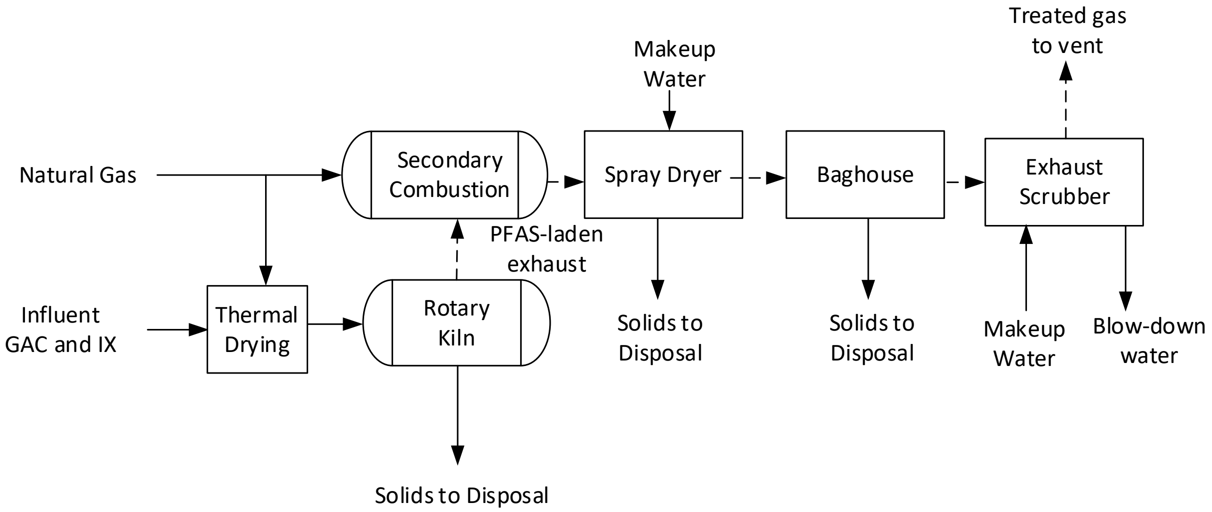


Figure 10-1 **Conceptual process flow diagram for sorption media regional high-temperature incineration facility**

10.4.2 Cost Estimates

Estimating the cost of a new high-temperature solid waste incinerator facility capable of effectively destroying fluorocarbon bonds (i.e., 1,100˚C) is difficult because the system requires highly specialized materials (e.g., combusting fluorocarbons generates hydrofluoric acid that will corrode conventional steel and refractory materials). It also requires ancillary operations to support raw waste handling/storage and waste ash processing. In 2016, Clean Harbors completed a $120 million expansion to add a third high-temperature hazardous waste incinerator to their El Dorado, Arkansas facility. The facility expansion can accept 60,000 tons/year of solid and liquid waste, including PFAS-containing wastes (Arkansas DEQ 2013). The Clean Harbors El Dorado Waste Incinerator Project's incinerator loading design basis (and the corresponding fluorocarbon loading) is not publicly available. However, for this report, the project was assumed to be a sufficient surrogate for estimating the costs of a new similarly sized high-temperature solid and liquid waste incinerator facility.

A new regional facility would also require the construction of several systems that were pre-existing and thus not included in the El Dorado expansion costs. These include waste receiving, ash treatment, scrubbers, and boilers. Therefore, the 2016 Clean Harbors El Dorado Incinerator Expansion Project cost underrepresents the costs for a new waste incinerator facility, and a scale factor of 1.5 (low-range) to 2.5 (high-range) was applied to the Clean Harbors El Dorado Waste Incinerator Project's cost. In addition, costs were adjusted for inflation using the *Chemical Engineering* magazine's Chemical Engineering Plant Cost Index (CEPCI) (Lozowski n.d.).

Table 10-1 presents the estimated 2022 cost for constructing a new, greenfield high-temperature waste incinerator facility capable of processing 60,000 tons/year of PFAS-containing waste streams to match the size of the facility expansion discussed above. This capacity is similar to the rate of spent GAC from 350 MGD of WRRF effluent treatment for PFAS using the media use rates estimated for this study. This cost estimate does not include costs associated with engineering or permitting, which could be substantial, depending on the degree of public support and comment.

Table 10-1 Estimated capital costs for a regional high-temperature incineration facility in Minnesota

Variable	Value
2016 Clean Harbors El Dorado Waste Incinerator expansion cost	\$120,000,000
Inflation adjustment factor (CEPCI May 2022/2016)	53.4% (831.1/541.7)
Estimated ancillary plant infrastructure scale factor[1]	2.0
Estimated 2022 new greenfield waste incinerator facility cost range (2022 dollars)	\$370,000,000 Range: (-30%) \$260,000,000 to (+50%) \$550,000,000

[1] The Estimated Ancillary Plant Infrastructure Scale Factor represents the additional capital cost associated with constructing waste receiving equipment (e.g., loading range and material handling equipment), waste storage tank, ash treatment, and metal recovery processes (lime silos, material handling equipment, basins, etc.), utilities (boilers, electrical, water), process buildings, and administrative buildings.

Operating costs for the facility are assumed to include the following:

- The bulk of material processed is spent GAC, delivered at 50% water content by weight
- Labor for operation, assumed to require 30 full-time employees (FTE)
- Equipment maintenance, assumed to be 5% of the initial capital cost
- Natural gas use, based on the operation of similar facilities and throughput
- Electrical use, based on experience with similar facilities
- Ash disposal, assuming that 50% of the initial, dry GAC mass ends as ash
- Water costs, pretreatment costs, and WRRF surcharges for cooling tower blowdown, scrubber water, wash water from ash handling, and boiler water blowdown

Income for the facility would primarily be gained through incineration fees per mass of waste incinerated. While these costs vary by waste characteristics and will likely vary in the future, based on feedback from existing vendors and information summarized in U.S. EPA's interim guidance on PFAS disposal and destruction (U.S. EPA 2020), the estimated waste processing fee charged by existing facilities is approximately \$1,300 per ton of waste received. Table 10-2 summarizes estimated annual O&M costs, income, and net profits for a regional high-temperature incineration facility.

Table 10-2 Annual estimated operational and maintenance costs and income for a regional high-temperature incineration facility handling spent GAC in Minnesota

Greenfield Incineration Facility	Unit	Unit Cost	Annual Quantity	Annual Cost[1]
Cost Analysis				
Staffing and administration	FTE	$75,000	30	($2,300,000)
Equipment maintenance	Percent of capital	$368,000,000	5%	($18,000,000)
Electrical use (for plant)	kWh	$0.09	19,000,000	($1,700,000)
Natural gas use (for combustion)	1,000 SCF	$8.14	2,900,000	($23,000,000)
Chemical use	tons	$170	1,000	($170,000)
Ash disposal	tons	$100	3,000[2]	($300,000)
Water costs, wastewater treatment, and surcharges[3]	$/gpm	$7,500	130	($980,000)
Other ancillary O&M costs not included here	Assumed 10% of items above			($4,800,000)
Total facility O&M Costs				**($52,000,000)**
Income analysis				
Income from incineration fees	tons wet spent media	$1,300	60,000	$78,000,000
Taxes on income	%	21%	$78,000,000	($16,000,000)
Total estimated annual facility net annual operating income				**$10,000,000**

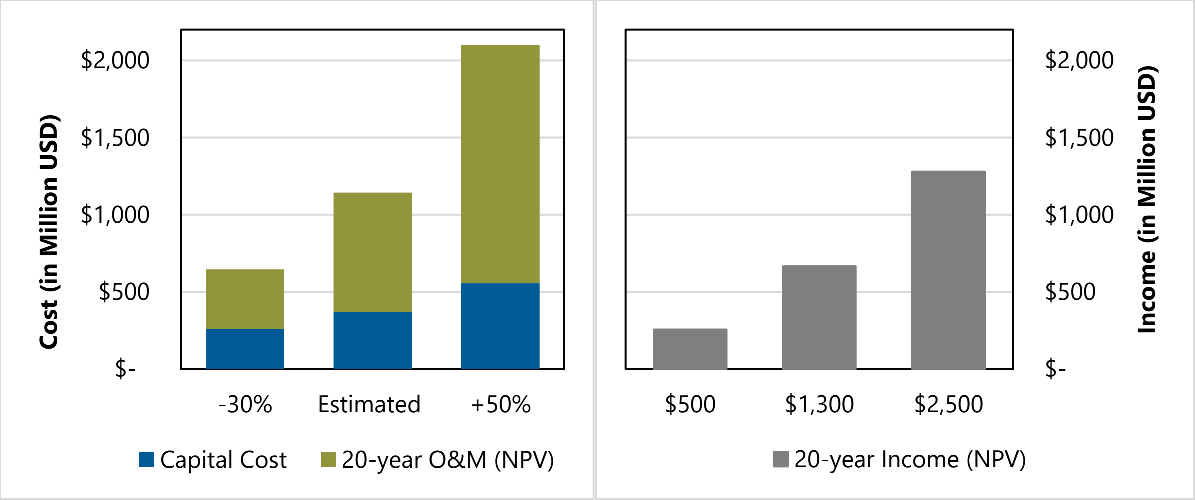
[1] Red text indicates expenses and black text indicates income. All annual costs subjected to +50%/-30% cost uncertainty range. Sums and products were rounded to two significant digits to reflect the uncertainty in the estimate, so some do not exactly match the sum or product of source values.

[2] Assumes 10% ash content of dry GAC and 50% initial water content of delivered material.

[3] Estimated water treatment and disposal costs of $1,500-$3,000/gpm for POTW discharge fees, plus $6,500-$10,000/gpm for pretreatment. Water treatment flow of approximately 130 gpm based on experience with similar facilities.

10.4.3 Economic Analysis

Twenty-year NPV costs are summarized in Figure 10-2. Generally, net annual income at $1,300/ton fees will be positive but may not be enough to pay back the initial capital investment. The payback time for the initial capital costs would likely be longer than 20 years, possibly closer to 50 years, which exceeds the typically-acceptable range for return on a large investment and may also exceed the operating lifetime of the facility. As a result, this project would likely require external financial support or higher fees, which may be possible given the lower anticipated transportation costs for a local facility summarized in Table 10-5.



Range of costs reflect the +50%/-30% range reflected in Tables 10-1 and 10-2.
Range of income reflects a range of potential disposal fees between $500 and $2,500 per ton.

Figure 10-2 **Estimated 20-year NPV and income ranges for regional high-temperature incineration facility**

Table 10-3 and Table 10-4 summarize the sensitivity analysis conducted for the regional facility concept. A range of 2%–6% real interest rate (achievable market rate interest, less inflation) was used to reflect a high degree of future uncertainty due to currently high inflation rates. A range was also used to reflect the potential fees the facility could charge for incineration, between $500/ton and $2,500/ton based on estimates for existing facility fees. The NPV of a 60,000 ton/year regional high-temperature incineration facility is the present value of the amortized capital cost and the sum of operation and maintenance costs over a specified evaluation period. An analysis of the sensitivity of the NPV to changes in tipping fee and real interest rate (Table 10-3) showed that the project is estimated to have a positive NPV if it can charge incineration fees over $2,000/ton. Using a transportation cost of $3/mile for 20-ton trucks ($100 savings per ton for decreasing trip length by 700 miles), this pricing is unlikely to be competitive, with out-of-state facilities currently charging approximately $1,300/ton. Table 10-4 illustrates NPV for different capital and O&M costs as well as fees and reflects the high level of uncertainty at this stage of analysis.

Table 10-3 Economic analysis for regional high-temperature incineration facility in Minnesota, in millions of USD—sensitivity of NPV to incineration fees and real interest rate

Real interest rate		2%	2%	6%	6%	Simple payback period (years)
Project evaluation period		10 years	20 years	10 years	20 years	
Incineration fees (USD per ton)	$500	-$620	-$830	-$580	-$690	No profit
	$1,000	-$420	-$450	-$410	-$430	No profit
	$1,500	-$200	-$59	-$230	-$150	19[1]
	$2,000	$16	$330	-$54	$120	9
	$2,500	$230	$730	$120	$400	6

[1] Some scenarios with negative 10-year or 20-year NPV have positive payback periods because the payback period does not include present value losses due to interest.

Table 10-4 Economic analysis for regional high-temperature incineration facility in Minnesota, in millions of USD—sensitivity to incineration fees and capital and O&M cost ranges (3% interest, 20 years)[1]

Metric		NPV at 3% interest (Million USD)			Simple payback period (years)		
Capital cost range		Low ($276)	Med ($368)	High ($460)	Low	Med	High
Incineration fees (USD per ton)	$500	-$300	-$790	-$1,700	No profit	No profit	No profit
	$1,000	$58	-$440	-$1,400	13	No profit	No profit
	$1,500	$410	-$86	-$1,000	6	19	No profit
	$2,000	$760	$270	-$690	4	9	No profit
	$2,500	$1,100	$620	-$330	3	6	32

[1] Cost range reflects both capital and operating cost ranges shown in Table 10-1 and Table 10-2.

Other items (externalities) considered in the economic analysis were benefits to Minnesota WRRFs, greenhouse gas impacts, and the potential for local air and noise pollution. The base case used for comparison assumes that the same amount of sorption media would be disposed of at existing, out-of-state regional high-temperature incineration facilities rather than at a new, in-state facility. Externality economics are summarized in Table 10-5. Local pollution externalities were not quantified but include economic costs associated with damage, decrease in land value, and loss of productivity; social costs such as medical costs; and environmental costs such as biodiversity and sustainability.

Table 10-5 Estimated economic externalities for regional high-temperature incineration in Minnesota (compared to out-of-state incineration)

Benefit externalities	Conversions used	Key metrics	Benefit or cost per year ($/year)
Trucking benefits for Minnesota WRRFs[1]	Trucking miles to cost	2,100,000 miles	$6,000,000
Greenhouse gas emissions benefits (decrease due to less trucking)[2]	Trucking ton-miles to cost Tons equivalent CO_2 to cost	42,000,000 ton-miles 7,500 tons equivalent CO_2	$400,000

[1] Benefits to WRRFs assume equal incineration fees for proposed versus existing out-of-state incinerators but a shorter shipping distance of 50 miles rather than 750 miles and $3/mile for 20-ton trucks. Total miles needed were estimated based on GAC use rates for Alternative 1a for municipal wastewater.

[2] GHG emission cost impacts assume the same energy use for incineration for the proposed versus existing out-of-state incinerator, with GHG savings due to shorter shipping distance based on the International Monetary Fund value of $50/ton (Gillingham 2019) with 161.8 grams of CO_2 per ton-mile of trucking, based on the Environmental Defense Fund (Mathers 2015).

The primary conclusion of the cost analysis of the regional high-temperature incineration facility is that tipping fees need to be over $1,500 to $2,000 (depending on final capital cost) to generate enough revenue over 20 years to offset the capital investment and operational costs.

10.5 Biosolids Pyrolysis/Gasification Facility Concept-Level Design

10.5.1 Design Basis and Equipment Needs

Outside of the Twin Cities metro area, most Minnesota WRRFs treat less than 20 MGD of wastewater influent and produce less than 20 dtpd of solids on average. A regional biosolids facility for PFAS destruction having a treatment capacity of 50 dtpd (200 wet tons of solids at 25% TS) could serve two or more local WRRFs in most areas of the state, except the Twin Cities metro region. Thus, 50 dtpd was selected as the biosolids treatment capacity for the regional pyrolysis/gasification conceptual design. Currently, two regional pyrolysis/gasification facilities in the United States can process more than 50 dtpd: one in New Jersey and the other in California.

A regional drying and pyrolysis/gasification facility requires the following:

- Biosolids receiving station and storage of biosolids
- Drying and pyrolysis/gasification treatment process (including conveyance, air treatment, and other ancillary processes as part of pyrolysis/gasification)
- Biochar storage
- Biochar loadout facility

An equipment vendor typically provides the treatment process as a complete package, including the dryer, pyrolyzer or gasifier, thermal oxidizer, and air emissions and handling equipment. Equipment and facilities supplied by the regional facility owner will be:

- Biosolids receiving station and conveyance
- Biosolids storage (short-term)
- Biochar storage and conveyance
- Biochar loadout
- Warehouse-style building to house dryer, pyrolyzer/gasifier, and thermal oxidizer
- Electrical, natural gas compressed air, and other supporting utilities to the drying and pyrolysis equipment

A summary of the key design parameters for the regional pyrolysis/gasification facility is provided in Table 10-6. For this study, the regional biosolids treatment facility was assumed to be constructed by one of the participating utilities on property already owned by the utility.

Table 10-6 Summary of design basis assumptions for regional biosolids pyrolysis/gasification facility

Design Parameter	Basis
Dewatered biosolids treatment capacity (dtpd)	50
Biosolids feedstock total solids (%TS)	25
Biosolids storage hopper volume (cubic feet, each)	6,400
Days of storage (total)	3
Receiving and hopper area footprint	100 ft x 50 ft
Biochar production rate (ton/dry ton of biosolids)	0.35-0.60
Biochar production (ton/day)	18-30
Days of storage of biochar	14
Biochar storage volume (cubic feet)	9,800
Dryer, pyrolysis/gasification, and thermal oxidizer system footprint	100 ft x 200 ft

A process flow diagram was developed to illustrate the concept of a regional drying and pyrolysis/gasification facility and is provided in Figure 10-3.

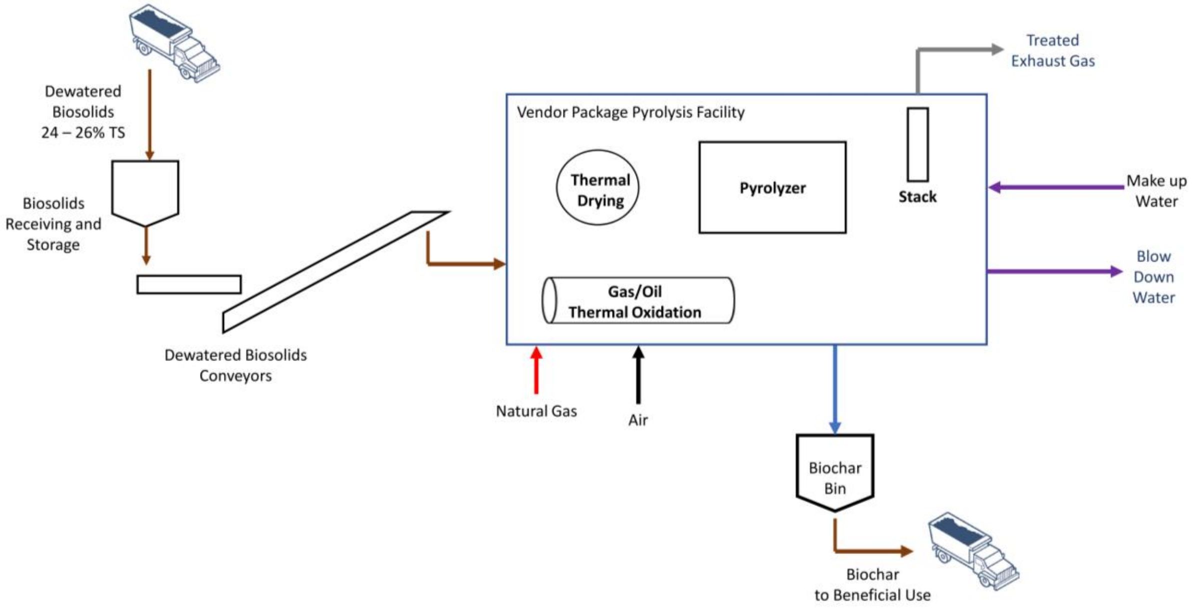


Figure 10-3 Conceptual process flow diagram for regional biosolids pyrolysis/gasification facility

10.5.2 Cost Estimates

Construction cost data for pyrolysis/gasification facilities handling from 4 dtpd to 50 dtpd were assembled and evaluated to develop the costs for a 50 dtpd regional facility (Figure 10-4). Cost estimates were prepared to Class 5 (AACE) accuracy. The estimates included all dryer and pyrolysis/gasification system equipment, piping and conveyance, product storage, ancillary systems, electrical, instrumentation, building, and indirect costs for constructing a complete PFAS destruction system for biosolids. Engineering fees were not included in the estimates.

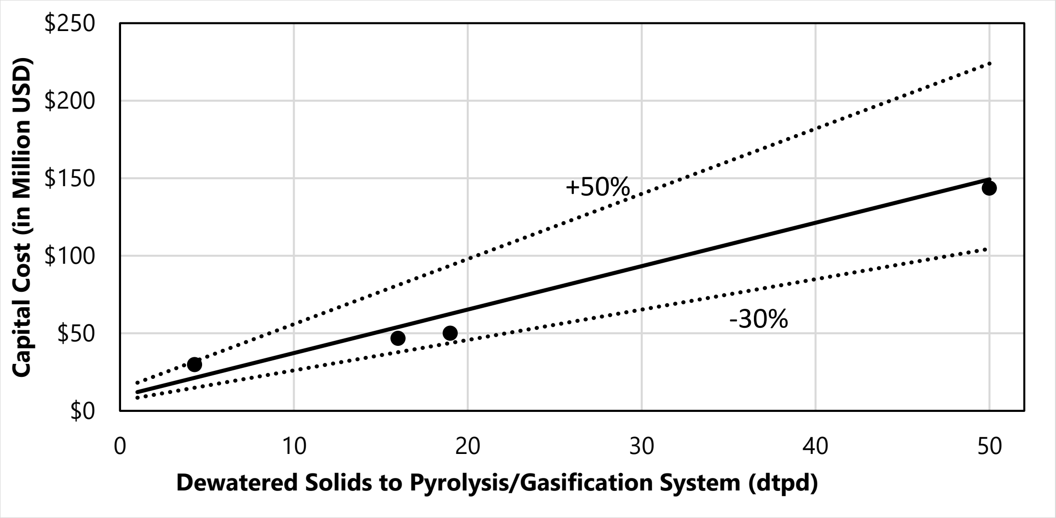


Figure 10-4 Construction cost in millions USD for a biosolids drying and pyrolysis/gasification facility with a capacity of up to 50 dtpd

A regional biosolids pyrolysis/gasification facility for PFAS destruction will likely require equipment in addition to what was included in the estimates used to develop the construction cost (Figure 10-4). Those items are:

- Biosolids receiving and conveyance
- Biosolids storage (short-term)
- Biochar storage and conveyance to loadout

For the conceptual 50 dtpd regional facility in this study, an additional $20 million was added to the capital cost estimate to account for the additional equipment. Table 10-7 summarizes the estimated capital costs for a regional biosolids pyrolysis/gasification facility.

Table 10-7 Estimated capital cost for a regional biosolids pyrolysis/gasification facility in Minnesota

Variable	Capital Cost
Biosolids pyrolysis/gasification process and facility, 50 dtpd	$140,000,000
Biosolids receiving, conveyance, and storage	$10,000,000
Biochar storage and loadout	$10,000,000
Total capital cost	$160,000,000 Range: (-30%) $110,000,000 to (+50%) $240,000,000

Operation and maintenance costs for the regional biosolids facility are assumed to include the following:

- Labor for operation and maintenance—assumed to require two FTEs
- Equipment maintenance—assumed to be 2% of initial capital cost
- Natural gas use at system startup
- Electricity input to the process

The operation and maintenance costs developed from three recent pyrolysis/gasification facility estimates and described in Section 7 of this Report can be applied to the regional facility. Estimates from pyrolysis/gasification systems larger than 10 dtpd showed a trend of decreasing costs per dry ton as the system size increased, as shown in Figure 10-5. A cost of $140 per dry ton was selected as a conservative O&M cost for a 50 dtpd regional facility based on existing installations, which translates to $2.56M in annual operating costs.

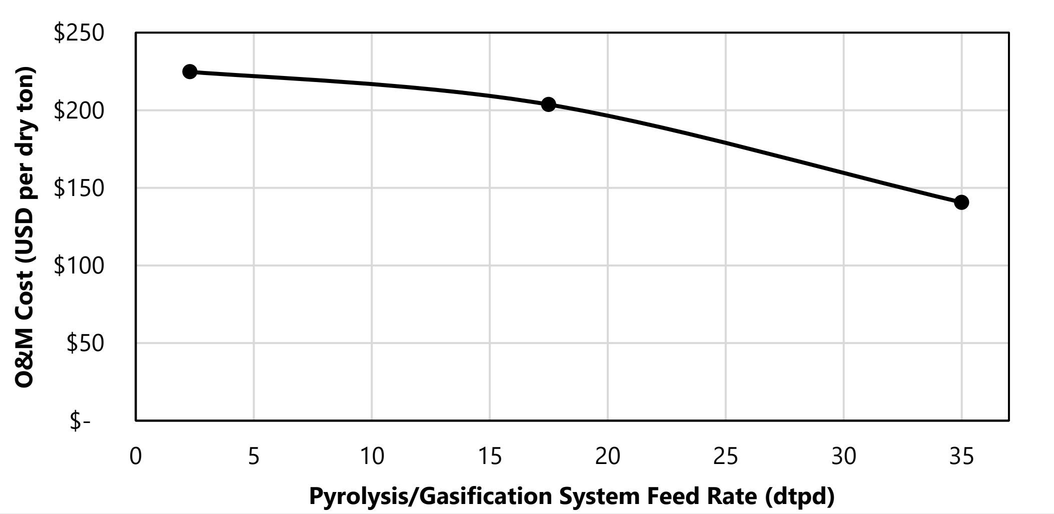


Figure 10-5 **Estimated O&M cost per mass for biosolids pyrolysis/gasification with thermal oxidation**

10.5.3 Economic Analysis

The economics of any regional biosolids pyrolysis/gasification facility will be unique. Many factors will influence the economic analysis, including any initial investment of the consortium in the system purchase, inflation of utility and commodity prices, fees charged per ton of biosolids received at the facility, and revenue generated from the sale of the biochar product. To simplify the economic analysis of a regional pyrolysis/gasification system, the utility constructing the pyrolysis/gasification facility was assumed to pay the facility's initial capital cost, which would then be amortized over the analysis period. Income would be obtained from the tipping fees on the biosolids received at the pyrolysis/gasification facility. The biochar product would not generate revenue or have a disposal cost. Energy recovered from the pyrolysis/gasification process will be fully used within the process.

The NPV of a 50 dtpd regional pyrolysis/gasification system is the present value of the amortized capital cost and the sum of operation and maintenance costs over a specified evaluation period. An analysis of the sensitivity of the NPV to changes in tipping fee and real interest rate is shown in Table 10-8. (This analysis demonstrates that the NPV is more sensitive to changes in real interest rate as the tipping fees increases. The scenarios with lower interest rates and the highest tipping fee charged over 20 years were the only scenarios with a positive NPV.

