Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances—Version 2 (2024)

INTERIM GUIDANCE FOR PUBLIC COMMENT
APRIL 8, 2024

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Abbreviations

AFFF	aqueous film-forming foam
APCD	air pollution control device
ARFF	aircraft rescue firefighting
BDL	below detection limit
BMP	best management practice
C	Celsius
CAA	Clean Air Act
CaF_2	calcium fluoride
CaO	calcium oxide
$Ca(OH)_2$	calcium hydroxide
C&D	construction and demolition
CDC	Centers for Disease Control and Prevention
CDR	Chemical Data Reporting
CEJST	Climate and Economic Justice Screening Tool
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CF_4	carbon tetrafluoride
C_2F_6	hexafluoroethane
C_3F_8	octafluoropropane
CFR	Code of Federal Regulations
CHES	Clean Harbors Environmental Services
CHF_3	fluoroform
CIC	combustion–ion chromatography
CI/MS	chemical ionization mass spectrometry
CKD	cement kiln dust
DE	destruction efficiency
DoD	Department of Defense
DOE	Department of Energy
DRE	destruction and removal efficiency
ECHO	Enforcement Compliance and History Online
EJ	environmental justice
EPA	United States Environmental Protection Agency
ESP	electrostatic precipitator
ESTCP	Environmental Security Technology Certification Program
F	Fahrenheit
FAA	Federal Aviation Administration
FBC	fluidized bed combustor
FF	fabric filter
FML	flexible membrane liner
FTIR	Fourier transform infrared spectrometry
FTOH	fluorotelomer alcohol
FTS	fluorotelomer sulfonate
FY 2020 NDAA	National Defense Authorization Act for Fiscal Year 2020
GAC	granular activated carbon
GCCS	gas collection and control system
HAP	hazardous air pollutant

HF	hydrogen fluoride
HFPO-DA	hexafluoropropylene oxide-dimer acid, 2,3,3,3-Tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy) propanoic acid, ($C_6F_{11}O_3H_2$)
H_2O_2	hydrogen peroxide
HWC	hazardous waste combustor
HWI	hazardous waste incinerator
LC/MS/MS	liquid chromatography/tandem mass spectrometry
LFG	landfill gas
LWAK	lightweight aggregate kiln
MDL	method detection limit
MF	microfiltration
MnO_2	manganese(IV) oxide
MSW	municipal solid waste
MWC	municipal waste combustor
NADP	National Atmospheric Deposition Program
NASA	National Aeronautics and Space Administration
NESHAP	National Emission Standards for Hazardous Air Pollutants
NF	nanofiltration
ng/L	nanograms per liter
NIOSH	National Institute for Occupational Safety and Health
NMOC	nonmethane organic compound
NPDES	National Pollutant Discharge Elimination System
NPDWR	National Primary Drinking Water Regulation
NSPS	New Source Performance Standards
NTA	non-targeted analysis
OECD	Organization for Economic Cooperation and Development
ORD	Office of Research and Development
OSTP	Office of Science and Technology Policy
OTM	Other Test Method
PAC	powdered activated carbon
PBPK	physiologically based pharmacokinetic
PCB	polychlorinated biphenyl
PFAA	perfluoroalkyl acid
PFAS	perfluoroalkyl and polyfluoroalkyl substances
PFASTT	PFAS Thermal Treatment Database
PFBS	perfluorobutanesulfonic acid ($C_4F_9SO_3H$)
PFC	perfluorocarbon
PFHxS	perfluorohexanesulfonic acid ($C_6F_{13}SO_3H$)
PFOA	perfluorooctanoic acid ($C_8F_{15}O_2H$)
PFOS	perfluorooctanesulfonic acid ($C_8F_{17}SO_3H$)
PIC	product of incomplete combustion
PID	product of incomplete destruction
PIGE	particle-induced gamma emission spectrometry
PITT	PFAS Innovative Treatment Team
POHC	principal organic hazardous constituent
POTW	publicly owned treatment works
ppb	parts per billion
ppmv	parts per million by volume

PTFE	polytetrafluoroethylene
PVDF	polyvinylidene fluoride or polyvinylidene difluoride
RCRA	Resource Conservation and Recovery Act
RDF	refuse-derived fuel
RO	reverse osmosis
RSEI	Risk-Screening Environmental Indicators
SBIR	Small Business Innovation Research
SDA	spray dryer absorber
SDWA	Safe Drinking Water Act
SERDP	Strategic Environmental Research and Development Program
SSI	sewage sludge incinerator
TOF	total organic fluorine
TRI	Toxics Release Inventory
TRL	technology readiness level
TSCA	Toxic Substances Control Act
TWTDS	treatment works treating domestic sewage
UF	ultrafiltration
UIC	underground injection control
U.S.C.	United States Code
USDW	underground source of drinking water
UST	underground storage tank
VOC	volatile organic compound
WWTP	wastewater treatment plant
XPS	X-ray photo-electron spectroscopy

Executive Summary

This 2024 update of the U.S. Environmental Protection Agency (EPA)'s 2020 interim guidance presents currently available information on the destruction and disposal of perfluoroalkyl and polyfluoroalkyl substances (PFAS) and PFAS-containing materials. It focuses on the current state of science and associated uncertainties for three large-scale capacity technologies that can destroy PFAS or control PFAS release into the environment: thermal destruction, landfills, and underground injection. It also includes a framework for evaluating emerging technologies for PFAS destruction or disposal.

EPA published the first edition of this guidance as required by the National Defense Authorization Act (NDAA) of 2020. The NDAA directs EPA to address the destruction and disposal of PFAS and specific PFAS-containing materials, including aqueous film-forming foam, contaminated media, textiles (other than consumer goods), and various wastes from water treatment. The NDAA also requires EPA to review and update the guidance as appropriate, but no less frequently than every three years.

The primary audience of this guidance is decision-makers who need to identify the most effective means for destroying or disposing of PFAS-containing materials and wastes. The audience may also include regulators, waste managers, and the public, including affected communities. EPA is recommending that managers of PFAS wastes consider the nature of the waste, location, potential for environmental release, and other factors to determine the most appropriate destruction, disposal, or storage method. As a general approach, EPA recommends that decision-makers prioritize the use of destruction and disposal technologies that have a lower potential for PFAS release to the environment, over destruction and disposal technology options with a greater potential for environmental release of PFAS. EPA acknowledges that each destruction and disposal technology has limitations. However, managing PFAS to minimize environmental releases during destruction and disposal activities supports protection of human health and the environment.

While the purpose of an effective destruction and disposal technology is to prevent or minimize environmental releases, it is also important to distinguish between a potential environmental release and a direct human exposure. A PFAS release does not inherently imply direct and immediate human exposure and a release does not necessarily present an unacceptable risk to specific populations.

EPA has developed a fact sheet for the public, including potentially affected communities, that provides a more concise and less technical presentation of key materials.

Key Findings and Updates

EPA describes destruction and disposal options based on each technology's potential to destroy PFAS or control PFAS release into the environment. This approach is consistent with EPA's mission to protect human health and the environment. There are several different types of technologies that have been used for PFAS treatment and disposal, and their potential to destroy PFAS or control PFAS releases is described herein (see Section 1). In general, the following technologies (in no particular order) have a lower potential for environmental release of PFAS compared to other technologies in the same category <u>and are viewed as the more protective technologies</u>:

- **Underground Injection - Permitted Class I non-hazardous industrial or hazardous waste injection wells** are the waste management approach with a lower potential for environmental release when compared to other destruction and disposal options. These wells may help ensure that injected fluids are confined and cannot enter underground sources of drinking water. However, the limited number of wells currently receiving off-site PFAS and waste transportation logistics may significantly limit the type and quantity of PFAS-containing fluids appropriate for underground injection.

- **Landfills - Permitted hazardous waste landfills** have the most protective landfill engineering controls and practices for the containment of PFAS waste and would be more effective at minimizing PFAS release into the environment than other landfill types. EPA recommends Subtitle C landfills when PFAS levels of the waste are relatively high and landfill disposal is the selected option. However, for all landfill types, new information demonstrates landfilling could have higher PFAS releases to the environment than previously thought in 2020.
- **Thermal Treatment - Permitted hazardous waste combustors** such as commercial incinerators, cement kilns, and lightweight aggregate kilns and granular activated carbon (GAC) reactivation units with thermal oxidizers may operate under conditions more conducive to destroying PFAS and controlling related products of incomplete combustion. Research suggests that the use of higher temperatures, well mixed combustion environments, and longer residence times may be more conducive to destroying PFAS and controlling related products of incomplete combustion. Although limited data have been obtained since the 2020 version of the interim guidance (including data suggestive of adequate temperature ranges to break down PFAS), uncertainties remain about the effectiveness of thermal treatment. EPA encourages additional testing with EPA-approved or EPA-evaluated methods by waste managers of thermal treatment operations, including for products of incomplete combustion and the presence of PFAS in all associated waste streams, to evaluate whether thermal treatment technologies are minimizing potential environmental releases. EPA's new analytical method, OTM-50, will allow better characterization of products of incomplete combustion (PICs) that will help to address some of these uncertainties when additional data are collected as recommended in this guidance (see Appendix A).

This list includes the three technology categories described in Section 3 and does not preclude new or emerging technologies. When considering the bullets above, it is important to note that real-world performance and testing data are generally limited. Additional performance and testing data—including data on destruction and removal of PFAS in thermal treatment devices, ongoing research activities, and long-term performance data for landfills and underground injection—may change EPA's understanding of each technology's ability to control PFAS. Data needs and priorities are summarized in this update.

EPA continues to seek collaboration with thermal treatment facilities to conduct air emission testing during thermal treatment of PFAS and PFAS-containing materials. EPA provides guidance for this and for independent analysis in Appendix A. In addition to performance and testing data, the 2024 guidance identifies other, high-priority data gaps that need to be addressed by researchers across government, academia, and industry for EPA to provide meaningful updates on effective destruction and disposal practices.

EPA partnered with industry and academia to collect data on four emerging technologies for PFAS destruction: mechanochemical degradation, electrochemical oxidation, gasification and pyrolysis, and supercritical water oxidation. While the results from these studies show promise for PFAS destruction, further work using newly available methods is needed to more fully characterize the outputs of these processes and to evaluate their performance for a wider range of PFAS-containing materials. Managers of PFAS and PFAS-containing materials may consider these or other emerging technologies for PFAS disposal or destruction. To assist PFAS material managers with evaluating whether an emerging destruction (or disposal) technology is suitable for a particular PFAS-containing material, EPA developed a technology evaluation framework. The framework provides a transparent, consistent approach for evaluating destruction and disposal technologies for PFAS and PFAS-containing material and includes considerations for communities. EPA recommends that managers of PFAS-containing materials use the technology evaluation framework to evaluate emerging destruction and disposal technologies and to inform their decisions about managing PFAS-containing materials. EPA also encourages technology developers to generate and publicly release data that can be used to complete the framework (see Section 6).

EPA updated tools, methods, and approaches for considering the impacts of potential releases and exposure on communities located near destruction and disposal facilities, including identifying vulnerable populations overburdened by cumulative impacts, incorporating vulnerability into decision-making, and engaging the community (see Section 4).

What's Next?

EPA and other government, academic, and private institutions will continue to conduct research to better understand PFAS destruction and disposal. EPA will consider public comments it receives on this version of the guidance as well as additional advancements in PFAS research and science to revise this interim guidance within the next three years.[1] For information about the Agency's plans and actions related to PFAS, visit EPA's website pages *PFAS Strategic Roadmap: EPA's Commitments to Action 2021-2024* and *Key Actions to Address PFAS*.

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[1] EPA may explore opportunities to provide more frequent technical updates as information becomes available.

1. Introduction

This second version interim guidance provides information on technologies that may be feasible and appropriate for the destruction or disposal of perfluoroalkyl and polyfluoroalkyl substances (PFAS) and PFAS-containing materials. It represents the current state of science and the associated uncertainties for large-capacity technologies that can destroy PFAS or control PFAS release into the environment. This is an update to the interim guidance the U.S. Environmental Protection Agency (EPA) issued in 2020.

EPA published the first version of this interim guidance and made it available for public comment.[2] EPA received 77 unique public comments (out of 5,066 total comments) on the interim guidance from states, Tribes, industries, trade organizations, environmental organizations, and members of the public. This updated version incorporates this public feedback.

The 2024 interim guidance contains the following new information:

Section 1: Introduction
- Updated review of PFAS destruction and disposal technologies.

Section 2: Description of PFAS-Containing Materials Identified in the FY 2020 NDAA
- Additional details on spent water treatment materials.
- Updated information on biosolids generation and management.

Section 3: Technologies for the Destruction and Disposal of PFAS and PFAS-Containing Materials
- Additional information on thermal treatment and landfills.
- Additional information on testing and monitoring at thermal treatment facilities.

Section 4: Considerations for Potentially Vulnerable Populations Living Near Likely Destruction or Disposal Sites
- Updated list of tools for vulnerability screening.

Section 5: Research Needs and Data Gaps for Destruction and Disposal Technologies
- Increased focus on research needs to inform future updates to this interim guidance.
- Updated information on ongoing research and development activities.

Section 6: Emerging Technologies for PFAS Destruction and Disposal (NEW)
- EPA efforts to identify, review, and test emerging technologies for PFAS destruction.
- Technology evaluation framework that utilizes a multiple-lines-of-evidence approach to evaluate a technology/PFAS material combination.

Appendix A: EPA Guidance to Conduct PFAS Emissions Field Testing at Commercial Thermal Destruction Sources (NEW)
- EPA request to access commercial sources to conduct air emissions testing during PFAS thermal destruction.
- Guidance for facilities to conduct source testing prior to accepting/processing PFAS materials at full-scale thermal destruction facilities.

Appendix B: Summary of the Clean Harbors Test Data (NEW)
- Two source test campaigns conducted at a hazardous waste combustor.

Appendix C: Summary of the Chemours Thermal Oxidizer Test Data (NEW)
- Source test campaign conducted at a chemical manufacturer.

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[2] Interim PFAS Destruction and Disposal Guidance; Notice of Availability for Public Comment. U.S. EPA. 85 Federal Register 83554. December 22, 2020.

Appendix D: Summary of Costs and Considerations (NEW)

- Summary of costs and factors that should be considered when estimating costs to destroy or dispose of PFAS and PFAS-containing materials.

1.a Purpose and audience of this interim guidance

The purpose of this interim guidance is to describe technologies for managing the destruction and disposal of PFAS-containing materials and to recommend practices associated with these technologies that minimize PFAS releases to the environment. This purpose is consistent with EPA’s mission to protect human health and the environment and the National Defense Authorization Act (NDAA) for Fiscal Year 2020, Public Law No: 116-92 (hereafter, “FY 2020 NDAA”), signed into law on December 19, 2019.

Section 7361 of the FY 2020 NDAA (see Figure 1-1) directs EPA to publish interim guidance on the destruction and disposal of PFAS and PFAS-containing materials no later than one year from the date of enactment of the FY 2020 NDAA. EPA published the initial interim guidance on December 18, 2020. The FY 2020 NDAA also requires EPA to review and revise the interim guidance at least every three years, if appropriate. This 2024 update fulfills that requirement.

The primary audience of this guidance is decision-makers who need to identify the most effective means for destroying or disposing of PFAS-containing materials and wastes. The audience may also include regulators, waste managers, and technology developers who can use the technology evaluation framework in Section 6 to evaluate emerging technology applicability to PFAS destruction or disposal. This guidance may also interest the general public; particularly communities near PFAS destruction and disposal sites who may have an opportunity to offer input or provide consultation to decision-makers regarding destruction and disposal decisions based on relevant decision-makers determination. EPA has developed a fact sheet for the public, including potentially affected communities, that provides a more concise and less technical presentation of this guidance.

This interim guidance meets one of many commitments EPA made under the Agency's PFAS Strategic Roadmap. The PFAS Strategic Roadmap, released in 2021, describes EPA's whole-of-Agency approach to address PFAS and identifies concrete actions EPA is taking to safeguard public health, protect the environment, and hold polluters accountable. For more information on EPA's actions to address PFAS, visit *PFAS Strategic Roadmap: EPA's Commitments to Action 2021-2024* and *Key Actions to Address PFAS*.

SEC. 7361. PFAS DESTRUCTION AND DISPOSAL GUIDANCE.

(a) IN GENERAL.—Not later than 1 year after the date of enactment of this Act, the Administrator shall publish interim guidance on the destruction and disposal of perfluoroalkyl and polyfluoroalkyl substances and materials containing perfluoroalkyl and polyfluoroalkyl substances, including—

(1) aqueous film-forming foam;
(2) soil and biosolids;
(3) textiles, other than consumer goods, treated with perfluoroalkyl and polyfluoroalkyl substances;
(4) spent filters, membranes, resins, granular carbon, and other waste from water treatment;
(5) landfill leachate containing perfluoroalkyl and polyfluoroalkyl substances; and
(6) solid, liquid, or gas waste streams containing perfluoroalkyl and polyfluoroalkyl substances from facilities manufacturing or using perfluoroalkyl and polyfluoroalkyl substances.

(b) CONSIDERATIONS; INCLUSIONS.—The interim guidance under subsection (a) shall—

(1) take into consideration—
    (A) the potential for releases of perfluoroalkyl and polyfluoroalkyl substances during destruction or disposal, including through volatilization, air dispersion, or leachate; and
    (B) potentially vulnerable populations living near likely destruction or disposal sites; and
(2) provide guidance on testing and monitoring air, effluent, and soil near potential destruction or disposal sites for releases described in paragraph (1)(A).

(c) REVISIONS.—The Administrator shall publish revisions to the interim guidance under subsection (a) as the Administrator determines to be appropriate, but not less frequently than once every 3 years.

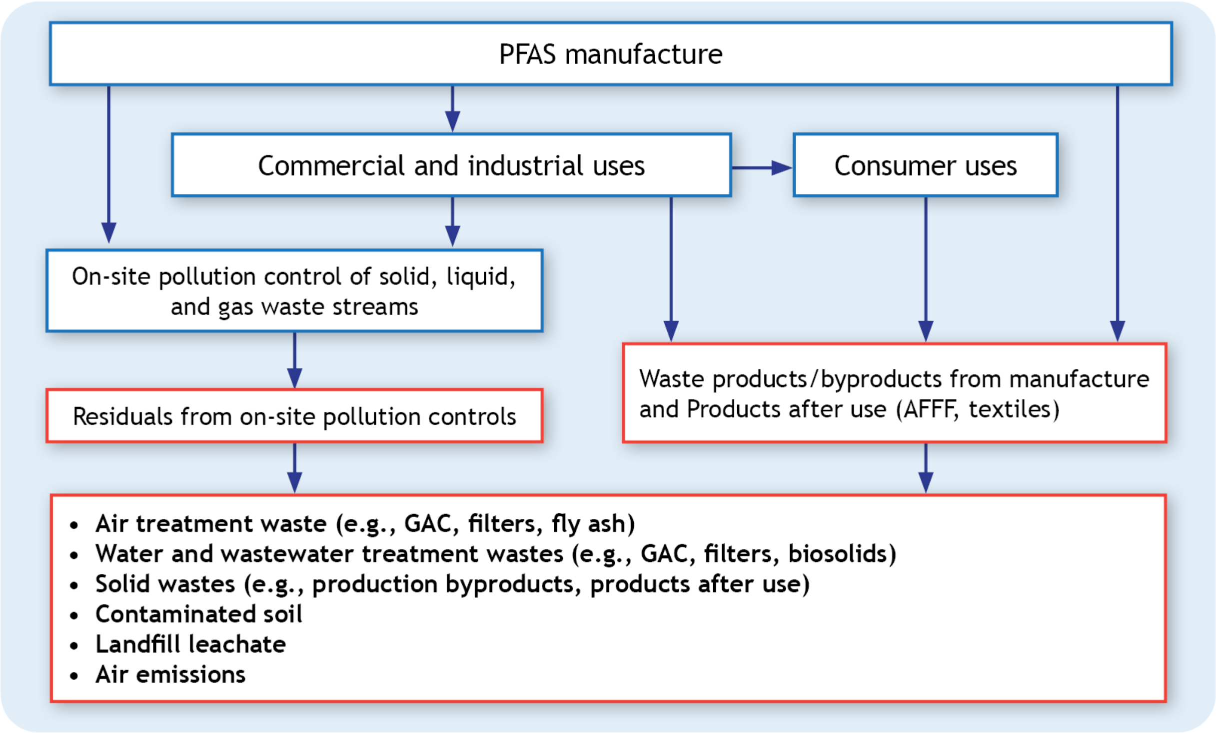
Figure 1-1. FY 2020 NDAA Section 7361.

1.b Scope and use of interim guidance

1.b.i PFAS and PFAS-containing materials in this interim guidance

Section 7361 of the FY 2020 NDAA (see Figure 1-1) lists six types of PFAS-containing materials and wastes. Although the information included in this interim guidance is likely to be suitable for other types of PFAS and PFAS-containing materials, this interim guidance addresses destruction and disposal centering on these six material types, which are described in more detail in Section 2. In this document, the PFAS-containing materials covered by the FY 2020 NDAA that will be destroyed or disposed of are referred to as “waste.”

Figure 1-2 shows conceptually how manufacturing activities could result in material streams that are within the intended scope of this interim guidance, including GAC and aqueous film-forming foam (AFFF).



Note: The red-outlined portions show where the FY 2020 NDAA material types occur in the course of manufacture, use, and disposal of PFAS and PFAS-containing materials that are within the scope of this interim guidance.

Figure 1-2. Generation of PFAS materials identified in the FY 2020 NDAA.

1.b.ii Destruction and disposal technologies addressed in this interim guidance

This interim guidance presents three widely-used, commercially available destruction and disposal technologies that may be effective for managing PFAS and PFAS-containing materials. Advances in scientific understanding allow EPA to make some recommendations, however, filling information gaps and addressing uncertainties will improve the scientific understanding and could lead to additional guidance in the future. EPA updates this guidance at least every three years.

This interim guidance describes technologies with the potential to destroy PFAS or control releases of PFAS into the environment. Other waste management options are not discussed, because they are not within the intended scope of this interim guidance. For example, land application of biosolids containing PFAS does not control PFAS releases into the environment.

Current technologies. In developing this second version of the interim guidance, EPA focused on the three widely-used, commercially available destruction and disposal technologies that may be effective for managing PFAS wastes—thermal treatment, landfills, and underground injection. EPA also focused on reviewing data and information about the ability of each of these technologies to manage PFAS-containing materials through containment or destruction (i.e., breaking carbon–fluorine bonds and mineralization) while limiting releases of PFAS to the environment. In doing so, EPA prioritized addressing the scientific issues and uncertainties highlighted in the 2020 interim guidance and, when possible, relied on publicly available, peer-reviewed data and information (see Section 3).

Emerging technologies. Concerns about the effectiveness of current, widely-used technologies for managing PFAS and PFAS-containing materials have motivated efforts to develop new technologies and apply existing technologies to PFAS materials. EPA is aware of and, in some cases, has participated in efforts to identify, develop, and test non-thermal destruction technologies for PFAS-containing materials (see Section 6).

In some cases, managers of PFAS and PFAS-containing materials may consider emerging technologies for PFAS destruction. When considering the use of emerging technologies, managers of PFAS waste should work with state, territorial, or Tribal government agencies. To assist PFAS material managers with evaluating whether an emerging destruction (or disposal) technology is suitable for a particular PFAS-containing material, EPA developed a technology evaluation framework (see Section 6). The framework provides a transparent, consistent approach for evaluating destruction and disposal technologies for PFAS materials, including considerations for communities, including vulnerable populations.

In 2024, EPA is neither recommending nor discouraging the use of any emerging technology for managing the PFAS-containing materials specified in the FY 2020 NDAA. Instead, the Agency recommends that managers of PFAS-containing materials use the technology evaluation framework to evaluate emerging destruction and disposal technologies and to inform their decisions about managing PFAS-containing materials. EPA also encourages technology developers to generate and publicly release data that can be used to complete the framework (see Section 6).

Generally, destruction and disposal of PFAS-containing materials are currently not federally regulated. PFAS-containing materials may be managed in non-hazardous and hazardous waste treatment and disposal systems. Some exceptions exist, such as risk management requirements in cases where permits for production of new chemicals specify methods to be used for destruction or disposal following the review of a Toxic Substances Control Act (TSCA) new chemicals notice. Unless governing regulations require specific actions to the contrary, this guidance recommends selecting an approach with a higher potential to control PFAS releases into the environment, as possible.

Table 1-1. Destruction and Disposal Technologies Discussed in This Interim Guidance, with Examples of PFAS-Containing Materials

Destruction and Disposal Technology, by Physical Phase of Materials	Examples of PFAS-Containing Materials (within the Scope of the FY 2020 NDAA) That Could Be Managed Using These Technologies
Solid phase: Landfill disposal Thermal treatment	• Drinking water, groundwater, and wastewater treatment residuals ○ Biosolids/sewage sludge ○ Spent GAC ○ Ion exchange resins • Air waste stream treatment residuals ○ Spent GAC ○ Fly ash • Contaminated soil • End-of-life products (e.g., textiles) • Solidified liquid wastes
Liquid phase: Underground injection Thermal treatment	• Sewage sludge (liquid) • Landfill leachate • AFFF (spent or concentrate)

Destruction and Disposal Technology, by Physical Phase of Materials	Examples of PFAS-Containing Materials (within the Scope of the FY 2020 NDAA) That Could Be Managed Using These Technologies
	• End-of-life products (e.g., spent cleaning solvents) • Pollution control residuals (e.g., concentrates) from PFAS production and use
Gas phase: Thermal treatment	• Landfill gas (LFG) • Emissions from manufacture, use, or destruction of PFAS

1.b.iii Use of this interim guidance

This interim guidance provides information and suggested considerations for evaluating destruction and disposal options. This second version of the interim guidance is based on currently available research and information in 2023 and is responsive to the scope of the FY 2020 NDAA. It presents background information on the manufacture and uses of PFAS, as well as solid, liquid, and gas waste streams containing PFAS, including those materials identified in the FY 2020 NDAA: AFFF, soils and biosolids, textiles, spent water treatment materials, landfill leachate, and PFAS waste streams from facilities manufacturing or using PFAS (see Section 2). Most significantly, it provides up-to-date information on potential releases during the destruction and disposal of PFAS and PFAS-containing materials (see Section 3) and identifies data gaps to be filled that can inform future EPA guidance (see Section 5). This version also incorporates information received during the 2020 Interim Guidance's public comment period.

This version of the interim guidance takes the following into account:

- It is based on currently available information on technology performance and capabilities for destruction and disposal of the PFAS and PFAS-containing materials specified in the FY 2020 NDAA (see Section 1.b.i).
- It focuses on three widely-used, commercially available destruction and disposal technologies that may be effective for managing PFAS wastes (i.e., thermal treatment, landfills, underground injection) (see Section 3).
- It advises how to assess and consider the impacts of potential releases and exposure on communities, including identifying vulnerable populations, incorporating vulnerability into decision-making, and performing community engagement (see Section 4). The FY 2020 NDAA states that the interim guidance should take into consideration potentially vulnerable populations living near destruction or disposal sites.
- It identifies research needs to inform future updates to this interim guidance and provides updated information on ongoing research and development activities (see Section 5).
- It discusses the development of emerging technologies and includes a framework for evaluating technology/PFAS material combinations (see Section 6).
- It does *not* establish what concentrations of PFAS in wastes, spent products, or other materials or media would necessitate destruction or disposal. Regulatory mechanisms are more appropriate for establishing such concentrations.
- It provides references to destruction and disposal facility locators that decision-makers can use to request cost estimates. EPA recommends obtaining cost estimates from applicable destruction and disposal facilities as described in Section 1.c.ii. In addition, Appendix D provides some cost

information that PFAS material managers may want to consider when evaluating different techniques to destroy or dispose of PFAS and PFAS-containing materials. Note that cost information presented in this appendix has a relatively high level of uncertainty associated with it. Moreover, the cost of PFAS destruction and disposal may change based on demand and evolution of available technologies. Additionally, overall costs may vary widely based on the type of materials or the distance to a facility.

This interim guidance is not a regulation. Any discussion of EPA's regulatory authorities is for the purpose of describing controls relevant to the destruction or disposal of PFAS and should not be considered a description of the applicability of those authorities or affect EPA's or any other agency's ability to enforce under these authorities in the future. For information about EPA's other plans and actions related to PFAS, visit EPA's *PFAS Strategic Roadmap: EPA's Commitments to Action 2021-2024* and *Key Actions to Address PFAS*.

1.c Considerations for managing PFAS and PFAS-containing materials

The information presented in this interim guidance can help managers of PFAS or PFAS-containing materials make informed decisions regarding destruction and disposal. To assist decision-makers, EPA reviews destruction and disposal options for thermal treatment, landfills, and underground injection based on the relative potential for releasing PFAS to the environment. This approach highlights destruction and disposal options with lower potential for PFAS releases to the environment compared to other options. This approach is consistent with EPA's mission to protect human health and the environment and is designed to facilitate decisions that protect human health and the environment as much as possible.

EPA recognizes that the potential to control PFAS releases to the environment is one of several factors to consider when selecting among options for destroying or disposing of PFAS and PFAS-containing materials in a way that is consistent with maximizing protection to public health and the environment. Other factors include whether it is imperative to destroy or dispose of the waste immediately, availability of interim storage or destruction and disposal options, the type and volume of waste materials, the concentrations of PFAS in the waste, and the presence of and potential impacts to communities, including vulnerable communities. In the following sections, EPA provides guidance for these decisions in terms of technology considerations and infrastructure considerations.

1.c.i Technology Considerations - Relative potential for PFAS releases to the environment

Using the information presented in Section 3, and considering the significant uncertainties that remain, EPA listed destruction and disposal options in terms of relative potential for releasing PFAS to the environment. When considering the data and information presented in Section 3, EPA considered the type of data available (e.g., laboratory-, pilot-, or field-scale studies), the amount of data available (e.g., data from different operating conditions), and the quality of the data.

When considering the order, it is important to note that available performance and testing data are generally limited. Additional performance and testing data—including data on destruction and removal of PFAS in thermal treatment devices, and long-term performance data for landfills and underground injection—are needed to support more specific guidance. When these data and information become available, EPA may reconsider and revise the order presented below.

As a general approach, EPA encourages managers of PFAS and PFAS-containing materials to prioritize destruction and disposal options with a lower potential for releasing PFAS to the environment over the use of destruction and disposal technology options with a higher potential for environmental release of PFAS. EPA also encourages testing with EPA-approved methods of thermal treatment operations, including products of incomplete combustion and the presence of PFAS in all associated waste streams (see Appendix A), to evaluate whether site-specific conditions are minimizing potential environmental releases.

While the purpose of an effective destruction and disposal technology is to prevent or minimize environmental releases, it is also important to distinguish between a potential environmental release and a direct human exposure. A PFAS release does not inherently imply direct and immediate human exposure and a release does not necessarily present an unacceptable risk to specific populations.

EPA encourages managers of PFAS and PFAS-containing materials to make decisions in consideration of factors discussed in this guidance to select current or future disposal or destruction technologies that protect human health and the environment as much as possible. Based on currently available information cited in this guidance, EPA has listed the following disposal and destruction options from lowest to highest based on their relative potential to release PFAS to the environment:

- **Interim storage with controls.** While not a destruction or disposal method, interim storage may be a short-term option if the destruction or disposal of PFAS and PFAS-containing materials is not imperative, on-site storage capacity is readily available, and interim storage has proper controls in place to reduce releases into the environment. Storage may be more appropriate for some PFAS materials than others. For example, EPA recommends interim storage of low volumes of containerized or high PFAS-concentration materials. In contrast, some materials may be less appropriate for storage because they are continuously generated or are typically high-volume. With proper engineering controls in place, interim storage can control PFAS releases in the short-term.
- **Underground injection (Class I non-hazardous industrial and hazardous waste wells).** EPA has determined the use of Class I non-hazardous industrial waste and hazardous waste wells for high concentration liquid PFAS waste has a lower potential for environmental release when compared to other PFAS destruction and disposal options, and there is relatively low uncertainty in this determination. The standards associated with the construction, operation, and monitoring of these Class I wells are designed to isolate liquid wastes deep below the land surface and ensure protection of underground sources of drinking water (USDWs). Class I hazardous waste wells operators must conduct mechanical integrity testing more often than Class I non-hazardous industrial waste operators. They also must establish and follow additional procedures for reporting and correcting mechanical integrity problems. Class I hazardous waste well operators must also develop and follow a waste analysis plan and conduct annual tests of cement at the base of the well. While the standards associated with Class I hazardous wells are more stringent than for non-hazardous industrial wells, EPA has determined that the probability of failures for both has been demonstrated to be low. While Class I wells are an option for managing PFAS-containing fluids, this technology may not be appropriate everywhere. The limited number of wells currently receiving PFAS, well location, and waste transportation logistics may significantly limit the type and quantity of PFAS-containing fluids appropriate for underground injection. Additional Class I wells may need to be constructed where geologically suitable, and existing well permits may need to be modified to meet the capacity needs for PFAS disposal (see Section 3.c.v).

- **Hazardous waste landfills (Resource Conservation and Recovery Act (RCRA) Subtitle C).** This class of landfills has the most stringent environmental controls in place for minimizing environmental releases and migration of some PFAS from disposed waste. EPA recommends Subtitle C landfills when PFAS levels of the waste are relatively high and landfill disposal is the selected option. Permitted hazardous waste landfills have relatively low quantities of landfill leachate[3], which lessens the probability of mobilizing PFAS that is reversibly bound to the waste. These landfills are required to handle and treat leachate as listed hazardous waste (hazardous waste number F039 per 40 CFR 261.31), lessening the likelihood of environmental release. Because hazardous waste landfills generally do not receive organic wastes that decompose, PFAS migration via LFG is anticipated to be relatively low but LFG collection and destruction equipment could be installed if anaerobic decomposition is shown (see Section 3.b). While recent studies have improved understanding of PFAS migration, additional research is needed to resolve uncertainties (see Section 3.b.vi).
- **Landfill disposal in all landfill types: Landfill disposal of stable polymeric PFAS**. Stable polymeric PFAS, such as polytetrafluoroethylene (Teflon™) and fluorinated ethylene propylene (FEP), are large molecules that are not susceptible to hydrolysis or oxidation. They are neither volatile nor water soluble and, as a result, they are expected to remain within the waste mass for long periods of time. This PFAS category tends not to migrate with the leachate and is unlikely to volatilize with the LFG; therefore, permitted hazardous and municipal solid waste (MSW) landfills (MSWLFs) may provide a good disposal option. Some data are available to support this assessment, but more data are needed to resolve uncertainties (see Sections 3.b.i and 3.b.vi).
- **GAC reactivation units with thermal oxidizers operating under certain conditions**. Carbon reactivation systems, with the associated use of off-gas incineration (i.e., afterburners operating at temperatures >1,100°C[4]) and gas scrubbing units, can potentially destroy PFAS without significant environmental releases, or without PFAS remaining on the reactivated carbon. However, as discussed in Section 3.a.i, more data are needed for confirmation, particularly regarding reactor conditions, differing carbons, and products of incomplete combustion (PICs). There is uncertainty associated with this option because it is based on limited research. While recent studies have improved understanding, additional research is needed to resolve uncertainties on PFAS emissions from full-scale reactivation facilities (see Section 3.a.v).
- **Thermal treatment units operating under certain conditions.** Hazardous waste combustors (HWCs), including commercial incinerators, cement kilns, lightweight aggregate kilns (LWAKs), and thermal oxidizers, that operate under certain conditions (i.e., feeding liquid PFAS-containing materials, higher temperatures >1,100°C[4], well mixed, and adequate residence time) may be more effective at adequately destroying (mineralizing) PFAS and minimizing PICs. There is uncertainty associated with this option because it is based on limited research and observations, there are limited data for the treatment of solid materials or containerized wastes, and there are limited emissions data (e.g., no data for PIC formation and the presence of PFAS in air pollution control device residuals) at full-scale facilities (see Section 3.a.v) due to previous methodology limitations.
- **Landfill disposal in MSWLFs that have composite liners and leachate and gas collection and treatment systems: Landfill disposal of volatile or water soluble PFAS.** MSWLFs receive non-hazardous waste and most have composite liners and gas collection systems. Soluble PFAS in these

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[3] EPA defines landfill leachate as the liquid that is formed when rain water filters through wastes placed in a landfill. When this liquid comes in contact with buried wastes, it leaches, or draws out, chemicals or constituents from those wastes (*https://www.epa.gov/landfills/municipal-solid-waste-landfills*).

[4] Maximum PIC destruction was observed at and above 1,090°C as described by Shields et al., 2023.

landfills are likely to be released over time in landfill leachate if they are not adequately bound or sequestered in immobile solids. Further research is needed on the ability of various solidification techniques to retain soluble PFAS for extended periods under conditions found in MSWLFs. Although MSWLFs generally have leachate collection and management processes in place, the typical practices employed are not expected to prevent further PFAS migration. In addition, MSWLFs generally receive significant quantities of organic wastes (e.g., food scraps) that decompose, and thereby can cause PFAS migration via LFG. Multiple studies have reported elevated levels of PFAS in leachate and LFG. Studies estimate that up to 15 percent of mobile PFAS disposed in MSW landfills is emitted to the environment over time. EPA does not recommend MSWLF disposal of media containing relatively high concentrations of soluble or volatile PFAS. While recent studies have improved understanding of PFAS migration in MSWLFs, additional research is needed to resolve uncertainties (see Section 3.b).

- **Thermal treatment at lower temperatures** including municipal waste combustors (MWCs), sewage sludge incinerators (SSIs), or HWCs operating at lower temperatures or feeding solid or containerized PFAS-containing materials. Some HWCs operate at temperatures near or below 1,100°C, MWCs typically operate between 850 and 1,000°C, and SSIs typically operate at even lower temperatures. There is uncertainty associated with this option because it is based on very limited research. While limited, existing datapoints suggest the potential for air emissions of PFAS and PICs orders of magnitude above detection limits at temperatures below 1,000°C (Shields et al., 2023). There are no data on the treatment of solid materials or containerized wastes at lower temperatures. There are currently insufficient data and information to conclude anything about PIC formation or PFAS air emissions from full-scale combustion units operating at these lower temperatures or when feeding solid materials or containerized wastes. Because there are insufficient data available, there is low confidence in the reliability of this technology to control PFAS releases (see Section 3.a).
- **Construction and Demolition (C&D) landfills: Landfill disposal of volatile, water soluble, or oxidizable PFAS.** This class of landfills may not have a composite liner or leachate collection system. Because of the potential for environmental releases, EPA does not recommend that PFAS waste, other than wastes containing stable polymeric PFAS, be disposed of in this type of landfill. While few studies have documented emissions of PFAS from C&D landfills, the known mobility of PFAS in landfills and lack of engineered controls at C&D landfills make them unsuitable for PFAS disposal. For these reasons, EPA does not expect that C&D landfills will minimize PFAS releases to the environment (see Section 3.b).

1.c.ii Infrastructure considerations – communities, costs, and capacity

Waste management infrastructure in the United States is a complex and varied system, crucial for managing the vast amounts of waste generated, including PFAS-containing waste. Therefore, in addition to considering potential for environmental release, decision-makers should consider site- or project-specific factors that may influence decisions about managing PFAS-contaminated wastes. Specific factors include, but are not limited to, the composition of the waste, the types and concentrations of PFAS, transportation costs, destruction and disposal costs, and impacts to communities.

