Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances

INTERIM GUIDANCE FOR PUBLIC COMMENT
DECEMBER 18, 2020

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Abbreviations

AFFF	aqueous film-forming foam
ARFF	aircraft rescue firefighting
BEA	Bureau of Economic Analysis
BDL	below detection limit
BLS	Bureau of Labor Statistics
BOHP/UV	petitjeanite ($Bi_3O(OH)(PO_4)^2$) microparticle ultraviolet
C	Celsius
CAA	Clean Air Act
C_2F_6	hexafluoroethane
C_3F_8	octafluoropropane
CaF_2	calcium fluoride
C&D	construction and demolition
CaO	calcium oxide
$Ca(OH)_2$	calcium hydroxide
CDR	Chemical Data Reporting
CEPCI	Chemical Engineering Plant Cost Index
CF_4	carbon tetrafluoride
CFR	Code of Federal Regulations
CHF_3	fluoroform
CIC	combustion–ion chromatography
CI/MS	chemical ionization mass spectrometry
CKD	cement kiln dust
DoD	Department of Defense
DOE	Department of Energy
DRE	destruction and removal efficiency
EIA	Energy Information Administration
EJ	environmental justice
EPA	United States Environmental Protection Agency
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
FY 2020 NDAA	National Defense Authorization Act for Fiscal Year 2020
GAC	granular activated carbon
GCCS	gas collection and control system
GDP	gross domestic product
GHGRP	Greenhouse Gas Reporting Program

H_2O_2	hydrogen peroxide
HAP	hazardous air pollutant
HF	hydrogen fluoride
HWC	hazardous waste combustor
HWI	hazardous waste incinerator
kGal	thousand gallons
LFG	landfill gas
LWAK	lightweight aggregate kiln
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
NSPS	New Source Performance Standards
NTA	non-targeted analysis
ODS	ozone-depleting substance
OECD	Organization for Economic Cooperation and Development
OTM	Other Test Method
PAC	powdered activated carbon
PBPK	physiologically based pharmacokinetic
PCB	polychlorinated biphenyl
PFAA	perfluoroalkyl acid
PFAS	perfluoroalkyl and polyfluoroalkyl substances
PFBS	perfluorobutanesulfonic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonate
PVDF	polyvinylidene fluoride or polyvinylidene difluoride
PIC	product of incomplete combustion
PIGE	particle-induced gamma emission spectrometry
PITT	PFAS Innovative Treatment Team
POTW	publicly owned treatment works
ppmv	parts per million by volume
PTFE	polytetrafluoroethylene
RCRA	Resource Conservation and Recovery Act
RDF	refuse-derived fuel
RO	reverse osmosis

SDA	spray dryer absorber
SDWA	Safe Drinking Water Act
SERDP	Strategic Environmental Research and Development Program
SSI	sewage sludge incinerator
STAR	Science to Achieve Results
TOF	total organic fluorine
TRI	Toxics Release Inventory
TSCA	Toxic Substances Control Act
UF	ultrafiltration
UIC	underground injection control
U.S.C.	United States Code
USDW	underground source of drinking water
VOC	volatile organic compound
WWTP	wastewater treatment plant
XPS	X-ray photo-electron spectroscopy

1. Introduction

1.a Statutory requirement

The National Defense Authorization Act for Fiscal Year 2020, Public Law No: 116-92 (hereafter, "FY 2020 NDAA"), was signed into law on December 19, 2019. Section 7361 of the FY 2020 NDAA (see text in Figure 1-1) directs the U.S. Environmental Protection Agency (EPA) to publish interim guidance on the destruction and disposal of perfluoroalkyl and polyfluoroalkyl substances (PFAS) and materials containing PFAS not later than one year from the date of enactment of the FY 2020 NDAA. This interim guidance fulfills that direction. EPA will review the interim guidance at least every 3 years and revise it, if appropriate based on the availability of new information or other factors.

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 S. 1790—1093 determines to be appropriate, but not less frequently than once every 3 years.

Figure 1-1. FY 2020 NDAA Section 7361.

1.b Scope, significance, and use of interim guidance document

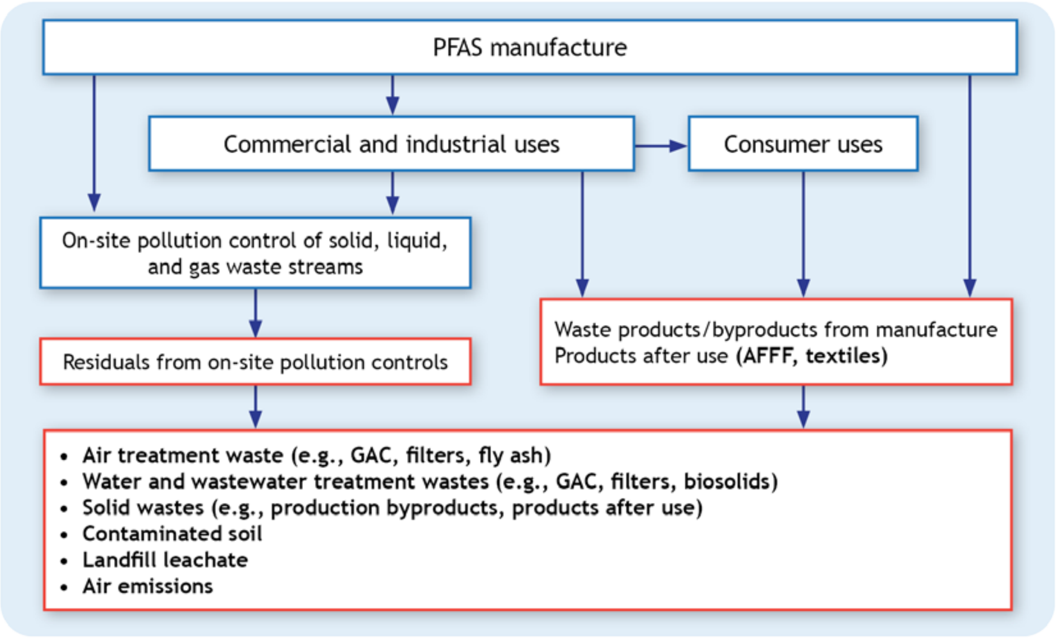
This interim guidance presents currently available information on PFAS destruction and disposal. It provides information on the current state of the science and the associated uncertainties for current commercially available disposal or destruction technologies. This interim guidance highlights what major uncertainties, if resolved, would allow for specific recommendations in the future. The present document describes several options to manage PFAS waste that may destroy or control its migration into the environment should destruction or disposal be required at this time. However, there remain several important data gaps, which this document describes.

Consistent with the FY 2020 NDAA, it is organized as follows:

- Section 2: Description of PFAS-Containing Materials Identified in the FY 2020 NDAA
- Section 3: Technologies for the Destruction and Disposal of PFAS and PFAS-Containing Materials
- Section 4: Considerations for Potentially Vulnerable Populations Living Near Likely Destruction or Disposal Sites
- Section 5: Planned Research and Development on Destruction and Disposal Technologies for PFAS and PFAS-Containing Materials

1.b.i PFAS and PFAS-containing materials identified in the FY 2020 NDAA

Section 7361 of the FY 2020 NDAA (see Figure 1-1) lists six types of PFAS-containing materials. Although the information included in this guidance would probably be suitable for other types of PFAS and PFAS-containing materials, this guidance addresses destruction and disposal for these six material types, which are described in more detail in Section 2. PFAS are either manufactured in the United States or imported, and then used (as an input or in a formulation) as processing aids or components of commercial and consumer products. Figure 1-2 shows conceptually how these activities could result in material streams that are in the intended scope of this interim guidance. A more global illustration of how PFAS-containing materials may be released to and migrate through the environment is presented in Figure 4-1.



Note: The red-outlined portions of this figure 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 Guidance scope

In developing this interim guidance, EPA identified and assessed existing information from published, publicly available sources relevant to destruction and disposal technologies. EPA also considered research and development that is in progress. Consistent with EPA's mission, the intent of this guidance is to identify and describe technologies that may control releases of PFAS waste to protect human health and the environment.

This interim guidance generally describes technologies that may be feasible and effective to varying degrees for the destruction or disposal of PFAS and PFAS-containing materials, based on currently available technical information. This document also identifies information gaps and uncertainties with the technologies and identifies ongoing research and development activities related to destruction and disposal technologies, which are designed to address some of these information gaps and uncertainties and may inform more specific guidance in the future (see Section 5). This interim guidance is not a rule and it is not a statement of policy. Any discussion of EPA's regulatory authorities is for the purpose of describing standards and controls relevant to the destruction or disposal of PFAS and should not be considered a description of the applicability of those authorities.

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

- It does *not* establish what concentrations of PFAS in wastes, spent products, or other materials or media would necessitate destruction or disposal. Regulatory mechanisms, and/or risk-based guidance, are more appropriate for establishing such concentrations. Instead, this guidance provides information and suggested considerations for evaluating destruction and disposal options.
- It focuses on available technologies that have the potential to destroy PFAS (i.e., break the carbon–fluorine bonds) or control migration of PFAS in the environment.
- It focuses on destruction and disposal technologies for the materials specified in the FY 2020 NDAA (see Section 1.b.i), including PFAS-containing wastes generated by pollution control technologies at the site of PFAS manufacture and commercial use of PFAS formulations. Such treatment wastes include, for example, spent activated carbon from filtration of air and water waste streams from industrial facilities and water treatment.
- It is based on currently available information on technology performance and capabilities for destruction and disposal of the PFAS-containing materials specified in the FY 2020 NDAA.
- Storage of PFAS and PFAS-containing materials is not discussed as a destruction or disposal technology. In some cases, however, interim storage may be an appropriate strategy until identified uncertainties are addressed and appropriate destruction and disposal technologies can be recommended. EPA encourages the safe storage of PFAS and PFAS-containing materials as needed, following manufacturers' recommended best management practices as well as in accordance with any relevant industry, federal, state, or local requirements or guidelines.

1.c Destruction and disposal technologies addressed in this interim guidance

PFAS are managed in non-hazardous and hazardous waste treatment and disposal systems. As shown in Table 1-1, this interim guidance focuses on three destruction and disposal technologies: thermal treatment, landfilling, and underground injection. Other current PFAS waste management options are not discussed, as they are not in the intended scope of this guidance described in Section 1.b.ii. The land application of biosolids and other wastes (e.g., pulp and paper sludges) containing PFAS, for example, does not meet the Section 1.b.ii goal of PFAS destruction or control of PFAS migration into the environment.

Table 1-1. Destruction and Disposal Technologies Discussed in This 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 o Biosolids o Spent granular activated carbon (GAC) o Ion exchange resins o Filters o High-pressure membranes • Air waste stream treatment residuals o Spent GAC o Fly ash • Contaminated soil • End-of-life products (e.g., textiles)
Liquid phase: Underground injection Thermal treatment	• Landfill leachate • Aqueous film-forming foam • 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 • Emissions from manufacture, use, or destruction

1.d Summary of destruction and disposal interim guidance

The FY 2020 NDAA requires that EPA publish interim guidance on the destruction and disposal of PFAS and PFAS-containing materials. This document contains guidance that is based on currently available research and information and is responsive to the scope of the FY 2020 NDAA. Most significantly, it provides the best up-to-date information on potential releases during the destruction and disposal of PFAS and PFAS-containing materials and identifies data gaps to be filled that can inform future EPA guidance.

This interim guidance 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: aqueous film-forming foam (AFFF), soils and biosolids, textiles, spent water treatment materials, and landfill leachate.

EPA evaluated destruction and disposal technologies that are currently available for the management of PFAS. This interim guidance presents three destruction and disposal technologies that may be effective and are commercially available: thermal treatment (destruction), landfilling (disposal), and underground injection (disposal). Each technology is characterized in terms of the types of PFAS and PFAS-containing materials that typically can be handled, possible design and operating parameters, potentially relevant testing and monitoring methods, and costs, where relevant information is available.

While significant uncertainties remain with respect to the potential for migration to the environment associated with the destruction and disposal of PFAS and PFAS-containing materials using the technologies identified, this guidance may enable a manager of PFAS or PFAS-containing materials to make informed decisions in the evaluation of existing destruction and disposal options. EPA recognizes that the relative uncertainty associated with technologies' capabilities to control migration of PFAS to the environment is one of several factors that the public considers in determining how to destroy or dispose of PFAS-containing materials. Other factors would include whether it is imperative to destroy or dispose of the waste immediately versus storing it and waiting for those uncertainties to be reduced, the cost and availability of destruction and disposal options, the type of waste materials, and the concentrations of PFAS in the waste. Managers of PFAS materials could consider the following existing destruction and disposal options in the order of lower uncertainty to higher uncertainty while considering the other factors mentioned above to come up with a decision that is as protective of the environment as possible.

1. **Interim storage.** While not a destruction or disposal method, interim storage may be an option if the immediate destruction or disposal of PFAS and PFAS-containing materials is not imperative. In general, interim storage (estimated to be anywhere from 2 to 5 years) would be utilized until research reduces the uncertainties associated with other options.

2. **Permitted deep well injection (Class I).** Underground injection would be limited to liquid-phase waste streams.

3. **Permitted hazardous waste landfills (RCRA Subtitle C).** These have the most stringent environmental controls in place and higher potential capacity to manage the migration of PFAS into the environment.

4. **Solid waste landfills (RCRA Subtitle D) that have composite liners and leachate collection and treatment systems.** These landfills receive non-hazardous waste and tend to have environmental controls commensurate with the waste they receive. These controls can vary from state to state.

The following options have higher levels of uncertainties regarding their capacity to manage the migration of PFAS into the environment. In order to reduce the uncertainties, interim storage may be considered for PFAS or PFAS-containing materials before these options are selected. If entities determine, after considering this guidance and the uncertainties discussed herein, that certain PFAS waste nonetheless currently needs to be treated in hazardous waste combustors, it is important that the manager of PFAS materials provide the hazardous waste combustion facility with the relative PFAS concentrations for these materials. EPA encourages the manager of PFAS-containing materials, the hazardous waste combustion facility, and the state to work together with EPA to develop and implement protocols for monitoring, emission testing, and data sharing. While developing and implementing these protocols is not a precondition, EPA considers it a key step and requests assistance in obtaining more information to inform research efforts and future guidance. EPA is very interested in collaborating on these protocols.

5. **Hazardous waste combustors.** These would include commercial incinerators, cement kilns, and lightweight aggregate kilns, subject to the considerations outlined in this guidance.
6. **Other thermal treatment.** This would include carbon reactivation units, sewage sludge incinerators, municipal waste combustors, and thermal oxidizers, subject to the considerations outlined in this guidance.

