Essential Chemistries

Providing Benefits Across the U.S. Economy

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U.S. Chamber of Commerce

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Executive Summary

The U.S. Chamber of Commerce (USCC) engaged third-party experts in environmental and economic policy to evaluate the economic and fiscal impacts of specific sectors reliant on essential fluorochemistries across the U.S. economy. This report examines the dependence of seven critical U.S. sectors, including aerospace manufacturing, data centers, defense equipment and systems, energy transition, health care, mobility, and semiconductors on essential fluorochemistries, including per- and polyfluoroalkyl (PFAS) substances. Essential fluorochemistries are vital for numerous technologies due to their reliability, effectiveness, and durability. Exploring replacements across these sectors is complex and challenging and will likely take decades. This study primarily addresses the key uses of fluoropolymers, fluorinated gases (f-gases), and other fluorinated substances, such as heat transfer fluids. Fluoropolymers are a type of extremely durable plastics that exhibit performance characteristics such as extreme heat, friction, chemical, and water resistance. F-gases are a group of synthetic gases that commonly include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), hydrofluoroolefins (HFOs), sulfur hexafluoride (SF6), and nitrogen trifluoride (NF3) and are often used as refrigerants and support important applications, including fire suppression and meter dose inhalers. Fluoropolymers and f-gases are key inputs to the seven critical sectors.

- **Aerospace manufacturing.** Ensure safety, efficiency, and reliability through their use in critical components, such as fuel systems, hydraulic fluids, and high-performance coatings.
- **Data centers.** Rely on f-gases to cool electronic components and in fire suppression systems.
- **Defense.** Requires them for critical applications, such as guided missiles, vehicles, and military personal protective equipment (PPE).
- **Energy transition and emerging energy technologies.** Contain coatings for solar panels, wind turbine towers and blades, and subcomponents of lithium-ion batteries for energy storage systems and electric vehicles.
- **Health care.** Uses primarily for medical device technologies, packaging drugs and medical equipment, and refrigerating drugs.
- **Mobility.** Employs in almost all aspects, from the semiconductors used for automatic controls to necessary engine coolants, in comfort heating and cooling, and in the production of automotive hoses, seals, and gaskets.
- **Semiconductor manufacturing:** Utilizes throughout semiconductor manufacturing, including in process chemistries, manufacturing equipment, and facilities infrastructure for integral performance properties not found in fluorine-free alternatives.

The U.S. Chamber, in collaboration with FTI Consulting, compiled this report to identify the materials and processes in each sector that are most vulnerable to the loss of essential fluorochemistries. We estimate the potential lost economic output, employment, labor income, and GDP, as well as the lost fiscal impacts for federal, state, and local governments should these fluorochemistries become unavailable as shown in Table 1. The share of the seven sectors dependent on essential fluorochemistries supports approximately 6.1 million jobs that would be at risk if these chemistries were no longer available. Furthermore, these sectors support over $2.4 trillion in output, nearly $1 trillion in GDP, over $550 billion in labor income, and over $200 billion in combined federal, state, and local tax revenues.

Table 1 – The Economic and Fiscal Impact of Selected Sectors Dependent on Fluorochemistries

Metric	Total Impacts	Unit
Employment	6.1	Million Jobs
Output	$2,413	(2024 $ billions)
GDP	$988	(2024 $ billions)
Labor Income	$553	(2024 $ billions)
Federal Tax Revenues	$140	(2024 $ billions)
State and Local Tax Revenues	$69	(2024 $ billions)

Table 2 – The Employment Impact of Selected Sectors Dependent on Fluorochemistries

Sector	Direct Jobs (thousands)	Indirect Jobs (thousands)	Induced Jobs (thousands)	Total Jobs (thousands)
Mobility	977.8	856.7	723.5	2,557.9
Semiconductors	293.2	526.0	531.2	1,350.4
Air Travel	387.1	76.8	251.5	715.4
Data Centers	139.5	324.7	191.5	655.6
Health Care	126.1	108.8	130.5	365.4
Defense	99.6	50.9	92.2	242.7
Energy Transition	77.0	67.0	68.4	212.3
Total	**2,100.2**	**2,010.7**	**1,988.8**	**6,099.7**

Table 2 depicts the U.S. job contribution of each of the seven sectors dependent on essential fluorochemistries.

Introduction and Context

Scientific breakthroughs in the mid-1900s led to the discovery of per- and polyfluoroalkyl substances (PFAS).[1] PFAS are a group of synthetic fluorine-based chemistries defined as having a chain of carbon and fluorine atoms linked together.[2] They are known for their exceptional strength and durability.[3] These essential fluorochemistries support the foundation of the modern economy, sustaining critical functions across many sectors.

Types of fluorochemistries are used in consumer products such as food packaging, cosmetics, and water-repellent materials despite the availability of potential replacement options. In food packaging, these chemicals have been used to provide grease resistance, but alternatives like wax-coated paper and biodegradable polymers can achieve comparable results. In cosmetics, PFAS can offer waterproofing and enhanced product texture and durability.[4] However, non-fluorinated alternatives have been identified to provide comparable results.[5] Water-repellent materials, commonly treated with PFAS, can instead utilize silicone or other coatings that offer comparable performance.[6] Companies in these selected sectors have made certain commitments to utilize alternatives where available.

Nevertheless, due to their exceptional performance and durability, fluorochemistries have proven to be indispensable, especially but not limited to the seven targeted sectors in this report— aerospace manufacturing, data centers, defense, energy transition, health care, mobility, and semiconductors. These chemistries add significant value to the U.S. economy, which is highlighted by the lack of available replacements in these sectors, with most viable alternatives, if feasible, projected to take 5 to 20 years to develop and implement. In the defense and semiconductor sectors, for example, some applications have undetermined time frames to create replacements for fluorochemistries.[7]

The U.S., along with many other countries worldwide, is considering public policies that could threaten the existence of all fluorochemistries and therefore cause severe disruption to our economy and the everyday products consumers depend on.

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[1] https://pfas-1.itrcweb.org/wp-content/uploads/2020/10/history_and_use_508_2020Aug_Final.pdf

[2] https://www.americanchemistry.com/chemistry-in-america/chemistries/fluorotechnology-per-and-polyfluoroalkylsubstances-pfas

[3] While these essential fluorochemistries are useful, environmental and health concerns have been raised due to the fact that the fluorine-carbon bond is so strong. These chemicals are slow to break down, causing buildup throughout the environment.

[4] https://www.fda.gov/cosmetics/cosmetic-ingredients/and-polyfluoroalkyl-substances-pfas-cosmetics

[5] https://one.oecd.org/document/ENV/CBC/MONO(2024)4/en/pdf

[6] https://www.coatingsworld.com/buyersguide/profile/siltech-corp/view_where-silicon-materials-can-replace-pfas/

[7] https://www.acq.osd.mil/eie/eer/ecc/pfas/docs/reports/Report-on-Critical-PFAS-Substance-Uses.pdf

This report summarizes the necessary uses of fluorochemistries required to support essential economic and societal functions across aerospace manufacturing, data centers, defense, energy transition, health care, mobility, and semiconductors. Combined, the share of these sectors dependent on essential fluorochemistries supports an estimated 6.1 million direct, indirect, and induced jobs across the U.S. economy.

To estimate the contribution of essential fluorochemistries to the U.S. economy, each of the seven selected sectors have been assigned a percentage or share of market value, indicating the extent to which the sector depends on fluorochemistries. Sectors that are entirely reliant on fluorochemistries and have no viable alternatives are assumed to be fully impacted, meaning that any disruption in essential fluorochemistries' supply would impact the entire production of the sector. For example, the automobile industry currently has no practical alternatives and is not expected to adopt substitutes on an industrywide scale for at least 15 years.[8] Therefore, this entire sector's contribution to the U.S. economy is included in the results. In some cases, like pharmaceuticals, where fluorochemistries are used mainly in packaging and refrigeration, only a portion of the sector's contribution to the overall economy is included.

[8] https://echa.europa.eu/documents/10162/57812f19-8c98-ee67-b70f-6e8a51fe77e5

Methodology and Approach

The IMPLAN Model

IMPLAN is a leading provider of commercial input-output (IO) models with its namesake IMPLAN model. IMPLAN is an IO model of regional and national economies, such as the economies of the U.S., Canada, European nations, and other developed economies globally.

IO models are a widely used economic tool that helps analyze the connections between different sectors of an economy. These models provide a way to measure the flow of goods and services between industries, representing all transactions occurring between sectors. They illustrate how the output of one sector becomes the input of another, creating a network of interdependencies. IMPLAN uses a Leontief Production Function, which is a type of IO model that describes the relationship between inputs and outputs in an economy assuming fixed proportions of inputs required to produce a unit of output across different sectors or industries.

Key Outputs

IMPLAN produces six main metrics, which are defined as the following:

Employment—The number of jobs identified are those supported in the sectors dependent on essential fluorochemistries.

Output—The value of an industry's production output is the sum of sales to final users (e.g., GDP) plus the sales to other industries (intermediate inputs). It is a measure of total economic activity.

GDP—GDP, or value-added, is defined as the total market value of all final goods and services. It is a measure of the wealth created by economic activity.

Labor Income—The household income provided is that which is supported by the jobs dependent on essential fluorochemistries.

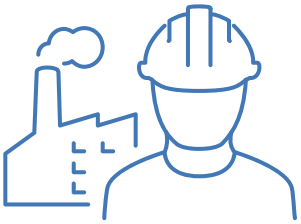
Federal Tax Revenues—Incremental tax revenues for the federal government are included because of higher levels of economic activity, such as higher income tax payments.

State and Local Tax Revenues—Incremental tax revenues for state and local governments are also included because of higher levels of economic activity, such as higher sales tax payments.

IMPLAN calculates how a direct change in employment or expenditures, the direct impact, will then influence the rest of the economy. IMPLAN describes these ancillary or ripple effects through its indirect and induced multiplier effects as shown in **Figure 1**.

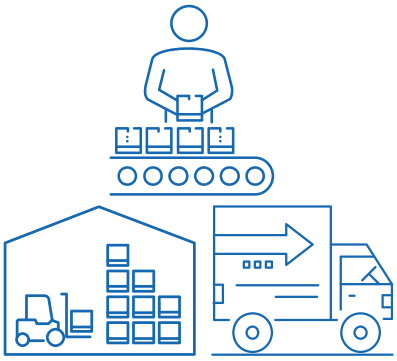
Figure 1

Direct Effects
Immediate impacts of a specific economic activity.



Example: Building a new factory creates direct effects like job creation and increased local spending.

Indirect Effects
Secondary impacts resulting from the initial economic activity.



Example: The factory construction boosts demand for raw materials, transportation services, and other industries, creating additional jobs and income.

Induced Effects
Tertiary impacts caused by increased household income generated by direct and indirect effects.

Example: Employees of the new factory spend their wages on goods and services, stimulating further economic activity and supporting local businesses.

The types of IMPLAN effects are defined as follows:

- ***Direct Effect:*** The direct effect is the direct employment or output associated with the production of products containing essential fluorochemistries. Examples include automobiles or airplane manufacturing.

- ***Indirect Effect:*** The indirect effect is the impact on the regional or national supply chain. For instance, automobile manufacturers may purchase finished tires from a tire company. Service sectors, such as legal or accounting, that may be employed by the manufacturer would also have indirect impacts.

- ***Induced Effect:*** The induced effect is the consumer expenditures supported by the wages paid to the employees of the direct and indirect economic sectors.

Total Effect: The total effect is the sum of the direct, indirect, and induced impacts.

Aerospace Manufacturing Sector Modeling

Essential fluorochemistries are vital to the aerospace manufacturing sector, with critical applications along the value chain and production stages. Their primary uses include hydraulic systems, wiring, and insulation due to their durability, high-temperature resistance, and corrosion protection. In hydraulic systems, fluoropolymers create high pressures with minimal water usage and protect metals from corrosion by altering electrical potential. Fluoropolymers are also utilized in aircraft components like seals, gaskets, and wiring insulation because of their high strength, lightweight, chemical resistance, and low friction properties. Additionally, f-gases are used in fire suppression systems.

There are currently no feasible alternatives to many uses of essential fluorochemistries in the aerospace manufacturing sector, where they are crucial for insulation, high-temperature permeability, and clear displays.[9] As such, all the sectors in the IMPLAN model related to the production of aircraft were included in the analysis, and their total direct, indirect, and induced impact on the U.S. economy was modeled.[10] Note, this analysis only examines the role of fluorochemistries in aerospace manufacturing rather than the entire air travel sector, including airlines.

Data Centers Sector Modeling

Data centers are a fixture of today's digitally connected society, and the sector is projected to grow rapidly. It is projected that over the next four years, there will be some 120–130 hyperscale data centers coming online, fueling the U.S. data center market that is expected to exceed $99 billion in total revenue by the end of 2024.[11,12] Essential fluorochemistries, including low global warming potential (GWP) f-gases, play a critical role in large-scale temperature control at data centers, both through traditional temperature control techniques and through new technologies, such as two-phase immersion cooling (2-PIC).[13] In traditional large-scale temperature control, f-gases are used in air-cooling systems for electronic components. In 2-PIC, electronic components are submerged in a fluorochemical heat transfer liquid with a low boiling point.[14] As the chemical evaporates, the rising vapor helps cool the components. The chemical then condenses and returns to the system, creating a closed loop. Additionally, f-gases play an important role in fire suppression systems in many data centers.

If these fluorochemistries were no longer available, data centers would be forced to find alternatives. To estimate the overall impact of data centers on the U.S. economy, the total revenue of the data center market

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[9] https://echa.europa.eu/documents/10162/57812f19-8c98-ee67-b70f-6e8a51fe77e5

[10] Note, IMPLAN does not differentiate between civilian and military aircraft manufacturing. As such, all aircraft, including military aircraft, are included in the aerospace manufacturing sector.

[11] https://www.statista.com/outlook/tmo/data-center/united-states

[12] https://www.srgresearch.com/articles/hyperscale-data-centers-hit-the-thousand-mark-total-capacity-is-doubling-every-four-years

[13] https://www.chemours.com/en/pfas-advocacy/data-centers

[14] https://www.gigabyte.com/Solutions/liquidstack-two-phase

was allocated across states based on the total number of data centers located in each state.[15] For example, Virginia, home to approximately 13% of all data centers in the U.S., was assigned 13% of the total data center market revenue. In each state, the total estimated revenue was modeled to estimate the direct, indirect, and induced economic contribution of data centers.

Defense Equipment and Systems Sector Modeling

The defense sector relies on essential fluorochemistries due to their unique properties that are needed in the development, production, and operation of critical equipment used by the Armed Forces.[16] Fluorochemistries contribute significant capabilities to national security because they provide exceptional thermal stability, chemical resistance, and performance in extreme environments, which are properties integral to mission-critical applications.[17]

Fluoropolymers are used in pyrotechnics and in the manufacture of munitions for missile systems.[18] In addition, fluorochemistries are used in firefighting foams used in military vessels and vehicles. Fluoropolymers are also used in coatings and other materials to enhance water and oil repellency and increase heat resistance.[19] Fluoropolymers like polytetrafluoroethylene (PTF) are used on textiles for manufacturing PPE, such as suits to guard personnel from chemical and biological threats. Additionally, most refrigerants used in military cooling and refrigeration applications can be classified as PFAS. Known non-PFAS alternatives may pose flammability, toxicity, or high-pressure concerns.[20] Currently, there are no viable replacements for essential fluorochemistries used to manufacture critical components used in the defense sector. The timeline for alternatives is projected to take at least 5 to 20 years.[21]

To quantify the economic impact of the share of the defense industry dependent on essential fluorochemistries, the IMPLAN model analysis assessed the economic impact of essential fluorochemistries to four defense applications—PPE, guided missiles, radar systems, and military tank manufacturing. The IMPLAN model contains individual sectors for guided missile manufacturing and military tank manufacturing. Because of a lack of viable alternatives, these sectors were included in the analysis, and their total direct, indirect, and induced impact on the U.S. economy was modeled.

Estimating the impact on the manufacturing of PPE and radar systems was more challenging to model because these businesses are subsectors of broader IMPLAN manufacturing sectors. FTI reviewed each subsector within the

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[15] https://www.datacentermap.com/usa/

[16] https://www.acq.osd.mil/eie/eer/ecc/pfas/docs/reports/Report-on-Critical-PFAS-Substance-Uses.pdf

[17] Ibid.

[18] Ibid.

[19] Ibid.

[20] Ibid.

[21] Ibid.

surgical appliance and supplies manufacturing sector, where PPE manufacturing is classified. Just 4 out of the 84 subsectors in this sector applied to the manufacturing of PPE, leading to the assumption that 4.8% of the larger sector would be affected.

The same methodology was applied to radar systems, where fluorochemistries are critical in the production of semiconductors, lithium batteries, and other critical electronic components along the defense supply chain.[22] Following a review of each subsector within the search, detection, and navigation instruments manufacturing sector within the IMPLAN model where radar systems are classified, it was assumed that only 1.7% of the broader sector is dependent on essential fluorochemistries. In both the PPE and radar cases, the share of the sector identified as dependent on fluorochemistries was used to model the direct, indirect, and induced economic contribution of the subsectors across states.

Energy Transition Sector Modeling

Essential fluorochemistries play a crucial role in renewable and clean energy technologies, such as solar panels and wind turbines. They are also integral to battery energy storage systems, electric vehicles, and the lithium-ion batteries that power them. These applications are vital to advancing the energy transition.[23]

In the wind and solar sector, fluoropolymer coatings help equipment withstand rain, hail, and environmental contaminants.[24] Fluoropolymers are used in paints and coatings on wind turbine towers and blades to provide weather resistance and increase service life.[25] Moreover, manufacturers use fluoropolymers in subcomponents in lithium-ion batteries, such as heat transfer materials or insulation.[26] The Department of Defense estimates that fully eliminating fluorochemistries from battery energy storage would likely take more than 10 years.[27]

To model the economic contribution of wind energy component manufacturing in the U.S., the total nationwide manufacturing capacity (in gigawatts) of towers, blades, and nacelles was identified from the U.S. Department of Energy's *Land-Based Wind Market Report: 2023 Edition*.[28] The total component cost per kilowatt was identified from the National Renewable Energy Laboratory's 2022 *Cost of Wind Energy Review*.[29] This data was used to estimate the total market size of each of the tower, blade, and nacelle manufacturing sectors in the U.S. This total market size was then allocated across states based on known

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[22] Ibid.

[23] https://www.chemours.com/en/pfas-advocacy/solar-wind-energy

[24] https://fluoropolymerpartnership.com/fluoropolymer-applications-and-uses/energy/

[25] https://www.chemours.com/en/pfas-advocacy/solar-wind-energy

[26] https://www.acq.osd.mil/eie/eer/ecc/pfas/docs/reports/Report-on-Critical-PFAS-Substance-Uses.pdf

[27] Ibid.

[28] https://www.energy.gov/sites/default/files/2023-08/land-based-wind-market-report-2023-edition.pdf

[29] https://www.nrel.gov/docs/fy24osti/88335.pdf

locations of tower, blade, and nacelle manufacturing facilities. In total, the total revenue of wind tower, blade, and nacelle manufacturers was estimated at over $10 billion.

Similarly, the total 2023 U.S. value of shipments of solar panels was identified from the U.S. Energy Information Administration (EIA) and allocated across states using the locations and manufacturing capacity of facilities.[30,31] The EIA provides data on 90% of shipments; after scaling to 100%, it was estimated that the size of the solar panel market in the U.S. was nearly $13 billion. Finally, lithium-ion battery pack prices were combined with the location and manufacturing capacity of battery manufacturing facilities across the U.S. to estimate total market size across states., The U.S. lithium-ion battery market was estimated at nearly $16 billion.

In each case, the estimated revenue for individual components was mapped to appropriate IMPLAN sectors (such as fabricated structural metal manufacturing for wind towers or storage battery manufacturing for lithium-ion batteries) and used to model the direct, indirect, and induced economic contribution of the sector across states.[32,33]

The U.S. lithium-ion battery market was estimated at nearly $16 billion.
In each case, the estimated revenue for individual components was mapped to appropriate IMPLAN sectors (such as fabricated structural metal manufacturing for wind towers or storage battery manufacturing for lithium-ion batteries) and used to model the direct, indirect, and induced economic contribution of the sector across states.

Health Care Sector Modeling

Fluoropolymers and f-gases play a crucial role in the health care sector owing to their limited chemical reactivity, strength, low friction, and role as insulators.[34] Medical device technologies, packaging for drugs and medical equipment, surgical tools that require sterilization, and refrigeration for pharmaceutical components like vaccines rely on the properties of fluorochemicals that are currently irreplaceable.[35,36] Some pharmaceuticals may be at risk; broad definitions of PFAS would include common medicines, such as Prozac and Lipitor.[37]

The use of fluorochemistries in the pharmaceutical industry is prevalent but not reflected in the ingredient list for the drugs themselves. Instead, fluoropolymers are

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[30] https://www.eia.gov/renewable/monthly/solar_photo/

[31] https://www.solarpowerworldonline.com/u-s-solar-panel-manufacturers/ Note, additional desktop research was performed to identify the available production capacity of both operating and partially operating plants.

[32] https://about.bnef.com/blog/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/

[33] https://www.charged-the-book.com/na-ev-supply-chain-map

[34] https://www.americanchemistry.com/chemistry-in-america/news-trends/blog-post/2023/overly-broad-pfas-restrictions-could-endanger-healthcare-quality-and-cost

[35] https://www.advamed.org/wp-content/uploads/2024/03/One-pager-final-PFAS-AdvaMed-2023.08.22.pdf

[36] https://www.americanchemistry.com/chemistry-in-america/news-trends/blog-post/2023/overly-broad-pfas-restrictions-could-endanger-healthcare-quality-and-cost

[37] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8933701/

often found in the packaging for drugs, while f-gases are used for the cold cycle refrigeration of drugs that require it.[38,39] Packaging made with fluorochemistries increases the shelf life for drugs and prevents humidity that could damage medicines, while refrigeration is essential for storing and transporting drugs as well as being critical in some labs where drugs are produced.[40,41] Since both the exact amount of f-gases and fluoropolymers used in the packaging and cooling and the extent to which existing drugs could be classified as PFAS are unknown, 30% of the pharmaceutical sector in IMPLAN was assumed to be dependent on these fluorochemistries.

Medical device manufacturing could also be affected if essential fluorochemistries were no longer available. Surgical tools manufacturing encompasses items like surgical knives, catheters, and other tools with more specialized applications.[42] Surgical tools must be sterile to ensure that no outside contaminants on the tools enter the patient's body. Fluorochemistries are essential to the sterility of medical devices critical to patient care. For example, in catheters, fluoropolymers help reduce the likelihood of clots and reduce the friction on the outside of the catheter to help with patient comfort.[43] Not all surgical tools included in the IMPLAN model's surgical tool manufacturing sector rely on fluorochemistries. However, some items rely directly on fluorochemistries, such as inhalers that use them as a propulsion mechanism for medicine.[44,45] Based on a review of each subsector within IMPLAN's surgical tool manufacturing sector, the Chamber and its experts estimated that roughly 22% of the total sector would be affected if essential fluorochemistries were no longer available.

Finally, medical technologies often rely on fluorochemistries. These supplies include medical wires, ventilators, implants like joint replacements, and support equipment like hospital gowns.[46,47,48] Fluorochemistries are also found in packages for medical supplies like needles to ensure they can be sterilized for patient care. Some subsectors in IMPLAN's medical supplies manufacturing sector model directly use plastics and components that would be drastically impacted by a ban. These subsectors were

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[38] https://www.chemours.com/en/pfas-advocacy/medical-devices

[39] https://www.advamed.org/wp-content/uploads/2024/03/One-pager-final-PFAS-AdvaMed-2023.08.22.pdf

[40] https://www.americanchemistry.com/chemistry-in-america/news-trends/blog-post/2023/overly-broad-pfas-restrictions-could-endanger-healthcare-quality-and-cost

[41] https://www.chemours.com/en/pfas-advocacy/medical-devices

[42] https://www.chemours.com/en/pfas-advocacy/medical-devices

[43] https://www.energy.gov/sites/default/files/2023-08/land-based-wind-market-report-2023-edition.pdf

[44] https://www.chemours.com/en/pfas-advocacy/medical-devices

[45] https://www.americanchemistry.com/chemistry-in-america/news-trends/blog-post/2023/overly-broad-pfas-restrictions-could-endanger-healthcare-quality-and-cost

[46] https://www.chemours.com/en/pfas-advocacy/medical-devices

[47] https://www.advamed.org/wp-content/uploads/2024/03/One-pager-final-PFAS-AdvaMed-2023.08.22.pdf

[48] https://www.americanchemistry.com/chemistry-in-america/news-trends/blog-post/2023/overly-broad-pfas-restrictions-could- endanger-healthcare-quality-and-cost

assumed to be fully affected if essential fluorochemistries were not available. Other subsectors manufacture goods that do not directly rely on fluoropolymers but rather are sterilized with fluorochemistries. For these subsectors, it was assumed that 30% of the subsector would be affected. The share of each subsector was summed to find the total share of the medical supplies manufacturing sector that could be impacted if essential fluorochemistries were no longer available.

Mobility Sector Modeling

Automobiles and heavy trucks are a part of everyday life for many across the U.S. and consist of thousands of individual parts.[49] For many, cars are not just a convenience but a necessity, enabling mobility and independence while supporting economic activity across the country. Recent estimates indicate that 74% of Americans have access to their own car, while only 14% do not have access to any car, including from friends, family, or rideshare options.[50]

Fluoropolymers are essential in mobility applications, especially in improving the performance and lifespan of various components. They are used in engine coolants, lubricants, and coatings to enhance fuel efficiency, minimize wear and friction, and prevent corrosion. Due to their ability to withstand heat, chemicals, and abrasion, fluoropolymers are also employed in the production of automotive hoses, seals, and gaskets.

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[49] https://www.chicagofed.org/publications/blogs/midwest-economy/2019/what-do-we-know-about-the-origin

[50] https://www.statista.com/forecasts/997211/car-ownership-in-the-us

Essential fluorochemistries are used extensively in automobiles, heavy trucks, and mobility solutions for mechanical components, electronics, air-conditioning, and electric vehicle (EV) batteries[51] due to their durability, heat, water, oil, and chemical resistance. Key applications include the following:

- ***Mechanical Components:*** Fluoropolymers are essential in manufacturing automotive lubricants, fuel hoses, seals, and gaskets. They provide critical properties such as water and oil repellence and resistance to extreme temperatures.

- ***Air-Conditioning Systems:*** Both combustion and electric vehicles use f-gases. HFC-134a is a common coolant with a GWP of 1,430, which replaced ozone-depleting CFC-12 coolants.[52] Advancements in the field have led to replacement options for HFC-134a with more environmentally friendly alternatives, such as lower GWP HFCs, HFC blends, and HFOs.[53]

- ***Electronics:*** There are an average of 1,000–3,000 semiconductors in modern vehicles. These are vital for safety features, fuel efficiency, infotainment, navigation, and electronic systems like power windows and door locks.

- ***Electric Vehicle Batteries:*** PFAS are critical in lithium-ion battery production and are used as a separator material to improve electrode adhesion, reduce short circuits, and enhance battery performance and safety. F-gases are also used as coolants to prevent battery overheating during charging.

Essential fluorochemistries contribute to decreased vehicle weight, increased fuel economy, and overall reliability, making vehicles safer and more advanced. They also extend the useful life of vehicles by providing durability and reducing wear and tear.

There are currently no viable substitutes for essential chemistries in the majority of automotive and mobility manufacturing, including critical applications like semiconductors and battery components.[54] Research suggests that it could take at least 15 years to develop and transition to PFAS-free alternatives in key applications like semiconductors and battery components.[55] All sectors in the IMPLAN model related to the production of automobiles were included in the analysis and their total direct, indirect, and induced impact on the U.S. economy was modeled.

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[51] Note, IMPLAN does not differentiate between EV and stationary storage battery manufacturing. As such, all batteries, including EV batteries, are included in the energy transition sector to avoid double counting.

[52] https://www.epa.gov/mvac/refrigerant-transition-environmental-impacts

[53] https://www.epa.gov/sites/default/files/2016-12/documents/international_transitioning_to_low-gwp_alternatives_in_res_and_com_ac_chillers.pdf

[54] https://www.semi.org/en/blogs/semi-news/fluorinated-chemicals-are-essential-to-semiconductor-manufacturing-and-innovation, https://echa.europa.eu/documents/10162/57812f19-8c98-ee67-b70f-6e8a51fe77e5

[55] Ibid.

Semiconductor Sector Modeling

In 2023, the U.S. exported $52.7 billion worth of semiconductors, making it the leading export in the electronic products category, and placing it sixth overall in total exports.[56] Semiconductors are essential to current and future technological advancements. The manufacturing process of semiconductors involves over 2,000 complex steps and utilizes a wide range of materials.[57] This intricate process relies heavily on chemicals, equipment, and facilities that incorporate fluoropolymers, which are integral to semiconductor production.

Fluorochemistries are used in semiconductor production due to their inertness, cleanliness, low flammability, temperature stability, durability, and other unique performance characteristics. These qualities are especially important in the following applications:

Photolithography: Fluorochemistries are used in critical photolithography formulations like chemically amplified resists, antireflective coatings, barrier layers, and buffer coatings which are essential to nanometer-scale precision in semiconductor devices.

Wet Chemistries: Fluorinated surfactants are added to wet chemistries such as etchants, wet clean chemistries, plating, and planarization to assist with wettability of nanometer-sized device features.

Plasma Etch/Wafer Clean and Deposition: Fluorinated gases are essential for directional etching and cleaning of silicon features and cleaning of chemical vapor deposition chambers.

Articles: Fluoropolymers are contained in semiconductor manufacturing equipment and facility infrastructure for safety, contamination control, resilience, and other factors.

Lubricants: Fluorinated lubricants are essential to the precision and reliability of robotics, automation, and vacuum systems needed to achieve nanoscale precision.

Heat Transfer Fluids: Fluorinated heat transfer fluids and fluorinated refrigerants ensure precise temperature control in specific manufacturing processes and enable testing of semiconductor products to ensure performance.

Assembly, Test, Packaging, and Substrates: Fluorochemistries provide the combination of necessary properties to ensure hermetic sealing, device durability, and other product reliability purposes for packaged semiconductor devices.

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[56] https://www.semiconductors.org/wp-content/uploads/2024/05/SIA-2024-Factbook.pdf

[57] https://www.semiconductors.org/wp-content/uploads/2023/05/FINAL-PFAS-Consortium-Background-Paper.pdf

Many materials used in these diverse applications are extremely difficult to replace, and most alternatives to replace fluoropolymers are projected to take more than 15 years to develop.[58] In certain applications such as plasma etch/wafer clean, non-fluorinated alternatives may not be viable substitutes due to the basic chemistry and physics of etching silicon and its compounds. When developing the assumptions for the economic analysis, it was assumed that the semiconductor sector would be fully impacted if essential fluorochemistries were not available.

The total market value of the U.S. semiconductor industry was first determined to be $275 billion using data from the Semiconductor Industry Association's 2023 and 2024 Factbooks.[59,60] The total market value was then proportionally allocated across states using IMPLAN data.

[58] https://www.semiconductors.org/wp-content/uploads/2023/05/FINAL-PFAS-Consortium-Background-Paper.pdf

[59] https://www.semiconductors.org/wp-content/uploads/2024/05/SIA-2024-Factbook.pdf

[60] https://www.semiconductors.org/the-2023-sia-factbook-your-source-for-semiconductor-industry-data/

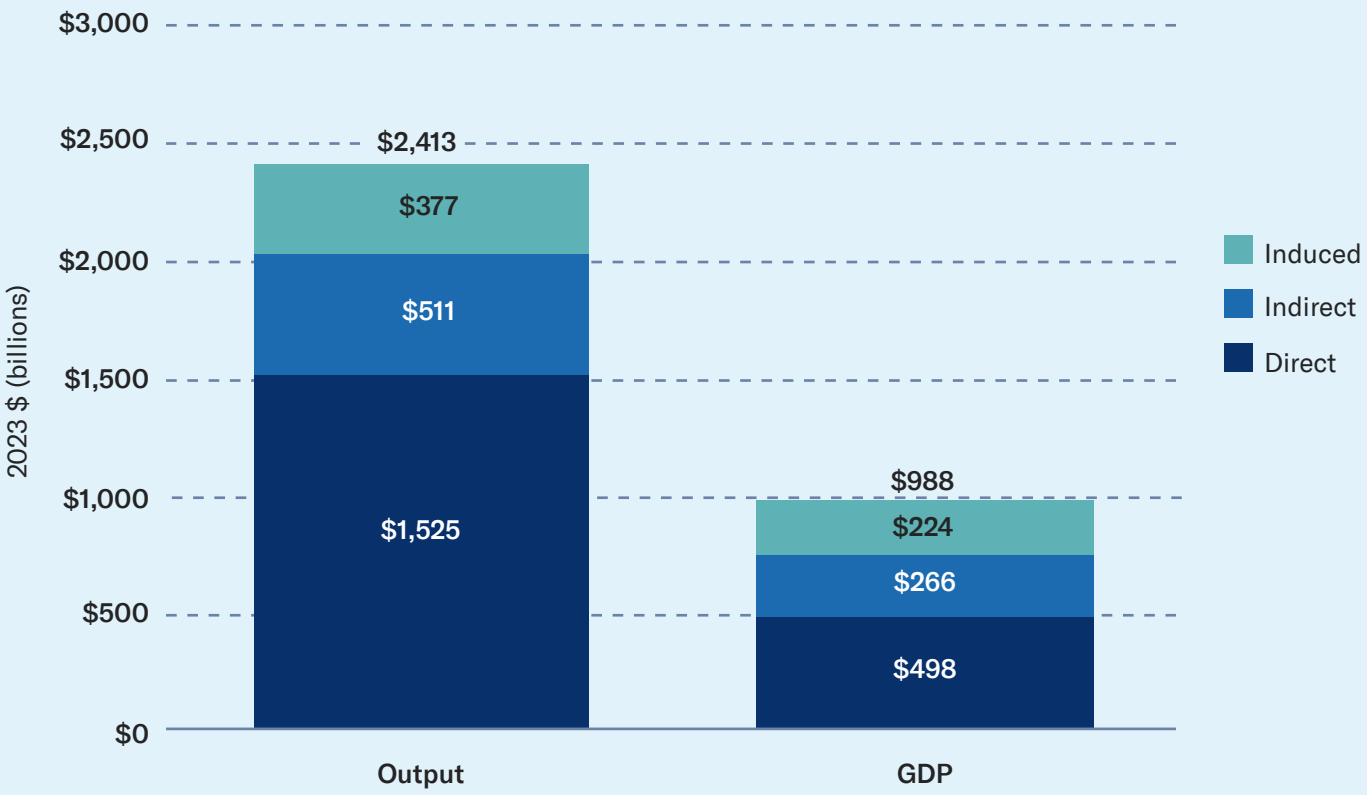
Economic Impact Results

This section describes the economic contribution of the seven selected sectors dependent on essential fluorochemistries to the U.S. economy.

Output and GDP Impacts

In total, these sectors contributed over $2.4 trillion of output to the U.S. economy as summarized in Figure 2. The direct output generated by sectors dependent on essential fluorochemistries surpassed $1.5 trillion. There were also $511 billion of indirect impacts and $377 billion of induced impacts. The seven sectors also support nearly $1 trillion in U.S. GDP.[61] This is equivalent to 3.7% of the total U.S. GDP and is similar in size to that of Saudi Arabia's GDP. Direct, indirect, and induced GDP contributions total $498 billion, $266 billion, and $224 billion, respectively.

Figure 2 – Output and GDP Impacts of Selected Sectors Dependent on Fluorochemistries



[61] https://www.bea.gov/news/2024/gross-domestic-product-fourth-quarter-and-year-2023-second-estimate, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=SA

Figure 3, summarizes the distribution of economic output impacts of the selected sectors across the U.S. states. California has the highest impact, with over $341 billion in output being generated in the state, followed by Texas and states in the Great Lakes region of the country.

Similar to Figure 3, Figure 4 summarizes the state-level GDP impact of the selected sectors dependent on essential fluorochemistries. GDP results typically mirror output results as GDP is a subset of output. As a result, the largest GDP impacts are seen in California, Texas, and states in the Great Lakes region, such as Michigan, Indiana, and Ohio. In some states, GDP impacts (representing value added) are noticeably lower than output (representing total sales). In regions like the Northeast, a car may be sold in New York, yet manufactured in another state, reflecting leakages across states.

Figure 3—Total Output Impact for States of Selected Sectors Dependent on Fluorochemistries

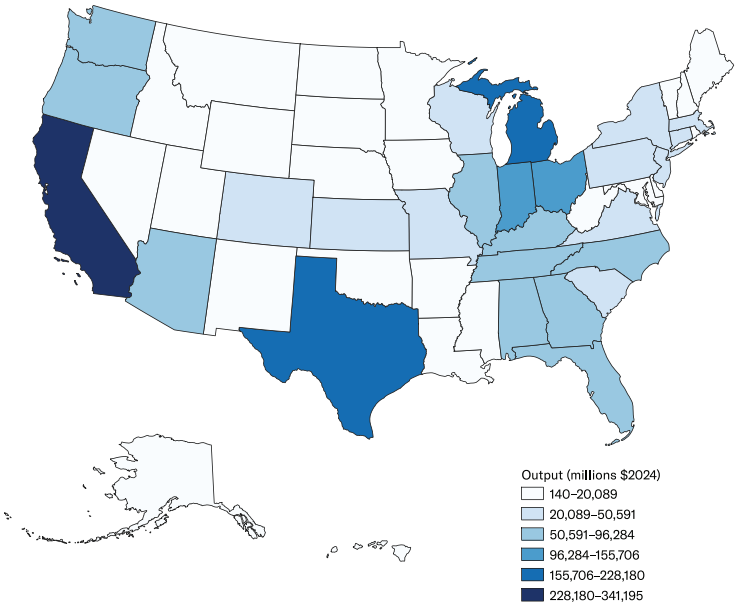


Figure 4—Total GDP Impact for States of Selected Sectors Dependent on Fluorochemistries

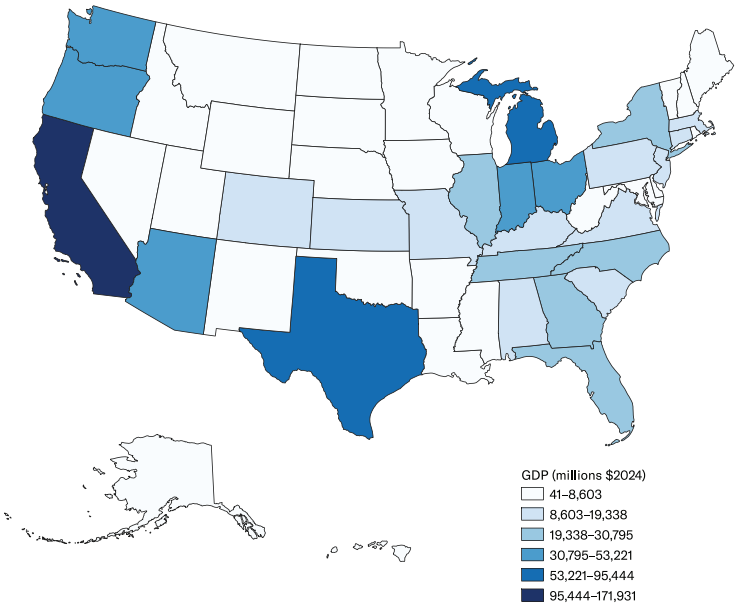


Figure 5 – Employment Impacts of Selected Sectors Dependent on Fluorochemistries

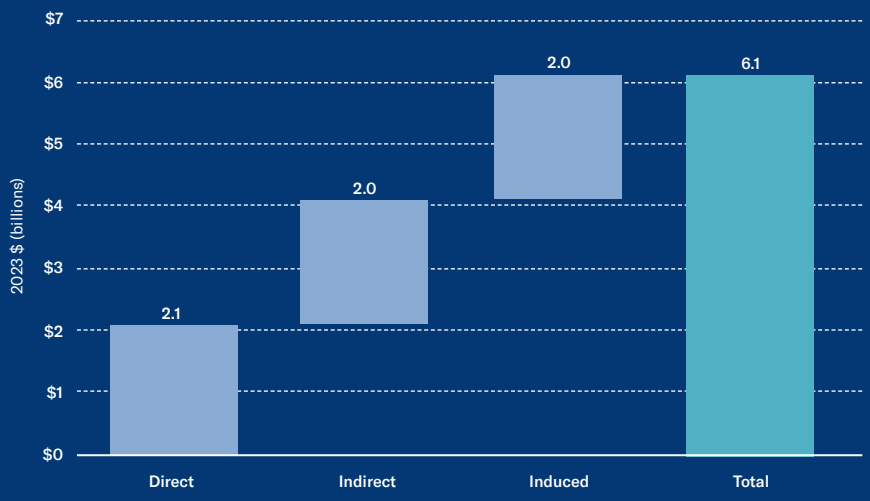
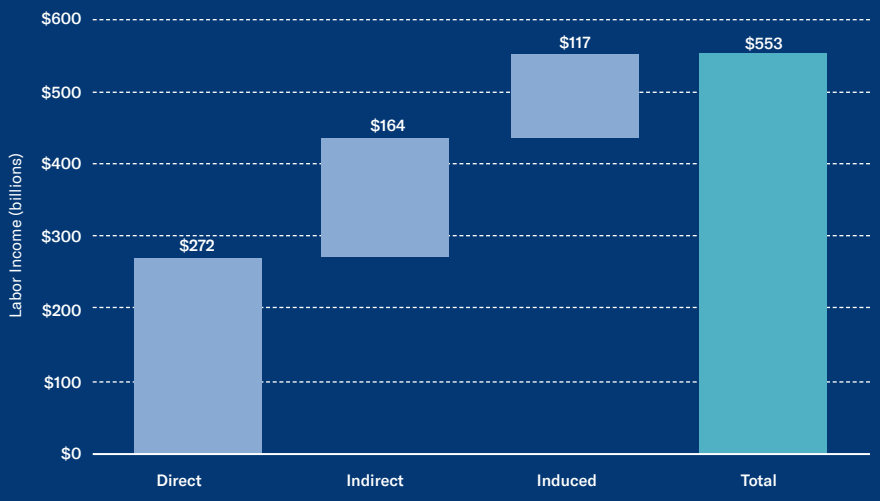


Figure 6 – Labor Income Impacts of Selected Sectors Dependent on Fluorochemistries



Employment and Labor Income Impacts

The selected sectors dependent on essential fluorochemistries support 6.1 million U.S. jobs as seen in Figure 5. Direct employment amounted to 2.1 million jobs, with 2 million jobs each being attributed to both indirect and induced employment.

Figure 6 summarizes the labor income impacts of the selected sectors dependent on essential fluorochemistries. Total labor income impacts are over $550 billion, with direct, indirect, and induced impacts totaling $272, $164, and $117 billion, respectively. The $272 billion in direct labor income is directly associated with the 2.1 million direct jobs across the selected sectors and equates to an average annual salary of $129,500.[62] This amount is close to double the median household income in the U.S. in 2022, indicating that workers in the selected sectors are typically earning well above the average wage for U.S. workers.[63]

[62] 272,000,000,000/2,100,000 = 129,500 rounding to the nearest hundred

[63] https://fred.stlouisfed.org/series/MEHOINUSA646N

Employment impacts are usually proportional to economic output and GDP because higher levels of economic activity generate increased demand for goods and services, leading to more employment opportunities to meet this demand. The state-level employment and labor income impacts of the selected sectors dependent on essential fluorochemistries summarized in Figure 7 and Figure 8 demonstrate that the employment and labor income impacts align with the trends of output and GDP impacts. Comparing labor income and employment reveals slight geographic variations in job distribution and labor income. These differences reflect wage disparities across various states.

Figure 7—Total Employment Impact for States of Selected Sectors Dependent on Fluorochemistries

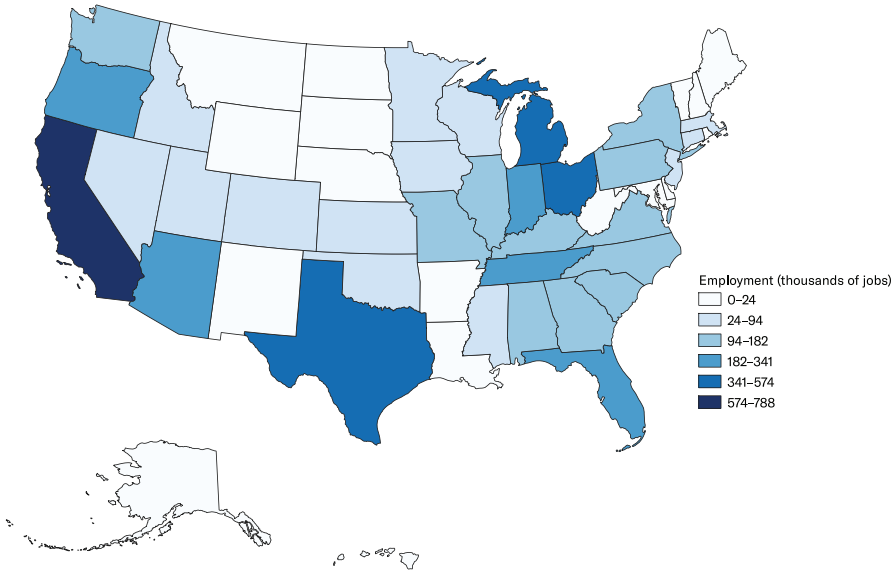
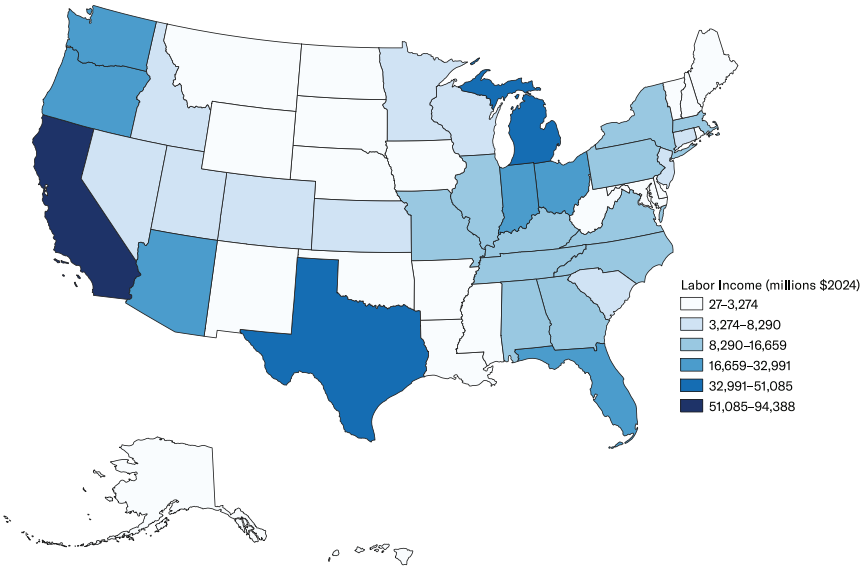


Figure 8—Total Labor Income Impact for States of Selected Sectors Dependent on Fluorochemistries



Federal, State, and Local Tax Revenue Impacts

Figure 9 summarizes the contribution of the selected sectors dependent on essential fluorochemistries to federal, state, and local tax revenues. The total impact on federal tax revenue is $140 billion, with direct, indirect, and induced impacts contributing $67 billion, $44 billion, and $30 billion, respectively.

Figure 9 – Federal, State, and Local Impacts of Selected Sectors Dependent on Fluorochemistries

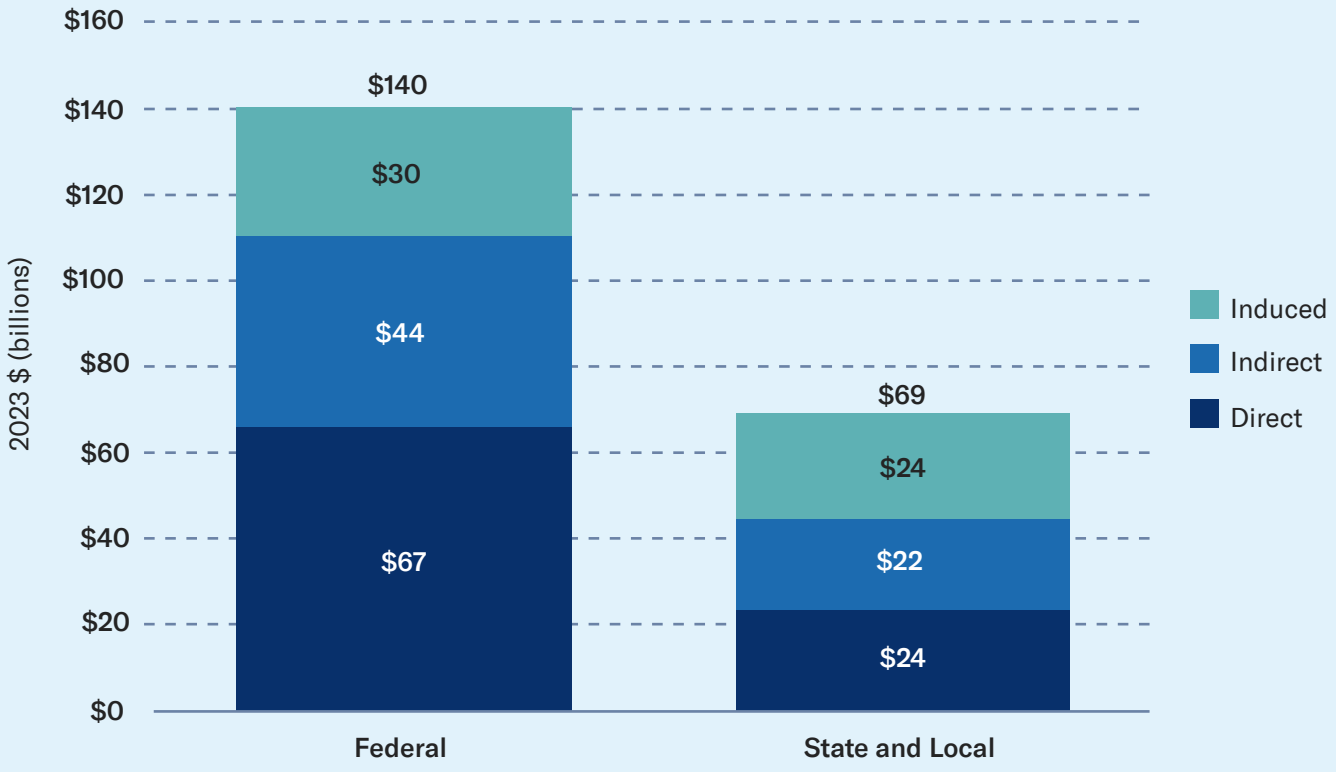


Figure 10 and Figure 11 show the distribution of tax revenues at the state level. These impacts generally follow the same distribution as the previous results. The economic activity of the sectors dependent on essential fluorochemistries generates taxable income and consumption, leading to greater tax collections. Also, state and local tax collection distributions depend on regional tax priorities. This connection is particularly evident in the Northeast, where higher state and local tax rates contribute to increased state and local tax revenue relative to output.

Figure 10—Total Federal Taxes Impact for States of Selected Sectors Dependent on Fluorochemistries

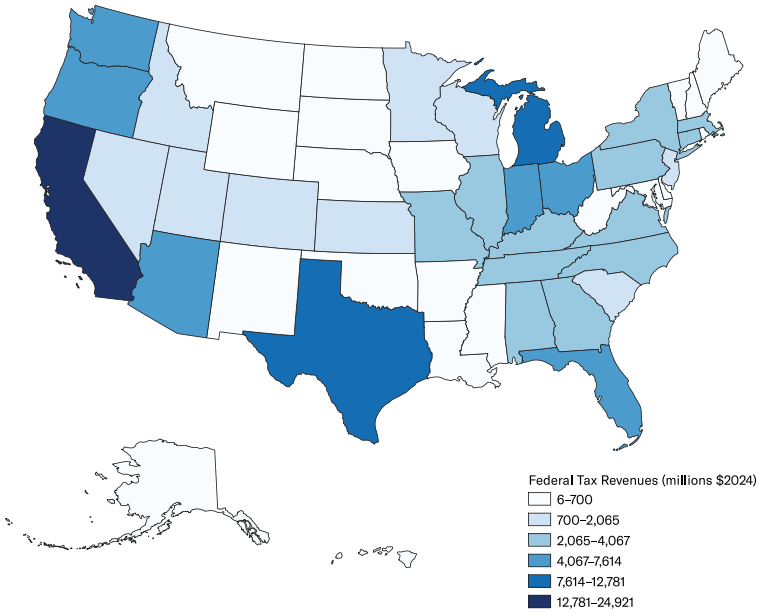
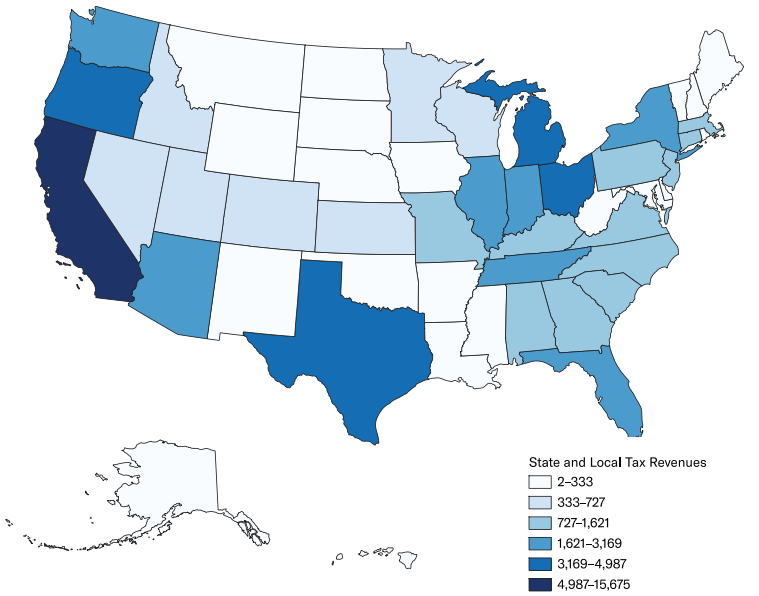


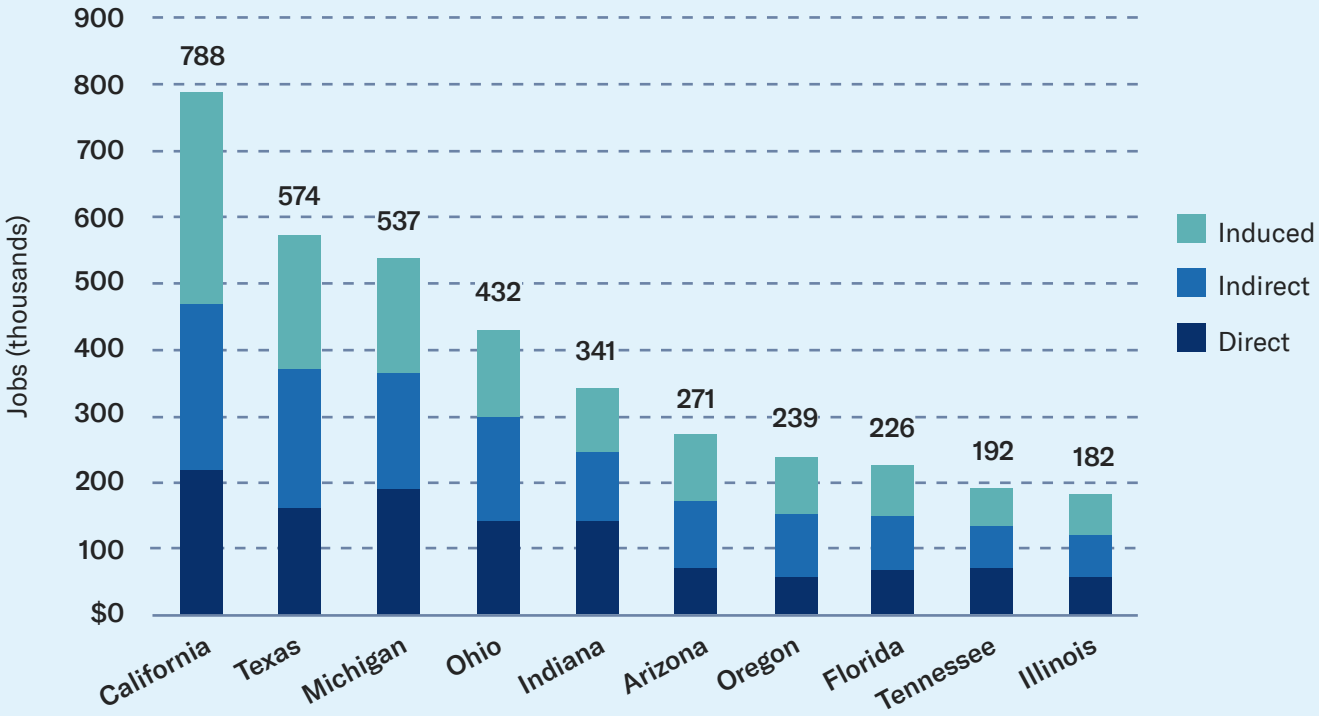
Figure 11—Total State and Local Taxes for States of Selected Sectors Dependent on Fluorochemistries



State and Sector-Specific Results

Figure 12 displays the states with the highest employment across the seven sectors that are dependent on essential fluorochemistries—aerospace manufacturing, data centers, defense equipment and systems, energy transition, health care, mobility, and semiconductors. Noticeably, California, Texas, and Michigan, which are hubs for the semiconductor, data centers, and mobility sectors, respectively, have the most jobs dependent on fluorochemistries.