EPA emphasizes the importance for decision-makers (managers of PFAS-containing materials making decisions about destruction and disposal) to consider potential impacts to nearby communities, including vulnerable populations, when evaluating destruction, disposal, and storage options. Those concerns are amplified because the uncertainties in the effectiveness of these options to limit or control environmental releases can contribute to adverse impacts, including potentially disproportionate and cumulative impacts, for vulnerable communities. Therefore, EPA recommends decision-makers screen communities located in the vicinity of potential releases from the destruction, disposal, and storage options (considering fate and transport) in order to consider the potential for community impacts, including adverse and disproportionate impacts (see Section 4), and to consider potential measures to address such impacts. Depending on site-specific circumstances (e.g., PFAS concentrations, impacted media, and potential exposure pathways), the size and shape of this area (vicinity) will vary. In deciding how to address PFAS waste, site-specific considerations and waste characteristics should factor into the decision. For example, destruction or disposal of waste with a high concentration of PFAS using a method that has a higher potential for environmental release may not be well suited for a site where there is greater likelihood of potential exposure to vulnerable populations.

The waste management infrastructure's design and operation are heavily influenced by regional needs, local regulations, and technological advancements. As a result, waste management options vary by the type of waste and by location due to factors like availability, feasibility, and transportation requirements. For instance, urban areas may incur higher disposal costs due to limited space while rural areas may face higher transportation costs to distant disposal facilities. Furthermore, technological advances specifically related to the management of PFAS-containing materials can potentially reshape the cost and operational landscape of PFAS waste management. EPA recommends that decision-makers request cost estimates directly from potentially applicable destruction and disposal facilities. In addition, decision-makers can refer to Appendix D, which summarizes costs and factors to consider when estimating costs to destroy or dispose of PFAS and PFAS-containing materials.

Decision-makers seeking lists of waste management sites in the United States can access various resources depending on the type of waste and location. It is important to note that often the most direct source is local government websites, such as county or city environmental services or public works departments. These websites typically provide comprehensive lists and maps of local facilities, along with their types, hours of operation, and accepted waste materials. For specialized waste like hazardous or medical waste, state environmental protection agencies or EPA are valuable resources. EPA's website, in particular, offers databases and tools such as *RCRAInfo*, which provides detailed information about facilities managing hazardous waste.

A general yet incomplete list of potential treatment and disposal facilities may also be available through the EPA Incident Waste Decision Support Tool (*I-WASTE DST*). This list includes landfills (hazardous waste, MSW, industrial, and C&D), HWCs, and nonhazardous combustors (sewage sludge and municipal waste) but does not include all technologies available for PFAS destruction and disposal (e.g., cement kilns, carbon reactivation facilities, and underground injection facilities). I-WASTE DST is updated periodically and is limited to information available online.

Similar to cost estimation, management capacity estimates can also be challenging. Facilities that can potentially manage PFAS-containing waste are not evenly distributed. Their number and capacity vary by region. Some areas across the United States face challenges due to limited available landfill space or capacity limits. Incineration and underground injection capacities can also be greatly influenced by technological capabilities and local regulations.

2. Description of PFAS-Containing Materials Identified in the FY 2020 NDAA

The FY 2020 NDAA identifies six types of materials that commonly contain PFAS (see Figure 1-1 and the Executive Summary). This section discusses each FY 2020 NDAA material type, its origin, potential sources of PFAS, current disposal and treatment methods, and potential releases to the environment.

Data on FY 2020 NDAA-relevant material types come from a variety of sources, and more PFAS data will be available from EPA-managed datasets in the near future. For example, EPA's Chemical Data Reporting (CDR) dataset includes production volumes for manufactured and imported amounts and conveys certain industrial processing and use activities. One data element distinguishes amounts that are recycled instead of discharged or released to a waste stream. In the 2020 CDR reporting cycle, submitters began using Organization for Economic Cooperation and Development (OECD)-based industrial processing and use codes to better harmonize those data (U.S. EPA, 2020a).

In 2022, EPA issued two memoranda recommending EPA and state National Pollutant Discharge Elimination System (NPDES) permitting authorities and publicly owned treatment works (POTW) pretreatment program authorities conduct certain activities to align wastewater and stormwater NPDES permits, pretreatment program implementation activities, and biosolids monitoring with the goals in EPA's *PFAS Strategic Roadmap* (U.S. EPA, 2022a, 2022d). The memoranda recommend that EPA and state permitting authorities use the most current sampling and analysis methods in their NPDES programs to identify known or suspected sources of PFAS and to take actions using their pretreatment and permitting authorities, such as imposing technology-based limits on sources of PFAS discharges. The memoranda will also help the Agency obtain comprehensive information through monitoring regarding the sources and quantities of PFAS discharges, informing other EPA efforts to address PFAS.

Additionally, EPA's Toxics Release Inventory (TRI) program collects data related to industrial releases and waste management of certain chemicals. The TRI dataset includes, among other information, quantities of environmental releases to all media above certain thresholds (including on-site disposals and land application), as well as quantities transferred to off-site waste management facilities, including POTW. Under Section 7321 of the FY 2020 NDAA, certain PFAS were added to the TRI list beginning with Reporting Year 2020 (U.S. EPA, 2020b). As of Reporting Year 2023 (reporting forms due by July 1, 2024), a total of 189 PFAS are on the TRI list. TRI reporting data can be accessed at *https://www.epa.gov/toxics-release-inventory-tri-program/tri-data-and-tools*.

In October 2023, EPA finalized the PFAS 8(a)(7) reporting rule under TSCA (88 FR 70516, October 11, 2023). In accordance with obligations under TSCA, as amended by the FY 2020 NDAA, the PFAS 8(a)(7) reporting rule requires any person that manufactures (including import) or has manufactured (including imported) PFAS or PFAS-containing articles in any year since January 1, 2011, to electronically report information regarding PFAS uses, production volumes, disposal, exposures, and hazards. The PFAS 8(a)(7) rule will help EPA better understand the sources and quantities of PFAS manufactured in the United States and provide EPA with the most comprehensive dataset of PFAS manufactured in the United States. EPA will begin receiving reports under the PFAS 8(a)(7) rule in 2025.

2.a Solid, liquid, or gas waste streams containing PFAS from facilities manufacturing or using PFAS

PFAS do not occur naturally. They are synthesized for use in a diverse array of industrial and commercial applications. Industrial waste streams containing PFAS stem from two main sources: (1) primary manufacturing facilities of PFAS and (2) secondary industries that use PFAS or manufacture finished products that contain PFAS. A 2009 survey by OECD identified 27 primary manufacturers and processors of PFAS globally (OECD, 2011). At the time of that survey, more than 90 percent of the global annual production of PFAS was generated by eight manufacturers (Posner et al., 2009), all of which participated in EPA's 2010/2015 Perfluorooctanoic Acid (PFOA) Stewardship Program (U.S. EPA, 2006).

The goal of the PFOA Stewardship Program was to reduce PFOA facility emissions and their use in products by 95 percent by 2010, compared with 2006 baseline levels, and to eliminate PFOA from all facility emissions and products by 2015 (U.S. EPA, 2006). Companies that did not participate in the PFOA Stewardship Program likely continue to use these chemical substances. Long-chain PFAS and their precursors may still be produced as unintentional byproducts and may persist in facility emissions and as product impurities in small quantities (3M Company, 1999; Boucher et al., 2019; Lehmler, 2009; Kissa, 2001). Perfluoroalkyl sulfonic acids containing six or more carbons and perfluoroalkyl carboxylic acids with seven or more carbons are generally considered to be long-chain PFAS. PFOA and PFOS are examples of long-chain PFAS, and PFBS and PFHxA are examples of short-chain PFAS. Furthermore, information on the toxicity and environmental fate and transport of alternative PFAS chemistries is limited (Sun et al., 2016; Wang et al., 2014).

For the 2020 CDR reporting cycle, 52 sites reported a total domestic manufacture and import production volume of 339,000 tons for PFAS in 2019. This represents the aggregate production volume for PFAS produced and imported into the United States across all industries. Although the aggregate production volume might not include all PFAS sources (for instance, a specific chemical or site may not meet reporting obligations), it provides a proxy quantity of all PFAS domestically produced and imported.

PFAS might be released into the environment at every step in the production process, including during synthesis, polymerization, application, transport, usage, waste stream management, and disposal (3M Company, 2000b).

Table 2-1 lists examples of PFAS uses and the resulting solid, liquid, and gas waste streams for primary and secondary manufacturers of PFAS-containing materials and certain service sectors as indicated by industry, national and global inventories, and research. However, this list is not exhaustive or representative of all current uses, applications, recovery and recycling practices, or treatment technologies that could affect the volume and characteristics of the resulting waste streams. EPA recognizes the need for continued research to better characterize the multi-media PFAS-containing materials targeted for destruction or disposal, as discussed in Section 5.a.

2.a.i Solid phase wastes

Primary manufacturing and secondary industrial use of PFAS can generate solid waste streams with PFAS-containing materials (OECD, 2011, 2015). For example, some PFAS synthesis processes can produce tars and polymers consisting of high-molecular-weight byproducts that are either fully or partially fluorinated. These byproducts can be recycled back into the process or treated as waste (3M Company, 2000a, 2000b). Solid wastes such as fly ash (e.g., thermal treatment) or spent GAC (e.g., drinking water treatment) can also be produced from PFAS incineration and other treatment processes.

Other important solid-phase materials include sludges and biosolids (see Section 2.c) that result from stabilizing or treating process waters and wastewaters, either on site or at a municipal wastewater treatment plant (WWTP)[5] that receives influent from industrial sources (Venkatesan & Halden, 2013). In addition to solids produced via treatment, spent water treatment media (such as activated carbon and ion exchange resins) are part of this waste stream (see Section 2.e). Other direct industrial sources of solid wastes containing PFAS include intentional residuals, such as cuttings and fibers from textile manufacturing (see Section 2.d), and materials unintentionally produced outside of product specification. The concentrations and composition of PFAS in solid wastes generated from primary and secondary industrial sources vary by facility and depend on factors such as facility- or industry-specific production processes and the types and quantities of PFAS produced or used (ITRC, 2020).

The characteristics of these solid phase PFAS-containing wastes vary significantly, depending on several factors. As discussed in Section 3.b, the type of PFAS (e.g., polymeric, soluble, or volatile PFAS) as well as the type of waste with which the PFAS is comingled (e.g., biodegradable or non-biodegradable) will dictate the potential and pathways for environmental release. The type of environmental release will, in turn, inform the most appropriate disposal option(s) for each type of PFAS-containing solid waste.

2.a.ii Liquid phase wastes

Primary manufacturers and secondary industrial users of PFAS can generate liquid phase wastes in the form of: (1) liquid byproducts of PFAS synthesis to be recycled or disposed of (e.g., to a landfill) following stabilization, solidification, or another management method; (2) process wastewater resulting from activities using PFAS as a processing aid (e.g., surfactant, emulsifier, mist suppressant, sizing agent) and production of finished products containing PFAS; (3) spills or unintentional releases of liquid wastes and products containing PFAS; and (4) AFFF/water/foam mixtures from the use of fire-extinguishing agents (see Section 2.b) for emergency response activities and emergency response trainings at industrial facilities.

Table 2-1 provides examples of liquid wastes containing PFAS generated by industrial sources and their uses. This is not an all-inclusive list of industries nor waste streams.

Another liquid phase waste stream is wastewater effluent discharged directly from a primary manufacturer or secondary industrial PFAS user. Effluent from wastewater treatment facilities that receive wastewater from industrial PFAS sources may also contain PFAS. According to several studies, conventional wastewater treatment technologies are generally ineffective at destroying or controlling PFAS (Schultz et al., 2006) and may result in higher measurable PFAAs (e.g., PFOA, perfluorooctane sulfonate [PFOS], and their homologues) when precursor compounds (e.g., fluorotelomers) are degraded during the treatment process (Buck et al., 2011; Dauchy et al., 2017a; Schultz et al., 2006; Sinclair & Kannan, 2006). Less often, primary industrial PFAS manufacturers have opted to transport liquid wastes off site for incineration (North Carolina Department of Environmental Quality, 2017).

2.a.iii Gas phase wastes

Studies suggest that PFAS in air emissions from manufacturing facilities are a source of both localized (i.e., within a short radius of the facility) and long-distance (i.e., global) transport of PFAS within the environment (Davis et al., 2007; Dreyer et al., 2009). Non-volatile forms of PFAS, such as the anionic

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[5] Regulations at 40 CFR part 122.2 and part 403.3 identify these “municipal wastewater treatment plants" as treatment works treating domestic sewage (TWTDS) or publicly owned treatment works (POTW), dependent on their ownership.

PFAAs (e.g., PFOA, PFOS, their homologues), are associated with airborne particulates when emitted as aerosols from stack emissions at primary manufacturing facilities (Barton et al., 2006; Dreyer et al., 2015). Gas phase emissions of volatile and semivolatile PFAS, and the subsequent transformation of precursor compounds into persistent PFAAs, are a potential mechanism for the atmospheric transport of PFAS. For example, volatile fluorotelomer alcohols (FTOHs) and perfluoroalkyl sulfonamides can transform into perfluoroalkyl carboxylic acids (e.g., PFOA and homologues) and perfluoroalkyl sulfonates (e.g., PFOS and homologues); these can be deposited at significant distances from their origin, which may result in soil and groundwater contamination (Dreyer et al., 2009; Ellis et al., 2004; Martin et al., 2006; Schenker et al., 2008).

Table 2-1. Examples of PFAS Waste Streams by Industry Type. This is not an all-inclusive list of industries or waste streams.

Industry Type	Uses	Examples of Waste Streams[a]			Source
		Solid	Liquid	Gas	
Primary chemical manufacturing	PFAS synthesis, feedstocks for primary products, feedstocks for secondary users, processing aids (fluoropolymers)	Process byproducts (tars), sludges/residuals, off-spec materials[b], treatment residuals (GAC/anion exchange resins), spill residues (replacement and legacy), *particulate emissions*	Degraded/stabilized process wastes, wastewater effluent, *stack emissions condensate*	Stack emissions, fugitive volatiles	3M Company (1999, 2000b)
Secondary Manufacturing (Industry Users of PFAS-Containing Materials)[c]					
Adhesives manufacturing	Component of solvent- and water-based adhesives, rubber to allow bonding to steel, and urea-formaldehyde adhesive resins for wood particleboard bonding	*Used filter media and filter residues, residues of cured adhesives, empty containers, used shop rags (from cleaning), contaminated soil (from spill cleanup residues)*	*Residues of liquid adhesives, off-spec products[b], contaminated wastewater (from spill cleanup residues)* *For cleaning: equipment startup, cleaning, and flushing wastes; spent cleaning solvents; and contaminated wastewater*	Stack emissions, fugitive volatiles	ASC (n.d.), RadTech International North America (2010)
Cleaning product manufacturing	Component of household cleaners; car wash products; automobile waxes; wiper fluid; strongly acidic or basic cleaners for concrete, masonry, airplanes		*Off-spec products[b], liquid residues from empty containers, and spills*	Stack emissions, fugitive volatiles	3M Company (1999)

Industry Type	Uses	Examples of Waste Streams[a]			Source
		Solid	Liquid	Gas	
	Used for removal of adhesives, dry cleaning of textiles or metal surfaces, machine parts cleaning after nickel plating, and removal of calcium sulfate from reverse osmosis membranes				
Computers/ electronics manufacturing	Component of sealant for electric circuits, zinc battery electrolyte, wetting agents in solders, polar solvents used before welding Used for removal of cured epoxy resins from integrated circuit modules, treatment of insulated wire, alkaline manganese battery MnO_2 cathode treatment, production of polymer electrolyte membrane for fuel cells, cleaning of electronic components, and coating of the surface of magnetic recording devices	*Collected airborne particulates for cleaning/surface preparation*	*Spent acid solution for cleaning/surface preparation, liquid residues from empty containers, and spills*	Stack emissions, fugitive volatiles	U.S. EPA (1990)
Film/ lithography manufacturing	Used in coatings for surface tension, static discharge, and adhesion control for films, papers, and printing plates, and as a surfactant in mixtures used to process imaging films	Rags and wipes discarded by applicator; solids coated with PFAS from processing, sampling, quality assurance; off-spec products[b]	Solvent waste, liquid residues from empty containers, spills, and unused application mix	Coating application exhaust	3M Company (1999), Bowden et al. (2002)
Metal plating/ fabrication	Used as a surfactant, wetting agent, and mist suppressing agent; as a wetting agent fume suppressant for chromium plating and chromium anodizing; as a dispersion product used to coat metals; as a	*Off-spec products[b]*	Spent plating or etching baths, rinse water effluent, liquid residues from empty containers, and spills	Stack emissions, fugitive volatiles	3M Company (1999), U.S. EPA (2009b)

Industry Type	Uses	Examples of Waste Streams[a]			Source
		Solid	Liquid	Gas	
	blocking agent for aluminum foil; in plating baths; and to treat metal surfaces				
Oil and gas drilling/ extraction/ refinery/ support	Component of chemical barrier used for containing oil spills Used as a surfactant for recovery in oil/gas recovery wells, a jet fuel/hydrocarbon solvent, and in hydraulic oils Used as a gasoline/petroleum product evaporation inhibitor in storage tanks in the following forms: a floating layer of cereal grains treated with PFAS, an aqueous layer containing PFAS		Applied product[d] (oil spills, oil and gas recovery wells), *liquid residues from empty containers, and spills*		UNEP (2011), Kissa (2001)
Paint/coating manufacturing	Component of coatings, paints, varnishes, dyes, ink jet printer inks, and ski waxes	*Pigment dust*	*Unused paint products, off-spec products[b], liquid residues from empty containers, and spills*	*Fugitive volatiles, atomized paint*	Waste Management and Research Center (1992)
Paper products/ packaging manufacturing	Waterproofing and grease proofing for products including food contact paper (e.g., plates, popcorn bags, pizza box liners, food containers, wraps), non-food contact applications (e.g., folding cartons, carbonless forms, masking papers)	Dusts; *solids coated with PFAS from processing, sampling, quality assurance; off-spec products[b]*	Spillage, cleanup, and releases during opening, rinsing, and cleaning of PFAS totes	Fugitive volatiles	U.S. EPA (2009a)
Pesticide/ fertilizer/ other agriculture chemical manufacturing	Pesticide and herbicide ingredients and packaging	*Particulate emissions*	*Liquid residues from empty containers, spills, off-spec products[b], cleaning of equipment, and process wastewaters*	*Fugitive volatiles*	U.S. EPA (2023b)

Industry Type	**Uses**	**Examples of Waste Streams**[a]			**Source**
		Solid	**Liquid**	**Gas**	
Plastic materials/ resins/ rubber product manufacturing	Used to make membranes used in fuel cells; chlor-alkali cells; water, caustic soda, and caustic potash electrolyzers; silicone rubber sealants; composite resins; polytetrafluoroethylene (PTFE, or Teflon); and polyvinylidene fluoride or polyvinylidene difluoride (PVDF) Processing aid for PVDF manufacture, mold-release agent in foam molding, and antiblocking agent for rubbers	Dusts, spillage (micropowders and resins), cuttings, scrap, debris, and off-spec products[b]; particulate emissions	*Liquid residues from empty containers, spills, and unused application mix*	Fumes from PTFE heating (volatile)	Ebnesajjad (2015)
Textiles/ apparel/ leather/ carpets/ fiber manufacturing	Dispersion products that coat fabrics: jackets, shoes, umbrellas, carpets, upholstery, leather, tents, sails	Solids coated with PFAS from cutting, shearing, packaging, lab and color sampling, quality assurance; flakes or dust containing PFAS; *off-spec products*[b]	Spills, wastewater effluent from product adhering to inside of drum, and unused application mix	Releases of vapors and aerosols during application of surface treatment and mechanical finishing	U.S. EPA (2009a)
Aerospace component manufacturing	Mechanical components such as tubing, hoses, and seals; brake and hydraulic fluid additive; wire and cable insulation; used in coating and paint		*Wastewater effluent*		FluoroCouncil (2019)
Automotive component manufacturing	Mechanical components such as tubing, hoses, and seals; brake and hydraulic fluid additive; anti-mist film on windshields; used in coating/paint; used in coatings or surface treatments of textiles and upholstery		*Wastewater effluent*		FluoroCouncil (2019), ITRC (2020)

Industry Type	Uses	Examples of Waste Streams[a]			Source
		Solid	Liquid	Gas	
Semiconductor manufacturing	Etching solutions for photolithography, glass etching, plastics etching, fused silica, aluminum; liquid etchant in photo mask rendering		Spent plating or etching baths, PFOA residues from photoresist developers associated with semiconductor liquid waste streams, liquid residues from empty containers, and spills Photoresists and antireflective coatings stripped off from semiconductor devices before shipment are present in waste solvent streams	Photoresists and antireflective coatings stripped off from semiconductor devices before shipment are present in waste gas streams	Bowden et al. (2002), Tremblay (2015)
Building and construction materials manufacturing	Component of cement and primers used to coat cement mortar; used in wire and cable insulation and coatings for wood particleboards	*Cuttings and debris, off-spec materials[b]*	*Wastewater effluent*		Buck et al. (2012), FluoroCouncil (2019), U.S. EPA (2009a)
Mining industry	Surfactant for recovery of metals from ores; used in ore flotation to separate metal salts from soil, electrowinning of metals, and nitrogen flotation to recover uranium	Contaminated rock from applied product[d]	Applied product[d]		ITRC (2020)
Medical uses	Video endoscopes; catheters; saline solutions for in vitro diagnostics; treatment/coatings for textiles such as hospital gowns, curtains, drapes; dialysis machines	*Laboratory/medical solid wastes (e.g., tubing, filters, films)*			FluoroCouncil (2019), Posner (2012)
Cosmetics and personal care product manufacturing	Used in cosmetics, hair conditioning formulations, hair creams, and toothpaste	*Off-spec materials[b]*	*Wastewater effluent*		Danish EPA (2018), FluoroCouncil (2019), Schultes et al. (2018)

Industry Type	Uses	Examples of Waste Streams[a]			Source
		Solid	Liquid	Gas	
Fire suppression systems[e]	AFFF and certain dry fire-extinguishing agents	Contaminated soil and debris from applied product[d]	Applied product[d]		See Section 2.b for more information. Gaines (2023)

[a] The italicized waste streams may contain PFAS, given what wastes the relevant industry sectors are known to generate and given applications of PFAS. The presence and concentration of PFAS have not been quantified.

[b] "Off-spec materials" or "off-spec products" are materials or products that do not meet specified standards or requirements and are discarded rather than sold or used.

[c] Some industries listed under "Secondary Manufacturing" may also include primary manufacturing of PFAS. The waste streams resulting from manufacture of PFAS in these industry sectors are addressed in the first row, "Primary chemical manufacturing."

[d] "Applied product" refers to the intentional application of a PFAS-containing product to the environment.

[e] Fire suppression systems, which include AFFF, are commonly found in manufacturing, storage, extraction and refining, and national defense facilities, as well as airports, fire departments, and other federal facilities (e.g., facilities operated by the National Aeronautics and Space Administration [NASA] and the U.S. Department of Energy [DOE]). Although this is an industrial use, not an industrial sector, the prevalence of AFFF in the above primary and secondary PFAS manufacturing industries warrants highlighting these waste streams.

2.b Aqueous film-forming foam

AFFFs are a group of PFAS-containing fire extinguishing agents for low-flashpoint hydrocarbon fuel fires (Tuve et al., 1964). AFFFs are intended for use where a significant flammable liquid fire hazard exists (FFFC, 2016).

AFFFs are based on synthetic fluorosurfactants that provide unique low surface tension and positive spreading coefficient characteristics. When mixed with water and applied, AFFFs form an aqueous film and a foam solution to coat the liquid fuel, seal fuel vapor, and reduce oxygen availability, extinguishing the fire and preventing burnback (FFFC, 2016; SERDP, 2020; Sheinson et al., 2002).

Until application, AFFF is managed as a concentrated product containing less than 2 percent PFAS fluorosurfactants by weight for a typical 3 percent AFFF concentrate (ITRC, 2020). AFFF is stored in either fixed, structural dispensing systems, such as those in hangars and aboard vessels, or in mobile, vehicle-based systems (i.e., aircraft rescue firefighting [ARFF] vehicles) (Field et al., 2017). Reserve AFFF concentrate inventory may be stored in hangars or warehouses. The amount of AFFF concentrate in the finished foam varies by manufacturer and application circumstances, but is usually between 1 and 6 percent, meaning the fluorosurfactants are diluted to less than a fraction of a percent (FFFC, 2016; ITRC, 2020).

A 2004 inventory estimated that there were 4.6 million gallons of legacy PFOS-containing AFFF in the United States (Darwin, 2011). AFFF inventory depletion is determined by frequency of use for firefighting, training, or testing; transfers between locations; and other factors. However, AFFF's characteristically long shelf life means there should be little disposal due to expiration (FFFC, 2016), increasing the possibility that legacy PFOS-containing AFFF concentrate remains in service or reserve inventories. Fluorotelomer-based AFFF surfactant products became available in the 1970s (Prevedouros, 2006). In 2017, the U.S. Department of Defense (DoD) edited its military specification for AFFF to include no more than 800 parts per billion (ppb) of PFOA and PFOS in the concentrate, the limit set by DoD Quality Systems Manual 5.1. However, this specification does not mention any other PFAS standards.

In the United States, AFFF and associated systems are or have been in service at federal facilities, civil airports, and oil refineries. Civilian fire departments also use or have used AFFF. The federal government is working to identify areas of current and former federal properties where PFOS- or PFOA-containing AFFFs have been used (Darwin, 2011; DoD, 2020). Through September 30, 2023, DoD has determined that 715 active military installations, base realignment and closure (BRAC) locations, National Guard facilities, and formerly used defense sites (FUDS) properties require an assessment of PFAS use or potential release. DoD is performing preliminary assessments/site inspections (PA/SIs) at these installations, which is the first phase of the cleanup process and may take two to three years to complete. As of September 30, 2023, DoD has completed the PA/SI phase at 570 installations. The Department has determined that no further action is required at 118 of these installations, while 452 are proceeding to the next step in the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process (DoD, 2024).

The FY 2020 NDAA prohibits AFFF use at any military installation, effective October 1, 2024 or up to two years later if the Secretary of Defense deems a waiver necessary. DoD issued a policy in January 2016 to discontinue land-based AFFF training and testing activities, unless the AFFF could be captured and properly disposed. Since then, DoD has managed any mission-critical AFFF use in response to an emergency event as a spill response to mitigate impacts to the environment (DoD, 2019, 2020). DoD, among other entities, is also investing in research and development for fluorine-free AFFF alternatives (SERDP, 2020). In 2023, DoD issued a new military specification for fluorine-free foam (MIL-PRF-32725) (DoD, 2023).

Examples of AFFF users and locations in the United States are listed in Table 2-2. Note that the list of sources in the table is non-exhaustive.

Table 2-2. Examples of AFFF Users and Locations in the United States

AFFF User	Locations	Comments
DoD	• Hundreds of military installations (active and former) with AFFF use • In-service systems installed at an estimated 1,350 locations in aircraft hangars and on an estimated 3,000 ARFF vehicles	• In 2016, DoD discontinued AFFF use for military installation training and testing unless the AFFF could be captured and properly disposed and is investing in fluorine-free alternatives • The FY 2020 NDAA requires DoD to end any land-based AFFF by October 1, 2024 (with extensions possible until 2026) • Sources: DoD (2017, 2019, 2020); CBO (2019); SERDP (2020)
NASA	• Multiple properties with ARFF apparatus • Five properties with fixed systems	• In late 2018, NASA issued order to cease training with AFFF • Source: SERDP (2020)

AFFF User	Locations	Comments
DOE	• Lawrence Berkeley National Laboratory • Brookhaven National Laboratory • Los Alamos National Laboratory • Strategic Petroleum Reserve facilities (Gulf of Mexico)	• Sources: DOE (2021 *DOE Initial Assessment of PFAS at DOE Sites*); Darwin (2011)
Airports and supporting facilities	• 523 Federal Aviation Administration (FAA)-certified civilian airports in 2018 • Since 2006, an annual average of nearly 600 certified airports • Supporting facilities include firefighting training sites, such as the FAA Technical Center's Fire Training Area	• Starting in 1972, FAA regulations allowed for the use of AFFF among a number of different extinguishing agents at civilian airports; since 2006, FAA guidance (FAA, 2006) provides that AFFF must conform to the applicable military specification (AC 150/5210-6 and MIL-F-23485F) at most civilian airports [a] • 80 percent of respondents to a 2017 survey of U.S. and Canadian airports reported training-related discharge directly to the ground; two-thirds reported testing-related discharge directly to the ground • FAA has taken steps to reduce AFFF discharges during testing since 2019 • Sources: DOT (2019); FAA (2006, 2019); Thalheimer et al., (2017); U.S. EPA (2020c)
Fire departments	• At civilian fire departments throughout the United States	• AFFF may be present at fire departments • Some states have begun inventorying and reporting having AFFF (e.g., Michigan, New Hampshire) • Some states have take-back programs to help local fire departments identify AFFF in inventory and assist with removal and disposal (e.g., Vermont) • Sources: Michigan PFAS Action Response Team (n.d.); New Hampshire Department of Environmental Services (2020); Vermont Agency of Natural Resources (n.d.)
Oil refineries and processing facilities	• Oil refineries and related facilities (e.g., storage facilities)	• Little information is available about AFFF in this sector, though published industry guidelines recommend AFFF for pipeline emergencies • Survey-based data suggest this sector is the second largest consumer of AFFF after federal agencies • Sources: Darwin (2011); Noll & Hildebrand (2016)

AFFF User	Locations	Comments
Ships and other vessels	• Ships and other marine vessels, including the U.S. Coast Guard	• Little information is available about AFFF quantities on ships • There has been a shift toward non-fluorinated AFFF for some uses including testing and training, though the Coast Guard has indicated that certain uses (e.g., required inspections) must continue to use fluorinated AFFF • Source: U.S. EPA (2020e)

[a] An exception exists for airports with low departure traffic and serving aircraft less than 90 feet in length. See 14 Code of Federal Regulations (CFR) 139.317 for more information (FAA, 2006).

Fate and transport of PFAS in AFFF after use depends on the release circumstances and chemical-specific properties. Though sometimes classified as incidental releases (Thalheimer et al., 2017), equipment failure, accidental releases, or operator error can result in substantial leaks (Anderson et al., 2016; Resolution Consultants, 2016; Leidos, 2016).

Engineering controls (such as dikes, barriers, or basins) may be installed at facilities with significant flammable liquid hazards to contain foam solution and runoff for later disposal (FFFC, 2016). Where such hazards do not significantly exist, or installed engineering controls are otherwise not practicable, firefighting personnel may block sewer drains or deploy portable dikes as containment measures (FFFC, 2016). Runoff can then be pumped out, and the affected environmental media can be removed for disposal (ITRC, 2020). C&D debris originating from facilities where AFFF was historically released may also be a source of PFAS in landfills and groundwater (Solo-Gabriele et al., 2020).

Though subject to site-specific characteristics and conditions, studies demonstrate AFFF use at airports is a source of PFAS in soil and groundwater (Ahrens et al., 2015; Dauchy et al., 2017b; Høisæter et al., 2019). Further, PFAA precursors from original AFFF concentrate products may transform in the environment to more mobile products over time (Houtz et al., 2013), expanding plumes long after AFFF use is discontinued.

In the 2022 EPA-issued memoranda that recommended NPDES and POTW pretreatment program permitting conditions (U.S. EPA, 2022a, 2022d), EPA recommended that NPDES stormwater permits contain best management practices (BMPs) to address and minimize AFFF discharges, as included in the Naval Air Station Whidbey Island MS4 NPDES Permit[6]:

- Prohibiting the use of AFFFs other than for actual firefighting.
- Eliminating PFOS- and PFOA-containing AFFFs.
- Requiring immediate clean-up in all situations where AFFFs have been used, including diversions and other measures that prevent discharges via storm sewer systems.

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[6] Naval Air Station Whidbey Island MS4 NPDES permit: *https://www.epa.gov/sites/default/files/2020-12/documents/r10-npdes-naval-air-station-whidbey-ms4-was026611-final-permit-2020.pdf*

2.c Soils and biosolids

As required by Clean Water Act Section 405(d), EPA established requirements for the final use or disposal of sewage sludge when it is: (1) applied to land as a fertilizer or soil amendment; (2) placed in a surface disposal site, including sewage sludge-only landfills; or (3) incinerated. The regulation at 40 CFR part 503 defines sewage sludge as “solid, semi-solid, or liquid residue generated during the treatment of domestic sewage in a treatment works.” Sewage sludge includes scum or solids removed in primary, secondary, or advanced wastewater treatment processes and any material derived from sewage sludge (e.g., a blended sewage sludge/fertilizer product) but does not include grit and screenings or ash generated by the incineration of sewage. Sewage sludge treated for land application is commonly referred to as “biosolids.”

Part 503 considers domestic septage as sewage sludge and sets separate requirements for domestic septage applied to agricultural land, forests, or reclamation sites. Influent containing PFAS that enters wastewater treatment facilities may result in the presence of PFAS in biosolids (Thompson et al., 2023; Helmer et al., 2022; Venkatesan & Halden, 2013). When biosolids are applied to land, there is the potential for leaching or runoff (Schaefer et al., 2022; Navarro et al., 2016; Lindstrom et al., 2011; Sepulvado et al., 2011; Washington et al., 2010). If landfilled instead, there are concerns with PFAS releases via landfill leachate and gaseous emissions, especially for highly organic material (Section 3.b). Alternatively, if incinerated, there is the potential for PFAS to be emitted as PICs (Section 3.a). Research needs and resources on possible emerging PFAS destruction technologies for biosolids (e.g., pyrolysis/gasification coupled with a thermal oxidizer and supercritical water oxidation) are shared in Sections 5 and 6. Across disposal and destruction technologies, there are capacity concerns and more research is needed on potential PICs/products of incomplete destruction (PIDs).

Total nationwide biosolids generation and management statistics in 2021 (reported to EPA’s biosolids program as of January 9, 2023) and data considerations are presented in Table 2-3. EPA does not have data on the volume of biosolids that contain PFAS; however, EPA is planning for the next National Sewage Sludge Survey in collaboration with the Effluent Guidelines Program Plan 15’s upcoming POTW influent study, both of which will focus on monitoring for PFAS. Additionally, EPA is currently conducting a refined risk assessment for PFOA and PFOS in biosolids (U.S. EPA, 2024), as well as recommending exposure mitigation measures and pretreatment program BMPs to reduce PFAS sources (U.S. EPA, 2022d).

Table 2-3. Biosolids Generation and Management in 2021

NPDES permits issued to POTW[a]	**16,109**
Biosolids NPDES permits[b]	9,834
Biosolids annual reporters (2021)[c]	2,519
Sewage Sludge generated in 2021 (metric tons)[d]	**4,548,462**
Land application of biosolids (metric tons)	1,955,684
Land disposal (also called surface disposal) (metric tons)	94,522
Incineration (metric tons)	633,054
Landfilling (metric tons)	1,808,136
Other management (metric tons)	57,066

[a] An NPDES permit is typically a license for a facility to discharge a specified amount of a pollutant into a receiving water under certain conditions. A POTW is a treatment works treating domestic sewage (TWTDS) that is owned, and usually operated, by a local or regional government agency (U.S. EPA, 2020b).

[b] Biosolids permits apply to any person or treatment works that prepares sewage sludge, applies sewage sludge to the land, or fires sewage sludge in a sewage sludge incinerator and to the owners/operators of surface disposal sites, as well as the exit gas from sewage sludge incinerator stacks (U.S. EPA, 2019).

[c] Annual reports are required for POTW that have a design flow rate equal to or more than one million gallons per day, that can serve populations of 10,000 or more, that are required to have approved pretreatment programs (Class I Sludge Management Facilities), or that are otherwise required to report (U.S. EPA, 2023a).

[d] Total amount of biosolids generated is reported by each TWTDS and may not equal the sum of component amounts reported for each management method. Biosolids totals do not represent PFAS presence in biosolids.

In addition to land application of PFAS-containing materials (e.g., biosolids), there are other scenarios where PFAS release to soils can occur. Direct release of PFAS into soils can occur through use of PFAS-containing products such as AFFF, and the discharge or application of treated industrial or municipal wastewater containing PFAS. PFAS can also be in soils due to unintentional contact, such as spills or leaks during the production, handling, transport, or use of PFAS-containing materials (see Table 2-4 for examples of industrial sources of PFAS in soils). Both direct and indirect soil impacts might also occur via the atmospheric deposition of PFAS released from stack emissions and atmospheric transformation products of volatile precursors, respectively (Davis et al., 2007; Dreyer et al., 2009; Schenker et al., 2008). Remediation wastes such as soils excavated during the cleanup of sites or during decommissioning of facilities where PFAS was manufactured, used, or applied may contain diverse mixtures of PFAS in elevated concentrations.

2.d Textiles, other than consumer goods, treated with PFAS

Because PFAS can repel oil, water, and stains, the textile industry uses these chemicals in a broad range of textile products other than consumer goods (apparel or household textiles). For example:

- PFAS can be used to treat outdoor equipment such as tents and sails (UNEP, 2011).
- Technical or occupational textiles, such as protective clothing for firefighters, can be treated with PFAS or woven from fluoropolymers (OECD, 2013).
- Medical garments can be treated with fluorinated polymers (OECD, 2013).
- Fluoropolymers can be spun into fibers and used to make sailcloth and fabric for fire suppression needs (Tokarsky & Uy, 2003).

- PTFE can be woven to make architectural fabrics, such as roofs, and can also be used to coat fiberglass for tensile structures or long-life structures (Fabric Architect, 2020).
- Textiles made from fiberglass coated with or saturated with PFAS are used for high-temperature or corrosive industrial environments. Kevlar and perfluoroplastic composite textiles are used for similar industrial environments (Robco, 2020).

Examples of typical PFAS-containing waste streams generated from textiles include discarded industrial or commercial textiles such as apparel, carpets, or personal protective equipment; solids coated with PFAS from cuttings and shearings; and fugitive volatiles from spray applications of textile surface treatments. The destruction and disposal technologies used for these waste streams include landfill disposal and thermal treatment. For examples of industrial waste streams from the textiles/apparel manufacturing industry, see Table 2-4.

2.e Spent water treatment materials

EPA published a proposed rule for a PFAS National Primary Drinking Water Regulation (NPDWR) for six PFAS in March 2023 that will require compliance once finalized and promulgated. Additionally, 12 states have established standards limiting the presence of various PFAS in drinking water. EPA has identified "best available technologies" for treating drinking water for PFAS to comply with the NPDWR; these technologies will produce residuals. The 2024 Interim Guidance details options available to manage these residuals while minimizing environmental exposures and releases to the extent feasible. EPA notes that there are multiple approaches for water systems to manage PFAS residuals that are generated when PFAS is removed from drinking water. As of December 2023, there are no specific federal regulatory requirements for PFAS disposal, and the presence of PFAS in treatment residuals does not impose any additional federal requirements, but they may be subject to regulatory attention. EPA's PFAS actions are updated on the webpage *Key EPA Actions to Address PFAS*.

Conventional drinking water treatment methods such as coagulation, flocculation, sedimentation, disinfection, and filtration do not remove PFAS found in source water. Therefore, residues from these processes such as grit, spent membrane, or filter elements are unlikely to contain significant PFAS.

Although novel technologies for removing PFAS from drinking water sources and groundwater are being developed, current processes known to be effective are activated carbon, anion exchange resins, and high-pressure membranes (reverse osmosis [RO] and nanofiltration [NF]) (U.S. EPA, 2022b, 2022c). This section discusses the residual streams of these three processes (see Section 3 for discussions on treatment and disposal considerations, Appendix D for costs and considerations, and Section 5 for discussions of research needs for more novel treatments) and regulatory considerations for drinking water treatment utilities.

Table 2-4 shows the primary residual streams by water treatment process, with options for reactivation, destruction, and disposal of these residuals.