This document describes a suite of technologies within the three categories noted above: thermal treatment (destruction), landfilling (disposal), and underground injection (disposal). The following have been found to have the greatest potential within each category to control migration of PFAS to the environment if used to destroy or dispose of PFAS-containing materials, based on the available information analyzed for this guidance document:

1. **Hazardous waste combustion** technologies (commercial incinerators, cement kilns, and lightweight aggregate kilns) can potentially achieve temperatures and residence times sufficient to break apart 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. Key uncertainties include the lack of PFAS-specific information on these facilities. EPA currently has no emission characterizations from these sources when they burn PFAS, and is working to develop measurement methodologies as well as gather information to conclude whether potential products of incomplete combustion (PICs) are adequately controlled. EPA recognizes that PICs are formed (even for nonfluorinated compounds); however, based on the unique characteristics of fluorine combustion chemistry, it needs to be determined whether thermal treatment devices and their associated post-combustion control devices are controlling fluorinated PICs. Additional research is needed to minimize or eliminate data gaps or current uncertainties. By the time of the next update to this guidance (within the next 3 years), EPA expects to complete sufficient research to address data gaps. EPA will then make a more informed recommendation on disposal of PFAS compounds and PFAS-containing substances using incineration.
2. **Hazardous waste or municipal solid waste landfills** are available, feasible, and effective, to varying degrees, 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 3-4) and as a result would be more effective at minimizing PFAS migration into the environment than other landfill types. Modern municipal solid waste landfills, when constructed with appropriate controls (e.g., liner system and leachate and gas collection and management systems), can also control the migration of PFAS into

the environment. Key uncertainties include that, even with these controls in place, the proper management of landfill gaseous and liquid releases needs to be applied for municipal solid waste and hazardous waste landfills to minimize PFAS migration into the environment (as described in Section 3.b.ii). Care must be taken to apply the leachate control technologies that are effective at containing (e.g., through solidification or recirculation) or destroying PFAS (see Table 3-6 for more information). Given the high level of uncertainty associated with PFAS behavior in landfills, research consistent with that described in Section 5—such as research on 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—will help to further evaluate this disposal method for PFAS and PFAS-containing wastes.

3. **Class I deep well injection** is another feasible and effective, to varying degrees, disposal option that normally should minimize migration of PFAS into the environment. However, the limited number of wells currently receiving PFAS, as well as location, waste transportation, and associated costs, may significantly limit the practicability of this disposal option. Unlike landfills, underground injection wells are only suited for disposal of liquids. Waste streams disposed of by underground injection will likely need to have low concentrations of suspended solids. This restriction may limit both the type and quantity of PFAS-related liquid waste streams.

Performance and testing data—including data on destruction and removal of PFAS in hazardous waste combustors and associated pollution controls, and long-term performance data for landfills and deep well injection—are insufficient to support more specific guidance at this time. See Section 3 for further information about these destruction and disposal methods and their uncertainties. As discussed below, EPA intends to fill gaps in knowledge associated with potential releases from these destruction and disposal methods before issuing further guidance.

The FY 2020 NDAA states that releases through volatilization, air dispersion, or leachate may impact vulnerable populations living near destruction or disposal sites. Accordingly, Section 4 of this document advises how to assess the impacts of potential releases and exposure on communities, including the identification of vulnerable populations, incorporation of vulnerability into risk assessment, and community engagement.

As described in Section 5, ongoing research is being conducted to address the gaps in the current state of knowledge about PFAS destruction and disposal technologies and PFAS monitoring methods. EPA's own research currently centers on better characterizing PFAS-containing materials targeted for destruction and disposal, assessing the effectiveness of existing and new methods of PFAS destruction and disposal, and developing PFAS monitoring methods. Status and updates on EPA's PFAS research are available at *https://www.epa.gov/chemical-research/status-epa-research-and-development-pfas*. EPA recognizes that additional information, which may be available from external stakeholders, may help EPA refine and update this guidance as appropriate.

This interim guidance serves as a baseline of destruction and disposal capabilities and uncertainties. As required by the FY 2020 NDAA, it will be reviewed and, if appropriate, updated within the next 3 years to reflect EPA's and other organizations' research on improving our understanding of current PFAS destruction and disposal technologies and developing new approaches. EPA will consider revising the guidance in less than 3 years if research results become available that would allow the Agency to issue more specific guidance on PFAS destruction and disposal.

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

The FY 2020 NDAA identifies six waste streams that commonly contain PFAS (see Figure 1-1 and Section 1.a). This section discusses each FY 2020 NDAA waste stream, its origins, potential sources of PFAS, current disposal and treatment methods, and potential releases to the environment.

Data on FY 2020 NDAA-relevant waste streams may 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 will begin to use Organization for Economic Cooperation and Development (OECD)–based industrial processing and use codes to better harmonize those data (U.S. EPA, 2020a).

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 (including on-site disposals and land application), as well as quantities transferred to off-site waste management facilities. Under Section 7321 of the FY 2020 NDAA, a total of 172 PFAS were added to the TRI list for reporting year 2020 (U.S. EPA, 2020b). The 2020 TRI data must be submitted by TRI-covered facilities by July 1, 2021; these data will be published shortly thereafter.

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). PFOA is a perfluoroalkyl acid (PFAA) and long-chain PFAS.

The goal of the PFOA Stewardship Program was to reduce PFOA facility emissions and PFOA 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). All eight of the participating manufacturers reported to EPA that they met these goals (U.S. EPA, 2014). Manufacturers achieved these goals by substituting the production and import of long-chain PFAS and their precursors with short-chain PFAS replacements and alternative chemistries. However, uses of these chemical substances continue by companies that did not participate in the PFOA Stewardship Program. 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). Furthermore, information on the toxicity and environmental fate and transport of alternative PFAS chemistries is limited (Sun et al., 2016; Wang et al., 2014).

In the 2016 CDR full dataset, primary manufacturers reported manufacturing (including importing) about 25,600 metric tons of PFAS at 38 sites in 2015. 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 synthesis, polymerization, application, transport, usage, and waste stream management and disposal (3M Company, 2000b). Table 2-1 lists important 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 consisting of high-molecular-weight byproducts that are either fully or partially fluorinated. These byproducts may be recycled back into the process, disposed of in a hazardous waste landfill, or incinerated (3M Company, 2000a, 2000b). Solid wastes may also be produced as fly ash or spent GAC resulting from PFAS incineration and other treatment processes.

Other important solid-phase wastes 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) that receives influent from industrial sources (Venkatesan & Halden, 2013). In addition to solids produced via treatment, spent water treatment media (such as 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).

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.

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 PFAAs (e.g., PFOA, PFOS, and 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

Industry Type	**Uses**	**Examples of Waste Streams**[a]			**Notes**
		Solid	**Liquid**	**Gas**	
Primary chemical manufacturing	PFAS synthesis, feedstocks for primary products, feedstocks for secondary users, processing aids (fluoropolymers)	Process byproducts (tars), sludges/biosolids, 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)

Industry Type	Uses	Examples of Waste Streams[a]			Notes
		Solid	Liquid	Gas	
Cleaning product manufacturing	Component of household cleaners; car wash products; automobile waxes; wiper fluid; strongly acidic or basic cleaners for concrete, masonry, airplanes 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		*Off-spec products,[b] liquid residues from empty containers, and spills*	Stack emissions, fugitive volatiles	3M Company (1999)
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)

Industry Type	**Uses**	**Examples of Waste Streams[a]**			**Notes**
		Solid	**Liquid**	**Gas**	
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 blocking agent for aluminum foil; in plating baths; and to treat metal surfaces	*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)
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/greaseproofing for products including food contact paper (plates, popcorn bags, pizza boxes, food containers, wraps), non-food contact applications (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 additive	*Particulate emissions*	*Liquid residues from empty containers, spills, off-spec products,[b] cleaning of equipment, and process wastewaters*	*Fugitive volatiles*	World Bank Group (1998)

Industry Type	Uses	Examples of Waste Streams[a]			Notes
		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; PTFE (polytetrafluoroethylene, 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, unused application mix, etc.	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/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]			Notes
		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 (tubing, filters, films, etc.)*			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]			Notes
		Solid	Liquid	Gas	
Fire suppression systems[e]	AFFF and dry fire-extinguishing agents	Contaminated soil and debris from applied product[d]	Applied product[d]		See Section 2.b for more information

[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 chemicals 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) and 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). Frequency of use for firefighting, training, or testing; transfers between locations; and other factors determine rates of AFFF inventory depletion. However, AFFF's characteristically long shelf life means little disposal due to expiration should occur (FFFC, 2016), increasing the possibility that legacy PFOS-containing AFFF concentrate remains in service or reserve inventories.

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 U.S. Department of Defense (DoD) is working to identify areas of active and former installations where PFOS- or PFOA-containing AFFFs have been used (Darwin, 2011; DoD, 2020). As of the end of FY 2019, the scope of this assessment of potential PFAS use or release has grown to comprise a more comprehensive inventory of DoD and National Guard installations, beyond just those with potentially significant historical AFFF use (DoD, 2020).

The FY 2020 NDAA prohibits any land-based fluorinated AFFF use effective October 1, 2024, or sooner, if the Secretary of Defense deems it practicable. DoD issued policy in January 2016 to discontinue land-based AFFF training and testing activities. 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).

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	• DoD discontinued land-based AFFF for training and testing in 2016 and is investing in fluorine-free alternatives • The FY 2020 NDAA requires DoD to end any land-based AFFF use no later than October 1, 2024 • Sources: DoD (2017, 2019, 2020); CBO (2019); SERDP (2020)
NASA	• Three centers with ARFF apparatus • Nine hangars, including Wallops Flight Facility	• NASA discontinued training with AFFF in late 2018 • Sources: SERDP (2020); NASA (2020)
DOE	• Lawrence Berkeley National Laboratory • Brookhaven National Laboratory • Los Alamos National Laboratory • Strategic Petroleum Reserve facilities (Gulf of Mexico)	• Sources: DOE (2016, 2017, 2020a, 2020b); Darwin (2011)
Airports and supporting facilities	• 523 Federal Aviation Administration (FAA)–certified civilian airports in 2018 • Since 2006, an annual average of nearly 600 certificated airports • Supporting facilities include firefighting training sites, such as the FAA Technical Center's Fire Training Area	• FAA regulations required certain AFFF quantities at civil airports starting in 1972; since 2006, FAA regulations require most civil airports to purchase military-specification AFFF[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	• Legacy PFOS AFFF may be present at fire departments • Some states have begun inventorying and reporting of AFFF (e.g., Michigan, New Hampshire) • Some states have take-back programs to help local fire departments identify AFFF in inventory and assisting with removal and disposition (e.g., Vermont) • Sources: Michigan Department of Environment, Great Lakes, and Energy (2020); New Hampshire Department of Environmental Services (2020); Vermont Agency of Natural Resources (n.d.)

AFFF User	Locations	Comments
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)
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 towards 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 as part of their response block sewer drains or deploy portable dikes as containment measures (FFFC, 2016). Runoff can then be pumped out and impacted environmental media removed for disposal (ITRC, 2020). Construction and demolition (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.

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 (commonly referred to as "biosolids") as a 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. 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. If the biosolids are applied to land, there is the potential for leaching or runoff. Alternatively, if the biosolids are incinerated, there is potential for PFAS to be emitted as PICs (Navarro et al., 2016; Sepulvado et al., 2011; Washington et al., 2010).

Total nationwide biosolids generation and management statistics in 2019 (reported to EPA's biosolids program as of May 5, 2020) and data considerations are presented in Table 2-3. EPA does not have data on the volume of biosolids that contain PFAS.

Table 2-3. Biosolids Generation and Management in 2019

National Pollutant Discharge Elimination System (NPDES) permits issued to publicly owned treatment works (POTWs)[a]	16,109
Biosolids NPDES permits[b]	9,834
Biosolids annual reporters (2019)[c]	2,273
Biosolids generated in 2019 (metric tons)[d]	4,751,267
Land application (metric tons)	2,439,320
Land disposal (also called surface disposal) (metric tons)	120,125
Incineration (metric tons)	765,464
Landfilling (metric tons)	928,131
Other management (metric tons)	498,227

[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 WWTP that is typically owned, and usually operated, by a local or regional government agency (U.S. EPA, 2020b).

[b] Biosolids permits apply to any person who 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 POTWs that have design flow capable of serving 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, 2017).

[d] Total amount of biosolids generated is reported by each POTW 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 wastes (e.g., biosolids), there are other scenarios where PFAS migration to soils can occur. Direct migration of PFAS into soils can occur through applications of PFAS-containing products such as AFFF, land application of PFAS-containing wastes (e.g., biosolids), 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 2-1 for examples of industrial sources of PFAS in soils). Both direct and indirect soil impacts might also occur via the atmospheric deposition of PFAS adsorbed to particulates 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 2-1.)

2.e Spent water treatment materials

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, 2016a, 2016b). This section discusses the residual streams of these three processes (see Section 3 for discussions on treatment and disposal considerations and costs, and Section 5 for discussions of research needs for more novel treatments).

2.e.i Activated carbon

Activated carbon (discussed more extensively in Section 3.a.i) is manufactured from carbon-rich sources such as wood and used to treat water or air by filtering contaminants (U.S. EPA, 2012). Activated carbon can be used in either powdered activated carbon (PAC) or GAC form. In PAC treatments, carbon is powdered and added to the water for treatment, and chemicals in the water then stick to the powdered carbon as the water passes through. In GAC treatments, small pieces of carbon adsorb to chemicals in water 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 other, more common treatment scenarios or for PFAS that are adsorbed more weakly (like the shorter-chain PFAS), the weight percent of PFAS will be orders of magnitude lower.

GAC can be reactivated and reused (see Section 3.a.i.2 for a discussion on GAC reactivation, and Section 3.a.vii for a discussion on the costs of 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 low-PFAS-containing water stream. Desorption will occur due to the disequilibrium between the liquid and solid phases. The resulting PFAS concentrations in the landfill leachate will vary greatly depending on conditions.

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.

Also similar to GAC, the 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 (like the shorter-chain PFAS) will yield much lower average weight percent of PFAS.

Assuming single-use resin is used, landfilling can be less expensive than incineration (see discussions of treatment costs for the respective waste management options in Section 3). 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.

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). Because the process is based on a rejection phenomenon, water treatment with high-pressure membranes creates a waste stream with potentially high concentrations of PFAS that needs to be treated and disposed. These waste streams also have high concentrations of salts, other contaminants, and dissolved organic matter.

Treatment of the concentrate residual stream can be challenging and the cost is likely 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.

2.f Landfill leachate containing PFAS

Landfill leachate (discussed in more detail in Section 3.b.iii) is the effluent formed by rainwater percolating through waste in landfills. Leachate generation may continue even after a landfill's closure period, as a result of inherent liquids 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. MSW and hazardous waste landfills are typically 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 3-5 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 WWTP 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 control (see Sections 3.a and3.c, respectively). The on-site leachate treatment technologies employed at landfills are explored in Table 3-4 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).