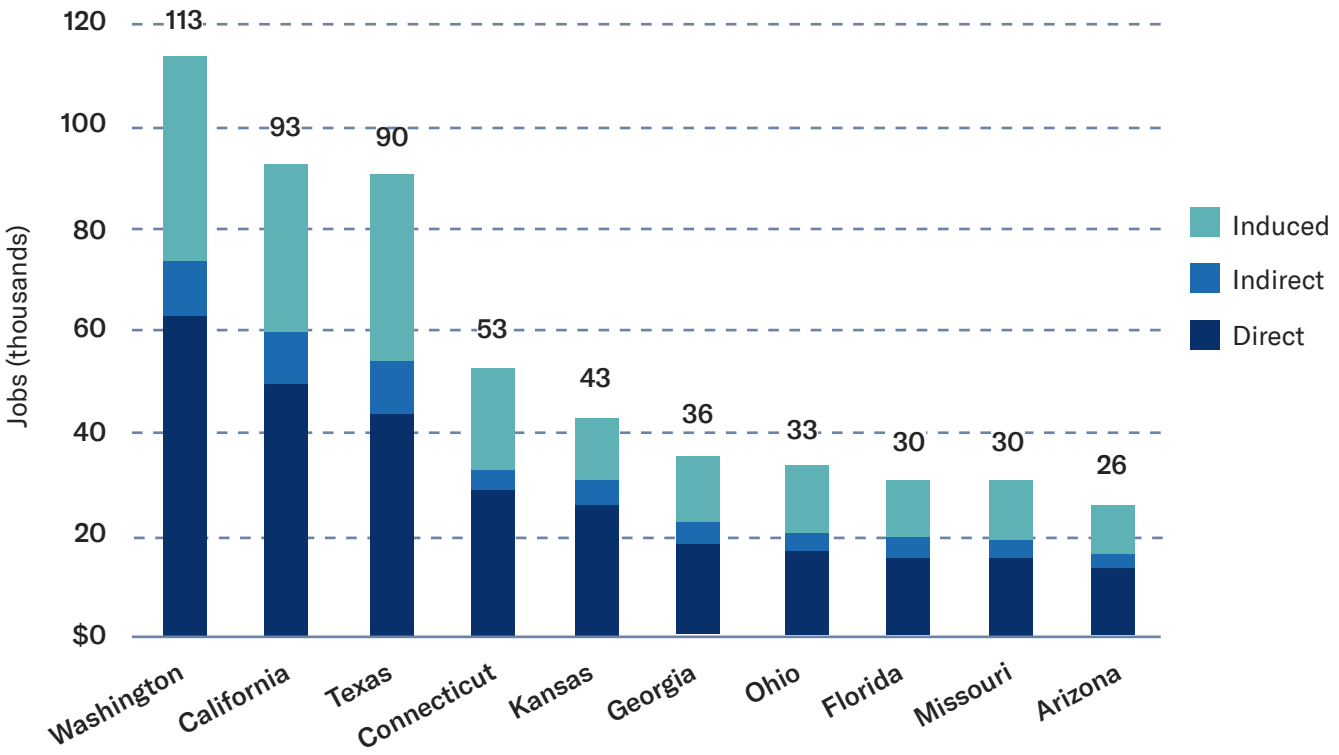
Figure 12—Top 10 States With Employment Dependent on Fluorochemistries



Aerospace Manufacturing

When comparing the top 10 states for aerospace manufacturing in terms of employment, notable states include Washington, California, and Texas as shown in Figure 13.[64] Washington's aerospace-related supply chain is the largest in the U.S., having produced over 33,000 commercial and military aircraft over the last 100 years.[65] California also boasts a strong aerospace sector, along with Texas, which is the biggest recipient of defense spending in the U.S. due to the production of the F-35 Joint Strike Fighter aircraft.[66,67,68]

Figure 13—Top 10 States With Employment in Aerospace Manufacturing Dependent on Fluorochemistries



[64] The IMPLAN model does not differentiate between civilian and military aircraft manufacturing. As such, all aircraft manufacturing is included in the Aerospace Manufacturing results.

[65] https://choosewashingtonstate.com/why-washington/our-key-sectors/aerospace/

[66] https://teamca.org/aerospace/

[67] https://gov.texas.gov/uploads/files/business/TexasAerospaceReport.pdf

[68] https://www.f35.com/f35/about/economic-impact.html

Figure 14—Total GDP Supported by the Aerospace Manufacturing Sector Dependent on Fluorochemistries

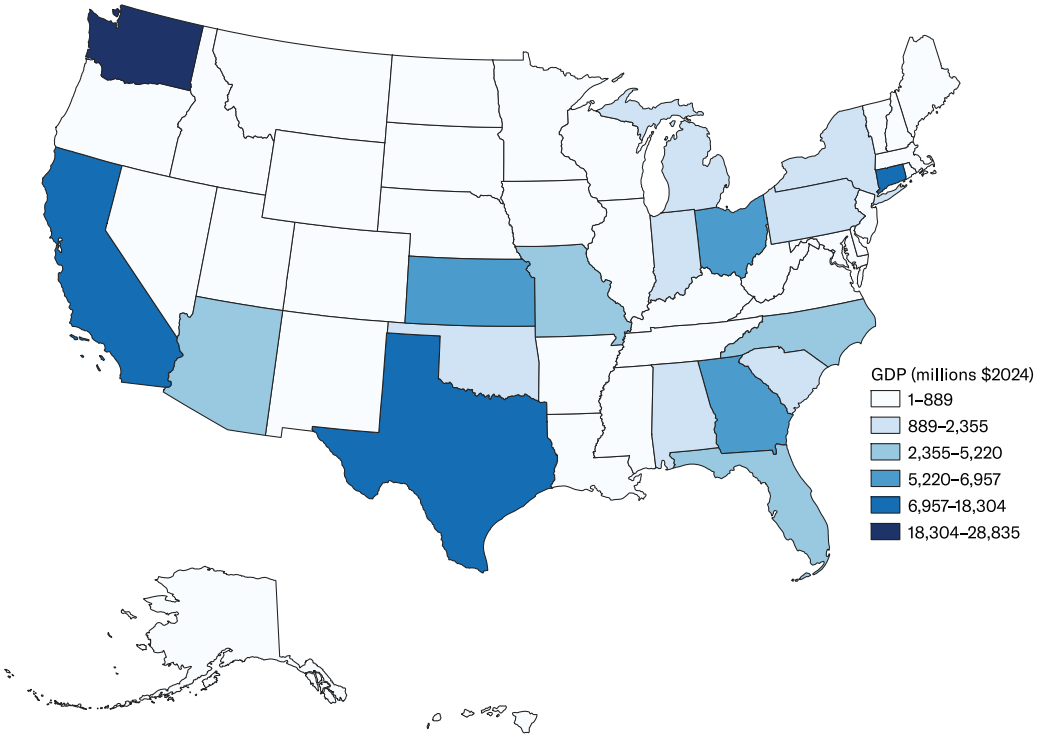


Figure 14 illustrates that the value creation from aerospace manufacturing dependent on essential fluorochemistries is highly concentrated in Washington, California, Texas, and Connecticut. Each state boasts economic strengths as Washington, California, and Texas have an array of aerospace manufacturers. Moreover, Connecticut is known as a leading player in manufacturing aircraft engine parts and hosts Aerospace Alley, which is an industrial hub with many advanced manufacturing companies.[69]

[69] https://www.advancect.org/our-economy/key-industries/aerospace-and-defense/

Data Centers

As shown in Figure 15, Virginia, Texas, and California are the top three states with the highest data center employment. Virginia is the most affected because it hosts one of the largest data center markets globally due to its availability of extensive fiber connectivity, tax incentives, and affordable power sources.[70,71] Dallas-Fort Worth in Texas and Silicon Valley in California are among the largest data center hubs in the U.S., boasting extensive inventories to meet high demand for data processing and storage.[72]

Figure 16 shows that data centers contribute the greatest amount of GDP in Virginia, California, Texas, and Ohio. Key economic clusters include California, which is home to Silicon Valley, and Virginia, which is known for its advanced technological infrastructure.

Figure 15—Top 10 States With Employment in the Data Centers Sector Dependent on Fluorochemistries

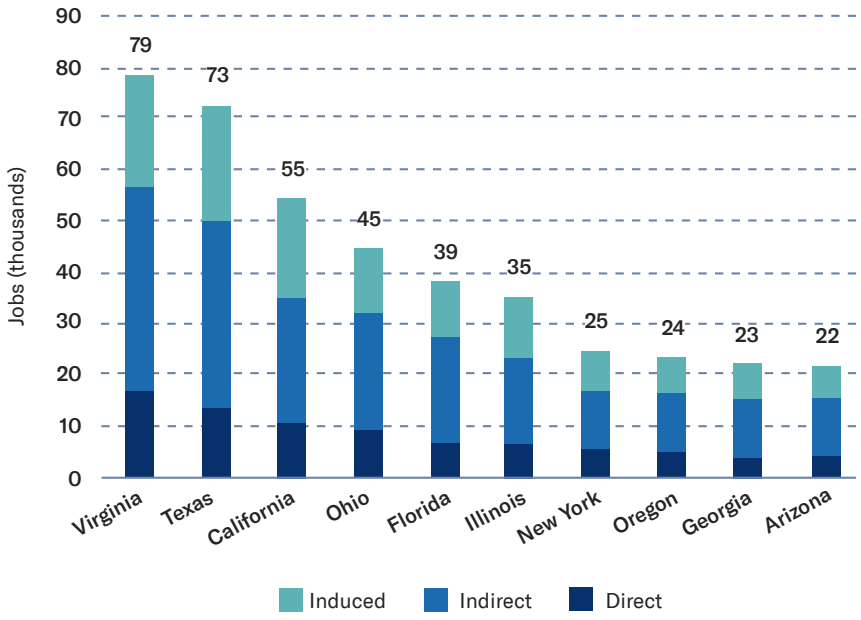
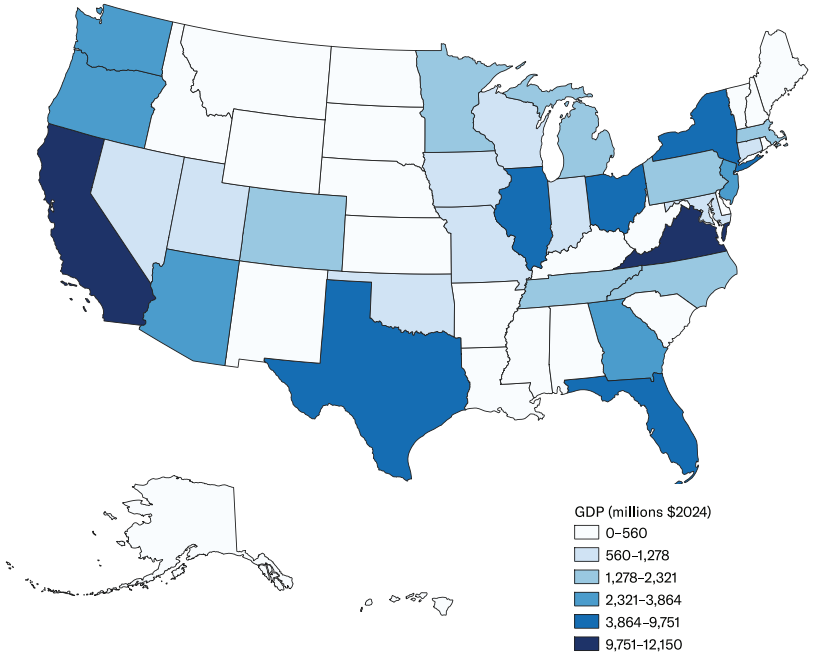


Figure 16—Total GDP Supported by the Data Centers Sector Dependent on Fluorochemistries



[70] https://www.datacenterdynamics.com/en/news/northern-virginia-tops-data-center-location-list-dominated-by-the-us/

[71] https://www.vedp.org/industry/data-centers

[72] https://www.cbre.com/insights/reports/global-data-center-trends-2024f

Defense

Fluorochemistries are a crucial component of the defense sector's supply chain. Any disruption in their availability could have significant impacts, jeopardizing jobs in California, Arizona, and across the U.S.

Other key states include those that are home to critical defense infrastructure, such as Colorado and Florida. The top 10 states for employment supported by the defense sector are displayed in Figure 17.

Figure 17—Top 10 States With Employment in the Defense Sector Dependent on Fluorochemistries

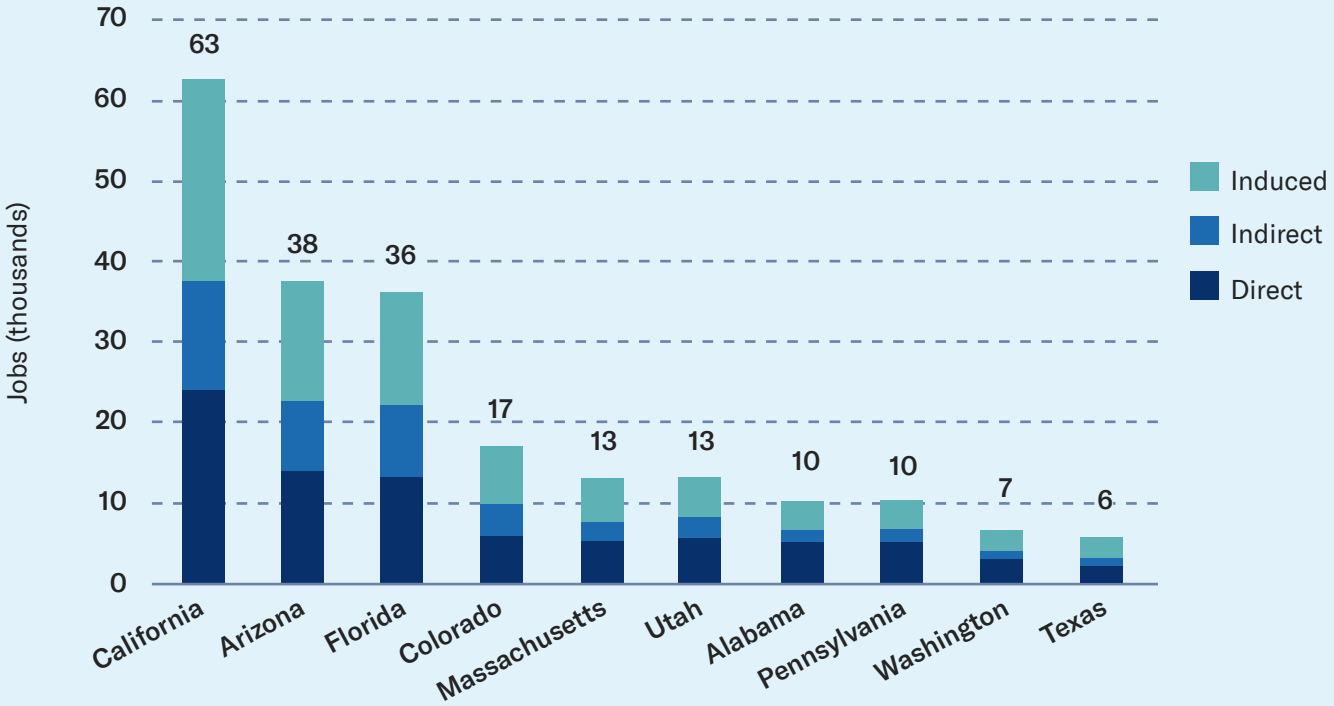


Figure 18—Total GDP Supported by the Defense Sector Dependent on Fluorochemistries

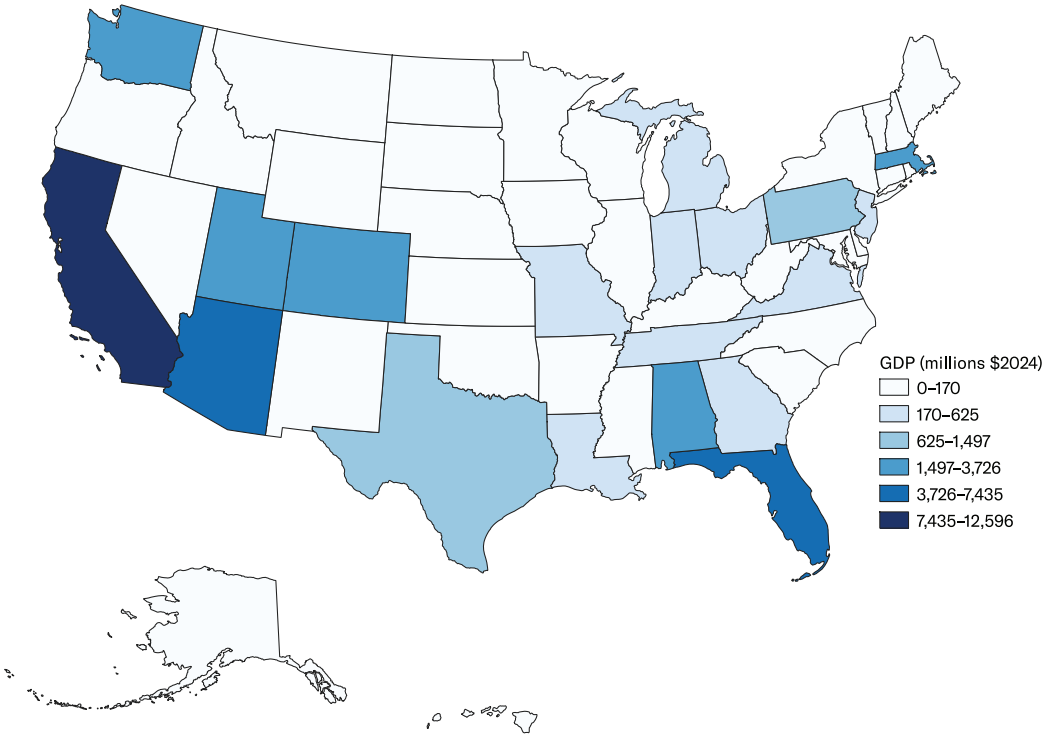


Figure 18 displays the GDP generated by the defense sector, highlighting that significant value is created in California, Florida, and Arizona. California, which ranks first in total defense contract expenditures, demonstrates its significant impact on national security in key industries like guided missile and electronics manufacturing.[73,74] Similarly, Florida ranks fifth nationally in defense contract expenditure and is the second largest producer of space and defense systems manufacturing in the U.S.[75,76] Additionally, Arizona is at the forefront of guided missile and space vehicle manufacturing, along with optics and photonics manufacturing.[77]

[73] https://business.ca.gov/industries/aerospace-and-defense/

[74] https://militarycouncil.ca.gov/wp-content/uploads/sites/81/2024/06/2023_California_Statewide_MEIS.pdf

[75] https://www.floridajobs.org/docs/default-source/communicationsfiles/2023-florida-manufacturing-report.pdf

[76] https://www.poweringflorida.com/explore-industries/aerospace-defense.html

[77] https://www.azcommerce.com/industries/aerospace-defense/

Energy Transition

Jobs supported by the production of energy transition components like solar panels and lithium-ion batteries are concentrated in Ohio, Georgia, and Nevada. These 3 states account for more than half of the jobs in the top 10 states, with a combined total of 108,700 positions, as illustrated in Figure 19. Employment in Ohio will be particularly affected by these changes, where approximately 24% of clean energy jobs are in manufacturing.[78]

The value created in the energy transition sector from supply chains dependent on essential fluorochemistries is shown in Figure 20, where Ohio, Georgia, Nevada, and Texas are leading contributors. There are multiple wind tower manufacturers in Texas, while Ohio and Georgia have large solar manufacturers. In addition, Nevada, Ohio, and Georgia all have significant battery manufacturing capacity.

Figure 19—Top 10 States With Employment in the Energy Transition Sector Dependent on Fluorochemistries

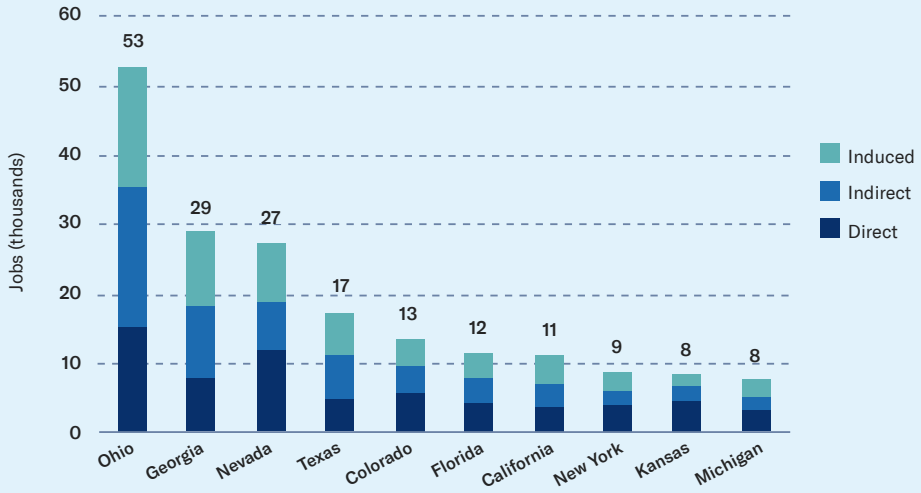
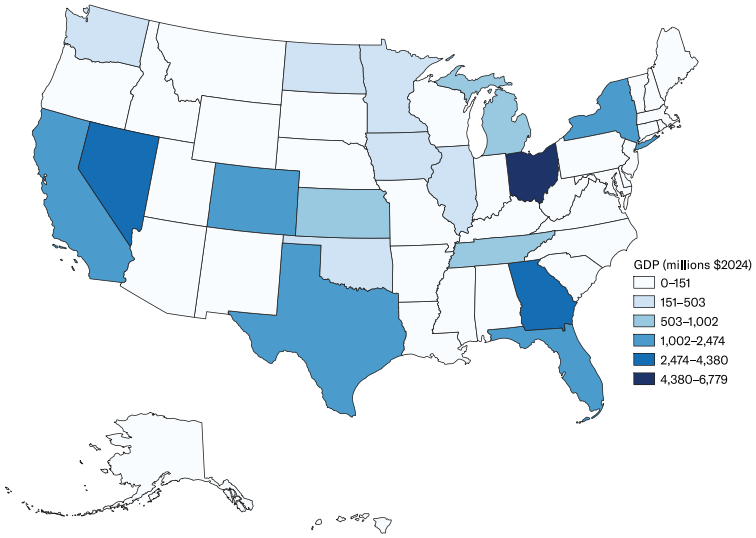


Figure 20—Total GDP Supported by the Energy Transition Sector Dependent on Fluorochemistries



[78] https://www.cleanjobsmidwest.com/state/ohio

Health Care

The health care sector utilizes fluorochemistries in manufacturing, particularly in states like California, New Jersey, and Illinois. As shown in Figure 21, the portion of the health care manufacturing sector reliant on fluorochemistries supports 243,600 in the top 10 states.

Figure 22 displays the distribution of GDP created by the share of the health care sector that is dependent upon fluorochemistries, with noticeable economic clusters in the Northeast, South, and Midwest. California, New Jersey, Illinois, Indiana, and Texas have the highest amount of GDP creation due to their robust medical device manufacturing sectors.

Figure 21—Top 10 States With Employment in the Health Care Sector Dependent on Fluorochemistries

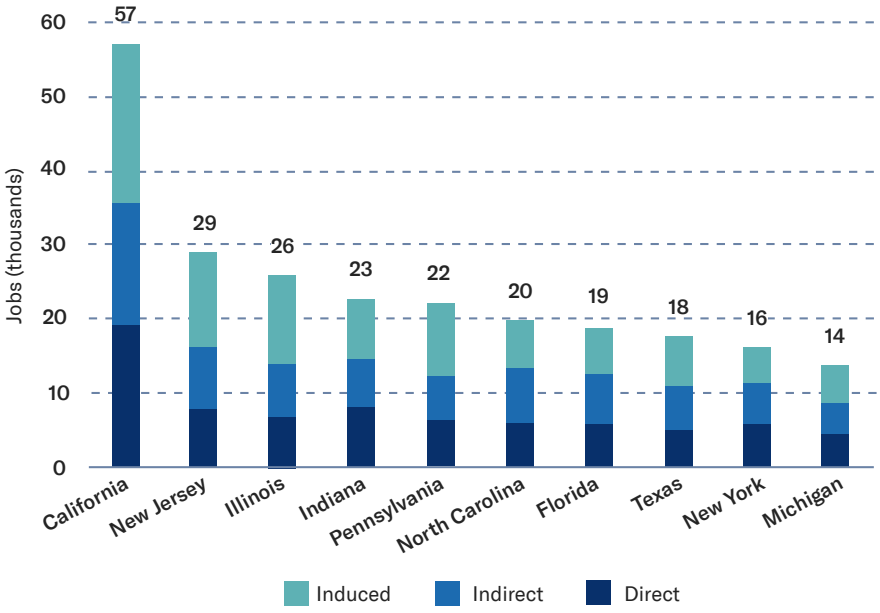
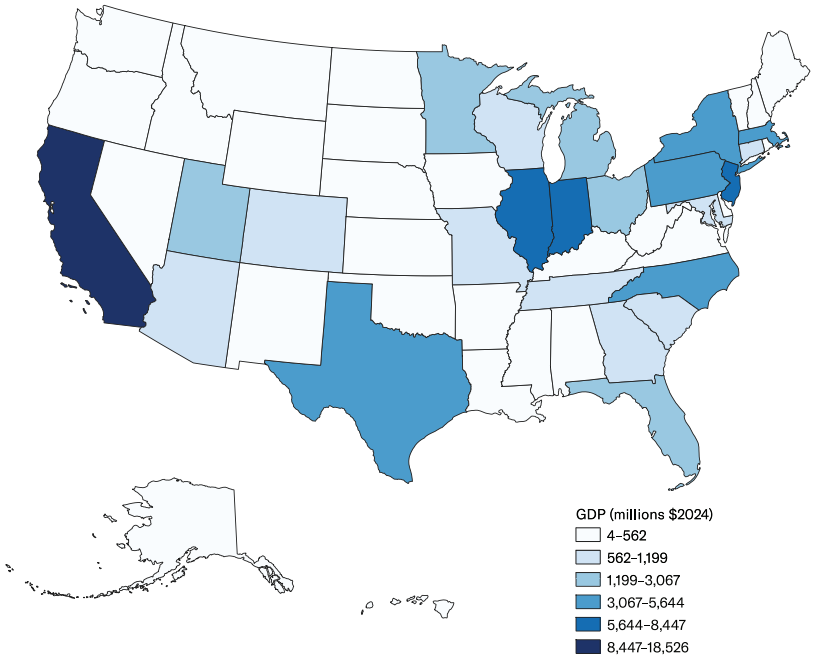


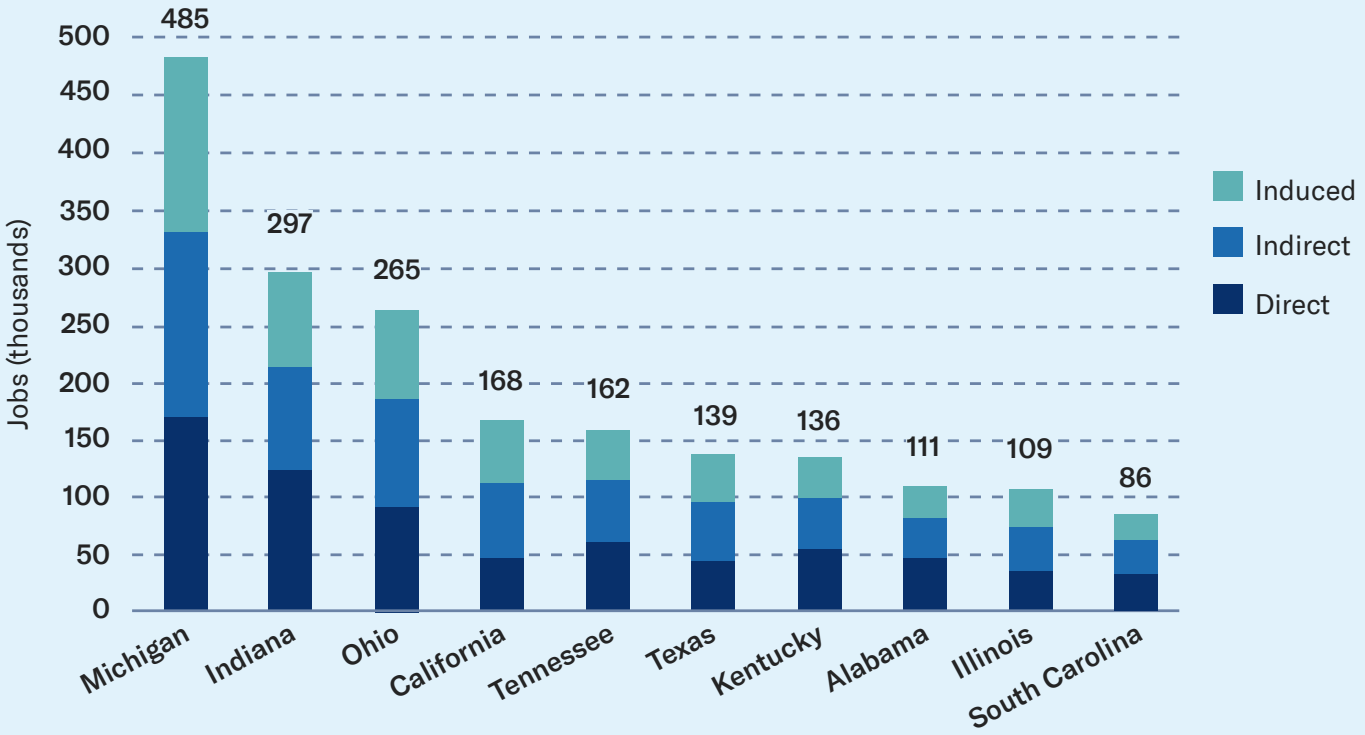
Figure 22—Total GDP Supported by the Health Care Sector Dependent on Fluorochemistries



Mobility

The mobility sector, which is heavily dependent on essential fluorochemistries, supports significant employment in Michigan, Indiana, and Ohio as seen in Figure 23. These states form America's industrial heartland, with Michigan known as the epicenter of the U.S. automotive industry. Michigan accounts for approximately 19% of national production and boasts the largest employment numbers in the sector, with around 484,600 jobs across the state dependent on fluorochemistries.[79]

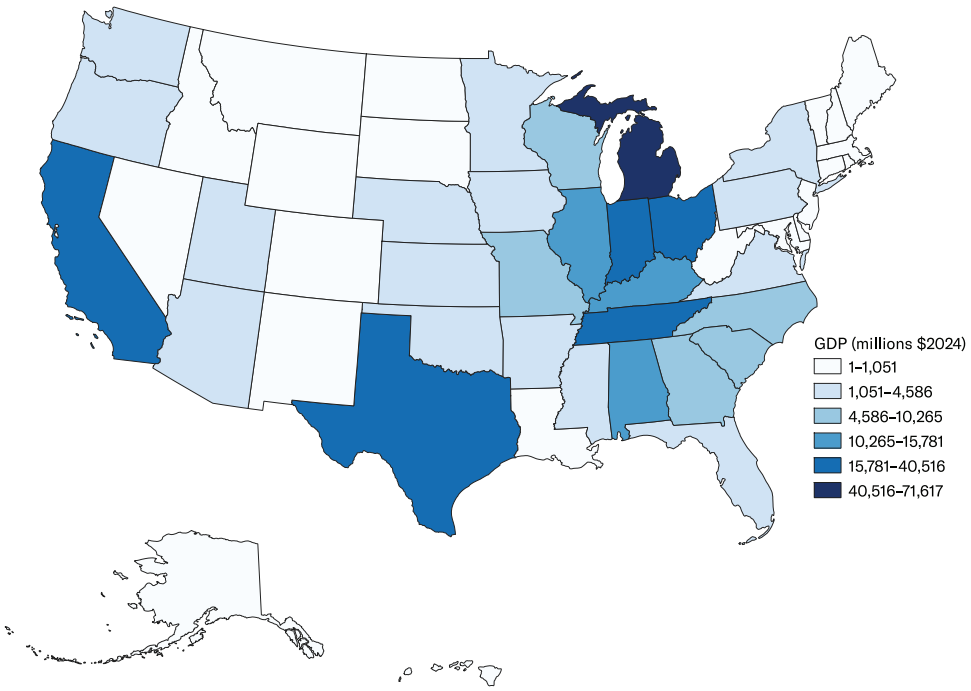
Figure 23—Top 10 States With Employment in the Mobility Sector Dependent on Fluorochemistries



[79] https://www.michiganbusiness.org/industries/mobility-and-automotive-manufacturing/

As illustrated in Figure 24, Michigan, Indiana, Ohio, and California generate the highest GDP from automotive manufacturing. Significant economic clusters include the Midwest and Southern states, such as Alabama, Georgia, and Kentucky, which reflects the recent growth and investment in automotive manufacturing in the region.[80]

Figure 24—Total GDP Supported by the Mobility Sector Dependent on Fluorochemistries



[80] https://siteselection.com/issues/2021/nov/it-s-everywhere.cfm

Semiconductors

As displayed in Figure 25, employment within the semiconductor sector is heavily concentrated in several key states, including California, Texas, and Oregon. Most notably, California, home to Silicon Valley, which hosts many technology giants, has the most jobs in this sector boasting more than 42,000 positions. These jobs are heavily dependent on essential fluorochemistries, making them vulnerable to disruptions in their availability. Texas also has significant employment in the sector due to the presence of specialized semiconductor companies.

Figure 26, shows that GDP in the semiconductor sector, which is highly dependent on fluorochemistries, is concentrated in key states such as California, Oregon, and Texas. California leads in both employment and GDP.

Figure 25—Top 10 States With Employment in the Semiconductor Sector Dependent on Fluorochemistries

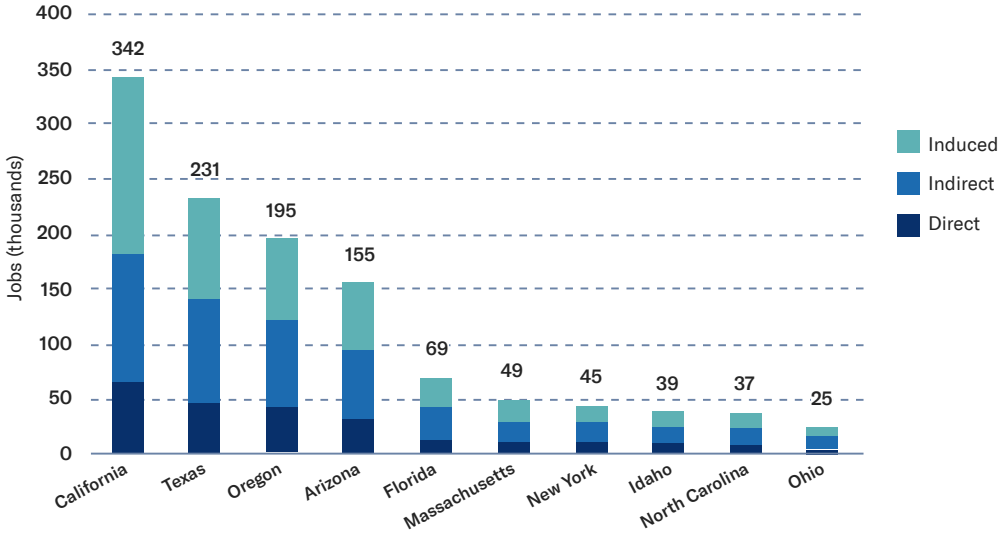
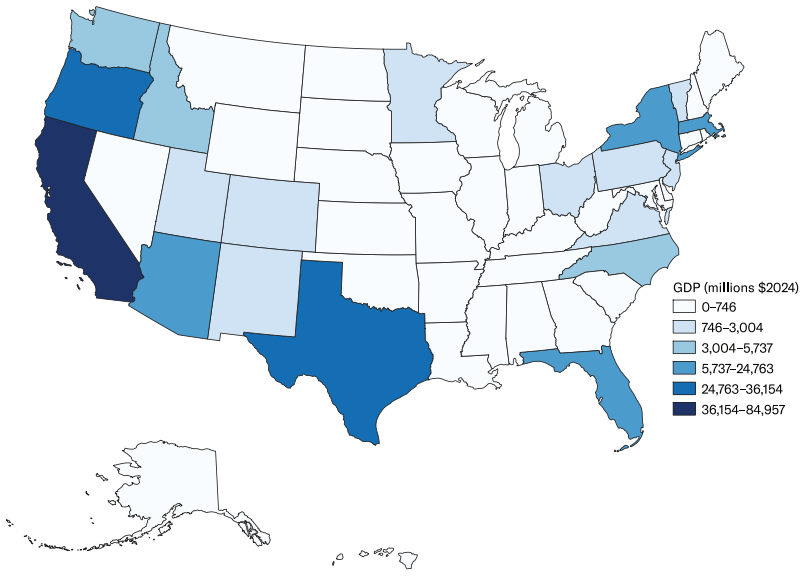


Figure 26—Total GDP Supported by the Semiconductor Sector Dependent on Fluorochemistries



Conclusions

The economic and fiscal impacts of the seven selected sectors reliant on essential fluorochemistries are significant to the U.S. economy. Each application of essential fluorochemistries addresses challenges that have no available and feasible replacement options. The key applications that are dependent upon these chemistries in each targeted sector include the following:

- In **aerospace manufacturing**, fluoropolymers are used to create hydraulic systems, wiring, and insulation materials, which enhances the durability of aircraft.
- F-gases are crucial to the operation of **data centers** because of air cooling, 2-PIC cooling, and fire suppression systems, which enable them to be efficient and safe.
- Essential fluorochemistries are integral to the manufacturing of guided missiles and tanks in the **defense** sector because they function well in extreme environments.
- In the **energy transition**, fluorochemistries support the development of renewable energy technologies, including solar panels, wind turbines, and lithium-ion batteries, by providing critical materials that improve efficiency and lifespan.
- Fluorochemistries in **health care** are vital to the production of medical devices, pharmaceuticals, diagnostic equipment, and product packaging, ensuring high standards of performance and safety.
- The **mobility** sector utilizes fluoropolymers to increase the lifespan and performance of mechanical components, such as air-conditioning systems, electronics, and electric vehicle batteries.
- **Semiconductors** use fluorochemistries as key components in the manufacturing process and are indispensable to the operation of modern semiconductor fabrication facilities.

Conclusions Cont.

The seven sectors chosen for analysis in this report highlight how crucial aspects of the U.S. economy rely on essential fluorochemistries. Collectively, essential fluorochemistries support nearly 4% of the U.S. GDP while upholding the jobs of over 6 million workers across these seven sectors. In addition, these chemistries support approximately $2.4 trillion in output, $988 billion in GDP, and $553 billion in labor income across the U.S. The share of these sectors dependent on essential

billion in federal tax revenues along with $69 billion in state and local tax revenues. Interrupting the use of essential fluorochemistries will impact all 50 U.S. states plus D.C. The states that will experience the most significant impacts from any sudden policy changes include California, Michigan, Texas, Ohio, and Indiana. These states are key hubs for the targeted industries, such as automotive manufacturing, defense, and health care for which fluorochemistries are indispensable

Appendix

Table 3—State-Level Impacts, All Seven Sectors

State	Output (million $2024)	Employment (thousand jobs)	GDP (millions $2024)	Labor Income (millions $2024)	Federal (millions $2024)	State and Local (millions $2024)
Alabama	64,266.1	140.8	17,785.9	10,475.0	2,494.4	1,168.2
Alaska	140.4	0.5	40.5	27.1	5.9	2.1
Arizona	96,284.2	271.4	44,114.4	24,106.1	6,309.6	2,654.6
Arkansas	7,919.1	23.6	2,555.3	1,563.2	19.6	9.7
California	341,194.6	788.0	171,931.5	94,387.8	12,512.0	7,328.1
Colorado	25,272.6	74.4	11,983.2	6,938.4	331.9	146.3
Connecticut	29,918.5	70.5	16,941.1	8,289.9	48.9	26.2
Delaware	855.6	2.4	422.5	175.7	0.1	0.1
District of Columbia	1,093.0	2.6	566.3	348.5	0.6	0.3
Florida	70,735.9	226.3	30,794.9	18,159.5	1,569.5	622.1
Georgia	58,328.3	164.2	24,341.6	13,762.9	35.8	16.1
Hawaii	531.7	1.7	229.1	130.3	30.5	18.8
Idaho	16,837.6	46.7	6,497.2	4,088.7	1,329.2	608.2
Illinois	76,957.6	181.7	29,403.0	16,659.1	4,744.3	2,836.4
Indiana	146,964.7	340.8	51,491.8	27,002.6	6,863.6	3,300.6
Iowa	11,250.9	34.3	3,872.8	2,477.7	570.2	279.6
Kansas	27,566.5	72.3	10,441.7	5,983.8	1,442.3	655.4
Kentucky	69,502.9	148.5	17,468.4	11,169.1	2,715.2	1,547.2
Louisiana	3,134.9	9.7	1,144.8	705.2	152.6	76.9
Maine	4,684.2	13.7	1,921.7	1,099.8	4,325.5	2,791.0
Maryland	7,906.9	21.0	3,728.9	1,948.2	1,066.5	685.4
Massachusetts	36,874.5	93.6	18,782.6	11,045.9	3,681.3	1,651.4
Michigan	228,180.5	537.2	79,458.5	43,636.3	11,311.8	5,143.2
Minnesota	19,750.2	57.7	8,603.1	5,130.9	3,030.4	1,685.9
Mississippi	16,990.3	36.3	3,740.2	2,408.9	545.8	333.3
Missouri	50,590.7	119.8	17,519.4	10,126.3	2,378.3	1,081.1
Montana	980.4	3.4	319.4	218.3	52.7	23.6
Nebraska	8,202.7	21.3	3,048.0	1,583.7	982.3	447.9
Nevada	12,965.3	39.7	5,554.8	3,475.0	921.3	369.9
New Hampshire	4,074.6	11.6	1,742.0	1,172.8	279.9	122.1
New Jersey	27,449.4	67.5	14,031.9	7,869.4	2,064.7	1,423.7
New Mexico	6,861.1	17.9	2,525.3	1,479.8	251.0	251.0
New York	49,429.7	125.1	23,246.4	13,657.4	3,859.7	2,470.5

North Carolina	56,567.8	151.5	23,679.8	12,058.0	3,097.1	1,551.6
North Dakota	3,218.9	8.3	953.6	632.8	1,190.8	266.9
Ohio	155,706.2	431.7	53,221.2	32,990.7	8,854.6	4,755.4
Oklahoma	14,107.0	43.2	4,605.7	3,273.6	984.7	389.1
Oregon	88,973.6	238.7	42,497.2	23,686.5	8,043.4	4,575.7
Pennsylvania	41,702.7	115.9	18,015.6	10,681.9	5,704.6	2,858.7
Rhode Island	1,612.5	3.8	718.9	342.3	92.2	56.2
South Carolina	48,774.5	108.3	13,507.9	7,877.2	1,953.3	1,142.8
South Dakota	4,351.1	13.4	1,414.1	934.7	219.1	72.3
Tennessee	82,944.5	191.9	26,884.1	15,360.1	4,257.1	2,078.4
Texas	216,927.9	574.5	95,444.2	51,085.1	16,536.6	5,950.6
Utah	20,088.9	63.4	8,321.3	4,978.8	1,225.8	567.1
Vermont	5,242.3	14.5	1,968.8	1,275.8	549.4	342.6
Virginia	43,742.0	126.8	19,338.4	10,650.9	2,708.6	1,309.3
Washington	75,854.3	170.0	40,743.0	20,129.4	7,339.9	2,727.8
West Virginia	5,037.6	13.0	1,844.7	1,023.7	234.3	115.0
Wisconsin	24,062.8	62.3	8,434.9	4,658.6	1,157.1	600.3
Wyoming	777.3	2.5	237.0	157.9	41.8	12.8

Table 4—State-Level Impacts, Aerospace Manufacturing Sector

State	Output (million $2024)	Employment (thousand jobs)	GDP (millions $2024)	Labor Income (millions $2024)	Federal (millions $2024)	State and Local (millions $2024)
Alabama	5,003.8	13.7	2,355.0	1,227.1	303.4	122.8
Alaska	69.0	0.3	25.7	17.9	3.8	1.2
Arizona	9,603.2	26.2	5,084.4	2,543.0	668.3	240.2
Arkansas	1,800.7	5.4	778.4	393.7	99.2	39.2
California	31,380.9	92.6	15,369.6	10,008.5	2,472.2	1,414.2
Colorado	1,123.7	3.3	578.4	339.9	84.4	33.4
Connecticut	23,009.8	52.5	13,807.6	6,514.1	1,886.7	939.9
Delaware	223.1	0.6	113.8	55.4	13.3	8.8
District of Columbia	32.9	0.1	13.0	12.7	1.8	0.3
Florida	9,850.7	30.4	4,409.0	2,636.6	712.7	230.4
Georgia	13,681.8	35.7	6,810.9	3,429.4	866.5	350.8
Hawaii	2.4	0.0	1.1	0.6	0.1	0.1
Idaho	344.2	1.1	111.4	77.4	18.6	7.7
Illinois	1,950.4	6.1	818.2	547.7	127.3	61.4
Indiana	4,081.0	9.6	2,241.1	956.1	250.2	89.6

Iowa	504.3	1.9	222.6	156.5	35.1	13.4
Kansas	15,743.6	42.7	6,956.9	3,821.4	935.1	401.2
Kentucky	1,317.2	4.1	538.4	340.2	75.3	35.6
Louisiana	699.9	2.0	295.2	185.1	39.6	19.1
Maine	1,106.7	3.1	489.7	260.8	65.0	40.6
Maryland	1,784.0	4.3	888.6	424.6	111.9	58.1
Massachusetts	2,031.5	6.0	829.9	695.0	164.4	69.2
Michigan	2,743.4	7.8	1,238.2	670.7	168.1	60.8
Minnesota	932.6	2.6	431.3	218.2	55.3	27.8
Mississippi	464.6	1.4	203.4	114.8	27.1	14.6
Missouri	11,018.1	30.3	5,219.6	3,141.6	728.3	281.2
Montana	145.0	0.6	57.1	44.8	10.5	4.2
Nebraska	216.1	0.7	78.3	52.7	11.9	5.1
Nevada	211.6	0.7	90.0	48.0	13.3	3.7
New Hampshire	645.2	1.9	241.1	162.8	38.0	14.8
New Jersey	854.6	2.4	413.7	237.2	61.7	34.2
New Mexico	183.1	0.5	86.3	45.5	11.2	4.1
New York	2,461.7	7.7	1,220.0	786.7	190.9	104.2
North Carolina	5,677.5	11.0	3,843.7	1,046.1	340.5	118.1
North Dakota	196.7	0.5	97.4	41.7	10.7	2.7
Ohio	12,123.7	33.1	6,300.1	3,270.7	798.0	312.5
Oklahoma	6,147.5	19.6	2,092.0	1,809.7	368.4	124.5
Oregon	1,606.2	5.6	732.8	518.5	120.5	77.8
Pennsylvania	4,880.3	14.8	2,099.0	1,502.8	345.2	139.9
Rhode Island	26.1	0.1	13.3	8.7	2.1	0.9
South Carolina	3,962.0	11.0	1,741.1	1,050.2	257.2	113.7
South Dakota	22.7	0.1	7.6	4.1	1.0	0.2
Tennessee	648.2	2.3	301.6	194.0	44.7	16.3
Texas	35,231.5	90.3	18,303.7	9,315.9	2,333.3	631.8
Utah	1,590.2	5.8	712.0	485.0	114.2	46.4
Vermont	607.6	2.1	225.2	179.7	39.5	20.0
Virginia	778.7	2.1	437.8	218.2	56.8	25.5
Washington	51,902.1	113.1	28,835.0	14,017.0	3,899.5	1,222.0
West Virginia	1,022.7	3.2	371.3	281.8	58.5	23.7
Wisconsin	828.8	2.4	331.6	207.1	49.6	20.7
Wyoming	36.4	0.1	7.2	3.0	0.9	0.3

Table 5—State-Level Impacts, Data Centers

State	Output (million $2024)	Employment (thousand jobs)	GDP (millions $2024)	Labor Income (millions $2024)	Federal (millions $2024)	State and Local (millions $2024)
Alabama	944.5	3.7	363.7	225.9	52.9	23.5
Alaska	-	-	-	-	-	-
Arizona	5,913.8	22.0	2,721.4	1,595.8	399.3	167.8
Arkansas	201.1	0.7	86.7	45.7	11.4	5.2
California	19,311.0	54.6	11,174.3	5,845.0	1,550.6	912.2
Colorado	4,083.7	13.4	2,069.4	1,167.9	295.6	119.5
Connecticut	1,364.4	4.4	678.5	410.1	111.2	52.3
Delaware	321.8	1.0	157.3	72.6	18.0	8.6
District of Columbia	976.0	2.4	505.3	311.3	55.2	22.5
Florida	10,196.9	38.9	4,730.7	2,706.1	742.2	253.7
Georgia	6,179.1	22.5	3,023.9	1,761.1	425.4	176.8
Hawaii	484.6	1.6	211.9	120.3	28.3	17.2
Idaho	351.8	1.3	147.3	82.9	21.0	9.5
Illinois	10,548.2	35.5	5,312.4	3,204.9	769.9	390.7
Indiana	2,600.6	9.7	1,079.2	662.1	151.6	75.3
Iowa	1,721.0	5.6	754.0	390.6	96.2	51.3
Kansas	977.4	3.3	426.2	236.2	57.6	24.0
Kentucky	1,374.7	5.2	560.1	349.1	77.5	38.5
Louisiana	860.8	3.3	331.5	193.1	42.5	20.6
Maine	297.5	1.1	122.8	76.1	18.1	9.5
Maryland	2,347.7	8.3	1,081.0	659.4	161.5	85.8
Massachusetts	3,784.4	11.5	1,983.4	1,195.3	309.1	118.6
Michigan	3,877.2	14.3	1,723.2	1,041.5	253.9	113.9
Minnesota	3,466.8	11.8	1,653.5	1,018.7	243.4	137.7
Mississippi	201.3	0.8	67.8	38.3	8.9	4.8
Missouri	2,718.9	9.3	1,277.8	741.1	174.9	68.8
Montana	215.5	0.8	79.1	47.8	11.9	4.6
Nebraska	1,123.6	3.5	545.6	251.8	64.7	28.0
Nevada	2,254.0	7.0	1,170.1	528.9	154.8	50.9
New Hampshire	510.3	1.7	243.2	153.3	36.7	12.6
New Jersey	5,074.2	15.9	2,645.9	1,532.1	398.9	210.4
New Mexico	615.0	2.0	258.4	128.8	32.4	19.1
New York	9,058.1	24.9	5,154.6	2,805.6	723.4	415.6
North Carolina	4,703.5	17.4	2,142.7	1,265.7	307.6	133.6
North Dakota	125.3	0.4	46.5	27.5	6.3	1.7

Ohio	11,985.4	45.0	5,206.4	3,121.1	724.8	382.7
Oklahoma	1,775.2	6.9	644.1	398.0	88.0	41.2
Oregon	7,480.7	23.8	3,863.5	2,033.3	520.0	265.2
Pennsylvania	4,955.9	17.4	2,320.7	1,425.7	340.6	161.2
Rhode Island	352.6	1.2	159.3	98.4	24.4	11.0
South Carolina	1,155.9	4.6	466.7	293.2	70.7	31.8
South Dakota	194.3	0.6	78.1	43.6	10.5	4.5
Tennessee	3,591.1	12.4	1,733.1	984.9	236.7	123.2
Texas	20,407.2	72.8	9,750.7	5,713.1	1,375.0	644.5
Utah	2,199.3	7.6	1,031.0	550.4	139.9	61.5
Vermont	209.4	0.7	88.6	52.8	12.5	6.4
Virginia	24,169.2	78.7	12,149.8	6,713.6	1,703.3	722.0
Washington	5,560.4	13.4	3,342.0	1,503.4	434.0	163.4
West Virginia	129.6	0.5	49.3	30.2	6.6	3.3
Wisconsin	2,476.7	8.4	1,155.0	631.2	157.6	77.3
Wyoming	557.1	1.9	185.1	126.0	33.2	9.3