Table 10-8 Economic analysis for regional pyrolysis/gasification facility in Minnesota, in millions of USD—sensitivity of NPV to biosolids tipping fees and real interest rate

	Real interest rate	2%	4%	6%	Simple payback period (years)
	Project evaluation period	20 years	20 years	20 years	
Tipping fee (USD per wet ton)	$50	-$147	-$150	-$153	>20
	$100	-$86	-$100	-$110	>20
	$150	-$26	-$49	-$68	>20
	$200	$35	$1	-$25	15

A second analysis fixed the interest rate to test the sensitivity of the NPV and payback period to the capital cost and tipping fees, as shown in Table 10-9. The lowest capital cost and highest tipping fee scenarios achieved a payback period of fewer than 20 years. Half of the scenarios, however, required more than 20 years to achieve a simple payback on the system and its operation.

Table 10-9 Economic analysis for regional pyrolysis/gasification facility in Minnesota, in millions of USD - sensitivity to tipping fees and capital and O&M cost ranges (3% interest, 20 years)

Metric		NPV at 3% interest (Million USD)			Simple payback period (years)		
Capital cost range		Low ($110)	Med ($160)	High ($240)	Low	Med	High
Tipping fee ($/wet ton)	$50	-$97	-$150	-$233	>20	>20	>20
	$100	-$41	-$94	-$178	>20	>20	>20
	$150	$13	-$40	-$123	10	>20	>20
	$200	$38	$15	-$68	1	10	>20

While Table 10-9 indicates the 20-year NPV of the conceptual regional pyrolysis/gasification facility is favorable only at the higher tipping fee and lower construction cost range, it is important to consider that costs and revenue streams were kept simplistic for this initial evaluation of conceptual lifecycle costs. This analysis assumed the owner of the regional facility would bear the full cost of construction and maintenance over the 20-year period, collecting revenue only from tipping fees.

A regional facility could decrease its capital cost and increase annual income by contracting with the individual WRRFs to contribute to the construction cost of the facility and to pay an annual O&M fee. A scenario was developed for a 50 dtpd regional facility that included capital cost contributions from the participating utilities, annual fees, and tipping fees. It was assumed the regional facility operated at 80%

capacity on average. Biochar revenue was not included because its market value is currently unknown. The parameters used and the resulting NPV of the project for the regional facility are shown in Table 10-10. This scenario demonstrates the financial benefit to the regional facility owner of cost-sharing for the construction of the facility and charging regular maintenance fees.

Table 10-10 NPV of a regional pyrolysis/gasification facility in Minnesota with capital cost and O&M contributions from individual WRRFs

Variable	Value
Regional pyrolysis/gasification facility treatment capacity (dtpd)	50
Regional pyrolysis/gasification facility construction cost	-$160,000,000
Number of utilities using the regional pyrolysis/gasification facility	5
Construction cost contribution per utility	$5,000,000
Annual maintenance fee per utility	$1,000,000
Tipping fee collected (per wet ton)	$150/wet ton
Dewatered biosolids processed (wet ton per day)	160
Real interest rate	3%
NPV (3% interest, 20 years)	$28,800,000

This scenario demonstrates that a regional pyrolysis/gasification facility is economically viable for the owner of the regional facility when participating utilities pay more than the tipping fees alone. The scenario was further developed to compare the costs to a utility for contracting with the regional pyrolysis/gasification facility to the cost of constructing and operating their own pyrolysis/gasification facility. The utility was assumed to construct a 10 dtpd pyrolysis/gasification facility on their existing site and use it to process an average of 8 dtpd. In Table 10-11, costs detailed in Section 7 of this Report for constructing and operating an independent, 10 dtpd pyrolysis/gasification facility are compared to the cost to the utility for being part of a regional facility.

Table 10-11 Comparison of cost to utility for construction and operation of an independent pyrolysis/gasification facility versus a regional facility

	Value to utility - independent facility	Value to utility – regional facility
Pyrolysis/gasification treatment capacity on-site (dtpd)	10	0
Dewatered biosolids processed/trucked (dtpd)	8	8
Dewatered biosolids processed (wet ton per day, 25% TS)	32	32
Utility contribution to pyrolysis/gasification facility construction cost	-$75,700,000	-$5,000,000
Power, natural gas, labor, and consumables annual cost (in year 1, cost escalated over 20 years)	-$600,000	$0
Annual maintenance fee for regional facility	$0	-$1,000,000
Tipping fee (per wet ton)	$0	-$150/wet ton
Biosolids hauling cost ($3/mile, 50 miles round trip)[1]	$0	-$11/wet ton
NPV (3% interest, 20 years) for individual utility	-$87,600,000	-$41,600,000

[1] Full truck load is approximately 14 tons of biosolids. WRRF requires 2.3 trucks per day.

This analysis shows that pyrolysis/gasification treatment of biosolids would be a significant investment for a WRRF producing 10 dtpd of biosolids. However, the cost to the utility would be lower when participating in a consortium of smaller biosolids producers to support a regional pyrolysis/gasification facility.

The primary conclusions of the cost analysis of the regional pyrolysis/gasification facility are summarized into the following:

- Lower capital costs and a lower interest rates make the regional facility more economically viable.
- Tipping fees over $150/wet ton can generate enough revenue over 20 years to offset the capital investment and operational costs of a regional facility.
- The NPV of a regional pyrolysis/gasification facility is improved significantly if the participating utilities contribute to the initial construction cost and pay an annual maintenance fee.
- The cost to the utility for sending biosolids to the regional pyrolysis/gasification facility is less than half the cost of building and operating their own facility.
- A regional pyrolysis/gasification facility is an economically viable option if a group of utilities needs to implement biosolids treatment for PFAS destruction.

10.6 Permitting and Siting Considerations

Permitting and building a new PFAS-focused waste management facility in Minnesota present significant barriers. Currently, no PFAS destruction facilities are located in Minnesota. However, the permitting requirements for similar facilities provide a framework for what could be expected. For example, public acceptance of this type of facility could be a primary barrier and care would be needed during planning and siting to ensure that such a facility would not disproportionately affect disadvantaged communities.

The air emissions associated with a PFAS destruction facility are expected to be between 10 and 50 tons/year each for PM, SO_2, VOCs, and NO_x (Arkansas DEQ 2013). In addition, the potential for PFAS emissions from these facilities needs to be evaluated. Multiple studies have demonstrated over 99.9% removal of target PFAS, with airborne concentrations below detection limits (Thoma et al. 2022; DiStefano et al. 2022; Davis 2020), but a full mass balance on organic fluorine has not been closed. Minnesota has air emission standards for PFBA, PFHxA, PFHxS, PFOA, and PFOS in the range of 0.05 to 10 $\mu g/m^3$ (Minnesota Department of Health n.d.), all of which were met in the Arkansas study referenced above for a high-temperature incineration facility similar to the potential facility outlined here. However, airborne PFAS emissions were measured on the order of 0.35 $\mu g /m^3$ in stack gas for the sum of the five regulated compounds listed above (DiStefano et al. 2022), suggesting some potential to exceed Minnesota standards as designed.

This type of facility would be difficult to permit, and if permittable, would likely take many years to do so. A new facility would likely trigger a mandatory Environmental Impact Statement (EIS) pursuant to Minn. R. 4410.4400 Subpart 12 or 13 or a discretionary EIS if the project would be viewed as controversial by the public. An EIS would likely require a minimum of three years to approve and may take more than 10 years. The EIS would require several technical analyses, potentially including an unprecedented Air Emissions Risk Assessment focusing on PFAS emissions. The facility would likely trigger an air dispersion modeling assessment to demonstrate compliance with the National Ambient Air Quality Standards and may require additional air pollution control equipment (the primary concern being nitrous oxide emissions), which could further increase costs and permitting time. The facility may generate PFAS-containing industrial stormwater and wastewater streams and may require site-specific PFAS treatment processes required by the National Pollutant Discharge Elimination System (NPDES) program. Depending on the siting of the facility and public interest in the project, the facility location could present environmental justice concerns and/or undergo substantial public scrutiny during the public comment periods that would delay the permitting timeline.

Permitting would likely be easier for an existing service provider that already operates high-temperature incineration because existing suppliers would have actual emissions data from their operating units. For a new facility, several conservative assumptions (e.g., post-control toxics concentrations, pre-control storage tank specifications, etc.) could cause permitting issues and may require additional analyses (e.g., toxic pollutants sensitivity analyses, modeling iterations, sampling campaigns, etc.).

11 PFAS Management Themes and Conclusions

11.1 Breaking the Cycle

Future work to reduce the human and environmental health impacts of PFAS could focus on breaking the cycle of continuous shifting between soils, groundwater, surface water, and the atmosphere. Breaking the cycle could include reducing the load of PFAS routed to the environment in waste streams (the focus of this study), reducing cross-media transfer of PFAS, and removing PFAS from the environment for final destruction. Other upstream options could include producing fewer PFAS-containing products to limit future PFAS discharges to the environment.

As described in Section 1, wastewater and solid waste management systems are key routes for PFAS to enter the environment from a multitude of consumer products. These sources were illustrated in Figure 1-1. This study has evaluated the feasibility of currently available technologies and estimated the associated costs to apply these technologies for end-of-pipe PFAS removal and destruction for four waste streams, which would contribute to breaking the continued cycling of PFAS in the environment. Summary costs presented in this section generally use the lowest cost alternative for each waste stream. The alternative selected for liquid waste streams was tertiary treatment followed by GAC adsorption and GAC reactivation or incineration, depending on the facility flow rate. The alternative selected for WRRF biosolids was pyrolysis/gasification with thermal oxidation. However, each project should evaluate site-specific requirements and constraints to select the most suitable alternative.

11.2 Costs per Mass of PFAS Removed

The results of this study show that the cost per mass of PFAS destroyed is lower for higher-concentration waste streams like mixed MSW landfill leachate, compost contact water, and to some extent, WRRF biosolids, relative to municipal WRRF effluent.

Removal and destruction of PFAS over a 20-year operating period are expected to cost from $2.7 to $18 million per pound of PFAS removed for WRRF effluent (including retrofits for tertiary treatment) and $1.0 to $2.7 million per pound for WRRF biosolids (including biosolids dewatering upgrades) (Table 11-1). These costs will vary depending on facility size, biosolids production rates, and the concentration and speciation of PFAS reporting to biosolids and effluent at each facility. In contrast, the estimated cost per pound of PFAS removed is considerably lower at large landfill facilities, with potential costs as low as $400,000 per pound of PFAS removed at landfills treating 100 gpm of leachate.

This finding highlights the high cost of removing PFAS at WRRFs. Lower costs per mass of PFAS may be achieved at upstream facilities and landfills due to the higher concentration of PFAS in those discharges versus blended municipal WRRF influent. Costs per mass of PFAS removed at municipal WRRFs decrease as the facility size increases, indicating PFAS removal at larger WRRFs may be more economical. Costs per mass of PFAS removed are higher in compost contact water than in other waste streams evaluated due to the economy of scale for implementing complex water treatment at low flow rates.

Table 11-1 Estimated cost per mass of PFAS removed from targeted waste streams over 20 years[1]

	Size/Production		
Municipal WRRF facility size[3]	0.1 MGD	1 MGD	10 MGD
Municipal WRRF effluent capital	$7,300,000	$32,000,000	$120,300,000
Municipal WRRF effluent annual O&M	$500,000	$1,400,000	$6,400,000
Total 20-year cost for municipal WRRF effluent[2]	$12,600,000	$46,900,000	$188,200,000
Cost per lb PFAS removed over 20 years[5]	$18,100,000	$6,800,000	$2,700,000
Municipal WRRF biosolids production[4]	On-site biosolids management for facilities smaller than 1 dtpd is not expected to be economical.	1 dtpd	10 dtpd
Municipal WRRF biosolids capital		$24,600,000	$85,200,000
Municipal WRRF biosolids annual O&M		$200,000	$800,000
Total 20-year cost for municipal WRRF biosolids		$26,800,000	$93,700,000
Cost per lb PFAS removed over 20 years[5]		$2,700,000	$1,000,000
Mixed MSW landfill facility size[3]	1 GPM	10 GPM	100 GPM
Mixed MSW landfill leachate capital	$300,000	$800,000	$4,800,000
Mixed MSW landfill leachate annual O&M	$400,000	$400,000	$700,000
Total 20-year cost for mixed MSW landfills	$4,600,000	$5,100,000	$12,300,000
Cost per lb PFAS removed over 20 years[5]	$12,000,000	$1,400,000	$400,000
Composting facility size[3]	1 GPM	10 GPM	100 GPM
Compost contact water capital	$300,000	$800,000	$4,800,000
Compost contact water annual O&M	$300,000	$300,000	$600,000
Total 20-year cost for composting facilities	$3,500,000	$4,400,000	$11,200,000
Cost per lb PFAS removed over 20 years[5]	$39,300,000	$4,500,000	$1,300,000

MGD = million gallons per day, dtpd = dry tons per day, and gpm = gallons per minute

[1] Costs presented here reflect estimated project cost (Class 5 per AACE) developed with an associated uncertainty of +50%/-30% for both capital and annual O&M cost estimates. Costs are based on design basis concentrations selected to be typical of those reported in WRRF effluent (Helmer, Reeves, and Cassidy 2022; Coggan et al. 2019; Thompson et al. 2022), biosolids (Venkatesan and Halden 2013; Helmer, Reeves, and Cassidy 2022), landfill leachate (Lang et al. 2017), and compost contact water (Wood Environment & Infrastructure Solutions Inc. 2019). All costs are rounded up to the nearest $100,000.

[2] 20-year costs reflect present value calculations using an interest rate of 7%.

[3] Upgrade costs for liquid-phase treatment in WRRF effluent, mixed MSW landfill leachate, and compost contact water are for PFAS separation and destruction using GAC adsorption with high-temperature incineration of media (at flows below 10 MGD) or GAC reactivation (at 10 MGD or higher). These include approximate costs for tertiary treatment retrofits (at WRRFs) or pretreatment processes (at mixed MSW landfill leachate and composting sites) likely needed at most facilities to provide the water quality required for GAC feed.

[4] Upgrade costs are for PFAS destruction in WRRF biosolids using pyrolysis or gasification with thermal oxidation of produced gasses. Costs include centrifuge dewatering to provide 25% solids material for process feed for each facility.

[5] Mass PFAS removed reflect the sum of assumed concentrations of PFAS targeted in this study (PFOA, PFOS, PFHxA, PFHxS, PFBA, PFBS, 6:2 FTS, PFOSA, N-EtFOSAA, and N-MeFOSAA) as previously documented in Sections 2.3, 6.1.2, 7.1.2, 8.1.2, 9.1.2 multiplied by the flow rate or solids production rate shown.

11.3 PFAS Management Options for Minnesota

Society's ability to manage PFAS in the environment will depend upon strategies to remove these chemicals from consumer products and identify and implement cost-effective technologies to remove and destroy PFAS. Removal of PFAS from WRRF effluent using technologies currently available may not be practical due to the high costs per mass of PFAS treated. By comparison, the cost for removal of PFAS from WRRF biosolids, mixed MSW landfill leachate, and compost contact water is more efficient. Still, it could also benefit from innovation and improvement in the efficiency of future remediation technologies. Upstream source control measures may prove to be a more cost-effective approach to reducing PFAS than the PFAS management alternatives evaluated in this study.

The results of this study suggest that the 20-year cost to retrofit existing WRRFs larger than 0.05 MGD (typical for a town of about 500 people) to remove and destroy PFAS from WRRF effluent and biosolids across Minnesota is on the order of at least $14 billion for the PFAS listed in Table 2-1. Cost estimates for implementation at all plants larger than 0.05 MGD in Minnesota are summarized in Table 11-2. These cost estimates are order-of-magnitude estimates based on the estimated number and size of facilities in the state, using the treatment targets selected by MPCA and design bases defined in this Report. These costs will vary depending on the actual facilities implementing treatment.

The estimates for municipal WRRF biosolids given in Table 11-2 do not include the cost to upgrade the largest WRRF in Minnesota to pyrolysis/gasification with thermal oxidation. To date, there is no application of pyrolysis/gasification systems for biosolids at the scale of Minnesota's largest WRRF and no cost information available to estimate the 20-year cost for such a system. The largest facility might need to install multiple units on-site. The size and number of units could be determined as pyrolysis/gasification systems develop and scale up.

An exact count of mixed MSW landfills and SSOM compost facilities in Minnesota is difficult to develop due to mixed wastes accepted at many facilities. However, using an estimate of 24 mixed MSW landfills and nine SSOM compost facilities results in estimated 20-year costs of between $77M–$160M and $28M–$60M, respectively.

Table 11-2 Estimated 20-year costs for PFAS removal from targeted waste streams in Minnesota, in million USD[1]

Municipal WRRF facility size[3]	0.1 MGD	1 MGD	10 MGD	300 MGD	Total for MN
Approximate # of facilities in Minnesota	100	155	27	1	283
Municipal WRRF effluent capital costs	$500 - $1,100	$3,500 - $7,400	$2,300 - $4,900	$1,300 - $2,800	$7,500 - $16,000
Municipal WRRF effluent annual O&M costs	$29 - $60	$150 - $330	$120 - $260	$110 - $230	$410 - $870
Total 20-year costs, municipal WRRF effluent[2]	$800 - $1,700	$5,100 - $11,000	$3,600 - $7,600	$2,400 - $5,200	$12,000 - $25,000
Municipal WRRF biosolids production[4]	**<1 dtpd**	**1 dtpd**	**10 dtpd**		**Total for MN**
Approximate # of facilities in Minnesota	1 (regional)	40	10		51
Municipal WRRF biosolids capital costs	$110–$240	$680–$1,500	$630–$1,400		$1,400–$3,100
Municipal WRRF biosolids annual O&M costs	$2.5–$5.3	$4.7–$10	$5.5–$12		$13–$27
Total 20-year costs, municipal WRRF biosolids[2]	$140–$300	$730–$1,600	$690–$1,500		$1,600–$3,300
Mixed MSW landfill facility size[5]	**1 gpm**	**10 gpm**	**100 gpm**		**Total for MN**
Approximate # of facilities in Minnesota	6	15	3		24
Mixed MSW landfill leachate capital costs	$1.0–$3.0	$8.0–$18	$10–$20		$20–$40
Mixed MSW landfill leachate annual O&M costs	$1.3–$2.8	$3.4–$7.2	$0.74–$1.6		$5.4–$12
Total 20-year costs, mixed MSW landfills[2]	$15–$32	$44–$94	$18–$38		$77–$160
Composting facility size[6]	**1 gpm**	**10 gpm**	**100 gpm**		**Total for MN**
Approximate # of facilities in Minnesota	4	4	1		9
Compost contact water capital costs	$0.84–$1.8	$2.2–$4.8	$3.4–$7.2		$6.4–$14
Compost contact water annual O&M costs	$0.78–$1.7	$0.81–$1.7	$0.42–$0.90		$2.0–$4.3
Total 20-year costs, composting facilities[2]	$9.1–$20	$11–$23	$7.8–$17		$28–$60

MGD = million gallons per day, dtpd = dry tons per day, and gpm = gallons per minute

[1] This statewide evaluation carries additional uncertainty related to approximations made for facility sizing, number of facilities, and degree of pretreatment needed. Costs are rounded to two significant figures. Costs are based on design basis concentrations selected to be typical of those reported in WRRF effluent (Helmer, Reeves, and Cassidy 2022; Coggan et al. 2019; Thompson et al. 2022), biosolids (Venkatesan and Halden 2013; Helmer, Reeves, and Cassidy 2022), landfill leachate (Lang et al. 2017), and compost contact water (Wood Environment & Infrastructure Solutions Inc. 2019).

[2] Twenty-year costs reflect present value calculations using an interest rate of 7%.

[3] WRRF upgrade costs for effluent treatment are for PFAS separation and destruction using GAC adsorption with high-temperature incineration of media at flow rates below 1.1 MGD and GAC reactivation at higher flow rates. These include approximate costs for tertiary treatment retrofits (at WRRFs) or pretreatment processes (at mixed MSW landfill leachate and composting sites) likely needed at most facilities to provide the water quality required for GAC or RO feed. This analysis excludes WRRFs below 0.05 MGD.

[4] WRRF upgrade costs are for PFAS destruction in biosolids using pyrolysis or gasification with thermal oxidation of produced gasses. Costs include centrifuge dewatering to provide 25% solids material for process feed for each facility. These assume that WRRFs treating more than 0.1 MGD but producing less than 1 dtpd biosolids would ship to one regional, 50-dtpd pyrolysis facility. The costs shown here do not include transporting biosolids to that facility. These costs also do not include a pyrolysis/gasification facility with thermal oxidation for Minnesota's largest WRRF because costs for a facility of this size are not available.

[5] Operating landfill facilities in Minnesota and their size and leachate reported for Minnesota landfills accepting primarily MSW, assuming equalization is present to limit peak leachate flows to twice the annual average leachate flow.

[6] Operating compost facilities in Minnesota and their size were estimated based on publicly available data.

Costs developed here are meant to reflect order-of-magnitude costs based on facilities in Minnesota using GAC for liquid streams and pyrolysis for biosolids. The 300 MGD WRRF facility PFAS treatment costs were developed as a separate cost estimate using available equipment. For a GAC facility of this size, there are many design, operation, and maintenance uncertainties that were not explicitly considered in this conceptual cost.

In addition to the costs of building and operating a PFAS removal system, operator training and infrastructure would need to be enhanced to properly operate these systems, which have not been implemented for wastewater treatment in Minnesota. For context, wastewater operators have spent decades developing, refining, and passing along operational knowledge that allows conventional wastewater technologies to operate. A similar multi-year process of operational training and knowledge acquisition would take time to develop for PFAS-related technologies to work as designed.

While PFAS removal and destruction in the waste streams considered in this study may appear infeasible because of their estimated high costs, this study only considered technologies currently commercially available at the applicable scale. This presents an opportunity to support innovation and creative approaches to address PFAS treatment in these waste streams. These opportunities could include funding scale-up projects of emerging technologies, funding demonstration studies of emerging technologies for real-world waste streams, and funding comprehensive investigations of PFAS mass balances using both existing destruction technologies (i.e., high-temperature incinerators) and emerging technologies.

11.4 Energy Use and Associated Carbon Dioxide Emission Equivalents

While PFAS removal and destruction could be a future priority for waste and wastewater managers, sustainability and climate impacts are also increasingly prioritized. Table 11-3 summarizes estimated energy usage and CO_2 equivalents per mass of target PFAS removed from the liquid waste streams. Estimates are shown for the mid-range flows only for each waste stream. These estimates account for the following:

- The electricity and natural gas used specifically by PFAS separation equipment within the WRRF, landfill, or compost facility
- The electricity and natural gas used at the site or disposal facility (as applicable) to combust the sorption media concentrate

These estimates focus on energy usage from PFAS separation and destruction technologies. They do not account for CO_2 emissions associated with the production or transportation of the GAC media or AIX resin, mineralization of waste materials being destroyed (e.g., media), or beneficial reuse of treatment byproducts (e.g., use of regenerated GAC). The estimates also do not include energy usage associated with pretreatment ahead of the PFAS management alternatives. Other studies have evaluated the life cycle environmental impacts of PFAS treatment options in more detail (Boyer, Ellis, et al. 2021; G. Li et al. 2022).

The estimated weight of CO_2 equivalents emitted per weight of target PFAS removed ranges from 50 tons CO_2-eq/lb PFAS removed for foam fractionation of mixed MSW landfill leachate up to 2,200 lb CO_2-eq/lb PFAS removed for WRRF effluent treated with GAC and AIX resin and offsite high-temperature incineration of the sorption media. The CO_2 emission rates per pound of PFAS removed are highest for alternatives using GAC or a combination of GAC and AIX resin, at an estimated 1,000 and 2,200 ton CO_2-eq/lb PFAS for compost contact water and WRRF effluent, respectively. The exception is mixed MSW landfill leachate treated with GAC, where the CO_2 emission rate is 250 lb CO_2-eq/lb PFAS. The CO_2 emission rates per pound of PFAS removed are relatively low for mixed MSW landfill leachate due to the relatively high PFAS content of these waste streams. Foam fractionation with high-temperature incineration of the foamate for mixed MSW landfill leachate and compost contact water treatment both have lower estimated CO_2 emissions per pound of PFAS removed relative to GAC adsorption with high-temperature incineration of the media.

Table 11-3 Estimated energy use and CO_2 equivalents for PFAS management alternatives

Waste Stream	Facility Size	Highest Ranking Alternatives	Estimated Electricity Use (MWh/y) [1,2,3]	Estimated Natural Gas Use (kSCF/y) [1,2,3]	Estimated CO_2 Equivalent Emissions from Energy Use (ton/y)[4]	Estimated CO_2 Equivalents per Mass PFAS (ton CO_2/lb PFAS)[4,5]
Municipal WRRF effluent	1 MGD (700 gpm)	GAC with high-temperature incineration (Alt 1a)	210	10,000	720	2,100
		GAC and AIX with GAC and AIX high-temperature incineration (Alt 6a)	220	11,000	770	2,200
Mixed MSW landfill leachate	0.014 MGD (10 gpm)	GAC with high-temperature incineration (Alt 1a)	70	250	50	250
		Foam fractionation with high-temperature incineration of foamate (Alt 8a)	20	40	10	50
Compost contact water	0.014 MGD (10 gpm)	GAC with high-temperature incineration (Alt 1a)	70	210	40	1,000
		Foam fractionation with high-temperature incineration of foamate (Alt 8a)	20	40	10	230

[1] Electricity and natural gas use reflect estimates based on preliminary sizing and operational needs developed for this study and are subject to the +50%/-30% uncertainty range used throughout for operational costs.

[2] Estimates include the electricity and natural gas used specifically by the PFAS management systems within the WRRF, landfill, or compost facility, as well as the electricity and natural gas used at the disposal facility (as applicable) to combust the sorption media or concentrate. These estimates do not account for CO_2 emissions associated with media production, transportation, destruction of the media or biosolids materials, or potential emissions associated with the beneficial reuse of treatment byproducts (e.g., use of biochar from pyrolysis). The estimates also do not include energy usage associated with pretreatment ahead of the PFAS management alternatives.

[3] The amount of natural gas and electricity used by a high-temperature incinerator was estimated, assuming 46 MMBTU/ton of waste and 209 kWh/ton of waste, respectively, based on similar project experience.

[4] CO_2 emissions were estimated based on U.S. EPA guidance values of 953.7 lbs CO_2 per MWh and 55.1 kg CO_2 per 1,000 cubic feet of natural gas (U.S. EPA 2022a).

[5] Mass PFAS removed reflects the sum of assumed concentrations of PFAS targeted in this study (PFOA, PFOS, PFHxA, PFHxS, PFBA, PFBS, 6:2 FTS, and N-EtFOSAA) as previously documented in Sections 2.3, 6.1.2, 7.1.2, 8.1.2, 9.1.2 multiplied by the flow rate shown.

[6] Estimated energy use and CO_2 equivalents for WRRF biosolids treatment alternatives were excluded from this analysis. The energy consumption/production and CO_2 equivalents are unique to each biosolids installation and not suitable for this analysis.