Table 2-4. Destruction and Disposal Options for Drinking Water Treatment Residuals Containing PFAS

Treatment Process	Residuals Generated	Destruction/ Disposal Option(s)	Section Reference
Granular Activated Carbon	Spent GAC	Reactivation	3.a.i.2
		Incineration	3.a
		Landfill	3.b

Treatment Process	Residuals Generated	Destruction/ Disposal Option(s)	Section Reference
Powdered Activated Carbon (PAC)	Spent PAC	Incineration	3.a
		Landfill	3.b
Ion Exchange	Single use and regenerative ion exchange: spent resins	Incineration	3.a
		Landfill	3.b
	Regeneration brine	Interim Storage	1.c
		Underground Injection	3.c.ii.1
RO/NF	Brine	Permitted discharge, direct or indirect	Not described in this guidance. Refer to permit.

The practices discussed in Table 2-4 are not in a hierarchical order and should be chosen based on site-specific conditions. The practices presented in Table 2-4 may help reduce and/or control unintentional PFAS releases to the environment.

2.e.i Activated carbon

Activated carbon (discussed more extensively in Section 3.a.i) is manufactured from carbon-rich sources such as coal or wood and is used to treat water or air by filtering contaminants (U.S. EPA, 2012). Activated carbon can be used in either PAC or GAC form. In PAC treatments, carbon is powdered and added to the water for treatment, and then chemicals in the water stick to the powdered carbon as the water passes through and typically carries the PAC along. In GAC treatments, chemicals in water adsorb to small pieces of carbon in a bed as the water passes through.

PAC application will remove some PFAS from water, though the amount of PFAS removed depends on many factors. For PAC treatment, the residual stream is the sedimentation sludge or the filter backwash solids that contain the PFAS-laden PAC along with the coagulant, coagulant aids (if used), natural particulates, and enmeshed organic carbon (Dudley et al., 2015). Given the many conditions that affect treatment, the weight percent PFAS in a PAC residual stream varies by many orders of magnitude but will be in the same range as GAC treatment, as discussed below.

For GAC, the range of PFAS concentrations on spent media can be estimated in several ways (Crone et al., 2019; U.S. EPA, 2020d). A conservatively high loading of PFAS onto GAC (using a GAC with a high-capacity potential, a strongly adsorbing PFAS, few competitive contaminants, low organic levels, and a high concentration in the feed water treated) is on the order of 2 percent by weight (e.g., 0.02 grams PFOS per gram of GAC). For more common treatment scenarios, or for PFAS that are adsorbed more weakly (i.e., the shorter-chain PFAS), the weight percent of PFAS will be orders of magnitude lower—about 1×10^{-5} grams PFAS per gram of GAC.

GAC can be reactivated and reused (see Section 3.a.i.2 for a discussion on GAC reactivation). If the GAC is landfilled, PFAS can desorb off the carbon into the landfill leachate if the GAC comes into contact with a water stream that contains low PFAS, or more strongly adsorbing constituents that can displace the PFAS. Desorption will occur due to the disequilibrium between the liquid and solid phases and will accelerate at higher temperatures where adsorption becomes less favorable for exothermically adsorbed contaminants. Therefore, the resulting PFAS concentrations in the landfill leachate impacted by spent GAC will vary greatly depending on conditions.

Typically, deep bed GAC does not require backwashing because the particulates in the water are removed ahead of the GAC system, but there may be instances where particulates deposit onto the GAC, creating a headloss that will require backwashing. If so, the backwash water may contain a PFAS foam that may need to be managed.

2.e.ii Ion exchange resins

Like GAC, ion exchange resins are utilized in fixed bed adsorbers. Similarly, the residual stream from this treatment is the spent media; however, ion exchange resins cannot be thermally reactivated like GAC. Due to several factors, the market is moving toward single-use media for anion exchange resin treatment with incineration as the final disposal point for the spent resin.

Final PFAS loadings onto resins vary widely. A conservatively high estimate of loading (calculated using a PFAS-selective resin, few competitive constituents, and a PFAS known to adsorb well) is expected to be in the order of 10 percent by weight for the strongly adsorbing PFAS (e.g., 0.1 gram PFOS per gram of resin). The higher percent weight than GAC is due to the high capacities of PFAS-selective resins. Like GAC, more typical scenarios for PFAS that are more weakly adsorbed (i.e., shorter-chain PFAS) will yield much lower average weight percent of PFAS.

Assuming single-use resin is used, landfilling may be less expensive than incineration. If the resin is landfilled, PFAS can desorb off the resin if the resin comes into contact with a water stream whose counter ions can displace the PFAS. The resulting leachate concentrations will vary tremendously depending on conditions. In rare cases, it may be appropriate to regenerate the ion exchange resins with a brine; however, the latest science has shown that an alcohol solvent is needed along with the inorganic exchange ion. This is difficult to do at the full-scale, especially for drinking water facilities. If done in this manner, the resulting regenerate brine will have high concentrations of PFAS and will need to be disposed of appropriately. In rare cases, there may not be a ready disposal option for this regenerate brine and interim storage may be appropriate. Before selecting interim storage, it is important to consider that generating routine volumes of waste can pile up over time, which may become more difficult to store than originally envisioned. Otherwise, regenerate brine may be handled like other high-strength liquid PFAS wastes.

Typically, resin beds do not require backwashing because the particulates in the water are removed ahead of the resin system, but there may be instances where particulates deposit onto the resin, creating a headloss that will require backwashing. If so, the backwash water may contain a PFAS foam that may need to be managed.

2.e.iii High-pressure membranes (reverse osmosis and nanofiltration)

High-pressure membranes are extremely effective for removing many PFAS from water to a high degree (Crone et al., 2019; U.S. EPA, 2020d). As high-pressure membranes are based on a rejection phenomenon, water treatment with them creates a waste stream with potentially high concentrations of PFAS as well as treated water with a lower pH. These waste streams also have high concentrations of salts, other contaminants, and dissolved organic matter.

Treatment of the concentrated residual stream can be challenging, and the cost will likely be high, similar to those for landfill leachates, ion exchange spent regenerates, and waters from highly contaminated sites. Many variables could affect the cost of treating these waste streams. At this time, there is no obvious treatment technology choice, especially given that the concentrated retentate stream is typically 20 percent of flow (Baruth, 2005). This represents a sizeable flow, especially for large membrane treatment systems, such as those used by large municipalities (e.g., treating 20 million gallons per day [4 million gallons per day] concentrate flow). This large-volume flow would prevent the use of batch treatment processes, which have higher efficiencies because they can process the water multiple times before discharge.

When the membranes lose their integrity or foul to the point of needed replacement, they will need to be disposed of. It is not anticipated that the materials of construction are high in PFAS unless they are specifically made of PFAS materials (e.g., Nafion). Also, the mass of PFAS remaining on the membrane surfaces should be minimal except in extreme cases.

2.e.iv Regulatory considerations for drinking water treatment utilities

Sites with reject water from high pressure membranes typically have a NPDES permit[7]. To meet NPDES statutory requirements to obtain an NPDES permit prior to discharging any pollutant to waters of the United States, drinking water treatment utilities using membranes must follow all NPDES permit or pretreatment program requirements, including those applicable to PFAS, for any permit or control mechanism issued for their facility. For more information, see EPA 2022d.

2.f Landfill leachate containing PFAS

Landfill leachate (discussed in more detail in Section 3.b.iii.5) is the liquid formed by rainwater percolating through waste in landfills. Leachate generation may continue even after a landfill's closure period, as a result of liquids inherent in the waste or if the cap system fails. There are different types of solid waste landfills characterized by the wastes managed, which also dictate the environmental controls employed. Hazardous waste landfills and most MSW landfills are required to collect the liquid leachate captured within the landfill liner and subsequently manage or treat the leachate. While PFAS concentrations in different landfill leachates have been documented (see Table 3-3 in Section 3.b), there are no monitoring or reporting requirements at the federal level for PFAS in landfill waste or leachate. Thus, existing treatment methods are being used to process leachate irrespective of PFAS concentrations.

Landfill leachate can be treated on site or off site. The most prevalent off-site management approach is to export leachate to a TWTDS, where it is mixed with wastewater and treated. However, as noted in Section 2.a.ii, conventional wastewater treatment technologies are generally unable to treat or control PFAS (Schultz et al., 2006). Other off-site treatment methods include incineration and underground injection (see Sections 3.a and 3.c, respectively). The on-site leachate treatment technologies employed at landfills are explored in Table 3-2 in Section 3.b.i. Some management approaches and treatment technologies represent significant pathways for PFAS release. Unlined impoundments, release to constructed wetlands, and land applications can release PFAS and potentially contaminate groundwater. Additional research is needed to determine the efficacy of landfill leachate treatments for PFAS (see Section 5).

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[7] The Clean Water Act prohibits anybody from discharging "pollutants from a point source" to a "Water of the United States" unless they have an NPDES permit. See 40 CFR Section 122.1(b)(1). The terms "pollutant," "point source," and "Waters of the United States" are defined at 40 CFR Section 122.2.

2.g Summary

PFAS are synthetic chemicals that are used in a diverse array of industrial and commercial applications. Industrial waste streams containing PFAS stem from two main sources: (1) primary manufacturing facilities of PFAS chemistry and (2) secondary industries that use PFAS-containing products and/or manufacture finished products containing PFAS. Ultimately, PFAS end up in solid, liquid, or gas waste streams from industrial facilities that manufacture or use PFAS and PFAS-containing products. Other common PFAS-containing waste streams include AFFF, biosolids, textiles, spent water treatment materials, and landfill leachate. Any of these waste streams can contribute to PFAS entering environmental media, including soil and groundwater. The potential destruction, disposal, and treatment technologies for processing these streams are discussed in Section 3.

2.h References

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3. Technologies for the Destruction and Disposal of PFAS and PFAS-Containing Materials

EPA has identified three existing and potentially available destruction and disposal technologies that may be effective for managing PFAS and PFAS-containing materials. These technologies are thermal treatment (Section 3.a), landfilling (Section 3.b), and underground injection (Section 3.c). Each subsection describes various considerations for these technological solutions, including types of treatment, potential for releasing PFAS into the environment, and uncertainties. References appear at the end of each subsection. See Section 6 for a discussion of emerging technologies that show potential to destroy PFAS. See Appendix D for a summary of costs and considerations.

3.a Thermal treatment

As the industrial and commercial use of fluorinated organic compounds grew over the past 70 years, their presence, compositions, and concentrations in materials that need to be destroyed or disposed of also grew. Organic fluorine-containing materials including flame suppressants, refrigerants, long- and short-chain PFAS, fluoropolymers, and their precursor chemicals have been commonly treated using a variety of thermal treatment technologies. These range from permitted HWCs and industrial furnaces to MWCs, SSIs, and thermal oxidizers designed to treat material and process gas emissions. Compared to landfills and underground injection, thermal treatment offers the potential advantage of mineralizing PFAS and preventing further release into the environment.

The carbon–fluorine bond is much stronger than the carbon–chlorine bond. Breaking the carbon–fluorine bond requires 1.5 times more energy and therefore higher temperatures and reaction times. Based on calculated bond energies, the most difficult fluorinated organic compound to decompose is carbon tetrafluoride (CF_4), which requires temperatures over 1,400°C (2,550°F) (Tsang et al., 1998). This is due to the compound's four carbon–fluorine bonds and symmetrical structure. The presence of carbon–carbon or carbon–hydrogen bonds (as in hexafluoroethane [C_2F_6] or fluoroform [CHF_3]) provides a weak point in the structure and thus significantly lowers temperatures needed for decomposition. Due to their thermal stabilities, short-chain fluorinated carbons such as CF_4, CHF_3, C_2F_6, and octafluoropropane (C_3F_8) may be good indicators of broader PFAS defluorination. In addition, these compounds may be relatively easy to monitor by Fourier transform infrared spectrometry (FTIR) and are targets measured in whole gas samples by Other Test Method 50 (OTM-50)[8], which makes them potential low-risk candidate surrogates for thermal destructibility trials.

Further, fluorinated organic compounds can be destroyed in flames by free radical initiation, propagation, and branching mechanisms. To increase the efficiency of these processes, it is important to provide high concentrations of hydrogen radicals (as in flames) to promote hydrogen fluoride (HF) formation, reducing the strong flame inhibition effects of fluorine radicals. There is concern that carbon–carbon bonds can be broken at moderate temperatures, leaving carbon–fluorine fragments. The fate of these carbon–fluorine radicals will depend on the local temperatures and concentrations of

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[8] EPA recently released the OTM-50 methodology *https://www.epa.gov/emc/emc-other-test-methods*.

other free radicals. If the local energies and free radical concentrations are low, these carbon–fluorine fragments may recombine to form fluorinated PICs. However, if the local temperatures and concentrations of free radicals (particularly hydrogen radicals) are high, as occurs in flames, the carbon–fluorine species is more likely to degrade further to CO_2 and HF.

The stability of perfluorinated radicals and their propensity to recombine present the potential for the creation of PFAS PICs distinctive from the original fluorinated compounds. These reactions are promoted by partial combustion caused by insufficient temperatures, time, and turbulence. Many PFAS are composed of very stable fluorinated carbon chains and relatively weak non-fluorinated functional groups. Often, the functional group is easily removed, allowing the fluorinated chain to react with other radicals and create a variety of compounds, which complicates the determination of destruction and removal efficiencies (DREs) and the identification of PICs (Wang et al., 2015). In addition, the presence of catalytic surfaces, often metals, may promote further reaction and PIC formation in post-combustion regions. PFAS PICs may be smaller in molecular weight than the original species or larger in molecular weight when formed via the recombination of two large radicals.

Thermal treatment units generally use high-temperature combustion and incineration to destroy organic materials and control organic pollutants. Incineration is an effective and permitted method for destroying certain halogenated organic chemicals including chlorinated solvents, polychlorinated biphenyls (PCBs), dioxin-laden wastes, brominated flame retardants, refrigerants, and ozone-depleting substances.

Combustion is described by complex sets of physical processes and elementary reactions involving many intermediate and free radical species. Even combustion of a simple fuel, such as methane, involves several hundred elementary reactions. For more complex fuels, or systems that include additional elements, such as fluorine, elementary reactions can number in the thousands or more. These elementary reactions describe pathways or mechanisms whereby large molecules, such as PFAS, decompose and transform during combustion.

Thermal treatment of halogenated organic compounds generates the corresponding halogen acid when sufficiently high temperatures and long residence times break the carbon–halogen bonds and the resulting halogen atoms react with available hydrogen. Thermodynamically, for a reacting system containing carbon, hydrogen, fluorine, and oxygen, chemical equilibrium favors the formation of carbon dioxide, water, and hydrogen fluoride. Unfortunately, complete decomposition is almost impossible to achieve due to kinetic (temperature) and transport (mixing) limitations. If temperatures are insufficient or mixing is incomplete at any point, complete conversion to hydrogen fluoride and carbon dioxide may not be achieved. This incomplete decomposition is the genesis of many pollutants from hydrocarbon fuels PICs. Certain thermal technologies can potentially achieve the operating conditions necessary to break down fluorinated organic compounds, but not every unit typically operates at these conditions. Data are lacking about the effectiveness of the characteristic operating conditions of the different thermal destruction technologies currently used to treat PFAS materials. Also, more measurement methods are needed to evaluate technology performance for both the destruction of specific chemical species and the formation of byproducts. As a result, EPA does not know if/which thermal treatment technologies are fully able to achieve adequate PFAS destruction and minimization of PFAS PICs.

Hazardous waste combustion technologies (commercial incinerators, cement kilns, and LWAKs) can potentially achieve temperatures and residence times sufficient to break apart the PFAS contained in the waste stream being thermally treated, but not every unit currently operates at those conditions and those that do may not operate at those conditions at all times. To assess the capability of HWCs to destroy the materials fed into them and ensure that harmful emissions into the environment are minimized, it is standard practice to evaluate the DRE of one or several principal organic hazardous constituents (POHCs) during a trial burn. POHCs are selected to be at least as difficult to destroy as the feed material, based on an incinerability index scale of how difficult a compound is to destroy. The existing index does not include PFAS compounds. Permitted hazardous waste facilities have stringent regulatory controls on temperatures and other important operating parameters and require greater than 99.99 percent DRE for each selected POHC. Data from pilot-scale experiments conducted by EPA researchers indicate that "several operating conditions above 1090 °C resulted in high destruction efficiency (DE)[9] and few detectable fluorinated PIC emissions. However, several conditions below 1,000 °C produced DEs greater than 99.99 percent for the quantifiable PFAS and mg/m^3 emission concentrations of several nonpolar PFAS PICs. These results suggest that DE alone may not be the best indication of total PFAS destruction, and additional PIC characterization may be warranted" (Shields et al., 2023).

For HWCs, DRE is calculated based on the amount of a specific chemical entering an incinerator and the amount of that same chemical exiting the incinerator. While the compound selected for DRE determination in an HWC is chosen based on the difficulty of destroying it, DRE does not account for chemical reactions or transformations into new/different organic compounds (i.e., PICs). Because DRE does not account for chemical transformations, it is not an accurate indicator, by itself, of complete PFAS destruction. Recent research (Shields et al., 2023) has demonstrated that PIC formation can occur even when high DRE is measured at temperatures below 1,000 C. It is not accurate to state that a high DRE by itself indicates complete destruction of PFAS and that no other PFAS are being emitted. Complete PFAS destruction, also referred to as "complete mineralization," results in the production of only HF and CO_2 and does not include the production of other PFAS or other fluorinated organic compounds. The term "adequate destruction" is used in this guidance because it is not feasible to measure complete mineralization due to methodological limitations.

To fully evaluate whether adequate destruction is occurring, EPA and other investigators need to sample and analyze for a range of chemicals exiting a thermal treatment device, including the specific PFAS in the feed material, other PFAS beyond those in the feed (i.e., potential PICs), and HF. EPA currently lacks test methods for measuring most PFAS before and after the incineration process, but new methods are being advanced that will provide more information in the coming years. Currently, standard methods are available for HF (e.g., EPA Method 26A) and a targeted list of semivolatile PFAS (i.e., Other Test Method 45 [OTM-45]), and other test methods are in development for a relatively small percentage of PFAS as surrogates for the class of PFAS compounds (see Section 3.a.iv).

For this second version of the interim guidance, PFAS destruction is defined as the severing of all carbon–fluorine bonds in a PFAS molecule and the mineralization of carbon and fluorine to CO_2, HF, and water. HF and some of the other products of combustion can be effectively removed in pollution control devices designed for acid gas removal. The PFAS Thermal Treatment Database (PFASTT) is a growing database that contains more than 2,000 records of 80 sources documenting the treatability of PFAS in different media via various thermal processes.

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[9] Destruction efficiency differs from destruction removal efficiency because samples were collected before any pollution control devices.

EPA currently has limited data characterizing emissions from HWCs that burn PFAS (Focus Environmental, 2021, 2022), along with data from a pilot-scale study at an EPA research facility (Shields et al., 2023). These studies are summarized below and provide some insight on the potential efficacy of thermal treatment in an HWC. To date, the commercial facility studies have focused on the removal of easily transformed PFAS target compounds, which is a significant limitation.

Clean Harbors Environmental Services. Two testing campaigns (2021 and 2022) were conducted at Clean Harbors Environmental Services' hazardous waste incinerator located in Aragonite, Utah (EA Engineering, Science, and Technology, Inc., PBC., 2021, 2022). Each test campaign was divided into three test conditions: Baseline (Condition 1), Augmented PFAS Feed (Condition 2, where known amounts of four or five target PFAS were fed to the incinerator), and Post-spiking Normal Operations (Condition 3, where AFFF was included in the incinerator feed). Clean Harbors used OTM-45 (*Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources*) for stack gas sampling and analysis. The 49 targeted PFAS analytes were measured using liquid chromatography/tandem mass spectrometry (LC/MS/MS) with isotope dilution. Utilizing the available analytical methods at the time, the Clean Harbors study demonstrated a DRE for the legacy PFAS in the 99.9999 percent range at high temperatures. Of the 49 compounds detected by OTM-45, 34 were non-detect in the stack gas and only 15 were detectable at extremely low concentrations. The tests appear to demonstrate that the facility's primary objective was met: "demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed during normal process operating conditions." Although a high DRE was achieved (greater than 99.999 percent) for the five selected PFAS compounds that were subjects of these studies, these tests did not collect data to fully support demonstration of adequate destruction as the production of PICs were not evaluated due to methodology limitations.

EPA PFAS thermal destruction research. Recently, EPA's Office of Research and Development (ORD) completed an initial study examining the relationship between destruction efficiency (DE) and PICs (Shields et al., 2023). This study used a pilot-scale research furnace and atomized a PFOS-dominant AFFF at various furnace locations and combustion environments. These included atomization through the flame with the natural gas auxiliary fuel and at various post-flame locations so that the AFFF would experience decreasing peak temperature exposures ranging from ~1,200°C to ~800°C (2,192°F to 1,472°F). Stack measurements included OTM-45 and a new draft GC/MS-based Other Test Method for non-polar volatile PFAS (OTM-50). Instead of DREs, this study calculated DEs, because samples were collected before any pollution control, i.e., removal equipment, including fabric filter and alkaline wet scrubber. Analysis of the AFFF and OTM-45 samples was used to calculate DEs for 10 PFAS quantified in the AFFF. OTM-50 was used to quantify concentrations of 30 PFAS PICs. Results indicate that several idealized operating conditions with peak temperatures above 1,090°C (1,976°F) resulted in high DEs (greater than 99.99 percent) and low PIC emissions that were near or below the detection limits. However, several conditions below 1,000°C (1,832°F) produced DEs greater than 99.99 percent for the quantifiable PFAS while simultaneously measuring emission concentrations of several volatile PFAS (mg/m^3). The study concluded that DE alone may not be the best indication of PFAS destruction.

Additional studies are necessary to more fully measure and evaluate the ability to approach complete mineralization and eliminate potential formation of PICs. EPA is working to advance new measurement methodologies (see Section 3.a.iv.1) and gather additional information to conclude whether potential PICs are adequately controlled (see Appendix A).

This section focuses on considerations associated with thermal treatment of PFAS and PFAS-containing materials. It discusses:

- The types of thermal treatment units that manage PFAS-containing materials and their ability to effectively destroy PFAS.
- The potential for environmental releases during these thermal treatment operations.
- PFAS monitoring methods relevant to these thermal treatment operations.
- Uncertainties and unknowns associated with thermally treating PFAS-containing materials, including the ability to effectively measure and monitor thermal treatment performance.

3.a.i Types of thermal treatment

The following subsections describe the types of thermal treatment devices that may have directly or indirectly received and treated the PFAS-containing materials identified in Section 2.a. These subsections focus on design and operation parameters that are important for destroying PFAS. Treatment devices described here include HWCs, non-hazardous waste combustors, carbon regeneration and reactivation units, and thermal oxidizers. Waste incinerators are typically classified by the type of waste they combust. Suggested resources for locating such facilities are included in Section 1.c.ii.

3.a.i.1 Hazardous waste combustors

HWCs include hazardous waste incinerators (HWIs), cement kilns, LWAKs, boilers, and hydrochloric acid production furnaces that burn hazardous waste. Two types of HWCs that have treated PFAS waste in the United States are commercial[10] incinerators and LWAKs.

All HWIs, LWAKs, and cement kilns are subject to RCRA and Clean Air Act (CAA) permitting requirements[11,12] that provide additional regulatory oversight and include operating requirements and emission limitations to safely and effectively treat regulated hazardous contaminants that may not be required for non-permitted facilities. These types of HWCs are subject to CAA Title V permitting requirements, and to maximum achievable control technology standards pursuant to Section 112 of the CAA (40 CFR part 63, subpart EEE). These standards include emission limitations for metals, dioxins/furans, particulate matter, hydrogen chloride and chlorine gas, and carbon monoxide or hydrocarbons, as well as limits on minimum organic DRE, but do not include emission limitations for PFAS. Also, under the authority of RCRA's "omnibus" clause (Section 3005(c)(3); see 40 CFR 270.32(b)(2)), RCRA permit writers may impose additional terms and conditions on a site-specific basis as may be necessary to protect human health and the environment. Due to these additional safeguards, permitted HWCs may operate under conditions more conducive to destroying PFAS and controlling related PICs relative to thermal treatment units that do not have both RCRA and CAA permits. Further, incinerators permitted to incinerate liquid PCBs are required to meet even more stringent operating requirements with respect to time and temperature (40 CFR 761.70(a)(1)) when incinerating PCBs, and these operating conditions may be even more conducive to destroying PFAS and controlling PIC

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[10] Commercial thermal treatment units primarily treat waste received from other facilities.

[11] Hazardous waste is regulated pursuant to RCRA authority. See 42 U.S.C. 6903. The regulatory definition is found in 40 CFR 261.3. PFAS is currently not a listed or characteristic hazardous waste, but a PFAS-containing waste may meet the regulatory definition of hazardous waste if PFAS is mixed with a listed hazardous waste or if a PFAS-containing mixture exhibits a hazardous characteristic (e.g., corrosivity or another characteristic stemming from the material that is mixed with PFAS) Waste managers must comply with RCRA hazardous waste requirement for the specific regulated hazardous waste, including storage limits, land disposal restrictions, and utilizing disposal and destruction facilities that are permitted to receive hazardous wastes.

[12] Hazardous-waste-burning cement kilns and LWAKs are a small subset of the total cement kiln and LWAK universe—i.e., most kilns do not burn hazardous waste.

formation. The following sections generally describe design and operational parameters of commercial HWIs, LWAKs, and cement kilns, focusing on parameters that are important for destroying PFAS. Design and operation information summarized for HWCs is generally based on background support documents for previous rulemakings (U.S. EPA, 2005b). Information on the numbers of HWC facilities is based on a 2019 national hazardous waste capacity assessment report (U.S. EPA, 2019). The capacity assessment report also provides a list of these facilities.

3.a.i.1.1 Commercial hazardous waste incinerators

Currently, there are 10 commercial HWI facilities operating in the United States. HWIs are designed to optimize temperatures, residence times, turbulence, and other parameters to ensure compliance with organic DRE requirements.[13] Three of these facilities are also permitted for incineration of PCBs. Most commercial HWIs use rotary kilns as primary combustion chambers to facilitate the thermal treatment of containerized wastes (e.g., in drums) and solid wastes such as contaminated soils. Low-heating-value aqueous wastes may also be pumped into the rotary kiln. The kiln maintains a continuous standing flame fueled by high-heating-value wastes and auxiliary fuels that maintain high temperatures. Typically, solids retention time in the kiln is 0.5 to 1.5 hours, while gas residence time through the kiln is usually around two seconds. Kiln flame/solids temperatures range from 650°C to 1,650°C (1,200°F to 3,000°F) (U.S. EPA, 2005b).

After combustion in the rotary kiln, wastes may be moved to an afterburner or secondary chamber. If an afterburner is used, additional high-heating-value gaseous and liquid wastes and auxiliary fuels may be added. The afterburner/secondary chamber is typically operated at about 1,100°C to 1,370°C (2,000°F to 2,500°F) with a gas residence time from one to three seconds to maximize organic destruction and minimize the formation of PICs (U.S. EPA, 2005b). Depending on the fuels used and waste streams introduced, combustion products might include carbon dioxide, water, nitric oxide, a variety of acid gases (sulfur dioxide, hydrochloric acid, HF, etc.), organic PICs, fly ash, and bottom ash constituents. Bottom ash is removed at the end of the kiln and from the bottom of the afterburner/secondary chamber and is typically disposed of in hazardous waste landfills (see Section 3.b). Fly ash entrained in the gas is removed downstream by fabric filters (FFs) or electrostatic precipitators, and acid gases are removed by gas scrubbers. Some HWIs use activated carbon injection systems to control mercury, dioxin/furan, and other emissions, and some also use TMT-15 (1,3,5-triazine-2,4,6(1H,3H,5H)-trithione, trisodium salt) injection for additional mercury and metals emissions control.

Limited studies of PFAS treatment in HWIs have been conducted (EA Engineering, Science, and Technology, Inc., PBC., 2021, 2022). These studies demonstrated treatment of five selected PFAS compounds in the feed material. However, these test data are not able to demonstrate adequate destruction of PFAS (Taylor, 2022) due to the lack of data concerning PIC formation.

3.a.i.1.2 Hazardous-waste-burning cement kilns

Currently, there are 11 hazardous-waste-burning cement kiln facilities in the United States. A cement kiln is a long, cylindrical, slightly inclined rotating furnace designed to calcine a blend of raw materials such as limestone, shale, clay, or sand to produce a key ingredient of Portland cement. These cement kilns burn hazardous-waste-derived fuels to replace some of the fossil fuels. Most burn liquid waste; some may also burn solids and small containers containing viscous or solid hazardous waste fuels.

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[13] DRE = $[1 - (W_{out} / W_{in})] \times 100\%$, where: W_{in} = mass feed rate of an organic compound into the combustion device and W_{out} = mass emission rate of the same organic compound in exhaust emissions. HWCs are required to achieve at least 99.99% DRE.

Extreme combustion conditions (e.g., temperatures above 1,650°C [3,000°F]), turbulent mixing, and long gas phase residence time (from four to as high as 16 seconds in long kilns) may effectively treat hazardous waste. Cement kilns use either electrostatic precipitators or baghouses to collect particulate and metal emissions, referred to as cement kiln dust (CKD). Portions of the CKD can be fed back into the kiln as a raw material feed or used in other industries as neutralizers or additives, but usually the excess CKD is land-disposed. Add-on acid gas air pollution control devices, such as wet or dry scrubbers, are typically not used. The high alkaline content of the raw material feeds already prevents or minimizes the formation and release of acid gases by providing for in situ absorption of chlorine and other halogens and sulfur.

Several laboratory studies have examined the potential benefit of treating PFAS wastes in cement kilns where the calcium in the raw limestone can react with fluorine to form calcium fluoride (CaF_2). These studies indicate that calcium species react readily with PFAS at relatively low temperatures (400-800°C) to promote mineralization of PFAS waste (Wang et al., 2011, 2013, 2015; Reidel et al., 2021). However, the currently available lab-scale data are insufficient to determine with confidence the effectiveness of treating PFAS waste in commercial cement kiln operations.

3.a.i.1.3 Hazardous-waste-burning lightweight aggregate kilns

There is one LWAK facility operating in the United States that burns hazardous waste. LWAKs thermally process raw material (clay, shale, and slate) in slightly inclined, rotating furnaces to produce a coarse aggregate used in lightweight concrete products. In hazardous-waste-burning LWAKs, liquid wastes are either blended directly with conventional fuels burned in the hot end of the kiln or pumped separately into the hot end flame. High combustion gas flame temperatures (above 1,650°C [3,000°F]) and high kiln gas residence times (over two seconds) are used to destroy hazardous organics. Kiln exhaust gases leave the cold upper end of the kiln at a temperature from 205°C to 540°C (400°F to 1,000°F). LWAKs use FFs to control dust contained in the exhaust gas. The collected dust can be recycled back into the kiln (at the hot or cold end) or mixed into the lightweight aggregate product. Some LWAKs also use wet or dry scrubbing for acid gas emissions control. For example, the currently permitted hazardous-waste-burning LWAK has dry scrubbing for acid gas control. There are insufficient data to determine the effectiveness of commercial LWAK facilities in treating PFAS waste.

3.a.i.2 Carbon regeneration and reactivation units

Carbon reactivation units or "furnaces" use high temperatures to thermally desorb contaminants from GAC, which allows for the carbon to be used again. Over a dozen large-scale companies and utilities in the United States reactivate sizeable quantities of GAC. In all, these entities operate about 17 commercial furnaces (Roskill Information Services Ltd., 2017). Four of these commercial furnaces operate under RCRA permits and applicable air permits. RCRA permits provide additional regulatory oversight and include operating requirements and emission limitations to promote safe and effective treatment of the hazardous contaminants; non-RCRA-permitted carbon reactivation furnaces may not be subject to such requirements. Due to these additional safeguards, RCRA-permitted furnaces may operate under conditions more conducive to destroying PFAS and controlling related PICs, relative to furnaces without RCRA permits. This discussion focuses on RCRA-permitted furnaces because EPA has more design and operational information on these devices as a result of the RCRA permitting process.

Reactivation[14] of spent carbon is generally carried out in multiple-hearth ("multi-hearth") or rotary kiln furnaces, although fluidized bed and infrared furnaces are also options. While the furnace designs vary, they all use high temperatures and residence times designed to eliminate the adsorbed contaminants and return the carbon to a virgin state for reuse.

During reactivation, spent GAC is typically exposed to drying, desorption, pyrolysis, and oxidation as it moves through the furnace. The drying stage eliminates moisture via evaporation and occurs when hot combustion gases at temperatures ranging from 100°C to 110°C (212°F to 230°F) contact the carbon. During the desorption stage, hydrocarbons, hydrogen, and water vapor escape the pores of the granular carbon at temperatures of 315°C to 400°C (600°F to 750°F). The pyrolysis stage eliminates any volatile compounds adsorbed within the carbon porosity, including residual moisture, and thermally decomposes other less-volatile compounds. Pyrolysis occurs when the carbon is exposed to temperatures up to 800°C (1,472°F) under inert conditions (i.e., low oxygen). A residue of carbonized char is formed from the adsorbed compounds during pyrolysis, which occupies some of the carbon porosity and must be removed in the next stage. The oxidative stage involves the controlled gasification of the pyrolyzed carbon at temperatures of around 800°C (1,472°F) in the presence of a mildly oxidizing atmosphere, usually steam or carbon dioxide or a mixture of both. This results in the elimination of most of the charred residue and exposes the original carbon-pore structure (Miguel et al., 2001).

The residence times required for carbon reactivation vary by unit design and the contaminant loads and concentrations. For example, two facilities using multi-hearth furnaces have residence times of at least 38 minutes at one facility and between 90 and 120 minutes at the second facility (Kentucky Energy and Environment Cabinet, 2019; U.S. EPA, 2018).[15]

To ensure adequate destruction and removal of any remaining contaminants, reactivation furnaces are typically equipped with afterburners/thermal oxidizers. To meet regulatory requirements, afterburners are designed to achieve 99.99 percent DRE via thermal oxidation. DRE for a reactivation/regeneration furnace is evaluated on a "total hydrocarbon" basis rather than for a specific most-difficult-to-destroy component, as is done for HWCs. This adds additional uncertainty to the question of whether a thermal treatment unit can effectively destroy PFAS. The temperature required to achieve 99.99 percent DRE depends on residence time as well as on the concentration of contaminants, but minimum temperatures are around 885°C (1,625°F) and maximum temperatures are as high as 1,316°C (2,400°F), with a minimum residence above one second (U.S. EPA, 2018).

Depending on the process or waste streams treated, a reactivation furnace can be equipped with add-on air pollution control equipment to ensure environmental standards are met. Equipment can include venturi scrubbers for particulate matter control, packed-bed scrubbers for acid gas and particulate matter control, and wet electrostatic precipitators or baghouses for additional particulate matter control. As discussed in Section 3.a.ii, carbon reactivation systems can degrade PFAS even at the lower temperatures (150°C–700°C, or 302°F–1,292°F).

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[14] "Reactivation" refers to a regeneration process that requires high temperatures. Regeneration also includes low-temperature processes, such as those using brines, solvents, oxidants, biological treatment, etc. These processes may not be as effective as reactivation for GAC (AWWA, 2018); therefore, they are not considered for this discussion.

[15] These two references are RCRA permits for Evoqua Water Technologies LLC and Calgon Carbon Corporation, two companies that accept spent activated carbon from off-site sources. They each hold RCRA permits, which allow them to treat spent carbon that meets the definition of hazardous waste.

3.a.i.3 Non-hazardous-waste combustion sources

Non-hazardous-waste incineration units in the United States includes SSIs at wastewater treatment facilities and MWCs. Under Section 129 of the CAA, these units are regulated for emissions of particulate matter, carbon monoxide, dioxins/furans, sulfur dioxide, nitrogen oxides, hydrogen chloride, lead, mercury, and cadmium. Because of this, the air pollution control devices employed by these units are intended to control these nine pollutants primarily. The following sections generally describe these incinerator types and their design and operational parameters that may influence the treatment of PFAS-containing waste (U.S. EPA, 1995).

3.a.i.3.1 Sewage sludge incinerators

An SSI unit is a combustion device that is used to burn dewatered sewage sludge. There are currently 170 SSI units operating at 86 facilities in the United States (U.S. EPA, 2016). The main types of SSIs are multi-hearth furnaces and fluidized bed combustors (FBCs).

The basic multi-hearth furnace is a vertical cylinder divided into zones. The sludge is dried at temperatures from 425°C to 760°C (800°F to 1,400°F) (U.S. EPA, 1995). Sludge combustion occurs as the temperature is increased to about 925°C (1,700°F) in successive zones. The gas residence times are typically four or five seconds. Emission controls on multiple hearths can include wet scrubbers, wet electrostatic precipitators, afterburners, and regenerative thermal oxidizers.

An FBC consists of a vertically oriented outer steel shell with nozzles designed to deliver fluidizing air at the base of the furnace within a refractory-lined grid. Air is injected into the furnace to fluidize the sludge and the sand. The combustion of the sludge occurs at temperatures from 750°C to 925°C (1,400°F to 1,700°F). The gas residence times are typically two to five seconds. Emission controls on FBCs can include venturi scrubbers, multicyclones, FFs, activated carbon injection, and carbon bed absorbers. There is substantial variation in the design and operation of SSIs and it has not been shown that standard operating conditions are effective for the treatment of PFAS. The data currently available are insufficient to make a determination about the effectiveness of SSIs in treating PFAS.

3.a.i.3.2 Municipal waste combustors

There are 193 MWC units operating at 75 facilities in the United States (Michaels & Krishnan, 2018). Three main classes of technologies are used to combust MSW: mass burn, refuse-derived fuel (RDF), and modular combustors. Mass burn and RDF combustors are the predominant designs.

With mass burn units, the MSW is combusted without any preprocessing other than removal of items too large to go through the feed system or hazardous materials, such as pressurized containers. In a typical mass burn combustor, refuse is placed on a grate that moves the waste through the combustor. The grates typically have three sections. On the initial grate section, referred to as the drying grate, the moisture content of the waste is reduced before ignition. Evaporated moisture is combined with the moisture from combustion and treated with the resulting combustion gases. The second grate section, referred to as the burning grate, is where most of the active burning takes place. The third grate section, referred to as the burnout or finishing grate, is where remaining combustibles in the waste are burned. Typical combustion temperatures for mass burn units can range from 800°C to 1,100°C (1,500°F to 2,012°F) (Reddy, 2016).

RDF combustors burn waste that has been processed to varying degrees to raise its heating value and provide a more uniform fuel. Most boilers designed to burn RDF use spreader stokers and typically operate at around 680°C (1,250°F). RDF-fired FBCs typically operate at bed temperatures of around 815°C (1,500°F) (Reddy, 2016).

Residence times of gases within MSW combustors vary from unit to unit, depending on design and operational factors such as furnace volume, excess combustion air percentage, whether flue gas recirculation is employed, and combustor operating load parameters (Scavuzzo, 1990; Themelis & Reshadi, 2009). Overall combustion air residence times have been calculated in the 7- to 10-second range for a small sampling of MWC design loads (Themelis & Reshadi, 2009). At temperatures above 980°C (1,800°F), the approximate residence time is about two seconds for full combustor loads (Scavuzzo, 1990).

Emission controls on MWCs can include spray dryer or dry sorbent injection, electrostatic precipitators, FFs, selective or non-selective catalytic reduction, and activated carbon injection.

There is substantial variation in the design and operation of MSW combustors. The data currently available are insufficient to make a determination about the effectiveness of MSW combustors to treat PFAS.