Table 6—State-Level Impacts, Defense Sector

State	Output (million $2024)	Employment (thousand jobs)	GDP (millions $2024)	Labor Income (millions $2024)	Federal (millions $2024)	State and Local (millions $2024)
Alabama	3,645.0	10.5	2,029.8	1,004.6	253.0	97.6
Alaska	2.3	0.0	0.6	0.4	0.1	0.0
Arizona	13,325.7	37.6	7,435.1	3,729.8	978.4	360.4
Arkansas	331.3	1.0	170.4	84.3	21.4	8.4
California	22,447.5	62.5	12,596.0	7,756.9	1,944.6	1,093.0
Colorado	6,398.0	17.1	3,725.8	1,980.4	506.6	191.3
Connecticut	51.7	0.1	30.8	12.7	3.8	2.1
Delaware	25.3	0.1	12.4	4.2	1.2	0.6
District of Columbia	0.4	0.0	0.2	0.2	0.0	0.0
Florida	11,206.6	36.2	5,726.5	3,451.1	930.8	288.7
Georgia	435.4	1.5	229.2	128.2	31.1	13.1
Hawaii	5.6	0.0	2.8	1.5	0.4	0.2
Idaho	9.4	0.0	3.4	2.0	0.5	0.3
Illinois	145.3	0.5	78.7	51.5	11.8	5.8
Indiana	370.9	1.2	191.6	99.0	24.1	10.3
Iowa	126.7	0.4	56.6	38.8	8.6	3.8
Kansas	47.8	0.1	23.5	13.1	3.2	1.3

Kentucky	237.5	0.8	107.4	68.9	15.2	7.2
Louisiana	432.9	1.2	215.8	114.9	26.2	11.7
Maine	202.2	0.8	102.1	63.2	15.0	8.3
Maryland	311.0	0.8	168.1	87.8	22.4	11.5
Massachusetts	4,190.5	13.4	2,165.8	1,729.3	413.3	161.7
Michigan	1,212.2	4.0	625.5	364.7	89.6	32.7
Minnesota	293.8	0.9	152.7	79.2	19.8	10.5
Mississippi	185.3	0.6	83.9	48.3	11.4	6.2
Missouri	903.8	2.5	472.1	251.7	60.8	22.9
Montana	10.0	0.0	3.6	2.2	0.5	0.3
Nebraska	27.3	0.1	16.3	5.9	1.6	0.7
Nevada	128.8	0.4	61.7	32.2	8.9	2.7
New Hampshire	154.4	0.5	72.9	55.4	12.5	4.8
New Jersey	477.6	1.3	268.1	154.9	40.0	22.1
New Mexico	223.5	0.6	118.2	64.4	15.7	5.4
New York	271.1	0.8	136.5	92.2	22.0	12.7
North Carolina	128.6	0.5	59.0	34.1	8.3	3.8
North Dakota	42.0	0.1	24.1	11.4	2.8	0.6
Ohio	738.8	2.0	347.5	161.9	41.2	19.2
Oklahoma	60.6	0.2	18.0	13.6	2.9	1.2
Oregon	64.5	0.2	28.6	17.6	4.2	2.4
Pennsylvania	3,234.9	9.8	1,496.5	985.6	232.7	97.0
Rhode Island	27.9	0.1	14.5	8.4	2.1	1.0
South Carolina	221.0	0.6	87.2	38.5	10.5	5.9
South Dakota	72.7	0.2	39.5	16.3	4.4	1.1
Tennessee	867.7	2.7	405.7	227.1	54.3	23.8
Texas	1,974.4	5.9	1,141.5	599.1	148.2	39.8
Utah	3,805.5	13.3	1,869.4	1,244.5	294.7	120.5
Vermont	10.1	0.0	4.1	2.4	0.6	0.3
Virginia	591.7	1.4	380.4	157.6	43.9	18.7
Washington	2,795.7	7.0	1,788.8	884.3	244.7	72.2
West Virginia	136.2	0.6	62.4	46.4	9.7	3.8
Wisconsin	174.0	0.5	70.6	36.6	9.3	4.6
Wyoming	24.0	0.1	7.1	3.0	0.9	0.2

Table 7—State-Level Impacts, Energy Transition Sector

State	Output (million $2024)	Employment (thousand jobs)	GDP (millions $2024)	Labor Income (millions $2024)	Federal (millions $2024)	State and Local (millions $2024)
Alabama	-	-	-	-	-	-
Alaska	-	-	-	-	-	-
Arizona	-	-	-	-	-	-
Arkansas	-	-	-	-	-	-
California	4,104.8	11.2	2,039.1	1,299.4	321.9	202.3
Colorado	3,987.5	13.3	1,527.4	1,075.8	253.9	104.1
Connecticut	-	-	-	-	-	-
Delaware	-	-	-	-	-	-
District of Columbia	-	-	-	-	-	-
Florida	3,345.5	11.5	1,361.7	923.6	243.3	86.7
Georgia	9,573.2	28.9	4,379.9	2,772.7	650.7	322.4
Hawaii	-	-	-	-	-	-
Idaho	-	-	-	-	-	-
Illinois	973.9	3.0	417.5	259.4	61.5	33.2
Indiana	131.1	0.4	53.6	32.6	7.5	3.8
Iowa	1,393.9	4.6	503.2	344.3	77.8	32.9
Kansas	2,448.4	8.5	767.1	539.7	122.4	54.5
Kentucky	-	-	-	-	-	-
Louisiana	-	-	-	-	-	-
Maine	-	-	-	-	-	-
Maryland	-	-	-	-	-	-
Massachusetts	-	-	-	-	-	-
Michigan	2,311.5	7.6	903.4	641.1	149.1	72.8
Minnesota	780.3	2.2	334.2	224.4	52.0	28.7
Mississippi	-	-	-	-	-	-
Missouri	-	-	-	-	-	-
Montana	-	-	-	-	-	-
Nebraska	-	-	-	-	-	-
Nevada	8,689.3	27.2	3,700.9	2,535.3	655.9	270.2
New Hampshire	-	-	-	-	-	-
New Jersey	-	-	-	-	-	-
New Mexico	-	-	-	-	-	-
New York	2,897.9	8.6	1,342.0	997.0	234.1	128.6
North Carolina	45.8	0.1	18.8	11.7	2.8	1.4
North Dakota	908.7	2.8	320.9	211.4	46.6	10.5

Ohio	16,948.8	52.6	6,779.2	4,326.0	982.8	515.8
Oklahoma	514.3	1.7	187.3	112.7	25.1	10.2
Oregon	-	-	-	-	-	-
Pennsylvania	-	-	-	-	-	-
Rhode Island	-	-	-	-	-	-
South Carolina	21.5	0.1	8.5	5.4	1.3	0.7
South Dakota	499.3	1.7	151.1	115.7	25.5	7.7
Tennessee	2,222.7	6.6	1,002.0	611.9	143.4	57.9
Texas	5,778.8	17.2	2,474.1	1,573.1	366.8	135.0
Utah	-	-	-	-	-	-
Vermont	-	-	-	-	-	-
Virginia	-	-	-	-	-	-
Washington	845.5	2.1	381.8	223.0	58.7	26.9
West Virginia	121.8	0.4	46.2	38.3	7.7	3.4
Wisconsin	-	-	-	-	-	-
Wyoming	-	–	–	-	-	-

Table 8—State-Level Impacts, Health Care Sector

State	Output (million $2024)	Employment (thousand jobs)	GDP (millions $2024)	Labor Income (millions $2024)	Federal (millions $2024)	State and Local (millions $2024)
Alabama	651.2	1.8	269.0	142.8	34.6	20.4
Alaska	16.2	0.1	3.7	2.5	0.5	0.2
Arizona	2,371.4	7.2	1,035.8	560.2	142.5	69.5
Arkansas	258.3	0.8	101.6	56.8	13.7	8.1
California	30,115.2	56.9	18,526.0	6,508.7	1,972.6	1,581.4
Colorado	2,640.2	7.2	1,198.6	625.4	160.6	79.0
Connecticut	1,942.2	4.6	1,163.5	520.3	151.6	102.0
Delaware	221.3	0.5	122.4	33.3	10.5	7.7
District of Columbia	71.7	0.1	41.4	20.5	4.0	4.2
Florida	6,768.7	18.9	3,067.2	1,490.1	420.5	206.8
Georgia	1,934.4	5.3	908.7	481.7	118.7	71.5
Hawaii	12.0	0.0	5.1	3.3	0.7	0.4
Idaho	114.9	0.3	40.1	24.1	6.0	3.6
Illinois	13,914.6	25.9	8,446.9	3,253.4	906.4	647.3
Indiana	12,538.8	22.8	7,356.4	2,306.4	685.5	355.8
Iowa	508.0	1.1	248.9	108.2	27.5	15.3
Kansas	952.6	2.1	408.3	210.1	50.3	38.4

Kentucky	770.7	1.7	372.8	148.3	38.8	27.1
Louisiana	250.3	0.7	97.8	47.7	11.2	6.9
Maine	696.5	1.8	308.3	162.1	40.3	38.5
Maryland	2,224.9	4.6	1,195.4	523.1	142.4	110.6
Massachusetts	6,263.7	11.3	3,988.8	1,423.8	433.3	251.5
Michigan	5,635.8	13.8	2,629.6	1,238.3	325.2	185.6
Minnesota	3,405.5	10.4	1,773.5	997.0	243.4	143.2
Mississippi	368.8	1.0	108.0	65.8	14.8	12.4
Missouri	2,074.3	4.8	944.9	415.0	106.3	65.5
Montana	119.6	0.4	37.6	23.6	5.7	2.9
Nebraska	986.9	2.5	561.6	212.3	57.5	27.4
Nevada	437.0	1.1	168.0	84.1	23.4	13.2
New Hampshire	449.3	1.4	206.8	139.3	32.1	18.2
New Jersey	14,119.8	29.0	7,960.8	4,177.2	1,099.5	854.4
New Mexico	398.1	1.0	120.3	62.9	15.2	9.2
New York	8,360.6	16.4	4,051.5	1,700.0	474.1	423.3
North Carolina	9,191.8	20.0	4,380.6	1,776.4	489.0	302.7
North Dakota	34.6	0.1	12.9	11.4	2.2	0.6
Ohio	3,569.6	8.9	1,707.5	759.4	193.4	131.8
Oklahoma	463.0	1.2	188.5	89.4	21.5	11.4
Oregon	537.9	1.5	211.1	127.1	30.7	23.5
Pennsylvania	10,160.9	22.2	5,644.2	2,597.9	670.4	384.3
Rhode Island	681.7	1.5	326.9	156.5	41.6	30.2
South Carolina	2,326.7	5.5	863.0	407.7	107.8	92.3
South Dakota	286.7	0.8	155.1	65.1	17.3	4.5
Tennessee	2,093.4	5.7	1,075.9	552.9	135.3	68.7
Texas	7,345.7	17.7	3,555.8	1,686.6	428.4	181.5
Utah	3,770.8	11.2	1,521.9	851.7	211.1	113.0
Vermont	171.9	0.5	60.4	39.7	9.1	7.9
Virginia	1,070.6	2.7	476.5	253.6	64.6	49.7
Washington	1,055.2	2.4	495.8	245.3	67.5	38.0
West Virginia	553.8	1.2	251.6	105.3	26.4	17.0
Wisconsin	1,674.5	4.7	706.1	379.5	94.5	62.9
Wyoming	21.2	0.0	6.6	2.4	0.8	0.9

Table 9—State-Level Impacts, Mobility Sector

State	Output (million $2024)	Employment (thousand jobs)	GDP (millions $2024)	Labor Income (millions $2024)	Federal (millions $2024)	State and Local (millions $2024)
Alabama	53,996.5	111.1	12,759.2	7,868.8	1,849.2	903.3
Alaska	45.3	0.1	7.7	4.5	1.0	0.6
Arizona	10,967.9	23.5	3,074.9	1,816.0	452.6	219.5
Arkansas	4,969.7	14.6	1,283.1	903.0	207.1	110.4
California	86,112.7	168.0	27,269.9	16,467.6	4,147.4	3,143.7
Colorado	2,094.6	6.0	734.4	463.3	113.1	53.1
Connecticut	2,930.6	7.2	980.8	667.6	175.3	94.6
Delaware	63.1	0.2	16.3	9.9	2.2	2.1
District of Columbia	2.3	0.0	0.7	0.5	0.1	0.1
Florida	7,441.0	21.4	2,309.2	1,450.0	388.1	172.7
Georgia	26,028.7	68.9	8,752.4	5,046.2	1,224.5	669.8
Hawaii	11.9	0.0	2.5	1.6	0.4	0.3
Idaho	1,857.8	5.4	526.8	356.7	86.0	42.2
Illinois	48,588.3	108.5	13,954.4	9,122.7	2,134.6	1,275.7
Indiana	127,116.3	296.9	40,515.8	22,912.7	5,446.8	2,630.4
Iowa	6,712.2	19.9	1,976.2	1,366.0	307.8	153.8
Kansas	7,184.7	15.0	1,778.3	1,117.0	262.0	130.2
Kentucky	65,519.9	136.0	15,780.9	10,193.4	2,245.0	1,299.8
Louisiana	846.4	2.4	191.9	157.3	31.4	17.5
Maine	834.0	2.4	251.6	167.0	39.0	26.0
Maryland	834.5	1.9	231.7	155.1	37.0	23.5
Massachusetts	1,063.9	2.4	300.2	216.0	52.8	26.3
Michigan	210,718.7	484.6	71,616.8	39,227.5	9,846.3	4,471.0
Minnesota	5,583.1	14.6	1,989.6	1,156.1	280.2	161.4
Mississippi	15,553.0	31.8	3,227.0	2,096.4	473.8	289.0
Missouri	31,992.5	67.3	8,859.4	5,131.7	1,200.6	585.2
Montana	418.5	1.3	116.9	84.1	20.0	9.7
Nebraska	5,696.9	14.2	1,778.6	1,021.3	242.6	118.3
Nevada	934.0	2.4	241.7	172.2	44.3	21.3
New Hampshire	715.8	1.8	252.0	153.3	37.1	17.2
New Jersey	1,908.5	5.0	579.2	442.4	107.1	72.5
New Mexico	80.2	0.2	21.4	11.8	2.9	1.7
New York	8,730.8	22.1	3,106.6	2,017.8	492.6	338.1
North Carolina	23,814.2	65.5	7,497.9	4,709.9	1,121.8	568.6
North Dakota	1,658.5	3.7	359.9	258.4	55.5	16.0

Ohio	102,421.8	265.1	29,876.4	19,438.5	4,418.7	2,489.0
Oklahoma	5,042.1	13.3	1,431.0	823.0	187.2	86.9
Oregon	4,700.0	12.6	1,507.5	908.5	221.7	128.0
Pennsylvania	14,205.2	39.5	4,585.6	3,010.1	706.5	391.6
Rhode Island	275.9	0.6	131.9	22.9	10.3	6.6
South Carolina	40,913.3	86.0	10,265.1	6,036.5	1,494.1	892.9
South Dakota	2,177.1	6.9	668.6	485.1	109.2	34.5
Tennessee	73,342.7	161.6	22,301.8	12,751.5	3,058.0	1,501.9
Texas	65,613.3	139.2	24,457.6	10,706.1	2,822.9	1,011.3
Utah	5,098.6	14.6	1,732.6	1,026.1	251.5	124.6
Vermont	332.1	0.8	84.9	59.6	13.5	9.2
Virginia	12,333.1	28.6	3,871.3	2,068.2	527.4	314.4
Washington	4,510.2	9.9	1,653.8	869.6	236.4	120.6
West Virginia	3,024.1	7.0	1,051.2	511.2	123.1	62.6
Wisconsin	18,700.3	45.6	6,096.7	3,358.0	834.5	428.7
Wyoming	138.5	0.4	31.0	23.5	6.0	2.1

Table 10— State-Level Impacts, Semiconductor Sector

State	Output (million $2024)	Employment (thousand jobs)	GDP (millions $2024)	Labor Income (millions $2024)	Federal (millions $2024)	State and Local (millions $2024)
Alabama	25.1	0.1	9.2	5.8	1.4	0.6
Alaska	7.5	0.0	2.9	1.8	0.4	0.1
Arizona	54,102.2	155.0	24,762.7	13,861.3	3,668.5	1,597.1
Arkansas	358.0	1.0	135.2	79.7	19.6	9.7
California	147,722.6	342.3	84,956.6	46,501.7	12,512.0	7,328.1
Colorado	4,944.8	14.1	2,149.3	1,285.7	331.9	146.3
Connecticut	619.8	1.7	279.8	165.2	48.9	26.2
Delaware	1.0	0.0	0.4	0.3	0.1	0.1
District of Columbia	9.7	0.0	5.8	3.3	0.6	0.3
Florida	21,926.5	68.9	9,190.5	5,501.9	1,569.5	622.1
Georgia	495.6	1.5	236.4	143.6	35.8	16.1
Hawaii	15.2	0.0	5.8	3.1	0.8	0.7
Idaho	14,159.6	38.6	5,668.1	3,545.7	1,197.0	544.9
Illinois	836.9	2.3	375.0	219.5	732.8	422.3
Indiana	126.0	0.3	54.2	33.6	297.9	135.4
Iowa	284.8	0.8	111.3	73.4	17.2	8.9
Kansas	212.1	0.6	81.4	46.2	11.6	5.8

Kentucky	282.9	0.8	108.8	69.2	263.5	139.1
Louisiana	44.6	0.1	12.5	7.0	1.7	1.1
Maine	1,547.4	4.5	647.2	370.7	4,148.1	2,668.2
Maryland	404.7	1.1	164.1	98.3	591.4	395.9
Massachusetts	19,540.5	49.1	9,514.5	5,786.6	2,308.5	1,024.1
Michigan	1,681.7	5.1	721.8	452.5	479.7	206.4
Minnesota	5,288.0	15.2	2,268.2	1,437.3	2,136.3	1,176.8
Mississippi	217.3	0.7	50.1	45.3	9.8	6.4
Missouri	1,883.1	5.5	745.6	445.4	107.4	57.4
Montana	71.9	0.2	25.0	15.8	4.1	2.0
Nebraska	151.9	0.4	67.6	39.8	603.8	268.4
Nevada	310.5	0.9	122.3	74.4	20.7	8.0
New Hampshire	1,599.7	4.3	726.0	508.6	123.4	54.6
New Jersey	5,014.6	13.7	2,164.2	1,325.5	357.6	230.0
New Mexico	5,361.1	13.6	1,920.7	1,166.4	490.6	211.4
New York	17,649.6	44.6	8,235.3	5,258.1	1,722.7	1,048.2
North Carolina	13,006.4	37.0	5,737.1	3,214.1	827.1	423.5
North Dakota	253.2	0.7	92.0	70.9	1,066.7	234.9
Ohio	7,918.1	24.9	3,004.1	1,913.1	1,695.6	904.3
Oklahoma	104.4	0.3	44.8	27.1	291.7	113.7
Oregon	74,584.3	195.0	36,153.8	20,081.5	7,146.4	4,078.9
Pennsylvania	4,265.6	12.3	1,869.6	1,159.8	3,409.2	1,684.6
Rhode Island	248.2	0.3	73.0	47.3	11.6	6.4
South Carolina	174.1	0.5	76.2	45.7	11.7	5.6
South Dakota	1,098.3	3.2	314.0	204.7	51.2	19.8
Tennessee	178.7	0.6	64.0	37.9	584.6	286.5
Texas	80,577.0	231.3	35,760.9	21,491.1	9,061.9	3,306.7
Utah	3,624.4	10.9	1,454.4	821.2	214.4	101.1
Vermont	3,911.1	10.3	1,505.6	941.7	474.2	298.8
Virginia	4,798.6	13.3	2,022.5	1,239.7	312.6	178.9
Washington	9,185.2	22.0	4,245.7	2,386.9	2,399.1	1,084.7
West Virginia	49.4	0.1	12.7	10.4	2.2	1.3
Wisconsin	208.4	0.6	74.8	46.1	11.6	6.1
Wyoming	-	-	-	-	-	-

U.S. Chamber of Commerce

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

INTERIM GUIDANCE FOR PUBLIC COMMENT
APRIL 8, 2024

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Addendum

Addendum
03/12/2025

Note that some of the tools listed on page 102 in Section 4.c.i "Identifying potentially vulnerable populations" are no longer available and they are not accessible through the web page hyperlinks in this guidance. Additionally, note that Executive Order (EO) 14096, "Revitalizing Our Nation's Commitment to Environmental Justice for All," referenced on page 101 in Section 4.c "Considering vulnerability" and page 106 in Section 4.c.iii "Considerations for community engagement" was rescinded on January 20, 2025, via EO 14148, "Initial Rescissions of Harmful Executive Orders and Actions."

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Abbreviations

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

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

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

Executive Summary

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

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

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

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

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

Key Findings and Updates

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

- **Underground Injection - Permitted Class I non-hazardous industrial or hazardous waste injection wells** are the waste management approach with a lower potential for environmental release when

compared to other destruction and disposal options. These wells may help ensure that injected fluids are confined and cannot enter underground sources of drinking water. However, the limited number of wells currently receiving off-site PFAS and waste transportation logistics may significantly limit the type and quantity of PFAS-containing fluids appropriate for underground injection.

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

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

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

EPA partnered with industry and academia to collect data on four emerging technologies for PFAS destruction: mechanochemical degradation, electrochemical oxidation, gasification and pyrolysis, and supercritical water oxidation. While the results from these studies show promise for PFAS destruction, further work using newly available methods is needed to more fully characterize the outputs of these processes and to evaluate their performance for a wider range of PFAS-containing materials. Managers of PFAS and PFAS-containing materials may consider these or other emerging technologies for PFAS disposal or destruction. To assist PFAS material managers with evaluating whether an emerging destruction (or disposal) technology is suitable for a particular PFAS-containing material, EPA developed

a technology evaluation framework. The framework provides a transparent, consistent approach for evaluating destruction and disposal technologies for PFAS and PFAS-containing material and includes considerations for communities. EPA recommends that managers of PFAS-containing materials use the technology evaluation framework to evaluate emerging destruction and disposal technologies and to inform their decisions about managing PFAS-containing materials. EPA also encourages technology developers to generate and publicly release data that can be used to complete the framework (see Section 6).

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

What's Next?

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

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

1. Introduction

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

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

The 2024 interim guidance contains the following new information:

Section 1: Introduction

- Updated review of PFAS destruction and disposal technologies.

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

- Additional details on spent water treatment materials.
- Updated information on biosolids generation and management.

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

- Additional information on thermal treatment and landfills.
- Additional information on testing and monitoring at thermal treatment facilities.

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

- Updated list of tools for vulnerability screening.

Section 5: Research Needs and Data Gaps for Destruction and Disposal Technologies

- Increased focus on research needs to inform future updates to this interim guidance.
- Updated information on ongoing research and development activities.

Section 6: Emerging Technologies for PFAS Destruction and Disposal (NEW)

- EPA efforts to identify, review, and test emerging technologies for PFAS destruction.
- Technology evaluation framework that utilizes a multiple-lines-of-evidence approach to evaluate a technology/PFAS material combination.

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

- EPA request to access commercial sources to conduct air emissions testing during PFAS thermal destruction.
- Guidance for facilities to conduct source testing prior to accepting/processing PFAS materials at full-scale thermal destruction facilities.

Appendix B: Summary of the Clean Harbors Test Data (NEW)

- Two source test campaigns conducted at a hazardous waste combustor.

Appendix C: Summary of the Chemours Thermal Oxidizer Test Data (NEW)

- Source test campaign conducted at a chemical manufacturer.

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

Appendix D: Summary of Costs and Considerations (NEW)

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

1.a Purpose and audience of this interim guidance

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

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

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

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

SEC. 7361. PFAS DESTRUCTION AND DISPOSAL GUIDANCE.

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

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

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

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

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

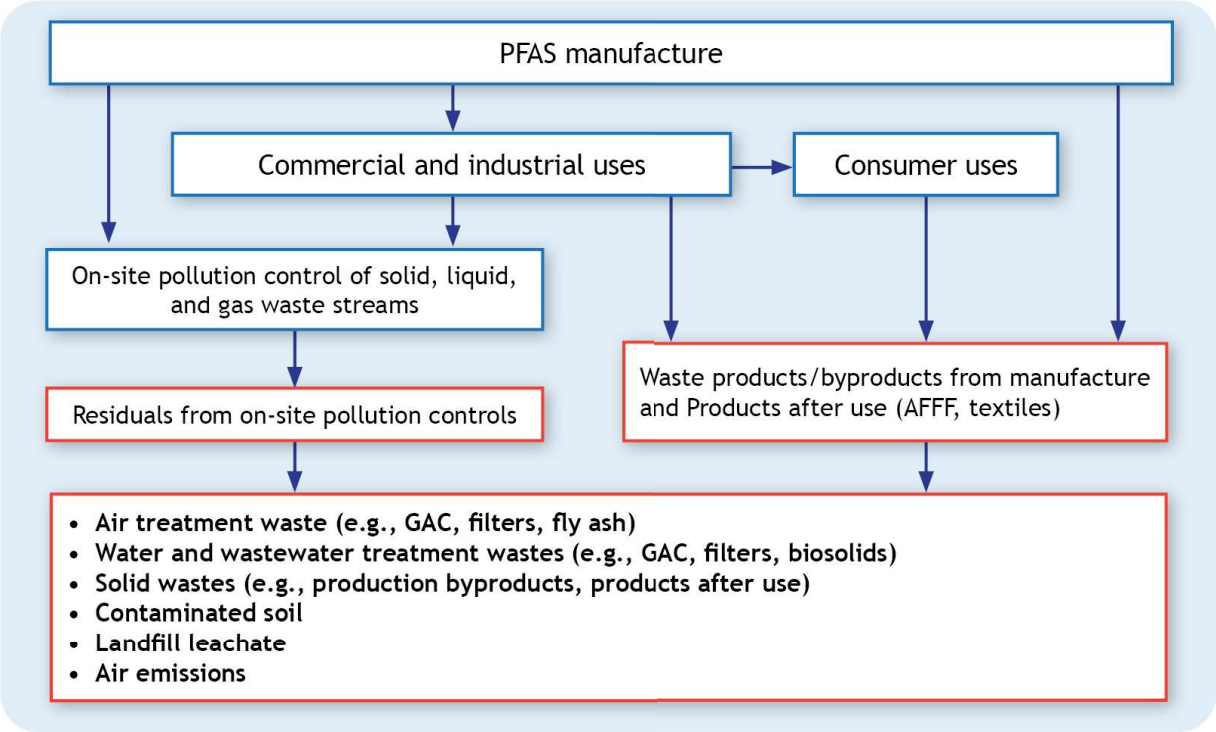
Figure 1-1. FY 2020 NDAA Section 7361.

1.b Scope and use of interim guidance

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

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

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



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

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

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

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

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

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

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

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

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

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

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

Destruction and Disposal Technology, by Physical Phase of Materials	Examples of PFAS-Containing Materials (within the Scope of the FY 2020 NDAA) That Could Be Managed Using These Technologies

Solid phase:
Landfill disposal
Thermal treatment
	• Drinking water, groundwater, and wastewater treatment residuals
	  ○ Biosolids/sewage sludge
	  ○ Spent GAC
	  ○ Ion exchange resins
	• Air waste stream treatment residuals
	  ○ Spent GAC
	  ○ Fly ash
	• Contaminated soil
	• End-of-life products (e.g., textiles)
	• Solidified liquid wastes

Liquid phase: Underground injection Thermal treatment	• Sewage sludge (liquid) • Landfill leachate • AFFF (spent or concentrate)

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

1.b.iii Use of this interim guidance

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

EPA emphasizes the importance for decision-makers (managers of PFAS-containing materials making decisions about destruction and disposal) to consider potential impacts to nearby communities, including vulnerable populations, when evaluating destruction, disposal, and storage options. Those concerns are amplified because the uncertainties in the effectiveness of these options to limit or control environmental releases can contribute to adverse impacts, including potentially disproportionate and

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.a.i Solid phase wastes

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

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

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

2.a.ii Liquid phase wastes

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

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

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

2.a.iii Gas phase wastes

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.b Aqueous film-forming foam

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

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

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

A 2004 inventory estimated that there were 4.6 million gallons of legacy PFOS-containing AFFF in the United States (Darwin, 2011). AFFF inventory depletion is determined by frequency of use for firefighting, training, or testing; transfers between locations; and other factors. However, AFFF's characteristically long shelf life means there should be little disposal due to expiration (FFFC, 2016), increasing the possibility that legacy PFOS-containing AFFF concentrate remains in service or reserve inventories. Fluorotelomer-based AFFF surfactant products became available in the 1970s (Prevedouros, 2006). In 2017, the U.S. Department of Defense (DoD) edited its military specification for AFFF to include

no more than 800 parts per billion (ppb) of PFOA and PFOS in the concentrate, the limit set by DoD Quality Systems Manual 5.1. However, this specification does not mention any other PFAS standards.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.c Soils and biosolids

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

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

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

Table 2-3. Biosolids Generation and Management in 2021

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

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

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

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

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

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

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

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

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

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

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

2.e Spent water treatment materials

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

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

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

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

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

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

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

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

2.e.i Activated carbon

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

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

For GAC, the range of PFAS concentrations on spent media can be estimated in several ways (Crone et al., 2019; U.S. EPA, 2020d). A conservatively high loading of PFAS onto GAC (using a GAC with a high-capacity potential, a strongly adsorbing PFAS, few competitive contaminants, low organic levels, and a high concentration in the feed water treated) is on the order of 2 percent by weight (e.g., 0.02 grams PFOS per gram of GAC). For more common treatment scenarios, or for PFAS that are adsorbed more weakly (i.e., the shorter-chain PFAS), the weight percent of PFAS will be orders of magnitude lower—about $1x10^{-5}$ grams PFAS per gram of GAC.

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

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

2.e.ii Ion exchange resins

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

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

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

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

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

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

Treatment of the concentrated residual stream can be challenging, and the cost will likely be high, similar to those for landfill leachates, ion exchange spent regenerates, and waters from highly contaminated sites. Many variables could affect the cost of treating these waste streams. At this time, there is no obvious treatment technology choice, especially given that the concentrated retentate

stream is typically 20 percent of flow (Baruth, 2005). This represents a sizeable flow, especially for large membrane treatment systems, such as those used by large municipalities (e.g., treating 20 million gallons per day [4 million gallons per day] concentrate flow). This large-volume flow would prevent the use of batch treatment processes, which have higher efficiencies because they can process the water multiple times before discharge.

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

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

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

2.f Landfill leachate containing PFAS

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

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

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

2.g Summary

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

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

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

3.a Thermal treatment

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

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

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

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

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

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

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

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

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

Hazardous waste combustion technologies (commercial incinerators, cement kilns, and LWAKs) can potentially achieve temperatures and residence times sufficient to break apart the PFAS contained in the waste stream being thermally treated, but not every unit currently operates at those conditions and

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

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

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

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

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

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

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

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

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

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

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

3.a.i Types of thermal treatment

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

3.a.i.1 Hazardous waste combustors

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

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

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

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

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

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

3.a.i.1.1 Commercial hazardous waste incinerators

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.a.i.3.1 Sewage sludge incinerators

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

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

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

3.a.i.3.2 Municipal waste combustors

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

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

RDF combustors burn waste that has been processed to varying degrees to raise its heating value and provide a more uniform fuel. Most boilers designed to burn RDF use spreader stokers and typically

operate at around 680°C (1,250°F). RDF-fired FBCs typically operate at bed temperatures of around 815°C (1,500°F) (Reddy, 2016).

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

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

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

3.a.i.4 Thermal oxidizers

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

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

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

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

3.a.ii Limitations and considerations in thermal treatments

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

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

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

In addition to incinerators and thermal oxidizers, cement kilns are also used for the destruction of hazardous wastes. Cement kilns operate at very high temperatures (exceeding 1,800°C [3,270°F]),

exhibit very large gas and solid residence times, and have the added advantage of providing a caustic environment for halogen reaction and acid neutralization. A cement kiln in Australia has received an operating permit from the government of Queensland to burn PFAS wastes. The permit requires annual monitoring for 21 PFAS (Department of Environment and Heritage Protection, 2018). Test results from 2017 indicate that a DRE in excess of 99.99 percent is possible for specific PFAS compounds at the conditions of the test (Cement Australia, 2017), but the results do not present data on overall PFAS destruction or potential formation of PICs.

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

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

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

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

performed. Liquids should preferably have direct flame contact or at least well mixed exposure to temperatures greater than 1,100°C.

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

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

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

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

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

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

Spray dryer absorber (SDA) technology has been applied to control emissions of halogen acids (including HCl and HF) from both MWCs and HWIs. This semi-dry scrubbing process is designed to inject an alkaline

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

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

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

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

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

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

3.a.iv Testing and monitoring

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

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

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

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

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

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

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

Current sampling of stationary source air emissions for semivolatile PFAS targets is based on EPA SW-846 Method 0010. Analysis of samples for a list of PFAS compounds is based on EPA Method 533—modified to include collection of both targeted and non-targeted PFAS in a single sampling system. Sampling includes heated or stack temperature probe extraction of emission gases followed by collection on filters, XAD sorbent media, and aqueous impingers. EPA released OTM-45, *Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources,* in January 2021 (U.S. EPA,

2021). OTM-45 experience indicates the method works well to measure targeted PFAS. OTM-45 is an effective and sensitive method to measure a list of PFAS included in the method. In coordination with the release of this guidance, EPA recently released OTM-50, which enables analysis of non-polar volatile PFAS.

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

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

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

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

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

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

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

3.a.v Uncertainties/unknowns

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

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

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

concentrations, impacted media, and potential exposure pathways), the size and shape of this area (vicinity) will vary.

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

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

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

3.a.vi Treatment commercial availability

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

3.a.vii Summary

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

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

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

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

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

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

Research and testing of PFAS destruction performance within MWCs is extremely limited, primarily comprising laboratory and pilot-scale studies (Aleksandrov et al., 2019; Taylor et al., 2014). For example, to assess whether PTFE is destroyed or reformed as PFAS, the Aleksandrov et al. study uses a pilot-scale rotary MWC with afterburner chamber combusting PTFE granules added to wood pellets (also firing natural gas). This study looked at a half-load scenario of 870°C (1,600°F) with a four-second residence time and a full-load scenario of 1,020°C (1,870°F) with a 2.7-second residence time. The study analyzed

for 31 PFAS compounds within the flue gas samples collected, assumed to represent a broad range of PFAS. While the laboratory and pilot-scale studies conclude that MSW incineration of PTFE is not a significant source of PFAS, the laboratory thermal reactor and the pilot incinerator used in these studies may not be representative of the design of MWC units currently operating in the United States. For example, the pilot-scale unit in the Aleksandrov et al. study is a rotary combustion chamber followed by an upflow afterburner. No MWC units operating in the United States have a similar configuration. In addition, while several PFAS species were analyzed for in these studies, it is important to note that there are far more PIC species possible, and no studies have thoroughly evaluated the types and quantities of PICs.

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

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

3.a.viii References for Section 3.a

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3.b Landfills

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.b.ii Types of landfills

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

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

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

Table 3-2 identifies the environmental controls required by RCRA and CAA for the landfill types defined in RCRA Subtitles C and D. RCRA regulations focus on the containment of solid waste and leachate, while CAA regulations focus on collection and control (destruction) of components in LFG. The landfill types

differ in how they are constructed, operated, controlled, monitored, and closed, reflecting the different types of waste they are allowed to receive.

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

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

Table 3-2. Required Environmental Controls by Landfill Type

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

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

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

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

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

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

3.b.ii.1 Hazardous waste landfills

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

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

3.b.ii.2 Municipal solid waste landfills

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

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

3.b.ii.3 Ash monofills

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

3.b.ii.4 Industrial landfills

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

3.b.ii.5 Construction and demolition landfills

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

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

PFAS are emitted from landfills via two possible routes: landfill leachate and LFG. Landfill leachate is liquid that has come into contact with solid waste and is either derived from the waste itself or the result of rainwater intrusion into the waste mass. Leachate contains soluble, suspended, or miscible

materials removed from such waste. LFG is the result of the natural decomposition of organic material in landfills under anaerobic conditions. LFG is composed of roughly 50 percent methane, 50 percent carbon dioxide, and a small amount of NMOCs.

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

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

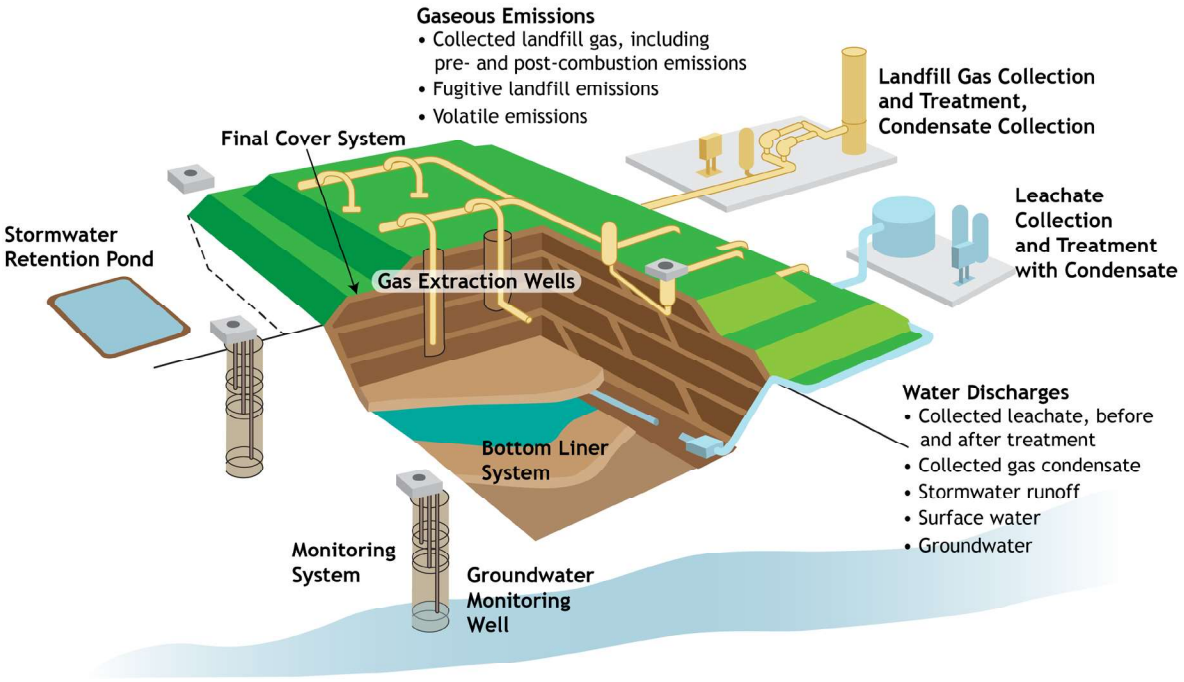

Figure 3-1. Engineered landfill components and potential PFAS release pathways.

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

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

The variation of landfill requirements among states poses a challenge for the long-term containment of existing PFAS in landfills: state requirements for landfill liners vary, and some landfills are not required to have liners because of waste type or quantities received. Additionally, RCRA-exempt sites do not require liners (40 CFR 258.1). Because PFAS are not a RCRA-regulated hazardous waste, existing unlined

landfills could include PFAS-containing wastes that are easily emitted into the environment. Depending on their mobility, PFAS compounds could impact groundwater if disposed of in an unlined landfill.

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

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

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

3.b.iii.2 Landfill gas collection system

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

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

3.b.iii.3 Final cover system

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

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

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

3.b.iii.5 Leachate discharge controls

3.b.iii.5.1 Leachate characteristics

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

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

The most common method for non-hazardous waste leachate disposal is off-site treatment at municipal WWTPs, where leachate is mixed with wastewater and treated. The dynamic nature of leachate characteristics, the presence of non-biodegradable compounds and ammonia, and the presence of emerging contaminants (such as PFAS) in the leachate may make it difficult for WWTPs to effectively treat the influent water. In some cases, a landfill with elevated PFAS in its leachate may burden a WWTP's ability to treat, remove, or destroy these compounds before discharge to the environment (Masoner et al., 2020). As mentioned in Section 2.a.ii, wastewater treatment technologies used at most municipal WWTPs are generally ineffective at destroying or controlling PFAS (Schultz et al., 2006) and as

a result may also be ineffective at treating PFAS-containing landfill leachate. Furthermore, in WWTPs, PFAS may bind to and accumulate in biosolids, which can lead to PFAS entering the environment if biosolids are applied to land. Some WWTPs have requested that landfill operators pretreat leachate on site, and some WWTPs are implementing surcharges based on the leachate quality. Underground injection is another form of off-site leachate management (see Section 3.c).

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

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

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

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

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

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

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

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

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

the PFAS concentration (ITRC, 2017). Leachate also may need to be pretreated before activated carbon treatment to avoid rapidly saturating the carbon.

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

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

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

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

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

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

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

3.b.iii.6 Landfill gas emission controls

3.b.iii.6.1 Landfill gas characteristics

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

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

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

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

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

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

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

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

LFG condensate is a liquid that has condensed in the LFG collection system piping during the extraction of gas from the landfill. In gases with high concentrations of water vapor, water condenses in pipes and

accumulates in traps staged throughout the collection network. This condensate contains volatile compounds and accounts for a relatively small percentage of flow from a landfill. Gas condensate is commonly collected and managed with the landfill leachate as liquid waste. PFAS has been detected in LFG condensate, with perfluorobutanesulfonic acid (PFBS) being the dominant species at a concentration of 1,000 nanograms per liter (Li, 2011).

3.b.iv Potential for releases during landfilling

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

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

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

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

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

3.b.v Testing and monitoring

Currently, there are no federal requirements for the monitoring of PFAS in landfill waste, leachate, condensate, or LFG. EPA and others are conducting studies to evaluate the effectiveness of landfills in

containing or managing PFAS (see Section 3.b). Landfill operators should include PFAS measurements with the regular leachate monitoring parameters that are regularly evaluated. Analyzing PFAS in LFG may pose a challenge for comparison across destruction/control technologies and types of landfills due to the lack of standardized testing (see Section 5.a for research needs).

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

3.b.vi Uncertainties/unknowns

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

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

3.b.vii Summary

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

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

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

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

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

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

See Appendix D for a summary of costs and considerations.

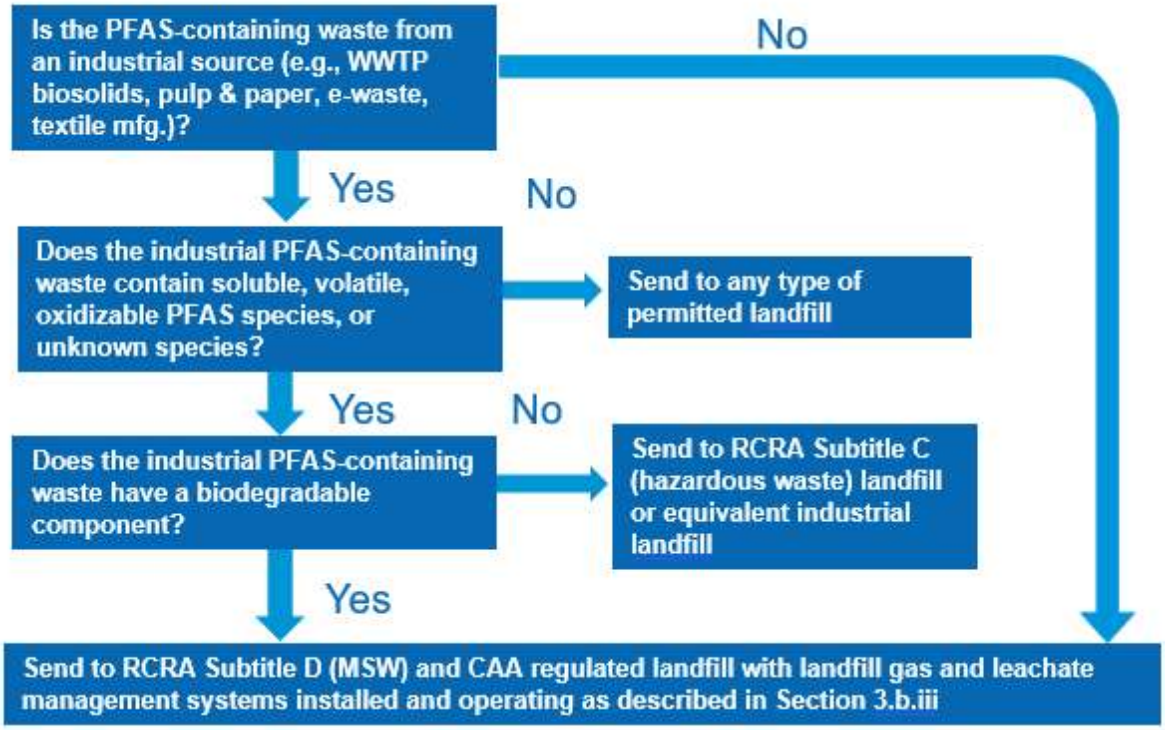

Figure 3-2. Decision framework for selection of landfill disposal for PFAS-containing industrial waste.

3.b.viii References for Section 3.b

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3.c Underground injection

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

3.c.i Types of wells

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

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

- **Class I** wells inject into geologic formations below the lowermost USDW and are further subdivided into four categories: municipal wastewater, radioactive waste, hazardous waste, and non-hazardous industrial waste disposal wells (see Figure 3-3).
- **Class II** wells are used for injection activities associated with oil and gas production and hydrocarbon storage.
- **Class III** wells are solution mining wells used to inject fluids for the purposes of dissolving and extracting minerals.
- **Class IV** wells, with limited exceptions, have been banned by EPA since 1984 and were used to inject hazardous or radioactive waste into or above geologic formations containing USDWs.

Figure 3-3. Class I wells.

- **Class V** wells include injection wells that are not included in Classes I, II, III, IV, or VI. EPA has identified multiple subtypes, including stormwater drainage wells, septic system leach fields, and agricultural drainage wells.
- **Class VI** wells are used to inject and geologically sequester carbon dioxide.

EPA has determined the use of Class I non-hazardous industrial waste and hazardous waste wells for high concentration liquid PFAS waste has a lower potential for environmental release when compared to other PFAS destruction and disposal options, and there is relatively low uncertainty in this

determination. Class I underground injection wells are designed to dispose of and isolate liquid waste below the land surface and beneath USDWs. The standards associated with the construction, operation, and monitoring of Class I wells are designed to ensure protection of USDWs. These standards include at least one confining layer between the zone in which the fluid will be emplaced and the lowest USDW. While Class I wells are an option for managing PFAS-containing fluids, this technology may not be appropriate everywhere. The suitability of a site for injection is dependent on the geologic formations in the area. Sites need to be evaluated to ensure that there is an appropriate confining zone and that there are geologic formations that can receive fluids.

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

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

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

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

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

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

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

Specific components of these requirements are discussed further below.

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

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

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

3.c.ii.3 Potential for Release

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

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

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

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

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

3.c.iii Availability

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

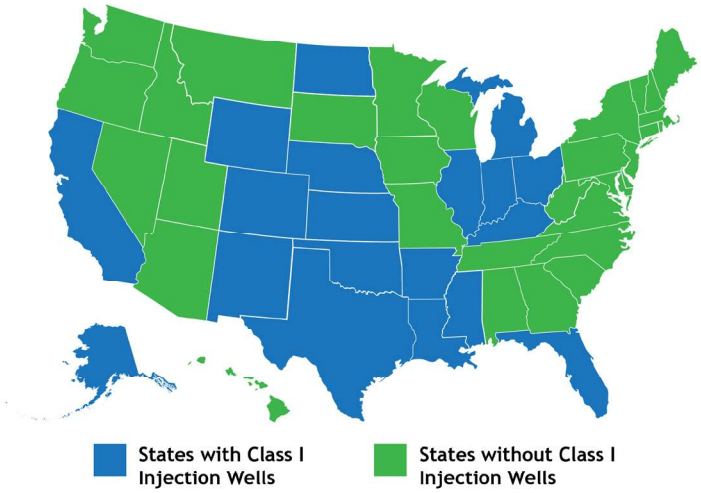

Figure 3-4. States with Class I non-hazardous or hazardous waste injection wells.

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

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

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

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

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

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

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

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

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

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

EPA anticipates the number of current Class I hazardous waste wells that would begin accepting new sources of PFAS-containing waste to be very limited due to the necessary modifications of Class I

hazardous waste well permits (e.g., increased injection volumes, changes to waste streams, no-migration petitions). These modifications would involve engineering and scientific evaluations, modeling, and public hearings.

3.c.iv Testing and monitoring

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

Broadly, Class I well operators must:

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

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

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

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

3.c.v Uncertainties/unknowns

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

When evaluating underground injection options, decision-makers (managers of PFAS-containing materials and PFAS-containing waste) should consider potential impacts to communities, including vulnerable populations. Underestimation of the potential for PFAS release could increase impacts to local communities, including vulnerable communities. EPA recommends that decision-makers screen

communities located in the vicinity of the destruction, disposal, and storage options in order to consider the potential for adverse, including any cumulative and disproportionate impacts (see Section 4), and potential measures to prevent, reduce, or address such impacts. Depending on site-specific circumstances (e.g., PFAS concentrations, impacted media, and potential exposure pathways), the size and shape of this area (vicinity) will vary.

3.c.vi Summary

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

See Appendix D for a summary of costs and considerations.

3.c.vii References for Section 3.c

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

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

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

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

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

The FY 2020 NDAA specifies that the interim guidance consider:

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

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

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

4.a Potential releases from destruction and disposal facilities

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

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

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

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

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

4.b Potentially vulnerable populations

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

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

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

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

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

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

4.c Considering vulnerability

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

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

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

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

4.c.i Identifying potentially vulnerable populations

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

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

4.c.i.1 EJScreen

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

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

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

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

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

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

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

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

EPA's *Enforcement Compliance and History Online* (ECHO) website lets users search for facilities in communities to assess their compliance with environmental regulations that protect human health and the environment. Permit writers may consider susceptibility and vulnerability when establishing permit

conditions and ECHO is a useful tool to evaluate whether a facility is currently violating or has previously violated those conditions. Users access ECHO to:

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

4.c.i.3 PFAS Analytic Tools

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

4.c.i.4 Private Domestic Well Map

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

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

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

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

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

4.c.i.6 EnviroAtlas

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

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

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

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

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

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

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

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

4.c.i.9 Tribal Data

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

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

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

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

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

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

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

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

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

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

4.c.iii Considerations for community engagement

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

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), where public hearings are requested for CAA Title V permits, 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. Advancing the goal of meaningful involvement is a core principle under EO 14096. Reaching out to the community and providing notification, information, and an opportunity for input before deciding whether to accept PFAS-containing waste for destruction or disposal will help build trust and support for operations and can reduce the likelihood of negative reactions stemming from unresolved concerns.

Meaningful community engagement typically includes two key elements:

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

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

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

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

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

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

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

4.d References

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

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

5.a Research needs to inform future guidance updates

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

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

EPA designated research needs associated with the underground injection of PFAS and PFAS-containing materials via Class I wells as a low priority. The agency made this designation because the standards associated with the construction, operation, and monitoring of Class I wells are designed to isolate liquid wastes deep below the land surface and ensure protection of underground sources of drinking water. As

a result, EPA expects underground injection of liquid PFAS waste to have a lower potential for environmental release, compared to managing PFAS wastes through thermal treatment or landfills. While data on the performance of Class I wells for managing liquid PFAS waste would be informative, the highest priority continues to be on characterizing PFAS releases from thermal treatment units and landfills.

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

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

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

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

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

5.b Current research efforts to address data gaps

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

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

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

identified in the PFAS Report. Additional information is available in the *CEQ Report on Biden-Harris Administration Progress on PFAS* (March 2023).[26]

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

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

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

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

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

5.b.ii EPA research and development activities

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

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

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

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

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

5.b.ii.2 Thermal treatment

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

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

5.b.ii.3 Landfills

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

5.b.ii.4 Extramural research

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

- In 2019, *EPA awarded grants to eight universities* to better understand the environmental risks posed by PFAS and identify practical approaches to manage their potential environmental impacts. Several of these projects focused on characterizing PFAS in landfills. Research

completed under these projects contributed to EPA's improved understanding of the potential for PFAS releases from landfills.

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

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

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6. Emerging Technologies for PFAS Destruction and Disposal

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

Development of new technologies typically involves the following stages:

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

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

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

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

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

6.a EPA's PFAS Innovative Treatment Team

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

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

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

6.a.i PITT-investigated emerging technologies

To further explore the potential for mechanochemical degradation of PFAS, ORD scientists partnered with colleagues in New Zealand to conduct a proof-of-concept case study using a benchtop ball mill, AFFF-spiked sand, and AFFF-contaminated soil (Gobindlal et al., 2023). Mechanochemical degradation is a treatment technology that uses a high-energy ball-milling device, with the option of co-milling reagents, to produce highly reactive conditions to degrade contaminants. Results from the AFFF-spiked sand showed a 99.99% destruction efficiency for the sum of all measured PFAS after 960 min, and results from the AFFF-contaminated soil indicate that measured PFAS were below the limit of detection

after 1440 min. Because this study analyzed PFAS in the solids after different ball milling time intervals, from 15 to 1440 min, the authors were able to identify increases in some of the measured PFAS before concentrations decreased, indicating the transformation of PFAS during ball milling. An extractable organic fluorine method was also used to determine the reduction in extractable organic fluorine before and after ball milling. In the case of AFFF-spiked sand, the authors reported a 97.8% reduction in extractable organic fluorine. A 53.5% reduction in extractable organic fluorine was reported for the AFFF-contaminated soil. Air emissions were not characterized as part of this study, making it difficult to determine whether full mineralization of PFAS occurred, and more work is needed in this regard. As noted in the study, more work is also needed to identify primary operations variables to inform the scalability of mechanochemical destruction.

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

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

In 2021, ORD also partnered with a company to conduct tests at industrial-scale supercritical water oxidation system (Sahle-Demessie et al., 2022). These tests used a dilute, FTS-based AFFF. The primary objective of the study was to determine the destruction efficacy of the PFAS in the input material. Analysis of the influent and effluent showed greater than 99.99% destruction of the total PFAS measured. The average sum of the targeted PFAS in the effluent was approximately 55 µg/L, but PFAS were also detected in the tap water used as quench water in the system, suggesting that the overall performance of the system could be improved if non-PFAS-contaminated water is used in the system. A secondary objective of the study was to characterize degradation products using non-targeted analysis and stack sampling for nonpolar volatile fluorochemicals. Non-targeted analysis of the effluent tentatively identified the shorter carbon-chain PFAS on the targeted analyte list, and the authors suggested a possible destruction mechanism that would be consistent with this result. Further work is

needed, however, to determine the destruction mechanism. The air emissions sampling did not detect targeted PFAS in air emissions above background levels; further work with finalized air methods (e.g., OTM-50) is needed to confirm this observation.