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 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 technological solutions that are commercially available and potentially have the capability to destroy PFAS or manage the migration of PFAS in PFAS-containing materials. These technologies are thermal treatment (Section 3.a), landfilling (Section 3.b), and underground injection control (Section 3.c). Each subsection describes various considerations of these technological solutions, including types of treatment, control devices and corresponding emissions, testing and monitoring, and uncertainties. References appear at the end of each subsection.

3.a Thermal treatment

Hazardous waste combustion technologies (commercial incinerators, cement kilns, and lightweight aggregate kilns [LWAKs]) can potentially achieve temperatures and residence times sufficient to break apart 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, but information on the efficacy of PFAS destruction in these facilities is currently lacking. EPA currently has no emission characterizations from these sources when they burn PFAS, and is working to develop measurement methodologies and gather information to conclude whether potential PICs are adequately controlled. EPA recognizes that PICs are inevitable (even for nonfluorinated compounds); however, based on the unique characteristics of fluorine combustion chemistry, it needs to be determined whether thermal treatment devices and their associated post-combustion control devices are adequately controlling 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.

Thermal treatment units use high-temperature chemical breakdown or incineration to control pollutants. Incineration is an effective and approved method for destroying certain halogenated organic chemicals including chlorinated solvents, polychlorinated biphenyls (PCBs), dioxin-laden wastes, brominated flame retardants, refrigerants, and ozone-depleting substances (ODSs). Fluorine, like chlorine and bromine, is a halogen; thus, PFAS fall into the category of halogenated chemicals.

PFAS are difficult to destroy due to the strength of the carbon-fluorine bond—a result of fluorine's electronegativity and the chemical stability of fluorinated compounds. Incomplete destruction or recombination of reactive intermediates can potentially result in the formation of new PFAS or other PICs of concern. Halogenated organic compounds generate the corresponding halogen acid when sufficiently high temperatures and long residence times break the carbon–halogen bond as the compounds thermally decompose and the resulting halogen atoms recombine with available hydrogen. For this interim guidance, PFAS destruction is defined as the complete severing of all carbon-fluorine bonds in a PFAS molecule. Severing all carbon-fluorine bonds results in conversion to carbon dioxide, hydrogen fluoride (HF), and other compounds. HF and some of the other products of combustion can be removed in pollution control devices.

This section focuses on the viability of thermal treatment of PFAS, discussing:

- The types of thermal treatment units that manage PFAS-containing waste 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 waste, including the ability to effectively measure and monitor thermal treatment performance.
- Operating costs and commercial availability for the thermal treatment operations known to handle PFAS-containing waste.

3.a.i Types of thermal treatment

The following subsections describe the types of thermal treatment devices potentially capable of treating PFAS-containing waste streams identified in Section 2.a, with a focus on design and operation parameters that are important for destroying PFAS. These include hazardous waste combustors (HWCs), non-hazardous waste combustors, carbon reactivation units, and thermal oxidizers. Waste incinerators are typically classified by the type of waste that they combust.

3.a.i.1 Hazardous waste combustors

HWCs are hazardous waste incinerators (HWIs), cement kilns, LWAKs, boilers, and hydrochloric acid production furnaces that burn hazardous waste.[1,2] Two types of HWCs that have treated PFAS waste in the United States are commercial[3] incinerators and LWAKs. Initial studies suggest that cement kilns may be effective at treating PFAS waste (see Section 3.a.ii).

All HWIs, LWAKs, and cement kilns are subject to Resource Conservation and Recovery Act (RCRA) and Clean Air Act (CAA) permitting requirements 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 that include emission limitations for metals, dioxin/furans,

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[1] Hazardous waste is regulated pursuant to Resource Conservation and Recovery Act 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).

[2] 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.

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

particulate matter, hydrogen chloride and chlorine gas, and carbon monoxide or hydrocarbons, as well as limits on minimum organic destruction and removal efficiency (DRE). 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. 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 previous rulemaking background support documents (U.S. EPA, 2005b) and numbers of HWC facilities are based on a 2019 national hazardous waste capacity assessment report (U.S. EPA, 2019). The capacity assurance report also provides a list of these facilities.

3.a.i.1.1 Commercial hazardous waste incinerators

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.[4] 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). The rotary kiln is followed by an afterburner where additional high-heating-value gaseous and liquid wastes, and auxiliary fuels are added. The afterburner 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 1 to 3 seconds to maximize organic destruction and minimize the formation of PICs. Depending on the fuels used and waste streams introduced, combustion products 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 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 dioxin/furan and other emissions.

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 or all of the fossil fuels. Most of them burn liquid waste; some may also burn solids and small containers containing viscous or solid hazardous waste fuels. Extreme combustion conditions (e.g., temperatures above 1,650°C [3,000°F]), turbulent mixing, and long gas phase residence time (from 4 to as high as 16 seconds in long kilns) can effectively

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[4] DRE = $[1 - (W_{out} / W_{in})] \times 100\%$, where: W_{in} = mass feedrate 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.

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 be 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.

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 kiln gas residence times (over 2 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.

3.a.i.2 Carbon 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 safely and effectively treat the hazardous contaminants, which may not be required for non-RCRA-permitted carbon reactivation furnaces. Due to these additional safeguards, RCRA-permitted furnaces may operate under conditions more conducive to destroying PFAS and controlling related PICs. This discussion focusses on RCRA-permitted furnaces because EPA has more design and operational information on these devices as a result of the RCRA permitting process. Reactivation[5] of spent carbon is generally carried out in multiple-hearth (or "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 ranging from 100°C to 110°C (212°F to 230°F) contact the carbon.

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[5] "Reactivation" refers to a regeneration process that requires high temperatures. Regeneration also includes low-temperature processes, including 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.

- 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 usually 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 different 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).[6]

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. The temperature required to achieve 99.99 percent DRE depends on residence time as well as 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 1 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. These 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.

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

Non-hazardous-waste incineration in the United States includes sewage sludge incinerators (SSIs) at wastewater treatment facilities and municipal waste combustors (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. 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, n.d.).

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 in the United States (U.S. EPA, 2016). The main types of SSIs are multi-hearth furnaces and fluidized bed combustors (FBCs).

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[6] 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.

The basic multi-hearth furnace is a vertical cylinder divided into zones. The sludge is dried at temperatures from 425°C to 760°C (800–1,400°F). Sludge combustion occurs as the temperature is increased to about 925°C (1,700°F) in successive zones. The gas residence times are typically 4 or 5 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 between 750°C and 925°C (1,400–1,700°F). The gas residence times are typically 2 to 5 seconds. Emission controls on FBCs can include venturi scrubbers, multicyclones, FFs, activated carbon injection, and carbon bed absorbers.

3.a.i.3.2 Municipal waste combustors

There are 193 MWC units operating 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. 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 around 815°C (1,500°F).

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 et al., 1990; Themelis & Reshadi, 2009). Overall combustion air residence times have been calculated in the 7–10 second range for a small sampling of MWC design loads (Themelis & Reshadi, 2009), with an approximate residence time at temperature above 980°C (1,800°F) of about 2 seconds at full combustor load (Scavuzzo et al., 1990).

Emission controls on MWCs can include spray dryer or dry sorbent injection, electrostatic precipitator or FF, selective or non-selective catalytic reductions, and activated carbon injection.

3.a.i.4 Thermal oxidizers

Thermal oxidizers are used to destroy volatile organic compounds (VOCs) and organic hazardous air pollutants (HAPs) from liquid and gaseous process streams at a manufacturing or production facility.

These devices are designed to optimize temperatures, residence times, and turbulence to address the composition of the feedstream 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 2 seconds, depending on site-specific criteria. Catalytic thermal oxidizers operate at lower temperatures than other types of thermal oxidizers—typically about 400°C (800°F) with similar residence times to non-catalytic thermal oxidizers—while achieving the same efficiency.

Emission controls for thermal oxidizers vary widely depending on the facility and the composition of the feedstreams. 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.

3.a.ii Ability of thermal treatment technologies to destroy PFAS

Combustion involves burning a fuel in the presence of excess atmospheric oxygen. Combustion progresses through a complex series of physical and chemical processes involving reactant interaction, mixing, and many elementary free radical reactions. The complete combustion of hydrocarbon fuels results in carbon dioxide and water; for PFAS, the final products also include HF. In practice, kinetic (temperature) and transport (mixing) limitations prevent complete combustion of fuels. This is related to the three *T*s (time, temperature, and turbulence) used to guide the design and operation of incinerators and thermal oxidizers to maximize complete waste destruction. In real world systems, incomplete combustion leads to emissions of carbon monoxide, soot, and other PICs.

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), requiring 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 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), making 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 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 depends on the local temperatures and concentrations of 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 radical) are high, as 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 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.

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 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.viii).

Carbon reactivation systems can degrade PFAS even at the lower temperatures (150°C–700°C) (302°F–1,292°F) seen in bench-scale research studies. Experimental data suggest that thermal destruction of PFAS will occur in two stages: during reactivation of the GAC, then when the offgas is introduced into a high-temperature zone as high as 1,000°C (Forrester, 2018; Watanabe et al., 2016, 2018; Xiao et al., 2020). Carbon reactivation systems, with the concomitant use of offgas incineration (i.e., afterburners) and gas scrubbing units, can destroy PFAS without significant environmental releases, or without PFAS remaining on the reactivated carbon. However, as discussed elsewhere in this interim guidance, more work is needed for confirmation particularly with regard to 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. Thermal oxidizers are being employed to destroy PFAS-containing liquid and gaseous streams, but the data are insufficient to allow conclusions on the overall efficiency of thermal oxidizers in PFAS destruction. 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 destruction of PFAS is currently unknown, a properly optimized thermal oxidizer can readily achieve a DRE of 99.99 percent of 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).

Processes involving calcium and alumina may have catalytic benefits and 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 (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 carbon dioxide and HF at comparable temperatures.

It is not well understood how effective high-temperature combustion is in 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 2 seconds of residence time at 1,000°C (1,830°F) (Yamada et al., 2005; Taylor et al., 2014). One recent field study examining the performance of a specially designed thermal oxidizer to destroy PFAS in process gases at a Chemours production facility near Fayetteville, North Carolina, indicated >99.999 percent destruction of five PFAS (Chemours, 2020). This implies the destruction of the original PFAS, but does not provide certainty that all carbon–fluorine bonds were severed. 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 (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).

3.a.iii 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 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 from 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, which could then be partitioning between solid CaF_2 and water in the precipitator, with most of the PICs retained in water then removed by activated carbon adsorption. EPA is not aware of peer-reviewed studies for measuring 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 drying lime in 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 the SDA may provide a potential co-benefit of controlling fluorinated PICs. The injection of PAC upstream of the FF subsequently 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.iv Potential for releases for thermal treatment technologies

Thermal treatment devices used to treat PFAS-containing waste (see Section 3.a.i for descriptions of these devices) are located in both rural and populated areas throughout the United States. Two possible sources of potential PFAS emissions from thermal treatment are the stack emissions and subsequent 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 limited 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 device equipment (e.g., fugitive emissions) and waste storage activities are another potential source of PFAS releases, if they are not adequately controlled.[7] There is also the potential for releases from management of thermal treatment process residuals such as liquid discharges from acid gas scrubbers, air pollution control device media, and incinerator bottom ash. For example, incinerator bottom ash disposed of in a landfill would be a possible source of release if it contains PFAS and the landfill lacks 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.

3.a.v 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 current lack of standardized methods to measure PFAS emissions and the limited availability of data on the performance of methods to measure PFAS introduce uncertainty in the understanding of the efficacy of thermal treatment approaches for destroying PFAS.

Ongoing method development has a broad focus that will address PFAS in various waste streams, stack and fugitive emissions, and ambient air. Method development also includes identification of PFAS that are potential PICs, not targeted in current established water methods such as Method 537.1. With the number and complexity of PFAS presently known, a simpler class-specific measurement is also being investigated to determine if 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.

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

Development of methods to measure PFAS in air has focused on compounds whose physical state is liquid or solid at room temperature. Method development to measure 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,

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[7] 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.

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 the high-volume air sampling protocol described in EPA compendium method TO-13a (U.S. EPA, 1999) or 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 method development and evaluation for stationary source air emissions is based on EPA SW-846 Method 0010—modified to include collection of both targeted and nontargeted 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 plans to release Other Test Method 45 (OTM-45), *Measurement of Selected Poly- and Perfluorinated Alkyl Substances from Stationary Sources,* based on this method development.

These field 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. 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, used to identify unknown PFAS, currently relies on high-resolution mass spectrometry, which generates qualitative information about the molecular formula of unknown PFAS. NTA is a critical component of thermal treatment emissions characterizations because it provides the only definitive approach for identifying unknown PFAS or PICs.

3.a.v.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 SUMMA canisters, as well as sorbent traps and cryogenic solvents. Issues such as sample reactivity, breakthrough volumes, and quantitative transfer to the analysis instrument complicate these approaches. Direct instrumental methods to measure volatile PFAS can suffer from lack of sensitivity compared with extractive methods that allow concentration prior to analysis. To develop more sensitive methods to measure volatile fluorocarbon compounds, EPA has investigated the use of SUMMA canisters for targeted and nontargeted volatile PFAS as well as PICs at multiple-source emissions tests, including a thermal treatment facility for AFFF-contaminated soil (U.S. EPA, 2020b). SUMMA canisters have been used to sample source emissions and perform targeted measurements for PFAS including TFE, HFP, E1, E2, 4:2 FTOH, and 6:2 FTOH. NTA has also been performed on the same samples. EPA and private sector investigators have used 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).

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.

EPA is evaluating FTIR as a suitable measurement technique for CF_4 and C_2F_6 in stationary source emissions. In addition, EPA is exploring the use of SUMMA canister sampling and sorbent traps for offline measurements of CF_4 and C_2F_6. The need to measure volatile PFAS at trace concentrations is based on the desire to introduce a known concentration of a hard-to-destroy fluorocarbon and evaluate the behavior of this compound when exposed to thermal treatment. This approach is consistent with the EPA approach to determine the DRE of fluorinated greenhouse gas abatement equipment in electronics manufacturing (U.S. EPA, 2010).

The quantitative measurement of total organic fluorine (TOF) is also being evaluated to represent all, or most, of the PFAS class of compounds as 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) (see Section 5.c). 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 associated with potential health risk of not knowing which PFAS or class of PFAS is present in the sample. 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 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.vi 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). The current lack of a standardized validated methodology for measuring PFAS gaseous emissions (see Section 3.a.v.2) makes consistent direct measurement of PFAS and potential PIC emissions not possible and limits understanding of combustion conditions under which relatively complete destruction of PFAS can occur. EPA also lacks detailed information on the amounts and concentrations of PFAS-containing materials that are generated and managed in thermal treatment devices.