11.5 Limitations on Use of Cost Estimates

Preliminary designs and costs were developed for a range of facility sizes to address design basis influent water and biosolids quality established for this study. Equipment sizing, media changeout frequency, and other factors are expected to vary across facilities depending on site-specific conditions and actual design bases, potentially pushing capital and O&M costs outside the range estimated for a specific design basis in this study. The costs presented here are intended to be useful for high-level, regional, and economic comparisons and are not appropriate for site-specific facility planning. Site-specific factors expected to influence actual technology selection, design, and costs include the following:

- Existing site infrastructure and treatment processes
- Space constraints and availability at the site
- Continuous versus intermittent nature of flows
- Water quality compared to design basis assumed
- Water quality variation
- PFAS concentrations and speciation
- Treatment goals for PFAS (concentrations, specific compounds, and reliability targets)
- Treatment goals for other parameters requiring removal
- Preferred site trade-offs for capital cost versus the level of operational complexity

11.6 Costs to Manage Short-Chain versus Long-Chain PFAS

Changing PFAS treatment targets and regulations complicate the estimation of treatment costs, especially O&M costs associated with sorption media changeout. While PFOA and PFOS have received the most regulatory attention, they are also two of the easier PFAS to remove from water because they are relatively hydrophobic. In contrast, short-chain PFAS, such as PFBA, PFHxA, and PFBS, prefer to stay in the water phase and are harder to remove through media sorption, AIX, and foam fractionation.

While 28 states have water phase guidelines (including drinking water, groundwater, surface water, and wastewater) for PFOA or PFOS, as of January 2023, only 14 states currently have water phase guidelines for PFBA or PFBS (ITRC 2023). The U.S. EPA's recently proposed National Primary Drinking Water Regulation for PFAS includes PFOA, PFOS, PFNA, PFHxS, PFBS, and HFPO-DA (U.S. EPA 2023). This list also favors long-chain compounds over short-chain compounds and more sorbable sulfonates over alkyl acids. The availability of appropriate water treatment and environmental remediation technologies should be considered as the types of PFAS in use evolve, and regulations around use and environmental discharge are updated.

Alternatives relying on GAC sorption or AIX media to separate PFAS from the water phase will require much more frequent sorption media changeout to remove short-chain compounds consistently. This results in higher O&M costs for facilities using GAC or AIX media to remove short-chain PFAS, especially at higher flow rates. Figure 11-1 illustrates the estimated O&M cost multiplier for targeting short-chain PFAS (PFBA or PFBS) versus targeting long-chain PFAS (PFOA). This multiplier varies between a factor of 1.1 and 1.7 and increases with increasing flow. Both indicate that media changeout increasingly affects O&M costs at relatively high flows, high influent PFAS concentrations, and a high ratio of short-chain to long-chain PFAS concentrations.

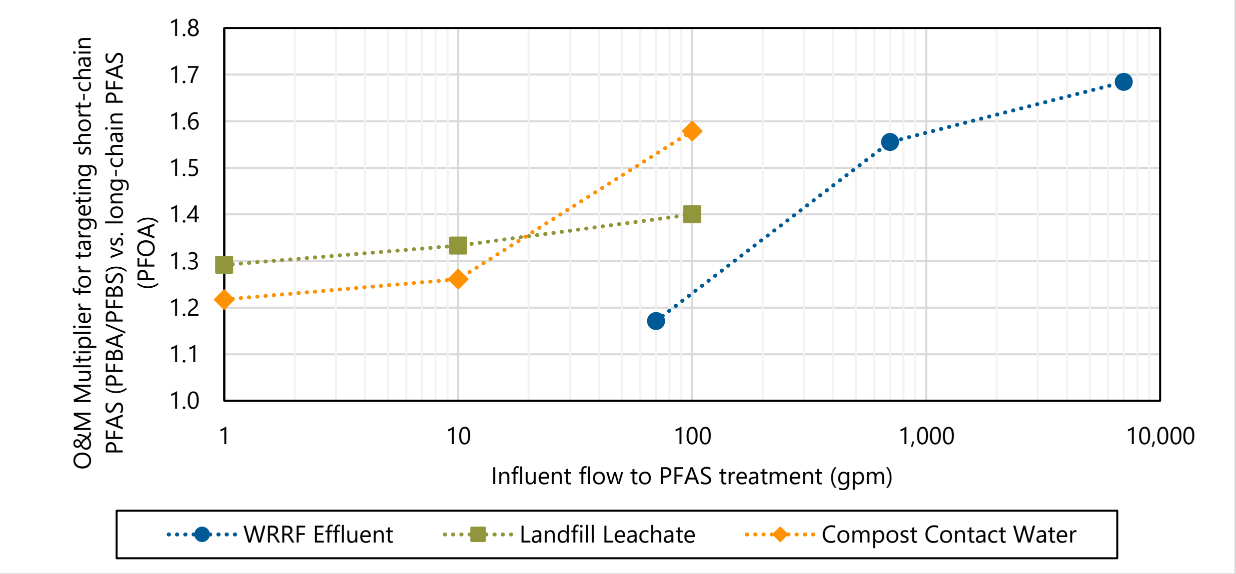


Figure 11-1 **Estimated O&M cost multiplier for GAC treatment targeting short-chain (PFBA or PFBS) removal versus long-chain (PFOA) removal for municipal WRRF effluent, mixed MSW landfill leachate, and compost contact water**

11.7 Technology Readiness

Except for foam fractionation, liquid treatment technologies currently available at commercial scales (i.e., GAC, AIX, modified clay, and RO) are considered general water treatment options; they remove many parameters and are not specifically designed for PFAS removal. More targeted technologies to further concentrate and destroy PFAS are being developed and have been demonstrated at bench and pilot scales. These technologies (including electrochemical oxidation, electrochemical or UV-assisted reduction, HALT, and SCWO) could potentially provide lower-cost and better implementable treatment at individual facilities, perhaps reducing or eliminating the need for regional or out-of-state high-temperature incineration facilities. However, due to investment and staffing challenges, the capacity of these technology vendors to scale-up equipment production is limited. Other challenges related to the evaluation of emerging PFAS destruction technologies include the following:

- Limited data on PFAS destruction efficacy at real sites with a full fluorine mass balance
- Potential for PFAS to escape with the gas phase
- Potential to produce alternate PFAS or other byproducts

- Ability to remove short-chain compounds
- Potential for scaling at high temperatures with salty feed streams
- High energy costs of some technologies, especially thermal technologies
- Regulatory uncertainty related to permitting installations and their emissions and discharges
- Ability to scale-up unit production, depending on future demand

Optimizing general destruction technologies for PFAS destruction continues to progress and needs additional scale-up opportunities to vet and optimize performance across a range of water quality and waste streams.

11.8 Future Research Needs

For PFAS management in the waste streams presented in this study to keep up with evolving regulations and public perception, the following research and development topics could be considered:

- Develop and apply regulatory pathways to permit facilities specifically for PFAS destruction
- Increase public and private investment in next-generation, lower-cost technologies to accelerate scale-up and implementation timelines
- Study full fluorine balance for next-generation PFAS separation and destruction technologies to understand destruction pathways and potential byproducts
- Conduct further research and support the development of low-temperature PFAS destruction options, with a specific focus on reducing full-scale treatment costs
- Consider safety concerns associated with PFAS aerosolization in existing and future processes

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Appendices

Appendix A

PFAS Chemical Characteristics and Most Similar "Target PFAS" Used in this Study

Appendix A PFAS Chemical Characteristics and Most Similar "Target PFAS" Used in this Study

Abbreviation	Name	CAS Number	Total No. C atoms	Number of fluorinated C atoms	MW	Fuctional group	Most Similar Target PFAS
PFMPA	Perfluoro-3-methoxypropanoic acid	377-73-1	4	3	230	COOH	PFBA
PFBA	Perfluorobutanoic acid	375-22-4	4	3	214	COOH	
PFMBA	Perfluoro-4-methoxybutanoic acid	151772-58-6	5	4	280	COOH	PFBA
PFPeA	Perfluoropentanoic acid	2706-90-3	5	4	264	COOH	PFHxA
NFDHA	Perfluoro-3,6-dioxaheptanoic acid	151772-58-6	5	4	296	COOH	PFHxA
PFHxA	Perfluorohexanoic acid	307-24-4	6	5	314	COOH	
PFHpA	Perfluoroheptanoic acid	375-85-9	7	6	364	COOH	PFOA
PFOA	Perfluorooctanoic acid	335-67-1	8	7	414	COOH	
PFNA	Perfluorononanoic acid	375-95-1	9	8	464	COOH	PFOA
PFDA	Perfluorodecanoic acid	335-76-2	10	9	514	COOH	PFOA
PFUnA	Perfluoroundecanoic acid	2058-94-8	11	10	564	COOH	PFOA
PFDoA	Perfluorododecanoic acid	307-55-1	12	11	614	COOH	PFOA
PFTrDA	Perfluorotridecanonic acid	72629-94-8	13	12	664	COOH	PFOA
PFTDA or PFTA or PFTeDA	Perfluorotetradecanoic acid	376-06-7	14	13	714	COOH	PFOA
PFBS	Perfluorobutane sulfonate	375-73-5	4	4	300	SO3H	
PFEESA	Perfluoro(2-ethoxyethane)sulfonic acid	113507-82-7	4	4	316	SO3H	PFBS
PFPeS	Perfluoropentanesulfonic acid	2706-91-4	5	5	350	SO3H	PFHxS
PFHxS	Perfluorohexane sulfonate	355-46-4	6	6	400	SO3H	
PFHpS	Perfluoroheptanesulfonic acid	375-92-8	7	7	450	SO3H	PFOS
PFOS	Perfluorooctane sulfonate	1763-23-1	8	8	500	SO3H	
9Cl-PF3ONS	9-chlorohexadecafluoro-3-oxanone-1-sulfonic acid	756426-58-1	8	8	533	SO3H	6:2 FTS
PFNS	Perfluorononanesulfonic acid	68259-12-1	9	9	550	SO3H	PFOS
PFDS	Perfluorodecane sulfonic acid	335-77-3	10	10	600	SO3H	PFOS
11Cl-PF3OUdS	11-chloroeicosafluoro-3-oxaundecane-1-sulfonic acid	763051-92-9	10	10	633	SO3H	6:2 FTS
PFDoS or PFDoDS	Perfluorododecanesulfonic acid	79780-39-5	12	12	700	SO3H	PFOS
PFOSA or FOSA	Perfluorooctanesulfonamide	754-91-6	8	8	499	SO2NH2	PFOS
ADONA	4,8-dioxa-3H-perfluorononanoic acid	919005-14-4	7	6	378	COOH	PFOA
HFPO-DA or GenX	Hexafluoropropylene oxide dimer acid	13252-13-6	6	5	330	COOH	PFHxA
4:2 FTS	4:2 Fluorotelomer sulfonate (1H,1H, 2H, 2H-Perfluorohexane sulfonic acid)	757124-72-4	6	4	328	CH2CH2SO3-	6:2 FTS
6:2 FTS	6:2 Fluorotelomer sulfonate (1H,1H, 2H, 2H-Perfluorooctane sulfonic acid)	27619-97-2	8	6	428	CH2CH2SO3-	
8:2 FTS	8:2 Fluorotelomer sulfonate (1H,1H, 2H, 2H-Perfluorodecane sulfonic acid)	39108-34-4	10	8	528	CH2CH2SO3-	6:2 FTS
3:3 FTCA	3:3 Fluorotelomer carboxylic acid (2H,2H,3H,3H-Perfluorohexanoic acid)	356-02-5	6	3	242	CH2COOH	PFBA
5:3 FTCA	5:3 Fluorotelomer carboxylic acid (2H,2H,3H,3H-Perfluorooctanoic acid)	914637-49-3	8	5	342	CH2COOH	6:2 FTS
7:3 FTCA	7:3 Fluorotelomer carboxylic acid (2H,2H,3H,3H-Perfluorodecanoic acid)	812-70-4	10	7	442	CH2COOH	6:2 FTS
MeFOSAA or NMeFOSAA	2-(N-Methylperfluorooctanesulfonamido)acetic acid	2355-31-9	11	8	571	SO2NCCOOH	EtFOSAA
EtFOSAA or NEtFOSAA	N-ethyl perfluorooctanesulfonamidoacetic acid	2991-50-6	12	8	585	SO2NCCOOH	EtFOSAA
MeFOSE or NMeFOSE	N-Methyl perfluorooctane sulfonamidoethanol	24448-09-7	11	8	557	SO2NCH2CH2OH	MeFOSAA
EtFOSE or NEtFOSE	N-Ethyl perfluorooctane sulfonamidoethanol	1691-99-2	12	8	571	SO2NCH2CH3	MeFOSAA
MeFOSA or NMeFOSA	N-Methyl perfluorooctane sulfonamide	31506-32-8	9	8	513	SO2NHCH3	MeFOSAA
EtFOSA or NEtFOSA	N-Ethyl perfluorooctane sulfonamide	4151-50-2	10	8	527	SO2NHCH3	MeFOSAA

Target PFAS highlighted in gray.

Appendix B

PFAS Separation and Destruction Technology Screening Table

Appendix B PFAS Separation and Destruction Technology Screening Table

Technology Category		Technology	Technology description	Highest degree of commercialization (examples: bench-scale, pilot scale, full-scale)	PFAS separation or destruction efficacy	Technology Readiness for PFAS[1]	Municipal WW	Landfill Leachate	Compost Contact Water	Municipal Biosolids	Sorption Media or Concentrates[2]	Demonstrated for PFAS Treatment at Scale[3]?	Demonstrated >90% Efficacy for PFAS[4]?
Separation Technologies	Membrane Separation	Nanofiltration (NF)/Reverse Osmosis (RO) Membrane Separation	PFAS separated into a concentrate stream by physical separation via high-pressure membranes. NF membranes typically have higher water recovery than RO due to larger membrane pore sizes.	Full-scale. Example vendors: Veolia, Evoqua, ROChem.	PFOS separation (membrane rejection) >99% for RO, and 90-99% for NF.[1]	9	X	X	X			Yes	Yes
		Ultrafiltration (UF)	PFAS separated into a concentrate stream by physical separation via low-pressure membranes.	Developing with regard to PFAS separation, though full-scale for other applications.[2]	30-43% PFOS removal, 47-98% PFOA removal. However, UF is not considered effective at removing PFAS because the pore size is larger than most PFAS.[2]	9	X	X	X			Yes	No
	Phase Separation	Foam Fractionation	PFAS stripped from liquid phase as foam using fine air bubbles. This technology takes advantage of the surfactant properties of PFAS at high concentrations. Can use ozone gas instead of air to achieve oxidation of some PFAS (largely PFAA precursors). Often paired with photodegradation or electrochemical oxidation to degrade separated PFAS.	Full-scale with 66,000 gpd application in Australia.[3] Pilot and bench-scale. Example vendors: EPOC Systems (single container units can treat between 50,000-160,000 gpd), Evocra (with ozone).	>96% PFOS removal in AFFF application[4] and 92% PFAS separation in leachate.[5] Up to 80% PFAS removal without ozone, up to 95% PFAS removal bench-scale when combined with ozone, lower removal for short-chain PFAS.[6]	8	X	X	X			Yes	Yes
	Thermal Separation	Thermal Evaporation/ Brine Concentration	Water is evaporated, with most PFAS and other dissolved constituents remaining in a brine or slurry requiring management (for example, dewatering and disposal in a landfill or via high temperature incineration). Some short-chain PFAS may evaporate with water and require downstream treatment. Can be applied with or without vapor condensation or re-compression. Could use waste heat if applied in a landfill setting.[7]	Widely used in wastewater treatment. Example vendor: Veolia.	Very limited data available on PFAS separation and partitioning. Some PFAS, especially smaller molecules, may partition into the air phase and subsequently into condensate.	9	X	X	X		X	Yes	No
		Direct-fired Desorption	Desorb PFAS from a solid media at <650°C where heat source in direct contact with the material of interest, creating a volatilized PFAS gas stream that requires further treatment, typically via thermal oxidation. Commonly applied for soils treatment, activated carbon, and other waste materials with higher throughput than indirect-fired desorption.	Limited information on application to biosolids, though full-scale for other applications. Example vendor: RLC Technologies.	No specific studies found on direct-fired desorption for PFAS in biosolids.	2				X		No	No
		Indirect-fired Desorption	Desorb PFAS from a solid media at <650°C in kiln where heat source is not directly in contact with combusting waste, creating a volatilized PFAS gas stream that requires further treatment, typically via thermal oxidation. Commonly applied for soils treatment and activated carbon.	Pilot-scale.[15]	Can achieve >99.9997% Removal when coupled with thermal oxidation.[8,9]	6				X		No	Yes

Technology Category		Technology	Technology description	Highest degree of commercialization (examples: bench-scale, pilot scale, full-scale)	PFAS separation or destruction efficacy	Technology Readiness for PFAS[1]	Municipal WW	Landfill Leachate	Compost Contact Water	Municipal Biosolids	Sorption Media or Concentrates[2]	Demonstrated for PFAS Treatment at Scale[3]?	Demonstrated >90% Efficacy for PFAS[4]?
Separation Technologies	Biological	Phyto-remediation/ Constructed Wetlands	Contaminants are bioaccumulated in plants. PFAS are not appreciably degraded by plants, but phytoremediation may concentrate PFAS from contaminated soils if plants are removed for disposal/destruction. Flow-through passive treatment using wetland sediments and plants to remove and sequester contaminants from the water phase.	Mature technology at full-scale, limited applications for PFAS treatment.	Limited uptake of PFAS by some plants in the range of 10%, with higher update for short-chain PFAS than longer chain PFAS.[10] Up to 42% of PFPeA recovered in a greenhouse study, the highest recovery of six PFAS studied. The lowest recovery observed for PFOS.[11,12] A mesocosm study of an engineered wetland treatment system for landfill leachate in St. Louis County MN demonstrated PFAS update by bulrush, cattails, and soil medium.[13]	5	X	X	X			Yes	No
	Flocculation/ Coagulation	Alum	PFAS sorbs to or incorporates with particles formed from alum addition and removed via settling with other solids.	Developing with regard to PFAS separation, though full-scale for other applications.[2]	PFOA and PFOS removal ranging from 1-40% has been observed depending on coagulant dose.[2]	7	X	X	X			No	No
		Polyaluminum Chlorides	PFAS sorbs to or incorporates with particles formed from polyaluminum chloride addition and removed via settling with other solids.	Developing with regard to PFAS separation, though full-scale for other applications.[2]	PFOA influent of 50-30,000 µg/L, resulted in 99% removal in one study and PFOA/PFOS influent o 1,000 µg/L, resulted in 1-25% removal based on coagulant dose in another study.[2]	7	X	X	X			No	Yes
		Ferric Salts	PFAS sorbs to or incorporates with particles formed from ferric salt addition and removed via settling with other solids.	Developing with regard to PFAS separation, though full-scale for other applications.[2]	PFOA and PFOS removal ranging from 1-50%. Removal improved to 48-95% when the pH was reduced to 4. Removal is dependent on coagulant dose.[2]	7	X	X	X			No	Yes
		Covalent Bound Hybrid Coagulants	PFAS sorbs to or incorporates with particles formed from addition of covalent-bound hybrid coagulants and removed via settling with other solids.	Bench-scale tests[2]	PFOA influent of 100 ug/L, resulted in 99% removal.[2]	4	X	X	X			No	Yes
		Specialty Coagulants	PFAS sorbs to or incorporates with particles formed from addition of specialty anionic coagulants such as PerfluorAd and removed via settling with other solids.	Developing with regard to PFAS separation, though full-scale for other applications.[2]	PFAS removal ranging from 87-98% on 380-480 ug/L influent. PFOA removal of 20% on 8 ug/L influent and PFOS removal of 80% on 236 ug/L.[2]	7	X	X	X			No	Yes
		Electro-coagulation	PFAS sorbs to or incorporates with particles generated by anode-cathode reactions of metal plates inserted into the water and removed via settling with other solids. The coagulant is created in the process instead of added.	Developing technology.[2]	PFOA removal of 99% on 1,000-100,000 ug/L influent.[2]	5	X	X	X			No	Yes
	Sorption	Granular Activated Carbon (GAC)	PFAS sorbs to hydrophobic GAC surface in a fixed-bed pressure vessel.	Full-scale. Example vendors: Calgon, Cabot, Evoqua.	GAC can remove PFAS to below detection limits until breakthrough occurs. Shorter chain PFAS have lower GAC loading capacities and faster breakthrough times than longer chain PFAS but can be effectively removed with increased change out frequency.[1]	9	X	X	X			Yes	Yes
		Reactivated GAC	Similar to virgin GAC, PFAS sorbs to the hydrophobic GAC surface in a fixed-bed pressure vessel. Reactivated GAC refers specifically to GAC that has been previously used and its sorption capacity has been recovered through thermal reactivation. Reactivated GAC can either be source separated (returned to the same site for reuse) or general pool reactivated GAC (i.e., multiple unknown sources).	Full-scale. Example vendors: Calgon, Cabot, Evoqua	PFAS removed via similar processes as virgin GAC. Similar bed volumes to breakthrough observed for PFOA and PFOS at two different remediation sites with low TOC (2 mg/L).[14] General pool GAC showed approximately 50% faster breakthrough in comparison to virgin and source separated GAC.[15]	9	X	X	X			Yes	Yes
		Carbon Nanotubes and Graphene	PFAS sorbs to the carbon nanotube (CNT) or graphene surface. Often paired with downstream exposure to UV light to photodegrade PFAS.	Developing technology.[2]	CNT and graphene removed PFAS to below detection limits during the sorption process.[16]	4	X	X	X			No	No

Technology Category		Technology	Technology description	Highest degree of commercialization (examples: bench-scale, pilot scale, full-scale)	PFAS separation or destruction efficacy	Technology Readiness for PFAS[1]	Municipal WW	Landfill Leachate	Compost Contact Water	Municipal Biosolids	Sorption Media or Concentrates[2]	Demonstrated for PFAS Treatment at Scale [3]?	Demonstrated >90% Efficacy for PFAS[4]?
Separation Technologies	**Sorption**	Colloidal Activated Carbon	PFAS sorbs to colloidal activated carbon particles in aqueous suspension. Colloidal activated carbon is primarily injected into groundwater to prevent plume mitigation.	Full-scale for remediation, but not for water treatment. Example vendor: Regenesis.	PFOA was reduced by 99% and PFOS by 98% in a shallow silty-sand anaerobic aquifer.[17]	9	X	X	X			No	Yes
		Ion Exchange Resins (Single-Use Media)	PFAS attaches to resin via surface charge interactions in a fixed bed pressure vessel. Once exhausted, media is removed and disposed.	Full-scale, example vendors: Calgon, Evoqua, ECT2, Purolite, ResinTech.	IX can remove PFAS to below detection limits until breakthrough occurs. Recommended for influent concentrations below 10 µg/L total PFAS. Affinity for removal by the resin increases with increasing carbon length within each subgroup of PFAS.[1]	9	X	X	X			Yes	Yes
		Ion Exchange Resins (Regenerable Media)	PFAS attaches to resin via surface charge interactions with resin support material in a fixed-bed pressure vessel. Once exhausted, media is regenerated onsite using a brine/solvent mixture and returned to service.	Full-scale, example vendor: Purolite, ECT2.	IX can remove PFAS to below detection limits until breakthrough occurs. Affinity for removal by the resin increases with increasing carbon length within each subgroup of PFAS. Removal capacity is generally less than single use resin.[1]	9	X	X	X			Yes	Yes
		Biochar	Similar to GAC, PFAS are removed via sorption to biochar in a fixed pressure vessel. The biochar is synthesized by heating biomass. Once exhausted, media is removed and disposed.	Developing technology evaluated at the bench and pilot scale.[2]	PFAS removal is dependent on the biochar type and if it is biologically active or inactive. Inactive biochar can remove 20-60% of short chain PFAS (3-6 carbons) and 90-99% of long chain PFAS [18]	6	X	X	X			No	Yes
		Powdered Activated Carbon (PAC)/Alum/ Kaolinite)	Similar to GAC, PFAS are removed via sorption to composite media of PAC, alum, and kaolinite. The media is added directly in process or tank (not fixed bed). Spent media is wasted and separated by settling or with low-pressure membrane filtration.	Proven technology in *in situ* remediation applications, no known full-scale water treatment applications. Example vendor: AquaBlok.[19]	99.9-99.99% removal of long and short chain PFAS.[20] The media immobilizes PFAS and has a higher affinity for short chain PFAS than GAC.[19]	6	X	X	X			No	Yes
		Super-Fine PAC	PFAS sorbs to powdered activated carbon (PAC) that has been ground to a super-fine powder and added in the process (e.g., within a tank). Superfine PAC then removed via membrane filtration.	Bench-scale tests.[21]	1.5-480 times higher adsorption than GAC, depending on the influent PFAS concentration, adsorbent size, pore content, and PFAS chain length.[21]	4	X	X	X			No	Yes
		Modified Clay	PFAS attaches to clay minerals, sometimes modified, via surface charge interactions. Media is in a fixed bed pressure vessel. Once exhausted, media is removed and disposed.	Full-scale: matCARE, Pilot study: Cetco Fluoro-sorb.	Can remove PFAS to below detection limits until breakthrough occurs. PFOA, PFOS, PFHxS, and PFBS removed to non-detect concentrations, with breakthrough of PFBS observed first.[22]	8	X	X	X			Yes	Yes
		Modified Adsorbents	PFAS sorbs to modified adsorbent media, which can include modified natural materials: polymer-coated sand, modified cyclodextrin, synthesized gel polymeric absorbents, metal-organic frameworks, or modified cellulose.	Developing technology.[2] Example vendor: Cyclopure	Similar or slightly higher PFAS removal to GAC for PFOA and PFOS. PFAS removal depends on the adsorbent modification.[2]	5	X	X	X			No	Yes
	Desorption	Ion Exchange Resin Solvent Regeneration	A proprietary solvent brine solution removes PFAS from the IX media by targeting removal of the ionic head and desorption of the fluorinated carbon tail from the media. The brine containing concentrated PFAS is distilled. Residual still bottoms can be disposed of directly or adsorbed onto a smaller amount of GAC.	Full-scale, example vendor: ECT2.	Regeneration removes sufficient PFAS to restore resin to virgin quality able to handle PFAS loading cycles consistent with virgin resin.[23]	8	X	X	X			Yes	Yes
		GAC Solvent Regeneration	A solvent solution is used to separate PFAS from the GAC media. The brine containing concentrated PFAS is distilled and recycled for future regenerations.	Pilot-scale, ready for commercialization. Example vendor: Battelle.[24]	Resin regeneration can achieve PFAS mass balance recovery of 97%-132%.[24]	6					X	No	Yes