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

6.b PFAS Destruction and Disposal Technology Evaluation Framework

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

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

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

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

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

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

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

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

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

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

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

6.b.i Key questions for technology evaluation

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

- **If available, what is the TRL for the technology/material combination of interest?** TRLs are generally assigned using the *definitions developed by NASA* (NASA, 2023), where level 1 corresponds to observation and reporting of basic scientific principles and level 9 corresponds to "flight proven"

technologies. TRLs may be determined through technology readiness assessments[28] or through other methods. If other methods are used, EPA recommends that users consider the source of reported TRLs and prioritize TRLs determined through independent technology readiness assessments over TRLs assigned by the technology developer.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.c References

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

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

Overall goals of the field tests are as follows:

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

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

Sampling Details:

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

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

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

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

Supplemental Information

Emissions sampling and analytical approaches

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

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

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

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

ORD research questions

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

Process characterization

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

Determine destruction removal efficiency (DRE)

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

Products of incomplete combustion/destruction (PICs/PIDs)

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

Alternative indicators of destruction performance

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

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

Analysis of fluorinated compounds in waste/effluent streams

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

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

Analysis of fluorinated compounds in final product materials, where applicable

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

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

Appendix B: Summary of the Clean Harbors Test Data

Summary

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

Introduction

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

General Process Description

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

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

Operational Description

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

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

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

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

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

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

Test Methods and Scope

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

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

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

Results

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

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

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

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

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

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

Conclusions

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

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

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Appendix C: Summary of the Chemours Thermal Oxidizer Test Data

Introduction

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

General Process Description

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

Operational Description

Test Methods and Scope

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

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

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

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

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

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

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

Results

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

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

Conclusions

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

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Appendix D: Summary of Costs and Considerations

Introduction

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

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

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

Thermal Treatment

Hazardous Waste

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

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

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

Limitations:

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

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

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

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

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

Limitations:

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

Landfills

Hazardous Waste

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

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

Limitations:

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

Non-Hazardous Waste (Municipal solid waste)

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

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

Limitations:

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

Non-Hazardous Waste (Liquid waste)

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

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

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

Limitations:

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

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

Underground Injection

Class I Wells (hazardous and non-hazardous)

Table D-6. Estimated Costs for Class I Wells

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

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

Limitations:

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

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

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Additional Resources

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> **Per the report:** *This study develops alternatives to remove and destroy per- and polyfluoroalkyl substances (PFAS) from water resource recovery facility (WRRF) effluent, biosolids, mixed municipal solid waste (MSW) landfill leachate, and compost contact water (waste streams) using currently feasible technologies (i.e., could be built today). The report summarizes estimated capital and operations and maintenance (O&M) cost ranges for the two highest-ranking PFAS management alternatives for four waste streams (WRRF effluent, WRFF biosolids, landfill leachate, and compost contact water).*

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

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

Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances—2026 Version

INTERIM GUIDANCE FOR PUBLIC COMMENT
APRIL 20, 2026

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Abbreviations

acfm	actual cubic feet per minute
AFFF	aqueous film-forming foam
AOF	absorbable organofluorine
APCD	air pollution control device
ARFF	aircraft rescue firefighting
BDL	below detection limit
BMP	best management practice
BRAC	base realignment and closure
BTU	British thermal unit
C	Celsius
CAA	Clean Air Act
CaF_2	calcium fluoride
CaO	calcium oxide
$Ca(OH)_2$	calcium hydroxide
C&D	construction and demolition
CDC	Centers for Disease Control and Prevention
CDR	Chemical Data Reporting
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CF_4	carbon tetrafluoride
C_2F_6	hexafluoroethane
C_3F_8	octafluoropropane
CFR	Code of Federal Regulations
CHES	Clean Harbors Environmental Services
CHF_3	fluoroform
CIC	combustion–ion chromatography
CIMS	chemical ionization mass spectrometry
CKD	cement kiln dust
CLIN	contract line item number
COD	chemical oxygen demand
CO_2	carbon dioxide
CV	coefficient of variation
CWA	Clean Water Act
cm	centimeter
DE	destruction efficiency
DoD	Department of Defense
DOE	Department of Energy
DoW	Department of War
DRE	destruction and removal efficiency
EOF	extractable organofluorine
EPA	United States Environmental Protection Agency
ESP	electrostatic precipitator
ESTCP	Environmental Security Technology Certification Program
F	Fahrenheit
FAA	Federal Aviation Administration
FBC	fluidized bed combustor

FF	fabric filter
FML	flexible membrane liner
FTCA	fluorotelomer carboxylic acids
FTIR	Fourier transform infrared spectrometry
FTOH	fluorotelomer alcohol
FTS	fluorotelomer sulfonate
FUDS	formerly used defense sites
FY 2020 NDAA	National Defense Authorization Act for Fiscal Year 2020
GAC	granular activated carbon
GCCS	gas collection and control system
HALT	hydrothermal alkaline treatment
HAP	hazardous air pollutant
HCl	hydrogen chloride
HDPE	high-density polyethylene
HF	hydrogen fluoride
HFPO-DA	hexafluoropropylene oxide-dimer acid, 2,3,3,3-Tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy) propanoic acid, ($C_6F_{11}O_3H_2$)
hr	hour
HRMS	high-resolution mass spectrometry
HWC	hazardous waste combustor
HWI	hazardous waste incinerator
H_2O_2	hydrogen peroxide
ITRC	Interstate Technology and Regulatory Council
kg	kilogram
L	liter
lb	pound
LC/MS/MS	liquid chromatography/tandem mass spectrometry
LFG	landfill gas
LWAK	lightweight aggregate kiln
MDL	method detection limit
MF	microfiltration
mg	milligram
MnO_2	manganese(IV) oxide
MSW	municipal solid waste
MWC	municipal waste combustor
m^3	cubic meter
NADP	National Atmospheric Deposition Program
NASA	National Aeronautics and Space Administration
NDAA	National Defense Authorization Act
NESHAP	National Emission Standards for Hazardous Air Pollutants
NF	nanofiltration
ng	nanogram
NIOSH	National Institute for Occupational Safety and Health
NMOC	nonmethane organic compound
NPDES	National Pollutant Discharge Elimination System
NPDWR	National Primary Drinking Water Regulation
NSPS	New Source Performance Standards

NTA	non-targeted analysis
OECD	Organization for Economic Cooperation and Development
OSTP	Office of Science and Technology Policy
OTM	Other Test Method
PAC	powdered activated carbon
PA/SI	preliminary assessments/site inspections
PBPK	physiologically based pharmacokinetic
PCB	polychlorinated biphenyl
PFAA	perfluoroalkyl acid
PFAS	perfluoroalkyl and polyfluoroalkyl substances
PFASTT	PFAS Thermal Treatment Database
PFBS	perfluorobutanesulfonic acid ($C_4F_9SO_3H$)
PFC	perfluorocarbon
PFHxS	perfluorohexanesulfonic acid ($C_6F_{13}SO_3H$)
PFOA	perfluorooctanoic acid ($C_8F_{15}O_2H$)
PFOS	perfluorooctanesulfonic acid ($C_8F_{17}SO_3H$)
PIC	product of incomplete combustion
PID	product of incomplete destruction
PIGE	particle-induced gamma emission spectrometry
PITT	PFAS Innovative Treatment Team
POHC	principal organic hazardous constituent
POTW	publicly owned treatment works
ppb	parts per billion
ppmv	parts per million by volume
PTFE	polytetrafluoroethylene
PVDF	polyvinylidene fluoride or polyvinylidene difluoride
RCRA	Resource Conservation and Recovery Act
RDF	refuse-derived fuel
RO	reverse osmosis
SBIR	Small Business Innovation Research
SDA	spray dryer absorber
SDWA	Safe Drinking Water Act
SERDP	Strategic Environmental Research and Development Program
SFP	side-chain fluorinated polymers
SSI	sewage sludge incinerator
S/S	solidification/stabilization
TD-GC/MS	thermal desorption-gas chromatography/mass spectrometry
TMC	thermomechanochemical
TOC	total organic carbon
TOF	total organic fluorine
TOP	total oxidizable precursor
TRI	Toxics Release Inventory
TRL	technology readiness level
TSCA	Toxic Substances Control Act
TWTDS	treatment works treating domestic sewage
UF	ultrafiltration
UIC	underground injection control

U.S.C.	United States Code
USDW	underground source of drinking water
UST	underground storage tank
VFC	volatile fluorinated compounds
VOC	volatile organic compound
WESP	wet electrostatic precipitator
WWTP	wastewater treatment plant
XPS	X-ray photo-electron spectroscopy
µg	microgram
$	United States dollar

Executive Summary

This 2026 update of the U.S. Environmental Protection Agency (EPA) interim guidance presents currently available information on the destruction and disposal of perfluoroalkyl and polyfluoroalkyl substances (PFAS) and PFAS-containing materials. This guidance focuses on updates to the current state of science and associated uncertainties for three large-scale capacity technologies that can destroy PFAS or control PFAS release into the environment: thermal treatment, landfills, and underground injection. This guidance document also discusses emerging technologies and provides a framework for evaluating these technologies for PFAS destruction or disposal. This guidance is non-binding and does not have the force and effect of law.

EPA published the first edition of this guidance on December 18, 2020, as required by the National Defense Authorization Act (NDAA) of 2020, and the second edition of this guidance on April 16, 2024. The NDAA directs EPA to address the destruction and disposal of PFAS and specific PFAS-containing materials, including aqueous film-forming foam (AFFF), contaminated media, textiles (other than consumer goods), and various wastes from water treatment. The NDAA also requires EPA to review and update the guidance as appropriate, but no less frequently than every three years. On April 28, 2025, the EPA Administrator committed to providing more frequent updates to the interim guidance—changing from every three years to annually—as EPA continues to assess the effectiveness of available treatment technologies.

The primary audience of this guidance are decision-makers (e.g., managers of PFAS and PFAS-containing materials making decisions about destruction and disposal) who need to identify effective means for destroying or disposing of PFAS-containing materials and wastes. The audience may also include regulators, waste managers, and the public, including affected communities. While this document highlights a few emerging approaches for PFAS destruction and disposal, EPA acknowledges that alternatives not discussed in this document may also be appropriate. EPA is recommending that managers of PFAS wastes consider the nature of the waste, location, potential for environmental release, and other factors to determine the most appropriate destruction, disposal, or storage method. As a general approach, EPA recommends that decision-makers prioritize the use of destruction and disposal technologies that have a lower potential for PFAS release to the environment over destruction and disposal technology options with a greater potential for environmental release of PFAS given similar costs or other considerations. EPA acknowledges that each destruction and disposal technology has limitations. This guidance is intended to assist with managing PFAS to minimize environmental releases during destruction and disposal activities supports protection of human health and the environment.

This guidance highlights effective PFAS destruction and disposal technologies to prevent or minimize environmental releases, while acknowledging the important distinction between a potential environmental release and human exposure and risk.

EPA has developed a fact sheet for the public, which provides a more concise and less technical presentation of key materials (see Appendix E).

Key Updates

EPA evaluated recent information pertaining to destruction and disposal options based on each technology's potential to destroy PFAS or control PFAS release into the environment. This approach is

consistent with EPA's mission to protect human health and the environment. This guidance describes several different types of technologies that are widely used and commercially available for PFAS treatment and disposal, and their potential to destroy PFAS or control PFAS releases is described herein (see Sections 1 and 3). The following technologies (listed in no relative order) generally have a lower potential for environmental release of PFAS compared to other technologies:

- **Underground Injection - Permitted Class I non-hazardous industrial or hazardous waste injection wells** are one of the regulatory waste management approaches that can provide reasonable assurance that injected fluids will remain isolated and not migrate into underground sources of drinking water (USDWs). However, over long timescales, uncertainties remain, including the long-term fate and transport properties of PFAS in the injection zone. These wells may help ensure that injected fluids are confined and cannot enter underground sources of drinking water. However, the limited number of wells currently receiving off-site PFAS and waste transportation logistics may significantly limit the type and quantity of PFAS-containing fluids appropriate for underground injection.
- **Landfills - Permitted RCRA Subtitle C hazardous waste landfills** incorporate the most stringent engineering controls and practices for containment and are expected to be more effective at minimizing PFAS release into the environment than other landfill types. EPA recommends landfills subject to Subtitle C of the Resource Conservation and Recovery Act (RCRA) when PFAS levels of the waste are relatively high, and landfill disposal is the selected option. However, for all landfill types, new information demonstrates that landfilling could result in higher PFAS releases to the environment than previously thought in 2024 (see Section 3.b).
- **Thermal Treatment - Permitted hazardous waste combustors** (HWCs) such as commercial incinerators, cement kilns, and lightweight aggregate kilns (LWAKs) and granular activated carbon (GAC) reactivation units with thermal oxidizers may operate under conditions more conducive to destroying PFAS and controlling related products of incomplete combustion (PICs). Research available since release of the 2024 Interim Guidance suggests that the use of higher temperatures, well mixed combustion environments, and longer residence times may be more conducive to destroying PFAS and controlling related PICs. Although newer, limited data have been obtained since the 2024 version of the interim guidance, uncertainties remain about the effectiveness of thermal treatment to adequately destroy PFAS or control release to the environment. EPA encourages additional testing with EPA-approved or EPA-evaluated methods by waste managers of thermal treatment operations (including testing for PICs present at the treatment device outlet and the presence of PFAS in all associated process and waste streams) to evaluate whether thermal treatment technologies are minimizing potential environmental releases. EPA's new analytical methods for a targeted list of polar semivolatile PFAS (Other Test Method 45 [OTM-45]) and volatile fluorinated compounds (OTM-50), as well as additional EPA methods under development for evaluating treatment of hard-to-destroy PFAS will allow better characterization of PICs which will help to address some of these uncertainties when additional data are collected as recommended in this guidance (Appendix A).

This list includes the three technology categories described in Section 3 and does not preclude the use of other new or emerging technologies. When considering the bullets above, it is important to note that real-world performance and testing data are generally limited. Additional performance and testing data—including data on destruction and removal of PFAS in thermal treatment devices, ongoing research activities, and long-term performance data for landfills and underground injection—may

change EPA's understanding of the ability of each technology to control PFAS. Section 4 of this updated guidance summarizes the data needs and priorities for research to inform future updates.

EPA continues to seek collaboration with thermal treatment facilities to conduct air emission testing during thermal treatment of PFAS and PFAS-containing materials (see Appendix A). In addition to performance and testing data, the 2026 guidance continues to identify other, high-priority data gaps that need to be addressed by researchers across government, academia, and industry for EPA to provide meaningful updates on effective destruction and disposal practices.

EPA partnered with industry and academia to collect data on emerging technologies for PFAS destruction, such as mechanochemical degradation, gasification and pyrolysis, and supercritical water oxidation. While the results from these studies show promise for PFAS destruction, further work using newly available methods is needed to more fully characterize the outputs of these processes and to evaluate their performance for a wider range of PFAS-containing materials. Managers of PFAS and PFAS-containing materials may consider these or other emerging technologies for PFAS disposal or destruction. To assist PFAS material managers with evaluating whether an emerging destruction (or disposal) technology is suitable for a particular PFAS-containing material, EPA developed a technology evaluation framework. The framework provides a transparent, consistent approach for evaluating destruction and disposal technologies for PFAS and PFAS-containing material and includes considerations for communities. EPA recommends that managers of PFAS-containing materials use the technology evaluation framework to evaluate emerging destruction and disposal technologies and to inform their decisions about managing PFAS-containing materials. EPA also encourages technology developers to generate and publicly release data that can be used to complete the framework (see Section 5).

Public Feedback and Next Steps

EPA and other government, academic, and private institutions will continue to conduct research to better understand PFAS destruction and disposal (see Section 4). EPA will consider public comments it receives on this version of the guidance, as well as additional advancements in PFAS research and science to publish annual updates.[1] This guidance will be published with a 60-day comment period. EPA will publish a Federal Register Notice with Instructions on how to submit comments. During the public comment period, EPA encourages the public to submit studies and data related to management of the PFAS-containing waste described in Section 2. Additionally, continued collaboration with industry researchers is encouraged to conduct emissions testing of PFAS treatment devices, including evaluation of PICs and products of incomplete destruction (PIDs).

[1] On April 28, 2025, the EPA Administrator committed to providing more frequent updates to the interim guidance—changing from at least every three years as required by the NDAA to annually.

1. Introduction

This 2026 version of the interim guidance provides information on technologies that may be feasible and appropriate for the destruction or disposal of perfluoroalkyl and polyfluoroalkyl substances (PFAS) and PFAS-containing materials. This guidance is non-binding and represents the current state of science and the associated uncertainties for large-capacity technologies that can destroy PFAS or control PFAS release into the environment. This is an update to the interim guidance the EPA issued in 2024 and utilizes information and data reviewed up until September 2025.

EPA published the second version of this interim guidance and made it available for public comment.[2] This updated version incorporates the feedback EPA received from the 37 unique comments on the interim guidance submitted by states, Tribes, industries, trade organizations, environmental organizations, and members of the public.

The 2026 interim guidance contains the following new information:

Section 1: Introduction

- Updated review of PFAS destruction and disposal technologies.

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

- Provided information regarding updates and planned revisions to the PFAS 8(a)(7) reporting rule under the Toxic Substances Control Act (TSCA [88 FR 70516, October 11, 2023]).
- Updated biosolids generation and management information.
- Updated information on the PFAS National Primary Drinking Water Regulations.

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

- Incorporated information from 2024 tests evaluating the PFAS destruction at hazardous waste incinerators in Aragonite, Utah and Port Arthur, Texas in Section 3.a.
- Added information from recent studies on thermal destruction of HFPO-DA into Section 3.a.i.1, laboratory- and facility-scale investigations of PFAS thermal treatment in sewage sludge incinerators (SSIs) into Section 3.a.i.3.1, and the efficacy of thermal oxidizers and carbon adsorption beds as PFAS control technologies at a fluoropolymer manufacturing facility into Sections 3.a.i.4 and 3.a.ii.
- Included published data evaluating landfill liner permeability and implications for PFAS transport and transformation in Section 3.b.ii.1, and added newly available published data on gas collection systems and implications for PFAS transport and transformation to Section 3.b.ii.2.
- Incorporated published ranges of PFAS concentrations measured in leachate samples from different types of landfills and municipal solid waste (MSW) landfill gas (LFG) condensate to Table 3-3 and data and information regarding PFAS concentrations in LFG samples from Subtitle D landfills to Section 3.b.ii.3.
- Updated Section 3.b.iii.6.2 regarding on- and off-site treatment technologies for landfill leachate that remove PFAS, and added new information on non-targeted analysis, uncertainties, and unknowns in Section 3.b.vi.
- Updated the information showing the locations of Class I wells in the United States using 2023 data in Section 3.c.iii.

[2] Interim PFAS Destruction and Disposal Guidance; Notice of Availability for Public Comment. U.S. EPA. 89 Federal Register 26879. April 16, 2024.

Section 4: Research Needs and Data Gaps for Destruction and Disposal Technologies

- Revised the table in Section 4.a based on new information presented in this document and public comments received on the 2024 interim guidance.
- Replaced discussion of current research efforts with links to ongoing, relevant federal research activities.

Section 5: Emerging Technologies for PFAS Destruction and Disposal

- Added information on the remaining PFAS Innovative Treatment Team (PITT) outputs in Section 5.a.
- Revised information on the technology evaluation framework in Section 5.b to incorporate suggestions from public comments received on the 2024 interim guidance.

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

- Expanded the list of inlet, intermediate, and outlet streams for sample collection and analysis to include process materials.
- Clarified the target analytes to include in an air emission source characterization.

Appendix B: Summary of the 2021 and 2022 Clean Harbors Test Data

- Added the test years (2021 and 2022) for the two source test campaigns conducted at an HWC to the appendix title.

Appendix C: Summary of the Chemours Thermal Oxidizer Test Data

- Expanded the table of destruction and removal efficiency (DRE) values to include the results for 2021, 2023, and 2024 from the test campaign conducted at a chemical manufacturer.

Appendix D: Summary of Costs and Considerations

- Updated the cost estimates for end-of-life management of PFAS materials by thermal treatment, landfilling, and underground injection from 2022 to 2024 dollars.

Appendix E: Fact Sheet for the 2026 Interim Guidance on the Destruction and Disposal of PFAS

- Added the fact sheet for the 2026 interim guidance document.

1.a Purpose and audience of this interim guidance

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

Section 7361 of the FY 2020 NDAA (see Figure 1-1) directs EPA to publish interim guidance on the destruction and disposal of PFAS and PFAS-containing materials no later than one year from the date of enactment of the FY 2020 NDAA. EPA published the initial interim guidance on December 18, 2020. The FY 2020 NDAA also requires EPA to review and revise the interim guidance at least every three years, if appropriate. The previous update was published in April 2024. On April 28, 2025, the EPA Administrator committed to changing the frequency of the interim guidance updates from every three years to annually as EPA continues to assess the effectiveness of available treatment technologies. This 2026 update fulfills that commitment.

The primary audience of this guidance are decision-makers who need to identify effective means for destroying or disposing of PFAS-containing materials and wastes based on their site-specific conditions, costs and other considerations. The audience may also include regulators, waste managers, and

technology developers who can use the technology evaluation framework in Section 5 to evaluate the applicability of emerging technologies to PFAS destruction or disposal. This guidance may also interest the general public, particularly communities near PFAS destruction and disposal sites. EPA has developed a fact sheet for the public that provides a more concise and less technical presentation of this guidance (see Appendix E).

SEC. 7361. PFAS DESTRUCTION AND DISPOSAL GUIDANCE.

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

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

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

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

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

Figure 1-1. FY 2020 NDAA Section 7361.

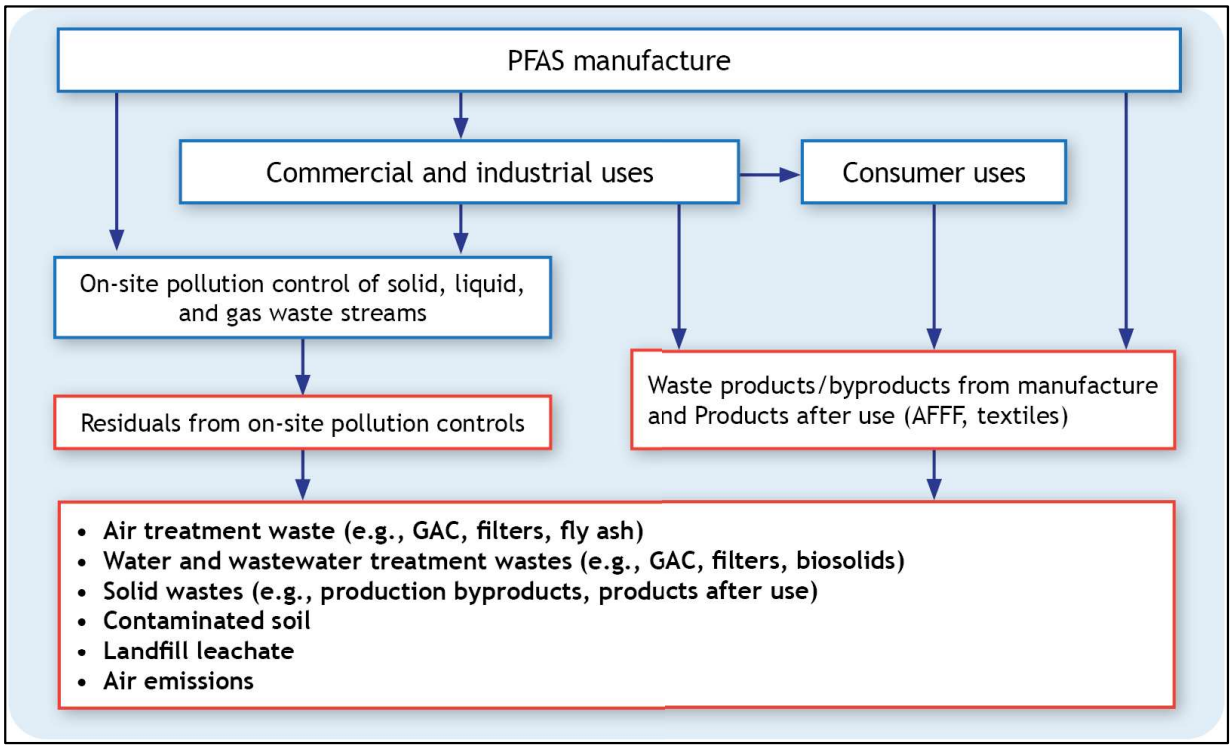
1.b Scope and use of interim guidance

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

Section 7361 of the FY 2020 NDAA (see Figure 1-1) lists six types of PFAS-containing materials and wastes[3]. Although the information included in this interim guidance is likely to be suitable for other types of PFAS and PFAS-containing materials, this interim guidance addresses destruction and disposal centering on these six material types, which are described in more detail in Section 2. In this document, the PFAS-containing materials covered by the FY 2020 NDAA that will be destroyed or disposed of are referred to as "waste."

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

[3] While there is no current EPA consensus definition of PFAS, perfluoroalkyl and polyfluoroalkyl substances can be generally characterized as a very large group of synthetic chemicals that due to their strong carbon-fluorine bonds, can be very persistent in the environment. EPA's ***CompTox Chemicals Dashboard*** maintains a master list of more than 12,000 chemicals that are potential PFAS, including 10,200 chemicals containing a specific defined structure and an additional 1,300 without explicit structures (polymers and other chemical substances of unknown or variable composition).



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

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

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

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

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

Current technologies. In developing this third version of the interim guidance, EPA focused on the three widely-used, commercially available destruction and disposal technologies that may be effective for managing PFAS wastes: thermal treatment, landfills, and underground injection. EPA also focused on reviewing recent data and information about the ability of each of these technologies to manage PFAS-containing materials through containment or destruction (i.e., breaking carbon–fluorine bonds and mineralization) while limiting releases of PFAS to the environment. In doing so, EPA prioritized addressing the scientific issues and uncertainties highlighted in the 2024 interim guidance and, when possible, relied on publicly available, peer-reviewed data and information (see Section 3).

Emerging technologies. Concerns about the effectiveness, availability, capacity, or cost of current, widely-used technologies for managing PFAS and PFAS-containing materials have motivated efforts to develop new technologies and apply existing technologies to PFAS materials. EPA is aware of and, in some cases, has participated in efforts to identify, develop, and test non-thermal destruction technologies for PFAS-containing materials (see Section 5).

Note that EPA is aware of additional information and technologies that were not considered for evaluation and are not mentioned in this guidance. EPA encourages continued collaboration with other government, academic, and private institutions to continue conducting research to better understand destruction and disposal of waste containing PFAS, and to be potentially included in future iterations of this guidance. EPA encourages technology developers to generate and publicly release data that can be reviewed, and to ensure the data are consistent with the tenets of gold standard science established in Executive Order 14303 (*Restoring Gold Standard Science*[4]).

In some cases, managers of PFAS and PFAS-containing materials may consider emerging technologies for PFAS destruction. When considering the use of emerging technologies, managers of PFAS-containing materials should work with state, territorial, or Tribal government agencies. To assist PFAS material managers with evaluating whether an emerging destruction (or disposal) technology is suitable for a particular PFAS-containing material, EPA developed a technology evaluation framework (see Section 5). The framework provides a transparent, consistent approach for evaluating destruction and disposal technologies for PFAS materials.

In 2026, EPA is neither recommending nor discouraging the use of any emerging technology for managing the PFAS-containing materials specified in the FY 2020 NDAA. Instead, the Agency recommends that managers of PFAS-containing materials use the technology evaluation framework to evaluate emerging destruction and disposal technologies and to inform their decisions about managing PFAS-containing materials. EPA also encourages technology developers to generate and publicly release data that can be used to complete the framework (see Section 5).

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

Table 1-1 presents examples of the PFAS destruction and disposal technologies discussed in this guidance document for materials in solid, liquid, and gas phases.

4 Available at: https://www.govinfo.gov/content/pkg/FR-2025-05-29/pdf/2025-09802.pdf.

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

Destruction and Disposal Technology, by Physical Phase of Materials	Examples of PFAS-Containing Materials (within the Scope of the FY 2020 NDAA) That Could Be Managed Using These Technologies

Solid phase:
Landfill disposal.
Thermal treatment.
	• Drinking water, groundwater, and wastewater treatment residuals:
	  ○ Biosolids/sewage sludge.
	  ○ Spent GAC.
	  ○ Ion exchange resins.
	• Air waste stream treatment residuals:
	  ○ Spent GAC.
	  ○ Fly ash.
	• Contaminated soil.
	• End-of-life products (e.g., textiles).
	• Solidified liquid wastes.

Liquid phase: Underground injection. Thermal treatment.	• Sewage sludge (liquid). • Landfill leachate. • AFFF (spent or concentrate). • End-of-life products (e.g., spent cleaning solvents). • Pollution control residuals (e.g., concentrates) from PFAS production and use.
Gas phase: Thermal treatment.	• LFG. • Emissions from manufacture, use, or destruction of PFAS.

1.b.iii Use of this interim guidance

This interim guidance provides information and suggested considerations for evaluating destruction and disposal options. This third version of the interim guidance is based on recent research and information available in 2025 and is responsive to the scope of the FY 2020 NDAA. 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: AFFF, soils and biosolids, textiles, spent water treatment materials, landfill leachate, and PFAS waste streams from facilities manufacturing or using PFAS (see Section 2). Most significantly, it provides up-to-date information on potential releases during the destruction and disposal of PFAS and PFAS-containing materials (see Section 3) and identifies data gaps to be filled that can inform future EPA guidance (see Section 4). This version also incorporates information received during the public comment period for the 2024 interim guidance document.

This version of the interim guidance:

- Is based on currently available information on technology performance and capabilities for destruction and disposal of the PFAS and PFAS-containing materials specified in the FY 2020 NDAA (see Section 1.b.i).

- Focuses on three widely-used, commercially available destruction and disposal technologies that may be effective for managing PFAS wastes (i.e., thermal treatment, landfills, underground injection) (see Section 3).
- Identifies research needs to inform future updates to this interim guidance (see Section 4).
- Discusses the development of emerging technologies and includes a framework for evaluating technology/PFAS material combinations (see Section 5).
- Does *not* establish what concentrations of PFAS in wastes, spent products, or other materials or media would necessitate destruction or disposal. Regulatory mechanisms are more appropriate for establishing such concentrations.
- Provides references to destruction and disposal facility locators that decision-makers can use to request cost estimates. EPA recommends obtaining cost estimates from applicable destruction and disposal facilities as described in Section 1.c.ii. In addition, Appendix D provides some cost information that PFAS material managers may want to consider when evaluating different techniques to destroy or dispose of PFAS and PFAS-containing materials. Note that cost information presented in this appendix is associated with a relatively high level of uncertainty. Moreover, the cost of PFAS destruction and disposal may change based on demand and evolution of available technologies. Additionally, overall costs may vary widely based on the type of materials or the distance to a facility.

This interim guidance is not a regulation, is non-binding, and does not pose any specific requirements on users. Discussion in this guidance of EPA's regulatory authorities is for the purpose of describing controls relevant to the destruction or disposal of PFAS and should not be considered a description of the applicability of those authorities or affect EPA's or any other agency's ability to enforce under these authorities in the future.

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

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

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

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

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

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

EPA is not endorsing any technology, but it is presenting the technologies' relative potential to minimize PFAS release; EPA encourages those that minimize PFAS release; managers should choose based on site specific conditions. As a general approach, EPA encourages managers of PFAS and PFAS-containing materials to prioritize destruction and disposal options with a lower potential for releasing PFAS to the environment over the use of destruction and disposal technology options with a higher potential for environmental release of PFAS given similar costs or other considerations. EPA also encourages testing with EPA-approved methods of thermal treatment operations, including PICs and the presence of PFAS in all associated waste streams (see Appendix A), to evaluate whether site-specific conditions are minimizing potential environmental releases.

While the purpose of an effective destruction and disposal technology is to prevent or minimize environmental releases, it is also important to distinguish between a potential environmental release and direct human exposure and risk.

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

- **Interim storage with controls.** While not a destruction or disposal method, interim storage may be a short-term option, if the destruction or disposal of PFAS and PFAS-containing materials is not imperative, on-site storage capacity is readily available, and interim storage has proper controls in place to reduce releases into the environment. Storage may be more appropriate for some PFAS materials than others. For example, EPA recommends interim storage of low volumes of containerized or high PFAS-concentration materials. In contrast, some materials may be less appropriate for storage because they are continuously generated or are typically high volume. With proper engineering controls in place, interim storage can control PFAS releases in the short term.

- **Underground injection (Class I non-hazardous industrial and hazardous waste wells).** EPA has determined the use of Class I non-hazardous industrial waste and hazardous waste wells for high-concentration liquid PFAS waste has a lower potential for environmental release when

compared to other PFAS destruction and disposal options, and there is relatively low uncertainty in this determination. The standards associated with the construction, operation, and monitoring of these Class I wells are designed to isolate liquid wastes deep below the land surface and ensure protection of USDWs. Operators of Class I hazardous waste wells must conduct mechanical integrity testing more often than Class I non-hazardous industrial waste operators. They also must establish and follow additional procedures for reporting and correcting mechanical integrity problems. Class I hazardous waste well operators must also develop and follow a waste analysis plan and conduct annual tests of the cement in place at the base of the well. While the standards associated with Class I hazardous wells are more stringent than for non-hazardous industrial wells, EPA has determined that the probability of failures for both has been demonstrated to be low. While Class I wells are an option for managing PFAS-containing fluids, this technology may not be appropriate everywhere. The limited number of wells currently receiving PFAS, well location, and waste transportation logistics may significantly limit the type and quantity of PFAS-containing fluids appropriate for underground injection. Additional Class I wells may need to be constructed where geologically suitable, and existing well permits may need to be modified to meet the capacity needs for PFAS disposal (see Section 3.c.v).

- GAC reactivation units with thermal oxidizers operating under certain conditions (applies only to GAC used for PFAS removal from drinking water treatment systems). GAC reactivation systems, with the associated use of off-gas thermal oxidizers (i.e., afterburners operating at temperatures greater than 1,100°C[5]) and gas scrubbing units, can potentially destroy PFAS without significant environmental releases, or without significant PFAS remaining on the reactivated carbon. However, as discussed in Section 3.a.i, more data are needed for confirmation, particularly regarding reactor operating conditions, differing GACs, evaluating GAC used for industrial processes and site remediation, and further characterization of PICs and PIDs. There is uncertainty associated with this option because it is based on limited research. While recent studies have improved understanding, additional research is needed to resolve uncertainties on PFAS emissions from full-scale reactivation facilities (see Section 3.a.v).
- **Thermal treatment units operating under certain conditions.** HWCs, including commercial incinerators, cement kilns, LWAKs, and thermal oxidizers, that operate under certain conditions (i.e., feeding liquid PFAS-containing materials, higher temperatures greater than 1,100°C[4], well mixed, and adequate residence time) may be more effective at adequately destroying (mineralizing) PFAS and minimizing PICs. There is uncertainty associated with this option because it is based on limited research and observations, there are limited data for the treatment of solid materials or containerized wastes, and there are limited emissions data (e.g., few test reports containing data for PIC formation and the presence of PFAS in air pollution control device [APCD] residuals) at full-scale facilities (see Section 3.a.v) due to previous methodology limitations. Site-specific considerations impact the ability of any thermal treatment unit to destroy PFAS; therefore, EPA encourages site-specific testing (see Appendix A) to determine if a particulate thermal treatment unit is suitable.
- **Hazardous waste landfills (RCRA Subtitle C).** This class of landfills has the most stringent environmental controls in place for minimizing environmental releases and migration of some

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

PFAS from disposed waste. EPA recommends Subtitle C landfills when PFAS levels of the waste are relatively high and landfill disposal is the selected option. Permitted hazardous waste landfills have relatively low quantities of landfill leachate[6], which lessens the probability of mobilizing PFAS that is reversibly bound to the waste. These landfills are required to handle and treat leachate as listed hazardous waste (hazardous waste number F039 per 40 Code of Federal Regulations [CFR] 261.31), lessening the likelihood of environmental release. Because hazardous waste landfills generally do not receive organic wastes that decompose, PFAS migration via LFG is anticipated to be relatively low but LFG collection and destruction equipment could be installed if anaerobic decomposition is demonstrated (see Section 3.b). While recent studies have improved understanding of PFAS migration, additional research is needed to resolve uncertainties (see Section 3.b.vi).

- **Landfill disposal of stable polymeric PFAS (all landfill types)**. Stable polymeric PFAS, such as polytetrafluoroethylene (Teflon™) and fluorinated ethylene propylene (FEP), are large molecules that are not susceptible to hydrolysis or oxidation. They are neither volatile nor water soluble and, as a result, they are expected to remain within the waste mass for long periods of time. This PFAS category tends not to migrate with the leachate and is unlikely to volatilize with the LFG; therefore, permitted hazardous and MSW landfills may provide a good disposal option. Some data are available to support this assessment, but more data are needed to resolve uncertainties (see Sections 3.b.i and 3.b.vi).

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

- **Thermal treatment at lower temperatures** including municipal waste combustors (MWCs), SSIs, or HWCs operating at lower temperatures or feeding solid or containerized PFAS materials. Some HWCs operate at temperatures near or below 1,100°C, while MWCs typically operate between 850 and 1,000°C, and SSIs typically operate at even lower temperatures. There is uncertainty associated with this option because it is based on very limited research. Limited data indicate the possibility of air emissions of some PFAS and PICs above the detection limits at

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

lower temperatures (Shields et al., 2023). No data are available regarding the treatment of PFAS-containing solid materials or containerized wastes at lower temperatures. There are currently insufficient data and information to conclude anything about PIC formation or PFAS air emissions from full-scale combustion units operating at these lower temperatures or when feeding solid materials or containerized wastes. Because insufficient data are available, there is low confidence in the reliability of this technology to control PFAS releases (see Section 3.a).

- **Disposal of volatile, water soluble, or oxidizable PFAS in construction and demolition (C&D) landfills.** This class of landfills may not have a composite liner or leachate collection system. Because of the potential for environmental releases, EPA does not recommend that PFAS waste, other than wastes containing stable polymeric PFAS, be disposed of in this type of landfill. While few studies have documented emissions of PFAS from C&D landfills, the known mobility of PFAS in landfills and lack of engineered controls at C&D landfills make them unsuitable for PFAS disposal. For these reasons, EPA does not expect that C&D landfills will minimize PFAS releases to the environment (see Section 3.b).

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

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

EPA emphasizes the importance for decision-makers (managers of PFAS-containing materials making decisions about destruction and disposal) to consider potential impacts to nearby communities when evaluating destruction, disposal, and storage options. In deciding how to address PFAS waste, site-specific considerations and waste characteristics should factor into the decision.

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

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

EPA websites, in particular, offer databases and tools such as *RCRAInfo*[7], which provides detailed information about facilities managing hazardous waste.

A general yet incomplete list of potential treatment and disposal facilities may also be available through the EPA Incident Waste Decision Support Tool (*I-WASTE DST*[8]). This list includes landfills (hazardous waste, MSW, industrial, and C&D), HWCs, and nonhazardous combustors (sewage sludge and municipal waste), but does not include all technologies available for PFAS destruction and disposal (e.g., cement kilns, carbon reactivation facilities, and underground injection facilities). *I-WASTE DST* is updated periodically and is limited to information available online.

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

[7] Available at: *https://enviro.epa.gov/envirofacts/rcrainfo/search*.

[8] Available at: *https://iwaste.epa.gov/*.

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

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

What's New in Section 2 of the 2026 Guidance Document?

- Information on updates and planned revisions to the PFAS 8(a)(7) reporting rule under TSCA (88 FR 70516, October 11, 2023).
- Updated biosolids generation and management information.
- Updated information on the PFAS National Primary Drinking Water Regulations.

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

Additionally, EPA's *Toxics Release Inventory (TRI) program*[9] collects data related to industrial releases and waste management of certain chemicals. The TRI program covers many, but not all, industry sectors and chemicals. Additionally, some facilities with a covered sector may not meet TRI reporting criteria. The TRI dataset includes, among other information, quantities of environmental releases to all media above certain thresholds (including on-site disposals and land application), as well as quantities transferred to off-site waste management facilities, including POTW. Under Section 7321 of the FY 2020 NDAA, certain PFAS were added to the TRI list beginning with Reporting Year 2020 (U.S. EPA, 2020b). As of Reporting Year 2023 (reporting forms due by July 1, 2024), a total of 189 PFAS are on the TRI list. TRI reporting data can be accessed at the *TRI Toolbox*[10].

In October 2023, EPA finalized the PFAS 8(a)(7) reporting rule under TSCA (88 FR 70516, October 11, 2023). In accordance with obligations under TSCA, as amended by the FY 2020 NDAA, the PFAS 8(a)(7) reporting rule requires any person that manufactures (including imports) or has manufactured (including imported) PFAS or PFAS-containing articles in any year since January 1, 2011, to electronically report information regarding PFAS uses, production volumes, disposal, exposures, and hazards. The PFAS 8(a)(7) rule will help EPA better understand and develop the most comprehensive dataset of PFAS sources and quantities manufactured in the United States. In May 2025, EPA announced an interim final rule which extended the dates of the reporting period for data submissions to April 13, 2026,

[9] Available at: *https://www.epa.gov/toxics-release-inventory-tri-program/what-toxics-release-inventory*.

[10] Available at: *https://www.epa.gov/toxics-release-inventory-tri-program/tri-data-and-tools*.

through October 13, 2026. On November 13, 2025, EPA proposed revisions and exemptions to the PFAS 8(a)(7) reporting rule and also proposed to amend the start date of the submission period to 60 days after the effective date of a future final rule. On April 13, 2026, EPA published a final rule that amended the submission period for the PFAS 8(a)(7) reporting rule to begin on January 31, 2027, or 60 days following the effective date of a forthcoming final action, whichever date is earlier. This final rule solely amends the start date of the data submission period; the proposed revisions in the November 2025 proposed rule will be addressed in a future final rule.

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 and may be released into the environment at every step in the production process, including during synthesis, polymerization, application, transport, usage, waste stream management, and disposal (3M Company, 2000b). Industrial waste streams containing PFAS stem from two main sources: (1) primary manufacturing facilities of PFAS, and (2) secondary industries that use PFAS or manufacture finished products that contain PFAS. A 2009 survey by OECD identified 27 primary manufacturers and processors of PFAS globally (OECD, 2011). At the time of that survey, more than 90 percent of the global annual production of PFAS was generated by eight manufacturers (Posner et al., 2009), all of which participated in EPA's 2010/2015 Perfluorooctanoic Acid (PFOA) Stewardship Program (U.S. EPA, 2006).

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

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

Table 2-1 lists examples of PFAS uses and the resulting solid, liquid, and gas waste streams for primary and secondary manufacturers of PFAS-containing materials and certain service sectors as indicated by industry, national and global inventories, and research. However, this list is not exhaustive or representative of all current uses, applications, recovery and recycling practices, or treatment technologies that could affect the volume and characteristics of the resulting waste streams. EPA recognizes the need for continued research to better characterize the multi-media PFAS-containing materials targeted for destruction or disposal, as discussed in Section 4.a.

2.a.i Solid-phase wastes

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

Other important solid-phase materials include sludges and biosolids (see Section 2.c) that result from stabilizing or treating process waters and wastewaters, either on site or at a municipal wastewater treatment plant (WWTP)[11] that receives influent from industrial sources (Venkatesan and Halden, 2013). In addition to solids produced via treatment, spent water treatment media (such as activated carbon and ion exchange resins) are part of this waste stream (see Section 2.e). Other direct industrial sources of solid wastes containing PFAS include intentional residuals, such as cuttings and fibers from textile manufacturing (see Section 2.d), and materials unintentionally produced outside of product specification. The concentrations and composition of PFAS in solid wastes generated from primary and secondary industrial sources vary by facility and depend on factors such as facility- or industry-specific production processes and the types and quantities of PFAS produced or used (ITRC, 2020).

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

2.a.ii Liquid-phase wastes

Primary manufacturers and secondary industrial users of PFAS can generate liquid-phase wastes in the form of: (1) liquid byproducts of PFAS synthesis to be recycled or disposed of (e.g., to a landfill) following stabilization, solidification, or another management method; (2) 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 training activities at industrial facilities. Table 2-1 provides examples of liquid wastes containing PFAS generated by industrial sources and their uses. This is not an all-inclusive list of industries nor waste streams.

Another liquid-phase waste stream is wastewater effluent discharged directly from a primary manufacturer or secondary industrial PFAS user. Effluent from wastewater treatment facilities that receive wastewater from industrial PFAS sources may also contain PFAS. According to several studies, conventional wastewater treatment technologies are generally ineffective at destroying or controlling PFAS (Schultz et al., 2006) and may result in higher measurable PFAAs (e.g., PFOA, perfluorooctane sulfonate [PFOS], and their homologues) when precursor compounds (e.g., fluorotelomers) are degraded during the treatment process (Buck et al., 2011; Dauchy et al., 2017a; Schultz et al., 2006;

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

Sinclair and 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, 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) which can be deposited at significant distances from their origin, and may result in soil and groundwater contamination (Dreyer et al., 2009; Ellis et al., 2004; Martin et al., 2006; Schenker et al., 2008).

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

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

Industry Type	Uses	Examples of Waste Streams[a]			Source
		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]			Source
		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)

Industry Type	Uses	Examples of Waste Streams[a]			Source
		Solid	Liquid	Gas	
Paper products/ packaging manufacturing	Waterproofing and grease proofing for products including food contact paper (e.g., plates, popcorn bags, pizza box liners, food containers, wraps), non-food contact applications (e.g., folding cartons, carbonless forms, masking papers).	Dusts; *solids coated with PFAS from processing, sampling, quality assurance; off-spec products.*[b]	Spillage, cleanup, and releases during opening, rinsing, and cleaning of PFAS totes.	Fugitive volatiles	U.S. EPA (2009a)
Pesticide/ fertilizer/ other agriculture chemical manufacturing	Pesticide and herbicide ingredients and packaging.	*Particulate emissions*	*Liquid residues from empty containers, spills, off-spec products*[b]*, cleaning of equipment, and process wastewaters.*	*Fugitive volatiles*	U.S. EPA (2023)
Plastic materials/ resins/ rubber product manufacturing	Used to make membranes used in fuel cells; chlor-alkali cells; water, caustic soda, and caustic potash electrolyzers; silicone rubber sealants; composite resins; polytetrafluoroethylene (PTFE, or Teflon); and polyvinylidene fluoride or polyvinylidene difluoride (PVDF). Processing aid for PVDF manufacture, mold-release agent in foam molding, and antiblocking agent for rubbers.	Dusts, spillage (micropowders and resins), cuttings, scrap, debris, and off-spec products[b]; particulate emissions.	*Liquid residues from empty containers, spills, and unused application mix.*	Fumes from PTFE heating (volatile)	Ebnesajjad (2015)
Textiles/ apparel/ leather/ carpets/ fiber manufacturing	Dispersion products that coat fabrics: jackets, shoes, umbrellas, carpets, upholstery, leather, tents, sails.	Solids coated with PFAS from cutting, shearing, packaging, laboratory and color sampling, quality assurance; flakes or dust containing PFAS; *off-spec products.*[b]	Spills, wastewater effluent from product adhering to inside of drum, and unused application mix.	Releases of vapors and aerosols during application of surface treatment and mechanical finishing.	U.S. EPA (2009a)

Industry Type	Uses	Examples of Waste Streams[a]			Source
		Solid	Liquid	Gas	
Aerospace component manufacturing	Mechanical components such as tubing, hoses, and seals; brake and hydraulic fluid additive; wire and cable insulation; used in coating and paint.		*Wastewater effluent*		FluoroCouncil (2019)
Automotive component manufacturing	Mechanical components such as tubing, hoses, and seals; brake and hydraulic fluid additive; anti-mist film on windshields; used in coating/paint; used in coatings or surface treatments of textiles and upholstery.		*Wastewater effluent*		FluoroCouncil (2019), ITRC (2020)
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 semiconduct or 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)

Industry Type	Uses	Examples of Waste Streams[a]			Source
		Solid	Liquid	Gas	
Mining industry	Surfactant for recovery of metals from ores; used in ore flotation to separate metal salts from soil, electrowinning of metals, and nitrogen flotation to recover uranium.	Contaminated rock from applied product.[d]	Applied product[d]		ITRC (2020)
Medical uses	Video endoscopes; catheters; saline solutions for in vitro diagnostics; treatment/coatings for textiles such as hospital gowns, curtains, drapes; dialysis machines.	*Laboratory/medical solid wastes (e.g., tubing, filters, films).*			FluoroCouncil (2019), Posner (2012)
Cosmetics and personal care product manufacturing	Used in cosmetics, hair conditioning formulations, hair creams, and toothpaste.	*Off-spec materials*[b]	*Wastewater effluent*		Danish EPA (2018), FluoroCouncil (2019), Schultes et al. (2018)
Fire suppression systems[e]	AFFF and certain dry fire-extinguishing agents.	Contaminated soil and debris from applied product.[d]	Applied product[d]		See Section 2.b for more information. Gaines (2023)

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

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

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

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

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

2.b Aqueous film-forming foam

AFFFs are a group of PFAS-containing fire extinguishing agents for low-flashpoint hydrocarbon fuel fires (Tuve et al., 1964) and 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 which extinguishes the fire and prevents burnback (FFFC, 2016; SERDP, 2020; Sheinson et al., 2002).

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

A 2004 inventory estimated that there were 4.6 million gallons of legacy PFOS-containing AFFF in the United States (Darwin, 2011). AFFF inventory depletion is determined by frequency of use for firefighting, training, or testing; transfers between locations; and other factors. However, AFFF's characteristically long shelf life means there should be little disposal due to expiration (FFFC, 2016), increasing the possibility that legacy PFOS-containing AFFF concentrate remains in service or reserve inventories. Fluorotelomer-based AFFF surfactant products became available in the 1970s (Prevedouros, 2006). In 2017, the U.S. Department of War (DoW) edited its military specification for AFFF to include no more than 800 parts per billion (ppb) of PFOA and PFOS in the concentrate, the limit set by the DoW *Quality Systems Manual 5.1*[12]. However, this specification does not mention any other PFAS standards.

In the United States, AFFF and associated systems are or have been in service at federal facilities, civil airports, and oil refineries. Civilian fire departments also use or have used AFFF. The federal government is working to identify areas of current and former federal properties where PFOS- or PFOA-containing AFFFs have been used (Darwin, 2011; DoD, 2020). Through March 31, 2025, DoW has determined that 723 active military installations, base realignment and closure (BRAC) locations, National Guard facilities, and formerly used defense site (FUDS) properties require an assessment of PFAS use or potential release. DoW is performing preliminary assessments/site inspections (PA/SIs) at these installations, which is the first phase of the cleanup process and may take two to three years to complete. As of March 31, 2025, DoW has completed the PA/SI phase at 703 installations. The Department has determined that no further action is required at 117 of these installations, while 586 installations are proceeding to the next step in the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process (DoW, 2025).

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

[12] Available at: *https://www.denix.osd.mil/edqw/denix-files/sites/43/2017/04/FINAL-QSM-5.1-SIGNED-010517-1.pdf*.

PRF-32725) (DoD, 2023). On *August 11, 2025*[13], DoW extended its deadline to end the use of AFFF until October 1, 2026, to provide more time to successfully transition to PFAS-free alternatives.

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
DoW	• Hundreds of military installations (active and former) with AFFF use. • In-service systems installed at an estimated 1,350 locations in aircraft hangars and on an estimated 3,000 ARFF vehicles.	• In 2016, DoW discontinued AFFF use for military installation training and testing unless the AFFF could be captured and properly disposed and is investing in fluorine-free alternatives. • The FY 2020 NDAA, asa modified by the FY 2026 NDAA, requires DoW to end use of AFFF at military installations by October 1, 2026 (with extensions possible until 2028). • Sources: DoD (2017, 2020); DoW (2019); CBO (2019); SERDP (2020)
NASA	• Multiple properties with AFFF apparatus. • Five properties with fixed systems.	• In late 2018, NASA issued order to cease training with AFFF. • Source: SERDP (2020)
DOE	• Lawrence Berkeley National Laboratory. • Brookhaven National Laboratory. • Los Alamos National Laboratory. • Strategic Petroleum Reserve facilities (Gulf of America).	• Sources: DOE (2021 *DOE Initial Assessment of PFAS at DOE Sites*[14]); Darwin (2011)
Airports and supporting facilities	• 523 Federal Aviation Administration (FAA)-certified civilian airports in 2018. • Since 2006, an annual average of nearly 600 certified airports. • Supporting facilities include firefighting training sites, such as the FAA Technical Center's Fire Training Area.	• Starting in 1972, FAA regulations allowed for the use of AFFF among a number of different extinguishing agents at civilian airports; since 2006, FAA guidance (FAA, 2006) provides that AFFF must conform to the applicable military specification (AC 150/5210-6 and MIL-F-23485F) at most civilian airports.[a] • 80 percent of respondents to a 2017 survey of U.S. and Canadian airports reported training-related discharge directly to the ground; two-thirds reported testing-related discharge directly to the ground. • FAA has taken steps to reduce AFFF discharges during testing since 2019. • Sources: DOT (2019); FAA (2006, 2019); Thalheimer et al. (2017); U.S. EPA (2020c)

[13] Available at: *https://texaschemistry.org/aws/TCC/pt/sd/news_article/599913/_PARENT/TCC_layout_details/true*.

[14] Available at: *https://www.energy.gov/sites/default/files/2022-11/DOE%20Initial%20PFAS%20Assessment%20-508.pdf*.

AFFF User	Locations	Comments
Fire departments	• At civilian fire departments throughout the United States.	• AFFF may be present at fire departments. • Some states have begun inventorying and reporting having AFFF (e.g., Michigan, New Hampshire). • Some states (e.g., Vermont) have take-back programs to help local fire departments identify AFFF in inventory and assist with removal and disposal. • Sources: Michigan PFAS Action Response Team (n.d.); New Hampshire Department of Environmental Services (2020); Vermont Agency of Natural Resources (n.d.)
Ships and other vessels	• Ships and other marine vessels, including the United States Coast Guard.	• Little information is available about AFFF quantities on ships. • There has been a shift toward non-fluorinated AFFF for some uses including testing and training, though the Coast Guard has indicated that certain uses (e.g., required inspections) must continue to use fluorinated AFFF. • Source: U.S. EPA (2020e)

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

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

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

Though subject to site-specific characteristics and conditions, studies demonstrate AFFF use at airports is a source of PFAS in soil and groundwater (Ahrens et al., 2015; Dauchy et al., 2017b; Høisaeter 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 (CWA) 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 (e.g., sewage sludge-only landfill), or (3) incinerated. The regulation at 40 CFR part 503 defines sewage sludge as "solid, semi-solid, or liquid residue generated during the treatment of domestic sewage in a treatment works." Sewage sludge includes scum or solids removed in primary, secondary, or advanced wastewater treatment processes and any material derived from sewage sludge (e.g., a blended sewage sludge/fertilizer product) but does not include grit and screenings or ash generated by the incineration of sewage. Sewage sludge treated for land application is commonly referred to as "biosolids." Part 503 considers domestic septage as sewage sludge and sets separate requirements for domestic septage applied to agricultural land, forests, or reclamation sites.

Influent that contains PFAS entering wastewater treatment facilities may result in the presence of certain PFAS in biosolids (Thompson et al., 2023; Helmer et al., 2022; Venkatesan and Halden, 2013). When biosolids are applied to land, there is the potential for leaching or runoff (Schaefer et al., 2022; Navarro et al., 2016; Lindstrom et al., 2011; Sepulvado et al., 2011; Washington et al., 2010). If landfilled instead, there are potential concerns with PFAS releases via landfill leachate and gaseous emissions, especially for highly organic material (Section 3.b). Alternatively, if incinerated, there is the potential for PFAS to be emitted as PICs (Section 3.a). Research needs and resources on possible emerging PFAS destruction technologies for biosolids (e.g., pyrolysis/gasification coupled with a thermal oxidizer and supercritical water oxidation) are discussed in Sections 4 and 5. Across disposal and destruction technologies, there are capacity concerns, and more research is needed on potential PICs/PIDs.

Total nationwide biosolids generation and management statistics in 2024 (reported to the EPA as of September 25, 2025) and data considerations are presented in Table 2-3. EPA does not have data on the volume or percentage of biosolids that contain PFAS. Additionally, EPA released the Draft Sewage Sludge Risk Assessment for PFOA and PFOS in January 2025 for public comment (U.S. EPA, 2025a).