Sampling and analytical methodologies must continue to be developed (see Section 5 research activities) so that emissions and other media from thermal treatment devices burning PFAS-containing materials can be adequately characterized. EPA recognizes that PICs are inevitable (even for nonfluorinated compounds); however, based on the unique characteristics of fluorine combustion chemistry, it needs to be determined whether thermal treatment devices are adequately controlling fluorinated PICs. Research efforts will address several issues. For example, are the operating temperatures at these various thermal treatment devices adequate to completely destroy PFAS? Can surrogate DRE or TOF indicators be used as reliable indicators to ensure potential PICs are being controlled? Can catalysts be used to enhance PFAS destruction efficiency? EPA and others continue to research these complex and important issues. See Section 5 for a summary of planned research activities specific to thermal treatment of PFAS.

3.a.vii Treatment costs and 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[8] in operation; over a dozen large-scale, commercial carbon reactivation companies with about 17 furnaces; 193 MSW incineration units; and 170 SSIs.

Costs associated with treating contaminated media using thermal treatment include operation and maintenance costs of the treatment technology, capital costs, waste transport costs (if applicable), and costs associated with regulatory compliance. Breakdowns of these costs for the thermal treatment units described in this guidance were not readily available. However, operating costs for commercial treatment units are reflected in the amounts these facilities charge to thermally treat the waste streams they receive. This cost can be characterized by a cost charged per ton to treat specific types of waste. Waste transport costs are also important to consider, because some commercial treatment options could involve transporting large volumes of waste over large distances.

Treatment of contaminated media in hazardous waste combustion devices, such as incinerators, involves costs associated with the high energy consumption needed to maintain elevated temperatures, as well as the regulatory and permitting costs associated with treating, handling, and storing these waste streams. Table 3-1 summarizes estimated costs to incinerate different types of hazardous waste, and Table 3-2 summarizes the costs to incinerate different types of non-hazardous waste. These estimates in Table 3-1 were used to assess costs and impacts of CAA regulations issued in 2005 (U.S. EPA, 2005a), acknowledging these costs likely have changed over the years. Halogenated waste streams are generally more expensive to treat, and costs are also influenced by whether the waste is a liquid, sludge, or gas.

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

Table 3-1. 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)	$1,218–1,770
Liquids, sludges, solids (non-halogenated)	$357–975
Lab packs	$6,042
Containerized gases	$2,924

[a] 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 2019 dollars using the Bureau of Economic Analysis (BEA) gross domestic product (GDP) deflator (BEA, 2020) 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.

Table 3-2. Estimated Costs to Incinerate Different Types of Non-Hazardous Waste

Incinerator Type	Estimated Cost per Ton of Waste
SSI	
Multiple hearth	$114[a]
Fluidized bed	$80[a]
MWCs	$60[b]

[a] Per dry ton, data provided by SSI owners/operators for 2006–2008. Assumed 2008 dollars. Costs were normalized to 2019 dollars using the BEA GDP deflator (BEA, 2020) 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 CEPCI, energy prices typically based on EIA data, and labor costs based on industry segment indices using BLS data.

[b] Average tipping fee per ton (2019 dollars) in states with operating MWCs.

MWCs charge tipping fees for waste disposal, often through long-term contracts with various municipalities. As such, whether a combustor accepts an additional waste stream may depend on its capacity and how much waste needs to be combusted under its current operations and contractual obligations. Similarly, to reduce sludge transportation costs, SSI units are typically located at, owned by, and operated by the POTWs generating the sludge they incinerate. As a result, an SSI may be sized to handle the sludge generation needs of the treatment works: it may not be capable of accepting more sludge or wastes from outside sources.

For MWCs, the costs represent the 2019 average tipping fee charged in states with waste-to-energy facilities (EREF, 2019). Compiled tipping fee rates for waste-to-energy facilities are not available, but this average price is expected to reflect the market price of tipping fees being charged by landfills and waste-to-energy facilities. SSI operating costs, not being typically marketed to the public, reflect facility-reported operating cost estimates provided during SSI regulatory development (U.S. EPA, 2016).

Costs associated with incinerating remediation waste such as contaminated soil can be estimated by assuming the contaminated soil will be treated in a commercial HWI. Some sites may treat contaminated soil either on-site or in nearby incinerators that are not required to obtain hazardous waste treatment permits. These incinerators may have lower operating costs due to fewer permitting requirements. Several factors affect costs for thermal treatment of contaminated soils, including soil type (e.g., clay content, particle size, moisture content, pH), type and concentration of contaminants that affect the necessary operating temperature, type of emission treatment needed, and type and frequency of maintenance needs such as changeout of filters or carbon (U.S. EPA, 2001). As a result of all these factors, the cost associated with incineration of remediation wastes vary and are site-specific. Ex situ incineration costs ranging from $168 to $3,256 per metric ton (normalized to 2019 dollars from 2016 dollars using the BEA GDP deflator [BEA, 2020]) have been reported (Ding et al., 2019; Vidonish et al., 2016).

With respect to carbon reactivation units, financial considerations favor the reactivation of spent GAC as opposed to disposal of the spent media and replacement with virgin 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, offgas permitting, public opinion, etc.). Table 3-3 contains example costs per weight of media for various disposal options. These data are derived from unit costs developed for EPA's work breakdown structure drinking water treatment cost models (Khera et al., 2013; U.S. EPA, 2020a). They are intended to reflect typical conditions and are based on estimates from multiple vendors. However, they do not account for site- or project-specific factors that could affect the cost of media replacement and disposal. Therefore, these unit costs are presented as examples only, to illustrate the tradeoffs between disposal options.

As seen in Table 3-3, thermal reactivation of GAC costs less, at $1.41 per pound, than disposing of spent GAC and replacing it with virgin carbon. This is due to the higher cost of virgin media ($1.88/pound versus $1.21/pound for reactivated) (normalized to 2019 dollars from 2018 dollars using the BEA GDP deflator [BEA, 2020]). Although the reactivation procedure results in the loss of a certain percentage of carbon, incorporating this factor does not change the general conclusion that reactivation is a lower-cost option. For example, the reactivation costs in the table incorporate a conservative estimate of 30 percent loss and remain lower than the replacement and disposal costs. Therefore, it is expected that entities treating PFAS-contaminated waters with GAC, as well as GAC manufacturers, will desire to reactivate their media.

Table 3-3. Example Disposal/Reactivation Costs for Spent GAC for Drinking Water Treatment (Derived from U.S. EPA, 2020a)

Method	Cost of Disposal ($/Pound of Media)	Cost of Disposal Plus Replacement Media ($/Pound of Media)[a]
Reactivated GAC—off-site	$0	$1.41
Disposal via landfill	$0.04	$1.92
Disposal via incineration	$0.36	$2.24

[a] Cost per pound is in 2018 dollars. Costs were normalized to 2019 dollars using the BEA GDP deflator for waste management and remediation services using a base year of 2002 (BEA, 2020). 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.

3.a.viii Summary

PFAS-containing waste can potentially be treated in several types of thermal treatment devices, including HWCs, MWCs and SSIs, and carbon reactivation furnaces, but further research is planned 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.

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

Given the unique characteristics of fluorine combustion chemistry (particularly the strength of the carbon-fluorine bond), complete thermal destruction of PFAS requires high temperatures and long residence times and likely benefits from direct flame contact. Studies suggest that combustion temperatures necessary to completely destroy PFAS may be reduced if certain catalysts are present in the thermal treatment system. However, available information on catalyst-aided PFAS destruction is limited. 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. 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, as well as 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 lacking. EPA currently has no emission characterizations from these sources when they burn PFAS, and is working to develop measurement methodologies as well as 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 carbon reactivation furnaces as for HWCs. Experimental data suggest that thermal destruction of PFAS will occur in two stages: during reactivation of the GAC, then when the offgas is introduced into a high-temperature zone as high as 1,000°C. As referenced in Section 3.a.i, a carbon reactivation furnace can be equipped with an afterburner to treat offgases at high temperatures to achieve 99.99 percent DRE. 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 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, 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) to assess whether the PTFE is destroyed or reformed as PFAS. This study looked at a half-load scenario of 870°C (1,600°F) with a 4-second residence time and a full-load scenario of 1,020°C (1,870°F) for a 2.7-second residence time. There were 31 PFAS compounds analyzed for 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 operating in the United States presently. 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, research (Wang et al., 2013) has investigated PFAS interactions with CaO and $Ca(OH)_2$ at moderate temperatures (200°C–900°C [390°F–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 resulting in 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 real-world design and operation of SSI and the lack of robust information on PIC formation.

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.

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3.b Landfills

Landfills control waste and corresponding pollutants through containment. Because of their many and varied uses, PFAS enter landfills as part of the general municipal waste stream, with some industrial waste, or in other PFAS-containing wastes, with a range of concentrations.

Hazardous waste or MSW landfills are available 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 3-4) and as a result would be more effective at minimizing PFAS migration into the environment than other landfill types. Modern MSW landfills, when constructed with appropriate controls (e.g., liner system and leachate and gas collection and management systems), can also control the migration of PFAS into the environment. EPA plans to conduct 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).

While landfills might serve as long-term containment sites for PFAS, they have not been designed explicitly for PFAS containment. For example, some hazardous waste landfills are designed to control specific chemicals (e.g., dioxins and other specific hazardous wastes), but it is unclear how effective they are at containing PFAS. Because landfills are a containment method and do not destroy PFAS, PFAS are expected to persist in landfills for the life of the compounds, which could be many years or until they are released. Landfill liners and cover systems are designed to contain leachate and control emissions, but even the best-designed systems will fail at some point unless they are replaced or the waste is removed. Thus, PFAS-containing wastes remain in the landfill until the liner or cap fails or until the waste is removed per future management action.

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 that may be present within the landfill from entering the environment. Landfills are commonly classified by the types of wastes they accept and/or by their ownership status.

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

- 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.
- Methods to monitor PFAS at landfills (and corresponding waste streams).
- Uncertainties and unknowns associated with landfilling PFAS-containing waste.
- Operating costs for landfill controls that address PFAS.

3.b.i 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 of, a landfill could be subject to regulation and permitting under RCRA, the CAA, and/or the Toxic Substances Control Act (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 requirements determine how the landfill must be constructed, operated, 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 and tend to have similar environmental controls within each category:

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

Table 3-4 compares some of the environmental controls required by landfill types as defined under RCRA Subtitles C and D. The landfill categories differ in how they are constructed, operated, monitored, and closed, reflecting the different types of waste they are allowed to receive. Subtitle C hazardous waste landfills are permitted to receive hazardous wastes, which has been evaluated and determined to pose potential risk to humans and the environment and therefore has the most stringent environmental controls in place; Subtitle D landfills that receive non-hazardous and non-putrescible waste tend to have environmental controls commensurate with the waste they receive. These controls can vary from state to state; for example, certain small MSW landfills in arid or remote locations are exempt from both design and groundwater monitoring requirements.

Table 3-4. Required Environmental Controls by Landfill Type

Landfill Type	Federally Regulated Under	Bottom Liner and Leachate Collection System	Gas Collection 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	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 3-5. 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.i.1 Hazardous waste landfills

Hazardous waste landfills are permitted to receive waste that is defined as "hazardous" under EPA's RCRA regulations. This waste either is explicitly listed as hazardous in the regulations or demonstrates at least one of certain characteristics (i.e., toxicity, corrosivity, reactivity, or ignitability). Any Subtitle C landfill is required to have a double liner system. Because most hazardous wastes are not biologically active, hazardous waste landfills typically do not have gas collection systems, although gas collection systems could be installed if a problem arises related to gas migration or gas emissions. Any hazardous waste landfill must have a final cover consisting of an FML covered by soil.

3.b.i.2 Municipal solid waste landfills

MSW landfills receive most of the waste generated by households and commercial facilities. An MSW landfill typically has at least a bottom liner and extensive gas collection and control system (GCCS) to collect the landfill gas (LFG) generated when the putrescible waste, such as food scraps and office paper, degrades over time. Some MSW landfills that receive less than 20 tons of waste per day are exempt from installing a liner under RCRA, while others might be exempt from installing a gas collection system under the CAA. Unlined MSW landfills are ineffective at managing the migration of mobile PFAS to groundwater (see Section 4.a). Additionally, those lacking gas collection systems could release fugitive PFAS associated with LFG emissions.

3.b.i.3 Ash monofills

Ash monofills are a subtype of MSW landfill that mainly receive ash from MSW incinerators but could also receive other waste streams such as biosolids from WWTPs. Ash monofills typically have a bottom liner and final cover requirements similar to other MSW landfills but typically do not require GCCSs due to the incineration removing putrescible waste. Solo-Gabriele et al. (2020) found ash monofills have lower PFAS concentrations than other landfill types, as shown in Table 3-5. While some landfill wastes, such as MSW ash, may be low in PFAS concentrations, the inclusion of higher-PFAS waste types may increase PFAS releases. 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.

Table 3-5. Average PFAS Concentrations in Different Types of Landfill Leachate Reported in Published Studies

Landfill type	Country	Mean PFAS Range (ng/L)	References
MSW landfill	USA	BDL–17,710	Solo-Gabriele et al., 2020; Lang et al., 2017; Huset et al., 2011
MSW landfill	Germany	BDL–2,968	Busch et al., 2010
MSW landfill	Spain	BDL–840.5	Fuertes et al., 2017
MSW landfill	Canada	BDL–8,700	Benskin et al., 2012
MSW landfill	Australia	BDL–1,700	Gallen et al., 2017
MSW landfill	China	BDL–41,600	Yan et al., 2015

Landfill type	Country	Mean PFAS Range (ng/L)	References
Ash monofill	USA	BDL–742	Solo-Gabriele et al., 2020
C&D debris landfill	USA	BDL–4,630	Solo-Gabriele et al., 2020

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

3.b.i.4 Industrial landfills

Industrial landfills receive solid wastes from industrial operations (non-municipal). Industrial landfills are often designed to manage specific waste streams (e.g., furnace slag, fly ash, and 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 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. Some waste types received at industrial landfills, including plastics and materials with polishes or coatings, are associated with high concentrations of PFAS (OECD, 2013).

3.b.i.5 Construction and demolition landfills

C&D landfills receive waste from construction, renovation, and demolition projects, and other material that may be considered inert. The exact list of materials for these types of landfills varies by state, but the wastes are generated in high volumes. The requirements for environmental controls at these landfills vary widely from state to state, ranging from no liner to a required composite liner. 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 putrescible waste received compared to MSW landfills. A GCCS may sometimes be necessary to remediate a specific issue, typically related to gases generated from the decay of drywall. Due to variability in control technologies and the potential lack of monitoring, C&D landfills are unlikely to manage the uncontrolled release of mobile PFAS; however, it is likely that C&D landfills receive some PFAS-containing wastes (e.g., building materials and carpeting with fluoropolymer coatings) (OECD, 2013; Solo-Gabriele et al., 2020).

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

PFAS are emitted from landfills via two possible routes: landfill leachate and LFG. Landfill leachate is the liquid that has passed through or emerged from solid waste and contains soluble, suspended, or miscible materials removed from such waste. LFG is the result of the natural decomposition of organic material in landfills. LFG is composed of roughly 50 percent methane, 50 percent carbon dioxide, and a small amount of nonmethane organic compounds (NMOCs).