Technology Category		**Technology**	**Technology description**	**Highest degree of commercialization (examples: bench-scale, pilot scale, full-scale)**	**PFAS separation or destruction efficacy**	**Technology Readiness for PFAS[1]**	**Municipal WW**	**Landfill Leachate**	**Compost Contact Water**	**Municipal Biosolids**	**Sorption Media or Concentrates[2]**	**Demonstrated for PFAS Treatment at Scale [3]?**	**Demonstrated >90% Efficacy for PFAS[4]?**
Destruction Technologies	**Redox Chemistry**	Solvated Electrons and Advanced Reduction Processes	Solvated electrons are generated in advanced reduction processes (ARP) by combining chemical reductants (e.g., Fe(II), sulfide, sulfite, iodide, or dithionite) with activating energy (e.g., ultrasound, UV, microwaves, or electron beams) to reductively cleave the C-F bonds of PFAS.	Active area of research and development at bench-scale.[1] Example start-up: Enspired Solutions (photo-reductive defluorination).	>90% degradation of PFOA and PFOS has been observed.[25,26] Destruction possible for longer-chain PFAS, but less efficient for short-chain PFAS. Degree of defluorination and reaction rates are dependent on chain length and head group. ARPs can be inhibited by presence of oxidants (e.g., oxygen).[25]	5	X	X	X			No	Yes
		Catalyzed Hydrogen Peroxide (CHP)	Hydrogen peroxide combined with a catalyst such as iron (i.e., for Fenton's reagent) or chelated manganese generate hydroxyl radicals. Certain processes can produce reductants such as superoxide which can mineralize PFAS and convert precursors to terminal PFAS.	Developing with regard to PFAS destruction, though full-scale for other applications.	Hydroxyl radicals attack head group, not fluorinated tail, so limited defluorination occurs. Limited degradation of PFCA and PFSA are observed, with PFAS precursors transformed to terminal PFCAs [1,27]. 68-89% PFOA with CHP with superoxide and hydroperoxide [28] Limited data for PFAS other than PFOA.	4	X	X	X			No	No
		Ozone	Ozone used as an oxidant to degrade contaminants, typically paired with UV light, hydrogen peroxide, or persulfate to generate hydroxyl radicals.	Developing with regard to PFAS destruction, though full-scale for other applications.[1]	Can transform PFAS precursors, but full defluorination unlikely with ozone alone. <25% degradation observed for PFBA, PFPeA, PFOA, PFBS, PFHxS, and PFOS in a bench-scale reactor [29]. Ozone can paired with foam fractionation and/or with UV for improved removal efficiency.[6]	7	X	X	X			No	No
		Activated Persulfate	Persulfate is chemically activated with heat or UV light to form sulfate radicals. Metallic catalyst activation and high pH/alkaline activation (commonly used in remediation applications of activated persulfate) appear to be less effective for PFAS degradation application.[27]	Developing with regard to PFAS destruction, though full-scale for other applications.[1]	Can mineralize PFCAs, but do not readily transform PFSAs.[1] Up to 90% removal of PFOA at bench-scale at 50 deg. C and a long-reaction time, but only 24% defluorination.[30]	7	X	X	X			No	Yes
		Photolysis	Photolysis includes several processes that transform or degrade contaminants using light: • Direct photolysis degrades contaminants that directly absorb light (typically UV light). • UV advanced oxidation processes combine UV light and a chemical oxidant to generate reactive species. • Photocatalysis combines UV light and a solid catalyst (Fe(III) or TiO2) to form reactive species.	Developing with regard to PFAS destruction, though full-scale for other applications.[1]	Limited removal for short-chain PFAS like PFBA and PFBS. 50-90% removal of long-chain with inclusion of a catalyst. Precursors like 6:2 FTS also removed.[31,32] 90% PFAS degradation with carbon nano-tube photocatalysts, with 62% of PFOA and 46% of PFOS completely defluorinated.[16]	7	X	X	X			No	Yes
		Electro-chemical Oxidation (Electrolysis)	Electrical currents passed through water degrade PFAS, either directly on the anode or indirectly in bulk water. May be paired with electrochemical reduction.	Active area of research and development at bench-scale and pilot scale.[1] Example vendor: AECOM De-Fluoro.	15% (PFBA)-97% (PFOA) removal. Preferential removal of PFOA over PFOS because PFOA preferentially adsorbs to anode surface.[33,34]	7	X	X	X		X	No	Yes
		Sonochemical Oxidation	Uses acoustic ultrasound waves (typically 100-1000 kHz) in water to cause cavitation and radical generation. Mechanisms of PFAS degradation are not well-defined in the literature. Additives (e.g., persulfate) or UV light can enhance degradation.	Active area of research and development at bench and pilot scales.[35]	>90% degradation of PFOS has been observed at high frequencies, [36] and can be enhanced with additives or UV light.[37] Some short-chains not fully degraded.[38]	6	X	X	X			No	Yes
		Plasma Technology	A strong electric field is applied to a gas (such as argon), generates ionized gas and electrons, forming strong oxidizing and reducing species that can degrade PFAS, with or without a catalyst.	Active area of research and development at bench and pilot scales. Several SERDP examples.[39]	>90% remove of long-chain PFAAs, 0-95% removal of short-chain PFAS.[40,41]	6	X	X	X			No	Yes

Technology Category		Technology	Technology description	Highest degree of commercialization (examples: bench-scale, pilot scale, full-scale)	PFAS separation or destruction efficacy	Technology Readiness for PFAS[1]	Municipal WW	Landfill Leachate	Compost Contact Water	Municipal Biosolids	Sorption Media or Concentrates[2]	Demonstrated for PFAS Treatment at Scale[3]?	Demonstrated >90% Efficacy for PFAS[4]?
Destruction Technologies	Redox Chemistry	Zero Valent Iron (ZVI)	Fine-grained metallic iron filings sorb and can reductively degrade contaminants. Mixed with inert sand or gravel in permeable reactive barriers (PRB) for groundwater or surface water treatment.	Developing with regard to PFAS removal/destruction, though full-scale for other applications.[1]	17-95% removal with ZVI for PFOA, PFHpA, PFOS, PFHpS, PFHxS, and PFBS, with 5-10% defluorination of PFOA and PFOS.[42]	7	X	X	X			Yes	No
		Alkaline Metal Reduction	Metallic reductants (e.g., Ti-citrate, nZn0, nNiFe0) reductively defluorinate PFAS, with higher rates under high pH/alkaline conditions.	Not commercially applied. Bench-scale studies have focused on PFOS and isomers.[1]	>95% transformation of PFOS, but intermediates identified; variability in efficiency depending on isomer.[43,44]	4	X	X	X			No	Yes
		Super Critical Water Oxidation (SCWO)	Wastewater, biosolids, or any organic waste (e.g., aqueous film-forming foam, AFFF) subjected to high temperature and pressure (374°C and pressure of 250 bar) to reach supercritical state for water where all organic material dissolve and can be oxidized. To be self-sustaining, waste streams require at least 2-3 MJ/kg or chemical oxygen demand >100 g/L, thus SCWO is applicable for destruction of biosolids and potentially for spent sorption media, but liquid waste streams would likely need a co-fuel.	Developing with regard to PFAS removal/destruction, though full-scale for other applications.[1] Demonstration studies online for biosolids. Example vendors: Battelle PFAS Annihilator, Aquarden Technologies, 374Water.	70% destruction for PFOS.[45] Other studies showed a greater than 99% reduction of the total PFAS identified in a targeted compound analysis, including PFOS and PFOA, with removal efficacy dependent on process design, residence time, and operating parameters.[46,47]	8				X	X	Yes	Yes
		Advanced Oxidation Processes (AOP)	Oxidants such as ozone, peroxide, persulfate, or UV light, produce reactive oxidant radicals to degrade contaminants. Includes previously listed technologies such as photolysis, ozone, and catalyzed hydrogen peroxide.	Multiple AOP are used in full-scale treatment, see specified technologies above for more detail.	See above for specified technologies. Hydroxl radicals attack head group, not fluorinated tail, so limited defluorination occurs. Achieving defluorination typically requires a reduction process as well, so 90% degradation unlikely with just AOP. 75% removal using UV/ozone, but not all defluorinated.[6]	9	X	X	X			Yes	No
		High-Energy Electron Beam (eBeam)	Electricity used to generate electrons, which form solvated electrons and oxidant radicals that facilitate advanced reduction and oxidation without chemical addition.[1]	Commercialized in chemical and food production applications, limited to bench scale for PFAS removal from water or biosolids.[1]	35%-96% defluorination of PFOA, with varying efficiencies based on pH, water chemistry, and oxidant addition,[48,49]	4	X	X	X	X		No	Yes
		Mechano-chemical degradation (MCD)	Solid media treated in high energy ball mills with reactants that produce oxidative radicals and plasma from impact of milling balls. These radicals and plasma react with fluorine to destroy PFAS.	Not developed at commercial scale, but piloted for treatment of contaminated soils.[50]	>99% destruction of PFAS from contaminated soils on lab scale, with limited PFAS byproducts.[50,51]	5				X	X	No	Yes
	Biodegradation	Mycoremediation/ Fungal Enzymes	Using fungi to degrade PFAS. Limited studies to-date. Some studies using lignolytic fungi (wood-rotting fungus).	Active area of research and development at bench scale.[12,52]	Limited data available. 20% degradation of PFOA and PFOS observed.[53] Up to 80% transformation of the precursor 6:2 FTOH degrading to other PFAS.[12,54,55]	3	X	X	X	X		No	No
		Bacterial Enzymes	Enzymes extracted from bacteria used to degrade contaminants. Could include monooxygenases and reductase enzymes used commercially in other applications.	Active area of research and development at bench scale.[56]	Bacterial enzymes that are known to definitively degrade/defluorinate are not well described in the literature.[12]	3	X	X	X	X		No	No
		Biotransformation/ defluorination	PFAS are (partially) degraded via microbial degradation under aerobic or anaerobic conditions. PFAS precursors that include non-fluorinated alkyl carbons can be readily transformed into short-chain terminal PFCAs.	Active area of research and development at bench scale.[1,12,56]	Rates of biodegradation are slow. Up to 60% removal of PFOA/PFOS via anaerobic defluorination over 60-day incubation.[57]	4	X	X	X	X		No	No

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Destruction Technologies	Thermal Destruction	GAC Thermal Reactivation	Thermal reactivation occurs in a multiple hearth or rotary kiln furnaces typically operated at approximately 980°C under low oxygen and introduction of steam. PFAS are desorbed and decomposed in the furnace and destroyed via thermal oxidation in an after burner (operated at a higher temperature than the furnace). The process restores most of the sorptive capacity of the media.	Full-scale. Example vendors: Calgon, Evoqua.	PFAS separation during reactivation is PFAS and temperature specific. Defluorination of 80-100% of both PFCAs and PFSAs occur at 1000°C. Decomposition of 80-100% of PFCAs and PFSAs occur at 500°C.[58]	9					x	Yes	Yes
		Hydrothermal Alkaline Treatment (HALT)	Heat and pressure are applied to a reactor at near-supercritical conditions (e.g., 350°C and 165 bar) and alkaline pH (using sodium hydroxide). Under these conditions, water behaves like a nonpolar solvent and shows catalytic degradation of organics. This is a similar process as Hydrothermal Liquefaction for biosolids.	Active area of research and development with prototypes available. Example startup: Aquagga	All 19 targeted PFAS in diluted AFFF samples were degraded in laboratory-scale batch reactor experiments to non-detectable concentrations (which were 100-500 ng/L) within 30 min.[59] PFSAs were more recalcitrant than PFCAs. This study also demonstrated nearly 100% defluorination efficiency.	7	X	X	X			No	Yes
		Low Temperature Mineralization in DMSO	Heat (20-120°C), sodium hydroxide, and the solvent dimethyl sulfoxide (DMSO) in water are used to mineralize PFCAs. DMSO promotes a low energy barrier to decarboxylation (removal of the PFCA head group) and sodium hydroxide promotes degradation to fluoride, small carbon-containing ions (formate, carbonate, oxalate, and glycolate), and trifluoroacetate.	Active area of research at bench scale.[60]	The study by Trang et al. (2022) demonstrated that most PFOA was degraded by over 90% after 24 hours of reaction at 120°C. Starting concentrations were relatively high, at approximately 90 mmol/L (or 37 g/L). Approximately 90% of the fluorine from PFOA was recovered as fluoride, with most of the remainder associated with trifluoroacetic acid. Similar degradation and recoveries were observed for other PFCAs and HFPO-DA. The proposed mechanism is not compatible with PFSAs.	3	X	X	X			No	Yes
		Pyrolysis with Thermal Oxidation (biosolids)	Thermochemical process where pre-dried (>75% total solids) biosolids are heated in a reactor typically from 200-590°C under a starved to no oxygen condition, producing PFAS-laden pyrogas, tars, oils and depending on the operating temperature, either inert material or biochar. Pyrogas routed to thermal oxidation at over 1000°C under excess air/oxygen to destroy PFAS.	Full-scale demonstration projects in place. Example vendors: Anaergia, Bioforcetech, Biowaste.	Complete removal from biochar. Additional studies required for air, water (from air treatment), however with a thermal oxidation PFAS destruction anticipated per below.[61] Temperature greater than 1,100°C for defluorination of PFAS in solids, but flue gas may contain some PFAS. Thermal oxidizer destroys PFAS at an efficiency greater than 99.99%.[8,62]	8				X		Yes	Yes
		Gasification with Thermal Oxidation (biosolids)	Thermochemical process where pre-dried (>75% TS) biosolids are heated in a reactor typically from 590-980°C with limited oxygen (~30% of required O2 for complete oxidation), producing PFAS-laden syngas and biochar. Syngas routed to thermal oxidation at over 1000°C under excess air/oxygen to destroy PFAS.	Full-scale demonstration projects in place. Example vendors: Aries, Ecoremedy.	Limited removal on gasification alone, but 99.5% total PFAS removal between feed and char when coupled with thermal oxidation.[63] Confidential results of full-scale system showed removal from media and air phases. Temperature greater than 1,100°C for defluorination of PFAS in solids, but flue gas may contain some PFAS. Thermal Oxidizer destroys PFAS at an efficiency greater than 99.99%.[8,62]	8				X		Yes	Yes
		Biosolids Incineration	Sewage sludge incinerators (SSIs) operate at 700-1,000°C to further reduce the volume of biosolid residue requiring final disposal. Byproducts are flue gas and ash. There are two types of incineration: multiple hearth furnace and fluidized bed.	Mature technology, full scale.	Limited information, with research ongoing. Some PFAS destruction may occur through an SSI with additional removal through the air pollution control systems. Complete destruction of PFAS (to CO_2, H_2O, HF, or SO_2) requires temperatures over 1,000°C.[64,65]	9				X	X	Yes	No
		Thermal Drying	Thermal dryers use direct or indirect heat to evaporate water from biosolids to reduce the volume of material. Biosolids particles are heated to less than 650°C within the dryer. Steam, particles, and air pollutants from drying process are treated prior to release to the atmosphere.	Mature technology, full scale.	Thermal drying is shown to impact some PFAS precursors, leading to an increase in concentration PFCAs and PFHxA. No evidence that thermal drying destroys PFAS in biosolids. [66]	9				X	X	No	No

Technology Category		Technology	Technology description	Highest degree of commercialization (examples: bench-scale, pilot scale, full-scale)	PFAS separation or destruction efficacy	Technology Readiness for PFAS[1]	Municipal WW	Landfill Leachate	Compost Contact Water	Municipal Biosolids	Sorption Media or Concentrates[2]	Demonstrated for PFAS Treatment at Scale[3]?	Demonstrated >90% Efficacy for PFAS[4]?
Destruction Technologies	Thermal Destruction	High-Temperature Incineration	Thermochemical process heating to greater than 1000°C under excess air/oxygen. This process is commonly used to destroy PFAS present in sorption media following adsorptive treatment.	Full-scale. Example vendors: Veolia, Clean Harbors.	Temperature greater than 1,100°C for defluorination of PFAS in solid materials, but flue gas may contain some PFAS. Thermal Oxidizer controls PFAS at an efficiency greater than 99.99%.[8,62]	9					X	Yes	Yes
		Cement Kiln (biosolids)	Rotary kiln process where biosolids are used as a fuel source to reduce the amount of other fuel (e.g., coal) needed. The biosolids must be dried to >90% to be used in this type of application.	Limited application for PFAS. Should not use more than 20% biosolids to coal fuel to limit air emission effects.[67]	Defluorination over 1,650°C. Thermal degradation currently being demonstrated for PFOA and PFOS in cement kilns by the formation of CaF_2 captured in the cement, using calcium as a catalyst and fluoride as a scavenger.[68] Cement kilns temperatures (1400°C-2000°C) allows for full destruction of PFAS compounds,[67] but major uncertainties remain around temperature and residence time requirements.	3				X	X	Yes	No
		Hydrothermal Liquefaction (HTL)	Uses temperature and pressure to convert wet organic matter, including PFAS-laden biosolids, to biocrude oil and methane rich gas at 360 deg. C, and 3000 psi. The process captures energy to keep the system running.	Demonstration studies only. Example vendor: Genifuel pilot is expected at Metro Vancouver around 2024.	One study found >99% transformation of fluorinated carboxylic acid structures, but lower for sulfonic acid structures.[69] Other findings indicated that HTL under the studied condition was not able to degrade all PFAS existed in sewage sludge.[70]	6				x		No	No

[1] Technology readiness level (TRL) assessment based on criteria outlined by the U.S. DOE in 2010, with TRL 9 reflecting the highest level, with commercial installations operated under the full range of expected conditions[71]. This study required TRL 8 or 9 to pass initial screening

[2] Sorption media refers to PFAS separation or destruction from sorption media such as granular activated carbon or ion exchange media.

[3] The demonstrated at scale criteria requires that liquid treatment technologies have been field implemented and are commercially available and that biosolids treatment technologies have been applied at pilot-scale applications. The different standards are due to biosolids PFAS treatment being less developed than liquid-phase PFAS treatment.

[4] The demonstrated efficacy criteria requires at least 90% PFAS separation or destruction for at least one of the targeted PFAS, which include PFOA, PFOS, PFHxA, PFBA, and PFBS as well as selected other compounds for specific media.

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Appendix C

PFAS Removal Performance by Technology

Technology	Reference	Study Description	PFBA	PFBS	PFHxA	PFHxS	PFOA	PFOS	6:2 FTSA	N-EtFOSAA	N-MeFOSAA
Separation – Membrane Separation		**RO/NF: Rejection (%) = $(1 - PFAS_{Permeate}/PFAS_{Feed}) \times 100\%$**									
RO/NF	Appleman et al. (2013)	Study evaluating polyamide membrane NF270 for the treatment of PFAS-spiked water. Three experiments were performed: virgin membranes fed with spiked DI water, and spiked artificial groundwater, and fouled membranes fed with spiked artificial groundwater. Results presented as range over various pressure and membrane/water configurations. Results from Table 2.	93-95	95-99	95	96-99	95-97	99	--	--	--
	Appleman et al. (2014)	Study evaluating 15 full-scale treatment systems for the treatment of PFAS compounds. Source waters for treatment systems included 11 surface waters, 6 groundwaters, 1 surface water and groundwater blend, and 2 treated wastewaters. Results from Table 2.	82-95	93-98	97-99	90-96	47-98	96-99	--	55-58	36-84
	Glover et al. (2018)	Full- and pilot-scale potable reuse plants. Average rejection rates are from Table 2. Rejection rates are constrained by analytical reporting limits.	>79	--	>96	>80	>77	>71	>78	--	--
	Franke et al. (2019)	Pilot-scale NF treatment system in Sweden treating groundwater. Rejection was calculated from Table 2.	98	95.7	95.4	95.6	96.5	95	--	--	--
Separation – Phase Separation		**Foam Fractionation: Removal Efficiency (%) = $(1 - PFAS_{Effluent}/PFAS_{Influent}) \times 100\%$**									
Foam Fractionation	Robey et al. (2020)	Bench-scale testing of landfill leachate. Removal estimates from Figures 2 and 3, rounded to the nearest 5%.	-5	25	50	95	95	95	70	95	95
	McCleaf et al. (2021)	Municipal landfill leachate treated in batch column tests. Removal estimates from Table 3.	38	60	66	97	99	98	90	40	11
	Smith et al. (2022)	Pilot-scale treatment of landfill leachate using a continuous system. Removal estimates from Figure SI.2, rounded to the nearest 5%.	0	10	25	90	90	95	90	90	90
	Burns et al. (2022)	Commercial-scale treatment of landfill leachate from Telge Recycling plant in Sweden. Removal estimates from Tables 5 and 6. Removal efficiency estimates were constrained by analytical reporting limits.	-1.1	15.7	37.3	>98.8	>99.7	>98.7	>97.2	97.3	>64.3
Separation – Media Sorption		**Approximate Bed Volumes to First Detection of Breakthrough**									
GAC	Woodard et al. (2017)	Pilot-scale study using Calgon F400 GAC to treat a groundwater matrix with four vessels in series with an overall EBCT of 20 minutes. Approximate bed volumes to breakthrough estimated from Exhibits 11-21.	~3,000	~3,500	~3,000	~3,000	~3,000	~3,000	~3,000	--	--
	Westreich et al. (2018)	This study using rapid small-scale column tests (RSSCT) to simulate a large-scale, fixed GAC bed. The tests were run for ~100,000 bed volumes. The tests were conducted using Calgon F400 and two types of reactivated carbon and untreated groundwater spiked with PFAS. Approximate bed volumes to breakthrough shown were estimated from Exhibits 4 through 10.	~10,000	~65,000–75,000	~55,000–70,000	~85,000–100,000	~75,000–85,000	~95,000–100,000	--	--	--
	Franke et al. (2019)	Full-scale nanofiltration membrane pilot plant combined with column adsorption experiments applying GAC and AIX material. Two different water types were tested, untreated groundwater and membrane reject water. AIX (A600) and GAC (F400). Approximate bed volumes to breakthrough estimated from Figure 2.	--	~5,000	~5,000	~5,000	~5,000	~5,000	--	--	--
	Liu et al. (2021)	Pilot scale system fed with groundwater compared four granular activated carbons The system was run with an empty bed contact time (EBCT) of 10 minutes per vessel. Approximate bed volumes to breakthrough estimated from Figure 1 for Calgon F400 GAC.	--	~15,000	~14,000	~17,500	~19,000	~27,000	--	--	--
AIX	Woodard et al. (2017)	Used ECT's Sorbix A3F to treat a groundwater matrix using three resin vessels in series with an overall EBCT of 7.5 minutes. Pilot test included an initial loading cycle to evaluate virgin resin removal capacity and subsequent alternating cycles of resin loading and regeneration to evaluate effectiveness of regenerated resin. Approximate bed volumes to breakthrough estimated from Exhibits 11-21.	~4,000	~21,000	~10,000	~21,000	~13,000	~21,000	~7,000	--	--
	Franke et al. (2019)	Full-scale nanofiltration membrane pilot plant combined with column adsorption experiments applying GAC and AIX material. Two different water types were tested, untreated groundwater and membrane reject water. AIX (A600) and GAC (F400). Approximate bed volumes to breakthrough estimated from Figure 2.	--	~18,000	~8,000	~17,000	~17,000	~19,000	--	--	--
	Boyer et al. (2021)	Review article summarizing use of anion exchange resins for PFAS removal. Table 3 of this review article summarizes bed volumes to breakthrough for various resins, media, and PFAS.	~698–120,000	~9,000–1,100,000	~2,764–70,000	~15,000–1,100,00	~100–1,100,000	~450–1,100,000	~10,000–120,500	--	--
	Ellis et al. (2022)	Pilot study using groundwater contaminated with aqueous film-forming foam. A series of resins were compared: A520E, PFA694E, CalRes 2301, and PSR2+ (A860 was also tested, BV to breakthrough are not shown here). Approximate bed volumes to breakthrough estimated from Figures 2 and Table 3.	~5,000–20,000	~70,000–180,000	~10,000–70,000	~120,000–180,000	~30,000–180,000	~180,000	--	--	--

Technology	Reference	Study Description	PFBA	PFBS	PFHxA	PFHxS	PFOA	PFOS	6:2 FTSA	N-EtFOSAA	N-MeFOSAA
Modified Clay	Najm et al. (2021)	RSSCTs compared PFAS removal between three types of GAC and modified clay (Fluoro-sorb 200). Tests were completed using groundwater used for drinking water from San Jose, California. Influent PFBS, PFHxS, and PFOS concentrations were 2.4 ng/L, 8.5 ng/L, and 7.8 ng/L, respectively. The modified clay RSSCT column was operated at a full-scale equivalent of 2-minute EBCT. Note that PFHxA was detected in the influent at just below 2 ng/L (below the analytical reporting limit). PFHxA broke through at 30,000 BV. No explanation was provided for the relatively low capacity of the modified clay for PFHxA.	--	>300,000	30,000 (refer to description)	>300,000	--	>300,000	--	--	--
	Grieco et al. (2021)	RSSCTs compared PFAS removal between GAC (F400) and modified clay (Fluoro-sorb 200). Both media were ground prior to testing. RSSCTs were completed using groundwater used for drinking water from the Orange County Water District. The modified clay RSSCT column was operated at a full-scale equivalent of 2 minute EBCT. Bed volumes shown are RSSCT bed volumes estimated from Figure 5. The range is based on samples with varying dissolved organic carbon concentrations. The influent PFBS and PFOA concentrations ranged from 2.93 to 15.6 ng/L and 6.59 to 22.0 ng/L, respectively.	--	~50,000-175,000	--	--	~225,000 -500,000	--	--	--	--
Separation – Media Sorption		**Removal Efficiency from Batch Isotherm or Kinetic Tests**									
Modified Clay	Yan et al. (2020)	PFAS-impacted groundwater collected from a former US Air Force base was used in batch adsorption experiments. The treatment of PFAS compounds with modified smectite clay (Fluoro-sorb 200) was studied. Removal efficiencies are estimated from Figure 1.	--	--	--	~94	~88	~94	~77	--	--
	Jiang et al. (2022)	Modified clay media was prepared in the laboratory using montmorillonite and the quaternary ammonium surfactant cetyltrimethylammonium chloride (CTAC). A series of batch isotherm and kinetic tests were completed. Five concentrations ranges of PFAS were tested in synthetic laboratory water. PFAS were dosed in combination. Removal efficiencies shown are estimated from Figure 4 for the level 5 PFAS concentrations (highest concentrations tested) after 4 hours of equilibration. Removal efficiencies at lower concentration ranges tested were all >80% at all equilibration times (1-24 hours).	--	>60	>50	>95	>95	~100	>90	~100	--
Destruction – Redox Chemistry		**Destruction (%) = 100 x (1 - ($PFAS_{effluent}$/$PFAS_{influent}$))**									
SCWO	Pinkard et al. (2021)	PFOS decomposition in a batch SCWO reactor. Hydrogen peroxide was used as the oxidant source. Compared to continuous SCWO reactors, batch reactors operate at long residence times and lower temperatures. Results of this study are presented as destruction efficiencies at 425–500°C, 0-min and 60-min residence time. Destruction efficiencies estimated from Figure 2.	--	--	--	--	--	39–70	--	--	--
	Krause et al. (2022)	Article summarizing three demonstration studies done by providers of SCWO systems (Battelle, Aquarden Technologies, and 374Water). PFOS-based AFFF (3M Lightwater) was used as the test solution. All three demonstrations were continuous SCWO systems. Destruction efficiencies estimated from Figure 1.	99–100	99–100	99–100	99–100	99–100	98–99	--	--	--
	McDonough et al. (2022)	A 1,000-fold AFFF foam was used for this pilot-scale study. Destruction efficiencies from Table 4.	99.97	99.99	99.99	99.99	99.99	99.99	--	--	--
Destruction – Thermal Destruction		**Decomposition (%) = (1 – $Mass_{Final}$/$Mass_{Initial}$)×100%**									
GAC Reactivation	Xiao et al. (2020)	Laboratory study of the decomposition of PFAS on the surface of GAC under varying heat treatment temperatures (200-900°C) and atmospheres flow (air, N_2, CO_2). Decomposition efficiencies from Figure 3a-h.	94.31–99.98	97.51–99.97	--	98.3–99.94	70.06–99.97	98.67–100	--	--	--
	Sonmez Baghirzade et al. (2021)	Review article of thermal reactivation of GAC. Percent decomposition ranges shown for temperatures between 175°C and 500°C from Figure 2a and Figure 3. Values for N_2 environment. Values estimated to the nearest 5%.	90–95	0–95	--	--	70–95	0–95	--	--	--
	Sasi et al., (2021)	Laboratory study of the effects of GAC and other porous media on PFAS thermal decomposition. Percent decomposition ranges shown for temperatures 150°C and 300°C. No pressure information given assuming atmospheric pressure. Values estimate from logarithmic plots in Figure 1.	0–99	--	--	--	0–99	--	--	--	--
	DiStefano et al. (2022)	GAC reactivation conducted at facility owned and operated by Calgon. PFAS extraction and analysis from spent and reactivated GAC samples during emissions testing. Destruction efficiencies calculated from Table 1 and averaged over the three emissions tests.	~99.97	~99.98	~99.98	~99.99	~99.99	~99.99	~99.13	~99.63	~99.68
Pyrolysis	Barranco et al. (2020)	A series of tests conducted on sand spiked with PFAS ranging from 6,000 to 19,000 µg/kg. Results at 650°C. No pressure information given assuming atmospheric pressure. Destruction efficiency estimated from Figure 4-2.	--	99.98	--	99.98	99.99	99.98	--	--	--

Technology	Reference	Study Description	PFBA	PFBS	PFHxA	PFHxS	PFOA	PFOS	6:2 FTSA	N-EtFOSAA	N-MeFOSAA
	Thoma et al., (2022)	Study of a commercial pyrolysis system. No PFAS were detected in the resulting biochar. Results are reported as a range from the two labs used to test PFAS concentrations. Values from Table 2 in the SI.	98.07–99.78	96.55	99.74–99.95	--	99.75–99.96	99.08–99.66	81.32	98.39–99.37	98.83–99.48

RO=reverse osmosis; NF=nanofiltration; GAC=granular activated carbon; AIX=anion exchange; SCWO=supercritical water oxidation; -- = Data not reported.