Table 2-3. Biosolids Generation and Management in 2024

NPDES permits issued to POTW[a]	**16,109**
Biosolids NPDES permits[b]	9,834
Biosolids annual reporters (2024)[c]	2,350
Sewage Sludge generated in 2024 (dry metric tons)[d]	**4,008,886**
Land application of biosolids (dry metric tons)	2,386,861
Land disposal (also called surface disposal) (dry metric tons)	102,456
Incineration (dry metric tons)	558,360
Landfilling (dry metric tons)	879,721
Other management (dry metric tons)	81,488

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

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

[c] Annual reports are required for POTWs that have a design flow rate equal to or more than one million gallons per day, that can serve populations of 10,000 or more, that are Class I Sludge Management Facilities (POTWs required to have approved pretreatment programs or facilities classified as such by the EPA or state), or that are otherwise required to report (U.S. EPA, 2025b).

[d] The total amount of biosolids generated is reported by each treatment works treating domestic sewage (TWTDS) and may not equal the sum of component amounts reported for each management method. Biosolids totals do not represent PFAS presence in biosolids.

Release of PFAS into soils can occur through use of PFAS-containing products such as AFFF, and the discharge or application of treated industrial or municipal wastewater containing PFAS. Unintentional contact, such as spills or leaks during the production, handling, transport, or use of PFAS-containing materials can also be the source of PFAS in soils (see Table 2-4 for examples of industrial sources of PFAS in soils). 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 and Uy, 2003).
- Textiles made from fiberglass coated 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 shearing; and fugitive volatiles from spray applications of textile surface treatments. The destruction and disposal technologies used for these waste streams include landfill disposal and thermal treatment. For examples of industrial waste streams from the textiles/apparel manufacturing industry, see Table 2-4.

2.e Spent water treatment materials

On April 10, 2024, EPA announced the final National Primary Drinking Water Regulations (NPDWR) for six PFAS. On May 14, 2025, EPA announced that the Agency will keep the NPDWR for PFOA and PFOS. EPA also announced its intent to extend the PFOA and PFOS Maximum Contaminant Level compliance deadlines. Additionally, EPA announced its intent to rescind the regulations and reconsider the regulatory determinations for PFHxS, PFNA, HFPO-DA (commonly known as GenX), and the Hazard Index mixture of these three PFAS plus PFBS to ensure the determinations and any resulting drinking water

regulation follow the Safe Drinking Water Act process. Additionally, as of March 2023, 9 states have established separate state level MCLs limiting PFAS in drinking water

EPA has identified "best available technologies" for treating drinking water for PFAS to comply with the NPDWR, and these technologies will produce residuals. The 2026 Interim Guidance details options available to manage these residuals while minimizing environmental exposures and releases to the extent feasible. EPA notes that there are multiple approaches for water systems to manage PFAS residuals that are generated when PFAS is removed from drinking water. As of January 2026, there are no specific federal regulatory requirements for PFAS disposal, and the presence of PFAS in treatment residuals does not impose any additional federal requirements.

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

Although novel technologies for removing PFAS from drinking water sources and groundwater are being developed, current processes known to be effective are activated carbon, anion exchange resins, and high-pressure membranes (reverse osmosis [RO] and nanofiltration [NF]) (U.S. EPA, 2022a, 2022b). This section discusses the residual streams of these three processes (see Section 3 for discussions on treatment and disposal considerations, Appendix D for costs and considerations, and Section 4 for discussions of research needs for more novel treatments) and regulatory considerations for drinking water treatment utilities.

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

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

Treatment Process	Residuals Generated	Destruction/ Disposal Option(s)	Section Reference
Granular Activated Carbon (GAC)	Spent GAC	Reactivation	3.a.i.2
		Incineration	3.a
		Landfill	3.b
Powdered Activated Carbon (PAC)	Spent PAC	Incineration	3.a
		Landfill	3.b
Ion Exchange	Single use and regenerative ion exchange: spent resins	Incineration	3.a
		Landfill	3.b
	Regeneration brine	Interim Storage	1.c.
		Underground Injection	3.c.ii.1
RO/NF	Brine	Permitted discharge, direct or indirect	Not described in this guidance. Refer to permit.

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

2.e.i Activated carbon

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

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

For GAC, the range of PFAS concentrations on spent media can be estimated in several ways (Crone et al., 2019; U.S. EPA, 2020d). A conservatively high loading of PFAS onto GAC (using a GAC with a high-capacity potential, a strongly adsorbing PFAS, few competitive contaminants, low organic levels, and a high concentration in the feed water treated) is on the order of 2 percent by weight (e.g., 0.02 grams PFOS per gram of GAC). For more common treatment scenarios, or for PFAS that are adsorbed more weakly (i.e., the shorter-chain PFAS), the weight percent of PFAS will be orders of magnitude lower—about $1x10^{-5}$ grams PFAS per gram of GAC.

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

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

2.e.ii Ion exchange resins

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

Final PFAS loadings onto resins vary widely. A conservatively high estimate of loading (calculated using a PFAS-selective resin, few competitive constituents, and a PFAS known to adsorb well) is expected to be in the order of 10 percent by weight for the strongly adsorbing PFAS (e.g., 0.1 grams of 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 adsorbed more weakly (i.e., shorter-chain PFAS) will yield much lower average weight percent of PFAS.

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

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

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

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

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

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

2.f Landfill leachate containing PFAS

Landfill leachate (discussed in more detail in Section 3.b.iii.5) is the liquid formed by rainwater percolating through waste in landfills. Leachate generation may continue even after a landfill's closure

period, due to liquids inherent in the waste or if the cap system fails. There are different types of solid waste landfills characterized by the types of wastes managed, which also dictate the environmental controls employed. Hazardous waste landfills and most MSW landfills are required to collect the liquid leachate captured within the landfill liner and subsequently manage or treat the leachate. While PFAS concentrations in different landfill leachates have been documented (see Table 3-3 in Section 3), 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 POTW or TWTDS, where it is mixed with wastewater and treated. However, as noted in Section 2.a.ii, conventional wastewater treatment technologies are generally unable to treat or control PFAS (see Table 3-4). Other off-site treatment methods include incineration and underground injection (see Sections 3.a and 3.c, respectively). The on-site leachate treatment technologies employed at landfills are explored in Table 3-2 in Section 3.b.i. Additional research is needed to determine the efficacy of landfill leachate treatments for PFAS (see Section 4).

2.g Summary

PFAS are synthetic chemicals 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 can end up in solid, liquid, or gas waste streams from industrial facilities that manufacture or use PFAS and PFAS-containing products. Other common PFAS-containing waste streams include AFFF, biosolids, textiles, spent water treatment materials, and landfill leachate. Any of these waste streams can contribute to PFAS entering environmental media, including soil and groundwater. The potential destruction, disposal, and treatment technologies for processing these streams are discussed in Section 3.

2.h References

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

EPA has identified three existing and potentially available destruction and disposal technologies that may be effective for managing PFAS and PFAS-containing materials. These technologies are thermal treatment (Section 3.a), landfilling (Section 3.b), and underground injection (Section 3.c). Each subsection describes various considerations for these technological solutions, including types of treatment, potential for releasing PFAS into the environment, and uncertainties. References appear at the end of each subsection. See Section 5 for a discussion of emerging technologies that show potential to destroy PFAS. See Appendix A for EPA guidance on conducting PFAS emissions field testing at commercial thermal destruction sources. See Appendix D for a summary of costs and considerations.

What's New in Section 3 of the 2026 Guidance Document?

- Section 3.a:
  - Added 2024 test reports on PFAS destruction at two incinerators (Clean Harbors and Veolia) and a recent study on treatment of HFPO-DA.
  - Discussed recent studies using sewage sludge incinerators (SSIs) and thermal oxidizers with carbon adsorbers for PFAS treatment.
- Section 3.b:
  - Discussed recent studies on using sewage sludge incinerators for PFAS treatment.
  - Added PFAS concentration data for MSW and ash landfill leachate, MSW LFG condensate, and LFG from RCRA Subtitle D landfills.
  - Added data on landfill liner permeability and gas collection systems and the implications for PFAS transport and transformation.
  - Updated the section regarding on- and off-site PFAS treatment technologies for landfill leachate.
  - Added new information on non-targeted analysis, uncertainties, and unknowns.
- Section 3.c:
  - Updated Class I well inventory using 2023 data.

3.a Thermal treatment

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

Thermal treatment units generally use high-temperature combustion and incineration to destroy organic materials and control organic pollutants. Incineration is an effective and permitted method for destroying certain halogenated organic chemicals including chlorinated solvents, polychlorinated

biphenyls (PCBs), dioxin-laden wastes, brominated flame retardants, refrigerants, and ozone-depleting substances.

Combustion is described by complex sets of physical processes and elementary reactions involving many intermediate and free radical species. Even combustion of a simple fuel, such as methane, involves several hundred elementary reactions. For more complex fuels or systems that include additional elements, such as fluorine, elementary reactions can number in the thousands or more. These elementary reactions describe pathways or mechanisms whereby large molecules, such as PFAS, decompose and transform during combustion. Generally, breaking carbon-fluorine (C-F) bonds require more energy and higher temperatures than needed to break C-C, C-Cl, and C-H in analogous molecules. Due to their thermal stabilities, short-chain perfluoroalkanes such as hexafluoroethane (C_2F_6) may be good indicators of broader PFAS decomposition (Guzman et al., 2025; Shields et al., 2025a; Troxler et al., 2025; Ram et al., 2025). In addition, these short-chain perfluoroalkanes may be relatively easy to monitor by FTIR (Weber et al., 2025) and are targets measured in whole gas samples by OTM-50 making them candidates for broad PFAS thermal decomposition. The exceptional stability of CF_4 requires much higher temperatures (above 1,400°C) to destroy compared to other fluorinated organics. Thus, while unrepresentative of broader PFAS destruction, CF_4 may be a useful species during PFAS thermal destructibility trials to confirm recovery of gases by FTIR or OTM-50.

Thermal treatment of halogenated organic compounds yields the corresponding halogen acid when utilizing sufficiently high temperatures, residence times, and mixing to promote mineralization. In the case of fluorinated organics, mineralization yields hydrogen fluoride (HF), carbon dioxide (CO_2), and water. If any of these parameters are insufficient, this treatment may lead to the formation of fluorinated PICs. Some of the PICs produced in the decomposition process may have higher thermal and chemical stabilities than the parent PFAS.

Introducing PFAS directly into a hydrocarbon-based flame can assist in their adequate destruction and mineralization. The flame may provide reactive free radicals which facilitate the initial decomposition of PFAS. Hydrogen containing radicals (e.g., H and OH) and water vapor facilitate the breakdown of remaining species resulting in HF formation (Weber et al., 2025). Fluorocarbon radicals generated from incomplete thermal treatment of PFAS contribute to fluorinated PICs due to their thermal stability and propensity to undergo radical-radical recombination (Krug et al., 2022; Xu et al., 2025; Guzman et al., 2025). Thus, it is important for hydrogen to be in stoichiometric excess relative to fluorine to minimize the formation of fluorinated PICs.

Many PFAS are composed of highly stable fluorinated carbon chains and relatively weakly-bonded, non-fluorinated functional groups. Often, the functional group is easily removed, allowing the fluorinated chain to decompose or react with other radicals and create a variety of intermediates and products. For example, Shields et al. (2023) observed temperature-dependent production of 1H-perfluoroalkanes and other volatile fluorinated PICs during pilot-scale incineration of an AFFF containing PFOS and PFHxS. Additionally, Rocchio et al. (2025) and Weber et al. (2025) recently demonstrated that inadequate thermal treatment of PFOA or HFPO-DA, respectively, may lead to regeneration of shorter perfluorocarboxylic acids as PICs.

Certain thermal technologies can potentially achieve the operating conditions (e.g., temperature, residence time, turbulence) needed to adequately destroy and mineralize fluorinated organic compounds, but not every unit typically operates at these conditions. Recent data shows promise for two facilities, but data are lacking about the effectiveness of the operating conditions in different

thermal destruction technologies and facilities. Further methods development to evaluate more classes of potential PICs and testing at individual facilities are needed to help determine the overall effectiveness of thermal treatment. As a result, EPA does not have specified conditions for the adequate destruction of PFAS, but promising results inform the recommendation for comprehensive testing following procedures in Appendix A at any thermal treatment facility planning to treat PFAS-containing waste.

Hazardous waste combustion technologies (e.g., commercial incinerators, cement kilns, and LWAKs) can potentially achieve temperatures and residence times sufficient to break apart the PFAS contained in the waste stream being thermally treated, but not every unit currently operates at those conditions and those that do may not operate at those conditions at all times. To assess the capability of HWCs to destroy the materials fed into them and ensure that harmful emissions into the environment are minimized, it is standard practice to evaluate the DRE of one or several principal organic hazardous constituents (POHCs) during a trial burn. POHCs are selected to be at least as difficult to destroy as the feed material, based on an incinerability index scale (i.e., the relative level of difficulty for destroying a particular compound); however, the existing index does not include PFAS compounds. Permitted hazardous waste facilities have stringent regulatory controls on temperatures and other important operating parameters and require greater than 99.99-percent DRE for each selected POHC. Some HWC are also permitted under TSCA to incinerate PCBs and have a further requirement to demonstrate a DRE of 99.9999 percent for PCBs as well as even more stringent operating requirements with respect to residence time and temperature (40 CFR 761.70(a)(1)) when incinerating PCBs.

For HWCs, DRE is calculated based on the amount of a specific chemical (e.g., POHC) entering a thermal treatment device compared to the amount of that chemical present at the exit. While the compound selected for DRE determination in an HWC is chosen based on the difficulty of destroying it, DRE does not account for chemical transformations into different organic compounds (i.e., PICs). Thus, DRE is not an accurate indicator, by itself, of complete PFAS mineralization. Shields et al. (2023) demonstrated that PIC formation can occur even when high DRE is measured at temperatures below 1,000°C. Therefore, it is not accurate to state that a high DRE of the parent molecule by itself indicates complete destruction of all PFAS. It is difficult to ascertain the complete destruction of the added PFAS, and subsequent PICs produced due to measurement limitations. Instead, the term “adequate destruction” is used in this guidance to represent appropriate PFAS and PIC attenuation, given the gaps in accuracy of current measurement methodologies. To fully evaluate whether adequate destruction is occurring, EPA and other investigators need to sample and analyze a range of chemicals present at the outlet of a thermal treatment device, including the specific PFAS in the feed material, other PFAS beyond those in the feed (i.e., potential PICs), and other fluorinated compounds. EPA is developing test methods for measuring most PFAS before and after the incineration process, and new methods are being advanced that will provide more information in the coming years. Currently, OTM-45 is available for a targeted list of polar semivolatile PFAS and OTM-50 for volatile fluorinated compounds (VFCs). Test methods are in development for semivolatile nonpolar PFAS as surrogates for the class of PFAS compounds and fluorinated compounds (see Section 3.a.iv).

For this version of the interim guidance, PFAS destruction is defined as the severing of all carbon–fluorine bonds in a PFAS molecule and the mineralization of carbon and fluorine to HF, CO_2, and water. HF and some of the other products of combustion can be effectively removed in pollution control devices designed for acid gas removal, although more research regarding the efficacy of these technologies for controlling PFAS PICs is warranted (see Section 4).

EPA currently has limited data characterizing emissions from HWCs that burn PFAS (Focus Environmental, 2021, 2022) (see Appendix B), a comprehensive test including an evaluation of PICs at Clean Harbors in Aragonite, Utah (Troxler, et al. 2025), a comprehensive test including an evaluation of PICs at Veolia in Port Arthur, Texas (Veolia North America, 2025), and data from a pilot-scale study at an EPA research facility (Shields et al., 2023, 2025a; Weber et al., 2025). These recent tests at Clean Harbors in Aragonite, Utah (Troxler et al., 2025) and Veolia in Port Arthur, Texas (Veolia North America, 2025), which include determination of PICs, are promising and indicate that some HWCs can operate under conditions where high mineralization of PFAs and minimal formation of PIC are possible. As each HWC is optimized for the type of waste it treats, additional testing is necessary to determine if and what site-specific conditions are necessary to achieve high DRE with a corresponding minimization of PIC formation. Additional studies are necessary to more fully measure and evaluate the ability to approach complete mineralization and eliminate potential formation of PICs. EPA is working to advance new measurement methodologies (see Section 3.a.iv.1) and gather additional information to conclude whether potential PICs are adequately controlled (see 6.cAppendix A).

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

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

3.a.i Types of thermal treatment

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

3.a.i.1 Hazardous waste combustors

HWCs include hazardous waste incinerators (HWIs), cement kilns, LWAKs, boilers, and hydrochloric acid production furnaces that burn hazardous waste. Two types of HWCs that have treated PFAS waste in the United States are commercial[15] incinerators and LWAKs. Currently, no LWAKs fire hazardous waste.

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

All HWCs are subject to RCRA and Clean Air Act (CAA) permitting requirements[16,17] that provide additional regulatory oversight and include operating requirements and emission limitations to safely and effectively treat regulated hazardous contaminants which may not be required for non-permitted facilities. These types of HWCs are subject to CAA Title V permitting requirements, and to maximum achievable control technology standards pursuant to Section 112 of the CAA (40 CFR part 63, subpart EEE). These standards include emission limitations for metals, dioxins/furans, particulate matter, hydrogen chloride (HCl) and chlorine gas, and carbon monoxide or hydrocarbons, as well as limits on minimum organic DRE, but do not include emission limitations for PFAS. Also, under the authority of RCRA's "omnibus" clause (Section 3005(c)(3); see 40 CFR 270.32(b)(2)), RCRA permit writers may impose additional terms and conditions on a site-specific basis as may be necessary to protect human health and the environment. Due to these additional safeguards, permitted HWCs may operate under conditions more conducive to destroying PFAS and controlling related PICs relative to thermal treatment units that do not have both RCRA and CAA permits. Further, incinerators permitted to fire liquid PCBs are required to meet even more stringent operating requirements with respect to time and temperature (40 CFR 761.70(a)(1)) when incinerating PCBs, and these operating conditions may be even more conducive to destroying PFAS and controlling PIC formation. The following sections generally describe the design and operational parameters of commercial HWIs, LWAKs, and cement kilns, focusing on parameters that are important for destroying PFAS. Design and operation information summarized for HWCs is generally based on background support documents for previous rulemakings (U.S. EPA, 2005b). Information on the numbers of HWC facilities is based on a 2019 national hazardous waste capacity assessment report (U.S. EPA, 2019) which also provides a list of these facilities. In addition to the commercial HWCs, many chemical facilities operate captive hazardous waste boilers and incinerators that only burn waste generated by that particular site or other sites owned by that parent company. These captive units may operate at temperatures lower than that of typical commercial units because of their narrow waste profile. Data gathered from commercial incinerators may not be indicative of potential control of a particular captive unit due to site-specific design and operating conditions.

3.a.i.1.1 Commercial hazardous waste incinerators

Currently, there are 10 commercial HWI facilities operating in the United States. HWIs are designed to optimize temperatures, residence times, turbulence, and other parameters to ensure compliance with organic DRE requirements.[18] Three of these facilities are also permitted for incineration of PCBs. Most commercial HWIs use rotary kilns as primary combustion chambers to facilitate the thermal treatment of containerized wastes (e.g., in drums) and solid wastes such as contaminated soils. Aqueous wastes that have low heating values may also be pumped into the rotary kiln.

The kiln maintains a continuous standing flame fueled by wastes with high heating values and auxiliary fuels that maintain high temperatures. Typically, solids retention time in the kiln is 0.5 to 1.5 hours,

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

[17] 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.

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

while gas residence time through the kiln is usually around two seconds. Kiln flame/solids temperatures range from 650°C to 1,650°C (1,200°F to 3,000°F) (U.S. EPA, 2005b).

After combustion in the rotary kiln, wastes may be moved to an afterburner or secondary chamber. If an afterburner is used, additional gaseous and liquid wastes with high heating values and auxiliary fuels may be added. The afterburner/secondary chamber is typically operated at about 1,100°C to 1,370°C (2,000°F to 2,500°F) with a gas residence time from one to three seconds to maximize organic destruction and minimize the formation of PICs (U.S. EPA, 2005b). Depending on the fuels used and waste streams introduced, combustion products might include CO_2, water, nitric oxide, a variety of acid gases (sulfur dioxide, hydrochloric acid, HF, etc.), organic PICs, fly ash, and bottom ash constituents. Bottom ash is removed at the end of the kiln and from the bottom of the afterburner/secondary chamber and is typically disposed of in hazardous waste landfills (see Section 3.b). Fly ash entrained in the gas is removed downstream by fabric filters (FFs) or electrostatic precipitators (ESPs), and acid gases are removed by gas scrubbers. Some HWIs use activated carbon injection systems to control mercury, dioxin/furan, and other emissions, and some also use TMT-15 (1,3,5-triazine-2,4,6(1H,3H,5H)-trithione, trisodium salt) injection for additional control of mercury and metal emissions.

EPA currently has limited data characterizing emissions from HWI that burn PFAS:

- Multi-year tests of a specially designed thermal oxidizer at a Chemours production facility (Focus Environmental, 2021, 2022, 2023, 2024), see Appendix C.
- A comprehensive test including an evaluation of PICs at Clean Harbors in Aragonite, Utah (Troxler et al., 2025).
- A pilot-scale study at an EPA research facility (Shields et al., 2023, 2025a; Weber et al., 2025).
- A comprehensive test including an evaluation of PICs at Veolia in Port Arthur, Texas (Veolia North America, 2025).

The Clean Harbors, EPA pilot-scale, and Veolia studies summarized below, and the Chemours production facility data summarized in Appendix C, provide some insight on the potential efficacy of thermal treatment in an HWI. To date, the commercial facility studies have focused on the removal of easily transformed PFAS target compounds, which is a significant limitation.

Clean Harbors Environmental Services. Two testing campaigns (2021 and 2022) were conducted at Clean Harbors Environmental Services' hazardous waste incinerator located in Aragonite, Utah (EA Engineering, Science, and Technology, Inc., PBC., 2021, 2022). These tests are summarized in detail in Appendix B. The incinerator is permitted under both the RCRA and TSCA programs. Each test campaign was divided into three test conditions: Baseline (Condition 1), Augmented PFAS Feed (Condition 2, where known amounts of four or five target PFAS were fed to the incinerator), and Post-spiking Normal Operations (Condition 3, where AFFF was included in the incinerator feed). OTM-45 (Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources) was used for stack gas sampling and analysis. The 49 targeted PFAS analytes were measured using liquid chromatography/tandem mass spectrometry (LC/MS/MS) with isotope dilution. Utilizing the available analytical methods at the time, the Clean Harbors study demonstrated a DRE for the legacy PFAS in the 99.9999-percent range at temperatures around 1,100°C. Of the 49 compounds detected by OTM-45, 34 were non-detectable in the stack gas and only 15 were detectable at extremely low concentrations. The tests appear to demonstrate that the facility's primary objective was met: "demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed

during normal process operating conditions." Although a high DRE was achieved (greater than 99.999 percent) for the five selected PFAS compounds that were subjects of these studies, these tests did not collect data to fully support demonstration of adequate destruction as the production of PICs were not evaluated due to methodology limitations.

A third test campaign (conducted by EPA, Clean Harbors, and SERDP in 2024 at Clean Harbors in Aragonite, Utah) performed the comprehensive testing outlined in Appendix A (Troxler et al., 2025). During the test, PFAS-containing AFFF and nine additional PFAS were added to the incinerator along with the typical hazardous waste feeds. The gaseous, liquid, and solid end products were sampled and analyzed for the presence of PFAS and other fluorinated compounds. The kiln exit temperature during testing was greater than 1,097°C (2,006°F) and the secondary combustion chamber was operated at greater than 1,120°C (2,048°F). Results showed that the measures of the incinerator's DRE ranged from 99.95 to 99.9999 percent for the added PFAS tested under these conditions. Additionally, the analyses of the gas phase emissions showed low to non-detectable levels of VFCs that could be considered destruction of PFAS PICs using OTM-50 and SW-846 Method 0010/8270. Finally, test runs were performed with the quantitative addition of C_2F_6 with the waste streams to investigate its potential use as a surrogate compound. The resulting DRE for C_2F_6 ranged from 99.999 to 99.9999 percent and were similar to those of the other spiked compounds. These results suggest correlation between high C_2F_6 DRE and the absence of PICs. While this result is promising, more field data is required to establish C_2F_6 as an appropriate surrogate compound. There were uncertainties and limitations to the data that should be considered when evaluating the overall effectiveness of thermal treatment for PFAS.

EPA PFAS thermal destruction research. EPA completed an initial study examining the relationship between destruction efficiency (DE) and PICs (Shields et al., 2023). This study used a pilot-scale research furnace and atomized a PFOS-dominant AFFF at various furnace locations and combustion environments. These included atomization through the flame with the natural gas auxiliary fuel and at various post-flame locations so that the AFFF would experience decreasing peak temperature exposures ranging from approximately 1,200°C to 800°C (2,192°F to 1,472°F). Stack measurements included OTM-45 and OTM-50. Instead of DREs, this study calculated DEs because samples were collected before any pollution control (i.e., removal equipment), including fabric filter and alkaline wet scrubber. Analysis of the AFFF and OTM-45 samples was used to calculate DEs for 10 PFAS quantified in the AFFF. OTM-50 was used to quantify concentrations of 30 PFAS PICs. Results indicate that several idealized operating conditions with peak temperatures above 1,090°C (1,976°F) resulted in high DEs (greater than 99.99 percent) and low PIC emissions that were near or below the detection limits. However, several conditions below 1,000°C (1,832°F) yielded substantial concentrations (milligrams per cubic meter [mg/m^3]) of volatile fluorinated PICs, despite achieving over 99.99-percent DE for PFAS quantified in the AFFF. The study concluded that DE alone may not be the best indication of PFAS destruction. Additionally, EPA recently assessed thermal treatment of atomized aqueous solutions of HFPO-DA (Weber et al., 2025). Here, HFPO-DA was destroyed efficiently (DE above 99.99 percent) at peak furnace temperatures at or above 750°C, but yielded fluorinated PICs whose concentrations decreased with increasing peak temperatures.

Veolia Environment SA. Veolia conducted two test campaigns at their HWI located in Deer Park, Texas in Summer and Fall 2024 (Veolia North America, 2025). The two campaigns consisted of multiple test conditions, firing of AFFF, AFFF-contaminated soil, AFFF with lime injection (1 test run), spent activated carbon, and an assessment of CF_4 as a potential POHC (1 run). Prior to each test campaign feed variation, a baseline test run was conducted while no PFAS were fed to the combustor. In addition to

stack samples analyzed by OTM-45 and OTM-50, liquid and solid residues (scrubber blowdown, ash, slag, and filter cake) were sampled and analyzed. The kiln exit temperature during testing was greater than 816°C (1,500°F) and the secondary combustion chamber was operated at temperatures greater than 1,093°C (2,000°F). During the baseline tests, even without detectable PFAS in the waste feeds, small amounts of some PFAS were detected at the stack. Some of these were detected in the process water used in the quench, the scrubbers, and the wet ESP (WESP) indicating the possibility of the process water being a contributing source to emissions. DRE was determined for all potential PFAS, but with decreasing input, DRE determinations become less reliable indicators, as the potential noise and detection limits become dominating factors in the calculations. DRE was assessed for every target PFAS according to OTM-45. In many cases, these evaluations were not indicative of performance due to the low feed rate and detection limits at the stack. The DRE results of 20 PFAS with the highest feed rates ranged from 99.807 to 99.9999 percent. For all PFAS introduced at a feed rate greater than 0.02 lb/hr, the DRE exceeded 99.99 percent. Results of the OTM-50 sampling for volatile, nonpolar PFAs showed detectable emissions of CF_4 in only 3 of 15 sample runs (including the DRE test run where CF_4 was spiked) and a single test run where heptafluoropropyl 1,2,2,2-tetrafluoroethyl ether was detected near the method detection limit (MDL). The single spiked run of CF_4 seems to indicate that it is not appropriate as a POHC with a DRE of 43 percent for CF_4 under identical conditions to those tests showing high DRE of select PFAS and minimal PIC formation (as demonstrated by the results of the OTM-50 analysis).

These recent tests at Clean Harbors in Aragonite, Utah (Troxler et al., 2025) and Veolia in Port Arthur, Texas (Veolia Environment SA, 2025) including determination of PICs are promising, indicating that some HWCs are capable of operating under conditions where high mineralization of PFAS and minimal formation of PIC are possible. As each HWI is optimized for the type of waste it treats, additional site-specific testing is necessary to determine if, and what site-specific conditions are necessary to achieve high DRE with a corresponding minimization of PIC formation. Additional studies are necessary to more fully measure and evaluate the ability to approach complete mineralization and eliminate potential formation of PICs. EPA is working to advance new measurement methodologies (see Section 3.a.iv.1) and gather additional information to conclude whether potential PICs are adequately controlled (see Appendix A).

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

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

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

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

A cement kiln in Australia has received an operating permit from the government of Queensland to burn PFAS wastes. The permit requires annual monitoring for 21 PFAS (Department of Environment and Heritage Protection, 2018). Test results from 2017 indicate that a DRE greater than 99.99 percent is possible for specific PFAS compounds at the conditions of the test (Cement Australia, 2017), but the results do not present data on overall PFAS destruction or potential formation of PICs.

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

The one LWAK facility in the United States that burned hazardous waste ceased operation in early 2024. LWAKs thermally process raw material (clay, shale, and slate) in slightly inclined, rotating furnaces to produce a coarse aggregate used in lightweight concrete products. In hazardous-waste-burning LWAKs, liquid wastes are either blended directly with conventional fuels burned in the hot end of the kiln or pumped separately into the hot end flame. High combustion gas flame temperatures (above 1,650°C [3,000°F]) and high kiln gas residence times (over two seconds) are used to destroy hazardous organics. Kiln exhaust gases leave the cold upper end of the kiln at a temperature from 205°C to 540°C (400°F to 1,000°F). LWAKs use FFs to control dust contained in the exhaust gas. The collected dust can be recycled back into the kiln (at the hot or cold end) or mixed into the lightweight aggregate product. Some LWAKs also use wet or dry scrubbing for acid gas emissions control. For example, the currently permitted hazardous-waste-burning LWAK has dry scrubbing for acid gas control. There are insufficient data to determine the effectiveness of commercial LWAK facilities in treating PFAS waste.

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

Carbon reactivation units or "furnaces" use high temperatures to thermally desorb contaminants from GAC, which allows for the carbon to be used again. Over a dozen large-scale companies and utilities in the United States reactivate sizeable quantities of GAC. In all, these entities operate about 17 commercial furnaces (Roskill Information Services Ltd., 2017). Four of these commercial furnaces operate under RCRA permits and applicable air permits. RCRA permits provide additional regulatory oversight and include operating requirements and emission limitations to promote safe and effective treatment of the hazardous contaminants; non-RCRA-permitted carbon reactivation furnaces may not be subject to such requirements. Due to these additional safeguards, RCRA-permitted furnaces may operate under conditions more conducive to destroying PFAS and controlling related PICs, relative to furnaces without RCRA permits. This discussion focuses on RCRA-permitted furnaces because EPA has more design and operational information on these devices because of the RCRA permitting process. Reactivation[19] of spent carbon is generally carried out in multiple-hearth ("multi-hearth") or rotary kiln furnaces, although fluidized bed and infrared furnaces are also options. While the furnace designs vary,

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

they all use high temperatures and residence times designed to eliminate the adsorbed contaminants and return the carbon to its original state for reuse.

During reactivation, spent GAC is typically exposed to drying, desorption, pyrolysis, and oxidation as it moves through the furnace. The drying stage eliminates moisture via evaporation and occurs when hot combustion gases at temperatures ranging from 100°C to 110°C (212°F to 230°F) contact the carbon. During the desorption stage, hydrocarbons, hydrogen, and water vapor escape the pores of the granular carbon at temperatures of 315°C to 400°C (600°F to 750°F). The pyrolysis stage eliminates any volatile compounds adsorbed within the carbon porosity, including residual moisture, and thermally decomposes other less-volatile compounds. Pyrolysis occurs when the carbon is exposed to temperatures up to 800°C (1,472°F) under inert conditions (i.e., low oxygen). A residue of carbonized char is formed from the adsorbed compounds during pyrolysis, which occupies some of the carbon porosity and must be removed in the next stage. The oxidative stage involves the controlled gasification of the pyrolyzed carbon at temperatures of around 800°C (1,472°F) in the presence of a mildly oxidizing atmosphere, usually steam or CO_2 or a mixture of both. This results in the elimination of most of the charred residue and exposes the original carbon-pore structure (Miguel et al., 2001).

The residence times required for carbon reactivation vary by unit design and the contaminant loads and concentrations. For example, two facilities using multi-hearth furnaces have residence times of at least 38 minutes at one facility and between 90 and 120 minutes at the second facility (Kentucky Energy and Environment Cabinet, 2019; U.S. EPA, 2018).[20]

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

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

A study on a full-scale carbon reactivation furnace (DiStefano, 2022) consisting of OTM-45 and EPA Method 26A measurements of HF conducted before and after the thermal oxidizer showed DRE greater than 99.99 percent for select PFAS, with most of the destruction occurring prior to the thermal oxidizer. However, these test data do not demonstrate adequate destruction of PFAS due to the lack of data concerning PIC formation. Another recent study on a full-scale carbon reactivation furnace

[20] 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.

(Mayerberger et al., 2025) utilized OTM-45 to calculate DREs of GAC-bound PFAS. Temperatures and operating conditions tested at this study yielded DREs greater than 99.99 percent for most detected PFAS (excluding GenX), with the majority of PFAS destruction occurring within the reactivation furnace, (i.e., prior to thermal oxidizer and other pollution control devices). The authors reported high levels of GenX in the OTM-45 test blanks, possibly due to contamination or method interference, complicating a reliable GenX DRE calculation. Additionally, OTM-50 and EPA Method 0010/8720 were employed to characterize fluorinated PICs/PIDs, resulting in no detectable PICs/PIDs at the kiln outlet and stack (e.g., pre- and post-pollution control device) locations. These results serve as a successful (albeit limited) example of adequate PFAS destruction within a GAC reactivation furnace, though subsequent demonstrations of destruction and removal of GAC-bound PFAS and secondary PICs/PIDs at similar facilities are warranted.

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

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

3.a.i.3.1 Sewage sludge incinerators

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

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

An FBC consists of a vertically oriented outer steel shell with nozzles designed to deliver fluidizing air at the base of the furnace within a refractory-lined grid. Air is injected into the furnace to fluidize the sludge and the sand. The combustion of the sludge occurs at temperatures from 750°C to 925°C (1,400°F to 1,700°F). The gas residence times are typically two to five seconds. Emission controls on FBCs can include venturi scrubbers, multicyclones, FFs, activated carbon injection, and carbon bed absorbers.

There is substantial variation in the design and operation of SSIs, and it has not been shown that standard operating conditions are effective for the treatment of PFAS. A study of a laboratory-scale continuous bubbling FBC operating at 1,562°F (850°C) examined DRE for 5 PFAS. While the DRE of individual PFAS was not assessed, the total PFAS DRE (with respect to the 5 compounds) was greater than 99.9 percent. However, these test data do not demonstrate adequate destruction of PFAS due to the lack of data concerning PIC formation (Urciuolo et al., 2025). A second study of PFAS emissions from two full-scale SSIs yielded unusable OTM-45 results due to issues with the analysis of samples, and the DRE estimates provided (95 percent) are overstated due to the analytical issues. This study also showed measurable PFAS in the process water supplied to the wet scrubber, and those same PFAS in the stack

samples, but could not determine if the emissions were a result of stripping in the scrubber. Emissions of short-chain volatile PFAS (CF_4, C_2F_6, and C_3F_8) were detected using EPA Method 320, suggesting incomplete mineralization of PFAS was occurring (Winchell et al., 2024). The data currently available are insufficient to determine the effectiveness of SSIs in treating PFAS.

3.a.i.3.2 Municipal waste combustors

There are 193 MWC units operating at 75 facilities in the United States (Michaels and 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. Emission controls on MWCs can include spray dryer or dry sorbent injection, ESPs, FFs, selective or non-selective catalytic reduction, and activated carbon injection.

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 grate typically has three sections. On the initial grate section, referred to as the drying grate, the moisture content of the waste is reduced before ignition. Evaporated moisture is combined with the moisture from combustion and treated with the resulting combustion gases. The second grate section, referred to as the burning grate, is where most of the active burning takes place. The third grate section, referred to as the burnout or finishing grate, is where remaining combustibles in the waste are burned. Typical combustion temperatures for mass burn units can range from 800°C to 1,100°C (1,500°F to 2,012°F) (Reddy, 2016).

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

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

Research and testing of PFAS destruction performance within MWCs is extremely limited, primarily comprising laboratory- and pilot-scale studies (Aleksandrov et al., 2019; Taylor et al., 2014). For example, to assess whether PTFE is destroyed or reformed as PFAS, the Aleksandrov et al. (2019) study uses a pilot-scale rotary MWC with afterburner chamber combusting PTFE granules added to wood pellets (also firing natural gas). This study looked at a half-load scenario of 870°C (1,600°F) with a four-second residence time and a full-load scenario of 1,020°C (1,870°F) with a 2.7-second residence time. The study analyzed the flue gas samples collected for 31 PFAS compounds, which were assumed to represent a broad range of PFAS. While the laboratory- and pilot-scale studies conclude that MSW incineration of PTFE is not a significant source of PFAS, the laboratory thermal reactor and the pilot incinerator used in these studies may not be representative of the design of MWC units currently operating in the United States. These studies determined emissions, but did not assess the destruction efficiency of the laboratory thermal reactor and the pilot incinerator. For example, the pilot-scale unit in the Aleksandrov et al. (2019) 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 these studies conducted analysis for several PFAS species, 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.

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

3.a.i.4 Thermal oxidizers

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

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

Annual testing campaigns (2020 and through 2025 tests reports are available and summarized in Appendix C) were conducted on a thermal oxidizer installed to control PFAS emissions at a Chemours chemical and plastics manufacturing plant located in Fayetteville, North Carolina. The objective of the tests was to ensure the thermal oxidizer and 4-stage scrubber system achieve a 99.99-percent emission reduction for hexafluoropropylene oxide dimer acid (HFPO-DA) and other PFAS. The test reports demonstrate a PFAS destruction efficiency above 99.99 percent for the specific compounds that were tested, although there was no discussion of possible PICs in the reports. The thermal oxidizer at the Chemours facility appropriately destroys the five PFAS compounds of interest that have been identified at the facility.

The thermal oxidizer at Chemours' Fayetteville works was sampled using OTM-50 for nonpolar VFCs that may be potential PICs. The published results and compliance data show that tetrafluoromethane was the only volatile fluorinated compound measured in the thermal oxidizer emissions (Shields et al., 2025b). The high concentrations of fluorinated compounds in the influent create high concentrations of fluorine radicals that can bond to trifluoromethyl radicals to form tetrafluoromethane that is too stable to be destroyed. From the percent-level PFAS and fluorochemical fed into the thermal oxidizer, only 2 to 4 parts per million by volume (ppmv) of tetrafluoromethane were measured. However, removal processes for more polar PICs or destruction of potential compounds not studied but potentially found in the facility waste streams are still unclear.

A test was performed in November 2021 on the regenerative thermal oxidizer at the Saint-Gobain Performance Plastics Merrimack, New Hampshire facility (Barr Engineering, 2022). This test included evaluations of OTM-45 at the inlet and the outlet of the thermal oxidizer and showed a DRE of 92 percent for PFOA and 75 percent for PFOS. However, these test data do not demonstrate adequate destruction of PFAS due to the lack of data concerning PIC formation. Further data are needed to assess the variety of configurations and operating conditions associated with thermal oxidizers, as exemplified by the broad range of DRE determinations and the lack of data on PIC formation.

3.a.ii Limitations and considerations in thermal treatments

Incinerator designs vary, resulting in differing operational and waste feed approaches (see Section 3.a.i). HWIs typically operate at very high average temperatures and employ auxiliary, primary, and secondary flames. The primary focus of hazardous-waste-burning cement kilns and LWAK is the production of cement or lightweight aggregate and not the destruction of waste, so product considerations may limit the usage of these types of units for destruction of PFAS-containing materials. MWCs typically operate at lower temperatures and often do not employ auxiliary primary or secondary flames. SSIs vary in design, often operating as dryers with very low temperatures. Even within the same incinerator, wastes can be introduced at different locations and can experience different residence time, temperature, and mixing histories. PFAS introduced into the main burner of a hazardous waste rotary kiln incinerator, along with auxiliary fuel, may experience very different conditions than the same waste introduced to the kiln as contained charges with solid wastes. These factors are expected to affect PFAS destruction and PIC formation. Limited studies have investigated the influence of various factors on PFAS destruction and PIC formation (see Section 3.a).

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

Thermal oxidizers have historically not been designed with destruction of PFAS as the primary focus, so most currently installed thermal and catalytic oxidizers may not be optimized for PFAS destruction. However, some thermal oxidizers are being used for halogenated wastes, including PFAS precursors. Thermal oxidizers are being employed to destroy PFAS-containing and gaseous streams, but the data are insufficient to allow conclusions on the overall efficiency of thermal oxidizers, in general, for PFAS destruction. For example, annual testing at Chemours Company's Fayetteville Works (Focus Environmental, Inc., 2020, 2021, 2022, 2023, and 2024) focused on five specific PFAS of interest found in waste gas streams at the facility. While the tests seem to prove a DRE of 99.999 percent for the five PFAS compounds, they do not present data on overall PFAS destruction and the potential formation of

PICs was investigated with OTM-50 only one time (Shields et al., 2025b). The results are promising but more studies would be beneficial (see Appendix B and Appendix C for summaries of the Clean Harbors and Chemours test data, respectively). EPA is currently unaware of any catalytic oxidizers being used specifically for the destruction of PFAS, particularly considering their site-specific design and optimization. Though data on the efficacy of thermal and catalytic oxidizers in destroying PFAS is currently limited, a properly optimized thermal oxidizer can readily achieve a DRE of 99.99 percent for VOCs.

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

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

It is not well understood how effective high-temperature combustion is at completely destroying PFAS or whether the process can form fluorinated or mixed halogenated organic byproducts. Few experiments have been conducted under oxidative and temperature conditions representative of different field-scale incineration devices used for PFAS destruction. Limited studies on the thermal destructibility of fluorotelomer-based polymers found no detectable levels of PFOA after two seconds of residence time at 1,000°C (1,830°F) (Yamada et al., 2005; Taylor et al., 2014). Recent field studies examining the performance of a specially designed thermal oxidizer in destroying PFAS in process gases at a Chemours production facility near Fayetteville, North Carolina, indicated greater than 99.999 percent destruction of five PFAS (Focus Environmental, Inc., 2020, 2021, 2022, 2023, and 2024). Similarly, the 2021 and 2022 Clean Harbors studies appear to show that the facility was able to achieve its primary objective: “demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed during normal process operating conditions.” A high DRE was achieved (greater than 99.999 percent) for the five selected PFAS compounds that were subjects of these studies (EA Engineering, Science, and Technology, Inc., PBC., 2021, 2022). However, these test data did not include characterization of potential PICs due to previous methodology limitations. More recent testing at Veolia Port Arthur (Veolia North America, 2025) and Clean Harbors (Troxler et al., 2025) included an examination of volatile PIC formation using OTM-50 and have promising results, indicating both high DRE of specific PFAS as well as minimal volatile PIC formation.

The Chemours annual tests and Clean Harbors 2021 and 2022 test results indicate the PFAS compounds measured were changed by the treatment, but the tests did not investigate PIC formation to show

adequate destruction of the original PFAS. As discussed previously, emission studies, particularly for potential PICs, are largely incomplete due to lack of validated sampling and measurement methods for the potentially large number of fluorinated and mixed halogenated organic compounds that might be formed. EPA continues to seek information on PFAS that may be present in APCD media (e.g., scrubber water, particulate matter control device media) and the presumed effectiveness of these air emission controls. The Veolia Port Arthur (Veolia North America, 2025), and 2025 Clean Harbors test (Troxler et al., 2025) both examined residuals from the control devices as well as the process water. These tests suggest that contaminated process water is a potential source of remission of PFAS into the environment. See Section 4 for more information about ongoing research and research needs.

Incineration may be a viable PFAS destruction technology if done under certain conditions. The preliminary research on thermal treatment of PFAS suggests that the minimum conditions for PFAS destruction include well mixed environments with temperatures greater than 1,100°C and optimized combustion stoichiometry (Shields et al., 2023). Full sale testing at Veolia, with the kiln operating at greater than 816°C and the secondary combustion chamber operating at greater than 1,093°C, provide results with high DRE and minimal PIC formation (Veolia North America, 2025). The Clean Harbors 2025 testing at Aragonite, Utah (Troxler et al., 2025), with the kiln operating at greater than 1,097°C and the secondary combustion chamber operating at greater than 1,120°C, also showed high DRE with minimal PIC formation. These conditions may adequately destroy PFAS and minimize PICs. However, evaluations have only been done on liquid-fired materials. No comparative studies that include PIC measurements on solids or containerized wastes have been performed. Liquids should preferably have direct flame contact or at least well mixed exposure to temperatures sufficient for adequate destruction of PFAS.

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

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

Thermal treatment systems including HWIs, MWCs, and SSIs are configured such that gas-phase effluent from the combustion chambers passes through a series of pollution control devices to remove acid gases, particulate matter, and sometimes mercury and other specific HAPs. The behavior of PFAS and PFAS-related PICs in these unit operations is largely unknown (see Section 4 for more information about research on this topic and others). Additionally, these control devices produce secondary waste streams in the form of fly ash and scrubber blowdown solutions, and PFAS and PFAS-related PICs may be present in these solid and liquid effluents depending on their vapor pressure and solubility.

Thermal oxidation processes used for treating PFAS-containing waste, such as incineration, generate HF as the most stable product from combustion of fluorocarbon compounds. HF is a CAA-listed HAP and is highly corrosive, which 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 treatment system with a potential for HF emissions typically uses a wet scrubber integrated with the oxidizer to control HF emissions. In a typical system, hot flue gas exiting the thermal treatment 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. 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 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 treatment system equipped with a quenching unit to treat PFAS-containing wastes may also limit catalytic reformation of fluorinated PICs, if they are formed in the oxidation/combustion chamber. Those PICs may be subsequently transferred into the liquid phase in the wet scrubber and then be partitioned between solid CaF_2 and water in the precipitator (most of the PICs retained in water are then removed by activated carbon adsorption). EPA is not aware of peer-reviewed studies that measure levels of fluorinated contaminants remaining in both the treated scrubber water stream and the dry CaF_2 stream. Such measurements could be useful for evaluating the potential environmental impacts of byproducts and residuals generated from thermal oxidation of PFAS-containing wastes.

Spray dryer absorber (SDA) technology has been applied to control emissions of halogen acids (including HCl and HF) from both MWCs and HWIs. This semi-dry scrubbing process is designed to inject an alkaline slurry, typically lime, to control acid and fly ash. Water in the fine slurry droplets is vaporized by heat carried by the flue gas, and the lime carried in the droplets neutralizes the halogen acids simultaneously in this two-phase reaction process. The cooled flue gas carries the dried acid neutralization product downstream to a particle collection device, typically an FF. PAC may also be injected into flue gas upstream of the FF to control emissions of mercury and chlorinated dioxins/furans from both MWCs and HWIs. Fly ash, dried acid neutralization product, and PAC are captured by the FF. The SDA/FF with PAC injection flue gas cleaning train produces no scrubber water. The addition of lime (a calcium compound) into the flue gas is known to be effective for forming CaF_2 through hydro-defluorination of PFOS at a moderate temperature of about 350°C (660°F) (Wang et al., 2015), which suggests that the SDA may provide a potential co-benefit of controlling fluorinated PICs. The injection of PAC upstream of the FF may create another potential co-benefit for capturing fluorinated PICs. Studies evaluating PFAS mitigation via SDA/FF with PAC injection (e.g., see research activities in Section 4) will help develop data on this potentially viable technology option.

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

Thermal treatment devices that may be used to treat PFAS-containing waste (see Section 3.a.i for descriptions of these devices) are located in both rural and more densely populated areas throughout the United States. Two possible sources of PFAS emissions from thermal treatment are stack emissions and the management of scrubber water and bottom ash/fly ash. As previously discussed, emissions from thermal treatment activities may contain PFAS if adequate combustion conditions are not achieved or if adequate acid gas scrubbers or other pollution control devices are not used. EPA is aware of a limited number of peer-reviewed studies that have investigated the extent to which emitted PFAS are transported and deposited to surrounding areas (see Section 2.a.iii). EPA plans to conduct research in this area to better characterize the extent to which PFAS deposition may occur near thermal treatment devices (see Section 4 for more information about these types of research activities).

Volatile PFAS releases from thermal treatment equipment (e.g., fugitive emissions) and waste storage activities are another potential source of PFAS releases, if they are not adequately controlled.[21] There is also the potential for releases from management of thermal treatment process residuals, such as APCD media, incinerator bottom ash, and liquids from acid gas scrubbers. For example, incinerator bottom ash disposed of in a landfill would be a possible source of release if the ash contained PFAS and the landfill lacked adequate controls (see Section 3.b for more information on landfill types and controls). HWIs, however, typically dispose of incinerator bottom ash in hazardous waste landfills, minimizing the potential for the release of PFAS to the environment.

3.a.iv Testing and monitoring

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

Ongoing method development by EPA has a broad focus that will address PFAS in various waste streams, stack and fugitive emissions, and ambient air (see Section 4 and Appendix A). Method development also includes identification of PFAS that are potential PICs, not targeted in established water methods such as Methods 533 and 537.1. Due to the number and complexity of PFAS that have already been identified, surrogates are also being investigated to determine if measurement of a single compound or a small group of compounds is adequate to characterize the completeness of thermal treatment for both targeted PFAS and potential PICs.

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

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

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

Ambient sampling for semivolatile PFAS roughly follows either the high-volume air sampling protocol described in EPA compendium Method TO-13a (U.S. EPA, 1999) or the National Atmospheric Deposition Program (NADP) approaches for wet and dry deposition sampling (NADP, 2020). High-volume air samples collect both water-soluble PFAS acids and salts and water-insoluble telomer alcohols. NADP

[21] 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.

sampling has focused on condensable and particulate-bound PFAS captured in polypropylene buckets to evaluate deposition due to rain.

Current sampling of stationary source air emissions for semivolatile PFAS targets is based on EPA SW-846 Method 0010. Analysis of samples for a list of PFAS compounds is based on EPA Method 533, modified to include collection of both targeted and non-targeted PFAS in a single sampling system. Sampling includes heated or stack temperature probe extraction of emission gases followed by collection on filters, XAD sorbent media, and aqueous impingers. EPA released OTM-45 (Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources) in January 2021 and revised the method in January 2025 (U.S. EPA, 2025a). Experience indicates that OTM-45 is an effective and sensitive approach to measure a list of PFAS included in the method.

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

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

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

EPA released OTM-50 (Sampling and Analysis of Volatile Fluorinated Compounds from Stationary Sources Using Passivated Stainless-Steel Canisters) in January 2025 (U.S. EPA, 2025b; Wallace et al., 2025) which enables analysis of non-polar VFCs and PFAS. OTM-50 utilizes silanized steel canisters to measure targeted VFCs and PICs emitted from thermal treatment facilities, as well as industrially-produced compounds (such as FC-116, HFC-23, HFC-125, E1, and E2) and potential PIDs (such as CF_4 through octadecafluorooctane). EPA is also developing the ability to characterize a more diverse set of possible PFAS PICs and measure VFCs at trace concentrations. The ability to measure trace concentrations will allow investigators to introduce a known concentration of a hard-to-destroy fluorocarbon and evaluate the behavior of this compound when exposed to specific thermal environments which is EPA's preferred approach to characterize a more diverse set of possible PFAS PICs. Though insufficient by itself, this approach is consistent with the EPA approach for determining the DRE of fluorinated greenhouse gas abatement equipment in electronics manufacturing (U.S. EPA, 2010).

NTA has also been performed on the same samples. These tools and OTM-45 are examples of monitoring methods that could be considered as additions to a potential PFAS waste management system or permit (e.g., RCRA).

EPA continues to evaluate FTIR as a suitable real-time measurement technique for volatile, non-polar fluorinated compounds (e.g., CHF_3, C_2HF_5, C_3F_8). Measurement of CF_4 and C_2F_6 by FTIR in stationary source emissions has been successfully demonstrated at pilot- (Krug et al., 2022) and commercial-scale (Troxler et al., 2025) operations. Additionally, the aluminum industry has used FTIR for several decades to monitor CF_4 and C_2F_6 formation (World Aluminium 2020). Favorable results have been noted between non-polar fluorinated PICs where both FTIR and OTM-50 were used (Weber et al., 2025; Troxler et al., 2025).

EPA has also recently investigated online chemical ionization mass spectrometry (CIMS) for measuring gas-phase PFAS compounds (Riedel et al., 2019). This technique was applied toward real-time monitoring of short-chain perfluorocarboxylic acids and other fluorinated PICs produced during pilot-scale experiments incinerating AFFFs (Mattila et al., 2024), and single-component aqueous solutions of PFOA (Rocchio et al., 2025) and HFPO-DA (Weber et al., 2025). A recent EPA-led study also used online CIMS to investigate CaO assisted thermal treatment of fluorotelomer alcohols (FTOHs) (Riedel et al., 2021). This technique performed comparably to thermal desorption-gas chromatography/mass spectrometry (TD-GC/MS) for monitoring temperature-dependent FTOH removal efficiencies. Additionally, this technique may be sufficiently sensitive for PFAS fugitive emissions and fenceline monitoring, though further research is needed to determine its efficacy for these applications.

The quantitative measurement of total organic fluorine (TOF) is also being evaluated to represent all, or most, of the PFAS class of compounds. This approach represents a simpler and more comprehensive measurement alternative to target list approaches that focus on a limited number of PFAS (Forster et al., 2023; Idjaton et al., 2024). Several potential techniques warrant consideration and additional evaluation, including (but not limited to) combustion–ion chromatography (CIC), particle-induced gamma emission spectrometry (PIGE) (Smith, et al., 2024), and X-ray photo-electron spectroscopy (XPS). For air and thermal treatment emissions, TOF must measure highly volatile as well as semivolatile PFAS. TOF analysis is an ongoing research area and data users must recognize the benefits of receiving general screening data for a wide array of potentially present PFAS, while also recognizing the limitations and uncertainties inherent in not knowing which PFAS or class of PFAS is present in the sample, including uncertainties associated with potential health risk. Non-targeted methods like extractable organofluorine/absorbable organofluorine (EOF/AOF) have higher quantitation limits (e.g., in the ppb range), which may be insufficient for capturing low PFAS concentrations in the environment. High-resolution mass spectrometry (HRMS) is crucial for identifying PFAS byproducts and degradation pathways, offering structural insight at low concentrations that EOF/AOF assays lack (Smith, et al., 2024). 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 emissions and control efficiency of HF as a HAP at emission outlets. Multiple studies of PFAS thermal decomposition and HF monitoring have demonstrated that EPA compliance methods for HF measurement are adequate to

meet this need. However, HF is difficult to transport through treatment and control equipment and is therefore not a candidate for using a mass balance approach to evaluate PFAS destruction efficiency. GC-HRMS is essential for analyzing volatile organofluorine compounds in gaseous emissions due to the difficulty of direct quantification without reference standards. Consideration should be given to closing the fluorine mass balance by combining non-targeted methods like EOF and total oxidizable precursor (TOP) analyses with targeted studies (Smith et al., 2024).