3.a.i.4 Thermal oxidizers

Thermal oxidizers are used to treat process gases and destroy volatile organic compounds (VOCs) and organic hazardous air pollutants (HAPs) at a manufacturing or production facility. Some types of thermal oxidizers are also able to accept liquid feed streams. Each thermal oxidizer is designed to optimize temperatures, residence times, and turbulence to address the composition of the particular feed stream at that unit and meet the requirements of a regulation or permit. Depending on the type of thermal oxidizer (direct-fired, regenerative, recuperative, or flameless), the operating temperature ranges from 760°C to 1,200°C (1,400°F to 2,190°F). The residence time of thermal oxidizers ranges from 0.5 to two seconds, depending on site-specific criteria. Catalytic thermal oxidizers operate at lower temperatures than other types of thermal oxidizers—typically at about 400°C (750°F) with similar residence times to non-catalytic thermal oxidizers—while achieving the same efficiency in destruction of VOCs.

Emission controls for thermal oxidizers vary widely depending on the facility and the composition of the feed streams. Existing thermal oxidizers may have no additional pollution controls or may use prefiltration (to prevent fouling of the oxidizer) and/or wet or dry scrubbers or FFs. Thermal oxidizers have historically not been designed with destruction of PFAS as the primary focus, so most currently installed thermal and catalytic oxidizers may not be optimized for PFAS destruction. However, some thermal oxidizers are being used for halogenated wastes, including PFAS precursors. The operating conditions for some thermal oxidizers have the potential to effectively treat PFAS, but the data currently available are insufficient to make a determination about effectiveness.

Chemours. Two testing campaigns (2020 and 2022) were conducted on a thermal oxidizer installed to control PFAS emissions at a Chemours chemical and plastics manufacturing plant located in Fayetteville, North Carolina. The objective of the tests was to determine how the thermal oxidizer and 4-stage scrubber system would achieve a 99.99 percent emission reduction, including the use of a surrogate for all PFAS, such as the hexafluoropropylene oxide (HFPO). The test reports demonstrate a PFAS destruction efficiency above the 99.99 percent for the specific compounds that were tested. HFPO was tested as a surrogate for all species of PFAS, but there are no concrete data showing the performance of the thermal oxidation process for PFAS species outside of the compounds tested. There was also no discussion of possible products of incomplete combustion in the reports. The thermal oxidizer at the

Chemours facility appropriately destroys the five PFAS compounds of interest that have been identified at the facility. However, removal processes for products of incomplete combustion or of destruction of potential compounds not studied but potentially found in the facility waste streams are still unclear.

3.a.ii Limitations and considerations in thermal treatments

Incinerator designs vary, resulting in differing operational and waste feed approaches (see Section 3.a.i). HWIs typically operate at very high average temperatures and employ auxiliary, primary, and secondary flames. MWCs typically operate at lower temperatures and often do not employ auxiliary primary or secondary flames. SSIs vary in design, often operating as dryers with very low temperatures. Even within the same incinerator, wastes can be introduced at different locations and can experience different time, temperature, and mixing histories. PFAS introduced into a hazardous waste rotary kiln incinerator's main burner, along with auxiliary fuel, may experience very different conditions than the same waste introduced to the kiln as contained charges with solid wastes. These factors are expected to affect PFAS destruction and PIC formation. Limited studies have investigated the influence of various factors on PFAS destruction and PIC formation (see Section 3.a).

Carbon reactivation systems can degrade PFAS even at the lower temperatures (150°C–700°C, or 302°F–1,292°F) seen in bench-scale research studies (Watanabe et al., 2018). Experimental data suggest that thermal destruction of PFAS occurs in two stages: first during reactivation of the GAC, and then when the off-gas is introduced into a high-temperature zone with temperatures as high as 1,000°C (Forrester, 2018; Watanabe et al., 2016, 2018; Xiao et al., 2020). DiStefano et al., (2022) showed >99.99 percent destruction of PFAS at a full-scale commercial reactivation facility with a large percentage of the PFAS destruction occurring in the furnace. The fluoride mass balance was reported to be 61.4 percent. Although this low percentage could be due to a number of factors, it may be due to the formation of PICs that were not quantitated in the analytical method. While carbon reactivations systems, with the concomitant use of off-gas incineration (i.e., afterburners) and gas scrubbing units, have the potential to remove PFAS from the activated carbon and destroy it, there is insufficient data to make a determination on its effectiveness. However, as discussed elsewhere in this interim guidance, more work is needed for confirmation, particularly with regard to full-scale reactor conditions, differing carbons, and PICs.

Thermal oxidizers have historically not been designed with destruction of PFAS as the primary focus, so most currently installed thermal and catalytic oxidizers may not be optimized for PFAS destruction. However, some thermal oxidizers are being used for halogenated wastes, including PFAS precursors. Thermal oxidizers are being employed to destroy PFAS-containing and gaseous streams, but the data are insufficient to allow conclusions on the overall efficiency of thermal oxidizers in PFAS destruction. For example, the two tests at Chemours Company's Fayetteville Works (Focus Environmental, Inc., 2020, 2022) focused on five specific PFAS of interest found in waste gas streams at the facility. While the tests seem to prove a DRE of 99.999 percent for the five PFAS compounds, they do not present data on overall PFAS destruction or potential formation of PICs. (See Appendices B and C for summaries of the Clean Harbors and Chemours test data.) EPA is currently unaware of any catalytic oxidizers being used specifically for the destruction of PFAS, particularly in light of their site-specific design and optimization. Though the efficacy of thermal and catalytic oxidizers in destroying PFAS is currently unknown, a properly optimized thermal oxidizer can readily achieve a DRE of 99.99 percent for VOCs.

In addition to incinerators and thermal oxidizers, cement kilns are also used for the destruction of hazardous wastes. Cement kilns operate at very high temperatures (exceeding 1,800°C [3,270°F]), exhibit very large gas and solid residence times, and have the added advantage of providing a caustic environment for halogen reaction and acid neutralization. A cement kiln in Australia has received an operating permit from the government of Queensland to burn PFAS wastes. The permit requires annual monitoring for 21 PFAS (Department of Environment and Heritage Protection, 2018). Test results from 2017 indicate that a DRE in excess of 99.99 percent is possible for specific PFAS compounds at the conditions of the test (Cement Australia, 2017), but the results do not present data on overall PFAS destruction or potential formation of PICs.

Processes involving calcium and alumina may have benefits and may require lower energies to destroy PFAS. Recent research (Wang et al., 2011, 2013, 2015) has investigated PFAS interactions with calcium oxide (CaO) and calcium hydroxide ($Ca(OH)_2$) at moderate temperatures (200°C to 900°C, or 390°F to 1,650°F) and found that these calcium species exhibit a pseudo-catalytic effect promoting PFAS destruction and fluorine capture at relatively low temperatures. Similar studies by the electronics industry indicate that alumina catalysts can effectively convert residual CF_4 and related species (generated by plasma arc techniques for etching purposes) to CO_2 and HF at comparable temperatures.

It is not well understood how effective high-temperature combustion is at completely destroying PFAS or whether the process can form fluorinated or mixed halogenated organic byproducts. Few experiments have been conducted under oxidative and temperature conditions representative of different field-scale incineration devices used for PFAS destruction. Limited studies on the thermal destructibility of fluorotelomer-based polymers found no detectable levels of PFOA after two seconds of residence time at 1,000°C (1,830°F) (Yamada et al., 2005; Taylor et al., 2014). Two recent field studies examining the performance of a specially designed thermal oxidizer in destroying PFAS in process gases at a Chemours production facility near Fayetteville, North Carolina, indicated greater than 99.999 percent destruction of five PFAS (Focus Environmental, Inc., 2020, 2022). Similarly, the recent Clean Harbors studies appear to show that the facility was able to achieve its primary objective: "demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed during normal process operating conditions." A high DRE was achieved (> 99.999 percent) for the five selected PFAS compounds that were subjects of these studies (EA Engineering, Science, and Technology, Inc., PBC., 2021, 2022). However, these test data did not include characterization of potential PICs due to previous methodology limitations.

The Chemours and Clean Harbor test results indicate the PFAS compounds measured were changed by the treatment, but the tests did not investigate whether the compounds were changed to carbon dioxide and hydrofluoric acid to show adequate destruction of the original PFAS. As discussed previously, emission studies, particularly for potential PICs, are largely incomplete due to lack of validated sampling and measurement methods for the potentially large number of fluorinated and mixed halogenated organic compounds that might be formed. EPA continues to seek information on PFAS that may be present in air pollution control device media (e.g., scrubber water, particulate matter control device media) and the presumed effectiveness of these air emission controls. (See Section 5 for more information about ongoing research and research needs.)

Incineration may be a viable PFAS destruction technology if done under certain conditions. The preliminary research on thermal treatment of PFAS suggests that the minimum conditions for PFAS destruction include well mixed environments with temperatures greater than 1,100°C and optimized combustion stoichiometry (Shields et al., 2023). These conditions may adequately destroy PFAS and minimize PICs. However, evaluations have only been done on liquid fired materials at a pilot scale. No comparative studies that include PIC measurements on solids or containerized wastes have been performed. Liquids should preferably have direct flame contact or at least well mixed exposure to temperatures greater than 1,100°C.

EPA encourages additional tests be performed to demonstrate the ability of a thermal treatment technologies to mineralize PFAS. EPA encourages testing to demonstrate destruction of parent compounds (OTM-45) and volatile PICs (OTM-50) based on suggested procedures in Appendix A) to show efficient thermal destruction of atmospherically transformative PICs of health and environmental concern.

3.a.ii.1 Other thermal treatment byproducts of concern

Thermal treatment systems including HWIs, MWCs, and SSIs are configured such that gas phase effluent from the combustion chambers passes through a series of pollution control devices to remove acid gases, particulate matter, and sometimes mercury and other specific HAPs. The behavior of PFAS and PFAS-related PICs in these unit operations is largely unknown (see Section 5 for more information about research on this topic and others). Additionally, these control devices produce secondary waste streams in the form of fly ash and scrubber blowdown solutions, and PFAS and PFAS-related PICs may be present in these solid and liquid effluents depending on their vapor pressure and solubility.

Thermal oxidation processes used for treating PFAS-containing waste, such as incineration, generate HF as the most stable product from combustion of fluorocarbon compounds. HF is a CAA-listed HAP. Highly corrosive, HF creates significant operation and maintenance issues by damaging thermal system materials such as furnace refractory and metal ductwork. Both wet scrubbing and semi-dry scrubbing processes have been applied to control HF emissions from thermal treatment sources.

A thermal oxidizer with a potential for HF emissions typically uses a wet scrubber integrated with the oxidizer to control HF emissions. Hot flue gas exiting the oxidizer is cooled rapidly in a quenching unit, and HF (which has high water solubility) is removed by the quenching water. The cooled flue gas then flows up through a multistep wet scrubbing tower for further HF removal by scrubbing water. Flue gas is scrubbed by a sodium hydroxide solution to neutralize the residual HF as the final scrubbing step. After exiting the tower, flue gas is emitted through a stack. All effluents, including those from the quenching unit and scrubber tower, are mixed with a $Ca(OH)_2$ solution in a reactor where calcium is combined with fluorine and precipitation of water-insoluble calcium fluoride (CaF_2) occurs. After dewatering, dry CaF_2 is sent to a landfill for disposal (see Section 3.b) or used to produce fluorine gas for new PFAS production, and wastewater is discharged from the plant after it is treated by activated carbon to remove trace fluorinated contaminants. Rapid cooling of hot flue gas is known to be effective in reducing catalytic reformation of chlorinated PICs such as dioxins during cooling of incineration flue gas.

A thermal oxidizer equipped with a quenching unit to treat PFAS-containing wastes may also limit catalytic reformation of fluorinated PICs if they are actually formed in the oxidizer. Those PICs may be subsequently transferred into the liquid phase in the wet scrubber. Those PICs could then be partitioned between solid CaF_2 and water in the precipitator, and most of the PICs retained in water are then removed by activated carbon adsorption. EPA is not aware of peer-reviewed studies that measure levels of fluorinated contaminants remaining in both the treated scrubber water stream and the dry CaF_2 stream. Such measurements could be useful for evaluating the potential environmental impacts of byproducts and residuals generated from thermal oxidation of PFAS-containing wastes.

Spray dryer absorber (SDA) technology has been applied to control emissions of halogen acids (including HCl and HF) from both MWCs and HWIs. This semi-dry scrubbing process is designed to inject an alkaline slurry, typically lime, to control acid and fly ash. Water in the fine slurry droplets is vaporized by heat carried by the flue gas, and the lime carried in the droplets neutralizes the halogen acids simultaneously in this two-phase reaction process. The cooled flue gas carries the dried acid neutralization product downstream to a particle collection device, typically an FF. PAC may also be injected into flue gas upstream of the FF to control emissions of mercury and chlorinated dioxins/furans from both MWCs and HWIs. Fly ash, dried acid neutralization product, and PAC are captured by the FF. The SDA/FF with PAC injection flue gas cleaning train produces no scrubber water. The addition of lime (a calcium compound) into the flue gas is known to be effective for forming CaF_2 through hydro-defluorination of PFOS at a moderate temperature of about 350°C (660°F) (Wang et al., 2015); this suggests that the SDA may provide a potential co-benefit of controlling fluorinated PICs. The injection of PAC upstream of the FF may create another potential co-benefit for capturing fluorinated PICs. Studies evaluating PFAS mitigation via SDA/FF with PAC injection (e.g., see research activities in Section 5) will help develop data on this potentially viable technology option.

3.a.iii Potential for releases for thermal treatment technologies

Thermal treatment devices that may be used to treat PFAS-containing waste (see Section 3.a.i for descriptions of these devices) are located in both rural and more densely populated areas throughout the United States. Two possible sources of PFAS emissions from thermal treatment are stack emissions and the management of scrubber water and bottom ash/fly ash. As previously discussed, emissions from thermal treatment activities may contain PFAS if adequate combustion conditions are not achieved or if adequate acid gas scrubbers or other pollution control devices are not used. EPA is aware of a limited number of peer-reviewed studies that have investigated the extent to which emitted PFAS are transported and deposited to surrounding areas (see Section 2.a.iii). EPA plans to conduct research in this area to better characterize the extent to which PFAS deposition may occur near thermal treatment devices (see Section 5 for more information about these types of research activities).

Volatile PFAS releases from thermal treatment equipment (e.g., fugitive emissions) and waste storage activities are another potential source of PFAS releases, if they are not adequately controlled.[16] There is also the potential for releases from management of thermal treatment process residuals, such as air pollution control device media, incinerator bottom ash, and liquids from acid gas scrubbers. For example, incinerator bottom ash disposed of in a landfill would be a possible source of release if the ash contained PFAS and the landfill lacked adequate controls (see Section 3.b for more information on landfill types and controls, and Section 4 for more information about environmental releases and vulnerable populations). HWIs, however, typically dispose of incinerator bottom ash in hazardous waste landfills, minimizing the potential for the release of PFAS to the environment. Again, information on partitioning of PFAS in control technology residuals is lacking at present.

Potential impacts to communities from releases from HWIs should also be considered. Considerations should include which media may be impacted by releases, and the potential exposure pathways resulting from releases. The characteristics of the potential exposed communities (demographics, socioeconomic status, other environmental exposures, health conditions, etc.) provide information regarding the potential for disproportionate and adverse impacts.

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[16] For example, CAA and RCRA regulations applicable to HWCs require controls to prevent/minimize combustion system leaks (e.g., due to positive pressure events in the combustion chamber), as well as controls to minimize releases from equipment and tanks that store or manage hazardous waste. See 40 CFR 63.1206(c)(5) and 264.1050–1090.

3.a.iv Testing and monitoring

Validated measurement methods are limited and under development for reliably identifying and quantifying if PFAS are released into the air from stationary sources. The limited scope of standardized methods to measure PFAS emissions and the limited availability of data using these methods to evaluate PFAS destruction at a variety of treatment devices introduce uncertainty in the understanding of the efficacy of thermal treatment approaches for destroying PFAS.

Ongoing method development by EPA has a broad focus that will address PFAS in various waste streams, stack and fugitive emissions, and ambient air (see Section 5 and Appendix A). Method development also includes identification of PFAS that are potential PICs, not targeted in established water methods such as Methods 533 and 537.1. Due to the number and complexity of PFAS that have already been identified, a simpler class-specific measurement is also being investigated to determine if measurement of a single compound or a small group of compounds is adequate to characterize the completeness of thermal treatment for both targeted PFAS and potential PICs.

These factors raise important risk communication challenges, particularly for communicating the potential significance of testing and monitoring results to adjacent communities. But the importance of encouraging appropriate information access for and dialogue with communities—and, in particular, with potentially vulnerable communities —cannot be overemphasized. Suggestions for risk communication are included in Section 4.

3.a.iv.1 Semivolatile PFAS sampling and analysis

Initial development of methods to measure PFAS in air or air sources has focused on compounds whose physical state is liquid or solid at room temperature. Methods for air have included the target compounds commonly found in water methods. The basis for measuring PFAS compounds from air or air sources involves evaluating and then modifying existing sampling and analysis methods for semivolatile organic compounds.

Filtered particulate, solid sorbent, and aqueous impinger media sampling procedures have been used to collect and recover a wider range of PFAS and associated byproducts in ambient air and source emissions (Barber et al., 2007; Martin et al., 2002). However, these sampling methods have some limits, including poor retention or chemical conversion of the PFAS during sampling and poor recovery during sample preparation prior to chemical analysis (Arp & Goss, 2008).

Ambient sampling for semivolatile PFAS roughly follows either the high-volume air sampling protocol described in EPA compendium Method TO-13a (U.S. EPA, 1999) or the National Atmospheric Deposition Program (NADP) approaches for wet and dry deposition sampling (NADP, 2020). High-volume air samples collect both water-soluble PFAS acids and salts and water-insoluble telomer alcohols. NADP sampling has focused on condensable and particulate-bound targeted PFAS captured in polypropylene buckets to evaluate deposition due to rain.

Current sampling of stationary source air emissions for semivolatile PFAS targets is based on EPA SW-846 Method 0010. Analysis of samples for a list of PFAS compounds is based on EPA Method 533—modified to include collection of both targeted and non-targeted PFAS in a single sampling system. Sampling includes heated or stack temperature probe extraction of emission gases followed by collection on filters, XAD sorbent media, and aqueous impingers. EPA released OTM-45, *Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources,* in January 2021 (U.S. EPA, 2021). OTM-45 experience indicates the method works well to measure targeted PFAS. OTM-45 is an effective and sensitive method to measure a list of PFAS included in the method. In coordination with the release of this guidance, EPA recently released OTM-50, which enables analysis of non-polar volatile PFAS.

These field sampling procedures collect samples that are subsequently transported to a laboratory for extraction and analysis. Analysis procedures include established water methods for targeted compounds and/or non-targeted analysis (NTA) for unknown PFAS. NTA is a research tool that can be used on OTM-45 and OTM-50 samples to investigate semivolatile polar and nonpolar PFAS recovered by these methods. High-resolution mass spectrometry can be used for both targeted analysis and NTA. Qualitative identification of PFAS by NTA reveals PICs/degradants formed during the thermal treatment of PFAS-contaminated media (Aleksandrov et al., 2019; McCord & Strynar, 2019; Newton et al., 2020). NTA currently relies on mass spectrometry, which generates qualitative information about the molecular formula of unknown PFAS. NTA is an important component in characterizing thermal treatment emissions because it provides an approach for identifying unknown PFAS or PICs.

3.a.iv.2 Gaseous volatile PFAS sampling and analysis

Volatile PFAS targets and thermal treatment byproducts from ducted emissions or in ambient air have been sampled using a variety of whole gas sample collection approaches, such as Tedlar® bags and passified canisters, as well as sorbent traps and cryogenic solvents. EPA and private sector investigators have sampled with specialized commercial sorbent traps and Tedlar® bags in laboratory-scale thermal destruction and ambient volatile PFAS measurement of targeted and non-targeted PFAS (Wang et al., 2013, 2015; Yamada et al., 2005). Issues such as sample reactivity, breakthrough volumes, and quantitative transfer to the analysis instrument complicate these approaches. Direct instrumental methods for measuring volatile PFAS (such as FTIR) can suffer from lack of sensitivity compared with extractive methods that allow concentration prior to analysis.

To develop more sensitive methods for measuring volatile fluorocarbon compounds, EPA has evaluated the use of steel canisters for targeted volatile PFAS as well as PICs during multiple-source emissions tests, including at a thermal treatment facility for AFFF-contaminated soil (U.S. EPA, 2020b). Canisters have been used to sample source emissions and perform targeted measurements for PFAS, including both industrially produced compounds (such as FC-116, HFC-23, HFC-125, E1, and E2) and potential PIDs (such as CF_4 through octadecafluorooctane). EPA is developing the ability to characterize a more diverse set of possible PFAS PICs and measure volatile PFAS at trace concentrations. The ability to measure trace concentrations will allow investigators to introduce a known concentration of a hard-to-destroy fluorocarbon and evaluate the behavior of this compound when exposed to specific thermal environments. EPA's preferred approach is to introduce a known concentration of a hard-to-destroy fluorocarbon and evaluate the behavior of this compound when exposed to specific thermal environments in order to characterize a more diverse set of possible PFAS PICs. Though insufficient by itself, this approach is consistent with the EPA approach for determining the DRE of fluorinated greenhouse gas abatement equipment in electronics manufacturing (U.S. EPA, 2010). NTA has also been performed on the same samples. Simultaneous with the release of this 2024 interim guidance, EPA will release OTM 50, which provides an approach and procedures for using silanized steel canisters to sample and analyze volatile PFAS compounds from thermal treatment sources. This and OTM-45 are examples of monitoring methods that could be considered for addition to a potential PFAS waste management system or permit (e.g., RCRA).

EPA continues to evaluate FTIR as a suitable real-time measurement technique for CF_4 and C_2F_6 in stationary source emissions. In addition, in ambient air, EPA also investigated chemical ionization mass spectrometry (CI/MS) to monitor individual PFAS in real time (Riedel et al., 2019). EPA found the technique sufficiently sensitive for fugitive emissions measurements or leak detection.

The quantitative measurement of total organic fluorine (TOF) is also being evaluated to represent all, or most, of the PFAS class of compounds. This approach represents a simpler and more comprehensive measurement alternative to target list approaches that focus on a limited number of PFAS. Several potential techniques warrant consideration and additional evaluation, including (but not limited to) combustion–ion chromatography (CIC), particle-induced gamma emission spectrometry (PIGE), and X-ray photo-electron spectroscopy (XPS). For air and thermal treatment emissions, TOF must measure highly volatile as well as semivolatile PFAS. TOF analysis is an ongoing research area: data users must recognize the benefits of receiving general screening data for a wide array of potentially present PFAS, while also recognizing the limitations and uncertainties inherent in not knowing which PFAS or class of PFAS is present in the sample, including uncertainties associated with potential health risk. In addition, to minimize the risk of PFAS false positives, techniques within a validated method or methods must be developed that demonstrate effective separation and removal of inorganic fluorine from organic fluorine (Koch et al., 2020). TOF is not specific to PFAS, and any fluorine-containing compounds (e.g., pesticides, pharmaceuticals) that are retained during extraction would be included in the organic fluorine measurement.

HF measurement is included in stationary source measurements to evaluate control efficiency of HF as a HAP at emission outlets. Multiple studies of PFAS thermal decomposition and HF monitoring have demonstrated that EPA compliance methods for HF measurement are adequate to meet this need. However, HF is difficult to transport through treatment and control equipment and is therefore not a candidate for mass balance to evaluate PFAS destruction efficiency.

3.a.v Uncertainties/unknowns

EPA is planning to collect additional information and conduct additional research to better understand PFAS destruction and evaluate emission control efficiency (see Section 5). EPA is working to develop a standardized validated methodology for measuring PFAS gaseous emissions (see Section 3.a.iv); however, EPA also lacks detailed information on the amounts and concentrations of PFAS-containing materials that are generated and managed in thermal treatment devices.

Development of sampling and analytical methodologies must continue (see Section 5 research activities) so that emissions and other media from thermal treatment devices burning PFAS-containing materials can be adequately characterized.

When evaluating thermal treatment options, decision-makers (e.g., permit writers, waste managers) should consider potential impacts to communities, including vulnerable populations. Uncertainties such as the overestimation of destruction and disposal capabilities, or a failure to account for potential PIC production and subsequent transformation back to PFAS of concern could have consequences for all nearby communities, including for vulnerable communities that may be disproportionately impacted. EPA recommends decision-makers screen communities located in the vicinity of potential releases from the destruction, disposal, and storage options (considering fate and transport) in order to consider the potential for adverse and disproportionate impacts (see Section 4), and to consider potential measures to prevent, reduce, or address such impacts. Depending on site-specific circumstances (e.g., PFAS concentrations, impacted media, and potential exposure pathways), the size and shape of this area (vicinity) will vary.

In order to provide more detailed recommendations, further data on the ability of thermal treatment units to completely mineralize PFAS-containing materials is necessary (see Appendix A and Section 5.a). Performance testing of all types of combustors is lacking. EPA recommends that full-scale thermal destruction facilities conduct performance testing prior to accepting and processing PFAS materials. Objectives of the testing should include:

- Demonstrate destruction of parent compounds and potential production of semivolatile and volatile PICs (using OTM-45 and OTM-50) to show efficient thermal destruction.
- Characterize PFAS being fed, including the feed rate, whether it is a concentrated or diluted stream, and how the PFAS are fed (e.g., containerized or direct feed).
- Demonstrate utilization of key combustion parameters (temperature, residence time, other conditions that impact mineralization) and include relevant data in the report.
- Characterize release of PFAS and PICs through the system by sampling at multiple points in the process (e.g., before and after a scrubber) and sampling all relevant effluent streams (e.g., scrubber blowdown and fly ash). Document and report operating parameters for all relevant control devices to EPA and relevant state, territorial, or Tribal authorities.

Further details on suggested parameters and procedures are provided in Table 5-1 and Appendix A.

3.a.vi Treatment commercial availability

Section 3.a.i describes the commercial availability of thermal treatment devices. The United States has about 22 commercial hazardous waste combustion facilities[17] in operation; over a dozen large-scale, commercial carbon reactivation companies with about 17 furnaces; 193 MSW incineration units at 75 facilities; and 170 SSIs at 86 facilities.

3.a.vii Summary

PFAS-containing waste can potentially be treated in several types of thermal treatment devices, including HWCs, MWCs, SSIs, and activated carbon reactivation furnaces, but further research is needed to gain a better understanding of what may be possible in practice. These treatment devices operate differently and handle different types of PFAS-containing media with varying concentrations. Even within the same category of thermal treatment device, designs and operating conditions may vary across sources in a way that could affect PFAS treatment efficiency. As a general approach, EPA encourages decision-makers to prioritize the use of destruction and disposal technologies that have a lower potential for PFAS release to the environment, over destruction and disposal technology options with a greater potential for environmental release of PFAS. EPA acknowledges that each destruction and disposal technology has limitations. However, managing PFAS to minimize environmental releases during destruction and disposal activities supports protection of human health and the environment.

There are limited characterizations of potential PFAS emissions from thermal treatment devices that burn PFAS-containing media, and EPA is not aware of any full emission characterizations that have been conducted at HWCs, MWCs, SSIs, or activated carbon reactivation furnaces or any studies to evaluate

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[17] This includes commercial incinerators, cement kilns, and LWAKs that are permitted to burn hazardous waste.

the formation of products of incomplete combustion resulting from inefficiency to convert PFAS into carbon dioxide and hydrogen fluoride. EPA is also not aware of any studies that have been conducted on the extent to which PFAS contaminants partition to air pollution control device residuals or bottom ash, which may also be a concern. This is likely (in part) because PFAS emission measurement methods and other analytical methodologies (e.g., for fly ash, other waste streams) are limited and continue to be developed. Data, however, from pilot-scale experiments conducted by EPA researchers suggest that temperatures above approximately 1,100°C / 2,012°F may result in high destruction efficiencies and few detectable fluorinated products of incomplete combustion.

Given the unique characteristics of fluorine combustion chemistry (particularly the strength of the carbon–fluorine bond), adequate thermal destruction of PFAS requires high temperatures and long residence times and likely benefits from direct flame contact. Hazardous waste combustion technologies (commercial incinerators, cement kilns, and LWAKs) can potentially achieve temperatures (~1,100°C / 2012°F) and residence times sufficient to break all carbon-fluorine bonds in the PFAS contained in the waste stream being thermally treated. Permitted hazardous waste facilities have stringent regulatory controls on temperatures and other important operating parameters to achieve a 99.99 percent destruction efficiency for other (non-PFAS) organic chemicals. Such facilities also have air pollution control devices to prevent certain gaseous and particulate pollutants from entering the atmosphere. However, information on the efficacy of PFAS destruction in these facilities is currently limited. EPA has limited data characterizing PIC emissions from these sources when they burn PFAS. EPA is working to develop measurement methodologies as well as to gather information to conclude whether PICs are adequately controlled. EPA recognizes that PICs are inevitable (even for nonfluorinated compounds); however, based on the unique characteristics of fluorine combustion chemistry, EPA believes it is important to determine whether thermal treatment devices and their associated post-combustion control devices are adequately controlling PICs, especially fluorinated PICs. Given all these factors, there is a current need to continue research activities investigating incineration of PFAS. After sufficient research has been completed to address the related knowledge and data gaps, EPA can make a more informed recommendation on disposal of PFAS compounds and PFAS-containing substances using incineration.

Similar conclusions can be drawn for activated carbon reactivation furnaces as for HWCs. Experimental data suggest that thermal destruction of PFAS will occur in two stages: first during reactivation of the GAC, and then when the off-gas is introduced into a high-temperature zone with temperatures as high as 1,000°C/1,832°F. As referenced in Section 3.a.i, an activated carbon reactivation furnace can be equipped with an afterburner to treat off-gases at high temperatures to achieve 99.99 percent DRE of VOC. In addition, scrubbers can be installed to remove acid gases. This is a promising treatment method, but more information is needed, including confirmation that PICs are controlled based on actual operations, establishment of standard operating conditions for activated carbon reactivation furnaces of various designs to ensure optimal destruction of PFAS, and an understanding of how thermal treatment influences the physical and chemical properties of GAC (in ways that can affect GAC's adsorption behavior and sorption capacity for PFAS).

Research and testing of PFAS destruction performance within MWCs is extremely limited, primarily comprising laboratory and pilot-scale studies (Aleksandrov et al., 2019; Taylor et al., 2014). For example, to assess whether PTFE is destroyed or reformed as PFAS, the Aleksandrov et al. study uses a pilot-scale rotary MWC with afterburner chamber combusting PTFE granules added to wood pellets (also firing natural gas). This study looked at a half-load scenario of 870°C (1,600°F) with a four-second residence time and a full-load scenario of 1,020°C (1,870°F) with a 2.7-second residence time. The study analyzed for 31 PFAS compounds within the flue gas samples collected, assumed to represent a broad range of PFAS. While the laboratory and pilot-scale studies conclude that MSW incineration of PTFE is not a significant source of PFAS, the laboratory thermal reactor and the pilot incinerator used in these studies may not be representative of the design of MWC units currently operating in the United States. For example, the pilot-scale unit in the Aleksandrov et al. study is a rotary combustion chamber followed by an upflow afterburner. No MWC units operating in the United States have a similar configuration. In addition, while several PFAS species were analyzed for in these studies, it is important to note that there are far more PIC species possible, and no studies have thoroughly evaluated the types and quantities of PICs.

As noted earlier in this section, Wang et al. (2013) investigated PFAS interactions with CaO and $Ca(OH)_2$ at moderate temperatures (200°C to 900°C, or 390°F to 1,650°F), both with and without sewage sludge. These experiments were conducted in a laboratory (i.e., combustion in a crucible within a muffle furnace) and found that these calcium species exhibit a pseudo-catalytic effect promoting PFAS destruction and fluorine capture at relatively low temperatures. The study did not investigate the evolution of PICs during the thermal treatment process. While this study shows promising results for the use of catalysts to achieve PFAS destruction and fluorine capture at low temperatures, along with the potential for full-scale application (since lime is occasionally added to sewage sludge to control odor at SSIs), it is important to note that, as with the MWC studies described above, there are caveats for applying these results to the real-world design and operation of SSIs.

More research is needed to address these issues and develop reliable measurement techniques. Section 5 summarizes EPA's continuing PFAS research, as well as a general proposal to collaborate with stakeholders to address these uncertainties promptly. See Appendix D for a summary of costs and considerations.

3.a.viii References for Section 3.a

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3.b Landfills

RCRA regulations define a landfill as “an area of land or an excavation in which wastes are placed for permanent disposal, and that is not a land application unit, surface impoundment, injection well, or waste pile” (40 CFR 257.2). The goal of solid waste landfills is to contain waste, and thereby restrict the release of contaminants within the landfill from entering the environment. Landfills are commonly classified by the types of waste they accept and/or by their ownership status.

Landfills control waste and corresponding pollutants through containment. Because of their many and varied uses, PFAS enter landfills as part of the general MSW stream, in industrial waste, or in other PFAS-containing wastes, with a range of concentrations. Types of landfills include MSW, hazardous waste, industrial, C&D, and ash monofill.

Some landfills are available disposal options for PFAS and PFAS-containing materials. MSW landfills commonly receive large quantities of wastes with significant PFAS concentrations (e.g., biosolids, septage, soils excavated during remediation, and phytoremediation biomass). These concentrations are much lower than some industrial or commercial wastes with high PFAS content (e.g., leather tannery, chrome plating, and textile industry waste). Permitted hazardous waste landfills employ the most extensive set of environmental controls (e.g., double liner systems with leachate collection/treatment and leak detection) and practices (e.g., comprehensive record keeping) that are currently available for the containment of commercial and industrial wastes with high PFAS content (see Table 3-2). Hazardous waste landfills are more effective at minimizing PFAS release into the environment than other landfill types. Note that hazardous wastes that are typically landfilled are not usually biodegradable; thus, most hazardous waste landfills do not have LFG collection and control systems installed and, therefore, may not be appropriate for disposal of biodegradable PFAS-containing wastes (e.g., biosolids) that may produce LFG. It is also noted that leachate from hazardous waste landfills is designated as hazardous waste (F039) and must be managed in accordance with specific requirements for hazardous waste. Nonetheless, some leachate treatment or management options cannot treat or destroy PFAS.

Most modern MSW landfills, when constructed and operated with appropriate controls (e.g., a flexible membrane liner system and leachate and LFG collection and management systems), can also help contain PFAS. However, research indicates that although MSW landfills contain PFAS for the most part, up to 5 percent of the PFAS may be released in the LFG and, 11 percent may be released in the leachate annually (Tolaymat et al., 2023). Also, leachate may be sent to wastewater treatment plants that are not capable of treating or destroying PFAS; thus, the PFAS in landfill leachate may be released to the environment. While some information is available, EPA plans to research to understand the effects of PFAS on liner integrity, gaseous emissions from landfills, the effectiveness of leachate treatment for PFAS removal, and the levels and types of PFAS in landfill leachate (see Section 5). MSW landfills present a good opportunity to dispose of lower-concentration PFAS waste such as biosolids, phytoremediation biomass, and contaminated soils. However, there is a need for additional research regarding the effectiveness of emerging PFAS separation and destruction treatment technologies on a landfill leachate matrix.

While landfills might serve as long-term containment sites, it is unclear how effective they are at containing PFAS. Because landfills are a containment method and do not destroy PFAS, PFAS are anticipated to persist in landfills for the life of the compounds, which could be many centuries.

Section 3.b focuses on the viability of landfilling as a means of containing PFAS and PFAS-containing material, discussing:

- The types of PFAS waste and how they behave within a landfill.
- The types of landfills that receive PFAS-containing waste.
- The types of environmental controls and their ability to effectively contain PFAS.
- The potential for environmental releases of PFAS associated with landfilling.
- Recommendations for deciding what type of landfill is most appropriate for PFAS-containing waste.

- Methods to monitor PFAS at landfills and corresponding waste streams.
- Uncertainties and unknowns associated with landfilling PFAS-containing waste.

3.b.i Types of PFAS and PFAS-Containing Materials

As described in the Executive Summary and Section 2, “PFAS” is a broad term for a wide range of chemicals. When disposed of in a landfill, these different types of PFAS may behave differently from one another and may require different considerations for the types of landfills that are suitable for disposal and the types of emissions controls that are necessary to contain the PFAS over time.

PFAS Polymers. Stable polymeric PFAS (e.g., PTFE or Teflon^{TM}) are less likely to migrate within a landfill by partitioning to the gas or liquid (i.e., leachate) phase and should not be confused with side-chain fluorinated polymers; however, physical abrasion of the polymers can lead to the creation of fluorinated microplastics that may be suspended in landfill leachate. Although fluoropolymers are highly resistant to chemical and thermal degradation, they can still break down into microplastics due to weathering and physical strain, increasing their dispersion and bioavailability (Lohmann et al., 2020). Fluorinated microplastics have been measured in landfill leachate (He et al., 2019), but because UV radiation and resulting oxidation in landfills is negligible and the physical processes that lead to abrasion and the development of microplastics are expected to be relatively low in landfills, the bulk of stable fluoropolymers would be expected to be retained for a long duration. Additionally, soluble, and volatile PFAS have been identified in fluoropolymers as synthesis byproducts or incomplete reactants.

Soluble PFAS. Soluble PFAS and precursors that degrade to soluble PFAS, including perfluoroalkyl acids such as PFOA, PFOS, PFHxS, PFBA, and HFPO-DA, can more easily and quickly partition to the liquid phase and become part of the landfill leachate. Landfills without an appropriate liner and leachate collection system (see Section 3.b.iii) will allow this PFAS-containing leachate to enter and contaminate the groundwater. It is therefore not appropriate to dispose of soluble PFAS in landfills without these controls in place.

Volatile PFAS. Volatile PFAS and forms that degrade to volatile PFAS, including alcohols such as FTOHs and FASEs may be released through uncollected or fugitive LFG. These types of PFAS should therefore be disposed of in landfills with LFG collection and control systems in place and operating (see Section 3.b.iii.6). Furthermore, PFAS waste that is comingled or combined with other waste determined to be biodegradable (see EPA Test Methods for biodegradability listed at *https://www.epa.gov/pesticide-labels/criteria-biodegradability-claims-products-registered-under-fifra*) should only be disposed of at landfills with gas collection and control systems in place. The biodegradable fraction of waste will produce LFG as it decomposes and allow volatile PFAS to be emitted from the landfill.

Mechanisms and rates of transformation. The behavior of PFAS in landfills is a complex and multifaceted process that involves various abiotic and biotic transformation and partitioning pathways. While the exact mechanisms and rates of transformation are not fully understood, both aerobic and anaerobic conditions in landfills can facilitate the conversion of PFAS precursors into more persistent terminal PFAS species. It is notable that fluorotelomer carboxylic acids (FTCAs) are a soluble intermediate transformation product which has been well documented to accumulate in biologically active anaerobic landfill conditions and is considered a landfill leachate contamination indicator. FTCAs result from the degradation of volatile PFAS such as FTOHs. For this reason, volatile PFAS-containing wastes should be managed in landfill environments which are also appropriate for soluble PFAS disposal.

As the environmental and health risks of PFAS are the subject of emerging research, it is essential to consider PFAS management strategies that minimize their release and transformation in landfills and other waste management systems. For example, Subtitle D MSW landfills are required to install a low-permeability liner prior to waste disposal, and LFG at MSW landfills is collected and managed based on the landfill's permitted design capacity and emission rate of nonmethane organic compounds (NMOCs) (40 CFR part 60, subparts Cf and XXX). Given these potential pathways for release, Table 3-1 summarizes the recommended engineering controls at landfills accepting PFAS waste based on the type of PFAS and the biodegradability of any comingled waste. It is noted that non-biodegradable stable polymeric PFAS do not require specific controls since they are not anticipated to migrate or biodegrade and generate gas, can be disposed in any type of landfill, and are not included in the table below. Also note that soluble PFAS comingled with biodegradable waste should have both control liquid and gaseous emissions, i.e., leachate collection and gas control.