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Appendix D

Media Breakthrough Curve Estimates

Appendix D: Media Breakthrough Curve Estimates

1 Introduction

Breakthrough modeling was completed to estimate the time (and volume of water treated) before target per- and polyfluoroalkyl substances (PFAS) breakthrough fixed bed media vessels to effluent concentrations matching treatment target of 5 ng/L. These estimates were used to inform ongoing operational and maintenance (O&M) costs associated with treatment alternatives implementing media treatment, including Alternatives 1a, 1b, 2a, 5a, 6a, and 6b. These alternatives assume the media vessels are operated in a lead-lag configuration. The modeling and other approaches described below were used to estimate breakthrough across the lead vessel only, assuming that the lead granular activated carbon (GAC), anion exchange (AIX) resin, or modified clay media bed would be exchanged after breakthrough. In effect, this assumes that the lag media bed would have minimal PFAS loading allowing for a more predictable changeout frequency. This is likely a conservative approach and that in actual practice the lead media bed may be operated past the first detection of PFAS breakthrough.

In the following sections, the term "bed volumes" will be used to describe the volumetric throughput of water treated through a fixed bed media vessel until a specific treatment criterion is reached. Bed volumes are a unitless measure reflecting the volume of water treated and is calculated as the total volume of water treated divided by the empty bed volume of the fixed media bed.

There are uncertainties in the estimated media replacement frequencies used in this study, and sites seeking to implement media sorption for PFAS removal should conduct pilot studies to accurately predict media replacement frequencies based on site-specific water quality and PFAS removal goals.

2 Background on Predicting PFAS Breakthrough of Fixed Bed Vessels

Sorption media in fixed bed columns requires replacement, regeneration, or reactivation once its sorption capacity is used up and breakthrough of target PFAS in vessel effluent exceed acceptable concentrations. Breakthrough times vary with the chemistry of specific PFAS targeted and with the chemical properties of the water. In general, PFAS with long, hydrophobic carbon chains (such as perfluoroocatanoic acid, PFOA) are removed more effectively than short chains (such as perfluorobutanoic acid, PFBA). Sorption media also tend to have a greater affinity for PFAS with sulfonic acid polar groups than PFAS with carboxylic acid polar groups. Natural organic matter (NOM) competes with PFAS for sorption sites and thus adversely impacts performance and increases the media usage rate. The concentration of major anions in the water will also influence the performance of AIX due to a similar competition mechanism. Breakthrough defines media usage rates and, hence, influences operating costs for the removal process.

For this study, PFAS removal through GAC was predicted by using an advection-dispersion-sink mass balance model (commonly applied for sorption processes in fixed bed reactors) coupled with a homogenous surface diffusion model (HSDM) as a way to estimate the frequency of GAC change-out (Burkhardt et al., 2022). Implementation of this model is detailed in Section 3.

In contrast to GAC, AIX resins and modified clay media have limited studies in the literature that have applied mechanistic-based models for PFAS removal. Dixit et al. provided batch isotherm data needed to solve a coupled mass balance and HSDM for PFAS removal through AIX resin columns (Dixit et al., 2021); however, the resin used by Dixit et al. has shown relatively low capacity for PFAS removal than other PFAS-specific AIX resins in flow-through column experiments (Ellis et al., 2022). Studies using other AIX resins with sufficient isotherm data to enable mechanistic modeling of PFAS removal through PFAS-specific AIX resins were not identified. There are examples of studies applying the Thomas model to describe PFAS removal through AIX resins (Ellis et al., 2022; Schaefer, Nguyen, et al., 2019). The Thomas model, however, is a descriptive model rather than a mechanistic model, so the fit parameters are specific to the study conditions (such as influent concentration, flow rate, and bed length) with limited applicability across projects and sites (Myers et al., 2023). Thus, modeling to predict PFAS removal and breakthrough through AIX resins was not completed. Instead, the bed volumes to breakthrough were estimated based on literature column studies (Boyer et al., 2021; Ellis et al., 2022; Franke et al., 2019; Woodard et al., 2017) and vendor input. For Alternatives 6a and 6b, in which AIX resin beds follow lead-lag GAC beds, modeling was not completed due to overall complexity in modeling AIX breakthrough with variable influent concentrations resulting from upstream GAC performance and breakthrough. Rather, for these two alternatives, it was assumed that the AIX resin beds are operated for one year between media change-out events.

For modified clay media, there are examples of flow-through column experiments in peer-reviewed literature (Grieco et al., 2021; Medina et al., 2022; Najm et al., 2021) as well as batch kinetic and isotherm tests (Jiang et al., 2022; Yan et al., 2020); however, no publicly available datasets were found showing successful development of a mechanistic breakthrough model for PFAS removal in a fixed bed system with modified clay media. Instead, bed volumes to breakthrough estimates were informed by literature column studies (Grieco et al., 2021; Medina et al., 2022; Najm et al., 2021) and vendor input, similar to the approach taken for AIX resin beds.

The approach taken to estimate the bed volumes to breakthrough for each alternative is summarized below in Table 1.

Table 1 Approach taken to estimate the change-out frequency of sorption media

Alternative	Waste Streams	Media	Approach to estimate media change-out frequency
1a	WRRF Effluent, Landfill Leachate, or Compost Contact Water	GAC	HSDM Modeling
1b	RO Concentrate of Landfill Leachate	GAC	HSDM Modeling
2a	WRRF Effluent	AIX	Publicly available breakthrough curves and vendor input
5a	Landfill Leachate or Compost Contact Water	Modified Clay	Publicly available breakthrough curves and vendor input
6a	WRRF Effluent	GAC	HSDM Modeling
		AIX	Assumed one year of operation
6b	RO Concentrate of WRRF Effluent	GAC	HSDM Modeling
		AIX	Assumed one year of operation

3 GAC Breakthrough Modeling

3.1 Model Background

For PFAS adsorption onto GAC, breakthrough was characterized using the mechanistic HSDM with PFAS partitioning between the media and water described by the Freundlich isotherm,

$$q = KC^{1/n} \tag{1}$$

in which q is the media-phase (i.e., surface) concentration and C is the water-phase concentration at equilibrium. The Freundlich isotherm parameters are determined either in suspended batch tests or by curve-fitting the breakthrough curve for a column study.

Both breakthrough modeling approaches allow calculation of breakthrough curves for individual PFAS for varying influent concentrations and reactor configurations. However, the application of either approach has two implicit assumptions. First, the modeled PFAS concentrations are within the range of concentrations for which the Freundlich isotherm were developed. Second, the chemical parameters of the water (e.g., NOM concentration and major anion concentrations) are similar to the test conditions associated with development of the Freundlich or Langmuir isotherm.

The water-phase concentration of an individual PFAS with distance in the column can be characterized by the following equation (Crittenden et al., 1986):

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - u_x \frac{\partial C}{\partial x} - \frac{3K_f(1-\varepsilon)}{\varepsilon R}\left[C - C_s\right] \tag{3}$$

in which C is the water-phase concentration, t is time, D_x is the dispersion coefficient, x is distance, u_x is the linear water velocity, K_f is the water-film mass transfer coefficient, ε is the bed porosity, R is the radius of a media particle, and C_s is the water-phase concentration at the surface of the media in equilibrium with the media-phase concentration. The initial condition for equation (3) is $C = 0$ at all points within the bed. The Danckwerts boundary conditions apply at the column's inlet and outlet:

$$u_x\left(C_{inf} - C\right)\Big|_{x=0} = -D_x \frac{\partial C}{\partial x}\Bigg|_{x=0} \tag{4}$$

$$\frac{\partial C}{\partial x}\Bigg|_{x=L} = 0 \tag{5}$$

in which C_{inf} is the influent water-phase PFAS concentration and L is the length (or depth) of the packed-bed.

The media-phase concentration of an individual PFAS with radial distance from the center of the spherical media can be described by the HSDM with Freundlich partitioning:

$$\frac{\partial q}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D_s \frac{\partial q}{\partial r}\right) \tag{6}$$

in which D_s is the surface diffusion coefficient. The initial condition for equation (6) is $q = 0$ at all points within the media particle. Equation 6 has two boundary conditions. First, at the center of the spherical media particle, the radial concentration gradient is 0 (Equation 7).

$$\frac{\partial q}{\partial r}\Bigg|_{r=0} = 0 \tag{7}$$

Second, the mass flux from the bulk water phase to the surface of the media equals the flux into the media (Equation 8):

$$K_f\left[C - C_s\right] = \rho_m D_s \frac{\partial q}{\partial r}\Bigg|_{r=R} \tag{8}$$

in which ρ_m is the density of a media particle. From equation 1, the water-phase concentration at the surface of the media is:

$$C_s = \left(\frac{q}{K}\right)^n\Bigg|_{r=R} \quad . \tag{9}$$

3.2 Model Input Parameters

3.2.1 System Flow and GAC Vessel Sizing

The modeled flow and GAC vessel size were selected to achieve an empty bed contact time (EBCT) of 15 minutes per vessel for each alternative.

3.2.2 Mass Transfer Parameters

For this work, the calculation of water-film mass transfer coefficient K_f followed Jarvie et al. (2005). The water-phase diffusion coefficient D_w for the individual PFAS were obtained from Schaefer et al. (2019). The surface diffusivities of PFAS on GAC (D_s) were calculated using the approach presented in Jarvie et al. (2005).

3.2.3 Freundlich Parameters

The recent literature was reviewed for Freundlich isotherms describing the accumulation of individual PFAS onto GAC. The available Freundlich isotherms were screened based on the following criteria:

- the isotherms should reflect individual PFAS concentrations in the ng/L to µg/L range, and not the mg/L range;
- the isotherms for individual PFAS should be developed under exposure to a mixture of PFAS, so that some degree of competitive effects is intrinsically included;
- the mixture of PFAS should include the short chain PFAS such as PFBA and PFBS; and
- the isotherms should be developed with exposure to natural organic matter (NOM), so that some degree of competitive effects is intrinsically included.

The GAC Freundlich isotherm parameters were obtained from a pilot-scale column study treating the effluent from a biological reactor at a water utility (Burkhardt et al., 2022). The selected data set used Calgon F400 as the GAC. The GAC columns were exposed to a total organic carbon (TOC) concentration of about 2.2 mg/L. The selected GAC Freundlich isotherm parameters are provided in Table 2.

Table 2 GAC Freundlich Isotherm Parameters (Calgon F400) (Burkhardt et al., 2022)

PFAS	K $[(\mu g/g)(L/\mu g)^{1/n}]$	1/n [unitless]
PFBA	10.6	0.70
PFBS	9.17	0.71
PFHxA	56.0	1.0
PFHxS	21.6	0.85
PFOA	62.3	1.0
PFOS	120	1.0

3.2.4 Influent PFAS Concentrations

PFAS concentrations used in the coupled mass balance and HSDM are summarized in Table 3. For all PFAS and modeling scenarios, the targeted breakthrough concentration was 5 ng/L.

For alternatives implementing RO (Alternatives 1b and 6b), an 85% water recovery was assumed for wastewater effluent and 65% recovery for landfill leachate. The PFAS rejection efficiency was assumed to be 100%.

Table 3 Assumed PFAS Concentrations for Each Waste Stream Used in Breakthrough Modeling

PFAS	Wastewater Effluent	Wastewater Effluent, Concentrate from RO	Landfill Leachate	Landfill Leachate, Concentrate from RO	Compost Contact Water
	Alts 1a, 6a	Alts 6b	Alt 1a	Alt 1b	Alt 1a
PFBA	15	75	950	2,714	450
PFBS	15	75	250	714	10
PFHxA	30	150	1,500	4,286	500
PFHxS	5	25	350	1,000	10
PFOA	40	200	900	2,571	30
PFOS	5	25	150	429	20
6:2 FTS	5	25	150	429	non-detect
N-EtFOSAA	non-detect	non-detect	150	429	non-detect

All concentrations in nanograms per liter (ng/L).

3.3 Model Implementation

Breakthrough curves were obtained from a split-operator finite-difference algorithm in which reactor transport (Equation 3) was solved separately from diffusive transport within the spherical GAC particle (Equation 6). The split-operator approach is well suited for situations with sharp breakthrough curves (Miller & Rabideau, 1993). The algorithm's accuracy was verified by comparing to the analytical solution for linear adsorption isotherms (Rosen, 1954).

3.4 GAC Breakthrough Modeling Results

The HSDM model results are summarized in Table 4.

Table 4 Estimated Bed Volumes to Breakthrough Across GAC Media Beds

PFAS	Wastewater Effluent	Wastewater Effluent, Concentrate from RO	Landfill Leachate	Landfill Leachate, Concentrate from RO	Compost Contact Water
	Alts 1a, 6a	Alt 6b	1a	1b	1a
PFBA	19,500	10,400	**5,100**	**3,600**	**6,400**
PFBS	**15,700**	**8,100**	6,000	4,300	18,600
PFHxA	21,700	15,000	10,800	9,100	12,800
PFHxS	N/A[2]	14,000	6,900	5,200	22,500
PFOA	20,500	12,900	10,000	7,900	22,200
PFOS	N/A[2]	42,500	29,600	23,700	49,100
6:2 FTS	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]
N-EtFOSAA	N/A[1]	N/A[1]	N/A[1]	N/A[1]	N/A[1]

All values are unitless bed volumes to breakthrough across a packed bed of Calgon F400 GAC.
The bed volumes to breakthrough used in O&M estimates are **bolded**.
N/A=Not available

[1] Freundlich isotherm parameters were not reported for 6:2 FTS or N-EtFOSAA in Burkhardt et al. (2022).

[2] Model runs were not long enough to observe breakthrough target for PFHxS and PFOS. These two PFAS are not expected to limit the GAC change-out frequency.

4 Bed Volume to Breakthrough Estimates

The bed volumes to breakthrough used to inform operational cost estimates are summarized in Table 5.

Table 5 Summary of estimated bed volumes to breakthrough used to inform operational cost estimates

Alternative	Waste Streams	Media	Bed Volumes to Breakthrough	Basis
1a	WRRF Effluent	GAC	10,000	HSDM Modeling[1]
	Landfill Leachate	GAC	5,100	HSDM Modeling
	Compost Contact Water	GAC	6,400	HSDM Modeling
1b	RO Concentrate of Landfill Leachate	GAC	3,600	HSDM Modeling
2a	WRRF Effluent	AIX Resin	20,000	Ellis et al. (2022)
5a	Landfill Leachate	Modified Clay	5,000	Vendor input and limited literature
	Compost Contact Water	Modified Clay	10,000	Vendor input and limited literature
6a	WRRF Effluent	GAC	10,000	HSDM Modeling[1]
		AIX Resin	140,000	Assumed one year of operation (140,000 bed volumes = 1 year)
6b	RO Concentrate of WRRF Effluent	GAC	8,100	HSDM Modeling
		AIX Resin	140,000	Assumed one year of operation (140,000 bed volumes = 1 year)

[1] HSDM modeling estimated bed volumes to breakthrough to be 15,700. Based on referenced literature (see Appendix C), the maximum bed volumes to breakthrough for GAC was assumed to be 10,000 bed volumes.

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Appendix E

Detailed Design Basis and Cost Tables

Appendix E

Alternative 1a (GAC, Incineration) – Municipal Wastewater

Appendix E: Table 1a - WW	Alternative 1a - GAC, Incineration			Units	Notes
Waste stream	Wastewater	Wastewater	Wastewater	--	
Design flow rate	0.1	1	10	MGD	
Design flow rate	70	700	7,000	gpm	Rounded to one significant digit.
Pressure Vessels					
Vessel capacity	6,000	20,000	60,000	lb	
# of lead/lag vessel trains	1	3	9	--	
# of vessels	2	6	18	--	
Media type	12x40	12x40	12x40	--	Reagglomerated, coal-based GAC.
Media apparent density	0.54	0.54	0.54	g/cm3	
Media volume, per vessel	150	470	1,600	ft3	Calculated based on target EBCT. Rounded to two significant digits.
Media weight, per vessel	5,100	16,000	54,000	lb	Calculated based on target EBCT. Rounded to two significant digits.
Empty-bed contact time, per vessel	15	15	15	minutes	
Vessel diameter	6.0	12	14	ft	Showing two significant digits.
Media bed depth	5.0	4.1	10.1	ft	Showing two significant digits.
Hydraulic loading rate	2.5	2.1	5.1	gpm/ft2	Showing two significant digits.
Estimated footprint, first train	800	2,400	3,300	ft2	Rounded to the nearest 100 ft2.
Estimated footprint, additional train	600	1,300	2,100	ft2	Rounded to the nearest 100 ft2.
Driving lane	No	Yes	Yes	--	
Pipe gallery	No	Yes	Yes	--	
Lab and bathroom	No	Yes	Yes	--	
Estimated footprint, total	800	5,000	20,100	ft2	Rounded to the nearest 100 ft2.
Estimated time to breakthrough	10,000	10,000	10,000	bed volumes	Based on modelled breakthrough of PFBS at 5 ng/L.
Estimated changeout frequency	100	100	100	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin GAC)	1	2	13	--	Rounded to nearest integer.
# Trucks per event (spent GAC)	1	3	25	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.

Appendix E: Table 1a - WW	Alternative 1a - GAC, Incineration			Units	Notes
Change-out events per year	3.7	3.7	3.7	--	Rounded to two significant digits.
Estimated media usage rate	22,000	220,000	2,000,000	lbs/year	Rounded to two significant digits.
Estimated media usage rate	0.60	0.60	0.55	lbs/1000-gal	Pounds per 1,000 gallons treated.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432

OPINION OF COST - SUMMARY

SHEET:	1	OF	1
BY:	RRM	DATE:	12/8/2022
CHECKED BY:	AJM2	DATE:	3/3/2023
APPROVED BY:	KMB	DATE:	3/20/2023
ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost
Municipal Wastewater - Alternative 1a

Total Treatment Flow Rate			Units
Low	Middle	High	
0.1	1	10	MGD
70	700	7000	GPM

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$184,000	$184,000	1	$1,063,000	$1,063,000	1	$6,104,000	$6,104,000	1,2,3,4
B	PFAS Separation Equipment	LS	1	$320,000	$320,000	1	$1,767,000	$1,767,000	1	$12,096,000	$12,096,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$160,000	$160,000	1	$884,000	$884,000	1	$6,048,000	$6,048,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$64,000	$64,000	1	$354,000	$354,000	1	$2,420,000	$2,420,000	1,2,3,4
E	Treatment Building	SF	800	$500	$400,000	5,000	$500	$2,500,000	20,100	$500	$10,050,000	1,2,3,4
F	Site Work	LS	1	$40,000	$40,000	1	$250,000	$250,000	1	$1,005,000	$1,005,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$240,000	$240,000	1	$1,326,000	$1,326,000	1	$9,072,000	$9,072,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$1,410,000			$8,140,000			$46,800,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$350,000		25%	$2,040,000		25%	$11,700,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$1,760,000			$10,180,000			$58,500,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$1,800,000**			**$10,200,000**			**$58,500,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$1,300,000			$7,200,000			$41,000,000	4,6
		50%			$2,700,000			$15,300,000			$87,800,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -30% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy range are not intended to include costs for future scope changes that are not part of the project as currently scoped or costs for risk contingency. Operation and maintenance costs are not included.

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or additional tasks following construction.

PREPARED BY: BARR ENGINEERING COMPANY

SHEET:	1	OF	1	
BY:	AJM2	DATE:	12/9/2022	
CHECKED BY:	RRM	DATE:	2/17/2023	
APPROVED BY:	KMB	DATE:	3/20/2023	

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432

OPINION OF COST - SUMMARY

ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable O&M Cost

Municipal Wastewater - Alternative 1a - GAC

Total Treatment Flow Rate			Units
Low	Middle	High	
0.1	1	10	MGD
70	700	7,000	GPM

				LOW FLOWRATE		MIDDLE FLOWRATE		HIGH FLOWRATE		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 12,000**		**$ 26,000**		**$ 155,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	11,700	$ 2,000	43,500	$ 6,000	361,700	$ 49,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	63,000	$ 9,000	121,800	$ 17,000	710,400	$ 95,000	1,2
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	30	$ 1,000	180	$ 3,000	700	$ 11,000	1
1.2	**MEDIA REPLACEMENT AND DISPOSAL**				**$ 129,000**		**$ 991,000**		**$ 4,971,000**	1
1.2.1	Media Purchase	LB	$ 2.50	22,200	$ 56,000	222,000	$ 555,000	0	$ -	1
1.2.2	Transportation - New Media Purchase	MILE	$ 3.00	3,300	$ 10,000	6,700	$ 21,000	0	$ -	1
1.2.3	Media disposal - Incineration	LB	$ 0.65	44,400	$ 29,000	444,000	$ 289,000	0	$ -	1
1.2.4	Transportation - Media incineration	MILE	$ 3.00	2,800	$ 9,000	8,400	$ 26,000	0	$ -	1
1.2.5	Media disposal - Reactivation (Destruction + Media)	LB	$ 2.00	0	$ -	0	$ -	1,998,000	$ 3,996,000	1
1.2.6	Transportation - Media reactivation	MILE	$ 3.00	0	$ -	0	$ -	166,500	$ 500,000	1
1.2.7	General Conditions - Service Provider - Mobilization	TRUCK PER EVENT	$ 5,000	5	$ 25,000	20	$ 100,000	95	$ 475,000	1
1.3	**MAINTENANCE**				**$ 19,000**		**$ 104,000**		**$ 668,000**	1
1.3.1	Process equipment maintenance	% equip. purchase	3%	1	$ 17,000	1	$ 91,000	1	$ 617,000	1
1.3.2	General building maintenance	sq foot	$ 2.50	800	$ 2,000	5,000	$ 13,000	20,100	$ 51,000	1
1.4	**ANALYTICAL MONITORING**				**$ 16,000**		**$ 36,000**		**$ 92,000**	1
1.4.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	40	$ 16,000	90	$ 36,000	230	$ 92,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	1	$ 100,000	1	$ 100,000	2	$ 200,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	1	$ 100,000	1
	Total Workforce	**Base Payroll**			$ 150,000		$ 150,000		$ 300,000	1
		Fringe Rate	0.5		$ 75,000		$ 75,000		$ 150,000	1
		Total Payroll			**$ 225,000**		**$ 225,000**		**$ 450,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 410,000**		**$ 1,400,000**		**$ 6,400,000**	3
	Estimated Uncertainty Range	-30%			$ 290,000		$ 980,000		$ 4,480,000	3,4
		+50%			$ 620,000		$ 2,100,000		$ 9,600,000	3,4
	Unit Cost per 1,000 gallons treated				$ 11.23		$ 3.84		$ 1.75	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Electric Power Research Institute and Water Research Foundation. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Report 3002001433. November 2013.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

Appendix E

Alternative 1a (GAC, Incineration) – Landfill Leachate / Compost Contact Water

Appendix E: Table 1a - LL/CCW	Alternative 1a - GAC, Incineration			Units	Notes
Waste stream	LL/CCW	LL/CCW	LL/CCW	--	
Design flow rate	0.00144	0.0144	0.14	MGD	
Design flow rate	1	10	100	gpm	Rounded to one significant digit.
Pressure Vessels					
Vessel capacity	90	750	10,000	lb	
# of lead/lag vessel trains	2	1	1	--	
# of vessels	4	2	2	--	
Media type	12x40	12x40	12x40	--	Reagglomerated, coal-based GAC.
Media apparent density	0.54	0.54	0.54	g/cm3	
Media volume, per vessel	2.0	21	210	ft3	Calculated based on target EBCT. Rounded to two significant digits.
Media weight, per vessel	70	710	7,100	lb	Calculated based on target EBCT. Rounded to two significant digits.
Empty-bed contact time, per vessel	15	15	15	minutes	
Vessel diameter	1.2	2.0	8.0	ft	Showing two significant digits.
Media bed depth	0.9	6.4	4.0	ft	Showing two significant digits.
Hydraulic loading rate	0.5	3.2	2.0	gpm/ft2	Showing two significant digits
Estimated footprint, first train	50	140	1,900	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.
Estimated footprint, additional train	40	100	1,300	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.
Driving lane	No	No	Yes	--	
Pipe gallery	No	No	Yes	--	
Lab and bathroom	No	No	No	--	
Estimated footprint, total	90	140	1,900	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.