3.a.v Uncertainties/unknowns

EPA is planning to collect additional information and conduct additional research to better understand PFAS destruction and evaluate emission control efficiency (see Section 4). EPA is also working to develop a standardized validated methodology for measuring PFAS gaseous emissions (see Section 3.a.iv); however, EPA lacks detailed information on the amounts and concentrations of PFAS-containing materials that are generated and managed in thermal treatment devices.

Development of sampling and analytical methodologies must continue (see Section 4 research activities) so that emissions and other media from thermal treatment devices burning PFAS-containing materials can be adequately characterized.

Uncertainties such as the overestimation of destruction and disposal capabilities, or a failure to account for potential PIC production and subsequent transformation back to PFAS of concern, could have consequences for all nearby communities.

To reduce uncertainties and provide more detailed recommendations, further data on the ability of thermal treatment units to mineralize PFAS-containing materials is necessary (see Appendix A and Section 4.a). Performance testing of all types of combustors is lacking. EPA recommends that full-scale thermal destruction facilities conduct performance testing prior to accepting and processing PFAS materials. Objectives of the testing should include:

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

Further details on suggested parameters and procedures are provided in Table 4-1 and Appendix A.

3.a.vi Treatment commercial availability

Section 3.a.i describes the commercial availability of thermal treatment devices. The United States has about 22 commercial HWC facilities[22] in operation, including over a dozen large-scale, commercial

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

carbon reactivation companies with approximately 17 furnaces, 193 MSW incineration units at 75 facilities (as of 2018), and 170 SSIs at 86 facilities (as of 2016).

3.a.vii Summary

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

There are limited characterizations of potential PFAS emissions from thermal treatment devices that burn PFAS-containing media, with a few tests at HWIs and a single test at a thermal oxidizer with a more complete emissions characterization, but EPA is not aware of any full emission characterizations that have been conducted at HWCs, MWCs, SSIs, or activated carbon reactivation furnaces or any studies to evaluate the formation of PICs resulting from inefficiency to convert PFAS into CO_2 and HF. EPA is also not aware of any studies that have been conducted on the extent to which PFAS contaminants partition to APCD residuals or bottom ash, which may also be a concern. This is likely (in part) because PFAS emission measurement methods and other analytical methodologies (e.g., for fly ash, other waste streams) are limited and continue to be developed. Data, however, from pilot-scale experiments conducted by EPA researchers suggest that temperatures above approximately 1,100°C (2,012°F) may result in high destruction efficiencies and few detectable fluorinated PICs.

Given the unique characteristics of fluorine combustion chemistry (particularly the strength of the carbon–fluorine bond), adequate thermal destruction of PFAS requires high temperatures and long residence times and likely benefits from direct flame contact. Hazardous waste combustion technologies (commercial incinerators, cement kilns, and LWAKs) can potentially achieve temperatures (~1,100°C [2,012°F]) and residence times sufficient to break all C-F bonds in the PFAS contained in the waste stream being thermally treated. Permitted hazardous waste facilities have stringent regulatory controls on temperatures and other important operating parameters to achieve a 99.99-percent and greater destruction efficiency for other (non-PFAS) organic chemicals. These facilities also have APCDs to prevent certain gaseous and particulate pollutants from entering the atmosphere. However, information on the efficacy of PFAS destruction in these facilities is currently limited and EPA has limited data characterizing PIC emissions from these sources when they burn PFAS. EPA is working to develop measurement methodologies as well as to gather information to conclude whether PICs are adequately controlled. EPA recognizes that PICs are inevitable (even for nonfluorinated compounds); however, based on the unique characteristics of fluorine combustion chemistry, EPA believes it is important to determine whether thermal treatment devices and their associated post-combustion control devices are adequately controlling PICs, especially fluorinated PICs. Given all these factors, there is a current need to continue research activities investigating incineration of PFAS. After sufficient research has been

completed to address the related knowledge and data gaps, EPA can make a more informed recommendation on disposal of PFAS compounds and PFAS-containing substances using incineration.

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

Research and testing of PFAS destruction performance within MWCs is extremely limited, primarily comprising laboratory- and pilot-scale studies (Aleksandrov et al., 2019; Taylor et al., 2014). While the laboratory- and pilot-scale studies conclude that MSW incineration of PTFE is not a significant source of PFAS, the laboratory thermal reactor and the pilot incinerator used in these studies may not be representative of the design of MWC units currently operating in the United States. In addition, while these studies analyzed several PFAS species, it is important to note that there are far more PIC species possible, and no studies have thoroughly evaluated the types and quantities of PICs.

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

More research is needed to address these issues and develop reliable measurement techniques. Section 4 summarizes EPA's continuing PFAS research, as well as a general proposal to collaborate with stakeholders to address these uncertainties promptly. See Appendix D for a summary of costs and considerations.

3.a.viii References for Section 3.a

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3.b Landfills

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

Landfills control waste and corresponding pollutants through containment. Because of their many and varied uses, PFAS enter landfills as part of the general MSW stream, in industrial waste, or in other PFAS-containing wastes, with a range of concentrations. The two major categories of landfills under RCRA are Subtitle C hazardous waste landfills and Subtitle D non-hazardous waste landfills. Subtitle D landfills include MSW landfills, ash monofils, C&D debris landfills, and industrial landfills. These landfills are required to have different types of control technologies depending on the types of wastes they are designed to contain (see Table 3-2) and, therefore, they can vary in their effectiveness to control releases of PFAS. In addition, there is a subclass of small landfills in the United States that are exempt from RCRA requirements 40 CFR 258.1(f).

The PFAS loading into different types of landfills will also vary markedly depending on the sources and types of wastes they receive. MSW landfills, for example, can include a diverse array of wastes with highly variable PFAS concentrations (e.g., household waste, biosolids, remediation wastes). In contrast, concentrations in wastes from industries that use PFAS directly in their operations (e.g., leather tannery, chrome plating, textile industry waste) can be considerably and consistently higher (USCPSC and RTI International, 2023; Gilchrist, 2022).

The behavior of PFAS in landfills is a complex and multifaceted process that involves various abiotic and biotic transformation and partitioning pathways. While the exact mechanisms and rates of transformation are not fully understood, both aerobic and anaerobic conditions in landfills have been demonstrated to facilitate conversion of PFAS precursors into more persistent, terminal PFAS species. The behavior of these terminal PFAS can differ markedly from precursors. While some information is available, EPA continues to collaborate with industry and the academic community to conduct research to address information and data gaps (see Section 4), including efforts to better 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.

As described in more detail in Section 3.b.i, while generalizations can be made for the properties of classes of PFAS (e.g., perfluoroalkyl acids, fluorotelomer carboxylic acids [FTCAs]), each class encompasses a wide range of physical-chemical properties based on the molecular structure of the individual PFAS, such as chain length. For example, while many perfluoroalkyl acids have high aqueous solubility, the degree of solubility decreases markedly at higher chain lengths. FTCAs are likewise regarded as soluble, but have also been measured in LFG and LFG condensate. Work is still ongoing to better understand the constraints of and conditions that promote transformation and partitioning.

While landfills are designed to serve as long-term containment sites, it is unclear how effective they are at containment of water-soluble or volatile PFAS for an extended duration. PFAS will not break down under the environmental conditions found inside a landfill; consequently, PFAS will persist in landfills for the life of the compounds. Therefore, since landfills are a containment rather than destruction method, landfills will emit volatile and soluble PFAS as long as LFG and leachate generation continue.

Section 3.b focuses on the viability of landfilling as a means of controlling releases of PFAS from contaminated wastes, including consideration of:

- The types of PFAS in wastes and how they behave within a landfill.
- The types of landfills that receive PFAS-containing waste.
- The types of environmental control technologies used for landfills and their ability to effectively contain or remove PFAS.
- The potential for environmental releases of PFAS associated with landfilling.
- Recommendations for deciding what type of landfill is most appropriate for PFAS-containing waste.
- Methods to monitor PFAS at landfills and corresponding waste streams.
- Uncertainties and unknowns associated with landfilling PFAS-containing waste.

3.b.i Types of PFAS and Potential for Release from Landfills

As described in Section 1 ,the term PFAS refers to very large group of synthetic chemicals that due to their strong carbon-fluorine bonds, can be very persistent in the environment. EPA's ***CompTox Chemicals Dashboard*** [23] maintains a master list of more than 12,000 chemicals that are potential PFAS, including 10,200 chemicals containing a specific defined structure and an additional 1,300 without explicit structures (polymers and other chemical substances of unknown or variable composition). It is not known how many of these compounds are in production or have already come to be disposed of in landfills. NTA techniques have identified as many as 651 different PFAS compounds in landfill leachate from China (Liu et al., 2022a). This number may increase as the ability to detect and measure PFAS further evolves. When disposed of in a landfill, different types of PFAS compounds may behave differently from one another and may require different considerations for the types of landfills that are suitable for disposal and the types of emissions controls that are necessary to contain the PFAS over time.

Descriptions of the different types of PFAS provided below are specific to the landfills section and are intended to provide context regarding PFAS release from landfills (e.g., in landfill leachate or in LFG).

PFAS Polymers. Stable PFAS polymers (e.g., PTFE or Teflon™) are generally inert, insoluble, and non-volatile and are unlikely to be released via landfill leachate or LFG. Stable polymers are less likely to migrate within a landfill by partitioning to the gas or liquid (i.e., leachate) phases. However, soluble and volatile PFAS have been identified in fluoropolymers as synthesis byproducts or incomplete reactants. Although stable polymers are highly resistant to chemical and thermal degradation, they can still be broken down by weathering and physical strain, increasing their dispersion and bioavailability (Lohmann et al., 2020). For example, studies have shown that physical abrasion of the polymers can create fluorinated microplastics that are then suspended in landfill leachate (He et al., 2019). However, because exposure to ultraviolet radiation and physical disturbance of the waste are expected to be relatively low after final placement in landfills, the bulk of stable polymers would be expected to be retained for a long duration. Side-chain fluorinated polymers (SFPs), which can be fluorotelomer- or perfluoroalkyl sulfonyl fluoride-based, are distinct from stable PFAS polymers in that they include fluorocarbon groups attached to a non-fluorinated backbone. The fluorinated side chains on SFPs can

[23] Available at: *https://comptox.epa.gov/dashboard/*.

cleave to form volatile or soluble PFAS. As such, EPA recommends using similar controls as are recommended for soluble PFAS. Information about the fate and transport of SFPs is limited.

Soluble PFAS. For the purposes of this section, soluble PFAS are those that would be found in landfill leachate. PFAS monomers, including perfluoroalkyl acids (e.g., PFAAs, PFOA, PFOS, PFHxS, PFBA, HFPO-DA) and precursors that can ultimately degrade to these acids, more readily and rapidly partition into landfill leachate than other types of PFAS due in part to ready dissociation of these compounds into anions over the range of pH values typically encountered within landfills. Landfills without an appropriate liner and leachate collection system (see Section 3.b.iii) may allow leachate containing these soluble PFAS to flow into the subsurface and enter groundwater. Note that longer-chain PFAS are less soluble (Lyu et al., 2022) and have higher affinity for solids. Therefore, C_9 (perfluorononanoic acid) and greater chain length perfluoroalkyl acids are less likely to stay in the aqueous phase (Kurwadkar et al., 2022).

Volatile PFAS. For the purposes of this section, volatile PFAS are those that would be found in LFG. Alcohols (e.g., FTOHs and FASEs) and precursors that degrade to volatile PFAS can partition into the gas phase and be emitted from landfills in LFG due to the shorter chain length and non-ionic structure associated with higher vapor pressures. The rate of volatilization may be influenced by site conditions, such as landfill temperature, and co-occurrence of other LFG. Landfills without appropriate LFG collection and control systems in place and operating (see Section 3.b.iii.6) may result in fugitive emission to surrounding ambient air.

For example, FTCAs are soluble intermediate transformation products of volatile precursors such as FTOHs (Wang et al., 2025). Accumulation of FTCAs has been documented under biologically active, anaerobic landfill conditions, and their presence in groundwater is considered an indicator of landfill leachate contamination. For this reason, volatile PFAS-containing wastes should be managed in landfill environments which are also appropriate for soluble PFAS disposal.

The environmental and health risks associated with different methods for PFAS destruction remain the subject of emerging research. In the interim, while alternate management methods are developed, EPA recommends that the focus of land disposal strategies be on minimizing releases from landfills. This includes low-permeability liner and gas collection systems installed prior to disposal of biodegradable PFAS-containing waste. Given these different potential pathways for release, Table 3-1 summarizes the recommended engineering controls at landfills accepting PFAS waste based on both the type of PFAS and the biodegradability of any comingled waste. Also note that soluble PFAS that are comingled with biodegradable waste should have both liquid and gaseous emissions controls (i.e., leachate collection and gas control).

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

Type of PFAS	Degradability of Comingled Waste	Landfills with Liner and Leachate Collection	Landfills with Gas Collection and Control
PFAS Polymers (e.g., PTFE)	Biodegradable		✓
Soluble PFAS (e.g., PFAAs)	Biodegradable	✓	✓
	Non-biodegradable	✓	
Volatile PFAS (e.g., FTOHs)	Biodegradable	✓	✓

Type of PFAS	Degradability of Comingled Waste	Landfills with Liner and Leachate Collection	Landfills with Gas Collection and Control
	Non-biodegradable	✓	✓

3.b.ii Types of landfills

Landfills are typically classified by ownership status and by the type of solid waste they are permitted to receive, which determines the types of environmental controls they must employ. Depending on the type of waste disposed, a landfill could be subject to regulation and permitting under RCRA, the CAA, and/or TSCA. RCRA regulates two types of landfills: Subtitle C facilities receive hazardous waste, while Subtitle D landfills are primarily intended for the management of non-hazardous waste and can include MSW landfills, industrial waste landfills, C&D waste landfills, and ash landfills. The CAA regulates air emissions from MSW landfills and TSCA regulates landfills that contain PCBs. The CWA (40 CFR Part 503) regulates management practices for the disposal of treated sewage sludge (i.e., biosolids) in monofills. The requirements under RCRA, CAA, TSCA, and CWA determine how the landfill must be constructed, operated, controlled, maintained, monitored, and closed when it reaches its final capacity.

Table 3-2 identifies the environmental controls required by RCRA and CAA for the landfill types defined in RCRA Subtitles C and D. RCRA regulations focus on the containment of solid waste and leachate, while CAA regulations focus on collection of LFG and control (i.e., destruction) of targeted pollutants. The landfill types differ in how they are constructed, operated, controlled, monitored, and closed. Subtitle C landfills and Subtitle D MSW landfills are subject to specific federal design standards, resulting in greater consistency in construction across the country. Controls at other Subtitle D landfills can vary more widely from state to state, and even from unit to unit. Requirements for bottom liners, leachate collection, and final cover requirements at industrial and C&D landfills may range from unspecified to comparable to federal standards.

Table 3-2. Required Environmental Controls by Landfill Type

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

PFAS concentrations have been detected in landfill leachates from various types of landfills, as shown in Table 3-3. Variation between studies for similar landfill types can be partly attributed to differences in the number and types of PFAS measured. Further, PFAS concentration data reported for landfills outside of the United States may be grossly different as the amounts and compositions of PFAS-containing materials disposed of, as well as weather, and landfill operations and controls may not be comparable and thus are provided for outside reference.

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

Matrix	Number of PFAS Detected (Number of PFAS in Method)	∑PFAS Range (ng/L)	Country	Reference
MSW Leachate	26 (26)	~2,000 – ~20,000	USA	Chen et al. (2024)
	44 (92)	36,000 – 74,000	USA	Smallwood et al. (2023)
	36 (91)	8,000 – 39,900	USA	Cerlanek et al. (2024)
	26 (26)	8,650 – 12,922	USA	Zhang et al. (2024)
	25 (26)	300 – 58,000	USA	Chen et al. (2023)
	10 (11)	15,000 – 18,000	USA	Solo-Gabriele et al. (2020)
	24 (24)	2,700 – 7,400	USA	Huset et al. (2011)
	30 (70)	2,000 – 29,000	USA	Lang et al. (2017)
	2 (2)	330 – 2,600	USA	Clarke et al. (2015)
	28 (28)	230 – 29,000	USA	Helmer et al. (2022)
	2 (2)	47 – 3,400	USA	Michigan Waste & Recycling Association (2019)
	22 (25)	1,400 – 125,000	USA	NWRA (2020)
	31 (40)	BDL – 104,000	USA	California Water Boards (2023)
	48 (92)	15,000 – 70,300	Puerto Rico	Robey et al. (2024)
	14 (14)	33 – 15,000	Australia	Gallen et al. (2016)
	9 (9)	210 – 46,000	Australia	Gallen et al. (2017)
	15 (15)	Not reported	Australia	Simmons (2019)
	25 (43)	31 – 13,000	Germany	Busch et al. (2010)
	24 (24)	2,500 – 36,000	Canada	Benskin et al. (2012)
	16 (18)	700 – 6,400	Canada	Li (2009)
	2 (2)	50 – 2,300	Canada	Gewurtz et al.
	16 (27)	2,200 – 6,100	Norway	Eggen et al. (2010)
	7 (8)	200 – 1,500	Norway	Kallenborn et al. (2004)
	4 (4)	210 – 610	Finland	Perkola & Sainio (2013)
	7 (10)	14 – 17,500	Ireland	Harrad et al. (2019)
	8 (16)	640 – 1,400	Spain	Fuertes et al. (2017)
	28 (30)	320 – 11,000	Norway	Knutsen et al. (2019)
	17 (26)	0.3 – 1,300	Sweden	Gobelius et al. (2018)
	11 (14)	7,300 – 290,000	China	Yan et al. (2015)
	33 (57)	3,040 – 109,000	China	Liu et al. (2022b)
	17 (17)	1,800 – 43,300	China	Huang et al. (2022)
	18 (18)	1,270 – 7,660	Singapore	Yin et al.

Matrix	Number of PFAS Detected (Number of PFAS in Method)	∑PFAS Range (ng/L)	Country	Reference
C&D Leachate	8 (9)	4,200 – 11,000	Australia	Gallen et al. (2017)
	24 (26)	270 – 30,500	USA	Chen et al. (2023)
	11 (11)	14,000 – 16,000	USA	Solo-Gabriele et al. (2020)
MSW Incineration Ash Leachate	9 (11)	2,800 – 3,400	USA	Solo-Gabriele et al. (2020)
	26 (26)	1,906 – 3,483	USA	Zhang et al. (2024)
	26 (26)	39 – 54,500	USA	Chen et al. (2023)
MSW Gas Condensate	26 (26)	199 – 80,900	USA	Chen et al. (2023)
	26 (26)	9,300 – 45,000	USA	Chen et al. (2024)
	26 (26)	14,000 – 18,000	USA	Zhang et al. (2024)
	53 (92)	3,000 – 50,000	USA	Smallwood et al. (2023)
Hazardous Waste Leachate (Primary)	17 (28)	570 – 377,000	USA	California Water Boards (2023)
Hazardous Waste Leachate (Secondary)	13 (24)	25 – 3,700	USA	California Water Boards (2023)

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

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

3.b.ii.1 Hazardous waste landfills

Subtitle C hazardous waste landfills are permitted to receive waste that is defined as "hazardous" under RCRA. Hazardous wastes include certain listed manufacturing or industrial process wastes or discarded commercial chemical products and wastes that exhibit one or more hazardous characteristics (i.e., toxicity, corrosivity, reactivity, or ignitability) as defined by RCRA (40 CFR Part 261 Subparts C and D). Hazardous wastes are generally required to be treated with specific technologies to reduce or eliminate the hazards their disposal would otherwise present, and many types of treated hazardous wastes are also required to meet numeric standards for underlying hazardous constituents prior to land disposal (40 CFR part 268). Federal RCRA regulations do not identify any PFAS-containing wastes as hazardous, but most states are authorized to implement RCRA Subtitle C regulations, and their regulations may be more stringent.

Subtitle C hazardous waste landfills are required to have control technologies (e.g., a double liner with a leachate collection/treatment system and leak detection) and practices (e.g., comprehensive record keeping of waste inputs) to minimize the risk of groundwater contamination. Additionally, when closed, these types of landfills must have a final cover consisting of an FML covered by soil. Hazardous waste landfills are generally not required to have gas collection and control systems because they are not intended to accept biodegradable wastes (e.g., biosolids, food scraps). As such, they are generally not biologically active and do not evolve large amounts of gases that could entrain volatile PFAS and lead to high levels of air emissions. However, LFG collection systems could be installed in a Subtitle C landfill to minimize risks related to gas release or gas emissions.

Although few states have proposed regulating PFAS-containing wastes as hazardous wastes, some states have recommended the use of specific treatment technologies for certain PFAS-containing wastes. For instance, some states such as Washington, encourage solidification/stabilization (S/S) of waste AFFF in a neutral material such as concrete prior to landfilling (Washington State Department of Ecology, 2024). A study by the United States Department of Transportation found that the addition of powered activated carbon to S/S pozzalonic binders significantly reduced PFAS leachate concentrations from PFAS-contaminated soil from a historic aviation fire training facility (Mishewitz and Ruehl, 2022).

Hazardous and non-hazardous solid wastes can contain PFAS, and hazardous waste landfills have been used for disposal of non-hazardous wastes containing PFAS. Therefore, it is likely that PFAS-containing wastes will continue to consume a fraction of hazardous waste landfill capacity. Although waste containing PFAS is currently not defined as hazardous waste under RCRA (unless the particular wastes are hazardous for some other reason), some waste generators, perhaps to be cautious, have been sending PFAS-containing wastes to hazardous waste facilities. To ensure hazardous waste landfill capacity is available in the future, EPA reviews and analyzes the *Biennial Hazardous Waste Report*[24] and other data to develop and then publish an assessment of national capacity for hazardous waste management.[25] The last such capacity assessment indicated that existing nationwide capacity remains adequate through 2044, and a new assessment is currently underway to incorporate new information and extend the time horizon. EPA will continue to work with states to monitor hazardous waste treatment and disposal capacity and report on the status.

3.b.ii.2 Municipal solid waste landfills

EPA estimates that in 2018, 50 percent of the MSW generated was landfilled (U.S. EPA, 2024). Wang et al. (2025) identified PFAS in common consumer products that ultimately are disposed in MSW landfills, and this type of landfill may routinely receive lower-concentration PFAS waste such as biosolids, phytoremediation biomass, and contaminated soils.

An MSW landfill typically has at least a bottom liner and an extensive gas collection and control system (GCCS) to collect the LFG generated when the biodegradable waste, such as food scraps and office paper, degrades over time. Also, under RCRA, MSW landfills that received waste after 1993 must install a composite liner that meets design criteria (40 CFR 258.40). However, MSW landfills that receive less than 20 tons of waste per day are exempt from installing a liner and monitoring groundwater under RCRA (40 CFR 258.1(f)(1)). MSW landfills that exceed specified thresholds for size (based on design capacity) and emissions of non-methane organic compounds (NMOCs) are required to install gas collection systems under current CAA regulations. LFG must be collected and managed according to the requirements of the CAA standards of performance (40 CFR part 60 subparts Cc, Cf, WWW, and XXX). Therefore, a subset of MSW landfills do not have gas collection and could release fugitive PFAS associated with LFG emissions. Similarly, unlined MSW landfills are ineffective at managing the release of mobile PFAS to groundwater (see Section 3.b.iii.1). The fate of PFAS in LFG managed through on-site GCCS including on-site flares, engines, boilers, and turbines is the topic of ongoing investigation.

Most modern Subtitle D MSW landfills, when constructed and operated with appropriate environmental controls (e.g., a flexible membrane liner system and leachate and LFG collection and management

[24] Available at: *https://www.epa.gov/hwpermitting/assessment-national-capacity-hazardous-waste-management*.

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

systems), can help to contain PFAS. However, research indicates that up to 5 percent of the PFAS may be released in the LFG and 11 percent may be released in the leachate annually (Tolaymat et al., 2023). Some MSW landfills have accepted PFAS manufacturing wastes, and as a result, PFAS concentrations in leachate are higher than the typical range expected in MSW landfill leachate (NWRA, 2020). Landfill leachate may be sent to wastewater treatment plants (WWTPs) that are incapable of treating or destroying PFAS. Thus, the PFAS in landfill leachate, unless pretreated before entering the WWTP, may be discharged in WWTP effluent or may end up in biosolids that are subsequently land-applied, incinerated, or returned to a landfill for disposal. There is a need for additional research regarding the effectiveness of emerging PFAS separation and destruction treatment technologies on a landfill leachate matrix. There also is a need for additional research on the physical and chemical properties, fate and transport, and transformation processes for PFAS precursors and intermediate and terminal degradation products.

3.b.ii.3 Ash monofills

Ash monofills are a subtype of Subtitle D landfills that mainly receive ash from MSW combustors, but could also receive smaller volumes of ash from other combusted waste streams, such as biosolids from POTWs. Ash monofills typically have a bottom liner and final cover requirements similar to other MSW landfills. However, they usually do not require LFG collection and control systems due to the use of combustion to remove biodegradable waste. Solo-Gabriele et al. (2020) found that ash monofills have lower PFAS concentrations than other landfill types, as shown in Table 3-3. While some landfilled wastes, such as MSW combustion ash, may have low PFAS concentrations, the inclusion of higher-concentration PFAS waste types in MSW combustion feed streams may increase MSW combustion ash PFAS content and potential for PFAS release. The PFAS in MSW combustion ash are remnants of incomplete combustion, since these facilities are generally designed to recover heat and generate electricity and not (currently) PFAS contaminant destruction.

New comparative studies show that the total detected PFAS concentration in MSW leachate samples ($\sum_{26}$PFAS mean: 9,641 ng/L) was higher than in MSW incinerator ash leachate samples ($\sum_{26}$PFAS mean: 2,621 ng/L) (Zhang et al., 2024). The variability of total detected PFAS concentrations in leachate was also higher for the MSW landfill (coefficient of variation, CV = 43 percent) compared to the MSW incinerator ash landfill (CV = 16 percent) (Zhang et al., 2024).

Studies have also examined PFAS concentrations in leachate at landfills where ash was co-disposed with other types of waste. A comprehensive study of co-disposal of MSW combustion ash (30 percent) with MSW (70 percent) and at a separate landfill with sewage sludge (4 percent) and ash (96 percent) found that PFAS concentrations were closer to those found in MSW landfill leachate or sludge leachate regardless of the amount of co-disposed ash ($\sum_{26}$PFAS). This phenomenon was hypothesized to occur due to preferential flow of leachate through the wastes instead of the ash which had lower hydraulic conductivity (Liu et al., 2022b).

With limited data on the breadth and concentrations of PFAS in ash monofill leachate, more research is needed to determine the PFAS and precursor content of ash from different combustion technologies and air pollution control systems.

3.b.ii.4 Industrial landfills

Industrial landfills receive non-hazardous solid waste from industrial operations (i.e., non-municipal) and are often designed to manage specific waste streams (e.g., furnace slag, pulp and paper mill sludges,

plastics) and the designs of industrial landfills vary widely based on the characteristics of the waste they receive. Requirements for environmental controls at these landfills also vary from state to state. Depending on the waste types and size of the landfill, some states do not require a liner; however, if a liner is required, a membrane cap can also be required.

Landfills that have historically received PFAS manufacturing wastes have been associated with high concentrations of PFAS in the leachate and environmental impacts (MPART, 2020). Some waste types received at industrial landfills, including plastics and materials with polishes or coatings, contain PFAS (OECD, 2013). Specifically, industrial processes such as leather tanning, chrome plating, and textile manufacture contribute to PFAS in the industrial solid waste stream (ITRC, 2022). Due to the variability in control technologies, industrial landfills may not be effective at containing PFAS and so are generally not believed to be an appropriate disposal option for PFAS-containing wastes.

3.b.ii.5 Construction and demolition landfills

C&D landfills receive waste from construction, renovation, and demolition projects, as well as other inert materials that are generated in high volumes, comparable to MSW waste generation (U.S. EPA, 2020b). GCCSs are not federally required in C&D landfills, due to the low levels of biodegradable waste received compared to MSW landfills, and there are also no federal regulations for C&D landfills to be equipped with a liner. States create their own requirements for environmental controls at these landfills, so requirements vary widely from state to state, ranging from no liner to a required composite liner. However, if a liner is required, a membrane cap may also be required.

C&D landfills are known to receive PFAS-containing wastes (e.g., building materials and carpeting with PFAS treatments) (OECD, 2013; Solo-Gabriele et al., 2020; Bečanová et al., 2016; Liu et al., 2024), and PFAS have been measured in the leachate from C&D landfills equipped with a leachate collection system (Chen et al., 2023). Thelusmond et al. (2025) estimated that C&D landfills in North Carolina generated more than double the PFAS mass flow (5.1 kg/year) from leachate production than MSW landfills (2.3 kg/year).

Due to the variability in state requirements for GCCSs, PFAS-containing wastes that also include a biodegradable component should not be disposed of at C&D landfills and C&D landfills that lack composite liners, leachate management systems, and GCCSs are unlikely to prevent release of soluble or volatile PFAS. Because stable PFAS polymers (e.g., PTFE found in some electrical insulation and membrane materials) are not expected to undergo chemical transformation in a C&D landfill, these types of PFAS compounds are likely to be contained in the C&D waste mass for a long period. However, C&D landfills may not be suitable for more mobile PFAS, such as non-polymer PFAS and SFPs, because these types of PFAS compounds are expected to release soluble PFAS and are a concern for C&D landfills.

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

PFAS are emitted from landfills via LFG and landfill leachate, which is any liquid that has contacted solid waste and is typically derived from the breakdown of waste itself or infiltration of rainwater into the waste. As such, controls to manage contaminants in landfills focus primarily on these two releases.

LFG results from the natural decomposition of organic material in landfill wastes under anaerobic conditions. Traditionally, LFG is composed of roughly 50 percent methane, 50 percent CO_2, and a small amount of NMOCs. Leachate can contain a combination of soluble, suspended, and miscible materials

extracted from the waste. As shown in Figure 3-1, landfills constructed with environmental controls (e.g., bottom liner, leachate collection system, gas collection system, final cover system) manage the release of contaminants into the environment. This figure is designed to be inclusive of all controls commonly encountered at landfills. However, it should be noted that the actual configuration of a particular landfill can vary widely by site due to differences in types of waste accepted, operating practices, site conditions, and state regulations.

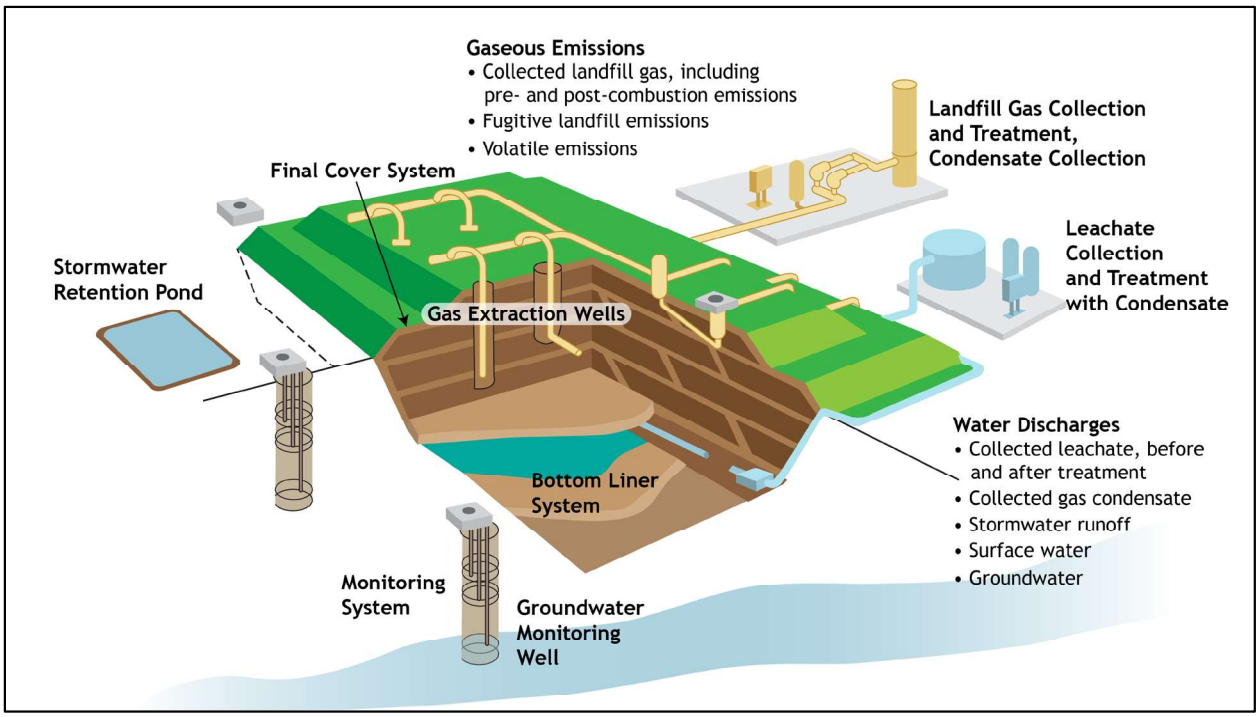

Figure 3-1. Engineered landfill components and potential PFAS release pathways.

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

Under RCRA (Subtitle C), any new landfill, replacement of an existing landfill, or lateral expansion of an existing landfill that received hazardous waste must have a double liner and leachate collection system to limit leachate through the bottom of the 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 generated inside the landfill will collect on top of the liner, so its design includes 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 waste (see Section 2.f and Section 3.b.iii.5).

Most landfills regulated under RCRA (Subtitle D) to receive non-hazardous waste are subject to design criteria that require either a composite liner and leachate collection 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.

Uncontrolled leachate could result in the release of PFAS into the environment. Because state requirements for landfill liners vary and some landfills are not required to have liners because of waste type or quantities received, the variation of landfill requirements among states poses a challenge for the

long-term containment of existing PFAS in landfills. Additionally, RCRA-exempt sites may not require any liner system (40 CFR 258.1). Because PFAS are not a RCRA-regulated hazardous waste, existing unlined landfills could receive PFAS-containing wastes that are readily released into the underlying groundwater.

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

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

New research on double HDPE geomembrane liner systems indicates that PFAS were detected in all primary and secondary leachate samples, at concentrations not significantly different from one another, suggesting their transport to secondary leachate collection systems (Robey et al., 2025). HDPE liner permeation experiments with PFAS (specifically PFAAs) indicate migration via permeation an unlikely possibility, given the quickest breakthrough times for 60-millimeter HDPE liners were estimated at approximately 1,500 years (Ahmad et al., 2024). Based on comparing chloride concentrations, PFAS concentrations in secondary leachate were often higher than expected if having been leaked from the primary liner, with PFAAs more likely to exceed expected levels (Robey et al., 2025). These disproportionately higher concentrations suggest that conditions within the secondary leachate collection system itself may be contributing to increased PFAS transformation, and/or that PFAS may be derived from another source, such as LFG (Robey et al., 2025). Wang et al. (2025) and Zhang et al. (2013) showed that FTOHs, the predominant PFAS found in LFG (Titaley et al., 2023), can biodegrade to FTCAs and eventually to PFCAs, both of which were found to be in higher proportions within the secondary leachate (Robey et al., 2025). Further, groundwater PFAS concentrations were found to represent a very small fraction (on average, 0.3 percent) of the total PFAS in secondary leachate, suggesting that the PFAS in the secondary leachate are mainly derived from within the landfill itself (Robey et al., 2025). Thus, PFAS migration through landfill liners and potential groundwater impacts remains a concern, highlighting the need for diligent leachate management and landfill liner quality control (Robey et al., 2025). The study underscores the importance of continued research into PFAS migration mechanisms and the potential environmental impacts of unidentified precursor PFAS in landfills (Robey et al., 2025).

3.b.iii.2 Landfill gas collection system

Landfills use GCCSs to manage gas generated from decomposing organic waste; however, not all landfills are required to collect LFG (see Table 3-2). A GCCS consists of a network of perforated pipes sunken into the waste mass. These “gas wells” are connected to a central blower that pulls gas from the wells. Despite the presence of a GCCS, gas can still migrate both through the surface of the landfill and

underground through the bottom of the landfill. The gas produced by MSW landfills contains about 50 percent methane that is usually collected and burned at the site via flares or for energy recovery.

As noted in Section 3.b.iii.6.1, research has found that soluble PFAS with relatively high vapor pressures can be emitted into the atmosphere via the gas generated at landfills (Ahrens et al., 2011; Hamid et al., 2018; Wang et al., 2020; Weinberg et al., 2011). Direct sampling methodologies are currently under development, and published concentrations of PFAS measured in situ are limited (Titaley et al., 2023; Lin et al., 2024). Many LFG destruction systems (e.g., flares, engines, boilers) generally operate lower than the 1,100°C necessary to achieve the mineralization of PFAS. Nonetheless, LFG collection and management systems (e.g., flares) must be present at MSW landfill sites that accept PFAS waste, especially biodegradable PFAS waste such as biosolids (Tansel et al., 2024) and some paper-based food packaging (Ye et al., 2024). The use of GAC prior to the flaring of LFG can be effective in removing contaminants of concern from LFG (Smallwood et al., 2024). Data on the fate of PFAS in LFG that is managed through on-site GCCS, including flares, are still limited. See Section 4 for potential research needs.

LFG is identified as a significant pathway for the release of volatile PFAS, as noted in studies by Lin et al. (2024) and Titaley et al. (2023). Research has detected various PFAS in landfill leachate, including perfluoroalkyl acids (PFAA), FTCAs, perfluoroalkyl acid precursors, and fluorotelomer alcohols (FTOHs), according to Lang et al. (2017), Robey et al. 2024 and 2025, Zhang et al. (2024), and Smallwood et al. (2023). Among these, volatile FTOHs are predominant in gas-phase PFAS within LFG, with concentrations ranging from 0.46 micrograms per cubic meter (µg/m³) to 14.0 µg/m³, as reported by Titaley et al. (2023) and Lin et al. (2024). These concentration levels are approximately two orders of magnitude greater than FTOH levels reported in ambient air collected near landfills. FTOHs are the most common neutral PFAS, constituting 87 to 97 percent of the total neutral PFAS concentration, as noted by Lin et al. (2024). Specifically, the 8:2 FTOH accounts for 50 to 79 percent of the total neutral PFAS in LFG (Lin et al., 2024).

The observed concentrations of neutral PFAS in LFG range from 22,000 to 33,000 ng/m³, with extrapolated total concentrations (i.e., beyond their calibration range) reaching between 210,000 and 940,000 ng/m³, which is significantly higher than previously reported levels, as highlighted by Lin et al. (2024). Even with conservative estimates, the mass of fluorine released in LFG (32 to 76 percent) is comparable to or exceeds the mass released in landfill leachate (24 to 68 percent), as stated by Lin et al. (2024).

PFAS are typically released early in the decomposition cycle of packaging materials, within about 10 days for high-fluorine materials, indicating that some PFAS may be released before LFG collection systems are installed, as Ye et al. (2024) suggest.

3.b.iii.3 Final cover system

After a regulated landfill has reached its designed and permitted capacity, it must be capped with a cover system. This system typically consists of some combination of soil and membrane materials and is primarily intended to reduce infiltration of rainwater into the landfill to minimize further leachate generation. The cover system also helps increase the efficiency of the GCCS and reduce uncontrolled gas emissions by acting as a barrier. Synthetic membranes and caps are more effective at controlling release of PFAS than earthen covers because of the lower overall hydraulic conductivity. Earthen covers are also more subject to wet/dry and freeze/thaw cycles and cracking that disrupt the compaction of the soil and

can result in greater LFG emissions (Ahrens et al., 2011; Tian et al., 2018; Wang et al., 2020; Weinberg et al., 2011).

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

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

3.b.iii.5 Leachate discharge controls

3.b.iii.5.1 Leachate characteristics

Leachate is the liquid effluent from landfills primarily generated through the percolation or infiltration of rainwater through waste. Leachate often contains high concentrations of biodegradable and non-biodegradable organic matter, dissolved and suspended solids, heavy metals, ammonia, and sulfur compounds (Mukherjee et al., 2015; Renou et al., 2008). PFAS concentrations in leachate are correlated with several physicochemical parameters, including leachate-specific conductivity, alkalinity, total organic carbon (TOC), ammonia, and chemical oxygen demand (COD) (Zhang et al., 2023). However, correlation between leachate PFAS and these parameters does not necessarily indicate causation (Zhang et al., 2023).

The waste type, age, climate at the landfill site, and methods of landfill operation all influence the characteristics of leachate. Some studies found that fresh leachate (from raw waste in transportation vehicles without any processing) initially had no measurable PFAS, but aged leachate showed higher PFAS concentrations, implying that non-target PFAS precursors may transform to measurable intermediate and terminal PFAS degradation products during the aging process (Busch et al., 2010; Eggen et al., 2010; Zhang et al., 2023). Liu et al. (2021) found significantly greater PFAS concentrations in landfill leachate than in leachate from waste transportation vehicles which also could have resulted from transformation processes (Liu et al., 2021). Moreover, landfills in wet, warm climates are most likely to have higher PFAS concentrations in the leachate, as heavy rainfall facilitates the leaching process (Lang et al., 2017; Tolaymat et al., 2024; Wei et al., 2019). Higher PFAS concentrations have also been measured in leachate from an elevated temperature MSW landfill (up to or exceeding 100°C) as compared to concentration in another cell from the same landfill at a lower temperature (less than 60°C), implying temperature-dependent increase in PFAS release and/or precursor transformation rates (Collins et al., 2024).

Leachate from older accumulated wastes (more than 10 years old) contained lower levels of PFAA precursors due to progressive biotransformation over time (Lang et al., 2017; El-Barkaoui et al., 2025). Similarly, waste subjected to prolonged anaerobic degradation exhibited higher PFAS concentrations and higher concentrations of terminal PFAAs relative to measurable PFAS precursors (Liu et al., 2021b; Tolaymat et al., 2023; El-Barkaoui et al., 2025). During the methanogenic phase, organic matter degradation can elevate pH, consequently deprotonating waste surfaces (e.g., organic matter), thereby

reducing their sorption capacity for PFAS and eventually increasing PFAS concentrations in the leachate (Allred et al., 2014; El-Barkaoui et al., 2025).

These factors result in highly variable leachate characteristics across landfill types and on a site-by-site basis. Subtitle C hazardous waste landfills are required to use a leachate collection system during their active and post-closure care periods to mitigate adverse impact to human health and the environment. Since the use of leachate collection systems at Subtitle D landfills varies by landfill type and state requirements, the efficacy of leachate management and PFAS emissions depends on the controls implemented. Because of the persistence of PFAS, the potential remains for leaching of PFAS during the post-closure care period and far beyond. Ideally, 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 a more detailed discussion on the types of leachates and associated PFAS.

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

The most common method for non-hazardous waste leachate disposal is off-site treatment at municipal WWTPs, where leachate is mixed with wastewater and treated. The dynamic nature of leachate characteristics, the presence of non-biodegradable compounds and ammonia, and the presence of emerging contaminants (such as PFAS) in the leachate may make it difficult for WWTPs to effectively treat the influent water. In some cases, a landfill with elevated PFAS in its leachate may burden the ability of a WWTP to treat, or remove, these compounds before discharge to the environment (Masoner et al., 2020). Thelusmond et al. (2025) calculated that, generally, leachate is a small contributor to PFAS mass loading of WWTPs; however, for small WWTPs (approximately 3,800 m^3/day), a large landfill receiving more than 51 centimeters (cm) of annual rainfall may contribute comparable PFAS mass loadings as those received from the domestic wastewater.

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). As a result, PFAS is more likely to accumulate in biosolids or be discharged to surface water in plant effluent, which can lead to uncontrolled release of PFAS into the environment. To date, no federal requirements exist for landfill leachate to be monitored or treated for PFAS prior to WWTP consideration for acceptance. However, WWTPs may need to establish additional monitoring and controls to ensure compliance with state-issued permits. For example, local limits developed at the municipal level in accordance with 40 CFR 403.5(c) to prevent the pass through of PFAS through the WWTP or prevent the inhibition of WWTP processes may require contributing sources (e.g., landfills) to install treatment, meet numeric discharge quality levels, or follow best management practices to reduce PFAS prior to introducing the leachate to the WWTP. The selected controls may be tailored to site specific end uses of the WWTP biosolids or effluent. For these reasons, some WWTPs have requested that landfill operators pretreat leachate on site, while others are implementing surcharges based on the leachate quality. Underground injection is another form of off-site leachate management in the United States (see Section 3.c).

Table 3-4 presents leachate management or treatment methods for the on-site management of leachate. Multiple technologies in the table are marked for further research—technologies for which, at the time of publishing, are under development (Sabba et al., 2025). “Secondary treatment required” refers to the remaining concentrated or captured PFAS, which must be disposed of after treatment. “Potential secondary release” refers to the potential for PFAS release or breakthrough during the treatment process. Leachate characteristics are site-specific; therefore, the effectiveness of leachate

technology should be evaluated on a site-by-site basis. (Table 3-3 lists average PFAS concentrations observed in different types of landfill leachate.)

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

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. Although recirculation tends to increase PFAS content and may result in larger fugitive emissions due to faster waste degradation, it can also decrease long-chain PFAS concentrations. This process potentially transforms landfills into 'PFAS sinks' rather than 'PFAS sources,' thereby minimizing the environmental footprint of these substances (Saha et al., 2024). Strategic placement of PFAS-containing waste in the upper landfill layers, where degradation can be controlled once the final cover is in place, can further reduce PFAS leaching (Saha et al., 2024). This method limits the likelihood of precipitation reaching the waste, thereby minimizing PFAS migration into the leachate (Saha et al.,2024).

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

Treatment Technology	Treatment Mechanism	Pros for PFAS Treatment	Cons for PFAS Treatment	References
Physiochemical Processes				
GAC	Adsorption	• Familiar technology • Effective for long-chain PFAS	• Secondary treatment required • Short-chain PFAS breakthrough • Potential secondary release • Cost	• McCleaf et al. (2017), Pan et al. (2016), Ross et al. (2018)
PAC with coagulation	Adsorption	• Effective for long-chain PFAS	• Secondary treatment required • Costly for high-volume leachate • Potential secondary release	• Bao (2014), Pan et al. (2016)
Polymeric adsorption	Adsorption	• Tailored for specific compounds	• Secondary treatment required • Potential secondary release	• Liu (2017)
Ion exchange resin	Ion exchange adsorption	• Specified for certain compounds • More effective than GAC for long-chain compounds	• Secondary treatment required • Less effective for short-chain PFAS • Potential secondary release	Dickenson and 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 and Sierra-Alvarez (2008)
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

Treatment Technology	Treatment Mechanism	Pros for PFAS Treatment	Cons for PFAS Treatment	References
Photocatalytic advance oxidation process	Oxidation	• Permanent degradation	• Potential side-product formation • Cost	Lockwood (2018), Ross et al. (2018)
Coagulation-flocculation	Precipitation	Limited data available	Limited data available	Bao (2014), Dickenson and 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
Foam fractionation	Separation	More research needed	• High PFAS emissions to the air	Smith et al. (2022 and 2023)
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 and 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 and Higgins (2016)
Ultrafiltration (UF); microfiltration (MF)	Physical separation	Not available	• Not effective for PFAS	U.S. EPA (2020a)
Climatic evaporation; thermal evaporation; mist evaporation	Volume reduction	Limited data available	• Potential secondary emissions	Cerlanek et al. (2024), Goukeh et al. (2025)
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
Underground injection	Containment	• Potential solution for PFAS concentrate	• Dependent on site geology • Regulatory approval	ITRC (2018)
Incineration	Thermal destruction	• PFAS destruction	• Potential secondary emissions (incomplete destruction) • Regulatory approval	ITRC (2017), Yamada et al. (2005)
Solidification	Containment	• Co-location with landfill • Reduces PFAS mobility • Could be used in combination with other treatment technologies	• Consumes air space in landfill • Unrealistic for large leachate volume	None identified
Biological Processes				
Activated sludge process sequencing; batch reactor; anaerobic; digestor; membrane bioreactor	Biological processes	Limited data available	• Limited by high concentrations of non-biodegradable organic matter	Ross et al. (2018), Saez et al. (2008), U.S. EPA (2020a)
Natural Processes				
Constructed wetlands; aerated ponds; phytoremediation; land application	Environmental release	Not available	• Direct release of PFAS	U.S. EPA (2020a)

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

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

may be further complicated by high concentrations of PFAS (Dickenson and 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 full range of PFAS found in landfill leachate. Activated carbon is a non-selective treatment method, expected to be less effective in higher strength effluents, such as landfill leachate, that contain nutrients and other compounds that compete for adsorption sites within the carbon. 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 COD 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.

Foam fractionation is a water treatment method that takes advantage of the surfactant-like behavior of many PFAS compounds. As air bubbles rise through contaminated water, PFAS molecules attach to their surfaces. These bubbles accumulate and create a surface foam that becomes concentrated with PFAS. By collecting and collapsing this foam, the process separates PFAS into a smaller, more concentrated volume (called foamate), leaving behind treated water with significantly reduced PFAS levels. Foam fractionation is emerging method for removing PFAS from contaminated waters, particularly from sources like AFFF and leachate. Smith et al. (2022) performed a pilot-scale study that evaluated continuous foam fractionation as a treatment for PFAS-contaminated landfill leachate. The process achieved around 60 percent total PFAS removal, with long-chain compounds removed at rates exceeding 90 percent, while short-chain PFAS showed much lower removal efficiencies (less than 30 percent). Operational factors like airflow rate, foam volume, and contact time influenced performance, but differences between batch and continuous modes were minimal. However, further research is needed to test for PFAS aerosolization and volatilization to better understand safety and prevention of PFAS emissions to the atmosphere (Smith et al., 2023).

Natural processes (such as constructed wetlands and phytoremediation) and biological processes (degradation, nitrification, and denitrification) are expected to be ineffective at treating and preventing

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

Leachate treatment through evaporation reduces the volume of leachate. Open-air evaporation methods may be effective at concentrating leachate but are a pathway for secondary PFAS releases to air. Commercial evaporators operated through the heat generated by the LFG combustion or other fuel sources are sometimes used at landfills. Exhaust gases emitted from the evaporators may be exposed to high temperatures, but those temperatures may not be high enough or last long enough to destroy PFAS (see Section 3.a). Two full-scale thermal landfill leachate evaporation systems were evaluated by Cerlanek et al. (2024). Samples analyzed included the feed leachate, residual evaporated leachate, sludge, and condensed vapor. PFAS concentrations were measured in both the evaporation vapors and residuals. It was estimated that the vapor pathway can emit 9 to 24 percent of feed leachate PFAS mass. Similarly, Goukeh et al. (2025) found that approximately 99.9 percent of FTOHs and between 0.14 to 6.8 percent of PFCAs were lost in a bench-scale rotary evaporator treating three landfill leachates and two synthetic leachates.

3.b.iii.6 Landfill gas emission controls

3.b.iii.6.1 Landfill gas characteristics

Under the anaerobic conditions that dominate landfill environments, organic waste (e.g., food waste, paper, cardboard) decomposes and generates LFG. In MSW landfills, LFG consists mostly of methane and CO_2. In most landfills where gas is collected, it is burned for energy or to destroy the methane and other organic chemicals it contains. Even at sites that actively collect LFG, a fraction (EPA estimates 25 percent, on average; U.S. EPA, 2025) of the LFG is emitted directly to the environment through the landfill surface and other routes. These uncontrolled emissions are referred to as fugitive losses.

Research has found that soluble PFAS with relatively high vapor pressures can be emitted into the atmosphere via the gas generated at landfills (Ahrens et al., 2011; Hamid et al., 2018; Wang et al., 2020; Weinberg et al., 2011). EPA is currently conducting research on direct LFG sample evaluation for PFAS concentrations (see Section 4).

Simulations show that methane, a major component of LFGs, can significantly affect PFAS behavior in landfill settings by competitively adsorbing with vapor-phase PFAS, particularly FTOHs, in montmorillonite-rich clay barriers, potentially leading to their accumulation within the barrier materials (Xu et al., 2025). As moisture content increases, methane's competitive advantage diminishes, allowing PFAS to maintain distinct adsorption regions within unsaturated montmorillonite pores, slowing its mobility, according to Xu et al. (2025). These findings may provide insights to improve landfill barrier soil designs to reduce PFAS fugitive emissions. However, the challenge of effectively destroying PFAS within collected LFG remains unresolved, as discussed in Section 3.b.iii.2.

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

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

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

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

Combustion temperatures and duration may prove to be critical factors for destruction of PFAS in LFG. While the operating temperature of on-site flare systems averages around 850°C (1,550°F) (U.S. EPA, 2008), power-generating engines and boiler systems may run even cooler. None of these systems operate at the temperature necessary to mineralize PFAS (1,100°C). The use of GAC prior to the combustion of LFG can be effective in removing contaminants of concern from LFG (Smallwood et al., 2024) and could be used to reduce PFAS flows to on-site LFG thermal destruction devices, reducing the potential for PFAS and PICs emissions. See Section 3.a for a more complete discussion on conditions required for PFAS destruction.

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

LFG condensate is a liquid that has condensed in the LFG collection system piping during the extraction of gas from the landfill. In gases with high concentrations of water vapor, water condenses in pipes and accumulates in traps staged throughout the collection network. This condensate contains volatile compounds and accounts for a relatively small percentage of flow from a landfill. Gas condensate is commonly collected and managed with the landfill leachate as liquid waste. PFAS has been detected in LFG condensate, with PFBS being the dominant species at a concentration of 1,000 ng/L (Li, 2011) and Chen et al. (2023) finding a maximum total PFAS concentration of 80,900 ng/L ($\sum_{26}$PFAS).

3.b.iv Potential for releases during landfilling

Over time, certain pollutants have increased potential to move into the environment beyond the footprint of the landfill. As water passes through the landfill, it may leach pollutants from the waste—including PFAS—and move them deeper into the waste mass. Controlled landfill leachate is collected and either reinjected, treated on site, or sent for off-site treatment. In the absence of leachate management systems, uncontrolled leachate releases occur when water travels through the waste, out of the landfill, and into groundwater or surface water (see Section 3.b.iii.1).

LFG can also contain heavy metals, organic chemicals, and methane gas and can produce explosive mixtures of gas in the vicinity of the landfill if not properly controlled. LFG capture technologies are

widely used to control gaseous emissions from landfills. However, not all landfills are required to install and operate LFG collection systems. Even when an LFG collection system is installed and properly operated, a fraction of LFG is emitted directly to the environment through the landfill surface and other routes as fugitive losses (see Section 3.b.iii.2).

Even years after landfill closure, direct human and ecological exposure to PFAS is possible if PFAS are emitted through the air or discharged to 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 during which landfills receive waste and the post-closure care period. Ideally, landfill areas could be used for other beneficial purposes after closure; however, this requires that potential risks from landfill contents be adequately managed. Direct exposure to PFAS from landfilled waste is possible for people living or working near landfills due to gaseous or water releases from the site. Additionally, if PFAS-containing wastes are present on trucks and moved to active cells, landfill employees are directly exposed to PFAS on the job. Research has shown elevated concentrations of PFAS in landfill ambient air (Hamid et al., 2018).