Table 3-1. Recommendations for Disposal of PFAS-Containing Waste by Type of PFAS, Waste Biodegradability, and Type of Landfill Controls to Reduce Risks of Environmental Release

Type of PFAS	Degradability of comingled waste	Landfills with liner and leachate collection	Landfills with gas collection and control
Stable polymeric PFAS (e.g., PTFE)	Biodegradable		✓
Soluble PFAS (e.g., PFAAs)	Biodegradable	✓	✓
	Non-biodegradable	✓	
Volatile PFAS (e.g., FTOHs)	Biodegradable		✓
	Non-biodegradable		✓

3.b.ii Types of landfills

Landfills are typically classified by ownership status and by the type of solid waste they are permitted to receive, which determines the types of environmental controls they must employ. Depending on the type of waste disposed, a landfill could be subject to regulation and permitting under RCRA, the CAA, and/or TSCA. RCRA regulates two types of landfills: Subtitle C facilities receive hazardous waste, while Subtitle D landfills are primarily intended for the management of non-hazardous waste and can include MSW landfills, industrial non-hazardous waste landfills, C&D waste landfills, and coal combustion residual landfills. The CAA regulates air emissions from MSW landfills and TSCA regulates landfills that contain PCBs. The requirements under RCRA, CAA, and TSCA determine how the landfill must be constructed, operated, controlled, maintained, monitored, and closed when it reaches its final capacity.

Although categories and environmental controls vary from state to state, the following categories of landfills exist in most states. Landfills tend to have similar environmental controls within each category:

- Hazardous waste
- MSW
- Ash monofill
- Industrial
- C&D debris

Table 3-2 identifies the environmental controls required by RCRA and CAA for the landfill types defined in RCRA Subtitles C and D. RCRA regulations focus on the containment of solid waste and leachate, while CAA regulations focus on collection and control (destruction) of components in LFG. The landfill types differ in how they are constructed, operated, controlled, monitored, and closed, reflecting the different types of waste they are allowed to receive.

- Subtitle C hazardous waste landfills that meet the minimum technology requirements set under RCRA.
- Subtitle C hazardous waste landfills are permitted to receive hazardous wastes that pose potential risk to humans and the environment and therefore have the most stringent environmental controls.
- Subtitle D MSW landfills are allowed to receive MSW and are required to install a low-permeability liner prior to waste disposal. LFG must be collected and managed according to the requirements of the CAA standards of performance (40 CFR part 60 subparts Cc, Cf, WWW, and XXX) at landfills that meet the regulatory requirement thresholds. Subtitle D landfills that receive non-hazardous and non-biodegradable waste tend to have environmental controls commensurate with the waste they receive. These controls can vary from state to state; for example, bottom liner, leachate collection, and final cover requirements for industrial and C&D landfills range from none to rigorous.

Note that certain small MSW landfills in arid or remote locations are exempt from RCRA design and groundwater monitoring requirements (40 CFR 258.1). See Sections 3.b.ii.2 and 3.b.iii.1 for additional exemptions.

Table 3-2. Required Environmental Controls by Landfill Type

Landfill Type	Federally Regulated Under	Bottom Liner and Leachate Collection System	Gas Collection and Control System	Final Cover
Hazardous waste	RCRA Subtitle C	Yes (double liner or better)	No	Flexible membrane liner (FML) cap
MSW	RCRA Subtitle D 40 CFR part 258 CAA 40 CFR parts 60 and 63	Yes (composite liner or better)	Yes (when regulatory size and emission thresholds are triggered)	FML cap
Ash monofills	RCRA Subtitle D 40 CFR part 257	Yes (composite liner or better)	No	Clay cap
Industrial	RCRA Subtitle D 40 CFR part 257	Varies by state, from no liner requirement to composite liner	No	Varies by state, from no requirements to FML cap
C&D debris	RCRA Subtitle D 40 CFR part 257	Varies by state, from no liner requirement to composite liner	No	Varies by state, from no requirements to FML cap

PFAS concentrations have been detected in landfill leachates from various types of landfills, as shown in Table 3-3.

Table 3-3. Range of PFAS Concentrations in Different Types of Landfill Leachate Reported in Published Studies. Adapted from Tolaymat et al., 2023.

Matrix	Number of PFAS Detected (Number of PFAS in Method)	∑PFAS Range (ng L^{-1})	Country	Reference
MSW Leachate	25 (26)	300 – 58,000	USA	Chen et al. (2023)
	10 (11)	15,000 – 18,000	USA	Solo-Gabriele et al. (2020)
	24 (24)	2,700 – 7,400	USA	Huset et al. (2011)
	30 (70)	2,000 – 29,000	USA	Lang et al. (2017)
	2 (2)	330 – 2,600	USA	Clarke et al. (2015)
	28 (28)	230 – 29,000	USA	Helmer et al. (2022)
	2 (2)	47 – 3,400	USA	Michigan Waste & Recycling Association (2019)
	22 (25)	1,400 – 125,000	USA	NWRA (2020)
	31 (40)	BDL – 104,000	USA	California Water Boards (2023)
	14 (14)	33 – 15,000	Australia	Gallen et al. (2016)
	9 (9)	210 – 46,000	Australia	Gallen et al. (2017)
	15 (15)	Not reported	Australia	Simmons (2019)
	25 (43)	31 – 13,000	Germany	Busch et al. (2010)
	24 (24)	2,500 – 36,000	Canada	Benskin et al. (2012)
	16 (18)	700 – 6,400	Canada	Li (2009)
	2 (2)	50 – 2,300	Canada	Gewurtz et al.
	16 (27)	2,200 – 6,100	Norway	Eggen et al. (2010)
	7 (8)	200 – 1,500	Norway	Kallenborn et al. (2004)
	4 (4)	210 – 610	Finland	Perkola & Sainio (2013)
	7 (10)	14 – 17,500	Ireland	Harrad et al. (2019)
	8 (16)	640 – 1,400	Spain	Fuertes et al. (2017)
	28 (30)	320 – 11,000	Norway	Knutsen et al. (2019)
	17 (26)	0.3 – 1,300	Sweden	Gobelius et al. (2018)
	11 (14)	7,300 – 290,000	China	Yan et al. (2015)
	33 (57)	3,040 – 109,000	China	Liu et al. (2022)
	17 (17)	1,800 – 43,300	China	Huang et al. (2022)
	18 (18)	1,270 – 7,660	Singapore	Yin et al.
C&D Leachate	8 (9)	4,200 – 11,000	Australia	Gallen et al. (2017)
	24 (26)	270 – 30,500	USA	Chen et al. (2023)
	11 (11)	14,000 – 16,000	USA	Solo-Gabriele et al. (2020)
MSW Incineration Ash Leachate	9 (11)	2,800 – 3,400	USA	Solo-Gabriele et al. (2020)
	26 (26)	39 – 54,500	USA	Chen et al. (2023)
MSW Gas Condensate	26 (26)	199 – 80,900	USA	Chen et al. (2023)
	53 (92)	3,000 – 50,000	USA	Smallwood et al. (2023)
Hazardous Waste Leachate (Primary)	17 (28)	570 – 377,000	USA	California Water Boards (2023)
Hazardous Waste Leachate (Secondary)	13 (24)	25 – 3,700	USA	California Water Boards (2023)

BDL = below detection limit; ng/L = nanograms per liter

The following subsections describe the types of landfills that are expected to contain PFAS or PFAS-containing materials, with a focus on design and operation aspects that EPA considers important from a PFAS-treatment perspective.

3.b.ii.1 Hazardous waste landfills

Hazardous waste landfills are permitted to receive waste that is defined as "hazardous" under RCRA. This waste either is explicitly listed as hazardous or demonstrates at least one of certain characteristics (i.e., toxicity, corrosivity, reactivity, or ignitability) as defined by RCRA. Hazardous waste landfills (Subtitle C landfills) can be used for non-hazardous wastes like PFAS, when the generator wants a more controlled solution. These landfills are required to have a double liner system and must adhere to waste pretreatment standards prior to disposal (40 CFR part 268). Most hazardous waste landfills are not biologically active because they do not typically accept biodegradable wastes (e.g., biosolids, food scraps), and therefore typically do not need to have gas collection systems. Conditions in these landfills are not expected to cause PFAS emissions via LFG, although gas collection systems could be installed if a problem arises related to gas release or gas emissions. Any hazardous waste landfill must have a final cover consisting of an FML covered by soil.

PFAS-containing waste is and will likely continue to consume a fraction of hazardous waste landfill capacity. Although waste containing PFAS is currently not defined as hazardous waste under RCRA (unless the particular wastes are hazardous for some other reason), some waste generators, perhaps to be cautious, have been sending PFAS-containing wastes to hazardous waste facilities. To ensure hazardous waste landfill capacity is available in the future, EPA reviews and analyzes the Biennial Hazardous Waste Report and other data to develop and then publish an assessment of national capacity for hazardous waste management.[18] The last such capacity assessment indicated that there is adequate capacity nationwide through 2044, and a new assessment is currently underway to incorporate new information and extend the time horizon. EPA will continue to work with states to monitor hazardous waste treatment and disposal capacity and report on the status.

3.b.ii.2 Municipal solid waste landfills

EPA estimates that in 2018, 50 percent of the MSW generated was landfilled (U.S. EPA, 2024). An MSW landfill typically has at least a bottom liner and an extensive gas collection and control system (GCCS) to collect the LFG generated when the biodegradable waste, such as food scraps and office paper, degrades over time. Some MSW landfills have accepted PFAS manufacturing wastes, and as a result, PFAS concentrations in leachate are higher than the typical range expected in MSW landfill leachate (NWRA, 2020). Under RCRA, MSW landfills that received waste after 1993 must install a composite liner that meets design criteria (40 CFR 258.40). However, MSW landfills that receive less than 20 tons of waste per day are exempt from installing a liner and monitoring groundwater under RCRA (40 CFR 258.1(f)(1)). MSW landfills that exceed specified thresholds for size (based on design capacity) and emissions of NMOCs are required to install gas collection systems under current CAA regulations. Therefore, a subset of MSW landfills do not have gas collection and could release fugitive PFAS associated with LFG emissions. Similarly, unlined MSW landfills are ineffective at managing the release of mobile PFAS to groundwater (see Section 4.a). The fate of PFAS in LFG that is managed through on-site GCCS including on-site flares, engines, boilers, and turbines is unknown.

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[18] Background information and links to related documents are available at *https://www.epa.gov/hwpermitting/assessment-national-capacity-hazardous-waste-management*.

3.b.ii.3 Ash monofills

Ash monofills are a subtype of MSW landfills that mainly receive ash from MSW incinerators but could also receive smaller volumes of other waste streams such as biosolids from WWTPs. Ash monofills typically have a bottom liner and final cover requirements similar to other MSW landfills. However, they usually do not require GCCSs due to the use of incineration to remove biodegradable waste. Solo-Gabriele et al., (2020) found that ash monofills have lower PFAS concentrations than other landfill types, as shown in Table 3-3. While some landfill wastes, such as MSW ash, may be low in PFAS concentrations, the inclusion of higher-PFAS waste types may increase PFAS release. With limited data on the presence of PFAS in ash monofill leachate, more research is needed to determine the PFAS and precursor content of ash from different incineration technologies and air pollution control systems.

3.b.ii.4 Industrial landfills

Industrial landfills receive solid waste from industrial operations (non-municipal). Industrial landfills are often designed to manage specific waste streams (e.g., furnace slag, fly ash, plastics). The designs of industrial landfills vary widely based on the characteristics of the waste they receive. Requirements for environmental controls at these landfills also vary from state to state. Depending on the waste types and size of the landfill, some states do not require a liner. If a liner is required, a membrane cap is often also required. Due to the variability in control technologies, industrial landfills may not be an effective disposal option for managing uncontrolled releases of PFAS. Landfills that have historically received PFAS manufacturing wastes have been associated with high concentrations in leachate and reported environmental impacts (MPART, 2020). Some waste types received at industrial landfills, including plastics and materials with polishes or coatings, are associated with high concentrations of PFAS (OECD, 2013). Specifically, industrial processes such as the leather tanning, chrome plating, and textile industries contribute to PFAS in the industrial solid waste stream (ITRC, 2022).

3.b.ii.5 Construction and demolition landfills

C&D landfills receive waste from construction, renovation, and demolition projects, as well as other inert materials that are generated in high volumes, comparable to MSW waste (U.S. EPA, 2020b). The requirements for environmental controls at these landfills vary widely from state to state, ranging from no liner to a required composite liner. C&D landfills receive some PFAS-containing wastes (e.g., building materials and carpeting with PFAS treatments) (OECD, 2013; Solo-Gabriele et al., 2020; Bečanová et al., 2016), and soluble PFAS have been noted in the leachate from C&D landfills that are equipped with a leachate collection system (Chen et al., 2023). If a liner is required, a membrane cap could also be required. GCCSs are not required in C&D landfills due to low levels of biodegradable waste received compared to MSW landfills. Therefore, PFAS-containing wastes that also include a biodegradable component should not be disposed of at C&D landfills. A GCCS may sometimes be necessary to remediate a specific issue, such as gases generated from the decay of drywall. C&D landfills that lack composite liners and leachate management systems are unlikely to prevent the migration of soluble or volatile PFAS types; however, longer chain PFAS polymers such as PTFE, which is found in some electrical insulation and membrane material, are less mobile and likely to be contained in the waste mass for a longer period.

3.b.iii Ability of engineered landfill components to contain PFAS

PFAS are emitted from landfills via two possible routes: landfill leachate and LFG. Landfill leachate is liquid that has come into contact with solid waste and is either derived from the waste itself or the result of rainwater intrusion into the waste mass. Leachate contains soluble, suspended, or miscible materials removed from such waste. LFG is the result of the natural decomposition of organic material in landfills under anaerobic conditions. LFG is composed of roughly 50 percent methane, 50 percent carbon dioxide, and a small amount of NMOCs.

Existing efforts to manage contaminants in landfills focus on controlling leachate and LFG emissions. As shown in Figure 3-1, landfills constructed with environmental controls (e.g., bottom liner, leachate collection system, gas collection system, final cover system) manage the release of contaminants into the environment.

The uses of the engineered landfill controls shown in Figure 3-1 vary by landfill type due to differences in types of waste accepted, operating practices, site conditions, and federal and state regulations.

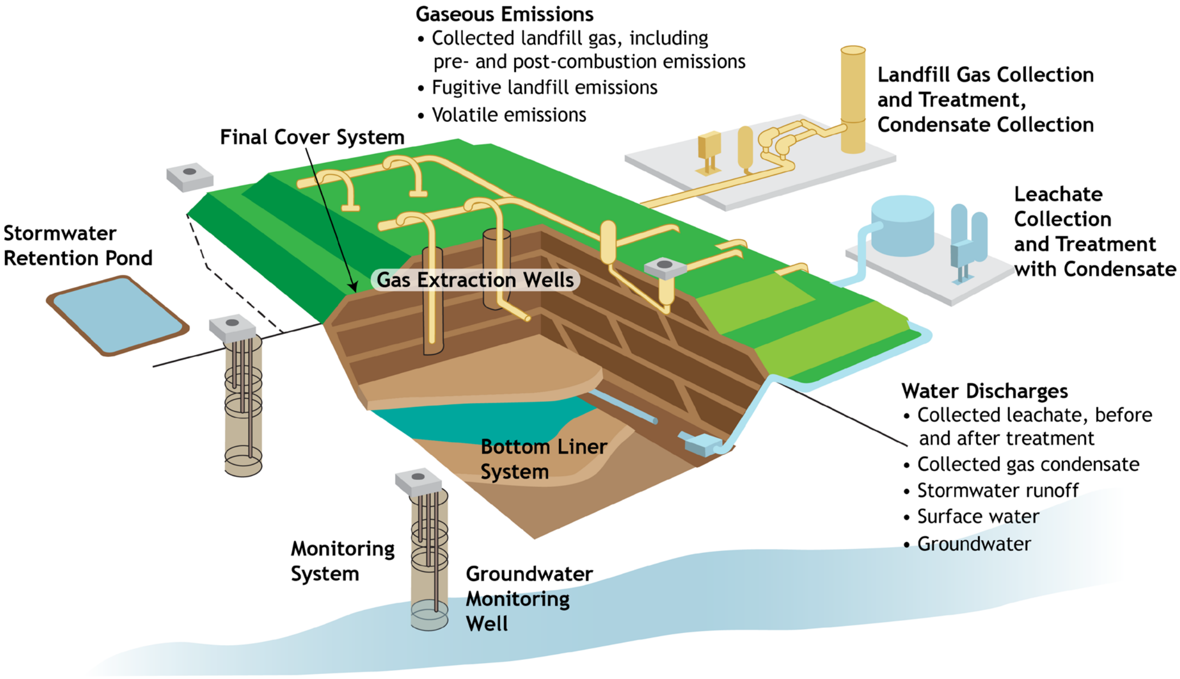

Figure 3-1. Engineered landfill components and potential PFAS release pathways.

3.b.iii.1 Bottom liner and leachate collection system

Under RCRA, any new landfill, replacement of an existing landfill, or lateral expansion of an existing landfill must have a double liner and leachate collection system if it receives hazardous waste, to limit leachate and gas release through the bottom of the landfill. Most landfills that are regulated under RCRA to receive non-hazardous waste are subject to design criteria that require either a composite liner and leachate collections system or a state-approved design that satisfies performance standards to ensure that regulated chemicals do not migrate beyond a specified distance from the landfill.

The variation of landfill requirements among states poses a challenge for the long-term containment of existing PFAS in landfills: state requirements for landfill liners vary, and some landfills are not required to have liners because of waste type or quantities received. Additionally, RCRA-exempt sites do not require liners (40 CFR 258.1). Because PFAS are not a RCRA-regulated hazardous waste, existing unlined landfills could include PFAS-containing wastes that are easily emitted into the environment. Depending on their mobility, PFAS compounds could impact groundwater if disposed of in an unlined landfill.

A liner is built of layers of clay and/or polymers (i.e., FMLs) designed to withstand the weight of waste and soil. Leachate will collect on top of the liner, so its design must include a leachate collection system contoured to collect leachate through a network of pipes leading to a low point called a sump. The collected leachate is pumped from the landfill and managed as liquid wastes (see Section 2.f and Section 3.b.iii.5). Uncontrolled leachate could result in the release of PFAS into the environment.

PFAS interactions with landfill liner materials have been the subject of limited studies. The most common types of FML are made with polyethylene geomembranes. PFAS diffusion through linear low-density polyethylene is reported below detection diffusion rates (Di Battista et al., 2020), and diffusion through high-density polyethylene may be even slower due to differences in material structure. PFAS likely pass through clay liners, which are required to have low hydraulic conductivity on the order of 10^{-6} centimeters per second, at the same rate as leachate and other constituents such as chloride (Li et al., 2015).

The most significant pathway for leachate (and PFAS) transmission through geomembrane or composite liners is via imperfections (e.g., flaws or holes) (Di Battista et al., 2020). A review of landfill liner performance reported median leakage rates of 44 and 33 liters per hectare per day for geomembrane and composite liners, respectively, and overall liner collection efficiency of 98 percent (Jain et al., 2023). Even if liners successfully prevent leachate from reaching groundwater, very few data exist on whether concentrated PFAS waste interacts with the different types of geotextiles used for landfill liners, thus affecting the performance of the liner. While the performance of clay liners may not be affected drastically, there is currently no research on the long-term stability of FML in the presence of PFAS.

3.b.iii.2 Landfill gas collection system

Landfills use GCCSs to manage gas generated from decomposing organic waste. A GCCS consists of a network of perforated pipes sunken into the waste mass. These “gas wells” are connected to a central blower that pulls gas from the wells. Despite the presence of a GCCS, gas can still migrate both through the surface of the landfill and underground through the bottom of the landfill. The gas produced by MSW landfills contains about 50 percent methane that is usually collected and burned off at the site via flares or for energy recovery; however, those systems for LFG destruction (e.g., flares, engines, boilers) typically operate up to 85°C—below the minimum temperature required to destroy PFAS.

Not all landfills are required to collect LFG (see Table 3-2). As noted in Section 3.b.iii.6.1, research has found that soluble PFAS with relatively high vapor pressures can be emitted into the atmosphere via the gas generated at landfills (Ahrens et al., 2011; Hamid et al., 2018; Wang et al., 2020; Weinberg et al., 2011). Direct sampling methodologies are currently under development, and published concentrations of PFAS measured *in situ* are limited to a single study (Titaley et al., 2023). LFG flares generally operate at approximately 650°C to 850°C, lower than the 1,100°C necessary to achieve the mineralization of PFAS. Nonetheless, LFG collection and management systems (e.g., flares) must be present at MSW landfill sites that accept PFAS waste, especially biodegradable PFAS waste such as biosolids. The use of GAC prior to the flaring of LFG can be effective in removing PFAS from LFG. Data on the fate of PFAS in LFG that is managed through on-site GCCS, including on-site flares, are still limited. See Section 5 for potential research needs.

3.b.iii.3 Final cover system

After a regulated landfill has reached its designed and permitted capacity, it must be capped with a cover system. This system typically consists of some combination of soil and membrane materials and is primarily intended to reduce infiltration of rainwater into the landfill to minimize leachate generation. The cover system also helps increase the efficiency of the GCCS and reduce uncontrolled gas emissions. Synthetic membranes and caps are more effective at controlling release of PFAS than earthen covers. Earthen covers are more subject to wet/dry cycles and cracking and are more likely to result in uncontrolled LFG emissions, which could contain PFAS (Ahrens et al., 2011; Tian et al., 2018; Wang et al., 2020; Weinberg et al., 2011).

3.b.iii.4 Other environmental controls and monitoring systems

In addition to the major infrastructure discussed above, solid waste landfills implement other practices and systems to protect human health and the environment. In active landfill cells, daily application of a material such as soil or inert waste covers exposed solid waste. Daily cover reduces leachate generation, gas emissions, and direct exposure to humans and wildlife. Access control for a landfill site, such as a fence, is typically also required to reduce direct human and ecological exposure to waste. Extensive monitoring networks are generally required to measure the landfill's impact on surface water and groundwater. RCRA Subtitle C requires all hazardous waste landfills to install groundwater monitoring wells. See Section 3.b.iii.5 for leachate discharge controls.

3.b.iii.5 Leachate discharge controls

3.b.iii.5.1 Leachate characteristics

Leachate is the liquid effluent from landfills primarily generated through the percolation or infiltration of rainwater through waste. Leachate often contains high concentrations of biodegradable and non-biodegradable organic matter, dissolved and suspended solids, heavy metals, ammonia, and sulfur compounds (Mukherjee et al., 2015; Renou et al., 2008). The waste type, age, climate at the landfill site, and methods of landfill operation dictate the characteristics of leachate. These factors result in highly variable leachate characteristics across landfill types and on a site-by-site basis. Subtitle C hazardous waste landfills are required to use a leachate collection system during their active and post-closure care periods to mitigate adverse impact to human health and the environment. Since the use of leachate collection systems at Subtitle D landfills varies by landfill type and state requirements, the efficacy of leachate management and PFAS emissions depends on the controls implemented. PFAS containment in landfills is expected to be indefinite, so the generation of PFAS-containing leachates remains a probability during the post-closure care period and beyond. Ideally, the leachate collected at the bottom of the landfill is removed and managed to minimize impacts to human health and the environment. See Section 2 for more a more detailed discussion on the types of leachates and associated PFAS.

3.b.iii.5.2 Off- and on-site management of leachate

The most common method for non-hazardous waste leachate disposal is off-site treatment at municipal WWTPs, where leachate is mixed with wastewater and treated. The dynamic nature of leachate characteristics, the presence of non-biodegradable compounds and ammonia, and the presence of emerging contaminants (such as PFAS) in the leachate may make it difficult for WWTPs to effectively treat the influent water. In some cases, a landfill with elevated PFAS in its leachate may burden a WWTP's ability to treat, remove, or destroy these compounds before discharge to the environment (Masoner et al., 2020). As mentioned in Section 2.a.ii, wastewater treatment technologies used at most municipal WWTPs are generally ineffective at destroying or controlling PFAS (Schultz et al., 2006) and as a result may also be ineffective at treating PFAS-containing landfill leachate. Furthermore, in WWTPs, PFAS may bind to and accumulate in biosolids, which can lead to PFAS entering the environment if biosolids are applied to land. Some WWTPs have requested that landfill operators pretreat leachate on site, and some WWTPs are implementing surcharges based on the leachate quality. Underground injection is another form of off-site leachate management (see Section 3.c).

Table 3-4 presents leachate management or treatment methods for the on-site management of leachate. Multiple technologies in the table are marked for further research—technologies for which, at the time of publishing, data do not exist to support or reject application for PFAS treatment. “Secondary treatment required” refers to the remaining concentrated or captured PFAS, which must be disposed of after treatment. “Potential secondary release” refers to the potential for PFAS release or breakthrough during the treatment process. Leachate characteristics are site-specific; therefore, the effectiveness of leachate technology should be evaluated on a site-by-site basis. (Table 3-3 lists average PFAS concentrations observed in different types of landfill leachate.)

Landfill operators should identify management or treatment methods that: (1) are suitable for the leachate at their specific sites and (2) meet the leachate discharge standards for chemicals and characteristics of leachate that are regulated. For example, leachate from a hazardous waste landfill is regulated as a listed hazardous waste (F039) and must be managed appropriately but that does not necessarily mean that treatment technologies are adequate to control the release of PFAS into the environment. For example, evaporation is often used to reduce leachate volume, which could lead to uncontrolled PFAS volatilization. The geography of the landfill site and cost-effectiveness of the methods play a crucial role in the identification of viable approaches to leachate management or treatment. For example, evaporation is often used to reduce dependence on treating a specific chemical(s) (e.g., ammonia). The use and effectiveness of leachate management strategies in removing or destroying PFAS during treatment varies (and, as noted in Section 3.b.vi, methods to quantify effectiveness are still under development). Leachate treatment technologies can be largely categorized into physiochemical processes, physical processes, biological processes, natural processes, and other management methods, as grouped in Table 3-4. Considering that leachate contains a variety of chemicals, a combination of physiochemical treatment processes can be used to narrowly target specific parameters for pre-treatment, or as part of a multi-step treatment strategy.

Table 3-4. Existing Landfill Leachate Treatment Technologies for PFAS Removal or Destruction

Treatment Technology	Treatment Mechanism	Pros for PFAS Treatment	Cons for PFAS Treatment	References
Physiochemical Processes				
GAC	Adsorption	• Familiar technology • Effective for long-chain PFAS	• Secondary treatment required • Short-chain PFAS breakthrough • Potential secondary release • Cost	• McCleaf et al. (2017), Pan et al. (2016), Ross et al. (2018)
PAC with coagulation	Adsorption	• Effective for long-chain PFAS	• Secondary treatment required • Costly for high-volume leachate • Potential secondary release	• Bao (2014), Pan et al. (2016)
Polymeric adsorption	Adsorption	• Tailored for specific compounds	• Secondary treatment required • Potential secondary release	• Liu (2017)
Ion exchange resin	Ion exchange adsorption	• Specified for certain compounds • More effective than GAC for long-chain compounds	• Secondary treatment required • Less effective for short-chain PFAS • Potential secondary release	Dickenson & Higgins (2016), McCleaf et al. (2017), Ross et al. (2018)
Zeolite	Ion exchange adsorption	• Inexpensive	• Secondary treatment required • Low surface area compared to GAC • Unknown reaction with short-chain PFAS	Chiang et al. (2017), Ochoa-Herrera & Sierra-Alvarez (2008)
Ozonation/ ozofraction-ation	Oxidation	• Potentially effective multi-contaminant removal	• Potential side-product formation • Secondary treatment required	Franke et al. (2019), Lin et al. (2012), Rahman et al. (2014), Ross et al. (2018)
Fenton oxidation	Oxidation	*Limited data available*	*Limited data available*	*None identified*

Treatment Technology	Treatment Mechanism	Pros for PFAS Treatment	Cons for PFAS Treatment	References
Photocatalytic advance oxidation process	Oxidation	- Permanent degradation	- Potential side-product formation - Cost	Lockwood (2018), Ross et al. (2018)
Coagulation-flocculation	Precipitation	*Limited data available*	*Limited data available*	Bao (2014), Dickenson & Higgins (2016), ITRC (2018), Rahman et al. (2014)
Chemical precipitation	Precipitation	*Limited data available*	*Limited data available*	*None identified*
Air stripping	Volatilization	*More research needed*	- Potential secondary emissions	*None identified*
Physical Processes				
RO	Physical separation	- Commonly used - Effective for short and long-chain PFAS	- Secondary treatment required for high-volume concentrate - Membrane fouling	Dickenson & Higgins (2016), Ross et al. (2018)
NF	Physical separation	- Uses less energy than RO - Effective for short- and long-chain PFAS	- Secondary treatment required	Boo et al. (2018), Dickenson & Higgins (2016)
Ultrafiltration (UF); microfiltration (MF)	Physical separation	*N/A*	- Not effective for PFAS	U.S. EPA (2020a)
Climatic evaporation; thermal evaporation; mist evaporation	Volume reduction	*Limited data available*	- Potential secondary emissions	*None identified*
Other On-Site Management Methods				
Recirculation	Containment	- Co-location with landfill	- Oversaturation - Potential surface water contamination - Dependent on climate	*None identified*
Underground injection	Containment	- Potential solution for PFAS concentrate	- Dependent on site geology - Regulatory approval	ITRC (2018)

Treatment Technology	Treatment Mechanism	Pros for PFAS Treatment	Cons for PFAS Treatment	References
Incineration	Thermal destruction	• PFAS destruction	• Potential secondary emissions (incomplete destruction) • Regulatory approval	ITRC (2017), Yamada et al. (2005)
Solidification	Containment	• Co-location with landfill • Reduces PFAS mobility	• Consumes air space in landfill • Unrealistic for large leachate volume	*None identified*
Biological Processes				
Activated sludge process sequencing; batch reactor; anaerobic; digestor; membrane bioreactor	Biological processes	*Limited data available*	• Limited by high concentrations of non-biodegradable organic matter	Ross et al. (2018), Saez et al. (2008), U.S. EPA (2020a)
Natural Processes				
Constructed wetlands; aerated ponds; phytoremediation; land application	Environmental release	*N/A*	• Direct release of PFAS	U.S. EPA (2020a)

3.b.iii.5.3 Leachate management and treatment technologies

Membrane treatments separate compounds from the leachate using mechanical filtration and pressure. Leachate passes through selective membranes (such as RO, NF, UF, and MF membranes) that divide it into two parts: permeate (which has passed through the membrane) and concentrate (which has not). The permeate and concentrate can then be treated as independent streams. The primary difference between these membranes is the pore size, which in turn affects the operating pressure and removal efficiency for different types of contaminants. RO is the most commonly used type of membrane for leachate treatment, while NF, UF, and MF are generally used in combination with other treatment technologies including RO. RO and NF are known to be effective in concentrating some PFAS, but UF and MF have pores that are too large to limit the release of most water-bound PFAS across the filtration membrane. Membrane fouling and a large amount of concentrate generation are two of the major drawbacks observed in implementing the membrane treatment system for landfill leachate and may be further complicated by high concentrations of PFAS (Dickenson & Higgins, 2016; ITRC, 2018; Ross et al., 2018).

An adsorption process with activated carbon is used for targeted removal of organic matter at some landfill sites. Activated carbon is known to be effective at trapping some PFAS, but it may need to be combined with other treatment methods to manage the range of PFAS found in landfill leachate. Activated carbon is a non-selective treatment method, expected to be less effective in nutrient-laden effluents such as landfill leachate. Once saturated, activated carbon needs to be reactivated through a pyrolysis process (see Section 3.a), collected as solid waste, or otherwise treated, with consideration of the PFAS concentration (ITRC, 2017). Leachate also may need to be pretreated before activated carbon treatment to avoid rapidly saturating the carbon.

Methods using ozone, Fenton's reagent, or advanced photocatalytic technologies are used to oxidize organic matter in the leachate. Ozone and hydrogen peroxide (H_2O_2) in combination with other oxidizing agents have been observed to remove up to 99 percent of chemical oxygen demand from leachate at different operating conditions (Renou et al., 2008) and may be effective at reducing or modifying certain PFAS in leachate (Ross et al., 2018). Ultraviolet photocatalytic advanced oxidation is known to be capable of destroying PFAS, but additional studies are needed to understand the subsequent products associated with this method (Lockwood, 2018; Ross et al., 2018).

Ion exchange processes using zeolite and magnetic ion exchange resin remove ammonia and organic matter, respectively. Ion exchange can be flexibly designed to address different compounds and may be effective at reducing PFAS in leachate; however, performance data are not currently available. As with activated carbon, the leachate may require pretreatment and the spent media would need to be handled as solid waste or otherwise treated.

Air stripping of landfill leachate is used for ammonia removal. While air stripping could be effective in the treatment pathway of leachate, if it is used before the removal of PFAS, it would likely lead to emissions of more volatile PFAS to air.

Recirculation of leachate within a landfill—a management strategy unique to MSW landfills—keeps the leachate within the landfill. Although recirculation can filter heavy metals and improve leachate quality, it is primarily used as a management option that may also help accelerate biodegradable waste decomposition. The recirculation of leachate in the landfill would return any PFAS to containment within the landfill. However, recirculation tends to increase the PFAS content of the landfill and may result in larger fugitive PFAS emissions since the waste will degrade faster.

Underground injection, specifically Class I injection, has also been used to manage landfill leachate in the United States (see Section 3.c).

Natural processes (such as constructed wetlands and phytoremediation) and biological processes (degradation, nitrification, and denitrification) are expected to be ineffective at treating and preventing release of many PFAS into the environment. Current biological treatment processes such as the activated sludge process and sequencing batch reactor have not been shown to be effective at treating many PFAS, but future research may show biological treatment can play a role in controlling some PFAS or converting them into other types of PFAS. Note that biological treatment does not necessarily result in PFAS releases directly into the environment, because the outputs can be further treated.

Leachate treatment through evaporation reduces the volume of leachate. Open-air evaporation methods may be effective at concentrating leachate but are a pathway for secondary PFAS releases to air. Commercial evaporators operated through the heat generated by the LFG combustion or other fuel sources are sometimes used at landfills. Exhaust gases emitted from the evaporators may be exposed to high temperatures, but those temperatures may not be high enough or last long enough to destroy PFAS (see Section 3.a).

3.b.iii.6 Landfill gas emission controls

3.b.iii.6.1 Landfill gas characteristics

Under the anaerobic conditions that dominate landfill environments, organic waste (e.g., food waste, paper, cardboard) decomposes and generates LFG. LFG in MSW landfills consists mostly of methane and carbon dioxide. In most landfills where gas is collected, it is burned for energy or to destroy the methane and other organic chemicals it contains. Even at sites that actively collect LFG, a fraction (EPA estimates 25% on average; AP-42, Vol.1, Chapter 2.4) of the LFG is emitted directly to the environment through the landfill surface and other routes. These uncontrolled emissions are referred to as fugitive losses.

Research has found that soluble PFAS with relatively high vapor pressures can be emitted into the atmosphere via the gas generated at landfills (Ahrens et al., 2011; Hamid et al., 2018; Wang et al., 2020; Weinberg et al., 2011). EPA is currently researching direct LFG sample evaluation for PFAS concentrations (see Section 5).

Unlike waste in MSW landfills, the C&D landfill waste that contributes most to LFG production is generally dominated by gypsum drywall (Yang et al., 2006). Gypsum drywall results in C&D LFG largely consisting of hydrogen sulfide, a highly pungent gas, with a smaller fraction of methane. Because C&D landfills generate a lower volume of gas than MSW landfills, LFG from C&D landfills is typically not collected and is often emitted to the environment without treatment.

3.b.iii.6.2 On- and off-site management of landfill gas

LFG collection and management are regulated under the CAA through New Source Performance Standards (NSPS) and National Emission Standards for Hazardous Air Pollutants (NESHAP) programs. After collection, LFG can be managed on site and burned using a flare. There are two basic types of flares common at MSW sites: open (candlestick) and enclosed flares. LFG can also be managed off site, where it is usually piped from the landfill to a nearby gas-fired system to generate heat or power.

On-site open flares must operate in accordance with key parameters for exit velocity and flare diameter for non-assisted flares (in 40 CFR 60.18). Additionally, a heat-sensing device must be installed to indicate continuous flame presence (but no specific temperature level). A landfill with an enclosed flare must reduce NMOCs to 20 parts per million by volume (ppmv) outlet or reduce NMOCs by 98 percent via a one-time performance test. Lowered emissions are maintained by following operating parameters set during the test for the requisite flare temperature and flow rate.

Combustion temperatures and duration may prove to be critical factors for destruction of PFAS in LFG. While on-site flare systems average 850°C (1,550°F) (U.S. EPA, 2008), power-generating engines and boiler systems may run even cooler. None of these systems operate at the temperature necessary to mineralize PFAS (1,100°C) as indicated in the EPA boiler database. See Section 3.a for a more complete discussion on conditions required for PFAS destruction.

Under the CAA regulations, if LFG is treated for sale or use in a beneficial energy recovery device, it must be treated according to a site-specific treatment plan before being utilized on site or piped out of the facility. Like liners, active gas collection systems are not required at all landfills, depending on the landfill size and level of NMOCs in the LFG. The presence or absence of an LFG collection and control system directly affects the release of PFAS via fugitive emissions.

LFG condensate is a liquid that has condensed in the LFG collection system piping during the extraction of gas from the landfill. In gases with high concentrations of water vapor, water condenses in pipes and accumulates in traps staged throughout the collection network. This condensate contains volatile compounds and accounts for a relatively small percentage of flow from a landfill. Gas condensate is commonly collected and managed with the landfill leachate as liquid waste. PFAS has been detected in LFG condensate, with perfluorobutanesulfonic acid (PFBS) being the dominant species at a concentration of 1,000 nanograms per liter (Li, 2011).

3.b.iv Potential for releases during landfilling

Over time, there is increased potential for certain pollutants to move into the environment beyond the footprint of the landfill. As water passes through the landfill, it may leach pollutants from the waste—including PFAS—and move them deeper into the waste mass. Controlled landfill leachate is collected and either reinjected, treated on site, or sent for off-site treatment. In the absence of leachate management systems, uncontrolled leachate releases occur when water travels through the waste, out of the landfill, and into groundwater or surface water (see Section 4).

LFG can also contain heavy metals, organic chemicals, and greenhouse gases and can produce explosive mixtures of gas in the vicinity of the landfill if not properly controlled (ATSDR, 2001). LFG capture technologies are widely used to control gaseous emissions from landfills. However, not all landfills are required to install and operate LFG collection systems. Even when an LFG collection system is installed and properly operated, a fraction of LFG is emitted directly to the environment through the landfill surface and other routes as fugitive losses (see Section 4).

Even years after landfill closure, direct human and ecological exposure to PFAS is possible if PFAS are emitted through the air, groundwater, or surface water, or if remaining waste is disturbed. Because landfills contain PFAS but are not designed to destroy these compounds, they represent a potential source of PFAS release well beyond the period in which landfills receive waste and the post-closure care period. Ideally, landfill areas could be used for other beneficial purposes after closure; this requires that potential risks from landfill contents be adequately managed. Direct exposure to PFAS from landfilled waste is possible for people living or working near landfills due to gaseous or water releases from the site. Additionally, if PFAS-containing wastes are present on trucks and moved to active cells, landfill employees are directly exposed to PFAS on the job. Research has shown elevated concentrations of PFAS in landfill ambient air (Hamid et al., 2018).

Potential impacts to vulnerable communities from landfill releases should also be considered. Considerations should include which media may be affected by releases, and the potential exposure pathways resulting from releases. The characteristics of the potential exposed communities (e.g., demographics, socioeconomic status, ambient exposures, health conditions) provide information regarding the potential for disproportionate and adverse health and environmental effects, including cumulative impacts.