Appendix E: Table 1a - LL/CCW	**Alternative 1a - GAC, Incineration**			**Units**	**Notes**
Estimated Time to Breakthrough - LL					
Estimated time to breakthrough	5,100	5,100	5,100	bed volumes	Based on modelled breakthrough of PFBS at 5 ng/L.
Estimated changeout frequency	50	50	50	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin GAC)	1	1	1	--	Rounded to nearest integer.
# Trucks per event (spent GAC)	1	1	1	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	7.3	7.3	7.3	--	Rounded to two significant digits.
Estimated media usage rate	1,400	5,500	73,000	lbs/year	Rounded to two significant digits.
Estimated media usage rate	2.66	1.05	1.39	lbs/1000-gal	Pounds per 1,000 gallons treated.
Estimated Time to Breakthrough - CCW					
Estimated time to breakthrough	6,400	6,400	6,400	bed volumes	Based on modelled breakthrough of PFBS at 5 ng/L.
Estimated changeout frequency	60	60	60	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin GAC)	1	1	1	--	Rounded to nearest integer.
# Trucks per event (spent GAC)	1	1	1	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	6.1	6.1	6.1	--	Rounded to two significant digits.
Estimated media usage rate	1,100	4,600	61,000	lbs/year	Rounded to two significant digits.
Estimated media usage rate	2.09	0.88	1.16	lbs/1000-gal	Pounds per 1,000 gallons treated.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

SHEET:	1	OF	1
BY:	RRM	DATE:	12/8/2022
CHECKED BY:	AJM2	DATE:	3/3/2023
APPROVED BY:	KMB	DATE:	3/20/2023
ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost Landfill Leachate / Compost Contact Water - Alternative 1a

Total Treatment Flow Rate			Units
Low	Middle	High	
0.00144	0.0144	0.144	MGD
1	10	100	GPM

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$16,000	$16,000	1	$42,000	$42,000	1	$294,000	$294,000	1,2,3,4
B	PFAS Separation Equipment	LS	1	$21,000	$21,000	1	$82,000	$82,000	1	$372,000	$372,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$11,000	$11,000	1	$41,000	$41,000	1	$186,000	$186,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$5,000	$5,000	1	$17,000	$17,000	1	$75,000	$75,000	1,2,3,4
E	Treatment Building	SF	90	$500	$45,000	140	$500	$70,000	1,900	$500	$950,000	1,2,3,4
F	Site Work	LS	1	$5,000	$5,000	1	$7,000	$7,000	1	$95,000	$95,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$16,000	$16,000	1	$62,000	$62,000	1	$279,000	$279,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$120,000			$320,000			$2,250,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$30,000		25%	$80,000		25%	$560,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$150,000			$400,000			$2,810,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$200,000**			**$400,000**			**$2,900,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$200,000			$300,000			$2,100,000	4,6
		50%			$300,000			$600,000			$4,400,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -30% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy range are not intended to include costs for future scope changes that are not part of the project as currently scoped or costs for risk contingency. Operation and maintenance costs are not included.

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or

PREPARED BY: BARR ENGINEERING COMPANY

SHEET:	1	OF	1	
BY:	AJM2	DATE:	12/9/2022	
CHECKED BY:	RRM	DATE:	2/17/2023	
APPROVED BY:	KMB	DATE:	3/20/2023	

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water

LOCATION: MINNESOTA

PROJECT #: 23621432

OPINION OF COST - SUMMARY

ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable O&M Cost

Landfill Leachate - Alternative 1a - GAC

Total Treatment Flow Rate			Units
Low	**Middle**	**High**	
0.00144	0.0144	0.144	MGD
1	10	100	GPM

				LOW FLOWRATE		**MIDDLE FLOWRATE**		**HIGH FLOWRATE**		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 10,000**		**$ 10,000**		**$ 13,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	8,200	$ 2,000	8,700	$ 2,000	13,200	$ 2,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	56,500	$ 8,000	57,400	$ 8,000	65,900	$ 9,000	1,2
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	0	$ -	0	$ -	70	$ 2,000	1
1.2	**MEDIA REPLACEMENT AND DISPOSAL**				**$ 118,000**		**$ 134,000**		**$ 390,000**	1
1.2.1	Media Purchase	LB	$ 2.50	1,400	$ 4,000	5,500	$ 14,000	73,000	$ 183,000	1
1.2.2	Transportation - New Media Purchase	MILE	$ 3.00	6,600	$ 20,000	6,600	$ 20,000	6,600	$ 20,000	1
1.2.3	Media disposal - Incineration	LB	$ 0.65	2,800	$ 2,000	11,000	$ 8,000	146,000	$ 95,000	1
1.2.4	Transportation - Media incineration	MILE	$ 3.00	5,500	$ 17,000	5,500	$ 17,000	5,500	$ 17,000	1
1.2.5	General Conditions - Service Provider - Mobilization	TRUCK PER EVENT	$ 5,000	15	$ 75,000	15	$ 75,000	15	$ 75,000	1
1.3	**MAINTENANCE**				**$ 3,000**		**$ 6,000**		**$ 24,000**	1
1.3.1	Process equipment maintenance	% equipment	3%	1	$ 2,000	1	$ 5,000	1	$ 19,000	1
1.3.2	General building maintenance	sq foot	$ 2.50	90	$ 1,000	140	$ 1,000	1,900	$ 5,000	1
1.4	**ANALYTICAL MONITORING**				**$ 24,000**		**$ 16,000**		**$ 16,000**	1
1.4.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	60	$ 24,000	40	$ 16,000	40	$ 16,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	1	$ 100,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	0.5	$ 50,000	1
	Total Workforce	**Base Payroll**			$ 100,000		$ 100,000		$ 150,000	1
		Fringe Rate	0.5		$ 50,000		$ 50,000		$ 75,000	1
		Total Payroll			**$ 150,000**		**$ 150,000**		**$ 225,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 310,000**		**$ 320,000**		**$ 700,000**	3
	Estimated Uncertainty Range	-30%			$ 220,000		$ 230,000		$ 490,000	3,4
		+50%			$ 470,000		$ 480,000		$ 1,050,000	3,4
	Unit Cost per 1,000 gallons treated				$ 590		$ 61		$ 13.32	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Electric Power Research Institute and Water Research Foundation. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Report 3002001433. November 2013.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

SHEET:	1	OF	1
BY:	AJM2	DATE:	12/9/2022
CHECKED BY:	RRM	DATE:	2/17/2023
APPROVED BY:	KMB	DATE:	3/20/2023
ISSUED:	DRAFT 1	DATE:	11/11/2022
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ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable O&M Cost

Compost Contact Water - Alternative 1a - GAC

Total Treatment Flow Rate			Units
Low	**Middle**	**High**	
0.00144	0.0144	0.144	MGD
1	10	100	GPM

				LOW FLOWRATE		**MIDDLE FLOWRATE**		**HIGH FLOWRATE**		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 10,000**		**$ 10,000**		**$ 13,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	8,200	$ 2,000	8,700	$ 2,000	13,200	$ 2,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	56,500	$ 8,000	57,400	$ 8,000	65,900	$ 9,000	1,2
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	0	$ -	0	$ -	70	$ 2,000	1
1.2	**MEDIA REPLACEMENT AND DISPOSAL**				**$ 86,000**		**$ 99,000**		**$ 314,000**	1
1.2.1	Media Purchase	LB	$ 2.50	1,100	$ 3,000	4,600	$ 12,000	61,000	$ 153,000	1
1.2.2	Transportation - New Media Purchase	MILE	$ 3.00	5,500	$ 17,000	5,500	$ 17,000	5,500	$ 17,000	1
1.2.3	Media disposal - Incineration	LB	$ 0.65	2,200	$ 2,000	9,200	$ 6,000	122,000	$ 80,000	1
1.2.4	Transportation - Media incineration	MILE	$ 3.00	4,600	$ 14,000	4,600	$ 14,000	4,600	$ 14,000	1
1.2.5	General Conditions - Service Provider - Mobilization	TRUCK PER EVENT	$ 5,000	10	$ 50,000	10	$ 50,000	10	$ 50,000	1
1.3	**MAINTENANCE**				**$ 3,000**		**$ 6,000**		**$ 24,000**	1
1.3.1	Process equipment maintenance	% equipment	3%	1	$ 2,000	1	$ 5,000	1	$ 19,000	1
1.3.2	General building maintenance	sq foot	$ 2.50	90	$ 1,000	140	$ 1,000	1,900	$ 5,000	1
1.4	**ANALYTICAL MONITORING**				**$ 24,000**		**$ 16,000**		**$ 16,000**	1
1.4.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	60	$ 24,000	40	$ 16,000	40	$ 16,000	1

Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	1	$ 100,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	0.5	$ 50,000	1
	Total Workforce	**Base Payroll**			$ 100,000		$ 100,000		$ 150,000	1
		Fringe Rate	0.5		$ 50,000		$ 50,000		$ 75,000	1
		Total Payroll			**$ 150,000**		**$ 150,000**		**$ 225,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 280,000**		**$ 290,000**		**$ 600,000**	3
	Estimated Uncertainty Range	-30%			$ 200,000		$ 210,000		$ 420,000	3,4
		+50%			$ 420,000		$ 440,000		$ 900,000	3,4
	Unit Cost per 1,000 gallons treated				$ 533		$ 55		$ 11.42	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Electric Power Research Institute and Water Research Foundation. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Report 3002001433. November 2013.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

Appendix E

Alternative 1b (RO, GAC, Incineration) – Landfill Leachate

Appendix E: Table 1b - LL	**Alternative 1b - RO, Concentrate to GAC and Incineration**			**Units**	**Notes**
Waste stream	LL	LL	LL	--	
Design flow rate	0.0014400	0.0144	0.144	MGD	
Design flow rate	1	10	100	gpm	Rounded to one significant digit.
Membranes					
Recovery	65%	65%	65%	%	Assumed, lower than WW due to higher salinity.
# of skids	1	1	1	--	
# Elements	2	7	54		
Membrane type	RO	RO	RO	--	
Flux	16	16	16	gfd	gfd = gallons per sq. ft. per day.
Concentrate management flow rate	0.0005	0.005	0.05	MGD	
Concentrate management flow rate	1	4	40	gpm	Rounded to one significant digit.
Estimated footprint, total (membranes)	10	300	700	ft2	
Pressure Vessels (GAC)					
Vessel capacity	90	250	2,000	lb	
# of lead/lag vessel trains	2	2	2	--	
# of vessels	4	4	4	--	
Media type	12x40	12x40	12x40	--	Reagglomerated, coal-based GAC.
Media apparent density	0.54	0.54	0.54	g/cm3	
Media volume, per vessel	2	5	41	ft3	Calculated based on target EBCT. Rounded to nearest integer.
Media weight, per vessel	70	170	1,400	lb	Calculated based on target EBCT. Rounded to two significant digits.
Empty-bed contact time, per vessel	15	15	15	minutes	
Vessel diameter	1.2	2.0	5.0	ft	Showing two significant digits.
Media bed depth	0.94	1.3	2.0	ft	Showing two significant digits.
Hydraulic loading rate	0.47	0.64	1.0	gpm/ft2	Showing two significant digits.
Estimated footprint, first train	50	60	900	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.

Appendix E: Table 1b - LL	**Alternative 1b - RO, Concentrate to GAC and Incineration**			**Units**	**Notes**
Estimated footprint, additional train	40	50	600	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.
Driving lane	No	No	Yes	--	
Pipe gallery	No	No	Yes	--	
Lab and bathroom	No	No	No	--	
Estimated footprint, total (GAC)	90	110	1,500	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.
Combined footprint, total	100	410	2,200	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.
Estimated time to breakthrough, GAC	3,600	3,600	3,600	bed volumes	Based on modelled breakthrough of PFBS at 5 ng/L.
Estimated changeout frequency, GAC	30	30	30	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin GAC)	1	1	1	--	Rounded to nearest integer.
# Trucks per event (spent GAC)	1	1	1	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	13	13	13	--	Rounded to two significant digits.
Estimated media usage rate	2,200	6,100	49,000	lbs/year	Rounded to two significant digits.
Estimated media usage rate	4.19	1.16	0.93	lbs/1000-gal	Pounds per 1,000 gallons treated.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

SHEET:	1	OF	1
BY:	RRM	DATE:	12/8/2022
CHECKED BY:	AJM2	DATE:	3/3/2023
APPROVED BY:	KMB	DATE:	3/20/2023
ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost

Landfill Leachate - Alternative 1b

Total Treatment Flow Rate			Units
Low	**Middle**	**High**	
0.0014	0.014	0.14	MGD
1	10	100	GPM

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$46,000	$46,000	1	$216,000	$216,000	1	$654,000	$654,000	1,2,3,4
B	PFAS Separation Equipment	LS	1	$31,000	$31,000	1	$92,000	$92,000	1	$679,000	$679,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$16,000	$16,000	1	$46,000	$46,000	1	$340,000	$340,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$7,000	$7,000	1	$19,000	$19,000	1	$136,000	$136,000	1,2,3,4
E	Treatment Building	SF	410	$500	$205,000	2,200	$500	$1,100,000	4,900	$500	$2,450,000	1,2,3,4
F	Site Work	LS	1	$21,000	$21,000	1	$110,000	$110,000	1	$245,000	$245,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$24,000	$24,000	1	$69,000	$69,000	1	$510,000	$510,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$350,000			$1,650,000			$5,010,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$90,000		25%	$410,000		25%	$1,250,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$440,000			$2,060,000			$6,260,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$500,000**			**$2,100,000**			**$6,300,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$400,000			$1,500,000			$4,500,000	4,6
		50%			$800,000			$3,200,000			$9,500,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -50% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy range are not intended to include costs for future scope changes that are not part of the project as currently scoped or costs for risk contingency. Operation and maintenance costs are not included.

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or additional tasks following construction.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

SHEET:	1	OF	1	
BY:	AJM2	DATE:	12/9/2022	
CHECKED BY:	RRM	DATE:	2/17/2023	
APPROVED BY:	KMB	DATE:	3/20/2023	

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable O&M Cost

Landfill Leachate - Alternative 1b - RO+GAC

Total Treatment Flow Rate Low	Middle	High	Units
0.00144	0.0144	0.144	MGD
1	10	100	GPM

				LOW FLOWRATE		MIDDLE FLOWRATE		HIGH FLOWRATE		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 10,000**		**$ 14,000**		**$ 45,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	10,600	$ 2,000	32,800	$ 5,000	254,000	$ 34,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	56,500	$ 8,000	57,400	$ 8,000	65,900	$ 9,000	1,2
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	0	$ -	10	$ 1,000	80	$ 2,000	1
1.2	**MEDIA REPLACEMENT AND DISPOSAL**				**$ 200,000**		**$ 217,000**		**$ 389,000**	1
1.2.1	Media Purchase	LB	$ 2.50	2,300	$ 6,000	6,500	$ 17,000	52,000	$ 130,000	1
1.2.2	Transportation - New Media Purchase	MILE	$ 3.00	11,700	$ 36,000	11,700	$ 36,000	11,700	$ 36,000	1
1.2.3	Media disposal - Incineration	LB	$ 0.65	4,600	$ 3,000	13,000	$ 9,000	104,000	$ 68,000	1
1.2.4	Transportation - Media incineration	MILE	$ 3.00	9,900	$ 30,000	9,900	$ 30,000	9,900	$ 30,000	1
1.2.5	General Conditions - Service Provider - Mobilization	TRUCK PER EVENT	$ 5,000	25	$ 125,000	25	$ 125,000	25	$ 125,000	1
1.3	**RO CONSUMABLES**				**$ 7,000**		**$ 20,000**		**$ 277,000**	1
1.3.1	Antiscalant	LB	$ 10	10	$ 1,000	100	$ 1,000	1,000	$ 10,000	1
1.3.2	Clean-in-place Chemicals	LB	$ 2	2,400	$ 5,000	8,400	$ 17,000	129,800	$ 260,000	1
1.3.3	RO Element Replacement (5-year Replacement)	Element	$ 700	1	$ 1,000	2	$ 2,000	10	$ 7,000	1
1.4	**MAINTENANCE**				**$ 3,000**		**$ 6,000**		**$ 41,000**	1
1.4.1	Process equipment maintenance	% equipment	3%	1	$ 2,000	1	$ 5,000	1	$ 35,000	1
1.4.2	General building maintenance	sq foot	$ 2.50	100	$ 1,000	400	$ 1,000	2,200	$ 6,000	1
1.5	**ANALYTICAL MONITORING**				**$ 36,000**		**$ 36,000**		**$ 36,000**	1
1.5.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	90	$ 36,000	90	$ 36,000	90	$ 36,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	1	$ 100,000	1	$ 100,000	1	$ 100,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	0.5	$ 50,000	1
	Total Workforce	**Base Payroll**			$ 150,000		$ 150,000		$ 150,000	1
		Fringe Rate	0.5		$ 75,000		$ 75,000		$ 75,000	1
		Total Payroll			**$ 225,000**		**$ 225,000**		**$ 225,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 490,000**		**$ 520,000**		**$ 1,100,000**	3
	Estimated Uncertainty Range	-30%			$ 350,000		$ 370,000		$ 770,000	3,4
		+50%			$ 800,000		$ 800,000		$ 1,700,000	3,4
	Unit Cost per 1,000 gallons treated				$ 932		$ 99		$ 20.93	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Electric Power Research Institute and Water Research Foundation. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Report 3002001433. November 2013.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

Appendix E

Alternative 2a (AIX, Incineration) – Municipal Wastewater

Appendix E: Table 2a - WW	Alternative 2a - AIX, Incineration			Units	Notes
Waste stream	Wastewater	Wastewater	Wastewater	--	
Design flow rate	0.1	1	10	MGD	
Design flow rate	70	700	7,000	gpm	Rounded to one significant digit.
Pressure Vessels					
Vessel capacity	38	201	450	ft3	
# of lead/lag vessel trains	2	2	9	--	
# of vessels	4	4	18	--	
Media type	AIX Resin	AIX Resin	AIX Resin	--	Polystyrenic gel.
Media apparent density	42.2	42.2	42.2	lb/ft3	
Media volume, per vessel	19	190	420	ft3	Calculated based on target EBCT. Rounded to two significant digits.
Media weight, per vessel	900	8,100	18,000	lb	Calculated based on target EBCT. Rounded to two significant digits.
Empty-bed contact time, per vessel	4	4	4	minutes	
Vessel diameter	3.0	8.0	12.0	ft	Showing two significant digits.
Media bed depth	2.6	3.7	3.7	ft	Showing two significant digits.
Hydraulic loading rate	5.0	7.0	6.9	gpm/ft2	Showing two significant digits.
Specific flow rate	0.9	1.7	1.7	gpm/ft3	
Estimated footprint, first train	200	2,400	2,900	ft2	Rounded to the nearest 100 ft2.
Estimated footprint, additional train	200	1,200	1,700	ft2	Rounded to the nearest 100 ft2.
Driving lane	No	Yes	Yes	--	
Pipe gallery	No	Yes	Yes	--	
Lab and bathroom	No	Yes	Yes	--	
Estimated footprint, total	400	3,600	16,500	ft2	Rounded to the nearest 100 ft2.
Estimated time to breakthrough	20,000	20,000	20,000	bed volumes	Based on maximum bed volumes treated in Ellis et al. (2022).
Estimated changeout frequency	50	50	50	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin resin)	1	1	5	--	Rounded to nearest integer.

Appendix E: Table 2a - WW	**Alternative 2a - AIX, Incineration**			**Units**	**Notes**
# Trucks per event (spent resin)	1	1	9	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	7.3	7.3	7.3	--	Rounded to two significant digits.
Estimated media usage rate	14,000	120,000	1,200,000	lb/year	Rounded to two significant digits.
Estimated media usage rate	0.38	0.33	0.33	lbs/1000-gal	Pounds per 1,000 gallons treated.

PREPARED BY: BARR ENGINEERING COMPANY

SHEET:	1	OF	1
BY:	RRM	DATE:	12/8/2022
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APPROVED BY:	KMB	DATE:	3/20/2023

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432

OPINION OF COST - SUMMARY

ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost

Municipal Wastewater - Alternative 2a

Total Treatment Flow Rate			Units
Low	Middle	High	
0.1	1	10	MGD
70	700	7000	GPM

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$78,000	$78,000	1	$995,000	$995,000	1	$6,982,000	$6,982,000	1,2,3,4
B	PFAS Separation Equipment	LS	1	$122,000	$122,000	1	$1,897,000	$1,897,000	1	$15,293,000	$15,293,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$61,000	$61,000	1	$949,000	$949,000	1	$7,647,000	$7,647,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$25,000	$25,000	1	$380,000	$380,000	1	$3,059,000	$3,059,000	1,2,3,4
E	Treatment Building	SF	400	$500	$200,000	3,600	$500	$1,800,000	16,500	$500	$8,250,000	1,2,3,4
F	Site Work	LS	1	$20,000	$20,000	1	$180,000	$180,000	1	$825,000	$825,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$92,000	$92,000	1	$1,423,000	$1,423,000	1	$11,470,000	$11,470,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$600,000			$7,620,000			$53,530,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$150,000		25%	$1,910,000		25%	$13,380,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$750,000			$9,530,000			$66,910,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$800,000**			**$9,600,000**			**$67,000,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$600,000			$6,800,000			$46,900,000	4,6
		50%			$1,200,000			$14,400,000			$100,500,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -30% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy range are not intended to include costs for future scope changes that are not part of the project as currently scoped or costs for risk contingency. Operation and maintenance costs are not included.

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or additional tasks following construction.

PREPARED BY: BARR ENGINEERING COMPANY

SHEET:	1	OF	1
BY:	AJM2	DATE:	12/9/2022
CHECKED BY:	RRM	DATE:	2/17/2023
APPROVED BY:	KMB	DATE:	3/20/2023

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable O&M Cost

Municipal Wastewater - Alternative 2a - AIX

Total Treatment Flowrate Low	Total Treatment Flowrate Middle	Total Treatment Flowrate High	Units
0.1	1	10	MGD
70	700	7000	GPM

				LOW FLOWRATE		MIDDLE FLOWRATE		HIGH FLOWRATE		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 12,000**		**$ 25,000**		**$ 153,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	11,700	$ 2,000	43,500	$ 6,000	361,700	$ 49,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	63,000	$ 9,000	121,800	$ 17,000	710,400	$ 95,000	1,2
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	10	$ 1,000	130	$ 2,000	580	$ 9,000	1
1.2	**MEDIA REPLACEMENT AND DISPOSAL**				**$ 218,000**		**$ 1,151,000**		**$ 11,096,000**	1
1.2.1	Media Purchase	CU FT	$ 320	280	$ 90,000	2,770	$ 887,000	27,600	$ 8,832,000	1
1.2.2	Transportation - New Media Purchase	MILE	$ 3.00	6,570	$ 20,000	6,570	$ 20,000	32,900	$ 99,000	1
1.2.3	Media disposal - Incineration	LB	$ 0.65	23,600	$ 16,000	233,800	$ 152,000	2,329,400	$ 1,515,000	1
1.2.4	Transportation - Media incineration	MILE	$ 3.00	5,550	$ 17,000	5,500	$ 17,000	49,900	$ 150,000	1
1.2.5	General Conditions - Service Provider - Mobilization	TRUCK PER EVENT	$ 5,000	15	$ 75,000	15	$ 75,000	100	$ 500,000	1
1.3	**MAINTENANCE**				**$ 8,000**		**$ 106,000**		**$ 822,000**	1
1.3.1	Process equipment maintenance	% equipment	3%	1	$ 7,000	1	$ 97,000	1	$ 780,000	1
1.3.2	General building maintenance	sq foot	$ 2.50	400	$ 1,000	3,600	$ 9,000	16,500	$ 42,000	1
1.4	**ANALYTICAL MONITORING**				**$ 24,000**		**$ 24,000**		**$ 92,000**	1
1.4.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	60	$ 24,000	60	$ 24,000	230	$ 92,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	1	$ 100,000	1	$ 100,000	2	$ 200,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	1	$ 100,000	1
	Total Workforce	**Base Payroll**			$ 150,000		$ 150,000		$ 300,000	1
		Fringe Rate	0.5		$ 75,000		$ 75,000		$ 150,000	1
		Total Payroll			**$ 225,000**		**$ 225,000**		**$ 450,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 490,000**		**$ 1,600,000**		**$ 12,700,000**	3
	Estimated Uncertainty Range	-30%			$ 350,000		$ 1,120,000		$ 8,890,000	3,4
		+50%			$ 740,000		$ 2,400,000		$ 19,050,000	3,4
	Unit Cost per 1,000 gallons treated				$ 13.42		$ 4.38		$ 3.48	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Electric Power Research Institute and Water Research Foundation. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Report 3002001433. November 2013.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

Appendix E

Alternative 5a (Modified Clay, Incineration) – Landfill Leachate / Compost Contact Water

Appendix E: Table 5a - LL/CCW	**Alternative 5a - Modified Clay Media, Incineration**			**Units**	**Notes**
Waste stream	LL/CCW	LL/CCW	LL/CCW	--	
Design flow rate	0.00144	0.0144	0.14	MGD	
Design flow rate	1	10	100	gpm	Rounded to one significant digit.
Flowrate per vessel	1	3	25	gpm	
Pressure Vessels					
Vessel capacity	3	5	38	ft3	
# of lead/lag vessel trains	1	3	4	--	
# of vessels	2	6	8	--	
Media type	Modified Clay	Modified Clay	Modified Clay	--	
Media apparent density	46.2	46.2	46.2	lb/ft3	
Media volume, per vessel	2	5	34	ft3	Calculated based on target EBCT. Rounded to nearest integer.
Media weight, per vessel	93	240	1,600	lb	Calculated based on target EBCT. Rounded to two significant digits.
Empty-bed contact time, per vessel	10	10	10	minutes	
Vessel diameter	1.2	1.5	3.0	ft	Showing two significant digits.
Media bed depth	1.3	2.5	4.7	ft	Showing two significant digits.
Hydraulic loading rate	0.9	1.9	3.5	gpm/ft2	Showing two significant digits.
Estimated footprint, first train	50	50	900	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.
Estimated footprint, additional train	40	40	400	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.
Driving lane	No	No	Yes	--	
Pipe gallery	No	No	Yes	--	
Lab and bathroom	No	No	No	--	

Appendix E: Table 5a - LL/CCW	**Alternative 5a - Modified Clay Media, Incineration**			**Units**	**Notes**
Estimated footprint, total	50	130	2,100	ft2	1 and 10 gpm rounded to the nearest 10 ft2. 100 gpm rounded to the nearest 100 ft2.
Estimated time to breakthrough - LL					
Estimated time to breakthrough	5,000	5,000	5,000	bed volumes	
Estimated changeout frequency	30	30	30	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin modified clay)	1	1	1	--	Rounded to nearest integer.
# Trucks per event (spent modified clay)	1	1	1	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	13	13	13	--	Rounded to two significant digits.
Estimated media usage rate	1,300	9,400	84,000	lb/year	Rounded to two significant digits.
Estimated media usage rate	2.47	1.79	1.60	lbs/1000-gal	Pounds per 1,000 gallons treated.
Estimated time to breakthrough - CCW					
Estimated time to breakthrough	10,000	10,000	10,000	bed volumes	
Estimated changeout frequency	60	60	60	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin modified clay)	1	1	1	--	Rounded to nearest integer.
# Trucks per event (spent modified clay)	1	1	1	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	6.1	6.1	6.1	--	Rounded to two significant digits.
Estimated media usage rate	600	4,400	40,000	lb/year	Rounded to two significant digits.
Estimated media usage rate	1.14	0.84	0.76	lbs/1000-gal	Pounds per 1,000 gallons treated.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

SHEET:	1	OF	1
BY:	RRM	DATE:	12/5/2022
CHECKED BY:	AJM2	DATE:	3/3/2023
APPROVED BY:	KMB	DATE:	3/20/2023
ISSUED:	DRAFT 1	DATE:	NA
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost Landfill Leachate / Compost Contact Water - Alternative 5a

Total Treatment Flow Rate			Units
Low	Middle	High	
0.00144	0.0144	0.144	MGD
1	10	100	GPM

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$13,000	$13,000	1	$28,000	$28,000	1	$262,000	$262,000	1,2,3,4
B	PFAS Separation Equipment	LS	1	$21,000	$21,000	1	$45,000	$45,000	1	$239,000	$239,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$11,000	$11,000	1	$23,000	$23,000	1	$120,000	$120,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$5,000	$5,000	1	$9,000	$9,000	1	$48,000	$48,000	1,2,3,4
E	Treatment Building	SF	50	$500	$25,000	130	$500	$65,000	2,100	$500	$1,050,000	1,2,3,4
F	Site Work	LS	1	$3,000	$3,000	1	$7,000	$7,000	1	$105,000	$105,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$16,000	$16,000	1	$34,000	$34,000	1	$180,000	$180,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$90,000			$210,000			$2,000,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$20,000		25%	$50,000		25%	$500,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$110,000			$260,000			$2,500,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$200,000**			**$300,000**			**$2,500,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$200,000			$300,000			$1,800,000	4,6
		50%			$300,000			$500,000			$3,800,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -50% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy range are not intended to include costs for future scope changes that are not part of the project as currently scoped or costs for risk contingency. Operation and maintenance costs are not included.