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

3.b.v Testing and monitoring

Currently, there are no federal requirements for the monitoring of PFAS in landfill waste, leachate, condensate, or LFG and analyzing for PFAS in LFG may pose a challenge for comparison across destruction/control technologies and types of landfills due to the lack of standardized testing (see Section 4.a for research needs). However, landfill operators should consider including PFAS measurements with the regular leachate monitoring parameters that are regularly evaluated.

EPA and others are conducting studies to evaluate the effectiveness of landfills in containing or managing PFAS (see Section 3.b) and the Agency and collaborators have developed and updated tools for monitoring and testing of landfill PFAS emissions that will provide a better understanding of environmental fate, transport and transformation of PFAs in landfills. EPA published an updated version of Method 1633 (i.e., 1633A) for quantitative analysis of a range of soluble and neutral PFAS in aqueous and solid matrices by liquid chromatography-tandem mass spectrometry (LC/MS/MS), and this method was validated in a variety of matrices including landfill leachate, groundwater, and biosolids. EPA worked with ASTM International to publish ASTM-D8421-11, an additional LC/MS/MS-based analytical method for aqueous matrices that was validated in leachate and groundwater matrices. In collaboration with researchers, EPA also published an integrated, standardized workflow for NTA of PFAS that can be used for identification of non-target PFAS in landfill emissions or in nearby air or groundwater, potentially including novel PFAS precursors for which no certified reference materials are available (Whitehead et al., 2025).

Waste and leachate matrices can present challenges for identification of unknowns due to high levels of background and interferences the limit reliable qualitative identification. This collection of best practices for NTA data acquisition and interpretation will help promote consistency and standardize laboratories' communication of confidence in identification of unknowns.

3.b.vi Uncertainties/unknowns

Additional sampling and analytical methodologies are needed to better characterize the fate, transport, and transformation of PFAS within landfills to provide accurate estimates of PFAS concentrations in waste inputs and landfill emissions and the potential for PFAS releases from leachate or LFG without adequate controls. Standardized analytical methods are needed for volatile PFAS and ultrashort chain PFAS in wastes, leachate and LFG, and aggregate analytical methods such as total organic fluorine and the total oxidizable precursors assay are also needed to simplify testing for a wide range of PFAS precursors and PFAAs.

As with thermal treatment, EPA lacks detailed information on the amounts and concentrations of PFAS and precursor compounds in wastes that are landfilled; however, limited research is providing some information on PFAS fate and partitioning in landfill environments. The bulk of PFAS seems to remain bound with the waste solids, with quantifiable percentages in LFG and leachate. However, there is a high level of uncertainty in these measurements and more data are needed.

A recent study of three MSW landfills in the United States estimated that LFG accounts for approximately 32 to 76 percent of the mass of fluorine/PFAS released from the landfills and 24 to 68 percent via landfill leachate (Lin et al., 2024). Based on data from two MSW landfills, 95 to 97 percent of PFAS leached from MSW was captured by the leachate collection system with 3 to 5 percent found within stormwater and less than 1 percent found in gas condensate and groundwater. These latter data were used in a mass balance to estimate an average mass flux of PFAS leached of 1.67 to 4.21 kg/year, which along with an estimate of the total mass of PFAS within the landfilled waste approximated a 40-year time span for PFAS to be released, assuming constant mass flux (Chen et al., 2024).

EPA has developed peer-reviewed and reliable toxicity data for only a handful of PFAS. Many PFAS precursors and intermediate and terminal degradation products do not have reliable data regarding physicochemical properties that could be used to improve modeling of their fate, transport, and transformation within landfills, or after release in landfill emissions. SFPs can be considered precursors due to their potential to release perfluoroalkyl acid side chains. Much is still unknown about SFP degradation rates in landfills.

Additionally, the efficacy of treatment options for PFAS captured by leachate and LFG collection systems is not well understood and is in some cases intrinsically entwined with TWTDS and thermal treatment options. EPA continues to research these complex and important issues. Refer to Section 4 for a summary of EPA and DoW's planned research activities specific to landfill containment, wastewater treatment, and thermal treatment of PFAS.

Further, current on-site LFG combustion systems—including flares, engines, and boilers—typically operate below the temperatures known to mineralize PFAS compounds (1,100°C and greater). This raises concerns about incomplete destruction and the potential formation of PICs. While GAC pre-treatment may help reduce PFAS concentrations before thermal treatment, the effectiveness of this approach in minimizing PIC formation remains unclear. Further research is needed to evaluate how combustion temperature, residence time, and pre-treatment strategies influence PFAS breakdown and PIC generation in LFG systems, especially under real-world operating conditions.

3.b.vii Summary

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

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

PFAS can be emitted with LFG that is generated as waste decomposes over time. On-site and off-site LFG management commonly uses flares, engines, or boilers to combust LFG. Combustion temperature and duration could be critical factors for the destruction of PFAS in LFG, as discussed in Section 3.a. The use of GAC for treatment of LFG prior to combustion should be explored further for removal of PFAS (Lin et al., 2024).

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

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

Given the high level of uncertainty associated with PFAS behavior in landfills, the effects of PFAS on liner integrity, gaseous emissions from landfills, the effectiveness of leachate treatment for PFAS removal,

and the levels and types of PFAS in landfill leachate, additional research and test data are needed to further evaluate this disposal method for PFAS and PFAS-containing wastes. See Figure 3-2 for a summary of recommended landfill disposal options for PFAS-containing wastes and considerations for selecting the best option based on waste and landfill characteristics.

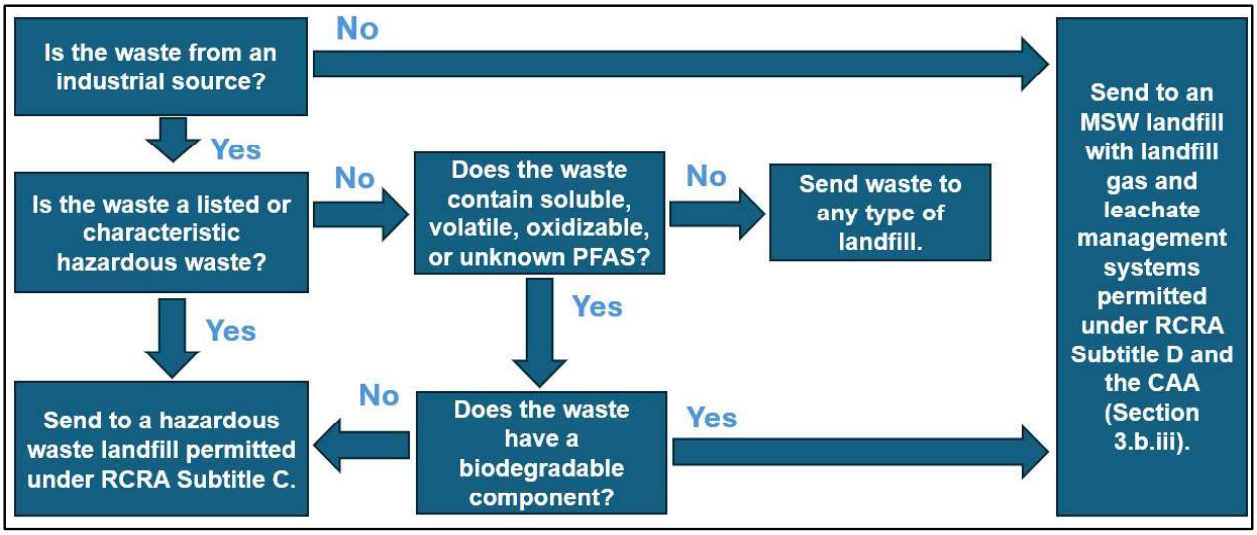

Figure 3-2. Decision framework for selection of landfill disposal for PFAS-containing industrial waste.

3.b.viii References for Section 0

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3.c Underground injection

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

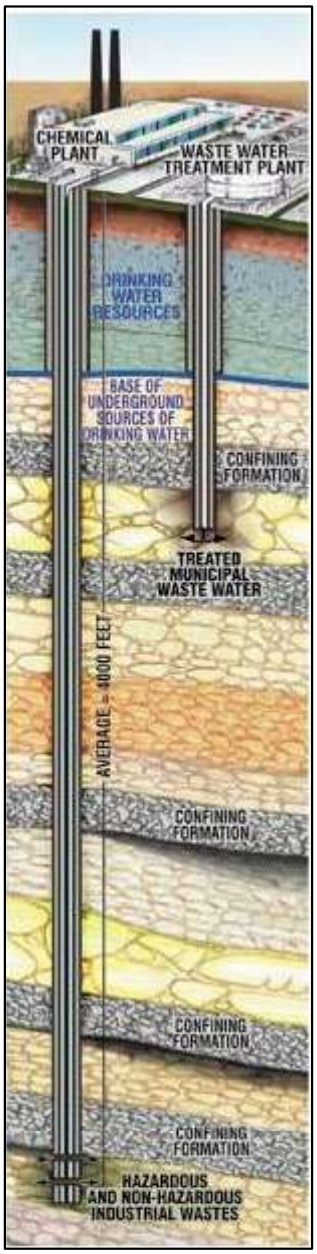

Figure 3-3. Class I wells.

3.c.i Types of wells

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

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

Class I wells inject into geologic formations below the lowermost USDW and are further subdivided into four categories: municipal wastewater, radioactive waste, hazardous waste, and non-hazardous industrial waste disposal wells (see Figure 3-3).

Class II wells are used for injection activities associated with oil and gas production and hydrocarbon storage.

Class III wells are solution mining wells used to inject fluids for the purposes of dissolving and extracting minerals.

Class IV wells, with limited exceptions, have been banned by EPA since 1984 and were used to inject hazardous or radioactive waste into or above geologic formations containing USDWs.

Class V wells include injection wells that are not included in Classes I, II, III, IV, or VI. EPA has identified multiple subtypes, including stormwater drainage wells, septic system leach fields, and agricultural drainage wells.

Class VI wells are used to inject and geologically sequester CO_2.

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

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

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

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

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

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

Final UIC regulations were published six years later, and federal and state regulation and oversight has been informed by extensive reviews of injection practices and the associated risks over time (U.S. EPA, 2001). The requirements for Class I wells under 40 CFR part 146 and 40 CFR part 148 (which applies to hazardous waste wells only) are designed to ensure that injected fluids cannot migrate into USDWs through either of two potential pathways: (1) loss of waste confinement, or (2) "improperly plugged or completed wells or other pathways near the well" (U.S. EPA, 2001). These requirements include, but are not limited to:

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

Specific components of these requirements are discussed further below.

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

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

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

3.c.ii.3 Potential for Release

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

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

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

Class I hazardous waste wells are highly protective of USDWs and include additional requirements beyond those of Class I non-hazardous industrial waste wells. The 1984 Hazardous and Solid Waste Amendments to RCRA prohibited land disposal of hazardous waste, including via underground injection, with limited exceptions. Hazardous waste disposal via Class I injection wells is permitted if the operator can demonstrate that the waste will remain where it has been injected for as long as it remains

hazardous (defined under regulation as a period of up to 10,000 years). To demonstrate this, Class I hazardous waste well operators must receive approvals of "no-migration petitions" from EPA.

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

3.c.iii Availability

Currently, the United States has 886 Class I wells. Approximately 50 percent of Class I wells are permitted for non-hazardous industrial waste injection and approximately 16 percent are permitted for hazardous waste disposal. The remainder are permitted for municipal wastewater disposal. EPA is aware of both non-hazardous industrial and hazardous Class I wells that manage PFAS-containing fluids. However, there is currently no national information on the number and location of Class I non-hazardous industrial or hazardous waste wells that could accept PFAS-containing waste or are willing to accept waste not generated on site.

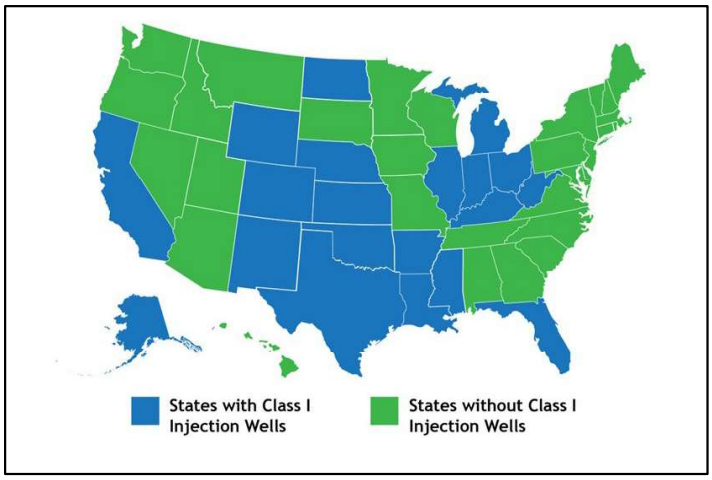

Figure 3-4. States with Class I non-hazardous or hazardous waste injection wells.

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

Table 3-5. Inventory of Permitted Class I Non-Hazardous and Hazardous Waste Wells in the United States (FY 2023; Source: EPA)[26]

Location of Wells		Number of Wells	
EPA Region	State/Tribe	Class I Non-Hazardous	Class I Hazardous
3	West Virginia	1	-
4	Florida	302	-
	Kentucky	2	-

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

Location of Wells		Number of Wells	
EPA Region	State/Tribe	Class I Non-Hazardous	Class I Hazardous
	Seminole Tribe	3	-
	Mississippi	4	4
5	Illinois	5	2
	Indiana	12	4
	Michigan	46	7
	Ohio	9	10
6	Arkansas	8	4
	Louisiana	17	19
	New Mexico	-	6
	Oklahoma	6	-
	Osage Nation	1	-
	Texas	82	78
7	Kansas	58	7
	Nebraska	11	-
8	Colorado	13	-
	North Dakota	8	-
	Wyoming	85	-
9	California	47	-
10	Alaska	25	-
Total		**745**	**141**

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

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

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

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

Hazardous waste wells are currently located in 10 states; however, most are in Texas and Louisiana. Most Class I hazardous waste wells are sited at industrial facilities and dispose of waste generated on site (U.S. EPA, 2016). There are currently no Class I hazardous waste wells in EPA Regions 1, 2, 3, 8, 9, or

10 (see Figure 3-4 and Table 3-5). Because of this geographic concentration of Class I hazardous waste wells, waste producers may face transportation and logistical challenges.

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

3.c.iv Testing and monitoring

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

Broadly, Class I well operators must:

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

Class I hazardous waste wells operators must conduct mechanical integrity testing more often than Class I non-hazardous industrial waste operators. They also must establish and follow additional procedures for reporting and correcting mechanical integrity problems. Operators of Class I hazardous waste wells 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*[27] and EPA Region 5's guidance on *Determination of the Mechanical Integrity of Injection Wells*[28].

3.c.v Uncertainties/unknowns

The fate and transport of PFAS in the subsurface depends on the chemical and physical properties of specific PFAS and the geochemical properties of the injection zone. Understanding of the long-term fate and transport properties of PFAS (including precursors) in the injection zone is currently limited. Studies have shown wide ranges in PFAS properties, and these can be altered by mixture effects and interactions with co-contaminants. This creates uncertainty in predictions of PFAS contaminant release

[27] Available at: *https://www.epa.gov/sites/production/files/2015-10/documents/page_uic-class1_summary_class1_reqs_508c.pdf*.

[28] Available at: *https://www.epa.gov/sites/production/files/2015-09/documents/r5-deepwell-guidance5-determation-mechanical-integrity-200802.pdf*.

and longevity in the injection zone. These uncertainties need to be considered in the development of the required no-migration petition for disposal of PFAS in Class I hazardous waste wells.

3.c.vi Summary

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

See Appendix D for a summary of costs and considerations.

3.c.vii References for Section 3.c

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

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

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

U.S. EPA (Environmental Protection Agency). (2023). *UIC Injection Well Inventory*. *https://www*.epa.gov/uic/uic-injection-well-inventory

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

EPA's understanding of potential PFAS releases from destruction and disposal activities continues to evolve as the results of testing and ongoing research activities become publicly available, but more research is needed to refine EPA's non-binding, interim guidance on the destruction and disposal of PFAS and PFAS-containing materials. This section identifies and prioritizes research needs that, if addressed, are expected to help EPA provide meaningful updates on effective destruction and disposal practices for PFAS-containing materials in future iterations.

What's New in Section 4 of the 2026 Guidance Document?

- Revised Table 4-1 based on new information presented in this document and public comments received on the 2024 interim guidance.
- Replaced discussion of current research efforts with links to ongoing, relevant federal research activities.

Addressing the research needs described in Section 4.a will require sustained effort across government, academic, and private institutions. Within the federal government, EPA, and DoW have been leaders in supporting the research, development, and demonstration of PFAS destruction and disposal technologies. Information on these activities can be found at:

- EPA's PFAS Innovative Treatment Team – Section 5.a
- EPA's Research on PFAS[29]
- DoW's Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) PFAS Projects[30]
- DoW's Defense Innovation Unit Prototype Projects[31]

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

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

[29] Available at: *https://www.epa.gov/chemical-research/research-and-polyfluoroalkyl-substances-pfas*.

[30] Available at: *https://www.serdp-estcp.org/Featured-Initiatives/Per-and-Polyfluoroalkyl-Substances-PFASs*.

[31] Available at: *https://www.diu.mil/pfas*.

EPA encourages all entities conducting PFAS destruction and disposal research to do so in a manner that is consistent with the tenets of gold standard science established in Executive Order 14303 (*Restoring Gold Standard Science*[32]) and further defined in a memorandum from the *Office of Science and Technology Policy dated June 23, 2025*[33].

4.a Research needs to inform future guidance updates

EPA has translated the uncertainties and data gaps identified throughout this interim guidance into research needs, which are presented in Table 4-1. The research needs in Table 4-1 are focused on advancing our ability to measure PFAS in materials and releases from destruction and disposal technologies and improving our understanding of the performance of thermal treatment units, landfills, and underground injection control wells for managing PFAS and PFAS-containing materials. Individually, the research needs identified in Table 4-1 are complex to address because of the variety of substances within the PFAS class, the range of PFAS-containing materials discussed in this interim guidance, and the variability in technology designs and operating conditions. Collectively, some of the research needs identified in Table 4-1 are dependent upon other research needs. For example, fully characterizing PFAS releases from destruction and disposal technologies is dependent upon the availability of methods for measuring PFAS in air, water, and solids. Because of the complexity of the research needs and their inter-dependence, EPA anticipates that it will take years for the research needs in Table 4-1 to be fully addressed.

EPA has also prioritized the research needs in Table 4-1 as either high, medium, or low based on the potential for results to inform future versions of this interim guidance. In general, EPA designated the characterization of potential PFAS releases from thermal treatment units and landfills as high priority because these data are essential for determining whether nearby populations living near destruction and disposal sites could be exposed to PFAS at unreasonable levels from these facilities. At the same time, EPA recognizes that current laboratory methods for identifying and quantifying PFAS are limited. As such, the Agency also considers the development of sampling and analytical methods to be medium or high priority. EPA does not, however, believe that characterizing PFAS releases from PFAS destruction and disposal activities should wait until additional analytical methods are available. Rather, EPA expects that characterizing PFAS releases from destruction and disposal sites will be iterative and that future characterization efforts will be informed and guided by past efforts and the availability of new methods. EPA also expects that data on PFAS releases from PFAS destruction and disposal technologies will be used to inform and prioritize future research efforts.

EPA designated research needs associated with the underground injection of PFAS and PFAS-containing materials via Class I wells as a low priority. The Agency made this designation because the standards associated with the construction, operation, and monitoring of Class I wells are designed to isolate liquid wastes deep below the land surface and ensure protection of USDWs. While data on the performance of Class I wells for managing liquid PFAS waste would be informative, the highest priority continues to be on characterizing PFAS releases from thermal treatment units and landfills.

[32] Available at: *https://www.govinfo.gov/content/pkg/FR-2025-05-29/pdf/2025-09802.pdf*.

[33] Available at: *https://www.whitehouse.gov/wp-content/uploads/2025/03/OSTP-Guidance-for-GSS-June-2025.pdf*.

Table 4-1. Prioritized Research Needs to Inform Future Guidance Updates

Topic	Research Needs	Priority
Thermal Treatment	Methods for sampling and analyzing PFAS in solid-, liquid-, and gas-phase waste streams from thermal treatment units:	
	• Organic fluorine (all phases).	Low
	• Targeted methods for non-polar, semivolatile PFAS (gas-phase).	High
	• Targeted methods for polar, volatile PFAS (gas-phase).	High
	• Targeted methods for cationic, zwitterionic, and nonionic PFAS (solid- and liquid-phase).	High
	Full-scale performance testing—following the parameters and procedures suggested in Appendix A—at:	
	• Hazardous waste combustors:	
	○ Commercial hazardous waste incinerators (HWI).	High
	○ Hazardous-waste-burning cement kilns.	High
	○ Hazardous-waste-burning lightweight aggregate kilns (LWAK).	Medium
	• Carbon regeneration and reactivation units.	High
	• Non-hazardous waste combustors:	
	○ Sewage sludge incinerators.	High
	○ Municipal waste combustors.	Medium
	○ Thermal oxidizers.	High
	Characterization of PFAS releases from thermal treatment units operating under different conditions/designs:	
	• Gas-phase emissions.	High
	• Air pollution control device (APCD) discharges.	High
	• Bottom ash.	High
	• Biosolids, remediated soil.	High
Landfills	Methods for sampling and analyzing PFAS to better characterize PFAS loading to and fate in landfills and releases from landfills to air, municipal WWTPs, and groundwater:	
	• "Aggregate" measurements that capture target and non-target PFAS (e.g., total organic fluorine, total oxidizable precursors).	Medium
	• Non-targeted analysis to better characterize occurrence and prevalence of novel PFAS.	High
	• Quantitative analytical methods for a wider array of precursors and intermediate and terminal transformation products:	Medium
	○ Volatile PFAS (e.g., FTOHs, FTACs).	
	○ PFAA precursors, including cationic, zwitterionic and non-ionic species.	
	○ Ultrashort chain PFAS (e.g., PFPrA).	
	Approaches for solidification and stabilization of PFAS-containing materials:	
	• Effectiveness of differing solidification and stabilization techniques.	High
	• Performance over time.	High
	Fate and transport of PFAS—including modeling transformation processes and partitioning between solid-, liquid-, and gas-phases in:	
	• Hazardous waste landfills.	High
	• Industrial waste landfills.	High
	• Municipal solid waste landfills.	Medium
	• Ash monofill landfills.	Low
	• Construction and demolition (C&D) landfills.	High
	Full-scale performance testing of engineered landfill components:	

Topic	Research Needs	Priority
	• Bottom liner and leachate collection systems. • On-site leachate treatment systems. • Gas collection and emission control systems. • Final cover systems.	Low High Low Low
	Characterization of PFAS releases from landfills operating in different regions and under different conditions/designs: • Gas-phase emissions, including PICs from flaring or incineration of MSW LFG. • Emissions in leachate collected in lined landfills. • Data on groundwater contamination from infiltration at unlined landfills or from permeation through liners at lined landfills.	 High High High
	Efficacy of PFAS removal during LFG and leachate treatment: • Conventional technologies. • Emerging technologies.	 High Medium
Underground Injection (Class I)	Performance data from wells that are managing PFAS-containing liquids: • Surface management practices. • Effects on injection performance.	 Low Low
	Long-term fate and transport of PFAS in injection zones of Class I wells: • Mixture effects. • Interactions with co-contaminants.	 Low Low
	Data on the presence/absence of PFAS in groundwater near Class I wells receiving PFAS-containing liquids and data on known failures or leaks from Class I wells receiving PFAS-containing liquids.	Low
Emerging Technologies	Lab-, pilot-, and field-scale research to test the effectiveness of emerging technologies for different PFAS-containing materials and to characterize the outputs for PFAS and non-PFAS constituents.[a]	High

[a] See Section 5 for discussion of emerging technologies. EPA encourages technology developers to generate and publicly release data that can be used to answer the questions presented in the technology evaluation framework in Section 5.b.

4.b References

Department of War (DoW). *DoD's Environmental Security Technology Certification Program, DIU Partner to Advance Remediation of PFAS as U.S. Defense Installations*. *https://www.diu.mil/pfas*

Department of War (DoW). *Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) PFAS Projects*. *https://www.serdp-estcp.org/Featured-Initiatives/Per-and-Polyfluoroalkyl-Substances-PFASs*

Executive Office of the President. *Restoring Gold Standard Science*. Executive Order 14303. 90 Federal Register 102. May 29, 2025. *https://www.govinfo.gov/content/pkg/FR-2025-05-29/pdf/2025-09802.pdf*

U.S. EPA (Environmental Protection Agency). (2025). *Research of Per- and Polyfluoroalkyl Substances (PFAS)*. *https://www.epa.gov/chemical-research/research-and-polyfluoroalkyl-substances-pfas*

5. Emerging Technologies for PFAS Destruction and Disposal

What's New in Section 5 of the 2026 Guidance Document?

- Added information on remaining PITT outputs in Section 5.a.
- Revised information on the technology evaluation framework in Section 5.b to incorporate suggestions from public comments received on the 2024 interim guidance.

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

Development of new technologies typically involves the following stages:

- Technology development often starts with exploring and understanding the basic scientific principles and processes that underly the technology. At this early stage, the primary focus is on gaining understanding of how the process works and whether it shows promise for a particular application (e.g., PFAS destruction).
- If the results of early experiments are promising, the next stage of development generally focuses on prototype development and testing under controlled conditions. This stage allows developers to better understand whether the technology is practical and effective at larger scales. It also provides developers with information on costs associated with manufacturing and operating units.
- In the final stage of development, the focus generally shifts to field-scale demonstration projects that allow developers to test the technology under a variety of real-world conditions and to develop better cost estimates for operation and maintenance. During this stage, developers may identify the best and most cost-effective applications for the technology. In the case of PFAS destruction and disposal, this may include identifying the types of PFAS materials best suited for the technology (e.g., high-concentration materials versus low-concentration materials).

At any stage of the technology development process, developers may determine that the technology is not applicable or is not cost-effective and development can stop.

In addition to research to identify and develop novel technologies for PFAS destruction, efforts are underway to apply existing destruction technologies—other than thermal treatment—to PFAS materials. In these cases, the scientific principles and processes underlying a technology may already be understood, but there is little information on the performance of the technology or its applicability to

PFAS materials. Evaluating the applicability of an existing technology to PFAS materials can occur at various scales:

- Laboratory- and pilot-scale studies can be used to evaluate the effectiveness of a technology under controlled conditions and to determine how operating conditions can affect PFAS destruction.
- Field studies can provide data from full-scale applications that reflect the variability seen in real-world operating conditions.

The purpose of this section is to: (1) provide an overview of EPA efforts to identify and test emerging technologies for PFAS destruction, and (2) outline the PFAS destruction and disposal technology evaluation framework, which provides a transparent, consistent approach for evaluating destruction and disposal technologies for PFAS materials. In addition to the EPA-investigated emerging technologies discussed in this section, the Agency is aware of other emerging technologies that are at various stages of development and implementation, such as smoldering combustion, hydrothermal alkaline treatment (HALT), advanced reducing processes (ARP), and non-thermal plasma technologies. For an additional, separate discussion of current PFAS treatment technologies, including emerging technologies, managers of PFAS-containing materials can refer to Section 12 of the *ITRC PFAS Technical and Regulatory Guidance Document*[34].

EPA encourages continued collaboration with other government, academic, and private institutions to continue conducting research to better understand destruction and disposal of waste containing PFAS, and to be potentially included in future iterations of this guidance. EPA encourages that technology developers generate and publicly release data that can be reviewed, and that data are consistent with the tenets of gold standard science established in Executive Order 14303 (*Restoring Gold Standard Science*[35]).

5.a EPA's PFAS Innovative Treatment Team

EPA initiated the PITT in 2020 as a short-term, dedicated, cross-office effort to identify, review, and conduct preliminary research on potential treatment technologies. Over six months, the multi-disciplinary PITT conducted state-of-the-science reviews of proposed methods to dispose and/or destroy PFAS in media and wastes. Several criteria were evaluated using available information, including efficacy, feasibility, performance, and costs of each technology, while also considering potentially hazardous byproducts. The PITT partnered with other agencies and states to conduct a competitive public challenge to identify solutions that were potentially overlooked and to encourage further development of potential technologies.

The PITT chose to focus on the effectiveness of a few technologies, such as mechanochemical degradation, gasification and pyrolysis, and supercritical water oxidation. These technologies showed theoretical promise of the sought-after criteria: PFAS destruction, production of few to no hazardous residuals or byproducts, commercial availability, and cost effectiveness for various contaminated matrices. References and discussion for each technology can be accessed in the PITT Research Briefs at

[34] Available at: *https://pfas-1.itrcweb.org/*.

[35] Available at: *https://www.govinfo.gov/content/pkg/FR-2025-05-29/pdf/2025-09802.pdf*.

PITT Research Briefs[36]. The identification of these technologies by the PITT should not be considered an endorsement or recommendation to use these technologies to destroy PFAS. Additional research is needed to determine the effectiveness of these technologies for different PFAS-containing materials and to characterize the outputs for PFAS and non-PFAS constituents. An overview of the results of the PITT's state-of-the-science review is available in *Developing Innovative Treatment Technologies for PFAS-Containing Wastes* (Berg et al., 2022).

After the state-of-the-science reviews, the PITT selectively encouraged development and research of the four chosen emerging technologies to better understand the potential for PFAS destruction, specifically AFFF, while avoiding creation or transfer of environmental hazards. The PITT conducted in-house research and partnered with industry and academia to collect data regarding the technologies and to encourage further development of the methods required to ascertain PFAS destruction efficacy. Additionally, during the PITT effort, a subsection of the team developed an innovative technology for a thermomechanochemical (TMC) waste treatment processing device. The TMC methodology and apparatus were patented by the U.S. Patent and Trademark Office in 2024 and 2025 (Whitehill et al., 2024; Whitehill et al., 2025).

Although the effort originally was allotted six months in 2020, the work initiated by the PITT results beyond the initial six-month timeframe. The sections below describe some of the results from this work.

5.a.i PITT-investigated emerging technologies

To further explore the potential for mechanochemical degradation of PFAS, EPA scientists partnered with colleagues in New Zealand to conduct a proof-of-concept case study using a benchtop ball mill, AFFF-spiked sand, and AFFF-contaminated soil (Gobindlal et al., 2023). Mechanochemical degradation is a treatment technology that uses a high-energy, ball-milling device (with the option of co-milling reagents) to produce highly reactive conditions to degrade contaminants. Results from the AFFF-spiked sand showed a 99.99-percent destruction efficiency for the sum of all measured PFAS after 960 minutes, and results from the AFFF-contaminated soil indicate that measured PFAS were below the limit of detection after 1,440 minutes. Because this study analyzed PFAS in the solids after different ball-milling time intervals, from 15 to 1,440 minutes, the authors were able to identify increases in some of the measured PFAS before concentrations decreased, indicating the transformation of PFAS during ball milling. An extractable organic fluorine method was also used to determine the reduction in extractable organic fluorine before and after ball milling. In the case of AFFF-spiked sand, the authors reported a 97.8-percent reduction in extractable organic fluorine. A 53.5-percent reduction in extractable organic fluorine was reported for the AFFF-contaminated soil. Air emissions were not characterized as part of this study, making it difficult to determine whether full mineralization of PFAS occurred, and more work is needed in this regard. As noted in the study, more work is also needed to identify primary operations variables to inform the scalability of mechanochemical destruction.

In 2020, EPA conducted a pilot study at a biosolids treatment facility using pyrolysis (Thoma et al., 2022). Pyrolysis is a process that decomposes materials at moderately elevated temperatures in an oxygen-free environment. During the pilot study, dried biosolids were fed into a pyrolysis reactor operating at approximately 610 °C (1,100 °F). The dried biosolids and the resulting biochar were sampled and tested for 41 target PFAS. Twenty-one PFAS were detected in the input biosolids, and none of the target PFAS were detected in the biochar. The pyrolysis system's target PFAS removal efficiencies were estimated to

[36] Available at: *https://www.epa.gov/chemical-research/pfas-innovative-treatment-team-pitt*.

range between greater than 81.3 percent and greater than 99.9 percent. The pilot study also included limited analysis of the air emission control system, with results indicating no transmission of the target PFAS to the air. It is important to note, however, that full characterization of PFAS using non-targeted methods was not performed and more work is needed to understand PFAS transformations and the destruction mechanism.

EPA also completed studies to test the effectiveness of supercritical water oxidation for treating AFFF. Supercritical water oxidation is a process that occurs when the temperature and pressure of water is above the critical point. Above the critical point, oxidation processes are accelerated. In 2020, EPA partnered with three companies to perform tests of their supercritical water oxidation systems on dilute, PFOS-based AFFF (Krause et al., 2022). During these demonstration tests, each system was operated under slightly different conditions, and each company analyzed samples of the influent and effluent for slightly different PFAS. The overall destruction efficiency of each system was calculated by summing the concentrations of the measured PFAS. In all cases, the overall destruction efficiency was found to be greater than 99 percent. It is important to note, however, that the sum of the PFAS measured in the effluent ranged from approximately 10 µg/L to approximately 100 µg/L, suggesting that further treatment of the effluent may be necessary. It is also important to note that non-targeted analysis was not conducted and air emissions were not monitored, making it difficult to assess the fate, transport, and transformation of PFAS with the supercritical water oxidation systems.

In 2021, EPA also partnered with a company to conduct tests at industrial-scale supercritical water oxidation system (Sahle-Demessie et al., 2022). These tests used a dilute, FTS-based AFFF. The primary objective of the study was to determine the destruction efficacy of the PFAS in the input material. Analysis of the influent and effluent showed greater than 99.99-percent destruction of the total PFAS measured. The average sum of the targeted PFAS in the effluent was approximately 55 µg/L, but PFAS were also detected in the tap water used as quench water in the system, suggesting that the overall performance of the system could be improved if non-PFAS-contaminated water is used in the system. A secondary objective of the study was to characterize degradation products using non-targeted analysis and stack sampling for nonpolar volatile fluorochemicals. Non-targeted analysis of the effluent tentatively identified the shorter carbon-chain PFAS on the targeted analyte list, and the authors suggested a possible destruction mechanism that would be consistent with this result. Further work is needed, however, to determine the destruction mechanism. The air emissions sampling did not detect targeted PFAS in air emissions above background levels; further work with finalized air methods (e.g., OTM-50) is needed to confirm this observation.

At this time, EPA is neither recommending nor discouraging the use of any emerging technology for managing PFAS-containing materials, including the technologies studied by the PITT. While the PITT studies generally indicated potential for PFAS destruction, further work using newly available methods is needed to more fully characterize the outputs of these processes and to evaluate their performance for PFAS-containing materials beyond AFFF.

5.b PFAS Destruction and Disposal Technology Evaluation Framework

Researchers have proposed metrics to evaluate PFAS destruction and disposal technologies, including technology readiness levels (TRLs), DREs of target compounds, fluorine mass balances, and others (Berg et al., 2022; Deeb et al., 2021; Krause et al., 2021). When used individually, these metrics fail to accurately capture comprehensive system performance or provide a holistic understanding of the potential for PFAS transformation and/or release to the environment. For example, DREs calculated

from targeted analyses using existing methods can result in underreporting of the total PFAS in a matrix because existing detection methods can only measure a fraction (e.g., 50 individual PFAS) of the total number of PFAS that may be present in a sample. Similarly, TRLs can fail to accurately reflect the current development stage of a technology by either reporting the overall maturity of the technology, instead of its specific PFAS application, or by relying on a niche, small-scale application to justify an overall readiness level.

These limitations drive the need for a comprehensive framework for evaluating a technology and its application to PFAS-containing materials. Such a framework should allow the user to prioritize the collection and consideration of different pieces of information. To meet these needs, EPA developed a technology evaluation framework that uses a multiple-lines-of-evidence approach to evaluate a technology/PFAS material combination (Table 5-1). The framework provides a transparent approach for evaluating and selecting a technology to reduce PFAS releases to the environment. EPA recommends that managers of PFAS-containing materials use the framework to evaluate emerging technologies, and to inform decisions about destruction and disposal of PFAS-containing materials.[37] EPA encourages technology developers to generate and publicly release data that can be used to answer the questions presented in the framework.

The framework comprises several topical sections: technology, material, analytical methods, disposal/destruction efficacy, community considerations, and regulatory requirements. Within each section, EPA has identified key pieces of information that, when considered together, provide a more holistic evaluation of a technology and its applicability for PFAS disposal or destruction.

The framework is intended to be an adaptable tool that allows the user to prioritize the collection and consideration of different pieces of information via the "priority" column in the framework. This allows users to address questions most relevant to their priorities and with respect to their decision context and the shared priority of preventing and mitigating potential exposures. Users may also choose to prioritize addressing certain questions before others to streamline their evaluation of a technology/material combination. For example, if a user of the framework is evaluating the performance of a destruction technology, the questions in the disposal efficacy section of the framework are not needed and could be removed from the framework. As another example, a user may prioritize answering questions under the technology section of the framework because those questions may rule out a technology for a particular application (e.g., the technology may not be available at the scale needed to process the PFAS-containing material of interest). Once a technology is ruled out, lower priority questions do not need to be answered. For further adaptability, if a user has particular needs or concerns that go beyond those currently identified in Table 5-1, the user may decide to add other categories and questions to the framework. For example, a user may want to add a category for pollution prevention and waste minimization considerations, if that is a relevant priority (e.g., Does the technology use toxic chemicals? Is the technology energy or resource intensive; or Does the technology produce large amounts of waste?). While users may not answer each question in the framework or may choose to add other questions according to their needs, EPA encourages users of the framework to

[37] The Interstate Technology and Regulatory Council (ITRC) PFAS Team developed the *PFAS Technical and Regulatory Guidance Document* (available at *https://pfas-1.itrcweb.org/*) to support state and federal environmental staff, as well as others, to gain a working knowledge of the current state of PFAS science and practice. Section 12 of the ITRC guidance document provides information on PFAS treatment technologies, including destruction technologies. Managers of PFAS-containing materials may find this resource useful when completing Table 5-1.

address as many questions as possible to inform decisions about the destruction and disposal of PFAS materials.

Table 5-1 shows this approach, followed by more detailed considerations for each question.

Table 5-1. Framework for Evaluating Destruction/Disposal Technologies for PFAS-Containing Materials

Category of Information	Key Questions	Priority[a]	Answer and Associated Notes for PFAS Material of Interest
Technology	If available, what is the TRL for the technology/material combination of interest?		
	Is the technology of interest available at the scale needed for the intended application?		
	Is a treatment train needed to meet the desired destruction/disposal outcome?		
Material	What PFAS-containing material has been used to test the performance of the technology of interest?		
	Which PFAS, and at what concentration ranges, have been used to test the performance of the technology of interest?		
	Are there non-PFAS constituents that may affect the performance of the technology of interest?		
Analytical methods	Which standardized or validated targeted analytical methods (e.g., OTM-45, EPA Method 1633A) have been used to characterize the performance of the technology for the PFAS-containing material of interest?		
	Has non-targeted analysis been performed on waste streams from the technology/material combination of interest? If so, are there other PFAS detected that should be considered when assessing this technology?		
	What other analytical approaches have been used to characterize the performance of the technology for the PFAS-containing material of interest?		
	Was the study design and the quality of the data generated during testing appropriate to evaluate the technology?		
Disposal efficacy	Have potential transformation and partitioning pathways been identified for the technology/material combination of interest?		
	Are engineering controls in place to prevent or minimize release of PFAS to the environment?		
	What is the longevity of the disposal technology?		

Category of Information	Key Questions	Priority[a]	Answer and Associated Notes for PFAS Material of Interest
	Has a fluorine mass balance been determined?		
	Does the disposal of the PFAS-containing material contribute to the potential release of non-PFAS constituents to the environment?		
Destruction efficacy	Is the mechanism of destruction understood?		
	Have all process inputs and outputs been characterized for PFAS to the extent possible given current analytical methods?		
	What is the reported destruction efficiency?		
	Have any PIDs (or PICs) been identified?		
	Has a fluorine mass balance been determined?		
	Have all process outputs been characterized for non-PFAS constituents to the extent possible given current analytical methods and understanding of the composition of the PFAS-containing material?		
Community Considerations	Has a destruction/disposal site been identified?		
	What are the characteristics of the surrounding community?		
	Are PFAS releases anticipated from the technology/material combination of interest?		
	Has the surrounding community been engaged?		
Regulatory requirements	Are there state or federal regulations that control emissions or releases from the technology of interest?		
	Are there state or federal regulations that control the management of the PFAS-containing material of interest?		

[a] Users can prioritize key questions using a variety of approaches. For example, questions could be labeled as *high, medium*, or *low* priority. Questions could also be prioritized using a numerical ranking system with *1* indicating questions to answer first, *2* indicating questions to answer second, and so forth.

5.b.i Key questions for technology evaluation

Technology. The first section of the framework focuses on the destruction or disposal technology. Key questions include:

If available, what is the TRL for the technology/material combination of interest? TRLs are generally assigned using the *definitions developed by NASA*[38] (NASA, 2023), where level 1 corresponds to observation and reporting of basic scientific principles and level 9 corresponds to "flight proven"

[38] Available at: *https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level*.

technologies. TRLs may be determined through technology readiness assessments[39] or through other methods. If other methods are used, EPA recommends that users consider the source of reported TRLs and prioritize TRLs determined through independent technology readiness assessments over TRLs assigned by the technology developer.

- **Is the technology of interest available at the scale needed for the intended application?** Some technologies may only be available as mobile, containerized units, which may be suitable for high-concentration, low-volume materials. These units may not be appropriate for low-concentration, high-volume materials where a stationary treatment unit with greater capacity is needed.
- **Is a treatment train needed to meet the desired destruction/disposal outcome?** If so, describe the treatment train needed and whether such technology is available and effective for the PFAS-containing material of interest. Note that treatment trains may produce materials that will also need to be managed.

Material. The second section of the framework focuses on the PFAS-containing material of interest. The six types of PFAS-containing materials discussed in this interim guidance vary in terms of phase, PFAS composition and concentration, physical and chemical properties, and overall composition (e.g., the presence of other contaminants). To understand the performance of a technology across the range of variations within a material type, the following key questions should be addressed:

- **What PFAS-containing material has been used to test the performance of the technology of interest?** The description of the material(s) used to evaluate a technology/material combination of interest should be specific as possible (e.g., 3M Light Water™ versus AFFF), and links to bulk material characterization should be included, if available. If the material evaluated is artificially contaminated (i.e., spiked with known PFAS species and concentrations), that should be noted because it may not be an accurate reflection of the performance of the technology for the intended application.
- **Which PFAS, and at what concentration ranges, have been used to test the performance of the technology of interest?** To best inform decisions on technology use, the PFAS and concentrations used to test performance should match the PFAS and concentrations anticipated for the intended application.
- **Are there non-PFAS constituents that may affect the performance of the technology of interest?** This could include constituents in the original PFAS-containing material or constituents that may be created or introduced during a treatment train or by the technology of interest. For example, hydrofluoric gas may be produced during PFAS destruction, which may cause corrosion.

Analytical methods. PFAS are a large class of substances, and there are various approaches for identifying and measuring PFAS. EPA recommends using a combination of approaches to characterize the performance of the technology for the PFAS-containing material of interest, including characterizing PFAS in emissions or waste streams from the technology of interest. Key questions to be addressed under this section include:

[39] See the *Technology Readiness Assessment Guide* for best practices for evaluating technology maturity. The guide, developed by the U.S. Government Accountability Office and released in January 2020, provides organizations with best practices for conducting high-quality assessments.

- Which standardized or validated targeted analytical methods (e.g., OTM-45, EPA Method 1633A) have been used to characterize the performance of the technology for the PFAS-containing material of interest? When possible, EPA recommends the use of standardized and/or validated methods for targeted analysis.
- Has non-targeted analysis been performed on waste streams from the technology/material combination of interest? If so, are there other PFAS detected that should be considered when assessing this technology? Non-targeted analysis is an important tool for characterizing PFAS in waste streams from a technology/material combination of interest because it can tentatively identify PFAS beyond those measured using targeted analytical methods.
- What other analytical approaches have been used to characterize the performance of the technology for the PFAS-containing material of interest? Other analytical approaches may include total oxidizable precursor assays and total organic fluorine assays for PFAS and analysis for non-PFAS substances (e.g., HF).
- **Was the study design and the quality of the data generated during testing appropriate to evaluate the technology?** For any quality assurance/quality control concerns identified, the user should determine whether it is appropriate to use the data to inform decisions about destruction and disposal of the PFAS-containing material using the technology of interest.

Disposal efficacy. Effective disposal of PFAS-containing material should prevent or minimize re-release of PFAS to the environment. Key questions for evaluating the efficacy of a disposal technology for a particular PFAS-containing material are identified below. (Questions included in this section should be skipped when evaluating a destruction technology.)

- **Have potential transformation and partitioning pathways been identified for the technology/material combination of interest?** The fate and transport of PFAS within a disposal technology can help inform whether PFAS may be present in emissions or releases from the technology. Note that the characteristics of the receiving matrix and environmental conditions can affect the fate and transport of PFAS within the disposal technology.
- **Are engineering controls in place to prevent or minimize release of PFAS to the environment?** If so, is there a monitoring system in place to evaluate the performance of the engineering controls?
- **What is the longevity of the disposal technology?** Because of the strength of the C-F bond, PFAS are persistent. It is important to consider the lifespan of the disposal technology and whether the technology can contain PFAS for very long timeframes.
- **Has a fluorine mass balance been determined?** If so, is there fluorine that is unaccounted for? In some cases, a fluorine mass balance may be impractical.
- Does the disposal of the PFAS-containing material contribute to the potential release of non-PFAS constituents to the environment? PFAS-containing materials may contain other, non-PFAS constituents. Depending on the identity of those constituents and their potential to impact human health and the environment, it may be important to consider whether appropriate engineering controls are in place to prevent or minimize releases of non-PFAS constituents.

Destruction efficacy. Destruction of PFAS should result in breaking C-F bonds without reforming PFAS and releasing PFAS to the environment. Key questions for evaluating the efficacy of a destruction technology for a particular PFAS-containing material are identified below. (Questions included in this section should be skipped when evaluating a disposal technology.)

- **Is the mechanism of destruction understood?** If so, has the destruction mechanism been experimentally confirmed, and have the reaction kinetics been determined? A thorough understanding of the destruction mechanism improves confidence in the performance of the technology of interest for PFAS.
- Have all process inputs and outputs been characterized for PFAS to the extent possible given current analytical methods? If not, what information may be missing?
- **What is the reported destruction efficiency?** Destruction efficiencies (or DREs) are generally reported for specific PFAS (e.g., PFOA or PFOS). As noted earlier, the destruction efficiency (or DRE) alone may not be sufficient to determine whether other PFAS may be released to the environment during the destruction process.
- **Have any PIDs (or PICs) been identified?** If so, which PFAS have been detected and at what levels? Are those PFAS regularly detected for this technology/material combination?
- **Has a fluorine mass balance been determined?** If so, is there fluorine that is unaccounted for? In some cases, a fluorine mass balance may be impractical.
- Have all process outputs been characterized for non-PFAS constituents to the extent possible, given current analytical methods and understanding of the composition of the PFAS-containing material? The destruction of PFAS-containing materials is expected to result in non-PFAS products. Depending on the identity of those products and their potential to impact human health and the environment, it may be important to consider whether appropriate engineering controls are in place to prevent or minimize releases of non-PFAS constituents. It may also be important to consider the effect of the destruction process on non-PFAS constituents in the PFAS-containing material of interest. Thus, the characterization of process outputs beyond PFAS may be warranted.

Community considerations. When considering destruction and disposal technologies for PFAS-containing materials, it is important to consider the community that may be exposed to potential PFAS releases from intended destruction or disposal. Key questions to consider include:

- **Has a destruction/disposal site been identified?** Some destruction technologies may be mobile, allowing for treatment and destruction to occur where PFAS-containing materials are generated or stored. Other technologies may be stationary, requiring PFAS-containing materials to be brought on site for destruction or disposal.
- **What are the characteristics of the surrounding community?** Different factors can influence the potential magnitude of community exposures, such as the size and distribution of the community near the destruction/disposal site, the proximity of the community to the destruction/disposal site, geographical characteristics where the community is located, and other considerations.
- **Are PFAS releases anticipated from the technology/material combination of interest?** If so, describe which PFAS may be released, at what levels, and over what duration. Also note whether there are controls in place to mitigate releases to avoid or minimize potential impacts to surrounding communities.
- **Has the surrounding community been engaged?** Sharing information about planned destruction or disposal activities for PFAS-containing materials allows community members to take actions to address concerns they may have. There may also be opportunities to collaborate with government officials and community leaders on engagement activities.

Regulatory requirements. Regulations regarding the destruction or disposal of PFAS-containing materials can vary from state to state and may change over time. Key questions to consider include:

- **Are there state or federal regulations that control emissions or releases from the technology of interest?** Such regulations may limit the amount of PFAS or other pollutants present in emissions or other releases from the technology of interest.
- **Are there state or federal regulations that control the management of the PFAS-containing material of interest?** Such regulations may specify or restrict destruction or disposal options for the PFAS-containing material of interest.

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Appendix A: EPA Guidance to Conduct PFAS Emissions Field Testing at Commercial Thermal Destruction Sources

The U.S. Environmental Protection Agency (EPA) is conducting per- and polyfluoroalkyl substances (PFAS) thermal destruction emissions characterization research to improve our understanding of the behavior of PFAS with respect to waste incineration and thermal treatment (e.g., hazardous waste, municipal waste, biosolids, contaminated soils, spent media), as well as thermal destruction emissions control technologies (e.g., afterburners, thermal and catalytic oxidizers). The following could be used by any entity evaluating thermal treatment of PFAS-containing materials either in collaboration with EPA or independently.

Overall goals of the field tests are as follows:

- Confirm/determine if thermal treatment under representative conditions can result in the thermal destruction of PFAS as defined by conventional destruction and removal efficiency (DRE) testing.
- Characterize potential products of incomplete combustion/destruction (PICs/PIDs) and evaluate the use of alternative, or surrogate, indicators of destruction performance.
- Confirm that any treated material is appropriate for any defined beneficial reuse (e.g., treated soils, reactivated granular activated carbon [GAC]).

To achieve these goals, it is necessary to determine the specific conditions (i.e., temperature, residence time, and turbulence) required to maximize DRE, minimize PICs/PIDs, and produce products appropriate for beneficial reuse. Because bench- and pilot-scale testing have limitations, actual test data under full-scale thermal treatment conditions are necessary to determine if representative thermal processes can achieve these goals.

Sampling Details:

- EPA is available to collaborate with the host site on the technical approach for source characterization. Testing would require multiple stack sampling methodologies performed by commercial stack testing companies, including the host's regular tester, if desired.
- All gas, liquid, and solid inlet, intermediate, and outlet streams would be collected and analyzed. This includes:
    - At the stack and including all air pollution control devices (APCDs).
    - All inlet streams (e.g., materials to be thermally treated, air or gas inlets, water), including samples taken prior to testing.
    - All process materials (e.g., water used for spray dryers and/or scrubbers, carbon, high pH solution for scrubbers) as they may contain PFAS and affect the results, if unknown.
    - All residual streams (e.g., bottom ash, baghouse and/or electrostatic precipitator [ESP] solids, scrubber effluent, spent carbon).
    - All final products (e.g., reactivated carbon, soils), if applicable.
- A comprehensive air emission source characterization would include:

- Samples would be collected for semivolatile polar PFAS using method OTM-45 and analyzed for targeted (known) PFAS. Samples would be collected for nonpolar volatile fluorinated compounds (VFCs) and PFAS using method OTM-50 and analyzed for targeted (known) fluorinated compounds and the identification of unknown detected volatile fluorinated compounds.
- Samples would be collected for other semivolatile nonpolar target compounds using methods SW-846 Methods 0010/3542/8270 with the inclusion of the Method 8270 procedure.
- Carbon hexafluoride (C_2F_6) and carbon tetrafluoride (CF_4) could be injected during one day of testing, ideally at multiple injection locations, as a surrogate measure of destruction efficiency if appropriate and permitted.
- Samples would be collected for other semivolatile target compounds using methods SW-846 Methods 0010/3542/8270 with the inclusion of the Method 8270 procedure.
- Hexafluoroethane (C_2F_6) could be injected during testing, ideally at the location most PFAS would be injected, or multiple injection locations if possible, as a surrogate measure of destruction efficiency if appropriate and permitted. Tetrafluoromethane (CF_4) can also be injected separately, if FTIR is being used, to ensure the injection system is working and to establish the gas residence time of the system to aid in the sampling of C_2F_6.

- Tests would be run under a single, representative process condition including the waste that would be co-fired with PFAS-containing material.
- EPA would prioritize testing several PFAS-containing materials, including but not limited to:
  - Incineration of aqueous film forming foam (AFFF).
  - Incineration of wastewater sludges.
  - Reactivation of spent GAC.
  - Incineration of municipal solid waste.
  - Thermal treatment of contaminated soils.
  - Incineration of spent ion exchange resins and their concentrated regeneration liquids.
- All sampling would be conducted under a well-documented sampling plan and quality assurance project plan.
- Final testing results would be shared with EPA, the state, local authorities.

Additional details on emission testing approaches can be provided upon request.

Supplemental Information

Emissions sampling and analytical approaches

Emissions samples would be collected for nonpolar, volatile, and polar and non-polar semivolatile PFAS compounds and analyzed for both targeted PFAS compounds, or method established endpoints.

EPA's Other Test Method 45 (OTM-45) would be used to collect polar semivolatile PFAS compounds for targeted analyses. The method's 50+ target analytes include many PFAS commonly found in AFFF. This would enable DE, DRE, and emission rate determination as appropriate for a known list of PFAS compounds along with identifying potential PFAS PICs/PIDs.

The OTM-50 canister sampling method would be used to collect nonpolar volatile PFAS compounds for targeted compound analyses. The current target list includes CF_4 and C_2F_6 as well as a procedure to identify unknown volatile fluorocarbons.

Non-targeted analyses (NTA) are an optional analytical tool for characterizing potential PICs/PIDs. HRMS, combined with chromatographic separation and multiple ionization techniques, is used to identify compounds present in collected samples. NTA could be performed on the OTM-45 samples. FTIR spectroscopy would be used to measure a variety of compounds in real-time, including HF, HCl, CO_2, and water; multiple PFAS compounds including CF_4 and C_2F_6; and multiple known PICs/PIDs. FTIR is particularly useful during injection of a surrogate compound.

EPA research questions

The following section describes detailed elements of the research questions EPA will ultimately work to address, as well as the input information that is needed. EPA requests an opportunity to engage with the host facility prior to developing a full sampling plan to better understand site-specific conditions and requirements.

Process characterization

Question: How does the process operation affect the destruction and removal of PFAS compounds present in the feed?

- Requires understanding of waste feed (e.g., description, concentration, other wastes), feed approach (e.g., liquid feed, through flame/post flame, co-fired, drums/barrels), and feed rate.
- Requires data on combustor operations and conditions (e.g., temperature, residence time).
- Requires data on air pollution control devices (APCDs) and their operation: configuration, operating parameters (e.g., temperature, pressure drop, pH of scrubbing liquid, gas velocity).

Determine destruction removal efficiency (DRE)

Question: What is the DRE and emission rate of the specific PFAS compounds present in the feed material?