Existing efforts to manage contaminants in landfills focus on controlling leachate and gaseous emissions. As shown in Figure 3-1, landfills constructed with environmental controls (bottom liner, leachate collection system, gas collection system, and final cover system, among other controls) 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 the variation in types of waste accepted, operating practices, site conditions, and federal and state regulations.

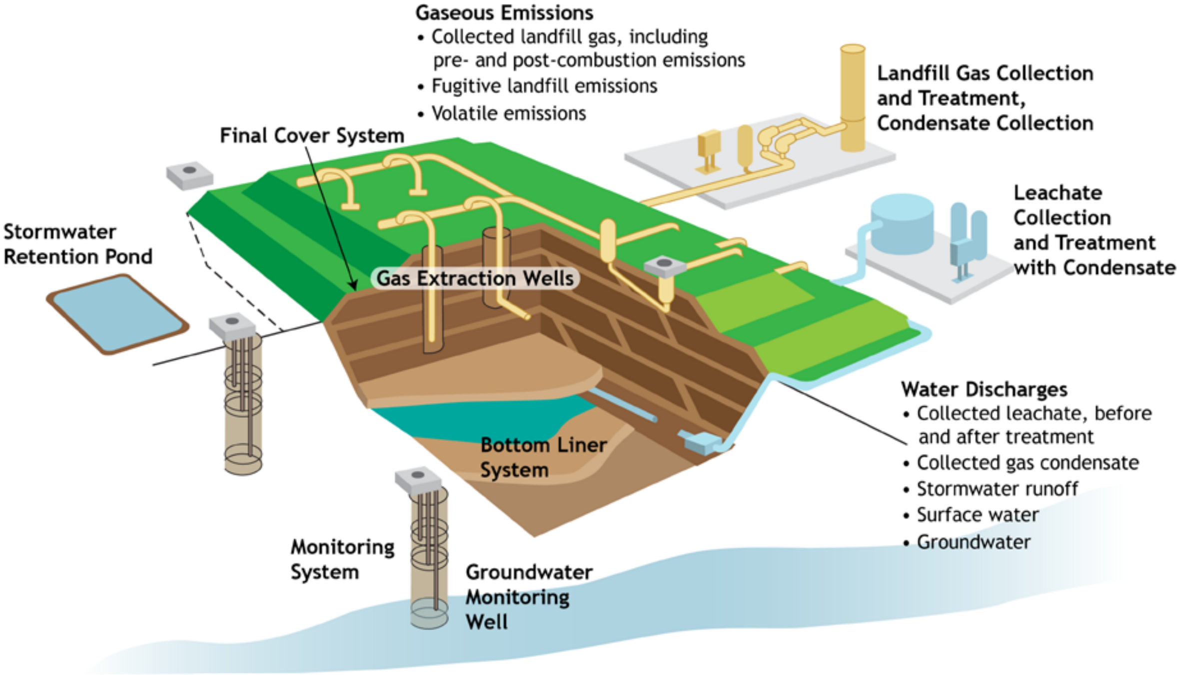

Figure 3-1. Engineered landfill components and potential PFAS release pathways.

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

Under RCRA, any new landfill, replacement of an existing landfill, or lateral expansions of an existing landfill must have a double liner and leachate collection system if it receives hazardous waste, in order to limit leachate and gas migration through the bottom of the landfill. Most landfills that are regulated under RCRA to receive non-hazardous waste are subject to design criteria with 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 types 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 may not require liners (40 CFR 258.1). Because PFAS are not a RCRA-regulated hazardous waste, existing unlined landfills could contain PFAS 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 on leachate management). Uncontrolled leachate could result in migration of PFAS into the environment.

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. Li (2011) investigated the effect of PFAS on sodium bentonite, a type of clay used in liners, and found PFAS did not significantly compromise the performance of bentonite liners (Li, 2011). 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.ii.2 Landfill gas collection system

Landfills use GCCSs to manage gas from decomposing organic waste. A GCCS consists of a network of perforated pipes sunken into the waste. These "gas wells" are connected to a central blower that pulls gas from the wells. Despite collection technologies, 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 a high level of methane that is usually burned off at the site via flares or for energy recovery.

As noted in Section 3.b.iv.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 LFG sample evaluation for PFAS concentrations is currently being researched by EPA. The effects of flaring on gaseous PFAS have not been demonstrated. See Section 5 for potential research needs.

3.b.ii.3 Final cover system

After a regulated landfill has reached its expected capacity, it must be capped with a cover system. This system consists of some combination of soil and membrane liners and is primarily intended to reduce infiltration of rainwater into the landfill to minimize leachate generation. It also helps increase the efficiency of the GCCS and reduce uncontrolled gas emissions. Synthetic liners and caps are more effective at controlling migration 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.ii.4 Other environmental controls and monitoring systems

Landfills control solid waste and corresponding pollutants through containment. Because of their many and varied uses, PFAS enter solid waste landfills as part of the general municipal waste stream, with industrial waste, or in other PFAS-containing solid wastes (e.g., solidification waste).

In addition to the major infrastructure discussed above, solid waste landfills implement other practices and systems. In active landfill cells, daily application of a cover material like soil or other 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 the chance of direct human and ecological exposure to waste. Extensive monitoring networks are generally required to measure the landfills impact on surface water, groundwater, and air. RCRA Subtitle C requires all hazardous waste landfills to install groundwater monitoring wells. See Section 3.b.iii for landfill controls.

3.b.iii Leachate discharge controls

3.b.iii.1 Leachate characteristics

Landfill leachate is the liquid effluent primarily generated through the percolation or infiltration of rainwater through waste. Leachates often contain high concentrations of biodegradable and nonbiodegradable 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 within the different landfill types. 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 leachate and associated PFAS.

3.b.iii.2 Off- and on-site management of leachate

The most common method for 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 nonbiodegradable compounds and ammonia, and the presence of emerging contaminants (like 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. Deep well injection is another form of off-site leachate management (see Section 3.c).

Table 3-6 presents leachate management or treatment methods used for the on-site management of leachate. The technologies it reviews may be subject to current research, and the table will be updated as new information is published. 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 3-5 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. 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. In some cases, leachate treatment strategies may depend 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.vii, 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 3-6. 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 3-6. 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	• Tailor 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)

Treatment Technology	Treatment Mechanism	Pros for PFAS Treatment	Cons for PFAS Treatment	References
Ozonation/ ozofractionation	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*
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				
Reverse osmosis (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)
Nanofiltration (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*

Treatment Technology	Treatment Mechanism	Pros for PFAS Treatment	Cons for PFAS Treatment	References
Deep well injection	Containment	- Potential solution for PFAS concentrate	- Dependent on site geology - Regulatory approval	ITRC (2018)
Incineration	Thermal destruction	- PFAS destruction	- Potential secondary emissions - 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; phyto-remediation; land application	Environmental release	*N/A*	- Direct release of PFAS	U.S. EPA (2020a)

3.b.iii.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 migration 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 like 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.

Underground injection control, specifically Class I deep well 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 results in reducing the volume of leachate. Open-air evaporation methods may be effective at concentrating leachate but could be 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.iv Landfill gas emission controls

3.b.iv.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 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), but direct LFG sample evaluation for PFAS concentrations is currently being researched by EPA. See Section 5 for details.

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 not collected and is often emitted to the environment without treatment.

3.b.iv.2 On- and off-site management of landfill gas

LFG collection and management are regulated under the CAA through National Emission Standards for Hazardous Air Pollutants (NESHAP) and the New Source Performance Standards (NSPS) 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 site 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 demonstrate a maximum 20 parts per million by volume (ppmv) NMOC outlet or 98 percent reduction in NMOC with a one-time performance test and 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), engine and boiler systems may run cooler and have a lower destructive potential for PFAS (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, which will affect the release of PFAS via fugitive emissions.

LFG condensate is a liquid that has condensed in the LFG collection system during the extraction of gas from the landfill. Gases with high concentrations of water vapor condense in traps staged throughout the network. 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 wastes. PFAS has been detected in LFG condensate, with perfluorobutanesulfonic acid (PFBS) being the dominant species at a concentration of 1,000 ng/L (Li, 2011).

3.b.v Potential for releases during landfilling

Over time, the potential increases 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 from PFAS-containing waste—and move them deeper. Controlled landfill leachate is collected and either reinjected, treated on-site, or sent to a POTW 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, despite the active capture of LFG, 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 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 as a result of 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 on the job. Research has shown elevated concentrations of PFAS in landfill ambient air (Hamid et al., 2018).

3.b.vi 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 5.b). However, the lack of standardized testing may pose a challenge for comparison across destruction/control technologies and types of landfills (see Section 5.a for research needs).

3.b.vii 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. There has not been enough research to determine what percent of PFAS can be expected to remain within the confines of landfills, with the many combinations of technology and operating parameters that exist across the thousands of landfills in the United States. Sampling and analytical methodologies must continue to be developed to quantify potential PFAS flows out of landfills, an effort that may be complicated by the long lifespan of some PFAS. Additionally, as detailed above, 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 WWTP 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.

3.b.viii Treatment costs

The United States has more than 2,600 MSW, around 1,000 stand-alone C&D debris, and at least 169 industrial (reporting to the Greenhouse Gas Reporting Program [GHGRP]) landfills in operation (U.S. EPA, 2020b, n.d.; DHS, 2017). Costs associated with containing PFAS in landfills are associated with tipping fees (gate rates) at landfills, which help pay for operation and maintenance, capital investment, and costs associated with regulatory compliance. The costs associated with sending PFAS wastes to landfills are difficult to assess because the available data are largely associated with general tipping fees for MSW on a per-ton basis.

Table 3-7, on the next page, presents the average tipping fees for one short ton of waste at an MSW landfill. The range of costs varies widely by state and region, with a lowest average state-level rate at $29.82 in Kentucky and the highest in the contiguous United States at $110 in Rhode Island; Alaska and Hawaii both have even higher rates. All regions have seen these rates increase over the 4-year period from 2016 to 2019. The national average 2019 tipping fee for MSW was $55.36, while C&D debris disposed of in MSW landfills was slightly lower at $54.04 (EREF, 2019). These costs are not reflective of any additional surcharges leveled for wastes associated with high PFAS concentrations. Hazardous waste, ash monofill, and industrial landfills are often explicitly designed and built for specific waste streams, and their costs vary widely from site to site.

Associated with the tipping fees is the cost burden associated with treating the leachate, which can also contain PFAS. The 2000 EPA rulemaking that led to the Landfill Effluent Guidelines identified 1,989 landfills, generating a median daily flow of 5,620 gallons of leachate (U.S. EPA, 2000). Lang et al. (2017) estimated 16.1 billion gallons of leachate generated in 2013, not including leachate recirculated in landfills. 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. These data currently do not include specific information on extra treatment considerations that may be required by an NPDES permit or by an industrial user permit for a discharge into a POTW to control the release of PFAS.

Table 3-7. Average MSW Tipping Fees per Ton for States and Regions (EREF, 2019)

Region/State	Average Tipping Fee	Region/State	Average Tipping Fee
Pacific	**$73.03**	**Midwest**	**$48.87**
Alaska	$154.92	Wisconsin	$65.00
Hawaii	$112.33	Minnesota	$63.52
Washington	$89.08	Missouri	$62.42
Nevada	$74.20	Illinois	$51.78
Oregon	$71.28	Iowa	$48.47
Idaho	$68.71	Indiana	$47.91
California	$55.56	Ohio	$44.35
Arizona	$43.39	Michigan	$41.97
		Kansas	$39.32
Northeast	**$66.53**	Nebraska	$39.21
Rhode Island	$110.00		
Delaware	$85.00		
New Jersey	$81.91		
Maine	$78.50	**Southeast**	**$45.25**
New Hampshire	$74.34	Florida	$55.08
Maryland	$68.57	Tennessee	$50.24
New York	$68.40	Georgia	$48.77
Pennsylvania	$68.07	South Carolina	$44.03
Virginia	$52.22	North Carolina	$43.87
West Virginia	$51.50	Mississippi	$38.70
Connecticut	N.A.	Alabama	$33.41
Massachusetts	N.R.	Kentucky	$29.82
Vermont	N.R.		
Mountains/Plains	**$50.71**		
Wyoming	$74.45	**South Central**	**$40.92**
Colorado	$62.04	Oklahoma	$50.22
Montana	$49.36	Arkansas	$40.23
South Dakota	$49.14	Texas	$40.18
North Dakota	$46.98	New Mexico	$38.28
Utah	$32.08	Louisiana	$33.28

Table 3-8 presents the average state-level metered rates for 1,000 gallons of industrial wastewater. The rates vary from $1.63 in Arkansas to $18.45—more than 10 times as much—in Washington. Though they show the variability in regional costs for industrial wastewater treatment, these figures are not commensurate with the rates explicitly reported for leachate treatment.

Table 3-8. Average State-Level Wastewater Treatment Prices for Large Industrial Consumers with an 8-Inch Wastewater Meter (DOE, 2017)

State	2016 Volume Charge per kGal[a]
Alabama	$7.51
Alaska	$7.49
Arizona	$2.88
Arkansas	$1.63
California	$3.61
Florida	$5.57
Georgia	$5.11
Illinois	$2.64
Kansas	$4.77
Louisiana	$6.04
New Mexico	$2.39
North Carolina	$4.00
Pennsylvania	$4.00
South Carolina	$2.12
Tennessee	$8.39
Texas	$4.79
Utah	$4.57
Virginia	$2.88
Washington	$18.45
Wisconsin	$3.53
Average	$5.05

[a] Cost per thousand gallons (kGal) is assumed to be in 2016 dollars. Costs were normalized to 2019 dollars using the BEA GDP deflator (BEA, 2020) for utilities using a base year of 2016.

Leachate treatment at POTWs has been reported between $33 and $125 per gallon depending on treatment method (Kremen, 2020). This cost does not represent any additional burdens associated specifically with PFAS treatment. Cost estimates were also identified for two on-site leachate treatments that were previously indicated as potential treatment options for leachate containing PFAS: RO and activated carbon.

A membrane bioreactor with RO is expected to provide treatment at $64 to $95 per 1,000 gallons for typical landfill leachate, while activated carbon may possibly provide treatment as low as $5.40 per 1,000 gallons using activated carbon with a sequencing batch reactor (Kremen, 2020). Again, though, neither of these ranges accounts for the additional burdens that may be associated with a PFAS-laden leachate (Cunningham, 2019). See Section 3.a (specifically Table 3-3) on thermal treatment for costs specifically associated with the regeneration or disposal of GAC.