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or additional tasks following construction.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

SHEET: 1 OF 1
BY: RRM DATE: 12/5/2022
CHECKED BY: RRM DATE: 2/17/2023
APPROVED BY: KMB DATE: 3/20/2023

ISSUED: DRAFT 1 DATE: NA
ISSUED: DRAFT 2 DATE: 12/22/2022
ISSUED: FINAL DATE: 3/24/2023
ISSUED: DATE:

Engineer's Opinion of Probable O&M Cost

Landfill Leachate - Alternative 5a - Modified Clay

Total Treatment Flow Rate			Units
Low	Middle	High	
0.00144	0.0144	0.144	MGD
1	10	100	GPM

				LOW FLOWRATE		MIDDLE FLOWRATE		HIGH FLOWRATE		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 10,000**		**$ 10,000**		**$ 13,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	8,200	$ 2,000	8,700	$ 2,000	13,200	$ 2,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	56,500	$ 8,000	57,400	$ 8,000	65,900	$ 9,000	1,2
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	0	$ -	0	$ -	70	$ 2,000	1
1.2	**MEDIA REPLACEMENT AND DISPOSAL**				**$ 73,000**		**$ 112,000**		**$ 470,000**	1
1.2.1	New Media Purchase	LB	$ 3.50	1,300	$ 5,000	9,400	$ 33,000	84,000	$ 294,000	1
1.2.2	Transportation - New Media Purchase	MILE	$ 3.00	11,700	$ 36,000	11,700	$ 36,000	11,700	$ 36,000	1
1.2.3	Media disposal - Incineration	LB	$ 0.65	2,600	$ 2,000	18,800	$ 13,000	168,000	$ 110,000	1
1.2.4	Transportation - Media incineration	MILE	$ 3.00	9,900	$ 30,000	9,900	$ 30,000	9,900	$ 30,000	1
1.2.5	General Conditions - Service Provider - Mobilization	TRUCK PER EVENT	$ 5,000	25	$ 125,000	25	$ 125,000	25	$ 125,000	1
1.3	**MAINTENANCE & MONITORING**				**$ 3,000**		**$ 4,000**		**$ 19,000**	1
1.3.1	Process equipment maintenance	% equipment	3%	1	$ 2,000	1	$ 3,000	1	$ 13,000	1
1.3.2	General building maintenance	sq foot	$ 2.50	50	$ 1,000	100	$ 1,000	2,100	$ 6,000	1
1.4	**ANALYTICAL MONITORING**				**$ 16,000**		**$ 36,000**		**$ 44,000**	1
1.4.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	40	$ 16,000	90	$ 36,000	110	$ 44,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	1	$ 100,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	0.5	$ 50,000	1
	Total Workforce	**Base Payroll**			$ 100,000		$ 100,000		$ 150,000	1
		Fringe Rate	0.5		$ 50,000		$ 50,000		$ 75,000	1
		Total Payroll			**$ 150,000**		**$ 150,000**		**$ 225,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 260,000**		**$ 320,000**		**$ 780,000**	3
	Estimated Uncertainty Range	-30%			$ 190,000		$ 230,000		$ 550,000	3,4
		+50%			$ 390,000		$ 480,000		$ 1,170,000	3,4
	Unit Cost per 1,000 gallons treated				$ 495		$ 61		$ 14.84	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Electric Power Research Institute and Water Research Foundation. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Report 3002001433. November 2013.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT:	Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION:	MINNESOTA
PROJECT #:	23621432

OPINION OF COST - SUMMARY

SHEET:	1	OF	1
BY:	RRM	DATE:	12/5/2022
CHECKED BY:	RRM	DATE:	2/17/2023
APPROVED BY:	KMB	DATE:	3/20/2023
ISSUED:	DRAFT 1	DATE:	NA
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable O&M Cost

Compost Contact Water - Alternative 5a - Modified Clay

Total Treatment Flow Rate			Units
Low	Middle	High	
0.00144	0.0144	0.144	MGD
1	10	100	GPM

				LOW FLOWRATE		MIDDLE FLOWRATE		HIGH FLOWRATE		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 10,000**		**$ 10,000**		**$ 13,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	8,200	$ 2,000	8,700	$ 2,000	13,200	$ 2,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	56,500	$ 8,000	57,400	$ 8,000	65,900	$ 9,000	1,2
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	0	$ -	0	$ -	70	$ 2,000	1
1.2	**MEDIA REPLACEMENT AND DISPOSAL**				**$ 34,000**		**$ 53,000**		**$ 219,000**	1
1.2.1	New Media Purchase	LB	$ 3.50	570	$ 2,000	4,400	$ 16,000	39,000	$ 137,000	1
1.2.2	Transportation - New Media Purchase	MILE	$ 3.00	5,500	$ 17,000	5,500	$ 17,000	5,500	$ 17,000	1
1.2.3	Media disposal - Incineration	LB	$ 0.65	1,100	$ 1,000	8,800	$ 6,000	78,000	$ 51,000	1
1.2.4	Transportation - Media incineration	MILE	$ 3.00	4,600	$ 14,000	4,600	$ 14,000	4,600	$ 14,000	1
1.2.5	General Conditions - Service Provider - Mobilization	TRUCK PER EVENT	$ 5,000	10	$ 50,000	10	$ 50,000	10	$ 50,000	1
1.3	**MAINTENANCE & MONITORING**				**$ 3,000**		**$ 4,000**		**$ 19,000**	1
1.3.1	Process equipment maintenance	% equipment	3%	1	$ 2,000	1	$ 3,000	1	$ 13,000	1
1.3.2	General building maintenance	sq foot	$ 2.50	50	$ 1,000	100	$ 1,000	2,100	$ 6,000	1
1.4	**ANALYTICAL MONITORING**				**$ 16,000**		**$ 36,000**		**$ 44,000**	1
1.4.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	40	$ 16,000	90	$ 36,000	110	$ 44,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	1	$ 100,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	0.5	$ 50,000	1
	Total Workforce	**Base Payroll**			$ 100,000		$ 100,000		$ 150,000	1
		Fringe Rate	0.5		$ 50,000		$ 50,000		$ 75,000	1
		Total Payroll			**$ 150,000**		**$ 150,000**		**$ 225,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 220,000**		**$ 260,000**		**$ 520,000**	3
	Estimated Uncertainty Range	-30%			$ 160,000		$ 190,000		$ 370,000	3,4
		+50%			$ 330,000		$ 390,000		$ 780,000	3,4
	Unit Cost per 1,000 gallons treated				$ 419		$ 49		$ 9.89	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Electric Power Research Institute and Water Research Foundation. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Report 3002001433. November 2013.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

Appendix E

Alternative 6a (GAC, AIX, Incineration) – Municipal Wastewater

Appendix E: Table 6a - WW	**Alternative 6a - GAC, AIX, Incineration**			**Units**	**Notes**
Waste stream	Wastewater	Wastewater	Wastewater	--	
Design flow rate	0.1	1	10	MGD	
Design flow rate	70	700	7,000	gpm	Rounded to one significant digit.
Pressure Vessels (GAC)					
Vessel capacity	6,000	20,000	60,000	lb	
# of lead/lag vessel trains	1	3	9	--	
# of vessels	2	6	18	--	
Media type	12x40	12x40	12x40	--	Reagglomerated, coal-based GAC.
Media apparent density	0.54	0.54	0.54	g/cm3	
Media volume, per vessel	150	470	1,600	ft3	Calculated based on target EBCT. Rounded to two significant digits.
Media weight, per vessel	5,100	16,000	54,000	lb	Calculated based on target EBCT. Rounded to two significant digits.
Empty-bed contact time, per vessel	15	15	15	minutes	
Vessel diameter	6	8	14	ft	Showing two significant digits.
Media bed depth	5	9	10	ft	Showing two significant digits.
Hydraulic loading rate	2.5	4.6	5.1	gpm/ft2	Showing two significant digits.
Estimated footprint, first train	800	2,400	3,300	ft2	Rounded to the nearest 100 ft2.
Estimated footprint, additional train	600	1,300	2,100	ft2	Rounded to the nearest 100 ft2.
Driving lane	No	Yes	Yes	--	
Pipe gallery	No	Yes	Yes	--	
Lab and bathroom	No	Yes	Yes	--	
Estimated footprint, total (GAC)	800	5,000	20,100	ft2	Rounded to the nearest 100 ft2.
Pressure Vessels (Single Use AIX)					
Vessel capacity	38	201	450	ft3	
# of lead/lag vessel trains	2	2	9	--	
# of vessels	4	4	18	--	
Media type	AIX Resin	AIX Resin	AIX Resin	--	Polystyrenic gel.
Media apparent density	42.2	42.2	42.2	lb/ft3	

Appendix E: Table 6a - WW	**Alternative 6a - GAC, AIX, Incineration**			**Units**	**Notes**
Media volume, per vessel	19	190	420	ft3	Calculated based on target EBCT. Rounded to two significant digits.
Media weight, per vessel	900	8,100	18,000	lb	Calculated based on target EBCT. Rounded to two significant digits.
Empty-bed contact time, per vessel	4	4	4	minutes	
Vessel diameter	3	8	12	ft	
Media bed depth	3	4	4	ft	
Hydraulic loading rate	5.0	7.0	6.9	gpm/ft2	
Specific flowrate	0.9	1.7	1.7	gpm/ft3	
Estimated footprint, first train	500	900	1200	ft2	Rounded to the nearest 100 ft2.
Estimated footprint, additional train	400	700	1000	ft2	Rounded to the nearest 100 ft2.
Estimated footprint, total (AIX)	900	1,600	9,200	ft2	Rounded to the nearest 100 ft2.
Combined footprint, total	1,700	6,600	30,000	ft2	Rounded to the nearest 100 ft2.
Estimated time to breakthrough, GAC	10,000	10,000	10,000	bed volumes	Based on modelled breakthrough of PFBS at 5 ng/L.
Estimated changeout frequency, GAC	100	100	100	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin GAC)	1	2	13	--	Rounded to nearest integer.
# Trucks per event (spent GAC)	1	3	25	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	3.7	3.7	3.7	--	Rounded to two significant digits.
Estimated media usage rate, GAC	22,000	220,000	2,000,000	lbs/year	Rounded to two significant digits.
Estimated media usage rate, GAC	0.60	0.60	0.55	lbs/1000-gal	Pounds per 1,000 gallons treated.
Estimated time to breakthrough, AIX	140,000	140,000	140,000	bed volumes	Based on the maximum bed volumes treated in Ellis et al. (2022).
Estimated changeout frequency, AIX	380	380	380	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin resin)	1	1	5	--	Rounded to nearest integer.

Appendix E: Table 6a - WW	Alternative 6a - GAC, AIX, Incineration			Units	Notes
# Trucks per event (spent resin)	1	1	9	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	1	1	1	--	Rounded to one significant digit.
Estimated media usage rate, AIX	1,800	16,000	160,000	lb/year	Rounded to two significant digits.
Estimated media usage rate	0.049	0.044	0.044	lbs/1000-gal	Pounds per 1,000 gallons treated.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

SHEET:	1	OF	1
BY:	RRM	DATE:	12/8/2022
CHECKED BY:	AJM2	DATE:	3/3/2023
APPROVED BY:	KMB	DATE:	3/20/2023

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost
Municipal Wastewater - Alternative 6a

Total Treatment Flow Rate			Units
Low	**Middle**	**High**	
0.1	1	10	MGD
70	700	7000	GPM

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$303,000	$303,000	1	$1,722,000	$1,722,000	1	$11,906,000	$11,906,000	1,2,3,4
B	PFAS Separation Equipment	LS	1	$442,000	$442,000	1	$3,203,000	$3,203,000	1	$25,661,000	$25,661,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$221,000	$221,000	1	$1,602,000	$1,602,000	1	$12,831,000	$12,831,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$89,000	$89,000	1	$641,000	$641,000	1	$5,133,000	$5,133,000	1,2,3,4
E	Treatment Building	SF	1,700	$500	$850,000	6,600	$500	$3,300,000	30,000	$500	$15,000,000	1,2,3,4
F	Site Work	LS	1	$85,000	$85,000	1	$330,000	$330,000	1	$1,500,000	$1,500,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$332,000	$332,000	1	$2,403,000	$2,403,000	1	$19,246,000	$19,246,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$2,320,000			$13,200,000			$91,280,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$580,000		25%	$3,300,000		25%	$22,820,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$2,900,000			$16,500,000			$114,100,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$2,900,000**			**$16,500,000**			**$114,100,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$2,100,000			$11,600,000			$79,900,000	4,6
		50%			$4,400,000			$24,800,000			$171,200,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -30% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy range are not intended to include costs for future scope changes that are not part of the project as currently scoped or costs for risk contingency. Operation and maintenance costs are not included.

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or additional tasks following construction.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

SHEET:	1	OF	1	
BY:	AJM2	DATE:	12/9/2022	
CHECKED BY:	RRM	DATE:	2/17/2023	
APPROVED BY:	KMB	DATE:	3/20/2023	

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432

OPINION OF COST - SUMMARY

ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable O&M Cost

Municipal Wastewater - Alternative 6a - GAC+AIX

Total Treatment Flow Rate			Units
Low	Middle	High	
0.1	1	10	MGD
70	700	7000	GPM

				LOW FLOWRATE		MIDDLE FLOWRATE		HIGH FLOWRATE		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 12,000**		**$ 27,000**		**$ 161,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	11,700	$ 2,000	43,500	$ 6,000	361,700	$ 49,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	63,000	$ 9,000	121,800	$ 17,000	710,400	$ 95,000	1,2
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	60	$ 1,000	230	$ 4,000	1,100	$ 17,000	1
1.2	**MEDIA REPLACEMENT AND DISPOSAL**				**$ 151,000**		**$ 1,140,000**		**$ 6,431,000**	1
1.2.1	New Media Purchase - GAC	LB	$ 2.50	22,200	$ 56,000	222,000	$ 555,000	0	$ -	1
1.2.2	Transportation - New Media Purchase - GAC	MILE	$ 3.00	3,300	$ 10,000	6,700	$ 21,000	0	$ -	1
1.2.3	Media disposal - Incineration - GAC	LB	$ 0.65	44,400	$ 29,000	444,000	$ 289,000	0	$ -	1
1.2.4	Transportation - Media incineration - GAC	MILE	$ 3.00	2,800	$ 9,000	8,400	$ 26,000	0	$ -	1
1.2.5	New Media Purchase - AIX	CU FT	$ 320	40	$ 13,000	380	$ 122,000	3,800	$ 1,216,000	1
1.2.6	Transportation - New Media Purchase - AIX	MILE	$ 3.00	900	$ 3,000	900	$ 3,000	4,500	$ 14,000	1
1.2.7	Media disposal - Incineration - AIX	LB	$ 0.65	3,400	$ 3,000	32,100	$ 21,000	320,700	$ 209,000	1
1.2.8	Transportation - Media incineration - AIX	MILE	$ 3.00	760	$ 3,000	760	$ 3,000	6,800	$ 21,000	1
1.2.9	Media disposal - Reactivation (Destruction + Media)	LB	$ 2.00	0	$ -	0	$ -	1,998,000	$ 3,996,000	1
1.2.10	Transportation - Media reactivation	MILE	$ 3.00	0	$ -	0	$ -	166,500	$ 500,000	1
1.2.11	General Conditions - Service Provider - Mobilization - GAC	TRUCK PER EVENT	$ 5,000	5	$ 25,000	20	$ 100,000	95	$ 475,000	1
1.2.12	General Conditions - Service Provider - Mobilization - AIX	TRUCK PER EVENT	$ 5,000	2	$ 10,000	2	$ 10,000	15	$ 75,000	1
1.3	**MAINTENANCE & MONITORING**				**$ 28,000**		**$ 181,000**		**$ 1,384,000**	1
1.3.1	Process equipment maintenance	% equipment	3%	1	$ 23,000	1	$ 164,000	1	$ 1,309,000	1
1.3.2	General building maintenance	sq foot	$ 2.50	1,700	$ 5,000	6,600	$ 17,000	30,000	$ 75,000	1
1.4	**ANALYTICAL MONITORING**				**$ 40,000**		**$ 60,000**		**$ 184,000**	1
1.4.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	100	$ 40,000	150	$ 60,000	460	$ 184,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	1	$ 100,000	1	$ 100,000	2	$ 200,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	1	$ 100,000	1
	Total Workforce	**Base Payroll**			$ 150,000		$ 150,000		$ 300,000	1
		Fringe Rate	0.5		$ 75,000		$ 75,000		$ 150,000	1
		Total Payroll			**$ 225,000**		**$ 225,000**		**$ 450,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 460,000**		**$ 1,700,000**		**$ 8,700,000**	3
	Estimated Uncertainty Range	-30%			$ 330,000		$ 1,190,000		$ 6,100,000	3,4
		+50%			$ 690,000		$ 2,550,000		$ 13,100,000	3,4
	Unit Cost per 1,000 gallons treated				$ 12.60		$ 4.66		$ 2.38	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Electric Power Research Institute and Water Research Foundation. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Report 3002001433. November 2013.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

Appendix E

Alternative 6b (RO, GAC, AIX, Incineration) – Municipal Wastewater

Appendix E: Table 6b - WW	**Alternative 6b - RO, Conc. to GAC and AIX, Incineration**			**Units**	**Notes**
Waste stream	Wastewater	Wastewater	Wastewater	--	
Design flow rate	0.1	1	10	MGD	
Design flow rate	70	700	7,000	gpm	Rounded to one significant digit.
Membranes					
Recovery	85%	85%	85%	%	Assumed.
# of skids	1	1	7	--	
Membrane type	RO	RO	RO	--	
# Elements	18	156	1,554	--	
Flux	16	16	16	gfd	gfd = gallons per sq. ft. per day.
Concentrate management flow rate	0.02	0.2	1.5	MGD	
Concentrate management flow rate	20	110	1,100	gpm	Rounded to two significant digits.
Estimated footprint, total (membranes)	600	700	3,500	ft2	
Pressure Vessels (GAC)					
Vessel capacity	750	6,000	20,000	lb	
# of lead/lag vessel trains	2	2	4	--	
# of vessels	4	4	8	--	
Media type	12x40	12x40	12x40	--	Reagglomerated, coal-based GAC.
Media apparent density	0.54	0.54	0.54	g/cm3	
Media volume, per vessel	21	120	560	ft3	Calculated based on target EBCT. Rounded to two significant digits.
Media weight, per vessel	710	4,100	19,000	lb	Calculated based on target EBCT. Rounded to two significant digits.
Empty-bed contact time, per vessel	15	15	15	minutes	
Vessel diameter	2.0	6.0	12	ft	Showing two significant digits.
Media bed depth	6.4	3.9	4.9	ft	Showing two significant digits.
Hydraulic loading rate	3.2	1.9	2.4	gpm/ft2	Showing two significant digits.
Estimated footprint, first train	200	2,200	3000	ft2	Rounded to the nearest 100 ft2.
Estimated footprint, additional train	100	1,000	1800	ft2	Rounded to the nearest 100 ft2.
Driving lane	No	Yes	Yes	--	

Appendix E: Table 6b - WW	**Alternative 6b - RO, Conc. to GAC and AIX, Incineration**			**Units**	**Notes**
Pipe gallery	No	Yes	Yes	--	
Lab and bathroom	No	Yes	Yes	--	
Estimated footprint, total (GAC)	300	3,200	8,400	ft2	Rounded to the nearest 100 ft2.
Pressure Vessels (AIX)					
Vessel capacity	5	38	201	ft3	
# of lead/lag vessel trains	3	2	3	--	
# of vessels	6	4	6	--	
Media type	AIX Resin	AIX Resin	AIX Resin	--	Polystyrenic gel.
Media apparent density	42.2	42.2	42.2	lb/ft3	
Media volume, per vessel	4	30	200	ft3	Calculated based on target EBCT. Rounded to one significant digit.
Media weight, per vessel	170	1,300	8,500	lb	Calculated based on target EBCT. Rounded to two significant digits.
Empty-bed contact time, per vessel	4	4	4	minutes	
Vessel diameter	1.5	3	8	ft	
Media bed depth	2	4	4	ft	
Hydraulic loading rate	3.8	7.8	7.3	gpm/ft2	
Specific flowrate	1.3	1.4	1.8	gpm/ft3	
Estimated footprint, first train	50	200	900	ft2	70 gpm rounded to the nearest 10 ft2. 700 and 7,000 gpm rounded to the nearest 100 ft2.
Estimated footprint, additional train	40	200	700	ft2	70 gpm rounded to the nearest 10 ft2. 700 and 7,000 gpm rounded to the nearest 100 ft2.
Estimated footprint, total	130	400	2,300	ft2	70 gpm rounded to the nearest 10 ft2. 700 and 7,000 gpm rounded to the nearest 100 ft2.
Combined footprint, total	1,100	4,300	14,200	ft2	Rounded to the nearest 100 ft2.

Appendix E: Table 6b - WW	**Alternative 6b - RO, Conc. to GAC and AIX, Incineration**			**Units**	**Notes**
Estimated time to breakthrough, GAC	8,100	8,100	8,100	bed volumes	Based on the modelled breakthrough of PFBS at 5 ng/L.
Estimated changeout frequency, GAC	80	80	80	days	Rounded down to the nearest 10 days.
# Trucks per event (dry GAC)	1	1	2	--	Rounded to nearest integer.
# Trucks per event (wet GAC)	1	1	4	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	4.6	4.6	4.6	--	Rounded to two significant digits.
Estimated media usage rate, GAC	6,900	55,000	370,000	lbs/year	Rounded to two significant digits.
Estimated media usage rate, GAC	0.19	0.151	0.101	lbs/1000-gal	Pounds per 1,000 gallons treated.
Estimated time to breakthrough, AIX	140,000	140,000	140,000	bed volumes	Based on the maximum bed volumes treated in Ellis et al. (2022).
Estimated changeout frequency, AIX	380	380	380	days	Rounded down to the nearest 10 days.
# Trucks per event (virgin resin)	1	1	1	--	Rounded to nearest integer.
# Trucks per event (spent resin)	1	1	2	--	Assumes spent media is 2x weight after use, requiring 2x trucks to remove than deliver. Rounded to nearest integer.
Change-out events per year	1	1	1	--	Rounded to one significant digit.
Estimated media usage rate, AIX	490	2,500	25,000	lb/year	Rounded to two significant digits.
Estimated media usage rate	0.013	0.007	0.007	lbs/1000-gal	Pounds per 1,000 gallons treated.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

SHEET:	1	OF	1
BY:	RRM	DATE:	12/8/2022
CHECKED BY:	AJM2	DATE:	3/3/2023
APPROVED BY:	KMB	DATE:	3/20/2023
ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost
Municipal Wastewater - Alternative 6b

Total Treatment Flow Rate			Units
Low	Medium	High	
0.1	1	10	MGD
70	700	7000	GPM

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$263,000	$263,000	1	$1,018,000	$1,018,000	1	$9,819,000	$9,819,000	1,2,3,4
B	PFAS Separation Equipment	LS	1	$467,000	$467,000	1	$1,804,000	$1,804,000	1	$23,530,000	$23,530,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$234,000	$234,000	1	$902,000	$902,000	1	$11,765,000	$11,765,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$94,000	$94,000	1	$361,000	$361,000	1	$4,706,000	$4,706,000	1,2,3,4
E	Treatment Building	SF	1,100	$500	$550,000	4,300	$500	$2,150,000	14,200	$500	$7,100,000	1,2,3,4
F	Site Work	LS	1	$55,000	$55,000	1	$215,000	$215,000	1	$710,000	$710,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$351,000	$351,000	1	$1,353,000	$1,353,000	1	$17,648,000	$17,648,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$2,010,000			$7,800,000			$75,280,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$500,000		25%	$1,950,000		25%	$18,820,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$2,510,000			$9,750,000			$94,100,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$2,600,000**			**$9,800,000**			**$94,100,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$1,900,000			$6,900,000			$65,900,000	4,6
		50%			$3,900,000			$14,700,000			$141,200,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -30% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy range are not intended to include costs for future scope changes that are not part of the project as currently scoped or costs for risk contingency. Operation and maintenance costs are not included.