Ensuring that PFAS-containing waste is properly disposed of in lined landfills with active gas collection systems where volatile PFAS or MSW landfills are involved, is instrumental in reducing PFAS emissions into the environment. Care must also be taken to avoid disposal of PFAS wastes in landfills that are known to have compromised liners, as PFAS in the leachate will migrate and contaminate groundwater.

3.b.v Testing and monitoring

Currently, there are no federal requirements for the monitoring of PFAS in landfill waste, leachate, condensate, or LFG. EPA and others are conducting studies to evaluate the effectiveness of landfills in containing or managing PFAS (see Section 3.b). Landfill operators should include PFAS measurements with the regular leachate monitoring parameters that are regularly evaluated. Analyzing PFAS in LFG may pose a challenge for comparison across destruction/control technologies and types of landfills due to the lack of standardized testing (see Section 5.a for research needs).

The lack of testing and monitoring limit effective risk communication and dialogue with adjacent communities. The importance of dialogue with communities, and in particular, communities that may be more vulnerable to PFAS exposures, cannot be overemphasized. Suggestions for risk communication are included in Section 4.

3.b.vi Uncertainties/unknowns

EPA plans to conduct further research on PFAS within landfills, including the potential for PFAS to migrate to leachate or LFG without adequate controls. As with thermal treatment, EPA lacks detailed information on the amounts and concentrations of PFAS and precursor compounds in wastes that are landfilled. Limited research is providing some information on PFAS fate and portioning in landfill environments. The bulk of PFAS seems to remain with the solid waste mass, with quantifiable percentages in LFG and leachate. However, there is high level of uncertainty in these values and more data are needed. Sampling and analytical methodologies must be developed to quantify potential PFAS flows out of landfills—an effort that may be complicated by the long lifespan of some PFAS. Additionally, the efficacy of treatment options for PFAS captured by leachate and LFG systems is not well understood and is in some cases intrinsically entwined with TWTDS and thermal treatment options. EPA continues to research these complex and important issues. Refer to Section 5 for a summary of EPA and DoD’s planned research activities specific to landfill containment, wastewater treatment, and thermal treatment of PFAS.

When evaluating landfill options, decision-makers (e.g., managers of PFAS-containing materials and PFAS-containing waste) should consider potential impacts to communities, including vulnerable populations. Uncertainties regarding LFG or leachate releases could have consequences for communities that are exposed and may be disproportionately affected. EPA recommends that decision-makers screen communities located in the vicinity of potential releases from the destruction, disposal, and storage options (considering fate and transport) in order to consider the potential for adverse or disproportionate impacts (see Section 4) and to consider potential measures to prevent, reduce, or address such impacts. Depending on site-specific circumstances (e.g., PFAS concentrations, impacted media, and potential exposure pathways), the size and shape of this area (vicinity) will vary.

3.b.vii Summary

Due to widespread use and disposal through typical waste management pathways, many PFAS-containing wastes are currently managed through containment in landfills. Though landfills (except C&D landfills) are designed for permanent waste containment and management of liquid and gas production, it is currently unclear if all landfills used to dispose of PFAS and PFAS-containing materials have controls that are effective for managing PFAS discharges and emissions from waste streams. PFAS-containing waste should not be placed in C&D landfills that don’t have liner systems to intercept and manage the leachate. Even with appropriate liners, research has shown an overall collection efficiency of 98 percent for geomembrane and composite liners. Given the chemical makeup of PFAS, some compounds are expected to persist in landfills for years.

As leachate passes through landfills, PFAS are released from degrading wastes. PFAS have been detected in the leachate for all types of landfills, and improper management of landfill leachate would result in PFAS releases. To date, research on the efficacy of wastewater treatment technologies in capturing or destroying PFAS in leachate is limited, as most landfills are not currently required to treat leachate for PFAS. The existing data suggest that adsorption and separation treatment mechanisms have been shown to concentrate or capture PFAS from landfill leachate (see Table 3-4). Other leachate management options can control the release of PFAS, including recirculation and solidification, which return PFAS to the landfill. Leachate treatment through natural processes such as constructed wetlands, land application, or ponds is ineffective for preventing the release of PFAS into the environment. More data are needed on the volatilization of PFAS during leachate handling and treatment.

PFAS can be emitted with LFG that is generated as waste decomposes over time. On-site and off-site LFG management commonly uses flares, engines, or boilers to combust LFG. Combustion temperature and duration could be critical factors for the destruction of PFAS in LFG, as discussed in Section 3.a.

To varying degrees, hazardous waste or MSW landfills are feasible and effective disposal options for PFAS and PFAS-containing materials. Permitted hazardous waste landfills employ the most extensive set of environmental controls (e.g., double liner systems with leachate collection and leak detection) and practices (e.g., extensive record keeping) that are currently available for the containment of PFAS waste (see Table 3-2) and as a result would be more effective at minimizing PFAS release into the environment than other landfill types. Hazardous waste landfills do not typically accept biodegradable wastes (e.g., biosolids, food scraps), and are not biologically active, so they do not generally need to be equipped to collect and control LFG. Therefore, hazardous waste landfills are not expected to cause PFAS emissions via LFG and may not be appropriate options for biodegradable PFAS-containing wastes.

Modern MSW landfills, when constructed with appropriate controls (e.g., liner system and leachate and gas collection and management systems), can also control the release of PFAS into the environment. Even with these controls in place, the proper management of landfill gaseous and liquid releases needs to be applied to minimize PFAS release into the environment (see Section 3.b.iii). Care must be taken to apply the leachate control technologies that are effective at containing (e.g., solidification, recirculation) or destroying PFAS (see Table 3-4).

Given the high level of uncertainty associated with PFAS behavior in landfills, the effects of PFAS on liner integrity, gaseous emissions from landfills, the effectiveness of leachate treatment for PFAS removal, and the levels and types of PFAS in landfill leachate—additional research will help to further evaluate this disposal method for PFAS and PFAS-containing wastes. See Figure 3-2 for a summary of recommended landfill disposal options for PFAS-containing wastes and considerations for selecting the best option based on both waste and landfill characteristics.

See Appendix D for a summary of costs and considerations.

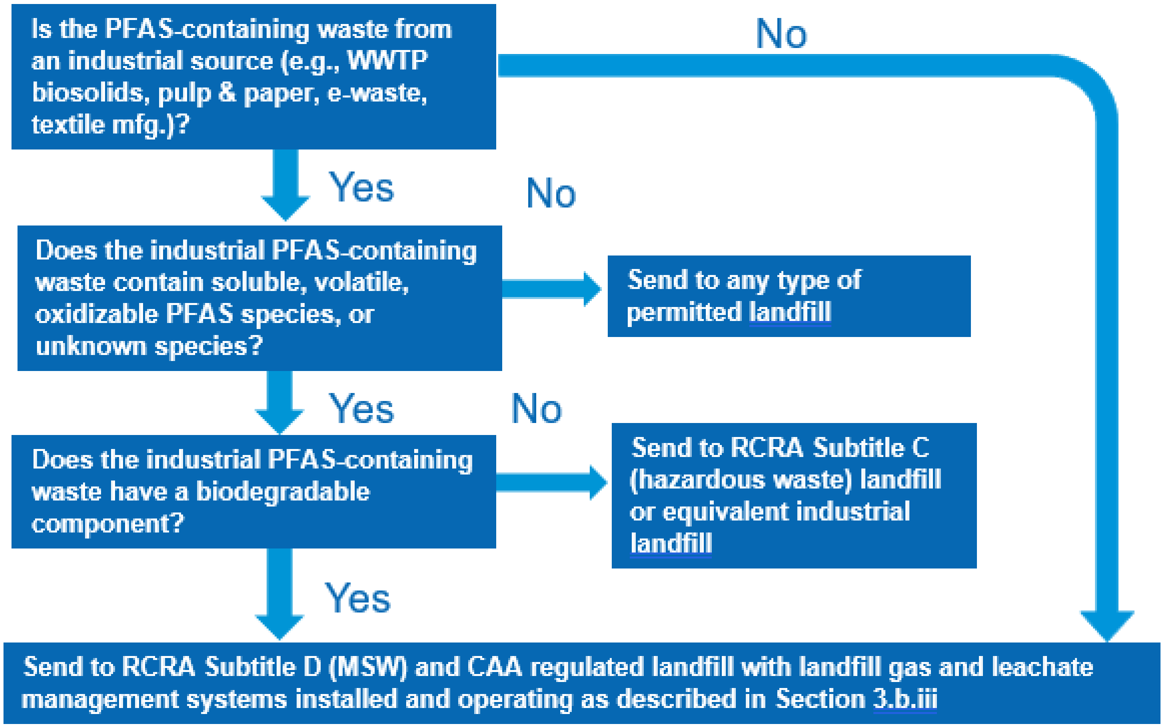

Figure 3-2. Decision framework for selection of landfill disposal for PFAS-containing industrial waste.

3.b.viii References for Section 3.b

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3.c Underground injection

Underground injection wells are a feasible and effective disposal option that normally should minimize release of PFAS into the environment. However, underground injection wells are only suited for the disposal of liquids and are restricted to locations with suitable geology. PFAS-containing fluids are currently handled similarly to other waste streams that are injected deep into geologic formations in Class I non-hazardous industrial and hazardous waste disposal wells, while shallow Class V wells would be inappropriate for the management of PFAS-containing fluids. The limited number of wells currently receiving PFAS and accepting off-site waste, well location, and waste transportation logistics may significantly limit the type and quantity of PFAS-containing fluids appropriate for underground injection.

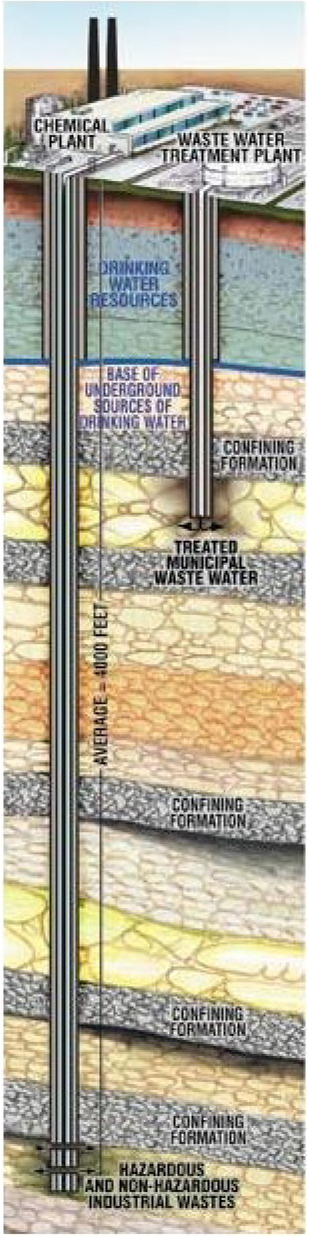

Figure 3-3. Class I wells.

3.c.i Types of wells

Underground injection is generally defined as the subsurface emplacement of fluids through a well. Under the Safe Drinking Water Act (SDWA), EPA is authorized to regulate the permitting of injection wells—including construction, operation, monitoring, and proper closure—for the purpose of protecting USDWs. Underground injection control (UIC) regulations are found in 40 CFR parts 144 to 148.

EPA's UIC program shares information for owners and operators of injection wells, regulators, and the public about safe injection well operations to prevent the contamination of USDWs. Under the UIC program, EPA regulates the permitting of the following well types:

- **Class I** wells inject into geologic formations below the lowermost USDW and are further subdivided into four categories: municipal wastewater, radioactive waste, hazardous waste, and non-hazardous industrial waste disposal wells (see Figure 3-3).
- **Class II** wells are used for injection activities associated with oil and gas production and hydrocarbon storage.
- **Class III** wells are solution mining wells used to inject fluids for the purposes of dissolving and extracting minerals.
- **Class IV** wells, with limited exceptions, have been banned by EPA since 1984 and were used to inject hazardous or radioactive waste into or above geologic formations containing USDWs.
- **Class V** wells include injection wells that are not included in Classes I, II, III, IV, or VI. EPA has identified multiple subtypes, including stormwater drainage wells, septic system leach fields, and agricultural drainage wells.
- **Class VI** wells are used to inject and geologically sequester carbon dioxide.

EPA has determined the use of Class I non-hazardous industrial waste and hazardous waste wells for high concentration liquid PFAS waste has a lower potential for environmental release when compared to other PFAS destruction and disposal options, and there is relatively low uncertainty in this determination. Class I underground injection wells are designed to dispose of and isolate liquid waste below the land surface and beneath USDWs. The standards associated with the construction, operation, and monitoring of Class I wells are designed to ensure protection of USDWs. These standards include at least one confining layer between the zone in which the fluid will be emplaced and the lowest USDW. While Class I wells are an option for managing PFAS-containing fluids, this technology may not be appropriate everywhere. The suitability of a site for injection is dependent on the geologic formations in the area. Sites need to be evaluated to ensure that there is an appropriate confining zone and that there are geologic formations that can receive fluids.

Class I wells for non-hazardous industrial and hazardous waste are currently being used for disposal of PFAS-containing fluids and are the focus of this section. PFAS-containing fluids that may be disposed of via Class I underground injection wells may originate from industrial activities such as chemical production (e.g., products and byproducts) and waste management operation (e.g., landfill leachate).

The standards associated with the permitting, construction, operation, and monitoring of Class I hazardous waste wells, which are regulated under RCRA and SDWA, are more stringent than for non-hazardous industrial waste disposal wells.

3.c.ii Siting, engineering, and operational controls

3.c.ii.1 Overview of the regulatory framework

Underground injection through Class I non-hazardous industrial and hazardous waste wells is a long-standing, well-regulated disposal technology. Underground injection has been used as a waste disposal practice in the United States since the 1930s, beginning with disposal of brines from oil production activities. Underground injection of wastewater from industrial facilities has been in practice since the 1950s. In response to concerns around underground injection activities and incidents of well failure, in 1974 (the same year the SDWA was enacted), “EPA issued a policy statement in which it opposed underground injection without strict control and clear demonstration that the wastes will not adversely affect groundwater supplies” (U.S. EPA, 2001).

Final UIC regulations were published six years later, and federal and state regulation and oversight has been informed by extensive reviews of injection practices and the associated risks over time (U.S. EPA, 2001). The requirements for Class I wells under 40 CFR part 146 and 40 CFR part 148 (which applies to hazardous waste wells only) are designed to ensure that injected fluids cannot migrate into USDWs through either of two potential pathways: loss of waste confinement or “improperly plugged or completed wells or other pathways near the well” (U.S. EPA, 2001). These requirements include, but are not limited to:

- Proper siting.
- Conducting geologic and hydrogeologic studies that demonstrate that injected fluids will not endanger USDWs.
- Implementing specific design, construction, and operation requirements.
- Implementing continuous monitoring and periodic monitoring and testing requirements.
- Performing appropriate well closure and plugging.

Specific components of these requirements are discussed further below.

3.c.ii.2 Class I non-hazardous industrial and hazardous waste wells

Underground injection to Class I non-hazardous industrial and hazardous waste wells reduces the potential risks of human exposure to injected materials, avoiding discharge to surface and shallow groundwater and generating little or no air emissions. When injected into non-hazardous industrial or hazardous waste Class I wells, fluids are placed below the lowermost USDW. The area into which waste is injected is referred to as the injection zone. Injection zones of Class I wells typically range from 1,700 to more than 10,000 feet in depth (U.S. EPA, 2001). Injection zones are porous and permeable geologic formations. They are separated from USDWs by one or more confining layers of impermeable rock. The confining layers prevent injected fluids from migrating vertically into a USDW.

Class I wells are sited in geological areas that are conducive to injection operations. Siting considerations include ensuring that injected fluids will not migrate through natural fractures and faults from the injection zone into USDWs. Likewise, well operators are required to demonstrate the absence of non-natural pathways (e.g., abandoned wells) or other nearby active wells that could allow for movement of injected fluids into USDWs, within a prescribed area surrounding the well (known as the area of review). In addition to the safeguards offered by siting, engineering, and operating requirements, well design and construction requirements incorporate redundant safety features, and construction materials are “corrosion-resistant and compatible with the wastewater and the formation rocks and fluids into which they come in contact” (U.S. EPA, 2001). Class I wells might also use multiple strings of well casing, inject through tubing set on a packer, and be constructed with adequate cement alongside the entire well string to protect any USDWs.

3.c.ii.3 Potential for Release

Permitted underground injection of fluids through Class I non-hazardous industrial and hazardous waste wells ensures that injected fluids are confined and cannot enter USDWs—the pathway of concern for this waste disposal technology. In its 2001 study of risks associated with Class I wells, EPA stated that the “probability of Class I well failures, both non-hazardous and hazardous, has been demonstrated to be low. In the unlikely event that a well would fail, the geology of the injection and confining zones serves as a final safety net against movement of wastewaters to USDWs” (U.S. EPA, 2001).

Injection well operators invest millions of dollars in the permitting, construction, and operation of wells. Development of Class I non-hazardous industrial and hazardous waste wells is a resource-intensive process, with the geologic limitations noted previously. In addition, siting requirements limit the areas in the country where Class I wells can be located (see Section 3.c.iii). Routine operation and maintenance include addressing requirements for extensive mechanical integrity testing, monitoring, and periodic submission of permit/no-migration petitions.

3.c.ii.4 Additional requirements for Class I hazardous waste wells

Class I hazardous waste wells are highly protective of USDWs and include additional requirements beyond those of Class I non-hazardous industrial waste wells. The 1984 Hazardous and Solid Waste Amendments to RCRA prohibited land disposal of hazardous waste, including via underground injection, with limited exceptions. Hazardous waste disposal via Class I injection wells is permitted if the operator can demonstrate that the waste will remain where it has been injected for as long as it remains hazardous (defined under regulation as a period of up to 10,000 years). To demonstrate this, Class I hazardous waste well operators must receive approvals of “no-migration petitions” from EPA.

No-migration petitions present information and modeling results using data on local and regional geology, waste characteristics, geochemical conditions of the well site, injection history, and many other factors, which EPA reviews to determine whether the petitioner has adequately demonstrated that the waste will not migrate from the disposal site for as long as it remains hazardous. Furthermore, Class I hazardous waste well facilities are subject to inspections and well operators must conduct annual testing and analysis to demonstrate they are meeting the conditions of the permit and that all assumptions, projections, and models are still appropriate and valid. This includes performing mechanical pressure tests and geophysical logging tests to assess well integrity both internally and externally to ensure injected fluids are being emplaced and are remaining within the injection zone.

3.c.iii Availability

The United States currently has 925 Class I wells. Slightly less than half (48 percent) are permitted for non-hazardous industrial waste injection. Approximately 15 percent are permitted for hazardous waste disposal. The remainder are permitted for municipal wastewater disposal. Currently, EPA is aware of both non-hazardous industrial and hazardous Class I wells that manage PFAS-containing fluids. However, there is currently no national information on the number and location of Class I non-hazardous industrial or hazardous waste wells that could accept PFAS-containing waste or are willing to accept waste not generated on site.

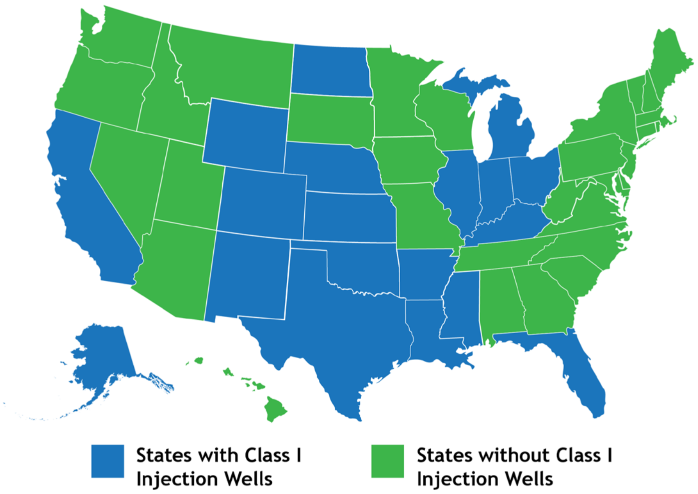

Figure 3-4. States with Class I non-hazardous or hazardous waste injection wells.

Figure 3-4 shows all states that currently have at least one permitted Class I injection well of any type (non-hazardous industrial or hazardous waste). Table 3-5 provides a more detailed breakdown of the number of permitted Class I wells by state.

Table 3-5. Inventory of Permitted Class I Non-Hazardous and Hazardous Waste Wells in the United States (FY 2022; Source: EPA)[19]

Location of Wells		Number of Wells	
EPA Region	State/Tribe	Class I Non-Hazardous	Class I Hazardous
4	Florida	343	-
	Kentucky	2	-
	Seminole Tribe	3	-
	Mississippi	4	4
5	Illinois	5	2

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[19] EPA's inventory of Class I non-hazardous waste wells consists of all non-hazardous waste wells, including municipal and industrial waste wells. However, the municipal waste wells are located exclusively in Florida.

Location of Wells		Number of Wells	
EPA Region	**State/Tribe**	**Class I Non-Hazardous**	**Class I Hazardous**
	Indiana	13	4
	Michigan	40	7
	Ohio	7	11
6	Arkansas	8	4
	Louisiana	16	19
	New Mexico	6	-
	Oklahoma	6	-
	Osage Nation	1	-
	Texas	83	77
7	Kansas	58	7
	Nebraska	11	-
8	Colorado	13	-
	North Dakota	8	-
	Wyoming	89	-
9	California	52	-
10	Alaska	22	-
Total		**790**	**135**

3.c.iii.1 Class I non-hazardous industrial waste wells

Non-hazardous industrial waste wells are currently located across 19 states and two Tribal lands, though the majority are in five states—Wyoming, Texas, Kansas, California, and Michigan. There are currently no Class I non-hazardous waste wells in EPA Regions 1, 2, or 3 (see Figure 3-4 and Table 3-5). Disposal to this type of well requires well operators to apply for and receive a permit for specific waste streams. Current Class I injection wells may have limited capacity for PFAS-containing fluids, as many of them are used for specific purposes and disposal of waste generated on site. To begin accepting PFAS-containing fluids, existing well permits would have to be modified to recognize that the facility is accepting waste from other entities and authorize the facility to inject modified waste streams.

Well operators must also consider the well's capacity to accept additional volumes of waste and the compatibility of the PFAS-containing fluids with the well material, the geochemistry of the injection formation and formation fluids, and the properties of other injected wastes.

3.c.iii.2 Class I hazardous waste wells

Hazardous waste wells are currently located in nine states; however, most are in Texas and Louisiana. Most Class I hazardous waste wells are sited at industrial facilities and dispose of waste generated on site (U.S. EPA, 2016). There are currently no Class I hazardous waste wells in EPA Regions 1, 2, 3, 8, 9, or 10 (see Figure 3-4 and Table 3-5). Because of this geographic concentration of Class I hazardous waste wells, waste producers may face transportation and logistical challenges.

EPA anticipates the number of current Class I hazardous waste wells that would begin accepting new sources of PFAS-containing waste to be very limited due to the necessary modifications of Class I hazardous waste well permits (e.g., increased injection volumes, changes to waste streams, no-migration petitions). These modifications would involve engineering and scientific evaluations, modeling, and public hearings.

3.c.iv Testing and monitoring

Class I non-hazardous industrial waste and hazardous waste disposal wells are subject to extensive testing and monitoring requirements established under federal regulations. Requirements for hazardous waste wells are more stringent than for non-hazardous industrial waste wells. Additionally, by law, states with primary enforcement authority for Class I wells may have more stringent testing and monitoring requirements. Class I monitoring and testing requirements are designed to ensure there are no leaks within or out of the well and that all injected fluid is contained in the injection zone.

Broadly, Class I well operators must:

- Analyze characteristics of injected fluids at a frequency that results in representative data.
- Continuously monitor and record injection pressure, annulus pressure, flow rate, and volume.
- Conduct internal and external mechanical integrity testing.
- Monitor for fluid release into the USDW within the area of review.

Class I hazardous waste wells operators must conduct mechanical integrity testing more often than Class I non-hazardous industrial waste operators. They also must establish and follow additional procedures for reporting and correcting mechanical integrity problems. Class I hazardous waste well operators must also develop and follow a waste analysis plan and conduct annual tests of cement at the base of the well (U.S. EPA, 2015).

Additional information on testing and monitoring requirements, including mechanical integrity testing, is included in EPA's summary document *Requirements for All Class I Wells and Class I Hazardous Waste Wells* and EPA Region 5's guidance on *Determination of the Mechanical Integrity of Injection Wells*.

Communicating testing and monitoring results with adjacent communities is particularly important given the high-profile nature of PFAS. The importance of encouraging dialogue with communities, especially communities that may be more vulnerable to PFAS exposures, cannot be overemphasized. Suggestions for risk communication are included in Section 4.

3.c.v Uncertainties/unknowns

The fate and transport of PFAS in the subsurface depends on the chemical and physical properties of specific PFAS and the geochemical properties of the injection zone. Understanding of the long-term fate and transport properties of PFAS (including precursors) in the injection zone is currently limited. Studies have shown wide ranges in PFAS properties, and these can be altered by mixture effects and interactions with co-contaminants. This creates uncertainty in predictions of PFAS contaminant release and longevity in the injection zone. These uncertainties need to be considered in the development of the required no-migration petition for disposal of PFAS in Class I hazardous waste wells.

When evaluating underground injection options, decision-makers (managers of PFAS-containing materials and PFAS-containing waste) should consider potential impacts to communities, including vulnerable populations. Underestimation of the potential for PFAS release could increase impacts to local communities, including vulnerable communities. EPA recommends that decision-makers screen communities located in the vicinity of the destruction, disposal, and storage options in order to consider the potential for adverse, including any cumulative and disproportionate impacts (see Section 4), and potential measures to prevent, reduce, or address such impacts. Depending on site-specific circumstances (e.g., PFAS concentrations, impacted media, and potential exposure pathways), the size and shape of this area (vicinity) will vary.

3.c.vi Summary

EPA has determined the use of Class I non-hazardous industrial waste and hazardous waste wells for high concentration liquid PFAS waste has a lower potential for environmental release when compared to other PFAS destruction and disposal options. Permitted underground injection of fluids through Class I non-hazardous industrial and hazardous waste wells ensures that injected fluids are confined and cannot enter USDWs—the pathway of concern for this waste disposal technology. Additional Class I wells may need to be constructed where geologically suitable, and existing well permits may need to be modified to meet the capacity needs for PFAS disposal. Research on the long-term fate and transport of PFAS (including precursors) to predict release potential in the injection zone could support future permits.

See Appendix D for a summary of costs and considerations.

3.c.vii References for Section 3.c

U.S. EPA (Environmental Protection Agency). (2001). *Class I Underground Injection Control Program: Study of risks associated with Class I underground injection wells* (EPA 816-R-01-007). *https://www.epa.gov/sites/production/files/2015-07/documents/study_uic-class1_study_risks_class1.pdf*

U.S. EPA (Environmental Protection Agency). (2015). *Requirements for all Class I wells and Class I hazardous waste wells. https://www.epa.gov/sites/production/files/2015-10/documents/page_uic-class1_summary_class1_reqs_508c.pdf*

U.S. EPA (Environmental Protection Agency). (2016). *Class I industrial and municipal waste disposal wells. https://www.epa.gov/uic/class-i-industrial-and-municipal-waste-disposal-wells*

U.S. EPA (Environmental Protection Agency). (2021). *UIC Injection Well Inventory. https://www.epa.gov/uic/uic-injection-well-inventory*

4. Considerations for Potentially Vulnerable Populations Living Near Likely Destruction or Disposal Sites

The FY 2020 NDAA specifies that the interim guidance consider:

- The potential for releases of PFAS during destruction or disposal, including through volatilization, air dispersion, or leachate.
- Potentially vulnerable populations living near likely destruction or disposal sites.

This section describes potential releases and exposure pathways associated with destruction or disposal sites. It defines potentially vulnerable populations and provides interim guidance on considering vulnerable populations when assessing the potential impacts of releases. This section also suggests approaches to screen communities located in the vicinity of the destruction, disposal, and storage options in order to consider the potential for adverse and disproportionate impacts and potential measures to prevent, reduce, or address such impacts. Depending on site-specific circumstances (e.g., PFAS concentrations, impacted media, and potential exposure pathways), the size and shape of this area (vicinity) will vary. Focusing on impacts and potential ways to protect vulnerable populations, such as children who are more vulnerable than adults to chemicals like PFAS, will ensure the protection of all populations exposed to PFAS.

The primary audience of this interim guidance is managers of PFAS-containing materials and PFAS-containing waste and regulators who need to identify the most effective means for destroying or disposing of these materials, including to protect nearby communities who may include vulnerable populations. Others may find it useful, such as communities themselves, as well as community relations personnel, and the public. This section is not a primer on risk assessment and risk communication; rather, it contains pointers and references to existing information.

4.a Potential releases from destruction and disposal facilities

EPA develops regulations, guidance, and policies that ensure the safe management and cleanup of waste.[20] Nonetheless, it is possible for destruction or disposal activities to release PFAS.

For example, as described in Section 3.a.iii, thermal treatment activities could potentially release PFAS to the environment via stack emissions if adequate combustion conditions are not achieved or adequate pollution control devices are not used. Releases can also occur from the management of thermal treatment process residuals such as liquid discharges from acid gas scrubbers, air pollution control device media, and incinerator bottom ash. In addition, if uncontrolled, leachate can travel out of landfills (see Section 3.b.i) and into groundwater or surface water. Disposal of PFAS could also result in potential

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[20] Information on EPA's actions to address PFAS can be found here: *https://www.epa.gov/pfas/key-epa-actions-address-pfas*

releases from increased transport, management, and handling of waste associated with all the available technologies.

Risk assessment and communication are important tools to help protect communities and the environment from potential releases of harmful substances. Tools from the risk assessment process may also be useful when considering whether a facility is an appropriate option for receiving PFAS-containing waste. Risk communication and community engagement are important for building trust and addressing concerns about potential releases. EPA has developed resources for assessing, managing, and communicating environmental risks, including interim guidance and tools available to stakeholders and the public. These resources are summarized in Section 4.c.

4.b Potentially vulnerable populations

To consider potential impacts on vulnerable populations in PFAS destruction and disposal decision contexts, it is helpful to keep in mind that vulnerability refers to characteristics of individuals or populations that place them at increased risk of an adverse health effect. Vulnerability includes the cumulative impacts of economic, demographic, social, cultural, psychological, and physical states of the individual person or population that influence patterns of exposure to environmental contaminants and alter the relationship between the exposure of the environmental agent and adverse health outcomes (U.S. EPA, 2019a).

Described in Guidelines for Exposure Assessment (U.S. EPA, 2019), EPA's Framework for Cumulative Risk Assessment (U.S. EPA 2003) describes four properties of vulnerability:

- Differential susceptibility: An increased likelihood of sustaining an adverse effect from exposure to an agent. For example, an individual, group, or population might be more likely to show a response to an agent at a lower dose than the general population because of a preexisting health condition (e.g., asthma, cardiovascular disease, disability), genetic variation, prior damage from exposure, concurrent exposures to other stressors or developmental or life stage [e.g., children, older adults, pregnant women]).
- Differential exposure: Differences in exposure (e.g., magnitude, duration, frequency, pathway, route) from a variety of factors, including life stage, socioeconomic status, and cultural characteristics. For example:
    - Children might have a higher exposure and proportionally higher body burden of pesticides than adults because of their behavior patterns or food consumption (Moya et al., 2004; NRC, 1993).
    - When neighborhoods are racially or economically segregated, low-income people and people of color might live in neighborhoods or conditions where pollution sources are more likely to be sited and concentrated and thus where they experience higher exposures to air pollution (Lopez, 2003).
    - Studies on fish consumption and subsistence fishing patterns have documented racial/ethnic differences that can increase exposure from persistent, bioaccumulative chemicals in fish or wildlife (Burger, 2000; Burger 2002a; Burger 2002b; Burger et al. 2001; Burger et al., 1999a; Burger et al., 1998; Burger et al., 1993; Burger et al., 1999b; Corburn, 2002).
    - Tribal Nations and Native Americans can be exposed differentially to toxicants when dietary patterns involve consumption of locally caught fish or game for traditional or religious reasons (Fitzgerald et al., 1999; Fitzgerald et al., 1995; Fitzgerald et al., 1998; Fitzgerald et al., 2001; Harper et al., 2002; Schell et al., 2003).

- Differential preparedness: The regulatory frameworks, protections, and resources that an individual, community or population uses or can access to withstand the insult of agents.
- Differential ability to recover: Refers to resources, repair, and resilience systems, such as income level, ability to move from an affected area or access to health care, which can affect recovery from the effects of an agent.

Communities with environmental justice concerns experience disproportionate and adverse human health or environmental burdens. These burdens may arise from a number of causes, including the cumulative impacts of inequitable access to clean water, clean air, natural places, and resources for other basic human health and environmental needs; the concentration of pollution, hazardous waste, and toxic exposures; and underinvestment in affordable housing that is safe and healthy and in basic infrastructure and services to support such housing, including safe drinking water and effective sewage management. The cumulative impacts of exposure to those types of burdens and other stressors, including those related to climate change and the environment, are also important indicators of vulnerable populations (Executive Order 14096, 2023).

The following sections provide examples of tools, methods, and approaches to identifying and considering vulnerable populations.

4.c Considering vulnerability

Executive Order (EO) 14096, "Revitalizing Our Nation's Commitment to Environmental Justice for All"" (issued by President Biden in April 2023), directs federal agencies to advance the goal of environmental justice, which means: "the just treatment and meaningful involvement of all people, regardless of income, race, color, national origin, Tribal affiliation, or disability, in agency decision-making and other federal activities that affect human health and the environment so that people:

(i) are fully protected from disproportionate and adverse human health and environmental effects (including risks) and hazards, including those related to climate change, the cumulative impacts of environmental and other burdens, and the legacy of racism or other structural or systemic barriers; and

(ii) have equitable access to a healthy, sustainable, and resilient environment in which to live, play, work, learn, grow, worship, and engage in cultural and subsistence practices."[21]

To advance this charge and apply the best available science on the vulnerability of exposure to children and other sensitive populations, EPA has developed tools, methods, and approaches to identify and assess the potential for adverse and disproportionate impacts, including risks, to potentially vulnerable populations, including communities with environmental justice concerns.

4.c.i Identifying potentially vulnerable populations

The consideration of potentially vulnerable populations living near likely PFAS destruction or disposal sites starts with identifying and characterizing adjacent and potentially exposed communities and populations. EPA provides the following tools to assist with this task:

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[21] See EO 14096, section 2(b), 88 FR 25251 (2023). EO 14096 builds on and complements EO 12898, "Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations" (1994).

4.c.i.1 EJScreen

This EJ mapping and screening tool (*EJScreen*) provides EPA with a nationally consistent dataset and approach for combining environmental and demographic indicators. EJScreen users choose a geographic area; the tool then provides demographic and environmental information for that area. This is EPA's principal tool for characterizing and identifying communities with environmental justice concerns next to facilities or sources of pollution. Users can download reports that summarize search findings.

To summarize how environmental indicators and demographics come together in the same location, EJScreen 2.2 uses 13 EJ indexes that reflect the following 13 environmental indicators:

- Particulate Matter 2.5
- Ozone
- Diesel Particulate Matter
- Toxic Releases to Air
- Air Toxics Cancer Risk
- Air Toxics Respiratory Hazard Index
- Traffic Proximity
- Lead Paint
- Risk Management Plan (RMP) Facility Proximity
- Hazardous Waste Proximity
- Superfund Proximity
- Underground Storage Tanks (USTs) and Leaking USTs
- Wastewater Discharge.

The EJ Indexes combine environmental indicators with information about the low-income and racial and ethnic minority population in a Census block group. A Census block group is the smallest level of geography you can get basic demographic data for, such as total population by age, sex, and race (U.S. Census Bureau, 2023). For example, the EJ Index for traffic combines:

- The traffic indicator
- The low-income population
- The racial and ethnic minority population.

EJScreen presents results in terms of percentiles, allowing community comparisons with the rest of the state, an EPA Region, or the nation, and to identify which communities may be potentially overburdened.

Users can also look at the factors independently. In addition, EJScreen offers several more maps based on demographic and socioeconomic data (e.g., U.S. Census data, the American Community Survey) as well as indicators of other stressors, such as certain health indicators and access to medical care.

4.c.i.2 Enforcement Compliance and History Online (ECHO)

EPA's *Enforcement Compliance and History Online* (ECHO) website lets users search for facilities in communities to assess their compliance with environmental regulations that protect human health and the environment. Permit writers may consider susceptibility and vulnerability when establishing permit conditions and ECHO is a useful tool to evaluate whether a facility is currently violating or has previously violated those conditions. Users access ECHO to:

- Search for facilities
- Investigate pollution sources
- Search for EPA enforcement cases
- Examine and create enforcement-related maps
- Analyze trends in compliance and enforcement data
- Identify facilities on or near Tribal land.

4.c.i.3 PFAS Analytic Tools

The *PFAS Analytic Tools* integrate 11 national datasets on PFAS into an interactive, web-based software. Users can filter data by PFAS or geographic area, explore application charts and maps, or download and open the files to explore the data. Information includes Clean Water Act discharges from permitted sources, a log of spills reported containing PFAS constituents, lists of facilities historically manufacturing and importing PFAS, federally owned locations where PFAS is being investigated, a history of known transfers of PFAS waste and how those wastes were managed, facilities that EPA knows is processing, releasing, and disposing of PFAS, PFAS detections in the environment (e.g., surface water, fish tissue), and drinking water testing results.[22] The data cover a broad list of PFAS and represent EPA's ongoing efforts to consolidate the growing amount of testing information that is available.

4.c.i.4 Private Domestic Well Map

EPA's *Private Drinking Water Wells* collection of online mapping tools provides information on drinking water providers and sources (including domestic [i.e., private] water wells and how many people are using them), as well as potential sources of contamination. Understanding the density and geospatial location of private domestic wells, and housing units relying on them, improves detection and response efforts.

EPA developed this mapping tool based on two methods to estimate private well density. The maps combine reported wells in 20 states with available well log data and the net housing unit method that is available in all 50 states for estimating domestic well use. The maps do not display the location of private wells. The value of this mapping tool is its identification of areas that may be vulnerable to groundwater contamination based on the presence of private wells. The source of contamination widget allows users to identify potential sources of contamination in defined locations.

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[22] Information available to EPA is limited. For example, EPA has identified transfers of PFAS waste in EPA's eManifest system that tracks shipments of federally regulated hazardous wastes. Since PFAS are not currently regulated as hazardous waste, though, this information is not required to be reported – resulting in an incomplete picture of PFAS waste transfers in the United States. What EPA is able to identify in eManifest comes from querying free text fields where PFAS information is mentioned or a state has regulated PFAS as a hazardous waste and has established a state hazardous waste code. The tool also shows release and transfer information from the Toxics Release Inventory. However, the number of reporting facilities and reported recipient facilities has been low since the beginning of PFAS TRI Reporting likely associated with the *de minimis* exemption. A final rulemaking removing that exemption may lead to a more complete picture of releases and transfers in future reporting years. The PFAS Analytic Tools does not currently include information on PFAS destruction efficiency or efficacy.

4.c.i.5 Risk-Screening Environmental Indicators (RSEI) model

EPA's Risk-Screening Environmental Indicators (RSEI) model helps policy makers, researchers, and communities explore data on toxic chemicals being managed by industrial and federal facilities. RSEI incorporates information from the TRI on the amount of toxic chemicals released or transferred from facilities, together with factors such as the chemicals' fate and transport through the environment, each chemical's relative toxicity, and potential human exposure. RSEI model results can be used to help establish priorities for further investigation and to look at changes in potential human health impacts over time.