3.b.ix Summary

Due to widespread use and disposal through typical waste management pathways, PFAS-containing wastes are currently managed through containment in landfills. Though landfills are designed for permanent waste containment and management of liquid and gas production, it is currently unclear if all landfills used for PFAS disposal have controls that are effective for managing PFAS discharges and emissions from waste streams. Given the chemical makeup of PFAS, some compounds are expected to persist in landfills for years.

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 3-4) and as a result would be more effective at minimizing PFAS migration into the environment than other landfill types. Modern MSW landfills, when constructed with appropriate controls (e.g., liner system and leachate and gas collection and management systems), can also control the migration of PFAS into the environment. Even with these controls in place, the proper management of landfill gaseous and liquid releases needs to be applied for MSW and hazardous waste landfills to minimize PFAS migration into the environment (as described in Section 3.b.ii). Care must be taken to apply the leachate control technologies that are effective at containing (e.g., solidification or recirculation) or destroying PFAS (see Table 3-6 for more information). Given the high level of uncertainty associated with PFAS behavior in landfills, research consistent with that described in Section 5—such as research on 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—will help to further evaluate this disposal method for PFAS and PFAS-containing wastes.

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 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 3-6). Furthermore, oxidation mechanisms show potential in destroying PFAS during treatment but are still in development and not widely used at this time. Other leachate management options can control the migration of PFAS into the environment, 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.

Additionally, PFAS can be emitted with LFG that is generated as waste decomposes over time. On-site and off-site LFG management commonly use flares 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.

3.b.x References for Section 3.b

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3.c Underground injection

Like landfills, underground injection wells are a feasible and effective, to varying degrees, disposal option that normally should minimize migration of PFAS into the environment. Unlike landfills, underground injection wells are only suited for disposal of liquids. A waste stream in the form of PFAS-containing fluids would currently be handled similarly to non-hazardous industrial and hazardous wastes that are injected deep into geologic formations. The limited number of wells currently receiving PFAS, as well as location, waste transportation, and associated costs, may significantly limit the type and quantity of PFAS-related liquid waste streams appropriate for underground injection.

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 underground sources of drinking water (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 are deep injection wells injecting 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 3-2).
- **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.

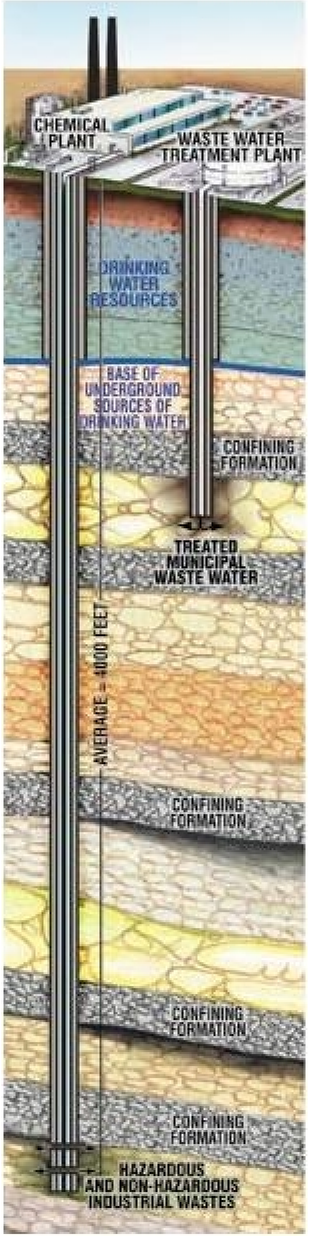

Figure 3-2. Class I well.

Class I wells in the non-hazardous industrial or hazardous waste categories are well suited for the management of PFAS-containing waste material. Class I underground injection wells are designed to dispose of and isolate liquid wastes 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 fluids that contain PFAS, this technology may not be appropriate everywhere. The suitability of a site for injection is dependent on the geologic formation in the area. Sites need to be evaluated to ensure that there is an appropriate confining zone and geologic formations that are able to receive fluids.

Class I wells for non-hazardous industrial and hazardous waste are currently being used for disposal of PFAS-containing fluid wastes 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 wastewaters 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 6 years later, and federal and state regulation and oversight has been informed by extensive reviews of injection practices and 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.
- Specific design, construction, and operation requirements.

- Continuous monitoring and periodic monitoring and testing requirements.
- 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 wastes are injected is referred to as the injection zone. Injection zones of Class I wells typically range from 1,700 to over 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 layer(s) 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 ensure appropriate protection of any USDWs.

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.iv). The typical construction cost to develop a Class I well has been estimated at $4 million to $6 million (deSilva, 2019). Routine operation and maintenance costs include those to address requirements for extensive mechanical integrity testing, monitoring, and periodic submission of permit/no-migration petitions.

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

Class I hazardous waste wells are highly protective of USDWs and avoid active seismic areas. 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 well 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 (including mechanical integrity tests—both mechanical pressure tests and geophysical logging tests used to assess well integrity both internally and externally to ensure injected fluids are being emplaced and remaining within the injection zone) to demonstrate they are meeting the conditions of the permit and that all assumptions, projections, and modeling are still appropriate and valid.

3.c.iii Availability and costs

The United States currently has 823 Class I wells. Slightly more than half (53 percent) are permitted for non-hazardous industrial waste injection. Approximately 18 percent are permitted for hazardous waste disposal. The remainder are permitted for municipal wastewater disposal. Currently, EPA is aware of two Class I sites that manage PFAS-containing fluids. One is in Michigan, where a non-hazardous industrial waste well facility is injecting PFAS-containing leachate from a landfill (Usher, 2019). In Texas, more than 50 million gallons of PFAS-containing waters have been injected into Class I hazardous waste wells (Marine, 2020).

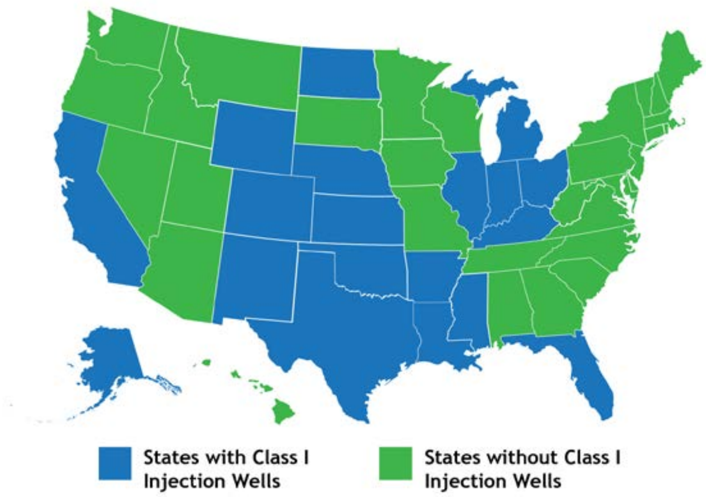

Figure 3-3. States with Class I non-hazardous or hazardous waste injection wells.

Figure 3-3 shows all states that currently have at least one permitted Class I injection well of any type (non-hazardous or hazardous waste). Table 3-9 provides a more detailed breakdown of the number of permitted Class I wells by state.

Table 3-9. Inventory of Permitted Class I Non-Hazardous and Hazardous Waste Wells in the United States (FY 2018; Source: EPA)[9]

Location of Wells		Number of Wells	
EPA Region	**State/Tribe**	**Class I Non-Hazardous**	**Class I Hazardous**
4	Florida	251	1
4	Kentucky	1	0
4	Seminole Tribe	3	0
4	Mississippi	8	5
5	Illinois	9	2
5	Indiana	0	4
5	Michigan	31	7
5	Ohio	5	12
6	Arkansas	8	3
6	Louisiana	17	19
6	New Mexico	6	0
6	Oklahoma	6	0
6	Osage Nation	1	0
6	Texas	92	77
7	Kansas	56	8
7	Nebraska	10	0
8	Colorado	16	0
8	North Dakota	8	0
8	Wyoming	85	0
10	Alaska	23	0

Class I well capacity is limited, which may affect the costs associated with deep well injection. A presentation in 2019 placed the cost for deep well injection at approximately $0.18 to $0.25 per gallon (deSilva, 2019). As mentioned above, the typical construction cost to develop a Class I well has been estimated at $4 million to $6 million (deSilva, 2019).

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

Non-hazardous industrial waste wells are located across 19 states, though the majority are in five states—Texas, California, Louisiana, Kansas, and Wyoming. Disposal to this type of well requires well operators to apply and receive permit modifications and assess long-term consequences of accepting new waste streams. Although current Class I injection wells may have limited capacity for PFAS-containing fluids, many of them are used for specific purposes and disposal of waste generated on-site. To accept PFAS-containing fluids, 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 weigh considerations around capacity to accept additional volumes of waste and compatibility of PFAS-containing waste streams with the well material, the geochemistry of the injection formation and formation fluids, and the properties of other injected wastes.

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[9] EPA's inventory of Class I non-hazardous waste wells consists of all non-hazardous waste wells, including municipal and industrial waste wells.

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

Most Class I hazardous waste wells in the United States are in Texas and Louisiana and are sited at industrial facilities and dispose of waste generated on-site (U.S. EPA, 2016). There are no Class I hazardous waste wells in EPA Regions 1, 2, 3, 8, 9, or 10 (see Figure 3-3 and Table 3-9). Because of this geographic concentration of Class I hazardous waste wells, waste producers may face transportation and logistical challenges. Estimates of trucking costs associated with transportation of waste fluid ranges from $0.01 to $0.19 per gallon (McCurdy, 2011).

There is currently no national information on the number and location of Class I hazardous waste wells that could accept PFAS-containing wastes, or that are willing to accept wastes not generated on-site. However, EPA anticipates the number of current Class I hazardous waste wells that would accept 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, and no-migration petitions) that 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 that 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 migration 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, and also must establish and follow 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*.

3.c.v Uncertainties/unknowns

The fate and transport of PFAS in the subsurface depends on:

- The chemical and physical properties of specific PFAS.

- 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 chemical properties, and these can be altered by mixture effects and interactions with co-contaminants. This creates uncertainty in predictions of PFAS contaminant migration and longevity in the injection zone. For disposal of PFAS in Class I hazardous waste wells, these uncertainties need to be considered in the development of the required no-migration petition.

3.c.vi Summary

As noted above, Class I (non-hazardous industrial or hazardous waste) wells are well suited for the management of PFAS waste material. 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. Research on the long-term fate and transport of PFAS (including precursors) to predict migration potential in the injection zone could support future permits.

3.c.vii References for Section 3.c

deSilva, V. (2019). *PFAS in landfill leachate.* *http://www.mowastecoalition.org/resources/Documents/2019%20conference/MWCC2019%20-deSilva%20(SCS)%20-PFAS-July%2016,%202019.pdf*

Marine, F. (2020). *Class I UIC wells to manage PFAS in wastewaters.* http://www.gwpc.org/sites/default/files/event-sessions/Marine%20-%20Class%20I%20PFAS.pdf

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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*

Usher, K. H. (2019, July 26). Landfill was responsible for PFAS in Cadillac wastewater. *Cadillac News. https://www.cadillacnews.com/news/landfill-was-responsible-for-pfas-in-cadillac-wastewater/article_2ae7a3c8-3193-5b8a-8ddf-6d695c3438c5.html*

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, defines potentially vulnerable populations, and provides guidance on considering vulnerable populations when assessing the potential impact of releases. It is intended to be useful to a diverse group of users: risk assessors, permit writers, risk managers, and community relations personnel, as well as the public. In some cases, regulators may be required to consider vulnerable populations during the permitting process or when making decisions about where to send waste or whether to accept waste. But it may also be appropriate to consider vulnerabilities in adjacent communities even when not required. The public may find this section useful to understand potential vulnerabilities in their communities. This section is not a comprehensive 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. Nonetheless, it is possible for destruction or disposal activities to release PFAS. Figure 4-1 illustrates some of these releases and how they could possibly reach vulnerable populations through multiple environmental media. For example, as described in Section 3.a.iv, thermal treatment activities could potentially release PFAS to the environment via stack emissions. 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. Even with active LFG capture, a fraction of LFG remains that is emitted directly to the environment through the landfill surface and other routes. Disposal of PFAS could also result in potential releases from increased transport, management, and handling of waste associated with all of the available technologies.

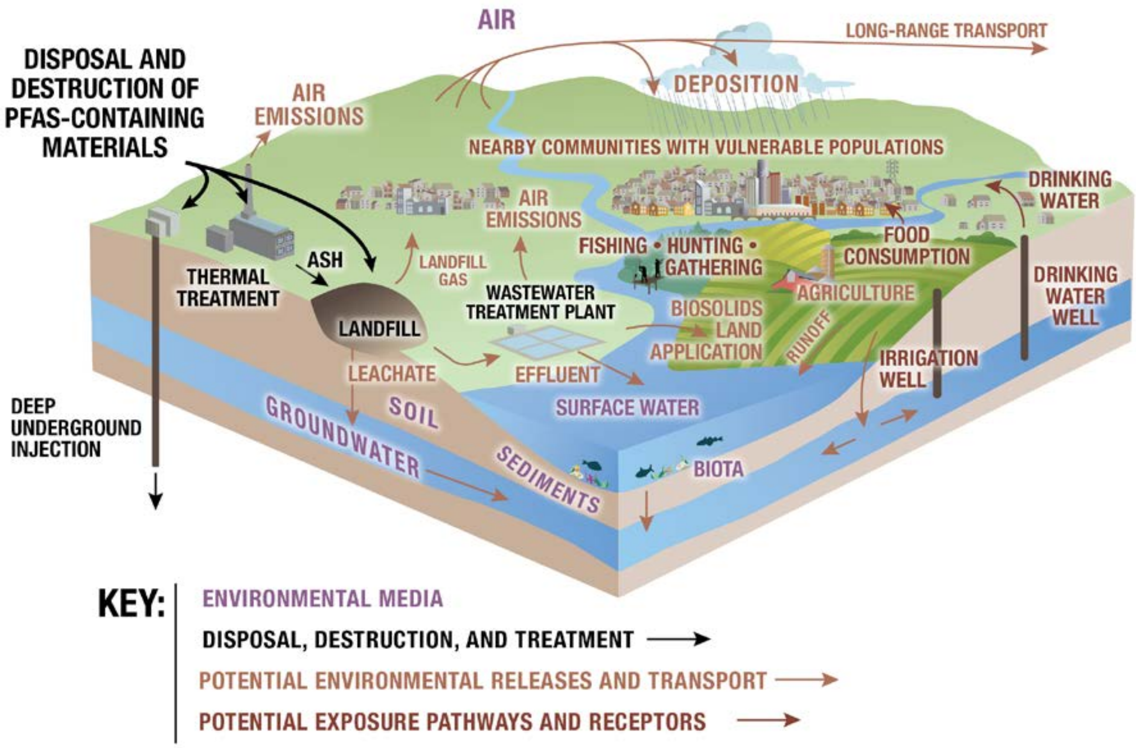

Figure 4-1. Conceptual model providing examples of potential releases from destruction and disposal of PFAS-containing materials, which the technologies covered in this guidance could help to control.[10]

Risk assessment and communication are important tools to protect communities and the environment from potential releases of harmful substances. Risk assessments are performed when a facility is being sited, or when there is a change in permit status (U.S. EPA, 2015a). 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 guidance and tools available to stakeholders and the public. These resources are summarized in Section 4.c.