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or additional tasks following construction.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

SHEET:	1	OF	1		
BY:	AJM2	DATE:	12/9/2022		
CHECKED BY:	RRM	DATE:	2/17/2023		
APPROVED BY:	KMB	DATE:	3/20/2023		

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable O&M Cost

Municipal Wastewater - Alternative 6b - RO+GAC+AIX

Total Treatment Flow Rate			Units
Low	Middle	High	
0.1	1	10	MGD
70	700	7000	GPM

				LOW FLOWRATE		MIDDLE FLOWRATE		HIGH FLOWRATE		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 34,000**		**$ 249,000**		**$ 2,381,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	179,200	$ 24,000	1,719,000	$ 229,000	17,113,000	$ 2,278,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	63,000	$ 9,000	121,800	$ 17,000	710,400	$ 95,000	1,2
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	40	$ 1,000	150	$ 3,000	500	$ 8,000	1
1.2	**MEDIA REPLACEMENT AND DISPOSAL**				**$ 112,000**		**$ 314,000**		**$ 1,994,000**	1
1.2.1	New Media Purchase - GAC	LB	$ 2.50	6,900	$ 18,000	55,200	$ 138,000	0	$ -	1
1.2.2	Transportation - New Media Purchase - GAC	MILE	$ 3.00	4,100	$ 13,000	4,100	$ 13,000	0	$ -	1
1.2.3	Media disposal - Incineration - GAC	LB	$ 0.65	13,800	$ 9,000	110,400	$ 72,000	0	$ -	1
1.2.4	Transportation - Media incineration - GAC	MILE	$ 3.00	3,500	$ 11,000	3,500	$ 11,000	0	$ -	1
1.2.5	New Media Purchase - AIX	CU FT	$ 320	10	$ 4,000	60	$ 20,000	2,800	$ 896,000	1
1.2.6	Transportation - New Media Purchase - AIX	MILE	$ 3.00	900	$ 3,000	900	$ 3,000	900	$ 3,000	1
1.2.7	Media disposal - Incineration - AIX	LB	$ 0.65	840	$ 1,000	5,100	$ 4,000	236,300	$ 154,000	1
1.2.8	Transportation - Media incineration - AIX	MILE	$ 3.00	760	$ 3,000	760	$ 3,000	1,500	$ 5,000	1
1.2.9	Media disposal - Reactivation (Destruction + Media)	LB	$ 2.00	0	$ -	0	$ -	368,000	$ 736,000	1
1.2.10	Transportation - Media reactivation	MILE	$ 3.00	0	$ -	0	$ -	33,100	$ 100,000	1
1.2.11	General Conditions - Service Provider - Mobilization - GAC	TRUCK PER EVENT	$ 5,000	10	$ 50,000	10	$ 50,000	20	$ 100,000	1
1.2.12	General Conditions - Service Provider - Mobilization - AIX	TRUCK PER EVENT	$ 5,000	2	$ 10,000	2	$ 10,000	5	$ 25,000	1
1.3	**RO CONSUMABLES**				**$ 55,000**		**$ 463,000**		**$ 4,617,000**	1
1.3.1	Antiscalant	LB	$ 10	670	$ 7,000	6,700	$ 67,000	67,000	$ 670,000	1
1.3.2	Clean-in-place Chemicals	LB	$ 2	21,600	$ 44,000	187,500	$ 375,000	1,867,000	$ 3,730,000	1
1.3.3	RO Element Replacement (5-year Replacement)	Element	$ 700	5	$ 4,000	30	$ 21,000	310	$ 217,000	1
1.4	**MAINTENANCE & MONITORING**				**$ 27,000**		**$ 104,000**		**$ 1,237,000**	1
1.4.1	Process equipment maintenance	% equipment	3%	1	$ 24,000	1	$ 93,000	1	$ 1,201,000	1
1.4.2	General building maintenance	sq foot	$ 2.50	1,100	$ 3,000	4,300	$ 11,000	14,200	$ 36,000	1
1.5	**ANALYTICAL MONITORING**				**$ 68,000**		**$ 60,000**		**$ 88,000**	1
1.5.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	170	$ 68,000	150	$ 60,000	220	$ 88,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	2	$ 200,000	2	$ 200,000	4	$ 400,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	1	$ 100,000	1	$ 100,000	2	$ 200,000	1
	Total Workforce	**Base Payroll**			$ 300,000		$ 300,000		$ 600,000	1
		Fringe Rate	0.5		$ 150,000		$ 150,000		$ 300,000	1
		Total Payroll			**$ 450,000**		**$ 450,000**		**$ 900,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 750,000**		**$ 1,700,000**		**$ 11,300,000**	3
	Estimated Uncertainty Range	-30%			$ 530,000		$ 1,190,000		$ 8,000,000	3,4
		+50%			$ 1,130,000		$ 2,550,000		$ 16,950,000	3,4
	Unit Cost per 1,000 gallons treated				$ 20.55		$ 4.66		$ 3.10	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Electric Power Research Institute and Water Research Foundation. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Report 3002001433. November 2013.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

Appendix E

Alternative 8a (Foam Fractionation, Incineration) – Landfill Leachate / Compost Contact Water

Appendix E: Table 8a - LL/CCW	**Alternative 8a - Foam Fractionation w/ Incineration**			**Units**	**Notes**
Waste stream	LL/CCW	LL/CCW	LL/CCW	--	
Design flow rate	0.0014	0.014	0.14	MGD	
Design flow rate	1,440	14,400	144,000	GPD	
Design flow rate	1	10	100	gpm	
Expected foamate flow rate	0.0014	0.014	0.144	GPD	
Expected foamate flow rate	0.000001	0.00001	0.0001	gpm	
Foam Fractionation Equipment					
# of package systems	1	1	1	--	
Primary fractionation vessels	2	2	4	--	
Secondary fractionation vessels	1	1	2	--	
Lab and bathroom	No	No	No		
Estimated footprint, total	1,000	1,000	1,000	ft2	Rounded to the nearest 100 ft2.

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

SHEET:	1	OF	1
BY:	KMB	DATE:	10/10/2022
CHECKED BY:	AJM2	DATE:	3/3/2023
APPROVED BY:	KMB	DATE:	3/20/2023
ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost Landfill Leachate / Compost Contact Water - Alternative 8a

Total Treatment Flow Rate			Units
Low	Middle	High	
0.00144	0.0144	0.144	MGD
1	10	100	GPM

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$742,000	$742,000	1	$742,000	$742,000	1	$883,000	$883,000	1,2,3,4
B	PFAS Separation Equipment	LS	1	$1,792,000	$1,792,000	1	$1,792,000	$1,792,000	1	$2,176,000	$2,176,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$896,000	$896,000	1	$896,000	$896,000	1	$1,088,000	$1,088,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$359,000	$359,000	1	$359,000	$359,000	1	$436,000	$436,000	1,2,3,4
E	Treatment Building	SF	1,000	$500	$500,000	1,000	$500	$500,000	1,000	$500	$500,000	1,2,3,4
F	Site Work	LS	1	$50,000	$50,000	1	$50,000	$50,000	1	$50,000	$50,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$1,344,000	$1,344,000	1	$1,344,000	$1,344,000	1	$1,632,000	$1,632,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$5,680,000			$5,680,000			$6,770,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$1,420,000		25%	$1,420,000		25%	$1,690,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$7,100,000			$7,100,000			$8,460,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$7,100,000**			**$7,100,000**			**$8,500,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$5,000,000			$5,000,000			$6,000,000	4,6
		50%			$10,700,000			$10,700,000			$12,800,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -30% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy range are not intended to include costs for future scope changes that are not part of the project as currently scoped or costs for risk contingency. Operation and maintenance costs are not included.

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or

PREPARED BY: BARR ENGINEERING COMPANY

SHEET: 1 OF 1
BY: AJM2 DATE: 12/9/2022
CHECKED BY: RRM DATE: 2/17/2023
APPROVED BY: KMB DATE: 3/20/2023

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

ISSUED: DRAFT 1 DATE: 11/11/2022
ISSUED: DRAFT 2 DATE: 12/22/2022
ISSUED: FINAL DATE: 3/24/2023
ISSUED: DATE:

Engineer's Opinion of Probable O&M Cost

Landfill Leachate & Compost Contact Water - Alternative 8a - Foam Fractionation

Total Treatment Flow Rate			Units
Low	Middle	High	
0.00144	0.0144	0.144	MGD
1	10	100	GPM

				LOW FLOWRATE		MIDDLE FLOWRATE		HIGH FLOWRATE		
Item Num.	Description of O&M Category	Unit of Measure	Unit Rate (USD/unit)	Annual Quantity	Annual Total (USD)	Annual Quantity	Annual Total (USD)	Annual Quantity	Annual Total (USD)	Notes
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 2,000**		**$ 4,000**		**$ 23,000**	1
1.1.1	Electricity - Combined process and non-process energy load	kWh	$ 0.13	2,000	$ 1,000	16,000	$ 3,000	159,000	$ 22,000	1,2
1.1.2	Natural gas - Non-process energy load (heating)	MMBTU	$ 15	40	$ 1,000	40	$ 1,000	40	$ 1,000	1
1.2	**CONCENTRATE AND RESIDUAL DISPOSAL**				**$ 9,000**		**$ 9,000**		**$ 9,000**	1
1.2.1	Concentrate and residual disposal - Incineration	LB	$ 0.65	10	$ 1,000	50	$ 1,000	440	$ 1,000	1
1.2.2	Transportation - Concentrate or residual disposal	MILE	$ 3.00	760	$ 3,000	760	$ 3,000	760	$ 3,000	1
1.2.3	General Conditions - Service Provider - Mobilization	TRUCK PER EVENT	$ 5,000	1	$ 5,000	1	$ 5,000	1	$ 5,000	1
1.3	**MISC CONSUMABLES**				**$ 5,000**		**$ 5,000**		**$ 9,000**	1
1.3.1	Bag/Cartridge Filters	50-ct	$ 750	5	$ 4,000	5	$ 4,000	5	$ 4,000	1
1.3.2	Chemical Feed	LB	$ 5	10	$ 1,000	90	$ 1,000	900	$ 5,000	1
1.4	**MAINTENANCE**				**$ 95,000**		**$ 95,000**		**$ 114,000**	1
1.4.1	Process equipment maintenance	% equipment	3%	1	$ 92,000	1	$ 92,000	1	$ 111,000	1
1.4.2	General building maintenance	sq foot	$ 2.50	1,000	$ 3,000	1,000	$ 3,000	1,000	$ 3,000	1
1.5	**ANALYTICAL MONITORING**				**$ 16,000**		**$ 16,000**		**$ 16,000**	1
1.5.1	Monitoring - Monthly samples	SAMPLE+SHIPPING	$ 400	40	$ 16,000	40	$ 16,000	40	$ 16,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	0.5	$ 50,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.5	$ 50,000	0.5	$ 50,000	0.5	$ 50,000	1
	Total Workforce	**Base Payroll**			$ 100,000		$ 100,000		$ 100,000	1
		Fringe Rate	0.5		$ 50,000		$ 50,000		$ 50,000	1
		Total Payroll			**$ 150,000**		**$ 150,000**		**$ 150,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 280,000**		**$ 280,000**		**$ 330,000**	3
	Estimated Uncertainty Range	-30%			$ 200,000		$ 200,000		$ 240,000	3,4
		+50%			$ 420,000		$ 420,000		$ 500,000	3,4
	Unit Cost per 1,000 gallons treated				$ 533		$ 53		$ 6.28	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on flow. Reference: Burns, D. J., Hinrichsen, H. M., Stevenson, P., & Murphy, P. J. C. (2022). Commercial-scale remediation of per- and polyfluoroalkyl substances from a landfill leachate catchment using Surface-Active Foam Fractionation (SAFF). Remediation Journal, 32, 139–150.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

Appendix E

Pyrolysis / Gasification – Municipal Wastewater Biosolids

Appendix E: Table 1 Solids	**Alternative Solids - Pyrolysis/Gasification**			**Units**	**Notes**
Waste stream	Solids	Solids	Solids	--	
Design flow rate	4	9	15	MGD	Biosolids industry standard: 1 mgd of influent flow produces 6 -7 dry ton/day of digested sludge.
Wet solids production rate	8	21	36	wet metric tons/day	25% total solids.
Dry solids production rate	2	6	10	dry US tons/day	
Number of dryers	1	1	1	--	
Type of dryer	Paddle	Paddle	Belt		Dried product is 90% TS from each dryer.
Evaporation rate	560	1400	2400	lb water/hr	
Pyrolysis unit capacity	3	3	10	dry US tons/day	
Number of pyrolysis units	1	2	1	units	
Dryer footprint	3,600	4,800	9,600	ft2	
Pyrolysis footprint	200	400	400	ft2	
Lab and bathroom	Yes	Yes	Yes	--	
Estimated footprint, total	5,300	7,000	13,000	ft2	Rounded to the nearest 100 ft2.

PREPARED BY: HAZEN on behalf of
BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

SHEET:	1	OF	1
BY:	HAZEN	DATE:	10/10/2022
CHECKED BY:	ALL	DATE:	12/12/2022
APPROVED BY:	HAZEN	DATE:	3/15/2023
ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost
Municipal Biosolids - Pyrolysis/Gasification

Total Treatment Flow Rate			Units
Low	Middle	High	
2	6	10	dry US ton/day
4	9	15	MGD

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$3,213,000	$3,213,000	1	$5,146,000	$5,146,000	1	$7,894,000	$7,894,000	1,2,3,4
B	PFAS Destruction Equipment	LS	1	$7,552,000	$7,552,000	1	$12,429,000	$12,429,000	1	$18,560,000	$18,560,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$3,776,000	$3,776,000	1	$6,215,000	$6,215,000	1	$9,280,000	$9,280,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$1,511,000	$1,511,000	1	$2,486,000	$2,486,000	1	$3,712,000	$3,712,000	1,2,3,4
E	Treatment Building	SF	5,300	$500	$2,650,000	7,000	$500	$3,500,000	13,000	$500	$6,500,000	1,2,3,4
F	Site Work	LS	1	$265,000	$265,000	1	$350,000	$350,000	1	$650,000	$650,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$5,664,000	$5,664,000	1	$9,322,000	$9,322,000	1	$13,920,000	$13,920,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$24,630,000			$39,450,000			$60,520,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$6,160,000		25%	$9,860,000		25%	$15,130,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$30,790,000			$49,310,000			$75,650,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$30,800,000**			**$49,400,000**			**$75,700,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$21,600,000			$34,600,000			$53,000,000	4,6
		50%			$46,200,000			$74,100,000			$113,600,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -30% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy range are not intended to include costs for future scope changes that are not part of the project as currently scoped or costs for risk contingency. Operation and maintenance costs are not included.

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or additional tasks following construction.

PREPARED BY: BARR ENGINEERING COMPANY		SHEET:	1	OF	1
		BY:	HAZEN	DATE:	12/9/2022
ENGINEER'S OPINION OF PROBABLE PROJECT COST		CHECKED BY:	ALL	DATE:	12/20/2022
		APPROVED BY:	HAZEN	DATE:	3/15/2023
PROJECT:	Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water	ISSUED:	DRAFT 1	DATE:	NA
LOCATION:	MINNESOTA	ISSUED:	DRAFT 2	DATE:	12/22/2022
PROJECT #:	23621432	ISSUED:	FINAL	DATE:	3/24/2023
OPINION OF COST - SUMMARY		ISSUED:		DATE:	

Engineer's Opinion of Probable O&M Cost

Municipal Biosolids - Pyrolysis/Gasification

Total Treatment Flow Rate			Units
Low	**Middle**	**High**	
2.3	5.8	10.0	US dry ton/day

				LOW FLOWRATE		**MIDDLE FLOWRATE**		**HIGH FLOWRATE**		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 123,000**		**$ 220,000**		**$ 386,000**	1
1.1.1	Electricity - process equipment	kWh	$ 0.13	252,300	$ 34,000	636,200	$ 85,000	1,097,000	$ 147,000	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	259,600	$ 35,000	342,800	$ 46,000	636,600	$ 85,000	1
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15.33	190	$ 3,000	250	$ 4,000	460	$ 8,000	1,2
1.1.4	Natural gas - Process fuel	MMBTU	$ 15.33	3,300	$ 51,000	5,500	$ 85,000	9,500	$ 146,000	1
1.2	**RESIDUALS DISPOSAL**				**$ 1,000**		**$ 2,000**		**$ 4,000**	1
1.2.1	Biochar management and disposal	tons	$ 100	10	$ 1,000	20	$ 2,000	40	$ 4,000	1
1.3	**MAINTENANCE**				**$ 38,000**		**$ 81,000**		**$ 144,000**	1
1.3.1	Process equipment maintenance, including materials	dry tons	$ 30	800	$ 24,000	2,100	$ 63,000	3,700	$ 111,000	1
1.3.2	General building maintenance	sq foot	$ 2.50	5,300	$ 14,000	7,000	$ 18,000	13,000	$ 33,000	1
1.4	**ANALYTICAL MONITORING**				**$ 12,000**		**$ 12,000**		**$ 12,000**	1
1.4.1	Monitoring - Monthly samples	SAMPLE	$ 400	30	$ 12,000	30	$ 12,000	30	$ 12,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	0.25	$ 25,000	0.75	$ 75,000	1	$ 100,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.25	$ 25,000	0.5	$ 50,000	0.5	$ 50,000	1
	Total Workforce	**Base Payroll**			$ 50,000		$ 125,000		$ 150,000	1
		Fringe Rate	0.5		$ 25,000		$ 62,500		$ 75,000	1
		Total Payroll			**$ 75,000**		**$ 188,000**		**$ 225,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 250,000**		**$ 510,000**		**$ 780,000**	3
	Estimated Uncertainty Range	-30%			$ 180,000		$ 360,000		$ 550,000	3,4
		+50%			$ 380,000		$ 770,000		$ 1,170,000	3,4
	Unit Cost per dry ton treated				*$ 298*		*$ 241*		*$ 214*	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on vendor-provided electricity consumption.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.

Appendix E

SCWO – Municipal Wastewater Biosolids

Appendix E: Table 2 Solids	Alternative Solids - SCWO			Units	Notes
Waste stream	Solids	Solids	Solids	--	
Design flow rate	2	8	15	MGD	Biosolids industry standard: 1 mgd of influent flow produces 6 -7 dry ton/day of digested sludge.
Wet solids production rate	6	30	60	wet metric tons/day	15% total solids.
Dry solids production rate	1	5	10	dry US tons/day	
SCWO unit capacity	1	5	5	dry US tons/day	
Number of units	1	1	2	--	
Lab and bathroom	Yes	Yes	Yes	--	
Estimated footprint, total	1,500	2,200	3,800	ft2	Rounded to the nearest 100 ft2.

PREPARED BY: HAZEN on behalf of
BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water
LOCATION: MINNESOTA
PROJECT #: 23621432
OPINION OF COST - SUMMARY

SHEET:	1	OF	
BY:	HAZEN	DATE:	10/10/2022
CHECKED BY:	ALL	DATE:	11/6/2022
APPROVED BY:	HAZEN	DATE:	3/15/2023
ISSUED:	DRAFT 1	DATE:	11/11/2022
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

Engineer's Opinion of Probable Capital Cost
Municipal Biosolids - SCWO

Total Treatment Flow Rate			Units
Low	Mid	High	
1	5	10	Dry US ton/day
2	8	15	MGD

			LOW FLOW RATE			MIDDLE FLOW RATE			HIGH FLOW RATE			
Cat. No.	**ITEM DESCRIPTION**	**UNIT**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**QUANTITY**	**UNIT COST**	**ITEM COST**	**NOTES**
A	General Conditions	LS	1	$1,213,000	$1,213,000	1	$2,955,000	$2,955,000	1	$5,909,000	$5,909,000	1,2,3,4
B	PFAS Destruction Equipment	LS	1	$3,188,000	$3,188,000	1	$7,668,000	$7,668,000	1	$15,335,000	$15,335,000	1,2,3,4
C	Piping and Appurtenances	LS	1	$1,594,000	$1,594,000	1	$3,834,000	$3,834,000	1	$7,668,000	$7,668,000	1,2,3,4
D	Electrical and Instrumentation/Controls	LS	1	$638,000	$638,000	1	$1,534,000	$1,534,000	1	$3,067,000	$3,067,000	1,2,3,4
E	Treatment Building	SF	500	$500	$250,000	1,650	$500	$825,000	3,300	$500	$1,650,000	1,2,3,4
F	Site Work	LS	1	$25,000	$25,000	1	$83,000	$83,000	1	$165,000	$165,000	1,2,3,4
G	Installation (Equipment and Piping)	LS	1	$2,391,000	$2,391,000	1	$5,751,000	$5,751,000	1	$11,502,000	$11,502,000	1,2,3,4
	CONSTRUCTION SUBTOTAL				$9,300,000			$22,650,000			$45,300,000	1,2,3,4,5
	CONSTRUCTION CONTINGENCY			25%	$2,330,000		25%	$5,660,000		25%	$11,330,000	1,4,5
	ESTIMATED CONSTRUCTION COST				$11,630,000			$28,310,000			$56,630,000	1,2,3,4,5
	ESTIMATED TOTAL PROJECT COST				**$11,700,000**			**$28,400,000**			**$56,700,000**	1,2,3,4,6
	ESTIMATED ACCURACY RANGE	-30%			$8,200,000			$19,900,000			$39,700,000	4,6
		50%			$17,600,000			$42,600,000			$85,100,000	4,6

Notes

[1] Limited design work completed.

[2] Quantities based on design work completed.

[3] Unit prices based on information available at this time.

[4] This feasibility-level (Class 5, 0-2% design completion per AACE International Recommended Practice No. 17R-97) cost estimate is based on preliminary designs, quantities and unit prices. Costs will change with further design. Time value-of-money escalation costs are not included. Contingency is an allowance for the net sum of costs that will be in the Final Total Project Cost at the time of the completion of design, but are not included at this level of project definition. The estimated accuracy range for the Total Project Cost as the project is defined is -30% to +50%. The accuracy range is based on professional judgement considering the level of design completed, the complexity of the project and the uncertainties in the project as scoped. The contingency and the accuracy

[5] Estimate costs are reported to nearest ten thousand dollars.

[6] Estimate costs are rounded up to nearest one hundred thousand dollars. Estimate costs are to construct each alternative. The estimated costs do not include planning, engineering and design, permitting, construction administration, maintenance, monitoring or

BARR

PREPARED BY: BARR ENGINEERING COMPANY

ENGINEER'S OPINION OF PROBABLE PROJECT COST

SHEET: 1	OF 1		
BY:	HAZEN	DATE:	12/9/2022
CHECKED BY:	ALL	DATE:	12/14/2022
APPROVED BY:	HAZEN	DATE:	3/15/2023
ISSUED:	DRAFT 1	DATE:	NA
ISSUED:	DRAFT 2	DATE:	12/22/2022
ISSUED:	FINAL	DATE:	3/24/2023
ISSUED:		DATE:	

PROJECT: Evaluation of Current Alternatives and Estimated Costs for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water

LOCATION: MINNESOTA

PROJECT #: 23621432

OPINION OF COST - SUMMARY

Engineer's Opinion of Probable O&M Cost

Municipal Biosolids - SCWO

Total Treatment Flow Rate			Units
Low	Middle	High	
1	5	10	US dry ton/day

				LOW FLOWRATE		MIDDLE FLOWRATE		HIGH FLOWRATE		
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Unit Rate (USD/unit)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
1	**VARIABLE COSTS**									
1.1	**UTILITIES**				**$ 22,000**		**$ 5,000**		**$ 10,000**	1
1.1.1	Electricity - Process equipment	kWh	$ 0.13	109,500	$ 15,000	-109,500	$ (15,000)	-219,000	$ (30,000)	1,2
1.1.2	Electricity - Non-process energy load (building power, HVAC, etc.)	kWh	$ 0.13	24,500	$ 4,000	80,800	$ 11,000	161,600	$ 22,000	1
1.1.3	Natural gas - Non-process energy load (heating)	MMBTU	$ 15.33	20	$ 1,000	60	$ 1,000	120	$ 2,000	1,2
1.1.4	Natural gas - Start-up fuel	MBTU/hr	$ 15.33	100	$ 2,000	520	$ 8,000	1,040	$ 16,000	1
1.2	**RESIDUALS DISPOSAL**				**$ -**		**$ 2,000**		**$ 4,000**	1
1.2.1	Ash management and disposal	tons	$ 100	0	$ -	20	$ 2,000	40	$ 4,000	1
1.3	**MISC Consumables**				**$ 500**		**$ 2,900**		**$ 5,800**	1
1.3.1	Chemical feed	tons	$ 145	4	$ 500	20	$ 2,900	40	$ 5,800	1
1.4	**MAINTENANCE**				**$ 98,000**		**$ 236,000**		**$ 470,000**	1
1.4.1	Process equipment maintenance, including materials	% equipment	3%	1	$ 96,000	1	$ 231,000	1	$ 461,000	1
1.4.2	General building maintenance	sq foot	$ 2.50	500	$ 2,000	1,700	$ 5,000	3,300	$ 9,000	1
1.5	**ANALYTICAL MONITORING**				**$ 12,000**		**$ 12,000**		**$ 12,000**	1
1.5.1	Monitoring - Monthly samples	SAMPLE	$ 400	30	$ 12,000	30	$ 12,000	30	$ 12,000	1
Item Num.	**Description of O&M Category**	**Unit of Measure**	**Annual Salary (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Annual Quantity**	**Annual Total (USD)**	**Notes**
2	**FIXED COSTS**									
2.1	**O&M LABOR**									
2.1.1	Water Treatment Operator	FTE	$ 100,000	0.25	$ 25,000	0.25	$ 25,000	0.5	$ 50,000	1
2.1.2	Shift Maintenance (Mechanical, Electrical)	FTE	$ 100,000	0.25	$ 25,000	0.25	$ 25,000	0.5	$ 50,000	1
	Total Workforce	**Base Payroll**			$ 50,000		$ 50,000		$ 100,000	1
		Fringe Rate	0.5		$ 25,000		$ 25,000		$ 50,000	1
		Total Payroll			**$ 75,000**		**$ 75,000**		**$ 150,000**	1
	ESTIMATED TOTAL ANNUAL OPERATING COSTS				**$ 210,000**		**$ 340,000**		**$ 660,000**	3
	Estimated Uncertainty Range	-30%			$ 150,000		$ 240,000		$ 470,000	3,4
		+50%			$ 320,000		$ 510,000		$ 990,000	3,4
	Unit Cost per dry ton treated				*$ 575*		*$ 186*		*$ 181*	

Notes

[1] Annual total cost values are rounded up to the nearest thousand USD.

[2] Assumed operating 7 days of operation per week, 365 days per year. Adjusted based on vendor-provided electricity consumption and generation.

[3] Values less than $1 million are rounded to the nearest ten thousand USD, and values greater than or equal to $1 million are rounded up to the nearest one hundred thousand USD.

[4] Operation and maintenance costs are based on a Class 5 capital cost estimate with a +50/-30% uncertainty as applicable for projects at less than 2% of full project definition per AACE International 17R-97. Operation and maintenance costs are also expected to have a +50/-30% uncertainty.