4.c.i.6 EnviroAtlas

EPA's *EnviroAtlas* highlights relationships between communities, land use, and environmental quality. The mapping functions help identify potential uses of land that, when combined with site contaminant data, may indicate possible exposure pathways. Such land use relationships can trigger deeper investigation into land uses to characterize relevant activities to inform site sampling and risk assessment.

The information gathered can be used to modify Conceptual Site Models, which are descriptions of contaminant sources, releases, transport pathways, and potential receptors. Accurate and complete Conceptual Site Models are required to ensure that samples are collected in appropriate media and risks are analyzed for potentially exposed receptors.

4.c.i.7 Climate and Economic Justice Screening Tool (CEJST)

The *Climate and Economic Justice Screening Tool* (CEJST) helps federal agencies identify disadvantaged communities geographically that are marginalized by underinvestment and overburdened by pollution. These communities are in Census tracts that are at or above the thresholds in one or more of eight categories of burden or are located on the lands of Federally Recognized Tribes.[23] The current version of the tool evaluates the likelihood of disadvantage based on climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development factors, each in combination with low-income or educational attainment status. The current version of the tool will be updated based on more feedback and research.

4.c.i.8 Centers for Disease Control and Prevention (CDC) EJ Dashboard

The Centers for Disease Control and Prevention (CDC) *EJ Dashboard* provides contextual public health messaging and allows users to evaluate several screening factors, including community characteristics, environmental exposures, health burden, and indexes. Assessments are based on ZIP code. and census tracts. Evaluating communities surrounding a facility may require the use of multiple ZIP codes and census tracts. Community characteristics include demographics and social vulnerability, as well as a description of the built environment (e.g., access to parks). The Social Vulnerability Index (SVI) uses U.S. Census data to determine the social vulnerability of every Census tract. Census tracts are subdivisions of counties for which the U.S. Census collects statistical data. The SVI ranks each tract across 15 social factors, including poverty, lack of vehicle access, and crowded housing, and groups them by theme.

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[23] Census tracts that are completely surrounded by disadvantaged communities and are at or above the 50th percentile for low-income are also identified as disadvantaged by the CEJST.

The EJ Dashboard also provides more information on environmental exposures, health, and EJ. The Environmental Exposures tab presents environmental pollutant data, including water quality, age of housing, $PM_{2.5}$, and ozone. It also includes factors related to climate change. Under “Health Burden,” users can examine health vulnerability based on access to health insurance and hospitals, disability, infant mortality, and percentage of low birth weights. The *Environmental Justice Index* is a calculation based on the combined rankings of the Environmental Burden Module, the Social Vulnerability Module, and the Health Vulnerability Module. The Environmental Justice Index represents a measure of cumulative impacts on human health and well-being.

4.c.i.9 Tribal Data

Tribal populations and Tribal lands can be identified in EJScreen, ECHO, PFAS Analytic Tools (U.S. EPA, 2023) or with Housing and Urban Development’s Tribal Directory Assessment Tool (TDAT): *https://egis.hud.gov/TDAT/*. For example, by clicking on a specific state, the user can identify Bureau of Indian Affairs Tribal boundaries and areas along with environmental media and other mapping layers. In addition, all lands of Federally Recognized Tribes, including Alaska Native Villages, are identified as disadvantaged in the CEJST.

4.c.ii Screening strategies to support waste management decision-making

There is no singularly definitive way to screen for the presence of and potential impacts on vulnerable populations. However, combining information on demographics and environmental and enforcement compliance could provide a useful indication of already overburdened or potentially vulnerable populations to inform decision-making. To avoid adding to disproportionate impacts, decisions regarding the destruction/disposal of PFAS-containing materials should be supported by an evaluation of communities located in the vicinity of the destruction, disposal, and storage. For example, less preferred facilities could be identified as those having a history of significant Clean Air Act violations, in an area with poor air quality and a high percentage of low-income people with significant air-related health disparities (e.g., asthma, lung cancer). This type of screening-level analysis can be used to identify communities with adverse and disproportionate impacts so as not to further exacerbate those impacts. It could also trigger questions for the facility regarding additional strategies to reduce the release of PFAS and other substances into the surrounding environment, including additional health protection, mitigation, and monitoring measures needed.

EPA has created several tools that can be helpful for screening, as have other federal and state agencies. Each tool has strengths and limitations. Options and suggestions for conducting a screening are described below.

EPA’s EJScreen (see Section 4.c.i.1) collates social and demographic information that provides insights into non-chemical stressors to communities and subpopulations. EJ screen provides data from the U.S. Census and the American Community Survey[24], as well as information on race, income, unemployment rate, limited English proficiency, educational attainment, and age. Users can drill down to learn about additional demographics, including population, health, housing, and other points of interest. These data can be particularly useful to characterize community resilience and limitations. EJScreen also has

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[24] The American Community Survey is an ongoing survey that annually provides vital demographic information about the United States (*https://www.census.gov/programs-surveys/acs*). Data are updated annually as a 5-year average. EJScreen version 2.2 includes 2017-2021 ACS 5-year summary file data.

important information about existing pollution levels. It is most robust for air quality, although it does have information on releases to water via NPDES permits and other sources.

EJScreen also provides indicators on health disparities. Other sources on health include CDC's EJ Dashboard. States may include additional details on health burdens on their websites and tools.

Collectively, this information can provide a snapshot of communities with environmental justice concerns, allowing the user to flag communities that may be stressed due to multiple factors. Decision-makers, for example, could perform additional screening at destruction and disposal facilities with communities exceeding the 80th (or another appropriate) percentile in multiple indicators, and therefore more closely consider vulnerable populations while evaluating destruction, disposal, and storage facilities.

Regarding compliance, EPA's ECHO tool (see Section 4.c.i.1) provides enforcement and compliance data on specific candidate destruction and disposal facilities. A history of Clean Water Act violations, for example, could be an indicator of disproportionately exposed communities, particularly if they rely on public water systems using a surface water source downstream of the facility. In addition, communities using private wells for drinking water may be more vulnerable to releases regulated under RCRA or CERCLA.

4.c.iii Considerations for community engagement

In certain cases, community engagement is required under law. For example, facilities must hold public meetings before submitting part B RCRA permit applications (U.S. EPA, 2013a) and public hearings if they are requested for CAA Title V permits. In some cases, EPA's policy is to consult and coordinate with Tribes (U.S. EPA, 2013b). Community engagement is not merely a matter of meeting requirements, though. Advancing the goal of meaningful involvement is a core principle under EO 14096[25]. Reaching out to the community and providing notification, information, and an opportunity for input before deciding whether to accept PFAS-containing waste for destruction or disposal will help build trust and support for operations and can reduce the likelihood of negative reactions stemming from unresolved concerns.

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Meaningful community engagement typically includes two key elements:

- Public outreach to disseminate relevant and accessible information to the community, including in relevant local languages and in formats accessible to individuals with disabilities.

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[25] *https://www.federalregister.gov/documents/2023/04/26/2023-08955/revitalizing-our-nations-commitment-to-environmental-justice-for-all*

- Public participation, which generally entails a dialogue with the community to ascertain information and viewpoints. This dialogue is particularly important because the community can provide local knowledge of health and existing conditions, identify concerns and issues that may not be readily apparent outside the community, and offer contextual/cultural perceptions and experience (U.S. EPA, 2016).

Although presenting highly technical information is always a challenge, involving vulnerable populations in a meaningful way may present different challenges and opportunities from those in a general public involvement effort. To foster meaningful participation of all community members, it may be important to address issues that could hinder a community's participation in the decision-making process. These may include time and resource constraints, language barriers, and lack of trust (U.S. EPA, 2016).

Examples of effective practices to engage diverse and vulnerable populations include the following:

- Early notification so that community input can be offered in a timely way and incorporated into the decision-making process.
- Conveying issues in ways that are tailored (for example, translation, timing, location) to each specific population.
- Bridging cultural and economic differences that affect participation.
- Developing trust between the government and potentially affected populations.
- Working closely with state and local partners, as well as other federal agencies, to present a unified, consistent message to communities.
- Developing stakeholder capacity or providing technical assistance to effectively participate in future decision-making processes (U.S. EPA, 2015b).

EPA has developed tools to assist the federal government, states, and private entities with community engagement and outreach. For example, the *Superfund Community Involvement Toolkit* (CI Toolkit, available at *https://www.epa.gov/superfund/superfund-community-involvement-tools-and-resources*) provides practical information to design and enhance community involvement activities. While the CI Toolkit is designed for users to quickly review and adapt a variety of community involvement tools to engage the community during all stages of the Superfund processes, the same tools can be adapted to engage communities adjacent to destruction and disposal facilities.

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5. Research Needs and Data Gaps for Destruction and Disposal Technologies

EPA has a better understanding of potential PFAS releases from destruction and disposal activities, but more research is needed. This section identifies high-priority data gaps that researchers across government, academia, and industry need to address. This additional research will help EPA provide meaningful updates on effective destruction and disposal practices for PFAS-containing materials. This section outlines research needs to inform future guidance updates and provides an overview of existing research activities to address these gaps.

5.a Research needs to inform future guidance updates

EPA has translated the uncertainties and data gaps identified throughout this interim guidance into research needs, which are presented in Table 5-1. The research needs in Table 5-1 are focused on advancing our ability to measure PFAS in materials and releases from destruction and disposal technologies and improving our understanding of the performance of thermal treatment units, landfills, and underground injection control wells for managing PFAS and PFAS-containing materials. Individually, the research needs identified in Table 5-1 are complex to address because of the variety of substances within the PFAS class, the range of PFAS-containing materials discussed in this interim guidance, and the variability in technology designs and operating conditions. Collectively, some of the research needs identified in Table 5-1 are dependent upon other research needs. For example, fully characterizing PFAS releases from destruction and disposal technologies is dependent upon the availability of methods for measuring PFAS in air, water, and solids. Because of the complexity of the research needs and their inter-dependence, EPA anticipates that it will take years for the research needs in Table 5-1 to be fully addressed.

EPA has also prioritized the research needs in Table 5-1 as either *high*, *medium*, or *low* based on the potential for results to inform future versions of this interim guidance. In general, EPA designated the characterization of potential PFAS releases from thermal treatment units and landfills as high priority because these data are essential for determining whether communities surrounding destruction and disposal sites could be exposed to PFAS at unreasonable levels from these facilities. At the same time, EPA recognizes that current laboratory methods for identifying and quantifying PFAS are limited. As such, the agency also considers the development of sampling and analytical methods to be medium or high priority. The agency does not, however, believe that characterizing PFAS releases from PFAS destruction and disposal activities should wait until additional analytical methods are available. Rather, EPA expects that characterizing PFAS releases from destruction and disposal sites will be iterative and that future characterization efforts will be informed and guided by past efforts and the availability of new methods.

EPA designated research needs associated with the underground injection of PFAS and PFAS-containing materials via Class I wells as a low priority. The agency made this designation because the standards associated with the construction, operation, and monitoring of Class I wells are designed to isolate liquid wastes deep below the land surface and ensure protection of underground sources of drinking water. As a result, EPA expects underground injection of liquid PFAS waste to have a lower potential for environmental release, compared to managing PFAS wastes through thermal treatment or landfills. While data on the performance of Class I wells for managing liquid PFAS waste would be informative, the highest priority continues to be on characterizing PFAS releases from thermal treatment units and landfills.

Table 5-1. Prioritized Research Needs to Inform Future Guidance Updates

Topic	Research Needs	Priority
Thermal Treatment	Methods for sampling and analyzing PFAS in solid-, liquid-, and gas-phase waste streams from thermal treatment units[a]	
	• Organic fluorine (all phases)	Low
	• Targeted methods for non-polar, semivolatile PFAS (gas-phase)	High
	• Targeted methods for cationic, zwitterionic, and nonionic PFAS (solid- and liquid-phase)	High
	Full-scale performance testing—following the parameters and procedures suggested in Appendix A—at:	
	• Hazardous waste combustors	
	○ Commercial hazardous waste incinerators	High
	○ Hazardous-waste-burning cement kilns	High
	○ Hazardous-waste-burning lightweight aggregate kilns	Medium
	• Carbon regeneration and reactivation units	High
	• Non-hazardous waste combustors	
	○ Sewage sludge incinerators	High
	○ Municipal waste combustors	Medium
	○ Thermal oxidizers	High
	Characterization of PFAS releases from thermal treatment units operating under different conditions/designs	
	• Gas-phase emissions	High
	• Air pollution control device discharges	High
	• Bottom ash	High
	• Biosolids, remediated soil	High
Landfills	Methods for sampling and analyzing PFAS in liquid- and gas-phase waste streams from landfills [a]	
	• Organic fluorine (liquid- and gas-phase)	Medium
	• Targeted methods for non-polar, semivolatile PFAS (gas-phase)	Medium
	• Targeted methods for cationic, zwitterionic, and nonionic PFAS (liquid-phase)	Medium
	Approaches for solidification and stabilization of PFAS-containing materials [a]	
	• Effectiveness of differing solidification and stabilization techniques	High
	• Performance over time	High
	Fate and transport of PFAS—including partitioning between solid-, liquid-, and gas-phases in: [a]	
	• Hazardous waste landfills	High
	• Industrial waste landfills	High
	• Municipal solid waste landfills	Medium
	• Ash monofill landfills	Low
	• Construction and demolition (C&D) landfills	High
	Full-scale performance testing of engineered landfill components	
	• Bottom liner and leachate collection systems	Low
	• On-site leachate treatment systems	High

Topic	Research Needs	Priority
	- Gas collection and emission control systems - Final cover systems	Low Low
	Characterization of PFAS releases from landfills operating in different regions and under different conditions/designs - Gas-phase emissions - Groundwater contamination	 High High
	Efficacy and potential release of PFAS during leachate treatment - Conventional technologies - Emerging technologies	 High Medium
Underground Injection (Class I)	Performance data from wells that are managing PFAS-containing liquids - Surface management practices - Effects on injection performance	 Low Low
	Long-term fate and transport of PFAS in injection zones of Class I wells - Mixture effects - Interactions with co-contaminants	 Low Low
	Data on the presence/absence of PFAS in groundwater near Class I wells receiving PFAS-containing liquids	Low
Emerging Technologies	Lab-, pilot-, and field-scale research to test the effectiveness of emerging technologies for different PFAS-containing materials and to characterize the outputs for PFAS and non-PFAS constituents.[b]	High

[a.] EPA is conducting research on this topic. See Section 5.b.ii for a high-level overview of EPA research and development activities.

[b.] See Section 6 for discussion of emerging technologies. EPA encourages technology developers to generate and publicly release data that can be used to answer the questions presented in the technology evaluation framework in Section 6.b.

5.b Current research efforts to address data gaps

Addressing the research and data gaps described in Section 5.a will require effort across government, academic, and private institutions. This section provides an overview of resources to learn more about prospective research activities.

5.b.i Governmental, academic, and industry research activities

In late 2021, the Office of Science and Technology Policy (OSTP) formed the interagency PFAS Strategy Team as part of the National Science and Technology Council (NSTC) to coordinate federal research on PFAS. In early 2023, the PFAS Strategy Team published the *Per- and Polyfluoroalkyl Substances (PFAS) Report*. The PFAS Report provides a high-level overview of research on PFAS as a chemical class by addressing the following strategic areas: removal and destruction; safer alternatives; sources and pathways of exposure; and toxicity. This document is a state-of-the-science report that includes research activities, gaps, and opportunities for the federal government. Following release of the PFAS Report, the PFAS Strategy Team initiated efforts to develop a federal strategic plan to address data gaps identified in the PFAS Report. Additional information is available in the *CEQ Report on Biden-Harris Administration Progress on PFAS* (March 2023).[26]

While this interim guidance only outlines major DoD and EPA research programs, a more complete overview of existing federal PFAS research activities is available in Appendix A of the OSTP PFAS Report. DoD is the largest federal funder of PFAS destruction and disposal research (see Appendix B, OSTP 2023). Within DoD, the Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) have been funding significant research on PFAS for several years. The goals of this research include:

- Improving PFAS analytical methods and AFFF site characterization
- Understanding PFAS ecotoxicological effects
- Developing tools for assessing the fate of PFAS in the subsurface
- Developing and validating *in situ* and *ex situ* PFAS treatment technologies.

In 2022, SERDP-ESTCP published its *Summary Report: Strategic Workshop on Management of PFAS in the Environment* (Leeson et al., 2022). This report identifies research and demonstration needs for PFAS fate and transport, sampling and analysis, thermal treatment, non-thermal destructive treatments, and concentration technologies. To address these research needs, SERDP and ESTCP fund a robust research program, with annual solicitations for proposals. Descriptions of all PFAS-related statements of need and funded projects are available at *https://www.serdp-estcp.org/Featured-Initiatives/Per-and-Polyfluoroalkyl-Substances-PFASs*. Additionally, the Defense Innovation Unit has begun funding opportunities for innovation in technology for on-site PFAS destruction and remediation.

Colleges and universities, who are the recipients of federal and other research funding, conduct cutting-edge research related to PFAS destruction and disposal. These institutions often bring together expertise from many disciplines. This collaboration enables the rapid development of innovative approaches for managing the constantly changing set of PFAS-containing materials.

Other entities have strong interests in expanding into the area of PFAS material management, disposal, and destruction. These entities include private industry, the operators of waste disposal operations and technologies, municipal water utilities, professional and trade associations, and relevant research foundations. These organizations are actively developing and marketing solutions to address PFAS material management, disposal, and destruction.

5.b.ii EPA research and development activities

As described above, EPA is one of many governmental, academic, and industry organizations engaged in research on PFAS destruction and disposal. EPA's ORD is conducting research to characterize PFAS-contaminated sites and sources, and to understand the fundamental mechanisms of PFAS destruction and disposal technologies. This section provides a high-level overview of EPA research activities to support future interim guidance updates.

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[26] See also White House Fact Sheet: Biden-Harris Administration Takes New Action to Protect Communities from PFAS Pollution (March 14, 2023): *https://www.whitehouse.gov/briefing-room/statements-releases/2023/03/14/fact-sheet-biden-harris-administration-takes-new-action-to-protect-communities-from-pfas-pollution/*.

5.b.ii.1 Characterizing PFAS-containing materials

EPA is developing laboratory-based aqueous leaching methods to characterize leaching behavior of organic constituents, including PFAS, from solid materials under a range of environmental conditions. These methods are based on existing SW-846 Leaching Environmental Assessment Framework (LEAF) methods for inorganic constituents of potential concern (U.S. EPA, 2023). The methods produce a source term (i.e., as a concentration or release rate). Screening-level or scenario-based assessments can use the source term to model transport in the subsurface environment (Garrabrants et al., 2021a and 2021b).

EPA is continuing to develop and validate robust analytical methods to detect and measure PFAS in aqueous, solid, and gas-phase samples. The data generated with these methods will improve the understanding of environmental fate and transport and help evaluate the effectiveness of various treatment and destruction technologies. The suite of PFAS analytical methods under development includes targeted methods validated for quantitative analysis of a wider range of target analytes and matrices; class-specific methods, such as adsorbable organic fluorine and the total oxidizable precursors assay, to screen for a range of PFAS precursors; and non-targeted analytical methods to identify novel PFAS.

5.b.ii.2 Thermal treatment

ORD continues to conduct laboratory- and pilot-scale research to describe the behavior and mechanisms of destruction of PFAS-containing materials subject to thermal treatment. ORD facilities include a pilot-scale incinerator (the Rainbow furnace) and rotary kiln. This research examines the operating conditions (time, temperature, and combustion parameters) necessary for adequate PFAS destruction using conventional thermal treatment. The goal is to develop a mechanistic understanding of PFAS behavior and help interpret results from full-scale field studies. This includes measuring the generation of PICs from different PFAS-containing materials.

ORD is also interested in opportunities to partner with thermal treatment facilities to conduct field-scale research. The goals of this research would be to determine if representative field conditions achieve adequate thermal destruction of PFAS as defined by conventional DRE; characterize potential PICs/PIDs; and evaluate alternate indicators of destruction performance. The details of this thermal treatment field testing request are outlined in Appendix A.

5.b.ii.3 Landfills

ORD is developing novel sampling and modeling approaches to identify PFAS and characterize fate and transport at contaminated sites and source areas, including landfills. ORD is also evaluating solidification and stabilization techniques for PFAS applications.

5.b.ii.4 Extramural research

EPA supports PFAS research and development efforts through several programs, including *research grants*, the *Small Business Innovation Research* (SBIR) program, *challenges and prizes*, and the *P3 Student Design Competition*. For example:

- In 2019, *EPA awarded grants to eight universities* to better understand the environmental risks posed by PFAS and identify practical approaches to manage their potential environmental impacts. Several of these projects focused on characterizing PFAS in landfills. Research completed under these projects contributed to EPA's improved understanding of the potential for PFAS releases from landfills.

- In 2021, EPA collaborated on the *Innovative Ways to Destroy PFAS* challenge. Partners included SERDP-ESTCP, the Environmental Council of States and the Environmental Research Institute of the States, the Michigan Department of Environment, Great Lakes and Energy, and the Colorado Department of Public Health and Environment. The goal of the challenge was to discover new technologies and approaches that have the potential to remove at least 99 percent of PFAS in unused AFFF without creating harmful byproducts.
- EPA's SBIR program has funded many small businesses developing technologies to test and treat PFAS. These companies are developing products to destroy PFAS in a range of media using technologies including plasma reactors, electrochemical processes, sonolysis, hydrothermal alkaline treatment, and mechanochemical destruction. More information on technologies funded by EPA's SBIR program is available at *https://www.epa.gov/sbir/test-and-treat-pfas-epa-sbir-technologies*.

Information on open solicitations can be found at *https://www.epa.gov/chemical-research/pfas-research-extramural-funding-opportunities*.

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6. Emerging Technologies for PFAS Destruction and Disposal

Because of their chemical and physical properties, PFAS can pose unique challenges for end-of-life materials management. As described in Section 3, the effectiveness of commonly used waste management technologies, such as thermal treatment and landfilling, for managing PFAS materials can vary. Additionally, current operating conditions and practices at some thermal treatment facilities and landfills may not be sufficient to limit releases of PFAS to the environment. Concerns about the effectiveness of widely-used technologies for managing PFAS materials call for innovative research and development efforts toward new technologies as well as testing to apply existing destruction technologies to PFAS materials at various scales.

Development of new technologies typically involves the following stages:

- Technology development often starts with exploring and understanding the basic scientific principles and processes that underly the technology. At this early stage, the primary focus is on gaining understanding of how the process works and whether it shows promise for a particular application (e.g., PFAS destruction).
- If the results of early experiments are promising, the next stage of development generally focuses on prototype development and testing under controlled conditions. This stage allows developers to better understand whether the technology is practical and effective at larger scales. It also provides developers with information on costs associated with manufacturing and operating units.
- In the final stage of development, the focus generally shifts to field-scale demonstration projects that allow developers to test the technology under a variety of real-world conditions and to develop better cost estimates for operation and maintenance. During this stage, developers may identify the best and most cost-effective applications for the technology. In the case of PFAS destruction and disposal, this may include identifying the types of PFAS materials best suited for the technology (e.g., high-concentration materials versus low-concentration materials).

At any stage of the technology development process, developers may determine that the technology is not effective or is not cost-effective and development can stop.

In addition to research to identify and develop novel technologies for PFAS destruction, efforts are underway to apply existing destruction technologies—other than thermal treatment—to PFAS materials. In these cases, the scientific principles and processes underlying a technology may already be understood, but there is little information on the performance of the technology or its applicability to PFAS materials. Evaluating the applicability of an existing technology to PFAS materials can occur at various scales:

- Laboratory- and pilot-scale studies can be used to evaluate the effectiveness of a technology under controlled conditions and to determine how operating conditions can affect PFAS destruction.
- Field studies can provide data from full-scale applications that reflect the variability seen in real-world operating conditions.

The purpose of this section is to: (1) provide an overview of EPA efforts to identify and test emerging technologies for PFAS destruction and (2) introduce the PFAS destruction and disposal technology evaluation framework, which provides a transparent, consistent approach for evaluating destruction and disposal technologies for PFAS materials.

6.a EPA's PFAS Innovative Treatment Team

EPA's ORD initiated the PFAS Innovative Treatment Team (PITT) in 2020 as a short-term dedicated, cross-ORD effort to identify, review, and conduct preliminary research on potential treatment technologies. Over six months, the multi-disciplinary PITT conducted state-of-the-science reviews of proposed methods to dispose and/or destroy PFAS in media and wastes. Several criteria were evaluated using available information, including efficacy, feasibility, performance, and costs of each technology, while also considering potentially hazardous byproducts. The PITT partnered with other agencies and states to conduct a competitive public challenge to identify solutions that were potentially overlooked and to encourage further development of potential technologies.

The PITT chose to focus on the effectiveness of four technologies: mechanochemical degradation, electrochemical oxidation, gasification and pyrolysis, and supercritical water oxidation. These four technologies showed theoretical promise of the sought-after criteria: PFAS destruction, production of few to no hazardous residuals or byproducts, commercial availability, and cost effectiveness for various contaminated matrices. References and discussion for each technology can be accessed in the four PITT Research Briefs at *https://www.epa.gov/chemical-research/pfas-innovative-treatment-team-pitt*. The identification of these technologies by the PITT should not be considered an endorsement or recommendation to use these technologies to destroy PFAS. Additional research is needed to determine the effectiveness of these technologies for different PFAS-containing materials and to characterize the outputs for PFAS and non-PFAS constituents. An overview of the results of the PITT's state-of-the-science review is available in *Developing Innovative Treatment Technologies for PFAS-Containing Wastes* (Berg et al., 2022).

After the state-of-the-science reviews, the PITT selectively encouraged development and research of the four chosen emerging technologies to better understand the potential for PFAS destruction, specifically AFFF, while avoiding creation or transfer of environmental hazards. The PITT conducted in-house research and partnered with industry and academia to collect data regarding the technologies and to encourage further development of the methods required to ascertain PFAS destruction efficacy. Although the effort originally was allotted six months in 2020, the work initiated by the PITT continues to produce journal articles, fact sheets, and ORD reports. Some of the results from this continued work are described below. When considering the timeline, including navigating the initial restrictions of the COVID-19 pandemic, note there were several hurdles to obtaining necessary data, such as limited access to industrial field sites, analytical methods development, and availability of standards.

6.a.i PITT-investigated emerging technologies

To further explore the potential for mechanochemical degradation of PFAS, ORD scientists partnered with colleagues in New Zealand to conduct a proof-of-concept case study using a benchtop ball mill, AFFF-spiked sand, and AFFF-contaminated soil (Gobindlal et al., 2023). Mechanochemical degradation is a treatment technology that uses a high-energy ball-milling device, with the option of co-milling reagents, to produce highly reactive conditions to degrade contaminants. Results from the AFFF-spiked sand showed a 99.99% destruction efficiency for the sum of all measured PFAS after 960 min, and results from the AFFF-contaminated soil indicate that measured PFAS were below the limit of detection after 1440 min. Because this study analyzed PFAS in the solids after different ball milling time intervals, from 15 to 1440 min, the authors were able to identify increases in some of the measured PFAS before concentrations decreased, indicating the transformation of PFAS during ball milling. An extractable organic fluorine method was also used to determine the reduction in extractable organic fluorine before and after ball milling. In the case of AFFF-spiked sand, the authors reported a 97.8% reduction in extractable organic fluorine. A 53.5% reduction in extractable organic fluorine was reported for the AFFF-contaminated soil. Air emissions were not characterized as part of this study, making it difficult to determine whether full mineralization of PFAS occurred, and more work is needed in this regard. As noted in the study, more work is also needed to identify primary operations variables to inform the scalability of mechanochemical destruction.

In 2020, ORD conducted a pilot study at a biosolids treatment facility using pyrolysis (Thoma et al., 2022). Pyrolysis is a process that decomposes materials at moderately elevated temperatures in an oxygen-free environment. During the pilot study, dried biosolids were fed into a pyrolysis reactor operating at approximately 610 °C (1100 °F). The dried biosolids and the resulting biochar were sampled and tested for 41 target PFAS. Twenty-one PFAS were detected in the input biosolids, and none of the target PFAS were detected in the biochar. The pyrolysis system's target PFAS removal efficiencies were estimated to range between >81.3% and >99.9%. The pilot study also included limited analysis of the air emission control system, with results indicating no transmission of the target PFAS to the air. It is important to note, however, that full characterization of PFAS using non-targeted methods was not performed and more work is needed to understand PFAS transformations and the destruction mechanism.

ORD also completed studies to test the effectiveness of supercritical water oxidation for treating AFFF. Supercritical water oxidation is a process that occurs when the temperature and pressure of water is above the critical point. Above the critical point, oxidation processes are accelerated. In 2020, ORD partnered with three companies to perform tests of their supercritical water oxidation systems on dilute, PFOS-based AFFF (Krause et al., 2022). During these demonstration tests, each system was operated under slightly different conditions, and each company analyzed samples of the influent and effluent for slightly different PFAS. The overall destruction efficiency of each system was calculated by summing the concentrations of the measured PFAS. In all cases, the overall destruction efficiency was found to be greater than 99%. It is important to note, however, that the sum of the PFAS measured in the effluent ranged from approximately 10 μg/L to approximately 100 μg/L, suggesting that further treatment of the effluent may be necessary. It is also important to note that non-targeted analysis was not conducted, and air emissions were not monitored, making it difficult to assess the fate, transport, and transformation of PFAS with the supercritical water oxidation systems.

In 2021, ORD also partnered with a company to conduct tests at industrial-scale supercritical water oxidation system (Sahle-Demessie et al., 2022). These tests used a dilute, FTS-based AFFF. The primary objective of the study was to determine the destruction efficacy of the PFAS in the input material. Analysis of the influent and effluent showed greater than 99.99% destruction of the total PFAS measured. The average sum of the targeted PFAS in the effluent was approximately 55 μg/L, but PFAS were also detected in the tap water used as quench water in the system, suggesting that the overall performance of the system could be improved if non-PFAS-contaminated water is used in the system. A secondary objective of the study was to characterize degradation products using non-targeted analysis and stack sampling for nonpolar volatile fluorochemicals. Non-targeted analysis of the effluent tentatively identified the shorter carbon-chain PFAS on the targeted analyte list, and the authors suggested a possible destruction mechanism that would be consistent with this result. Further work is needed, however, to determine the destruction mechanism. The air emissions sampling did not detect targeted PFAS in air emissions above background levels; further work with finalized air methods (e.g., OTM-50) is needed to confirm this observation.

At this time, EPA is neither recommending nor discouraging the use of any emerging technology for managing PFAS-containing materials, including the technologies studied by the PITT. While the PITT studies generally indicated potential for PFAS destruction, further work using newly available methods is needed to more fully characterize the outputs of these processes and to evaluate their performance for PFAS-containing materials beyond AFFF.

6.b PFAS Destruction and Disposal Technology Evaluation Framework

Researchers have proposed metrics to evaluate PFAS destruction and disposal technologies, including technology readiness levels (TRLs), DREs of target compounds, fluorine mass balances, and others (Berg et al., 2022; Deeb et al., 2021; Krause et al., 2021). When used individually, these metrics fail to accurately capture comprehensive system performance or provide a holistic understanding of the potential for PFAS transformation and/or release to the environment. For example, DREs calculated from targeted analyses using existing methods can result in underreporting of the total PFAS in a matrix. That's because existing detection methods can only measure a fraction (e.g., 50 individual PFAS) of the total number of PFAS that may be present in a sample. Similarly, TRLs can fail to accurately reflect the current development stage of a technology by either reporting the overall maturity of the technology, instead of its specific PFAS application, or by relying on a niche, small-scale application to justify an overall readiness level.

These limitations drive the need for a comprehensive framework for evaluating a technology and its application to PFAS-containing materials. Such a framework should allow the user to prioritize the collection and consideration of different pieces of information. To meet these needs, EPA developed a technology evaluation framework that uses a multiple-lines-of-evidence approach to evaluate a technology/PFAS material combination (Table 6-1). The framework provides a transparent approach for evaluating and selecting a technology to reduce PFAS releases to the environment. EPA recommends that managers of PFAS-containing materials use the framework to evaluate emerging technologies, and to inform decisions about destruction and disposal of PFAS-containing materials.[27] EPA encourages technology developers to generate and publicly release data that can be used to answer the questions presented in the framework.

The framework comprises several topical sections: technology, material, analytical methods, disposal/destruction efficacy, community considerations, and regulatory requirements. Within each section, EPA has identified key pieces of information that, when considered together, provide a more holistic evaluation of a technology and its applicability for PFAS disposal or destruction.

The framework is intended to be an adaptable tool that allows the user to prioritize the collection and consideration of different pieces of information via the "priority" column in the framework. This allows users to address questions most relevant to their priorities and with respect to their decision context

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[27] The Interstate Technology and Regulatory Council (ITRC) PFAS Team developed the *PFAS Technical and Regulatory Guidance Document* (available at *https://pfas-1.itrcweb.org/*) to support state and federal environmental staff, as well as others, to gain a working knowledge of the current state of PFAS science and practice. Section 12 of the guidance document provides information on PFAS treatment technologies, including destruction technologies. Managers of PFAS-containing materials may find this resource useful when completing Table 6-1.

and the shared priority of preventing and mitigating potential exposures. Users may also choose to prioritize addressing certain questions before others to streamline their evaluation of a technology/material combination. For example, if a user of the framework is evaluating the performance of a destruction technology, the questions in the disposal efficacy section of the framework are not needed and could be removed from the framework. As another example, a user may prioritize answering questions under the technology section of the framework because those questions may rule out a technology for a particular application (e.g., the technology may not be available at the scale needed to process the PFAS-containing material of interest). Once a technology is ruled out, lower priority questions do not need to be answered. While users may not answer each question in the framework, EPA encourages users of the framework to address as many questions as possible to inform decisions about the destruction and disposal of PFAS materials.

Table 6-1 shows this approach, followed by more detailed considerations for each question.

Table 6-1. Framework for Evaluating Destruction/Disposal Technologies for PFAS-Containing Materials

Category of Information	Key Questions	Priority[a]	Answer and Associated Notes for PFAS Material of Interest
Technology	If available, what is the TRL for the technology/material combination of interest?		
	Is the technology of interest available at the scale needed for the intended application?		
	Is a treatment train needed to meet the desired destruction/disposal outcome?		
Material	What PFAS-containing material has been used to test the performance of the technology of interest?		
	Which PFAS, and at what concentration ranges, have been used to test the performance of the technology of interest?		
	Are there non-PFAS constituents that may affect the performance of the technology of interest?		
Analytical methods	Which targeted analytical methods (e.g., OTM-45, draft EPA Method 1633) have been used to characterize the performance of the technology for the PFAS-containing material of interest?		
	Has non-targeted analysis been performed on waste streams from the technology/material combination of interest?		
	What other analytical approaches have been used to characterize the performance of the technology for the PFAS-containing material of interest?		
	Are there any concerns about the quality of the data generated during testing?		
Disposal efficacy	Have potential transformation and partitioning pathways been identified for the technology/material combination of interest?		
	Are engineering controls in place to prevent or minimize release of PFAS to the environment?		

Category of Information	Key Questions	Priority[a]	Answer and Associated Notes for PFAS Material of Interest
	What is the longevity of the disposal technology?		
	Has a fluorine mass balance been determined?		
	Does the disposal of the PFAS-containing material contribute to the potential release of non-PFAS constituents to the environment?		
Destruction efficacy	Is the mechanism of destruction understood?		
	Have all process inputs and outputs been characterized for PFAS to the extent possible given current analytical methods?		
	What is the reported destruction efficiency?		
	Have any PIDs (or PICs) been identified?		
	Has a fluorine mass balance been determined?		
	Have all process outputs been characterized for non-PFAS constituents to the extent possible given current analytical methods and understanding of the composition of the PFAS-containing material?		
Community Considerations	Has a destruction/disposal site been identified?		
	What are the characteristics of the surrounding community?		
	Are there potentially vulnerable populations and/or communities with environmental justice concerns near the destruction/disposal site?		
	Are PFAS releases anticipated from the technology/material combination of interest?		
	Has the surrounding community been engaged?		
Regulatory requirements	Are there state or federal regulations that control emissions or releases from the technology of interest?		
	Are there state or federal regulations that control the management of the PFAS-containing material of interest?		

[a] Users can prioritize key questions using a variety of approaches. For example, questions could be labeled as *high, medium*, or *low* priority. Questions could also be prioritized using a numerical ranking system with *1* indicating questions to answer first, *2* indicating questions to answer second, and so forth.

6.b.i Key questions for technology evaluation

Technology. The first section of the framework focuses on the destruction or disposal technology. Key questions include:

- **If available, what is the TRL for the technology/material combination of interest?** TRLs are generally assigned using the *definitions developed by NASA* (NASA, 2023), where level 1 corresponds to observation and reporting of basic scientific principles and level 9 corresponds to "flight proven" technologies. TRLs may be determined through technology readiness assessments[28] or through other methods. If other methods are used, EPA recommends that users consider the source of reported TRLs and prioritize TRLs determined through independent technology readiness assessments over TRLs assigned by the technology developer.

- **Is the technology of interest available at the scale needed for the intended application?** Some technologies may only be available as mobile, containerized units, which may be suitable for high-concentration, low-volume materials. These units may not be appropriate for low-concentration, high-volume materials, where a stationary treatment unit with greater capacity is needed.
- **Is a treatment train needed to meet the desired destruction/disposal outcome?** If so, describe the treatment train needed and whether such technology is available and effective for the PFAS-containing material of interest. Note that treatment trains may produce materials that will also need to be managed.

Material. The second section of the framework focuses on the PFAS-containing material of interest. The six types of PFAS-containing materials discussed in this interim guidance vary in terms of phase, PFAS composition and concentration, physical and chemical properties, and overall composition (e.g., the presence of other contaminants). To understand technology performance across the range of variations within a material type, the following key questions should be addressed:

- **What PFAS-containing material has been used to test the performance of the technology of interest?** The description of the material(s) used to evaluate a technology/material combination of interest should be specific as possible (e.g., 3M Litewater versus AFFF), and links to bulk material characterization should be included, if available. If the material evaluated is artificially contaminated (i.e., spiked with known PFAS species and concentrations), that should be noted because it may not be an accurate reflection of the performance of the technology for the intended application.
- **Which PFAS, and at what concentration ranges, have been used to test the performance of the technology of interest?** To best inform decisions on technology use, the PFAS and concentrations used to test performance should match the PFAS and concentrations anticipated for the intended application.
- **Are there non-PFAS constituents that may affect the performance of the technology of interest?** This could include constituents in the original PFAS-containing material or constituents that may be created or introduced during a treatment train or by the technology of interest. For example, hydrofluoric gas may be produced during PFAS destruction, which may cause corrosion.

Analytical methods. PFAS are a large class of substances, and there are various approaches for identifying and measuring PFAS. EPA recommends using a combination of approaches to characterize the performance of the technology for the PFAS-containing material of interest, including characterizing PFAS in emissions or waste streams from the technology of interest. Key questions to be addressed under this section include:

- **Which targeted analytical methods (e.g., OTM-45, draft EPA Method 1633) have been used to characterize the performance of the technology for the PFAS-containing material of interest?** When possible, EPA recommends the use of standardized and/or validated methods for targeted analysis.

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[28] See the *Technology Readiness Assessment Guide* for best practices for evaluating technology maturity. The guide, developed by the U.S. Government Accountability Office and released in January 2020, provides organizations with best practices for conducting high-quality assessments.

- **Has non-targeted analysis been performed on waste streams from the technology/material combination of interest?** Non-targeted analysis is an important tool for characterizing PFAS in waste streams from a technology/material combination of interest because it can tentatively identify PFAS beyond those measured using targeted analytical methods.
- **What other analytical approaches have been used to characterize the performance of the technology for the PFAS-containing material of interest**? Other analytical approaches may include total oxidizable precursor assays and total organic fluorine assays for PFAS and analysis for non-PFAS substances (e.g., HF).
- **Are there any concerns about the quality of the data generated during testing?** For any quality assurance/quality control concerns identified, the user should determine whether it is appropriate to use the data to inform decisions about destruction and disposal of the PFAS-containing material using the technology of interest.