4.b Potentially vulnerable populations

Considering vulnerability and susceptibility in risk assessment can help protect populations at greatest risk.

- "Susceptibility" refers to the likelihood of being affected by a chemical or pollutant. Intrinsic (biological) and extrinsic (exposure-related) factors can influence a person's susceptibility to pollutants, or a population's. That is, different individuals and populations might have different susceptibilities.

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[10] Figure 4-1 provides examples of possible releases and exposures that could be associated with destruction and disposal of PFAS-containing materials, but it is not intended to be exhaustive.

- "Vulnerability" refers to differences in risk resulting from the combination of both intrinsic differences in susceptibility and extrinsic (or acquired) factors (U.S. EPA, 2020a).

These intrinsic and extrinsic factors may influence the health outcomes of people exposed to harmful substances.

Intrinsic, or biological, factors are differences in risk resulting from variations in both a person's response (sensitivity) to a harmful substance and their exposure (U.S. EPA, 2020a). Intrinsic factors include age, gender, race/ethnicity, life stage (e.g., infancy, adolescence, adulthood, pregnancy/lactation), and genetic polymorphisms. These biological factors cannot be changed. Toxicokinetic differences among individuals that affect how easily a chemical is absorbed, metabolized, and excreted are also important factors. A person's susceptibility to an environmental stressor is an important determinant of both the *occurrence* and *severity* of an adverse effect. Infants, children, adults of reproductive age, and the elderly are examples of populations that may be more vulnerable due to intrinsic factors.

Extrinsic factors are external influences that may be important to consider when assessing human exposure and risk. Extrinsic factors include socioeconomic status, disease status, nutrition status, geographic proximity to sources of exposure, and various lifestyle choices. In many cases, these factors can be changed. Individuals with pre-existing diseases, geographic proximity to sources of contaminants, and lifestyle factors (e.g., exercise, smoking, alcohol consumption) are examples of populations that may be more vulnerable due to extrinsic factors.

Vulnerability may also result from disproportionately high exposures to a chemical substance or mixtures of chemical substances. Due to a range of existing physical, chemical, biological, social, and cultural factors, certain populations are more exposed to environmental chemicals or experience greater adverse effects from exposures of similar magnitude due to preexisting health stressors (U.S. EPA, 2003). Examples of vulnerability due to disproportionately high exposures include workers in industries that manufacture, handle, or dispose of PFAS-containing materials; communities living next to facilities that may be releasing chemicals to the environment; children, who may be more highly exposed based on body size, intake rates of food and environmental media, and activity patterns; and hunters, gatherers, and fishers, who may be consuming foods that contain higher concentrations of contaminants.

Socioeconomic status is a potential risk modifier for some communities (e.g., low-income, minority, indigenous groups). Socioeconomic status can influence factors such as diet, nutrition, housing quality, and access to health care—and consequently health status. Some studies have found that the presence of pollution sources in a given area (e.g., high-traffic roadways, industrial sites, hazardous waste sites) correlates with the proportion of minority, low-income, or indigenous populations (U.S. EPA, 2013a, 2019), which can, in turn, lead to higher exposure and disease burdens.

In some cases, these factors are cross-cutting (i.e., are both intrinsic and extrinsic) and the combination of high exposures (extrinsic) and increased individual susceptibility to environmental stressors (intrinsic) may lead to a predisposition to higher health risks.

Many of these cross-cutting issues are related to environmental justice (EJ) concerns, which encompass the disproportionate exposure and impacts associated with environmental releases. EPA has defined "potential EJ concerns" as "the actual or potential lack of fair treatment or meaningful involvement of minority populations, low-income populations, tribes, and indigenous peoples" (U.S. EPA, 2015b, 2016c). In practice, vulnerability in this context can be considered as "disproportionate impacts on minority populations, low-income populations, and/or indigenous peoples" (U.S. EPA, 2015b, 2016c).

The following sections provide examples of different factors that may contribute to vulnerability to PFAS.

4.c PFAS and vulnerability

There is evidence that exposure to certain PFAS can lead to adverse health outcomes in humans. If humans, or animals, ingest certain PFAS (by eating or drinking food or water than contains PFAS), the PFAS are absorbed, and can accumulate in the body. PFAS stay in the human body for long periods of time. As a result, as people get exposed to PFAS from different sources over time, the level of PFAS in their bodies may increase to the point where they suffer from adverse health effects (U.S. EPA, 2020b).

Research on the two most well-studied PFAS (PFOA and PFOS) demonstrates that they can cause reproductive and developmental, liver and kidney, and immunological effects in laboratory animals (U.S. EPA, 2020b). Both chemicals have caused tumors in animal studies. The most consistent findings from human epidemiology studies are increased cholesterol levels among exposed populations, with more limited findings (U.S. EPA, 2020b) related to:

- Infant birth weights.
- Effects on the immune system.
- Cancer (for PFOA).
- Thyroid hormone disruption (for PFOS).

People with pre-existing conditions, such as liver or kidney disease or immunocompromised status, may be more susceptible to certain PFAS that may target these systems.

Children may be particularly vulnerable to certain PFAS exposures, as they can be both more exposed and more sensitive to health effects. Children drink more water, eat more food, and breathe more air per pound of body weight than adults, which can increase their exposure to PFAS in food and the environment. Breast milk from mothers with PFAS in their blood and formula made with water containing PFAS can expose infants to PFAS, and it may also be possible for children to be exposed in utero during pregnancy. Young children who crawl on floors and put objects or hands in their mouths may have a higher risk of exposure to PFAS in household dust or cleaning products (U.S. EPA, 2018, 2019a). Because of these cross-cutting biological, physiological, and exposure factors, children may be more sensitive to the effects of chemicals such as certain PFAS.

EPA developed drinking water health advisories for PFOA and PFOS to be protective of adverse developmental effects to fetuses during pregnancy or to breastfed infants, which are the groups most sensitive to the potential harmful effects of PFOA and PFOS (U.S. EPA, 2016a, 2016b).

Certain populations may be highly exposed to environmental contaminants because they live or work near the sources of release or presence in the environment (U.S. EPA, 2003). They may also be disproportionately impacted, due to a variety of cross-cutting factors, including EJ concerns, low socioeconomic status, etc. In the case of PFAS, these groups could include people living near a facility that manufactures PFAS, or those living near and using PFAS-contaminated environments (e.g., drinking water, fishing, hunting, and recreation). Site-specific data on PFAS releases and exposures may be needed to understand such complex interactions and co-exposures.

Tribal and indigenous populations may also be more exposed to environmental hazards than the general population due to subsistence lifeways and diets, outdoor activities, or cultural practices. For example, unique tribal practices, such as increased consumption of locally harvested fish and shellfish, might expose tribal and indigenous populations to higher concentrations of contaminants such as PFAS that accumulate in these organisms (U.S. EPA, 2019c).

Workers involved in the manufacture, use, transport, transfer, handling, and storage of PFAS-containing waste also may be subject to higher exposures relative to the general population. The National Institute for Occupational Safety and Health (NIOSH) defines a hierarchy of controls to mitigate occupational hazards (*https://www.cdc.gov/niosh/topics/hierarchy/default.html*) based on the most effective to least effective measures, as follows: (1) eliminate the hazard, (2) substitute the hazard, (3) apply engineering controls, (4) use administrative controls, and (5) use personal protective equipment. In some situations, a combination of controls may be most effective at minimizing worker exposures.

4.d Considering vulnerability

Under Executive Order 12898, "Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations" (*https://www.epa.gov/laws-regulations/summary-executive-order-12898-federal-actions-address-environmental-justice*), federal agencies are directed to identify and address the disproportionately high and adverse human health or environmental effects of their actions on minority and low-income populations to the greatest extent practicable and permitted by law. In response to these mandates, EPA has developed tools, methods, and approaches to identify and assess the risks of potentially vulnerable populations.

4.d.i Identifying potentially vulnerable populations

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

- EPA EnviroMapper: *https://geopub.epa.gov/myem/efmap/index.html*
- EPA Environmental Justice Screening and Mapping Tool (EJScreen): *https://www.epa.gov/ejscreen*

4.d.ii Incorporating vulnerability into risk assessment

EPA provides many tools to assist with the development of risk assessments (*https://www.epa.gov/risk*). Highlighted here is specific guidance that may be helpful to addressing key aspects of vulnerability.

A particularly useful document that presents technical approaches and methods to help analysts (including economists, risk assessors, and others) analyze potential EJ concerns is the *Technical Guidance for Assessing Environmental Justice in Regulatory Analysis* (U.S. EPA, 2016c). Although it is designed for regulators, it is broadly useful to external analysts and stakeholders.

- *https://www.epa.gov/environmentaljustice/technical-guidance-assessing-environmental-justice-regulatory-analysis*

For considerations in assessing risks to children, refer to the EPA *Framework for Assessing Risks of Environmental Exposure to Children:*

- *https://cfpub.epa.gov/ncea/risk/hhra/recordisplay.cfm?deid=22521*

For information on exposure considerations for identified potentially vulnerable and highly exposed populations in the quantitative and/or qualitative assessment of risk, refer to EPA's ExpoBox:

- *https://www.epa.gov/expobox/exposure-assessment-tools-lifestages-and-populations-highly-exposed-or-other-susceptible#fac*

For considerations of tribal and indigenous lifeways, refer to these tools:

- EPA memo on traditional ecological knowledge: *https://semspub.epa.gov/src/document/11/500024668*
- Amendments to Superfund Hazard Ranking System guidance incorporating Native American traditional lifeways: *http://semspub.epa.gov/src/document/11/175862*

For PFAS, which can reside in the human body for months to years, it is particularly important to consider toxicokinetics in the risk assessment using physiologically based pharmacokinetic (PBPK) modeling. For information on available PBPK models for PFAS, refer to the health effects support documents for PFOA and PFOS and EPA's guidance on the use of PBPK modeling in risk assessment:

- *https://www.epa.gov/ground-water-and-drinking-water/supporting-documents-drinking-water-health-advisories-pfoa-and-pfos*
- *https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=157668*

4.d.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 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. It can also have the following benefits under this guidance: reaching out to the community before accepting 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.

Meaningful community engagement typically includes two key elements:

- Public outreach to disseminate relevant information to the community.
- Public participation, which generally entails a dialog 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, 2016c).

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, 2016c).

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

- 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 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 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 to enable 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.

4.e References

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U.S. EPA (Environmental Protection Agency). (2016b). *Drinking water health advisory for perfluorooctanoic acid (PFOA)* (EPA 822-R-16-005). *https://www.epa.gov/sites/production/files/2016-05/documents/pfoa_health_advisory_final_508.pdf*

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U.S. EPA (Environmental Protection Agency). (2020a). *Exposure assessment tools by lifestages and populations—highly exposed or other susceptible population groups. https://www.epa.gov/expobox/exposure-assessment-tools-lifestages-and-populations-highly-exposed-or-other-susceptible*

U.S. EPA (Environmental Protection Agency). (2020b). *Basic information on PFAS. https://www.epa.gov/pfas/basic-information-pfas#main-content*

5. Planned Research and Development on Destruction and Disposal Technologies for PFAS and PFAS-Containing Materials

5.a Research needs

EPA's PFAS action plan identifies key gaps in the current state of the science to support decision-makers, including gaps in the science of PFAS destruction and disposal. These gaps represent opportunities to increase the effectiveness and decrease the cost of PFAS destruction and disposal by refining existing approaches and developing new technologies (U.S. EPA, 2019). EPA is leading a robust research and development program to address these gaps by leveraging in-house expertise and external partnerships. EPA will incorporate this increased knowledge into future versions of this guidance to help decision-makers choose the most effective PFAS disposal options for their circumstances.

Research is needed in three broad areas:

1. **Research to better characterize the multi-media PFAS-containing materials targeted for destruction or disposal (referenced in Section 3.b.vi),** including methods to sample and analyze materials and to characterize the efficacy of remediation and treatment technologies. This includes a fuller understanding of which PFAS occur in which materials at what concentrations, as well as a better understanding of the basic chemical-physical properties that relate to those PFAS' persistence or recalcitrance under different destruction or disposal conditions. This information will help managers of PFAS materials decide which management alternatives are most appropriate for given material streams.
2. **Research to measure and assess the effectiveness of existing methods for PFAS destruction, improve existing methods, and/or develop new methods for PFAS destruction (referenced in Sections 2.e, 2.f, and 3.a.ii–3.a.viii).** This includes a better understanding of the fundamental chemical and physical conditions needed to fully defluorinate PFAS, break the carbon–fluorine bonds, and prevent the formation of potentially environmentally harmful substances associated with incomplete destruction (PICs). Continuing efforts to understand how to optimize incineration and other thermal treatments, including catalytic approaches, will provide the information necessary to design effective PFAS treatment methods. Currently, this research is limited by the ability to measure and quantify PFAS during thermal treatment including potential fluorinated PICs. This research need extends beyond thermal treatments to include multi-media measurement methods suitable for other potential destructive technologies and approaches, such as electron beam, BOHP/UV, and plasma.

3. **Research to measure and assess the effectiveness of existing methods for PFAS disposal, improve existing methods, and/or develop new methods for PFAS disposal (referenced in Sections 2.e, 2.f, and 3.b).** This includes better understanding of the environmental persistence, mobility, fate, and transport of different PFAS-containing materials, waste streams, and sources (e.g., AFFF, textiles, biosolids, landfill leachate) under different disposal conditions (e.g., landfills, deep well injection, material separation) to ensure that PFAS sequestered or stabilized in material streams have no opportunity to reenter the environment.

While EPA's research has been delayed by COVID-19 and by public concerns about EPA collecting data in communities, research is proceeding. Status and updates on EPA's PFAS research are available at *https://www.epa.gov/chemical-research/status-epa-research-and-development-pfas*.

5.b Current federal research and development activities

EPA and DoD are currently the primary federal agencies engaged in research and development of PFAS destruction and disposal; they coordinate efforts and external partnerships to ensure coverage, leverage opportunities and resources, and avoid duplication of effort. They also coordinate with other federal and state agencies doing research in this area.