Disposal efficacy. Effective disposal of PFAS-containing material should prevent or minimize re-release of PFAS to the environment. Key questions for evaluating the efficacy of a disposal technology for a particular PFAS-containing material are identified below. (Questions included in this section should be skipped when evaluating a destruction technology.)

- **Have potential transformation and partitioning pathways been identified for the technology/material combination of interest?** The fate and transport of PFAS within a disposal technology can help inform whether PFAS may be present in emissions or releases from the technology. Note that the characteristics of the receiving matrix and environmental conditions can affect the fate and transport of PFAS within the disposal technology.
- **Are engineering controls in place to prevent or minimize release of PFAS to the environment?** If so, is there a monitoring system in place to evaluate the performance of the engineering controls?
- **What is the longevity of the disposal technology?** Because of the strength of the carbon–fluorine bond, PFAS are persistent. It is important to consider the lifespan of the disposal technology and whether the technology can contain PFAS for very long timeframes.
- **Has a fluorine mass balance been determined?** If so, is there fluorine that is unaccounted for? In some cases, a fluorine mass balance may be impractical.
- **Does the disposal of the PFAS-containing material contribute to the potential release of non-PFAS constituents to the environment?** PFAS-containing materials may contain other, non-PFAS constituents. Depending on the identity of those constituents and their potential to impact human health and the environment, it may be important to consider whether appropriate engineering controls are in place to prevent or minimize releases of non-PFAS constituents.

Destruction efficacy. Destruction of PFAS should result in breaking carbon–fluorine bonds without reforming PFAS and releasing PFAS to the environment. Key questions for evaluating the efficacy of a destruction technology for a particular PFAS-containing material are identified below. (Questions included in this section should be skipped when evaluating a disposal technology.)

- **Is the mechanism of destruction understood?** If so, has the destruction mechanism been experimentally confirmed, and have the reaction kinetics been determined? A thorough understanding of the destruction mechanism improves confidence in the performance of the technology of interest for PFAS.
- **Have all process inputs and outputs been characterized for PFAS to the extent possible given current analytical methods?** If not, what information may be missing?

- **What is the reported destruction efficiency?** Destruction efficiencies (or DREs) are generally reported for specific PFAS (e.g., PFOA or PFOS). As noted earlier, the destruction efficiency (or DRE) alone may not be sufficient to determine whether other PFAS may be released to the environment during the destruction process.
- **Have any PIDs (or PICs) been identified?** If so, which PFAS have been detected and at what levels? Are those PFAS regularly detected for this technology/material combination?
- **Has a fluorine mass balance been determined?** If so, is there fluorine that is unaccounted for? In some cases, a fluorine mass balance may be impractical.
- **Have all process outputs been characterized for non-PFAS constituents to the extent possible given current analytical methods and understanding of the composition of the PFAS-containing material?** The destruction of PFAS-containing materials is expected to result in non-PFAS products. Depending on the identify of those products and their potential to impact human health and the environment, it may be important to consider whether appropriate engineering controls are in place to prevent or minimize releases of non-PFAS constituents. It may also be important to consider the effect of the destruction process on non-PFAS constituents in the PFAS-containing material of interest. Thus, the characterization of process outputs beyond PFAS may be warranted.

<u>Community considerations</u>. When considering destruction and disposal technologies for PFAS-containing materials, it is important to consider the community that may be exposed to potential PFAS releases from intended destruction or disposal. Key questions to consider include:

- **Has a destruction/disposal site been identified?** Some destruction technologies may be mobile, allowing for treatment and destruction to occur where PFAS-containing materials are generated or stored. Other technologies may be stationary, requiring PFAS-containing materials to be brought on site for destruction or disposal. The use of mobile technologies may allow flexibility in siting to avoid potential impacts on overburdened and vulnerable communities.
- **What are the characteristics of the surrounding community?** See Section 4 for tools and approaches that can be used to characterize communities near destruction/disposal sites.
- **Are there potentially vulnerable populations and/or communities with environmental justice concerns near the destruction/disposal site?** Section 4 provides tools and strategies that can be used to screen nearby communities for potentially vulnerable populations and/or communities with environmental justice concerns.
- **Are PFAS releases anticipated from the technology/material combination of interest?** If so, describe which PFAS may be released, at what levels, and over what duration. Also note whether there are controls in place to mitigate releases to avoid or minimize potential impacts to surrounding communities.
- **Has the surrounding community been engaged**? Sharing information about planned destruction or disposal activities for PFAS-containing materials allows community members to take actions to address concerns they may have. There may also be opportunities to collaborate with government officials and community leaders on engagement activities.

<u>Regulatory requirements</u>. Regulations regarding the destruction or disposal of PFAS-containing materials can vary from state to state and may change over time. Key questions to consider include:

- **Are there state or federal regulations that control emissions or releases from the technology of interest?** Such regulations may limit the amount of PFAS or other pollutants present in emissions or other releases from the technology of interest.

- **Are there state or federal regulations that control the management of the PFAS-containing material of interest?** Such regulations may specify or restrict destruction or disposal options for the PFAS-containing material of interest.

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Appendix A: EPA Guidance to Conduct PFAS Emissions Field Testing at Commercial Thermal Destruction Sources

The U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) is conducting per- and polyfluoroalkyl substances (PFAS) thermal destruction emissions characterization research to improve our understanding of the behavior of PFAS with respect to waste incineration and thermal treatment (e.g., hazardous waste, municipal waste, biosolids, contaminated soils, spent media), as well as thermal destruction emissions control technologies (e.g., afterburners, thermal and catalytic oxidizers). The following could be used by any entity evaluating thermal treatment of PFAS-containing materials either in collaboration with EPA or independently.

Overall goals of the field tests are as follows:

- Confirm/determine if thermal treatment under representative conditions can result in the thermal destruction of PFAS as defined by conventional destruction and removal efficiency (DRE) testing.
- Characterize potential products of incomplete combustion/destruction (PICs/PIDs) and evaluate the use of alternative, or surrogate, indicators of destruction performance.
- Confirm that any treated material is appropriate for any defined beneficial reuse (e.g., treated soils, reactivated granular activated carbon [GAC]).

To achieve these goals, it is necessary to determine the specific conditions (i.e., temperature, residence time, and turbulence) required to maximize DREs, minimize PICs/PIDs, and produce products appropriate for beneficial reuse. Because bench- and pilot-scale testing have limitations, actual test data under full-scale thermal treatment conditions are necessary to determine if representative thermal processes can achieve these goals.

Sampling Details:

- EPA is available to collaborate with the host site on the technical approach for source characterization. Testing would require multiple stack sampling methodologies performed by commercial stack testing companies, including the host's regular tester, if desired.
- All gas, liquid, and solid inlet, intermediate, and outlet streams will be collected and analyzed. This includes:
    - At the stack and including all air pollution control devices
    - All inlet streams (e.g., materials to be thermally treated, air or gas inlets, water), including samples taken prior to testing
    - All residual streams (e.g., bottom ash, baghouse and/or electrostatic precipitator [ESP] solids, scrubber effluent, spent carbon)
    - All final products (e.g., reactivated carbon, soils), if applicable
- A comprehensive air emission source characterization would include:
    - Samples would be collected for semivolatile PFAS, using method OTM-45 targeted (known) PFAS, or method established endpoints. Samples would be collected for volatile PFAS, using

method OTM-50 and analyzed for targeted (known) PFAS in samples and the identification of unknown detected volatile fluorocarbons.

- Samples would be collected for other semivolatile target compounds using methods SW-846 Methods 0010/3542/8270 with the inclusion of the Method 8270 procedure. Carbon hexafluoride (C_2F_6) and carbon tetrafluoride (CF_4) could be injected during one day of testing, ideally at multiple injection locations, as a surrogate measure of destruction efficiency if appropriate and permitted.
- Tests would be run under a single, representative process condition including the waste that would be co-fired with PFAS-containing material.
- EPA would prioritize testing several PFAS-containing materials, including but not limited to:
  - Incineration of aqueous film forming foam (AFFF)
  - Incineration of wastewater sludges
  - Reactivation of spent GAC
  - Incineration of municipal solid waste
  - Thermal treatment of contaminated soils
  - Incineration of spent ion exchange resins and their concentrated regeneration liquids
- All sampling would be conducted under a well-documented sampling plan and quality assurance project plan.
- Final testing results would be shared with EPA, the state, local authorities.

Additional details on emission testing approaches can be provided upon request.

Supplemental Information

Emissions sampling and analytical approaches

Emissions samples would be collected for polar, nonpolar, volatile, and semivolatile PFAS compounds and analyzed for both targeted PFAS compounds, or method established endpoints.

EPA's Other Test Method (OTM) 45 would be used to collect polar semivolatile PFAS compounds for targeted analyses. The method's 50+ target analytes include many PFAS commonly found in AFFF. This would enable DE, DRE, and emission rate determination as appropriate for a known list of PFAS compounds.

The OTM-50 canister sampling method would be used to collect nonpolar volatile PFAS compounds for targeted compound analyses. The current target list includes CF_4 and C_2F_6 as well as a procedure to identify unknown volatile fluorocarbons.

Non-targeted analyses (NTA) are an optional analytical tool for characterizing potential PICs/PIDs. High resolution mass spectrometry, combined with chromatographic separation and multiple ionization techniques, is used to identify compounds present in collected samples. NTA could be performed on the OTM-45 samples. Fourier transform infrared (FTIR) spectroscopy would be used to measure a variety of compounds in real-time, including hydrogen fluoride (HF), hydrogen chloride (HCl), carbon dioxide (CO_2), and water (H_2O); multiple PFAS compounds including CF_4 and C_2F_6; and multiple known PICs/PIDs. FTIR is particularly critical during surrogate compound injection.

ORD research questions

The following section describes detailed elements of the research questions ORD will ultimately work to address, as well as the input information that is needed. ORD requests an opportunity to engage with the host facility prior to developing a full sampling plan to better understand site-specific conditions and requirements.

Process characterization

- **Question:** How does the process operation affect the destruction and removal of PFAS compounds present in the feed?
- Requires understanding of waste feed (e.g., description, concentration, other wastes), feed approach (e.g., liquid feed, through flame/post flame, co-fired, drums/barrels), and feed rate
- Requires data on combustor operations and conditions (e.g., temperature, residence time)
- Requires data on air pollution control devices (APCD) and their operation: configuration, operating parameters (e.g., temperature, pressure drop, pH of scrubbing liquid, gas velocity)

Determine destruction removal efficiency (DRE)

- **Question:** What is the DRE and emission rate of the specific PFAS compounds present in the feed
- material?
- Requires known input rate and identity of PFAS compounds in waste
- Requires evaluation of the extent of PFAS mineralization
- Requires replicate sampling of polar semivolatile organics using OTM-45 for quantitative measurement of feed PFAS compounds in emissions
- Requires sampling across multiple APCDs

Products of incomplete combustion/destruction (PICs/PIDs)

- **Question:** Are PICs/PIDs formed during thermal treatment and measured by OTM-50 present and, if so, what are they and under what conditions?
- Requires replicate sampling of polar, nonpolar, semivolatile, and volatile organics for non-targeted compound analysis using OTM-45, OTM-50, and Method 0010/3542/8270.
- Requires sampling across multiple APCDs.

Alternative indicators of destruction performance

Question: Can easily measured/monitored, hard-to-destroy compounds serve as alternative (surrogate) indicators for PFAS adequate destruction or PID formation conditions?

- Requires injection of known concentrations/masses of CF_4 and C_2F_6 (approximately 10 parts per million by volume stack equivalent) at representative waste injection locations
- Requires on-line FTIR monitoring of the surrogate compounds, PICs, HF, HCl and other compounds of interest
- Requires initial background signal baseline
- Requires concurrent OTM-50 sampling for analysis of surrogate compounds and known PICs

Analysis of fluorinated compounds in waste/effluent streams

Question: What is the fate of PFAS compounds across the entire thermal system?

- Requires sampling of all discharges
  - Gas sampling prior to and after APCDs (e.g., spray dryer, wet scrubber, baghouse and/or ESP, activated carbon injection)
  - Sampling of solid and liquid discharges (e.g., bottom ash, baghouse and/or ESP solids, scrubber effluent analyses, spent carbon)

Analysis of fluorinated compounds in final product materials, where applicable

Question: What PFAS remain in the material treated, such as reactivated GAC or treated soils?

- Requires sampling of influent and effluent materials
  - Sampling of solid materials (e.g., spent carbon and reactivated carbon)

Appendix B: Summary of the Clean Harbors Test Data

Summary

Two testing campaigns were conducted at Clean Harbors Environmental Services' (CHES) hazardous waste combustor (HWC) located in Aragonite, Utah. Each test campaign was divided into three test conditions: Baseline (Condition 1), Augmented Per- and Polyfluorinated Alkyl Substances (PFAS) Feed (Condition 2, where known amounts of four or five target PFAS were fed to the incinerator), and Post-spiking Normal Operations (Condition 3, where aqueous film-forming foam [AFFF] was included in the incinerator feed). Clean Harbors used the *Other Test Method 45 (OTM-45) Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources* (OTM-45) from the U.S. Environmental Protection Agency (EPA) for stack gas samples. The 49 targeted PFAS analytes were measured using liquid chromatography/tandem mass spectrometry (LC/MS/MS) with isotope dilution. The tests appear to demonstrate that the primary objective, "demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed during normal process operating conditions," was achieved for the five selected PFAS compounds that were subjects of these studies.

Introduction

Two testing campaigns were conducted at CHES HWC located in Aragonite, Utah. The first campaign was conducted from June 17 to 19, 2021 and the second from February 17 to 19, 2022. The stated principal objective of the test program was to "demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed during normal process operating conditions," with secondary objectives of conducting a mass balance of PFAS in process streams and demonstrating high hydrogen fluoride (HF) removal that would be associated with a high destruction of PFAS. This summary presents a high-level overview of both tests' final reports as well as a third-party review of the 2021 test performed by Dr. Philip H. Taylor under contract to CHES.

General Process Description

The HWC tested at the CHES Aragonite facility consists of a slagging rotary kiln incinerator followed by an afterburner. Solid waste materials and containerized wastes are fed into the rotary kiln only, while liquid wastes may be injected directly into rotary kiln or the afterburner. The air pollution control device system for the HWC as tested[29] consists of a spray dryer/gas quench followed by activated carbon injection upstream of a fabric filter (particulates, dioxin/furan, and mercury control). Following the fabric filter, the gases enter a sodium carbonate saturator/wet scrubber (sulfur dioxide, hydrogen chloride, hydrogen fluoride control) with TMT-15 (1,3,5-triazine2,4,6(1H,3H, 5H)-trithione, trisodium salt, used for additional mercury and metals control) injection.

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[29] Stack testing was performed in the exit duct of the wet scrubber instead of at the stack for safety reasons (lack of scaffolding). The HWC is equipped with a wet electrostatic precipitator (WESP) following the wet scrubber and prior to the stack, but the WESP was decommissioned in 2004 and is no longer in service. These tests were conducted prior to the WESP although the stack location is the test location for compliance performance tests for the facility.

Operational Description

Each test campaign was divided into three test conditions: Baseline (Condition 1), Augmented PFAS Feed (Condition 2), and Post-Spiking Normal Operations (Condition 3), with the waste feed matrices as follows:

1. **Condition 1.** Normal matrix of liquid materials (waste fuel, clean fuels, sludge, and aqueous wastes) and solid waste materials (containerized, shredded, and bulk solid wastes). Following the 2021 testing, CHES determined that the sludge stream fed to the kiln during all three conditions included some AFFF. During the first run of the 2022 testing, CHES determined that AFFF was inadvertently being fed into the afterburner's corrosive waste port. The testing team decided to be consistent with runs 2 and 3 and continued the AFFF feed, with additional amounts of AFFF fed during Condition 3.
2. **Condition 2.** Normal matrix of liquid materials (waste fuel, clean fuels, sludge, and aqueous wastes) and solid waste materials (containerized, shredded, and bulk solid wastes), with the addition of augmented feed rates of four (2021) or five (2022) PFAS (or their equivalent potassium salt). The four PFAS are perfluorooctanioic acid (PFOA), perfluorooctanesulfonic acid (PFOS), perfluorohexane sulfonic acid (PFHxS), hexafluoropropylene oxide-dimer acid (HFPO-DA), and perfluorobutanesulfonate (PFBS, 2022 only). The target feed rate of the PFAS was estimated to be .0816 pounds per hour or around 0.62 grams per minute in 2021 for all PFAS, but the HFPO-DA was increased to 2.2 grams per minute in the 2022 testing to reflect the method detection limit (MDL) for this compound. Similarly, the PFBS feed rate was 0.33 grams per minute on average to reflect the MDL. The PFAS were fed in boxed containers to the rotary kiln via the containerized solid conveyor in approximately 10-gram portions of all PFAS compounds about every 15 minutes for the duration of these test runs.
3. **Condition 3.** Normal matrix of liquid materials (waste fuel, clean fuels, sludge, and aqueous wastes) and solid waste materials (containerized, shredded, and bulk solid wastes). For this test condition, AFFF concentrate was also fed (neat) to the incinerator. In 2021, the AFFF was fed via the containerized solids in 5-gallon buckets at a rate of 176 pounds per hour. During the 2022 test, the AFFF was labeled as Ansulite and was fed through the educt station to the incinerator directly from a tote bin. The AFFF feed rate ranged from 244 pounds per hour to 316 pounds per hour during the 2022 test.

The rotary kiln was operated in a temperature range between 1,893°F and 2,008°F for the 2021 test and between 1,949°F and 2,219°F for the 2022 test. The afterburner was operated at 2,052°F to 2,110°F during the 2021 test and 2,048°F to 2,075°F for the 2022 test. Oxygen content (free) at the exit of the rotary kiln was maintained between 8 and 9 percent and ranged from 6 to 7 percent for the afterburner for both test campaigns. Clean Harbors estimates that non-combustible material is retained within the combustor for approximately 60 minutes, while combustion gas residence time of the afterburner is two to three seconds.

For the 2021 test, the temperature of the flue gas was reported as 369°F following the spray dryer; between 341°F and 343°F following the fabric filter; between 166°F and 168°F at the saturator outlet; and 148°F to 153°F at the stack. For the 2022 test, the temperature of the flue gas was reported as

363°F following the spray dryer; between 168°F and 170°F at the saturator outlet; and 149°F to 151°F at the stack. The following table lists the air pollution control device operational parameters during the testing campaigns.

Test Campaign	Stack gas flow (acfm)	Soda Ash Flow (lb/hr)	Carbon Injection (lb/hr)	TMT-15 flow (lb/hr)
2021	66,793–68,761	452–789	30.7–31.5	3.95–4.48
2022	51,053–53,640	411–1594	32.0–33.1	3.64–4.00

Test Methods and Scope

During both testing campaigns, samples of stack gases and process streams were taken and analyzed for 49 PFAS target compounds, with the stated analytical objective of characterizing as many streams entering or exiting the incinerator as possible. Clean Harbors used EPA's *Other Test Method 45 (OTM-45) Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources* (OTM-45) for stack gas samples (as noted earlier, "stack" meaning the exit duct from the wet scrubber as it was deemed a safer sampling location than the actual stack). The 49 targeted PFAS analytes were measured using LC/MS/MS with isotope dilution.

Process streams sampled included waste fuels, clean fuels, waste feeds, process water, and residuals (liquids and solids), as well as some pre-test sampling of chemical inputs (soda ash, activated carbon, and TMT-15). As noted in the reports, however, due to the waste profile matrix complexity and the heterogeneity of all three solid waste streams, they were not sampled or analyzed for PFAS. Absent any final EPA-approved methods for media other than drinking water, LC/MS/MS analysis was used to measure the targeted PFAS compounds in the process stream samples.

In addition to the 49 PFAS analytes, the HF concentration of the stack gas was measured using EPA Method 26A. The AFFF-containing material in the 2021 test was analyzed for the 49 target PFAS both before and after chemical oxidation as a total oxidizable precursor assay (TOPA). During the 2022 test, a TOPA and total organic fluorine assay (TOFA) were performed on the AFFF-containing materials. The objective of performing TOPA is to "reveal perfluoroalkyl acid (PFAA), fluorotelomer sulfonate (FTS), and possibly other precursors that are not identifiable with targeted PFAS analysis." TOFA, as described in the 2022 report, identifies the mass of compounds containing carbon-fluorine bonds, and was performed using combustion ion chromatography following a laboratory in-house method for adsorbable organo-fluorine.

Results

According to the tests and third-party review, the primary objective of determining the destruction and removal efficiency (DRE) of each of the spiked (augmented feed) PFAS was achieved. The calculated DREs for each test (triplicate test run average) and PFAS compound are as follows:

PFAS Analyte	2021 Test DRE (%)	2022 Test DRE (%)
PFOA (perfluorooctanioic acid)	99.999943	99.99990
PFOS (perfluorooctanesulfonic acid)	99.999955	99.99977
PFHxS (perfluorohexane sulfonic acid)	99.999977	99.99996

PFAS Analyte	2021 Test DRE (%)	2022 Test DRE (%)
HFPO-DA (hexafluoropropylene oxide – dimer acid)	99.999979	99.99984
PFBS (perfluorobutanesulfonate)	n/a	99.99997

Both test reports note that none of the other 45 (or 44, in 2022) target PFAS analytes were present in the waste feed at levels sufficient to demonstrate 99.9999 percent DRE without spiking, even though stack gas concentrations were non-detect in many cases. According to the 2021 test report, there were three other PFAS present in the waste feeds at sufficient mass feed rate without spiking to enable demonstration of DRE's exceeding 99.999 percent. These included PFOS, 6:2 fluorotelomer sulfonate (FTS), and 8:2 FTS. The report stated that the FTS compounds are common constituents of AFFF.

As for the secondary objectives, the results are, as stated within Dr. Taylor's review, "most difficult to achieve as they involve more complex sampling issues." With respect to the secondary PFAS mass balance objective, he notes that "some of the PFAS that was not sampled in the infeed may have been more difficult to gasify and burn, contrary to the assertions in the report." However, he concurs with the report statements that the PFAS DRE is conservative.

The objective of demonstrating high HF removal that would be associated with a high destruction of PFAS is seemingly not achieved, primarily due to analytical issues. Dr. Taylor notes that "the sinks for the HF were not accurately quantitated leading to some questions about the validity of the reported HF removal efficiency." He further notes that the assumption that all fluorine in the waste if converted to HF is challenged, as there would be a required excess of hydrogen to fluorine to be demonstrated, which are not provided for in the data. Further, he stated that there is a "demonstrated lack of accuracy of the analytical methods for measuring inorganic fluorine in the residual streams," which, in his opinion, leads to a very low fluorine recovery mass balance. He concluded that, "development of better analysis methods for complex matrices for inorganic fluorine are needed before high HF removal efficiencies can be reported at full scale."[30]

Conclusions

The tests appear to demonstrate that the primary objective, "demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed during normal process operating conditions," was achieved for the five selected PFAS compounds that were subjects of these studies. However, this study did not evaluate the formation of PICs due to previous methodology limitations. Dr. Taylor, in his review, noted this as well: "The larger question from an environmental viewpoint is the complete mineralization of these substances and prevention of emission of highly stable C_1-C_2 PFCs (perfluorocarbons)." Dr. Taylor concludes that CHES' results, although promising and demonstrating reduction of a limited selection of specific PFAS compounds, did not support complete mineralization.

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[30] Although not stated by Dr. Taylor in his assessment, another possible reason for lack of finding inorganic fluorine (HF) could be the result of poor conversion (mineralization) of PFAS to HF and carbon dioxide during incineration. This may indicate formation of non-target PFAS or fluorocarbons during incineration that were not measured by these tests.

References

EA Engineering, Science, and Technology, Inc., PBC. (2021). *Report on PFAS destruction testing results at Clean Harbors' Aragonite, Utah hazardous waste incinerator* (Final).

EA Engineering, Science, and Technology, Inc., PBC. (2022). *Report on PFAS destruction testing results at Clean Harbors' Aragonite, Utah hazardous waste incinerator* (Final).

Taylor, P. (2022). *Final report: Assessment of a report on PFAS destruction testing results at Clean Harbors' Aragonite, Utah hazardous waste incinerator*. Prepared for Clean Harbors Environmental Services, Inc.

Appendix C: Summary of the Chemours Thermal Oxidizer Test Data

Introduction

Chemours Company FC, LLC, located in Fayetteville, North Carolina, manufactures chemicals and plastics and was required to install a thermal oxidizer to control per- and polyfluoroalkyl substances (PFAS) emissions. After installation, tests were conducted in March 2020 and March 2022. The objective of the tests was to determine how "the Thermal Oxidizer and 4-stage Scrubber system will achieve the emission reduction [of 99.99 percent], including the use of a surrogate for all PFAS, such as the hexafluoropropylene oxide (HFPO)." This summary presents a high-level review of the two tests' reports.

General Process Description

The thermal oxidizer at the Chemours facility operates at 10 million BTU per hour and is powered by natural gas. Waste gases from both polymer and monomer production are fed into the thermal oxidizer. The gaseous emissions from the oxidizer are fed into the four-stage packed bed column scrubber system while solid calcium fluoride (CaF_2) is removed, collected, and disposed of off site. The scrubber has three water scrubbing stages and one caustic scrubbing stage and is stated to remove hydrogen fluoride (HF) from the final emissions.

Operational Description

Test Methods and Scope

The tests done on the thermal oxidizer focused on five PFAS compounds: HFPO, hexafluoropropylene oxide-dimer acid (HFPO-DA), hexafluoropropylene oxide-dimer acid fluoride (HFPO-DAF), carbonyl fluoride (COF_2), and Flouroether E-1. These compounds were selected because they are handled and used at the Fayetteville facility. The compounds have varying chemical structures and properties and cannot be sampled and tested in the same manner.

Modified Method 18 sampling was used to capture the PFAS compounds. This method uses six fluoropolymer (PFA) impingers charged with methanol arranged in a series and captures the compounds using chemical reactions and condensation.

To capture HFPO-A, the facility needed to use Modified Method 0010 sampling with a heated probe and filter, condenser coil, XAD-2 resin cartridge, deionized water impingers, and a silica gel impinger. In addition to the normal Modified Method 0010 sampling process, this test added a second XAD-2 resin cartridge to monitor possible target PFAS breakthrough.

Three compounds, HFPO, HFPO-DAF, and COF_2, were sampled by chemical reaction. The sample gas was passed through the series of methanol impingers. The compounds then react with the methanol, and each produced unique ether compounds that were monitored and quantified using SW-846 Method 8260.

The strategy used to sample Flouroether E-1 and HFPO-DA was to capture the compounds through condensation and dissolution in the same methanol impingers. The volatile organic compound, Flouroether E-1, was then quantified using SW-846 Method 8260b. The semivolatile organic compound HFPO-DA was quantified using EPA Method 537.

Samples were taken from the polymer production and monomer production waste gas feed lines to capture the initial amount of PFAS compounds they produced as waste and give them a baseline concentration of PFAS prior to treatment. The other sampling location was in the stack after the thermal oxidizer and scrubber. This location would show how effective the process was at destroying the targeted PFAS compounds.

The sampling and testing methods only captured the amount of target PFAS compounds and did not measure any products of incomplete combustion. Although the four-stage scrubber was implemented to reduce the possible HF emissions, there was no sampling of HF.

Results

The results of the tests showed that the mandated 99.99 percent destruction of targeted PFAS compounds had been achieved. In both testing years the average PFAS destruction and removal efficiency (DRE) was above 99.999 percent with no result being lower than 99.999 percent. Results were presented as a total FPAS destruction efficiency with the amount of each target PFAS compound summed to provide an aggregate destruction efficiency. The total PFAS destruction efficiencies for each run and each year are as follows:

Year	Run 1	Run 2	Run 3	Average
2020	99.99982%	99.99974%	99.99986%	99.99981%
2022	99.99951%	99.99966%	99.99967%	99.99961%

Conclusions

The test reports demonstrate a PFAS destruction efficiency above the 99.99 percent that was mandated for the Chemours facility for the specific compounds that were tested. HFPO was tested as a surrogate for all species of PFAS, but there are no concrete data showing the performance of the thermal oxidation process for PFAS species outside of the compounds tested. There was also no discussion of possible products of incomplete combustion in the reports. The thermal oxidizer at the Chemours facility appropriately destroys the five PFAS compounds of interest that have been identified at the facility. However, removal processes for products of incomplete combustion or of destruction of potential compounds not studied but potentially found in the facility waste streams are still unclear.

References

Focus Environmental, Inc. (2020). *Thermal oxidizer performance test report Chemours Company Fayetteville Works.* Prepared for the Chemours Company Fayetteville Works Plant. *https://www.chemours.com/en/-/media/files/corporate/fayetteville-works/2020-03-thermal-oxidizer-test-report.pdf*

Focus Environmental, Inc. (2022). *Thermal oxidizer performance test report Chemours Company Fayetteville Works.* Prepared for the Chemours Company Fayetteville Works Plant. *https://www.deq.nc.gov/coastal-management/gis/data/air-sampling/chemours-feb-2022-de-test-report-final/download?attachment*

Appendix D: Summary of Costs and Considerations

Introduction

This appendix provides some estimates of costs for end-of-life management of PFAS materials by thermal treatment, landfilling, and underground injection. The cost information presented is relatively uncertain and is likely most suitable to make comparisons between techniques.

The cost to destroy or dispose of PFAS and PFAS-containing materials can vary widely depending on a number of factors. Waste management infrastructure's design and operation are heavily influenced by regional needs, local regulations, and technological advancements. As a result, waste management costs vary by the type of waste and by location due to factors like availability and transportation costs. In addition, technological advances specifically related to the management of PFAS-containing materials can potentially reshape the cost and operational landscape of PFAS waste management. Multiple factors and limitations contribute to cost variability and should be considered when using the information in this appendix.

- Market conditions such as supply and demand change frequently, resulting in fluctuating costs.
- Location of destruction and disposal options and transportation affect case-by-case costs.
- Transportation costs or any special handling costs for accepting and treating additional waste are not included in most of these estimates, thus actual costs would vary.
- Costs may be affected by permitting and state/local requirements for PFAS-containing material, which vary depending on state/local regulations, public input, and possible environmental justice concerns.

Thermal Treatment

Hazardous Waste

Table D-1. Estimated Costs to Incinerate Different Types of Hazardous Waste (U.S. EPA, 2005a)

Hazardous Waste Type	Estimated Thermal Treatment Cost per Ton[a]
Liquids, sludges, solids (halogenated)	$1,300-1,889
Liquids, sludges, solids (non-halogenated)	$381-1,040
Lab packs	$6,448
Containerized gases	$3,120

[a] Costs were developed for hazardous waste combustors (HWC) that were affected by the 2005 National Emission Standards for Hazardous Waste Pollutants (NESHAP), including commercial incinerators, cement kilns, lightweight aggregate kilns, and commercial HWC boilers. Cost per ton is assumed to be in 2002 dollars, the same year basis of the regulation from which these costs were obtained. Costs were normalized to 2022 dollars using the Bureau of Economic Analysis (BEA) gross domestic product (GDP) deflator (U.S. BEA, 2023) for waste management and remediation services using a base year of 2002. Note that applying the BEA GDP deflator for this industry sector is a top-down approach. For regulatory purposes, a bottom-up approach is typically used, accounting for capital costs based on the Chemical Engineering Plant Cost Index (CEPCI), energy prices typically based on Energy Information Administration (EIA) data, and labor costs based on industry segment indices using Bureau of Labor Statistics (BLS) data.

Limitations:

- Costs have likely changed since 2002 and scaling costs to 2022 contributes to uncertainty.

- Does not include transportation costs or any special handling costs for accepting and treating additional waste materials.

Table D-2. Example Disposal/Reactivation Costs for Drinking Water Treatment Residuals (Derived from U.S. EPA, 2020a)

Method	Cost of Disposal ($/Pound of Media)	Estimated Cost of Disposal Plus Replacement Media ($/Pound of Media)[a]
Reactivated GAC—off-site	$0	$1.74
Disposal via landfill	$0.06	$2.35
Disposal via incineration	$1.28	$3.57

[a] Cost per pound is in 2022 dollars. For GAC, on-site reactivation is possible. However, the utility or site would have to have ample workforce, managerial, and financial (both capital and operating) resources to justify this choice. It is likely to be cost-effective only for very large facilities and would require consideration of other factors including availability of land and public opinion. Due to the complex analysis needed, a full comparison of off-site versus on-site is beyond the scope of this document.

Limitations:

- These estimates are presented as examples only to illustrate tradeoffs. Actual site-specific costs are likely to vary based on factors including the quantity of media reactivated/replaced and are used as an example of trends. In this example, reactivated GAC and virgin GAC are estimated to be $1.51 per pound and $2.29 per pound, respectively.
- All unit costs assume 21,000 lbs of GAC reactivated/replaced.
- For reactivated GAC, it is assumed that the “replacement” media is the returned reactivated media plus the replacement of the GAC lost during reactivation with virgin media (assumed to be 30 percent).
- Disposal costs assume 10 miles of transportation to the disposal site.
- Incineration costs are based on incineration of ion exchange resin media. Incineration of GAC could be somewhat more expensive, depending on the relative fuel value of the spent media.
- The analysis is complex and a number of issues need to be considered at the site level, such as those that affect costs (cost of energy, shipping, labor, construction, operation, sampling, etc.) and those that affect other matters (practicality, public versus private ownership, contract availability, regional reactivation availability, off-gas permitting, public opinion, etc.).

Landfills

Hazardous Waste

Table D-3. Estimated Costs to Landfill A Representative Type of PFAS-Containing Material (Defense Logistics Agency (DLA), 2023)

Hazardous Waste Type	Estimated Cost per Ton of Waste
Aqueous film-forming foam (AFFF) and other PFAS-related Solids/Debris, Non-RCRA, >100 parts per million (ppm) PFAS for direct disposal at RCRA Subtitle C Landfill (e.g., contract line item number (CLIN) PF06B1)	$1,300-3,660 ($0.65-1.83/lb)

Limitations:

- The DLA pricing web application lists current government contracts for destroying or disposing of PFAS and PFAS-containing materials and may be useful for government contract cost estimates. The estimated cost per ton (lb) of waste appears to include removal and disposal costs for the specific material, although a portion of transportation costs may be attributed to other cost elements of each respective contract so transportation costs may not be fully reflected in these costs.
    - **Per the DLA pricing web application:** The prices contained in the database were awarded based on contract terms and conditions, procurement requirements, and price reasonableness determinations. The prices and contract information in the database are for reference only.
- Users of the DLA pricing web application are cautioned that each contract was developed to meet specific requirements for specific geographic regions or military installations. There are multiple variables that result in the pricing information displayed, including contract award date, proximity to DLA-approved disposal facilities, quantities of PFAS material estimated for disposal in proportion to other hazardous waste on the contract, reoccurring need for services, and whether PFAS material is disposed of in bulk or whether there are small, limited quantities.
- Pricing is provided here for bulk waste types for disposal at a Subtitle C hazardous waste landfill. Pricing for multiple waste types with varying units of measure for disposal, including containerized waste, are provided in the DLA pricing web application.
- The estimated cost in the table above only applies to a limited number of military installations and only considered bulk pricing from 600 to 10,000 pounds. Pricing is expected to differ for containerized waste and should be considered when relying on this cost information.

Non-Hazardous Waste (Municipal solid waste)

Table D-4. Average MSW Tipping Fees per Ton by U.S. Region (EREF, 2022)

Region	Average Tipping Fee ($/ton)	Region	Average Tipping Fee ($/ton)
Pacific	$69.02	Northeast	$75.92
Mountains/Plains	$50.84	Southeast	$48.70
Midwest	$62.02	South Central	$50.84

Limitations:

- MSW landfills emit more PFAS than originally thought in 2020. Research estimates that although MSW landfills contain PFAS for the most part, up to 5 percent of the PFAS may be released in the landfill gas and, 11 percent may be released in the leachate annually (Tolaymat et al., 2023). Thus, MSW tipping fees may not be a relevant data point for cost information.

Non-Hazardous Waste (Liquid waste)

Table D-6. Average Industrial Wastewater Rates by U.S. Region (Unger et al, 2023)

Region	$/1,000 gal	Region	$/1,000 gal
Pacific	$11.90	Northeast	$4.82
Mountains/Plains	$3.12	Southeast	$7.52
Midwest	$4.77	South Central	$5.20

[a] Data are consolidated by region and the number of data points varies by region. American Water Works Association (AWWA) water and wastewater rate surveys were used to gather historical rate data for water and wastewater utilities in the United States. These datasets were compiled and assessed to produce a single dataset of time series rate data for 112 water utilities and 76 wastewater utilities located throughout the United States.

Limitations:

- These data do not include specific information on extra treatment considerations that may be required by a national pollutant discharge elimination system (NPDES) permit or by an industrial user permit for a discharge into a POTW to control the release of PFAS. Thus, similar to the cost of landfilling PFAS waste, the associated treatment of PFAS-laden leachate is difficult to assess because the available data are associated with typical industrial wastewater generators or typical landfill leachate.

One report examined the cost to manage landfill leachate on site (U.S. EPA, 2021). Based on review of the treatment processes and technologies that are currently used, the cost to manage leachate on site is highly variable but generally ranges between $10-150/1,000 gallons ($0.01-0.15/gallon). Capital costs can range from hundreds of thousands to several million dollars. The report lists multiple limitations and does not specify treatment for PFAS.

Underground Injection

Class I Wells (hazardous and non-hazardous)

Table D-6. Estimated Costs for Class I Wells

Underground Injection Cost	$/1,000 gal[a]
Deep well injection	$190-270 (deSilva, 2019)
Trucking costs	$10-200 (McCurdy, 2011)

[a] Costs were normalized to 2022 dollars using the Bureau of Economic Analysis (BEA) gross domestic product (GDP) deflator (U.S. BEA, 2023) for waste management and remediation services using a base year of 2019.

Limitations:

- Class I well capacity is limited, which may affect the costs associated with deep well injection.
- Because of the geographic concentration of Class I wells, waste producers may face transportation and logistical challenges.
- To begin accepting PFAS-containing fluids, owners/operators of existing Class I wells may incur costs to modify their permits to accept waste from other entities or new waste streams.

Another source includes costs for disposing of sewage sludge and indicates that among fees and transportation costs is a $37.50 per ton fee for deep well injection of leachate (CDM Smith, 2020).

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Additional Resources

Barr Engineering Co. and Hazen and Sawyer. (2023). 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 Air Pollution Control Agency. *https://www.pca.state.mn.us/sites/default/files/c-pfc1-26.pdf*

> **Per the report:** *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). The report summarizes estimated capital and operations and maintenance (O&M) cost ranges for the two highest-ranking PFAS management alternatives for four waste streams (WRRF effluent, WRFF biosolids, landfill leachate, and compost contact water).*

Defense Logistics Agency (DLA) (2023). DLA Disposition Services hazardous waste disposal pricing web application. *https://public.logisticsinformationservice.dla.mil/hazmat/SearchParameters.aspx* (accessed March 2024).

> The pricing web application lists Department of Defense contracts for destroying or disposing of PFAS and PFAS-containing materials. The website is organized by multiple contract line item numbers (CLIN), each of which describes a material or waste stream and a unit of measure for disposal. The site lists contracts and pricing for available disposal technologies, including solidification and disposal in a hazardous waste landfill. The application may be useful as a reference for historical pricing for Department of Defense contracts.
>
> **Per the DLA pricing web application:** *The prices contained in the database were awarded based on contract terms and conditions, procurement requirements, and price reasonableness determinations. The prices and contract information in the database apply to Department of Defense requirements and are for reference only.*