- EPA presently supports a research program focused on end-of-life management of PFAS-containing materials, primarily by thermal treatment (as referenced in Section 3.a), advanced oxidation processes, wastewater, and landfills (as referenced in Sections 2.f and 3.b). **Thermal treatment research** focuses on understanding and modeling the behavior of PFAS under a range of thermal conditions (e.g., temperature, residence time, turbulence, exposure to flame, effect of catalysts) to better understand the conditions required to defluorinate PFAS, thereby informing selection of appropriate thermal treatment for various PFAS-containing materials. EPA is also studying the **behavior of PFAS and non-PFAS byproducts** that may result from incomplete thermal treatment (e.g., thermal PICs) and subsequently move through different emission control processes. This research informs the consequences of incomplete thermal treatment in terms of these treatment byproducts and the secondary waste streams generated by control processes and will help inform selection of viable control technology options. It includes methods for **sampling and analyzing PFAS in air emissions and ambient air** to enable monitoring of the environment and testing effectiveness of PFAS control technologies.

  EPA scientists are also examining the fate of PFAS during **wastewater treatment operations** and the **disposal of wastewater residuals** (e.g., sludges and biosolids). This research also examines the **benefits of pretreatment technologies** to treat PFAS in high-strength waste streams prior to disposal via wastewater, separation, and destruction technologies. Finally, EPA is examining the **presence and management of PFAS in different landfill types** and **controlling emissions and discharges**. This research effort includes the evaluation of the effectiveness of leachate treatment technologies to manage PFAS.

  EPA also supports partnerships through extramural vehicles such as the *Science to Achieve Results* (STAR) competitive grant program and the *Small Business Innovation Research* (SBIR) program, both of which have provided funding in recent years to develop and commercialize approaches and technologies to advance the practice of PFAS destruction and disposal.

- DoD supports extensive investments in PFAS-related destruction and disposal research via multiple programs. The most significant research has been funded through the *Strategic Environmental Research and Development Program* (SERDP) and the *Environmental Security Technology Certification Program* (ESTCP) (DoD, 2020). SERDP focuses on development and application of innovative technologies; ESTCP focuses on promoting the transfer and commercialization of promising innovative technologies. Both focus on technologies to solve DoD environmental challenges, which include **remediation of PFAS sites** and **disposal of PFAS-containing materials**. In addition, DoD funds research to **characterize sources** and **other PFAS research** specific to PFAS' unique needs or functions as well as the **development of fluorine-free AFFF** to reduce future inputs of PFAS into the environment.
- Other federal and state agencies and departments fund limited PFAS research focused on PFAS destruction and disposal. These include programs within the National Institute of Environmental Health Sciences *Superfund Research Program*, the U.S. Department of Agriculture, the National Science Foundation, NASA, and DOE. These efforts range from fundamental research to characterize physical-chemical behaviors under various conditions to research on specific ways to **dispose of unique wastes** (e.g., PFAS in agricultural products). Collaboration occurs at the scientist-to-scientist level, and information is exchanged through regular scientific conferences and publications.

In addition to EPA, DoD, and other agencies, there are two other significant sources of research and development related to PFAS destruction and disposal:

- Private industry, the operators of waste disposal operations and technologies, municipal water utilities, professional and trade associations, and relevant research foundations have strong interests in expanding into the area of PFAS material management, disposal, and destruction. These areas offer a growing investment opportunity that provides a valuable service to society, and organizations are actively developing and marketing solutions to address PFAS. EPA is exploring opportunities to partner with industry, municipalities, and associations to **leverage occurrence, emission/discharge, and treatment data** from sources of PFAS-containing waste. Access to existing industry data could speed the pace at which EPA documents the capabilities of destruction and disposal technologies for different materials and waste streams.
- Many colleges and universities have engineering and science departments that conduct cutting-edge research on many topics related to PFAS destruction and disposal. These institutions often bring together expertise from many disciplines, enabling the rapid development of innovative approaches for managing the constantly changing set of PFAS-containing materials.

5.c Near-term EPA research and development initiatives

The following activities are on a near-term (1–2 years) trajectory, including technologies in late stages of testing and development:

- **PFAS measurement methods.** Development of methods for **sampling and analyzing PFAS** in environmental media, waste streams, and manufactured products is critical to characterize the effectiveness of management approaches and technologies for destruction and disposal of PFAS. These measurements include air (emissions and ambient), wastes, waters, and solids. EPA is using advanced methods such as **high-resolution mass spectrometry** for targeted analysis for known PFAS and nontargeted analysis to discover and document unknown PFAS (e.g., thermal PICs). This research builds on existing EPA expertise and methods for aqueous, solid, and air media (e.g., modifying the existing Modified Method 5 sampling trains to characterize air emissions). Characterizing air emissions requires expansion of method applicability to complex mixtures of byproducts and PICs. EPA will publish a draft Other Test Method 45 by the end of 2020, which will include measurement of semivolatile targeted compounds. EPA is also evaluating and developing other sampling and measurement tools to characterize performance of these technologies, such as **TOF analysis** using **CIC** and **FTIR techniques** to measure the broader suite of compounds with carbon–fluorine moieties without identifying specific chemicals. These tools, in combination with more traditional targeted measurements, have a role in characterizing sources, evaluating the fate and transport of PFAS, and monitoring the destruction and disposal approaches used to manage PFAS.

- **Fundamental understanding of PFAS thermal treatment.** EPA is researching the **incineration conditions** (e.g., temperature, residence time, reactor configuration, turbulence) needed to fully defluorinate PFAS. This includes **testing different catalysts** (e.g., calcium and aluminum) that can be added during incineration or used in separate unit operations to defluorinate more effectively and at lower temperatures. Research is also looking at whether **free fluorine can be controlled**. Results will be incorporated into **databases and models** to enable users to make predictions for different PFAS materials under different disposal conditions.

  This work is being done in bench- and pilot-scale facilities and will enable material managers to **determine the thermal conditions** needed to dispose of different materials (e.g., hazardous waste, MSW, AFFF). It will include assessing the **effectiveness of air pollution control technologies** such as afterburners, baghouses, and scrubbers. This information can then be applied to the current universe of incinerators, industrial oxidizers, and other thermal treatment facilities. EPA will use the thermodynamic and kinetic dataset to **add fluorine chemistry to existing computational fluid dynamic models** for reacting combustion environments to predict potential PFAS destruction and PIC formation in incinerator environments of practical interest.

- **Effectiveness of full-scale PFAS incineration operations.** EPA is partnering with real-world facilities to understand the **operational effectiveness of commercial PFAS thermal treatment**, including HWIs, GAC regeneration facilities, SSIs, municipal waste incinerators, thermal oxidizers, and facilities that thermally treat soils and solid waste contaminated by PFAS. This research involves characterizing the untreated waste inputs, sampling at various stages during treatment, and sampling the stack emissions in order to characterize the efficacy of the treatment process and understand the ultimate fate of the PFAS during treatment.

- **PFAS destruction toolkit.** EPA has established a PFAS Innovative Treatment Team (PITT) to expeditiously identify, review, and test novel (as referenced in Section 2.e) but readily available solutions for destroying PFAS in media and wastes. Such solutions may include traditional destruction methods (e.g., common incineration processes) and novel technologies that might, involve **non-traditional thermal treatment, photolysis, hydrolysis, catalysis, or bioremediation**. For example, EPA recently announced the Innovative Ways to Destroy PFAS Challenge (U.S. EPA, 2020), which challenges problem-solvers to identify a non-thermal way of destroying PFAS in concentrated

AFFF, while creating the least amount of potentially harmful byproducts. Such different approaches will be assembled as a “toolkit” for use by EPA programs and regions, states and tribes, federal agencies, and industry.

- **Management of PFAS-containing treatment media.** Research is focused on evaluating PFAS destruction **efficiency during the reactivation, regeneration, or disposal of PFAS-containing sorbent media**, such as GAC and ion exchange resins. Sorbent media are used in many applications including managing industrial emissions and discharges, in various water treatment operations including drinking water production, and for stabilizing wastes. GAC reactivation is economically favored over replacement with virgin carbon. Therefore, if the PFAS in spent media can be completely removed and destroyed during reactivation, GAC adsorption and subsequent reactivation could be economical and sustainable for certain PFAS treatment scenarios. EPA is researching the **efficacy of regeneration, including reactivation processes** for spent media and to manage emissions and wastes generated during these processes. Where the risk, liability, or costs are too high for reusing these sorbents, disposal will be required. Researchers are **evaluating the benefits, efficacy, and costs** of destructive approaches (e.g., incineration) compared to disposal (e.g., landfilling).
- **PFAS management in landfills.** Researchers are **investigating the composition of PFAS** in landfilled materials (e.g., MSW, C&D debris**), characterizing air and waste emissions**, and **characterizing the concentrations and treatment of PFAS in leachate**. The research will also investigate the efficacy of existing treatment technology for the management of PFAS in landfill leachate and consider innovative technologies. Finally, researchers will **examine potential impacts to and suitability of landfill liners and leachate collection system from PFAS**. Research grants have also been awarded to leverage academic, state, and other research organizations to address the **waste characterization of source materials and leachates, fate and transport of PFAS, and destruction of PFAS**.
- **PFAS treatment methods leading to destruction and disposal.** Because PFAS are a complex mixture of chemicals and often occur with other contaminants or in complex matrices, treatment approaches may require a combination of treatment technologies, commonly referred to as treatment trains, to remove non-PFAS contaminants or background matrix components (e.g., dissolved organic carbon) before the PFAS can be effectively treated. As a result, PFAS may be sequestered or concentrated during certain unit operations. These operations do not themselves result in PFAS destruction or disposal; however, they may help increase the efficiency of treatment and destruction/disposal operations. For example, they can concentrate PFAS, reduce the bulk mass of material requiring treatment, or immobilize PFAS to allow time for ultimate destruction/disposal. EPA is exploring **technologies for treatment trains to treat PFAS-containing wastes, including composting, solidification/stabilization involving sorbents and chemical stabilizers, novel energy-intensive technologies for point dischargers, and installation of membranes to slow or halt PFAS movement.**
- **PFAS hazard, exposure, risk assessment, and prioritization.** In addition to research that directly supports PFAS destruction and disposal, EPA is conducting a broader program of research and development that encompasses the entire risk paradigm. Research on **human and ecological hazards, toxicity, and exposure** will help inform which PFAS or groups of PFAS pose the highest risk and therefore should be prioritized for destruction or disposal. Research on PFAS exposure includes

measuring and modeling PFAS fate and transport to better understand the potential for exposures and opportunities for management interventions to break exposure pathways. Better understanding of risk is also critical to setting benchmarks and thresholds for deciding when destruction or disposal efforts are needed, and when the results can be deemed to be successful. A better understanding of risk will enable risk managers to make informed decisions about the tradeoffs between different risk management solutions, leading to better environmental outcomes.

5.d Longer-term EPA research and development initiatives

The following activities are on a longer-term (3+ years) trajectory, including technologies in pioneering stages of early development:

- **Continuous monitoring technology for PFAS in source and ambient air.** This will include mobile/portable measurement and sensor devices to enable fenceline monitoring and discovery of any fugitive emissions in PFAS destruction and disposal operations.
- **Atmospheric fate, transport, and deposition of PFAS.** It is known that many PFAS are emitted to the atmosphere either by design or by accident, but little is known about the chemical transformations that occur, or about the distribution, dispersion, deposition, and potential for remobilization into the atmosphere. EPA is applying proven atmospheric pollution models to enable predictions about fate, transport, and deposition of PFAS in the air (as referenced in Section 3.a).
- **New and innovative technologies for destroying and disposing of PFAS.** Technology development from proof of concept to full-scale demonstration and validation requires significant time and resources and is most effectively achieved by partnering across government, academia, and industry. These ongoing partnerships are coordinating research to accelerate the most promising new technologies and approaches for the end-of-life disposal of PFAS. EPA and its partners are developing and evaluating innovative technologies such as **electron beam treatment** for aqueous and solid wastes, **cold vapor plasma technologies** for liquid wastes, **oxidative and reductive catalysts**, **higher-efficiency and reactive sorbents**, **mechanochemical ball milling**, **supercritical water oxidation, pyrolysis/gasification, electrochemical oxidation, stabilizing agents**, and **thermal catalysts**. In addition, EPA is developing **cost and performance models** for existing and innovative technologies to compare technologies on a cost and efficacy basis. These models will also allow for the optimization of treatment operations and treatment trains for PFAS. Continued development of the most promising innovative technologies also requires industry partners that have the experience and resources to commercialize these technologies and provide the capacity and the costing to make these viable solutions to this complex problem.

5.e Data and information needs to inform future guidance updates

There are many stakeholders with interests in destruction and disposal of PFAS, and many of these stakeholders have generated data and other information that, if made available, could greatly enhance the speed at which EPA can refine and extend this guidance. EPA is always seeking to partner with entities that have information to share. The following discussion identifies the most critical information gaps where information from outside entities might help to strengthen future guidance.

The highest-priority data and information needs to inform future guidance updates include:

- Data and other information generated through pilot tests of sampling and analysis methods for PFAS in stack emissions. EPA would like to know what sampling approaches have been tried, which ones have worked or not worked, and what data were generated during the tests regarding the presence of PFAS, including PICs (as referenced in Section 3.a.iv).
- Data and other information generated through thermal treatment tests of different PFAS and PFAS-containing materials under different thermal conditions including temperatures, holding times, measures of turbulence, and presence or absence of flames. EPA would like to increase the database of basic information about thermal conditions required to destroy different PFAS, as well as what specific PICs are produced under what conditions (as referenced in Sections 3.a.ii–3.a.vi).
- Data and information about approaches for efficiently controlling the emission of PICs, and about PFAS that may be present in air pollution control device media (scrubber water, particulate matter control device media) and bottom ash (as referenced in Section 3.a.ii).
- Data and other information regarding (1) the presence of different PFAS in landfill leachate samples, (2) the effectiveness of different treatment systems that have been tested for removing PFAS from landfill leachate, and (3) the rate of PFAS migration and transformation from unlined landfill cells and the concomitant impacts on groundwater (as referenced in Sections 2.f and 3.b).
- Information about PFAS destruction and disposal operators that might be willing to work with EPA and its partners to grant access to facilities and operations, so as to enable EPA to generate additional data to address the information gaps listed above.

Additional information that would better inform future guidance includes:

- Data and information about surrogates that have been tested in incineration and can serve as reference materials for further testing of PFAS destruction.
- Data and information about facility operator's information needs from EPA or from other sources to better manage the safe destruction and disposal of PFAS-containing materials.
- Data and information about PFAS disposal or destruction approaches or technologies other than those discussed in Section 2, with particular emphasis on quantitative data regarding the transformations and mass balance (for destructive technologies) or fate and transport (for disposal technologies) for PFAS subjected to such approaches (as referenced in Section 2.e).

5.f References

DoD (Department of Defense). (2020). *DoD-funded research on PFAS.* *https://www.serdp-estcp.org/Featured-Initiatives/Per-and-Polyfluoroalkyl-Substances-PFASs/DoD-PFAS-Page/DoD-PFAS-Page/(language)/eng-US*

U.S. EPA (Environmental Protection Agency). (2019). *EPA's per- and polyfluoroalkyl substances (PFAS) action plan* (EPA 823R18004). *https://www.epa.gov/pfas/epas-pfas-action-plan*

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