- Requires known input rate and identity of PFAS compounds in waste.
- Requires evaluation of the extent of PFAS mineralization.
- Requires replicate sampling of polar semivolatile organics using OTM-45 for quantitative measurement of feed PFAS compounds in emissions.
- Requires sampling across multiple APCDs.

Products of incomplete combustion/destruction (PICs/PIDs)

Question: Are PICs/PIDs formed during thermal treatment and measured by OTM-50 present and, if so, what are they and under what conditions?

- Requires replicate sampling of polar, nonpolar, semivolatile, and volatile organics for non-targeted compound analysis using OTM-45, OTM-50, and Method 0010/3542/8270.
- Requires sampling across multiple APCDs.

Alternative indicators of destruction performance

Question: Can easily measured/monitored, hard-to-destroy compounds serve as alternative (surrogate) indicators for PFAS adequate destruction or PID formation conditions?

- Requires injection of known concentrations/masses of C_2F_6 (approximately 10 to 30 parts per million by volume (ppmv) stack equivalent) at representative waste injection locations (CF_4 can be used as a tracer gas to assist in the process).
- The evaluation is greatly benefitted by on-line FTIR monitoring of the surrogate compounds, PICs, HF, HCl, and other compounds of interest.
- Requires initial background signal baseline, normal operation without the addition of the perfluorocarbons.
- Requires concurrent OTM-50 sampling for analysis of surrogate compounds and known PICs.

Analysis of fluorinated compounds in waste/effluent streams

Question: What is the fate of PFAS compounds across the entire thermal system?

- Requires sampling of all discharges:
  - Gas sampling prior to and after APCDs (e.g., spray dryer, wet scrubber, baghouse and/or ESP, activated carbon injection).
  - Sampling of solid and liquid discharges (e.g., bottom ash, baghouse and/or ESP solids, scrubber effluent analyses, spent carbon).

Analysis of fluorinated compounds in final product materials, where applicable

Question: What PFAS remain in the material treated, such as reactivated GAC or treated soils?

- Requires sampling of influent and effluent materials:
  - Sampling of solid materials (e.g., spent carbon and reactivated carbon).

Appendix B: Summary of the 2021 and 2022 Clean Harbors Test Data

Summary

Two testing campaigns were conducted at the Clean Harbors Environmental Services (CHES) hazardous waste combustor (HWC) located in Aragonite, Utah. Each test campaign was divided into three test conditions: Baseline (Condition 1), Augmented Per- and Polyfluorinated Alkyl Substances (PFAS) Feed (Condition 2, where known amounts of four or five target PFAS were fed to the incinerator), and Post-spiking Normal Operations (Condition 3, where aqueous film-forming foam [AFFF] was included in the incinerator feed). Clean Harbors used the Other Test Method 45 (OTM-45) Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources (OTM-45) from the U.S. Environmental Protection Agency (EPA) for stack gas samples. The 49 targeted PFAS analytes were measured using liquid chromatography/tandem mass spectrometry (LC/MS/MS) with isotope dilution. The tests appear to demonstrate that the primary objective, "demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed during normal process operating conditions," was achieved for the five selected PFAS compounds that were subjects of these studies.

Introduction

Two testing campaigns were conducted at CHES HWC located in Aragonite, Utah. The first campaign was conducted from June 17 to 19, 2021, and the second from February 17 to 19, 2022. The stated principal objective of the test program was to "demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed during normal process operating conditions," with secondary objectives of conducting a mass balance of PFAS in process streams and demonstrating high hydrogen fluoride (HF) removal that would be associated with a high destruction of PFAS. This summary presents a high-level overview of both tests' final reports as well as a third-party review of the 2021 test performed by Dr. Philip H. Taylor under contract to CHES.

General Process Description

The HWC tested at the CHES Aragonite facility consists of a slagging rotary kiln incinerator followed by an afterburner. Solid waste materials and containerized wastes are fed into the rotary kiln only, while liquid wastes may be injected directly into rotary kiln or the afterburner. The air pollution control device (APCD) system for the HWC as tested[40] consists of a spray dryer/gas quench followed by activated carbon injection upstream of a fabric filter (particulates, dioxin/furan, and mercury control). Following the fabric filter, the gases enter a sodium carbonate saturator/wet scrubber (sulfur dioxide, hydrogen chloride, hydrogen fluoride control) with TMT-15 (1,3,5-triazine2,4,6(1H,3H, 5H)-trithione, trisodium salt, used for additional mercury and metals control) injection.

[40] Stack testing was performed in the exit duct of the wet scrubber instead of at the stack for safety reasons (lack of scaffolding). The HWC is equipped with a wet electrostatic precipitator (WESP) following the wet scrubber and prior to the stack, but the WESP was decommissioned in 2004 and is no longer in service. These tests were conducted prior to the WESP although the stack location is the test location for compliance performance tests for the facility.

Operational Description

Each test campaign was divided into three test conditions: Baseline (Condition 1), Augmented PFAS Feed (Condition 2), and Post-Spiking Normal Operations (Condition 3), with the waste feed matrices as follows:

1. **Condition 1.** Normal matrix of liquid materials (waste fuel, clean fuels, sludge, and aqueous wastes) and solid waste materials (containerized, shredded, and bulk solid wastes). Following the 2021 testing, CHES determined that the sludge stream fed to the kiln during all three conditions included some AFFF. During the first run of the 2022 testing, CHES determined that AFFF was inadvertently being fed into the afterburner's corrosive waste port. The testing team decided to be consistent with runs 2 and 3 and continued the AFFF feed, with additional amounts of AFFF fed during Condition 3.
2. **Condition 2.** Normal matrix of liquid materials (waste fuel, clean fuels, sludge, and aqueous wastes) and solid waste materials (containerized, shredded, and bulk solid wastes), with the addition of augmented feed rates of four (2021) or five (2022) PFAS (or their equivalent potassium salt). The four PFAS are perfluorooctanioic acid (PFOA), perfluorooctanesulfonic acid (PFOS), perfluorohexane sulfonic acid (PFHxS), hexafluoropropylene oxide-dimer acid (HFPO-DA), and perfluorobutanesulfonate (PFBS, 2022 only). The target feed rate of the PFAS was estimated to be 0.0816 pounds per hour or around 0.62 grams per minute in 2021 for all PFAS, but the HFPO-DA was increased to 2.2 grams per minute in the 2022 testing to reflect the method detection limit (MDL) for this compound. Similarly, the PFBS feed rate was 0.33 grams per minute on average to reflect the MDL. The PFAS were fed in boxed containers to the rotary kiln via the containerized solid conveyor in approximately 10-gram portions of all PFAS compounds about every 15 minutes for the duration of these test runs.
3. **Condition 3.** Normal matrix of liquid materials (waste fuel, clean fuels, sludge, and aqueous wastes) and solid waste materials (containerized, shredded, and bulk solid wastes). For this test condition, AFFF concentrate was also fed (neat) to the incinerator. In 2021, the AFFF was fed via the containerized solids in 5-gallon buckets at a rate of 176 pounds per hour. During the 2022 test, the AFFF was labeled as Ansulite and was fed through the educt station to the incinerator directly from a tote bin. The AFFF feed rate ranged from 244 pounds per hour to 316 pounds per hour during the 2022 test.

The rotary kiln was operated in a temperature range between 1,893°F and 2,008°F for the 2021 test and between 1,949°F and 2,219°F for the 2022 test. The afterburner was operated at 2,052°F to 2,110°F during the 2021 test and 2,048°F to 2,075°F for the 2022 test. Oxygen content (free) at the exit of the rotary kiln was maintained between 8 and 9 percent and ranged from 6 to 7 percent for the afterburner for both test campaigns. Clean Harbors estimates that non-combustible material is retained within the combustor for approximately 60 minutes, while combustion gas residence time of the afterburner is two to three seconds.

For the 2021 test, the temperature of the flue gas was reported as 369°F following the spray dryer; between 341°F and 343°F following the fabric filter; between 166°F and 168°F at the saturator outlet; and 148°F to 153°F at the stack. For the 2022 test, the temperature of the flue gas was reported as 363°F following the spray dryer; between 168°F and 170°F at the saturator outlet; and 149°F to 151°F at the stack. The following table lists the APCD operational parameters during the testing campaigns.

Test Campaign	Stack Gas Flow (actual cubic feet per minute [acfm])	Soda Ash Flow (lb/hr)	Carbon Injection (lb/hr)	TMT-15 Flow (lb/hr)
2021	66,793–68,761	452–789	30.7–31.5	3.95–4.48
2022	51,053–53,640	411–1594	32.0–33.1	3.64–4.00

Test Methods and Scope

During both testing campaigns, samples of stack gases and process streams were taken and analyzed for 49 PFAS target compounds, with the stated analytical objective of characterizing as many streams entering or exiting the incinerator as possible. Clean Harbors used EPA's Other Test Method 45 (OTM-45), *Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources*, for stack gas samples (as noted earlier, "stack" meaning the exit duct from the wet scrubber as it was deemed a safer sampling location than the actual stack). The 49 targeted PFAS analytes were measured using LC/MS/MS with isotope dilution.

Process streams sampled included waste fuels, clean fuels, waste feeds, process water, and residuals (liquids and solids), as well as some pre-test sampling of chemical inputs (soda ash, activated carbon, and TMT-15). As noted in the reports, however, due to the waste profile matrix complexity and the heterogeneity of all three solid waste streams, they were not sampled or analyzed for PFAS. Absent any final EPA-approved methods for media other than drinking water, LC/MS/MS analysis was used to measure the targeted PFAS compounds in the process stream samples.

In addition to the 49 PFAS analytes, the HF concentration of the stack gas was measured using EPA Method 26A. The AFFF-containing material in the 2021 test was analyzed for the 49 target PFAS both before and after chemical oxidation as a total oxidizable precursor assay (TOPA). During the 2022 test, a TOPA and total organic fluorine assay (TOFA) were performed on the AFFF-containing materials. The objective of performing TOPA is to "reveal perfluoroalkyl acid (PFAA), fluorotelomer sulfonate (FTS), and possibly other precursors that are not identifiable with targeted PFAS analysis." TOFA, as described in the 2022 report, identifies the mass of compounds containing carbon-fluorine bonds, and was performed using combustion ion chromatography following a laboratory in-house method for adsorbable organo-fluorine.

Results

According to the tests and third-party review, the primary objective of determining the destruction and removal efficiency (DRE) of each of the spiked (augmented feed) PFAS was achieved. The calculated DREs for each test (triplicate test run average) and PFAS compound are as follows:

PFAS Analyte	2021 Test DRE (%)	2022 Test DRE (%)
PFOA (perfluorooctanioic acid)	99.999943	99.99990
PFOS (perfluorooctanesulfonic acid)	99.999955	99.99977
PFHxS (perfluorohexane sulfonic acid)	99.999977	99.99996
HFPO-DA (hexafluoropropylene oxide – dimer acid)	99.999979	99.99984
PFBS (perfluorobutanesulfonate)	Not available	99.99997

Both test reports note that none of the other 45 (or 44, in 2022) target PFAS analytes were present in the waste feed at levels sufficient to demonstrate 99.9999-percent DRE without spiking, even though stack gas concentrations were non-detect in many cases. According to the 2021 test report, there were three other PFAS present in the waste feeds at sufficient mass feed rate without spiking to enable demonstration of DRE's exceeding 99.999 percent. These included PFOS, 6:2 fluorotelomer sulfonate (FTS), and 8:2 FTS. The report stated that the FTS compounds are common constituents of AFFF.

As for the secondary objectives, the results are, as stated within Dr. Taylor's review, "most difficult to achieve as they involve more complex sampling issues." With respect to the secondary PFAS mass balance objective, he notes that "some of the PFAS that was not sampled in the infeed may have been more difficult to gasify and burn, contrary to the assertions in the report." However, he concurs with the report statements that the PFAS DRE is conservative.

The objective of demonstrating high HF removal that would be associated with a high destruction of PFAS is seemingly not achieved, primarily due to analytical issues. Dr. Taylor notes that "the sinks for the HF were not accurately quantitated leading to some questions about the validity of the reported HF removal efficiency." He further notes that the assumption that all fluorine in the waste if converted to HF is challenged, as there would be a required excess of hydrogen to fluorine to be demonstrated, which are not provided for in the data. Further, he stated that there is a "demonstrated lack of accuracy of the analytical methods for measuring inorganic fluorine in the residual streams," which, in his opinion, leads to a very low fluorine recovery mass balance. He concluded that, "development of better analysis methods for complex matrices for inorganic fluorine are needed before high HF removal efficiencies can be reported at full scale.[41]

Conclusions

The tests appear to demonstrate that the primary objective, "demonstrate the ability of the high-temperature incineration system at Aragonite to effectively destroy PFAS in the waste feed during normal process operating conditions," was achieved for the five selected PFAS compounds that were subjects of these studies. However, this study did not evaluate the formation of PICs due to previous methodology limitations. Dr. Taylor, in his review, noted this as well: "The larger question from an environmental viewpoint is the complete mineralization of these substances and prevention of emission of highly stable C_1-C_2 PFCs (perfluorocarbons)." Dr. Taylor concludes that CHES' results, although promising and demonstrating reduction of a limited selection of specific PFAS compounds, did not support complete mineralization.

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EA Engineering, Science, and Technology, Inc., PBC. (2021). Report on PFAS destruction testing results at Clean Harbors' Aragonite, Utah hazardous waste incinerator (Final).

EA Engineering, Science, and Technology, Inc., PBC. (2022). Report on PFAS destruction testing results at Clean Harbors' Aragonite, Utah hazardous waste incinerator (Final).

[41] Although not stated by Dr. Taylor in his assessment, another possible reason for lack of finding inorganic fluorine (HF) could be the result of poor conversion (mineralization) of PFAS to HF and carbon dioxide during incineration. This may indicate formation of non-target PFAS or fluorocarbons during incineration that were not measured by these tests.

Taylor, P. (2022). Final report: Assessment of a report on PFAS destruction testing results at Clean Harbors' Aragonite, Utah hazardous waste incinerator. Prepared for Clean Harbors Environmental Services, Inc.

Appendix C: Summary of the Chemours Thermal Oxidizer Test Data

Introduction

Chemours Company FC, LLC, located in Fayetteville, North Carolina, manufactures chemicals and plastics and was required to install a thermal oxidizer to control per- and polyfluoroalkyl substances (PFAS) emissions. Tests have been conducted annually since installation. The objective of the tests was to determine how "the Thermal Oxidizer and 4-stage Scrubber system will achieve the emission reduction [of 99.99 percent], including the use of a surrogate for all PFAS, such as the hexafluoropropylene oxide (HFPO)." This summary presents a high-level review of the two tests' reports.

General Process Description

The thermal oxidizer at the Chemours facility operates at 10 million British thermal units (BTUs) per hour and is powered by natural gas. Waste gases from both polymer and monomer production are fed into the thermal oxidizer. The gaseous emissions from the oxidizer are fed into the four-stage packed bed column scrubber system while solid calcium fluoride (CaF_2) is removed, collected, and disposed of at an off-site location. The scrubber has three water scrubbing stages and one caustic scrubbing stage and is stated to remove hydrogen fluoride (HF) from the final emissions.

Operational Description

Test Methods and Scope

The tests done on the thermal oxidizer focused on five PFAS compounds: HFPO, hexafluoropropylene oxide-dimer acid (HFPO-DA), hexafluoropropylene oxide-dimer acid fluoride (HFPO-DAF), carbonyl fluoride (COF_2), and Fluoroether E-1. These compounds were selected because they are handled and used at the Fayetteville facility. The compounds have varying chemical structures and properties and cannot be sampled and tested in the same manner.

Modified Method 18 sampling was used to capture the PFAS compounds. This method uses six fluoropolymer (PFA) impingers charged with methanol arranged in a series and captures the compounds using chemical reactions and condensation.

To capture HFPO-A, the facility needed to use Modified Method 0010 sampling with a heated probe and filter, condenser coil, XAD-2 resin cartridge, deionized water impingers, and a silica gel impinger. In addition to the normal Modified Method 0010 sampling process, this test added a second XAD-2 resin cartridge to monitor possible target PFAS breakthrough.

Three compounds (HFPO, HFPO-DAF, and COF_2) were sampled by chemical reaction. The sample gas was passed through the series of methanol impingers. The compounds then react with methanol, and each produced unique ether compounds that were monitored and quantified using SW-846 Method 8260.

The strategy used to sample Fluoroether E-1 and HFPO-DA was to capture the compounds through condensation and dissolution in the same methanol impingers. The volatile organic compound, Fluoroether E-1, was then quantified using SW-846 Method 8260b. The semivolatile organic compound HFPO-DA was quantified using EPA Method 537.

Samples were taken from the polymer production and monomer production waste gas feed lines to capture the initial amount of PFAS compounds they produced as waste and to provide a baseline concentration of PFAS prior to treatment. The other sampling location was in the stack after the thermal oxidizer and scrubber. This location would show how effective the process was at destroying the targeted PFAS compounds.

The sampling and testing methods only captured the amount of target PFAS compounds and did not measure any products of incomplete combustion (PICs). Although the four-stage scrubber was implemented to reduce the possible HF emissions, there was no sampling of HF.

Results

The results of the tests showed that the mandated 99.99 percent destruction of targeted PFAS compounds had been achieved. In both testing years the average PFAS destruction and removal efficiency (DRE) was above 99.999 percent with no result being lower than 99.999 percent. Results were presented as a total FPAS destruction efficiency with the amount of each target PFAS compound summed to provide an aggregate destruction efficiency. The total PFAS destruction efficiencies for each run and each year are as follows:

Year	Run 1	Run 2	Run 3	Average
2020	99.99982%	99.99974%	99.99986%	99.99981%
2021	99.99920%	99.99968%	99.99963%	99.99951%
2022	99.99951%	99.99966%	99.99967%	99.99961%
2023	99.99951%	99.99964%	99.9972%	99.9988%
2024	99.99934%	99.99964%	99.99934%	99.99944%

Conclusions

The test reports demonstrate a PFAS destruction efficiency above the 99.99-percent level that was mandated for the Chemours facility for the specific compounds that were tested. HFPO was tested as a surrogate for all species of PFAS, but there are no definitive data showing the performance of the thermal oxidation process for PFAS species outside of the compounds tested. There was also no discussion of possible PICs in the reports. The thermal oxidizer at the Chemours facility appropriately destroys the five PFAS compounds of interest that have been identified at the facility. However, removal processes for PICs or products of incomplete destruction of potential compounds not studied but potentially found in the facility waste streams are still unclear.

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Focus Environmental, Inc. (2021). Thermal oxidizer performance test report Chemours Company Fayetteville Works. Prepared for the Chemours Company Fayetteville Works Plant. *https://deq.nc.gov/coastal-management/gis/data/air-sampling/week-1-26-2021-chemours-de-test-report-30-mar-21/download*

Focus Environmental, Inc. (2022). Thermal oxidizer performance test report Chemours Company Fayetteville Works. Prepared for the Chemours Company Fayetteville Works Plant. *https://www.deq.nc.gov/coastal-management/gis/data/air-sampling/chemours-feb-2022-de-test-report-final/download?attachment*

Focus Environmental, Inc. (2023). Thermal oxidizer performance test report Chemours Company Fayetteville Works. Prepared for the Chemours Company Fayetteville Works Plant. *https://edocs.deq.nc.gov/AirQuality/DocView.aspx?id=412229&dbid=0&repo=AirQuality*

Focus Environmental, Inc. (2024). Thermal oxidizer performance test report Chemours Company Fayetteville Works. Prepared for the Chemours Company Fayetteville Works Plant. *https://edocs.deq.nc.gov/AirQuality/DocView.aspx?id=487475&dbid=0&repo=AirQuality*

Appendix D: Summary of Costs and Considerations

Introduction

This appendix provides some estimates of costs for end-of-life management of PFAS materials by thermal treatment, landfilling, and underground injection. The cost information presented has limitations and is highly variable and is likely most suitable to make comparisons between techniques.

The cost to destroy or dispose of PFAS and PFAS-containing materials can vary widely depending on a number of factors. Waste management infrastructure's design and operation are heavily influenced by regional needs, local regulations, and technological advancements. As a result, waste management costs vary by the type of waste and by location due to factors like availability and transportation costs. In addition, technological advances specifically related to the management of PFAS-containing materials can potentially reshape the cost and operational landscape of PFAS waste management. Multiple factors and limitations contribute to cost variability and should be considered when using the information in this appendix.

- Market conditions such as supply and demand and macroeconomics change frequently, resulting in fluctuating costs.
- Location of destruction and disposal options and transportation affect case-by-case costs.
- Transportation costs or any special handling costs for accepting and treating additional waste are not included in most of these estimates, thus actual costs would vary.
- Costs may be affected by permitting and state/local requirements for PFAS-containing material, which vary depending on state/local regulations, public input, and geographic location.

Thermal Treatment

Hazardous Waste

Table D-1. Estimated Costs to Incinerate Different Types of Hazardous Waste (U.S. EPA, 2005a)

Hazardous Waste Type	Estimated Thermal Treatment Cost per Ton[a]
Liquids, sludges, solids (halogenated)	$1,221-1,774
Liquids, sludges, solids (non-halogenated)	$358-976
Laboratory packs	$6,054
Containerized gases	$2,929

[a] Costs were developed for hazardous waste combustors (HWC) that were affected by the 2005 National Emission Standards for Hazardous Air Pollutants (NESHAP), including commercial incinerators, cement kilns, lightweight aggregate kilns, and commercial HWC boilers. Cost per ton is assumed to be in 2002 dollars, the same year basis of the regulation from which these costs were obtained. Costs were normalized to 2024 dollars using the Bureau of Economic Analysis (BEA) gross domestic product (GDP) deflator (U.S. BEA, 2025) for waste management and remediation services using a base year of 2002. Note that applying the BEA GDP deflator for this industry sector is a top-down approach. For regulatory purposes, a bottom-up approach is typically used, accounting for capital costs based on the Chemical Engineering Plant Cost Index (CEPCI), energy prices typically based on Energy Information Administration (EIA) data, and labor costs based on industry segment indices using Bureau of Labor Statistics (BLS) data.

Limitations:

- Costs have likely changed since 2002 and scaling costs to 2024 contributes to uncertainty.
- Does not include transportation costs or any special handling costs for accepting and treating additional waste materials.

Table D-2. Example Disposal/Reactivation Costs for Drinking Water Treatment Residuals (Derived from U.S. EPA, 2020a)

Method	Cost of Disposal ($/lb of Media)	Estimated Cost of Disposal Plus Replacement Media ($/lb of Media)[a]
Reactivated GAC—off-site	$0	$1.63
Disposal via landfill	$0.06	$2.21
Disposal via incineration	$1.20	$3.35

[a] Cost per pound is in 2024 dollars. For GAC, on-site reactivation is possible. However, the utility or site would have to have ample workforce, managerial, and financial (both capital and operating) resources to justify this choice. It is likely to be cost-effective only for very large facilities and would require consideration of other factors including availability of land and public opinion. Due to the complex analysis needed, a full comparison of off-site versus on-site is beyond the scope of this document.

Limitations:

- These estimates are presented as examples only to illustrate tradeoffs. Actual site-specific costs are likely to vary based on factors including the quantity of media reactivated/replaced and are used as an example of trends. In this example, reactivated GAC and virgin GAC are estimated to be $1.42 per pound and $2.15 per pound, respectively.
- All unit costs assume 21,000 lbs of GAC reactivated/replaced.
- For reactivated GAC, it is assumed that the "replacement" media is the returned reactivated media plus the replacement of the GAC lost during reactivation with virgin media (assumed to be 30 percent).
- Disposal costs assume 10 miles of transportation to the disposal site.
- Incineration costs are based on incineration of ion exchange resin media. Incineration of GAC could be somewhat more expensive, depending on the relative fuel value of the spent media.
- The analysis is complex and a number of issues need to be considered at the site level, such as those that affect costs (cost of energy, shipping, labor, construction, operation, sampling, etc.) and those that affect other matters (practicality, public versus private ownership, contract availability, regional reactivation availability, off-gas permitting, public opinion, etc.).

Landfills

Hazardous Waste

Table D-3. Estimated Costs to Landfill a Representative Type of PFAS-Containing Material (Defense Logistics Agency (DLA), 2023)

Hazardous Waste Type	Estimated Cost per Ton of Waste (2024$)
Aqueous film-forming foam (AFFF) and other PFAS-related Solids/Debris, Non-RCRA, >100 parts per million (ppm) PFAS for direct disposal at RCRA Subtitle C Landfill (e.g., contract line item number (CLIN) PF06B1)	$1,301-3,664 ($0.65-1.83/lb)

Limitations:

- The DLA pricing web application lists current government contracts for destroying or disposing of PFAS and PFAS-containing materials and may be useful for government contract cost estimates. The estimated cost per ton of waste appears to include removal and disposal costs for the specific material, although a portion of transportation costs may be attributed to other cost elements of each respective contract so transportation costs may not be fully reflected in these costs.
    - **Per the DLA pricing web application:** The prices contained in the database were awarded based on contract terms and conditions, procurement requirements, and price reasonableness determinations. The prices and contract information in the database are for reference only.
- Users of the DLA pricing web application are cautioned that each contract was developed to meet specific requirements for specific geographic regions or military installations. There are multiple variables that result in the pricing information displayed, including contract award date, proximity to DLA-approved disposal facilities, quantities of PFAS material estimated for disposal in proportion to other hazardous waste on the contract, reoccurring need for services, and whether PFAS material is disposed of in bulk or whether there are small, limited quantities.
- Pricing is provided here for bulk waste types for disposal at a Subtitle C hazardous waste landfill. Pricing for multiple waste types with varying units of measure for disposal, including containerized waste, are provided in the DLA pricing web application.
- The estimated cost in the table above only applies to a limited number of military installations and only considered bulk pricing from 600 to 10,000 pounds. Pricing is expected to differ for containerized waste and should be considered when relying on this cost information.

Non-Hazardous Waste (Municipal solid waste)

Table D-4. Average MSW Tipping Fees per Ton by U.S. Region (EREF, 2022)

Region	Average Tipping Fee (2024$/ton)	Region	Average Tipping Fee (2024$/ton)
Pacific	$64.81	Northeast	$71.28
Mountains/Plains	$47.74	Southeast	$45.73
Midwest	$58.23	South Central	$47.74

Limitations:

- MSW landfills emit more PFAS than originally thought in 2020. Research estimates that although MSW landfills contain PFAS for the most part, up to 5 percent of the PFAS may be released in the landfill gas (LFG) and, 11 percent may be released in the leachate annually (Tolaymat et al., 2023). Thus, MSW tipping fees may not be a relevant data point for cost information.

Non-Hazardous Waste (Liquid waste)

Table D-5. Average Industrial Wastewater Rates by U.S. Region (Unger et al., 2023)

Region	$/1,000 gallon	Region	$/1,000 gallon
Pacific	$11.64	Northeast	$4.71
Mountains/Plains	$3.05	Southeast	$7.35
Midwest	$4.66	South Central	$5.08

[a] Data are consolidated by region and the number of data points varies by region. Cost per gallon is expressed in 2024 dollars. American Water Works Association (AWWA) water and wastewater rate surveys were used to gather historical rate data for water and wastewater utilities in the United States. These datasets were compiled and assessed to produce a single dataset of time series rate data for 112 water utilities and 76 wastewater utilities located throughout the United States.

Limitations:

- These data do not include specific information on extra treatment considerations that may be required by a national pollutant discharge elimination system (NPDES) permit or by an industrial user permit for a discharge into a POTW to control the release of PFAS. Thus, similar to the cost of landfilling PFAS waste, the associated treatment of PFAS-laden leachate is difficult to assess because the available data are associated with typical industrial wastewater generators or typical landfill leachate.

One report examined the cost to manage landfill leachate on site (U.S. EPA, 2021). Based on review of the treatment processes and technologies that are currently used, the cost to manage leachate on site is highly variable but generally ranges between $10.78-161.77/1,000 gallons ($0.01-0.16/gallon). Capital costs can range from hundreds of thousands to several million dollars. The report lists multiple limitations and does not specify treatment for PFAS.

Underground Injection

Class I Wells (hazardous and non-hazardous)

Table D-6. Estimated Costs for Class I Wells

Description	Underground Injection Cost ($/1,000 gallon)[a]
Deep well injection	$178-254 (deSilva, 2019)
Trucking costs	$9-188 (McCurdy, 2011)

[a] Costs were normalized to 2024 dollars using the Bureau of Economic Analysis (BEA) gross domestic product (GDP) deflator (U.S. BEA, 2025) for waste management and remediation services using a base year of 2019.

Limitations:

- Class I well capacity is limited, which may affect the costs associated with deep well injection.
- Because of the geographic concentration of Class I wells, waste producers may face transportation and logistical challenges.
- To begin accepting PFAS-containing fluids, owners/operators of existing Class I wells may incur costs to modify their permits to accept waste from other entities or new waste streams.

Another source includes costs for disposing of sewage sludge and indicates that among fees and transportation costs is a fee ($40.44 per ton) for deep well injection of leachate (CDM Smith, 2020).

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> **Per the report:** *This study develops alternatives to remove and destroy per- and polyfluoroalkyl substances (PFAS) from water resource recovery facility (WRRF) effluent, biosolids, mixed municipal solid waste (MSW) landfill leachate, and compost contact water (waste streams) using currently feasible technologies (i.e., could be built today). The report summarizes estimated capital and operations and maintenance (O&M) cost ranges for the two highest-ranking PFAS management alternatives for four waste streams (WRRF effluent, WRFF biosolids, landfill leachate, and compost contact water).*

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> The pricing web application lists Department of War (DoW) contracts for destroying or disposing of PFAS and PFAS-containing materials. The website is organized by multiple CLINs, each of which describes a material or waste stream and a unit of measure for disposal. The site lists contracts and pricing for available disposal technologies, including solidification and disposal in a hazardous waste landfill. The application may be useful as a reference for historical pricing for DoW contracts.
>
> **Per the DLA pricing web application:** *The prices contained in the database were awarded based on contract terms and conditions, procurement requirements, and price reasonableness determinations. The prices and contract information in the database apply to DoW requirements and are for reference only.*

Appendix E: Fact Sheet for the 2026 Interim Guidance on the Destruction and Disposal of PFAS

U.S. Environmental Protection Agency has issued an update to the *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS)*[42].

The non-binding, interim guidance provides recommendations for managers of PFAS and PFAS-containing materials to protect human health and the environment. It also contains a new technology evaluation framework to help analyze the safety and effectiveness of new destruction and disposal (D&D) technologies. The interim guidance does not establish requirements for destruction or disposal of PFAS materials. For more information about PFAS and what EPA is doing to address PFAS, visit EPA's *PFAS website*[43].

The interim guidance summarizes scientific information on current understanding of PFAS and focuses on three widely used and commercially available D&D technologies[44]:

1) Underground injection.
2) Landfills.
3) Thermal treatment under certain conditions, which includes incineration.

The interim guidance summarizes research needs and data gaps and calls for increased collaboration with EPA to collect data and enhance decision-making, as well as describes new EPA test methods.

Key Updates in 2026:

Updated information on destruction and disposal technologies

EPA is not endorsing any technology, but is presenting the technologies' relative potential to minimize PFAS release. As a general approach, EPA encourages managers of PFAS and PFAS-containing materials to consider site-specific conditions and to use D&D options that have a lower potential for releasing PFAS to the environment as described in Section 1 of the interim guidance. In general, the following technologies (in no relative order) have a lower potential for environmental release of PFAS compared to other technologies or operating conditions within the categories of storage, underground injection, landfilling, and thermal treatment:

- **Underground injection–Permitted Class I non-hazardous industrial or hazardous waste injection wells:** The standards associated with the construction, operation, and monitoring of these Class I wells are designed to isolate liquid wastes deep below the land surface and ensure protection of underground sources of drinking water. While Class I wells are an option for managing PFAS-containing fluids, this technology may not be appropriate or available everywhere (Section 3).

[42] Available at: *https://www.epa.gov/pfas/interim-guidance-destroying-and-disposing-certain-pfas-and-pfas-containing-materials-are-not*.

[43] Available at: *http://www.epa.gov/pfas*.

[44] For general information on these technologies, see EPA websites for *incineration*, *landfills*, and *underground injection*. Please note that these resources are not specific to PFAS and not all information in them may be relevant to PFAS D&D.

- **Landfills–Permitted RCRA Subtitle C hazardous waste landfills:** When landfill disposal is selected and PFAS concentration of the waste is relatively high, EPA recommends using a hazardous waste landfill. These types of landfills have the most stringent engineering controls and practices for minimizing environmental release of PFAS from leachate and landfill gas. These controls are especially important for certain types of PFAS-containing materials that break down more easily in landfill conditions. However, for all landfill types, new information demonstrates landfilling could result in higher PFAS releases to the environment than previously thought in 2024 (Section 3).
- **Thermal treatment–Permitted hazardous waste combustors that operate under certain conditions:** New research since 2024 indicates that thermal treatment units operating under certain conditions are more effective at destroying PFAS and minimizing environmental releases or human exposures. Certain hazardous waste combustors and certain granular activated carbon (GAC) reactivation units may operate under these conditions, but uncertainties remain. For example, more information is needed to determine whether harmful products of incomplete combustion (PICs) or PFAS air emissions are formed by units operating at lower temperatures (e.g., municipal waste combustors). EPA's new analytical methods for a targeted list of polar semivolatile PFAS (Other Test Method 45 [*OTM-45*[45]]) and volatile fluorinated compounds (*OTM-50*[46]) that, as well as additional EPA methods under development for evaluating treatment of hard-to-destroy PFAS will allow better characterization of PICs which will help to address some of these uncertainties. The updated interim guidance encourages testing with a range of methods at thermal treatment facilities before accepting large quantities of PFAS-containing materials (Section 3 and Appendix A).
- The interim guidance discusses these and other PFAS D&D technologies, plus testing and research needs to improve technology performance, improve understanding of PFAS behavior, and reduce uncertainties (Section 4).

Emerging Destruction and Disposal Technologies

Federal entities and many companies and researchers are developing and testing new PFAS D&D technologies (e.g., the *PFAS Technical and Regulatory Guidance Document*[47] developed by the Interstate Technology and Regulatory Council, and the Department of War's *Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) PFAS Projects*[48] website). EPA encourages technology developers to generate and publicly release data that can be reviewed, and to ensure the data are consistent with the tenets of gold standard science established in Executive Order 14303 (*Restoring Gold Standard Science*[49]). The guidance provides a technology evaluation framework to help analyze the safety and effectiveness of new D&D technologies, and notes the need for innovation, research, and validation (Section 5).

[45] Available at: *https://www.epa.gov/emc/emc-other-test-methods#Other%20Test%20Methods*.

[46] Available at: *https://www.epa.gov/emc/emc-other-test-methods#Other%20Test%20Methods*.

[47] Available at: *https://pfas-1.itrcweb.org/*.

[48] Available at: *https://serdp-estcp.mil/focusareas/e18ec5da-d0de-47da-99f9-a07328558149*.

[49] Available at: *https://www.govinfo.gov/content/pkg/FR-2025-05-29/pdf/2025-09802.pdf*.

Public Input and Participation

EPA has opened a *docket*[50] to take input on the interim guidance. We welcome public input on how to improve the interim guidance and this fact sheet.

Public Feedback and Next Steps

EPA and other government, academic, and private institutions will continue to conduct research to better understand PFAS destruction and disposal (see Section 4). EPA will consider public comments it receives on this version of the guidance, as well as additional advancements in PFAS research and science to publish annual updates[51]. This guidance will be published with a 60-day comment period. EPA will publish a Federal Register Notice with instructions on how to submit comments. During the public comment period, EPA encourages the public to submit studies and data related to management of the PFAS-containing waste described in Section 2. Additionally, continued collaboration with industry and researchers is encouraged to conduct emissions testing of PFAS treatment devices, including evaluation of PICs and products of incomplete destruction (PIDs).

[50] Available at: *https://www.regulations.gov/document/EPA-HQ-OLEM-2020-0527-0003*.

[51] On April 28, 2025, the EPA Administrator committed to providing more frequent updates to the interim guidance—changing from every three years to annually.

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Bench scale incineration of polychlorotrifluoroethylene

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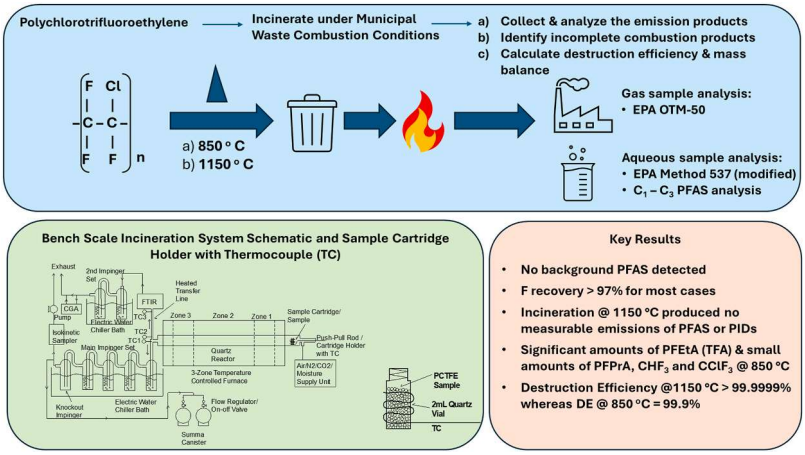
HIGHLIGHTS

- Bench-scale incineration of PCTFE was evaluated for PFAS emissions.
- A rigorous QA/QC was applied to minimize background PFAS below 2.00 ng/L.
- Over 96 % F and 82 % Cl recovery was achieved.
- Incineration at 1150 °C produced no measurable emissions of PFAS or PIDs.
- At 850 °C, TFA, PFPrA, CHF_3, and $CClF_3$ were observed.
- PFAS Destruction Efficiency at 1150 °C > 99.9999 % whereas DE at 850 °C = 99.9%.

GRAPHICAL ABSTRACT



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ABSTRACT

Polychlorotrifluoroethylene (PCTFE) was incinerated under Municipal Waste Combustion (MWC) conditions to determine if targeted poly- and perfluoroalkyl Substances (PFAS) were emitted. A bench-scale incineration system was custom built to thermally gasify solid PCTFE, incinerate under controlled conditions, and collect effluent gases using an aqueous impinger sampling train and gas canisters for subsequent analyses. Incineration was conducted at 1150 °C and 850 °C, temperatures used in the US and Europe, respectively, with the gas composition that mimics the post combustion zone of municipal waste combustors.

The aqueous impinger samples were analyzed for targeted PFAS using EPA Method 537 with laboratory modification, while the non-aqueous gaseous effluent was analyzed for products of incomplete destruction (PIDs) using EPA OTM-50. Neither PFAS nor gaseous PIDs were detected at 1150 °C. At 850 °C, 198 – 228 μg/L of perfluoroethanoic acid and 117 – 142 ng/L of perfluoropropanoic acid were detected. Also, 4.96 – 5.06 ppb of trifluoromethane and 49.0 – 54.7 ppb of chlorotrifluoromethane were detected in the gaseous mixture. For PFAS analysis, only the PFAS compounds defined within the analytical methods were analyzed.

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Calculations showed that PFAS destruction efficiency (DE) at 1150 °C was high (>99.9999%) whereas at 850 °C DE was reduced to 99.9% mainly due to the formation of perfluoroethanoic acid. These PFAS DEs corresponded to emission concentrations (ng/m^3) of 51.2 and 67,468 at the high and low temperature conditions, respectively. Data shows the Global Warming Potential (GWP) impact from greenhouse gases emitted at 850 °C was insignificant compared to CO_2. The Ozone Depletion Potential (ODP) of the observed PIDs at 850 °C was also insignificant compared to other emission sources.

1. Introduction

Polychlorotrifluoroethylene (PCTFE) is a nonflammable fluoropolymer (FP) with the lowest water vapor transmission rate of any fluoroplastic. It has high tensile strength and good thermal characteristics. These properties make it versatile for applications in pharmaceuticals, aerospace, chemical processing, cryogenics, medical implants, electronics, optics, petrochemicals, semiconductors, and laboratory equipment.

Recent estimates indicate that 6800 tonnes of PCTFE are produced globally (Sales et al., 2022). Although FPs have been widely accepted as safe substances, their potential degradation to non-polymeric short chain PFAS are of concern. The high bond energy of the C–F bond in FPs prevents them from degrading to non-polymeric PFAS under intended use conditions, as well as at end-of-life.

Ellis et al. performed the thermal decomposition of PCTFE at about 500 °C and identified chlorodifluoroacetic acid (CDFA) and chloropentafluoropropylene (CPFP) as major decomposition products using gas chromatography tandem mass spectrometry (GC–MS/MS) and ^{19}F nuclear magnetic resonance (NMR) spectroscopy techniques (Ellis et al., 2001; 2003). Myers et al. used ultrahigh-resolution mass spectrometry and mass defect filtering techniques to identify thermal decomposition products of PCTFE at 400 °C and 800 °C, respectively (Myers et al., 2013). Thermogravimetric analysis of PCTFE in air and nitrogen at 200 to 890 °C detected 4,4-dichlorohexafluoro-1-butene in the nitrogen pyrolysis above 500 °C along with chlorotrifluoroethene, chloropentafluoro-1-propene, 1,1,2-trichlorotrifluoroethane, and trichloromonofluoromethane (Dolatabad, 2025).

A *Conversio Market & Strategy GmbH* report (Lindner et al., 2022) concludes that "Almost 84 % of all FP in use were incinerated at the end of life in energy recovery or thermal destruction processes." In order to understand the emissions under these conditions, the incineration of polytetrafluoroethylene (PTFE) and a mixture of FPs at a pilot-scale facility, wherein PTFE was incinerated at temperatures of 870 °C (residence time 4 s) and 1020 °C (residence time 2.7 s), did not show any significant difference in measured PFAS (Aleksandrov et al., 2019). Furthermore, measured PFAS emissions were not found to increase with increased PTFE loading. PFAS were not detected or was present in sub-ppt concentrations, including trifluoroacetic acid (TFA) in the stack gases and in the solid and liquid residues when a FP mixture was combusted under very similar combustion conditions (temperatures of 860 °C and 1095 °C for residence times of 2.0 s) (Gehrmann et al., 2024).

Although FPs such as PTFE, polyvinylidene fluoride (PVDF) and fluoroelastomer (FKM) have been incinerated and their end-of-life products have been identified, incineration of PCTFE and its end-of-life products has not been reported (Gehrmann et al., 2024). Therefore, the objective of this study was to study the incineration of PCTFE under standard MWC operating conditions to identify and quantify potential emission products, and to elucidate the conditions required to completely mineralize PCTFE. Data generated from this study will be useful for regulatory agencies to consider next steps and recommend suitable disposal methods for downstream materials that contain PCTFE.

In the US, typical MWC operating temperatures are above 1160 °C and gas residence time above 2.4 s (Aleksandrov et al., 2019). In the EU, MWCs are required to reach the temperature of 850 °C and gas residence times of 2 s in a controlled and homogeneous fashion, and even under the most unfavorable conditions. The temperature must be raised to 1100 °C for at least 2 s if hazardous waste streams containing more than 1 % halogenated organic substances are incinerated (European Parliament, 2000).

Under the current work, a bench scale high temperature flow reactor system was custom built and operated at two different temperatures: high temperature at 1150 °C and low temperature at 850 °C, representing typical MWC operating conditions in the US and the minimum temperature requirement in the EU. A real-time fourier-transform infrared (FTIR) spectrometer was used to measure the combustion end products such as carbonyl fluoride (COF_2), hydrogen fluoride (HF), hydrogen chloride (HCl), carbon dioxide (CO_2) and water (H_2O). Aqueous samples from the impinger train system were analyzed for short (C_1 – C_3) and long ($\geq C_4$) chain PFAS. Separate analyses were also conducted to measure volatile fluorocarbons (VFCs), including chlorofluorocarbons (CFCs).

2. Experimental procedures

Fig. 1 illustrates the bench-scale PCTFE incineration system developed for this study. The following carrier gases were used: Zero grade air (21 vol (vol) % O_2, 79 vol % N_2), Ultra High Pure (UHP) Nitrogen (N_2), and UHP Carbon Dioxide (CO_2) were supplied by Airgas. Gas flow rates were controlled by Mass Flow Controllers (MFCs, Alicat MC series) set to 4.24 mL/min for air, 2.55 mL/min for N_2, and 0.40 mL/min for CO_2, achieving a typical MWC off-gas composition (10 – 12 vol % O_2, 5 – 6 vol % CO_2). Air and N_2 gas mixture was passed through a temperature-controlled humidifier to reach 8.1 - 8.5 vol % and 10 – 11 vol % moisture content for high- and low temperature studies, respectively. Moisture levels were monitored with FTIR spectrometer (MKS, MultiGas 2030). The total gas flow of humidified gas was 8 L/min.

A fused silica quartz tube (5.0 cm OD x 4.6 cm ID) served as the reactor, with lengths of 137 cm (54-inch) for high temperature and 122 cm (48-inch) for low temperature studies. The longer reactor length used for the high temperature test was to manage exit heat. The reactor was connected to the gas transfer line using stainless steel flanges coated with Silcolloy® 2000 (SilcoTek) and heated in a 3-zone temperature-controlled furnace (Zone 1, 2, and 3, heating element length: 15, 46, and 15 cm, Thermcraft, SST-3.00-0-30-3C-D2155-BE). The effective length, maintaining ±5% of target temperature, was 69 cm for both temperatures. The maximum and minimum temperatures within effective length, as well as the midpoint temperature of each zone, are presented in Table 2. The reactor temperature profile is also presented in the supplemental information (SI), Fig. S1. The average temperatures were calculated over the effective length, which is defined as the region of the reactor where the temperature remained within ±5 % of the target temperature. Temperature was measured by thermocouple (TC) (KMQXL-125U-48, OMEGA) with thermocouple reader (HH501DK, OMEGA) with air flow of 8 L/min. The gas residence time was calculated based on the reactor volume, which is dependent on the effective length determined by the temperature profile as described above and furnace temperature.

For incineration, a 1 g PCTFE sample (1-2 mm diameter beads obtained from a manufacturer) was placed in a 2 mL quartz vial, and the vial was wrapped with a thermocouple (OMEGA KMQXL-062G) to measure the gasification temperature. Table 1 summarizes the amount of sample gasified and the test duration for each test. Mass of sample gasified was approximately 0.5 to 0.6 g. The test duration for the lower

temperature tests (Test # 5, 6, and 7) and the last high temperature (Test # 4) was slightly longer to increase the total gas volume to attain 2 m^3 sampling volume through the main impinger. The sample gasification rate was approximately 0.09 to 0.1 g/h.

The vial position was manually adjusted to obtain a steady gasification rate. The HF concentration, monitored by FTIR spectrometer, was used to maintain steady gasification. After gasification and incineration, the sample vial was removed from the furnace and placed near the inlet flange to terminate gasification. The humidified gas mixture continued to flow through the reactor, and the effluent gas was collected in the impinger until the HF concentration fell below the threshold level (1 ppm). This period is referred to as steam cleaning. This process has been routinely applied in our previous work to achieve a high fluorine mass balance (Taylor et al., 2014). The duration of steam cleaning varied between the high- and low-temperature studies, depending on the time required for the HF concentration to decrease to the threshold level.

The off gas exiting the reactor was split, with one stream flowing onto the main impinger sampling train and the other to the FTIR spectrometer connected to a second impinger sampling train. An isokinetic sampler (Apex, X5000) sampled gas to the main impinger set at approximately 6 L/min with moisture. The main impinger set comprised five 500 mL glass impingers (Apex, GN-9A) filled with 250 mL PFAS-free water, provided by SGS (British Columbia, Canada), in the first four and an empty knockout impinger last. The remaining gas flowed to the FTIR spectrometer to monitor off gas components, including HF, HCl, COF_2, H_2O and CO_2, before passing through the second impinger set, consisting of two 500 mL glass impingers (Apex, GN-9A) filled with 250 mL PFAS-free water. A list of compounds monitored by FTIR spectrometer is summarized in the SI, Table S1.

Table 1
Sample gasification conditions.

Test #	Temperature (°C)	Sample Gasified (g)	Test Duration (hr)	Gasification Rate (g/hr)
1	1150	0.4834	5.55	0.087
2		0.4683		0.084
3		0.4600		0.083
4		0.4939	6.0	0.082
5	850	0.6248	6.0	0.104
6		0.5767		0.096
7		0.5864		0.098

Approximately 1.7 - 2.0 m^3 of gas sample was passed through the main impinger sampling train for PFAS, fluoride, and chloride ion analysis, while another ~0.9 m^3 gas sample was passed through the second impinger sampling train for fluoride and chloride ion analysis.

Four high-temperature tests at 1150 °C (Tests 1–4) and three low-temperature tests at 850 °C (Tests 5–7) were conducted. Targeted PFAS measurements were performed in triplicate at 1150 °C and 850 °C, with an additional experiment conducted at 1150 °C. The initial three high-temperature tests were performed without canister gas sampling because the newly developed OTM-50 (EPA, 2025a) sampling and analysis was not yet available at the analytical laboratory. Following the high-temperature series, three low-temperature tests were carried out with canister gas sampling. Subsequently, one additional

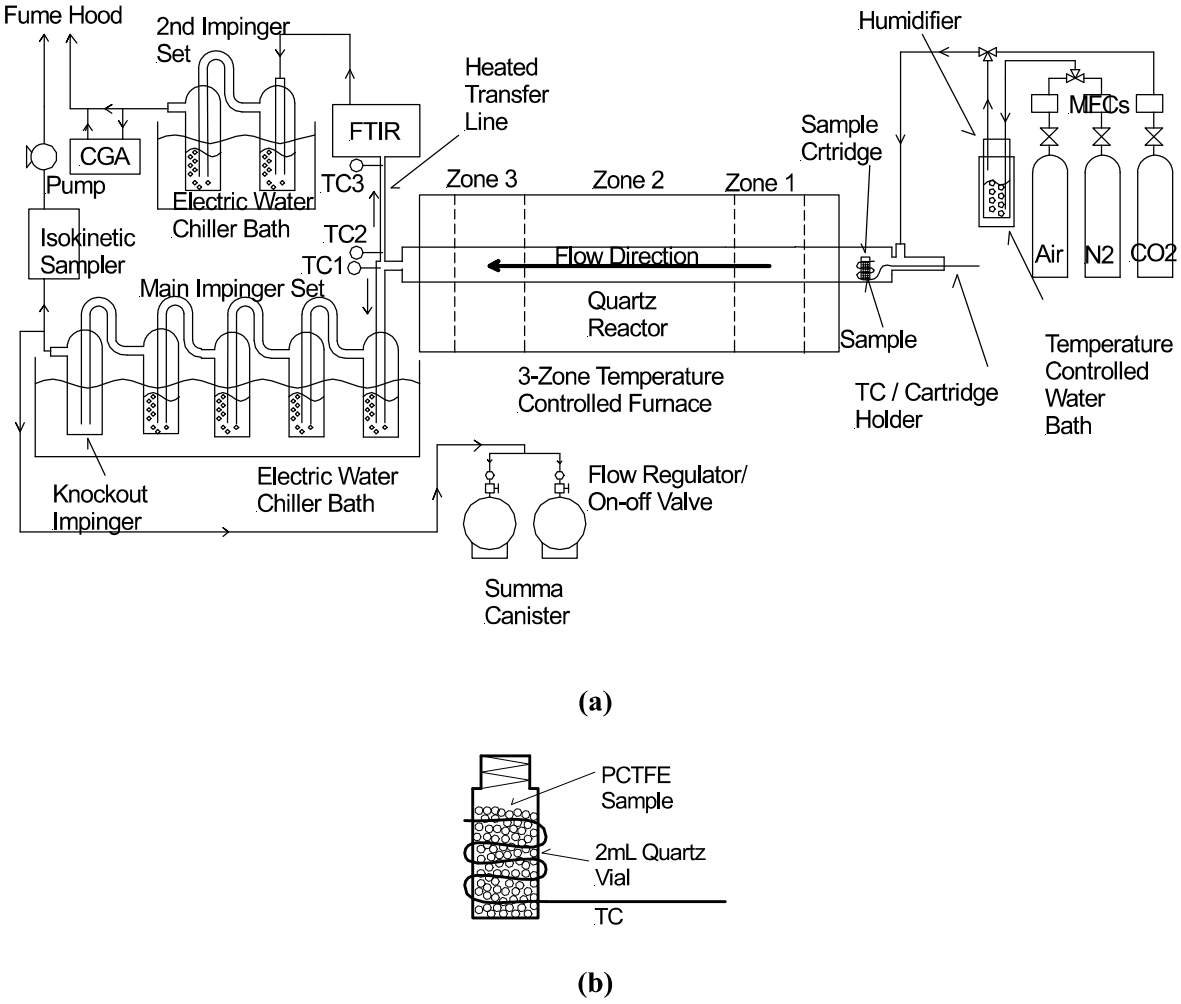

Fig. 1. (a) Schematic of the bench scale PCTFE incineration system and (b) sample cartridge holder with TC

Table 2
Summary of experimental conditions.

Parameters	High Temperature	Low Temperature
Reactor Length (cm)	137	122
Reactor OD (cm)	5.0	
Reactor ID (cm)	4.6	
Effective Length (cm)	69	
Average Temperature within Effective Length (°C)	1150	852
Highest Temperature (°C)	1160	862
Lowest Temperature (°C)	1101	822
Middle of Zone 1 Temperature (°C)	1101	822
Middle of Zone 2 Temperature (°C)	1158	860
Middle of Zone 3 Temperature (°C)	1148	856
Gas Residence Time (s)	1.8	2.3
Air Flow Rate (L/min)	4.24	
N_2 Flow Rate (L/min)	2.55	
CO_2 Flow Rate (L/min)	0.4	
Total Flow Rate (L/min) (Dry-gas basis)	7.19	
Moisture (%)	8.5	10
Expected O_2 Conc (%)	11.1	
Expected CO_2 Conc (%)	5.0	
Run Duration (hour)	5.55	6.00
Impinger Gas Sampling Volume (m^3)	2.59	2.86
Steam Cleaning Time (hour)	~0.5	~1.5
Sample Gasified (g)	~0.5	
Main Impinger Set Analysis	PFAS (EPA Method 537 M) C_1 - C_3 PFAS Analyses[a] F^- and Cl^- (Method 9056A)	
2nd Impinger Set Analysis	F^- and Cl^- (Method 9056A)	
Canister Gas Sampling	Only the 4th run	Triplicate runs

[a] Analytical laboratory's internal method.

high-temperature test was conducted with canister gas sampling included.

Aqueous samples from the main impinger were analyzed by Eurofins TestAmerica, Knoxville, TN for PFAS ($\geq C_4$, four or more carbon atoms) using EPA method 537 (EPA, 2009) with laboratory modification (hereafter referred to as 537 M). A total of 36 PFAS compounds listed in the SI, Table S2 were analyzed, compared to the 14 PFAS listed in the standard EPA Method 537. Short-chain PFAS (C_1–C_3), listed in the SI, Table S3, were analyzed independently by another external laboratory using Ultra-High Performance Liquid Chromatography - Mass Spectrometry/Mass Spectrometry (UHPLC-MS/MS) combined with solid phase extraction (SPE) technique. In addition, both the main impinger and second impinger aqueous samples were analyzed for fluoride (F^-) and chloride (Cl^-) ions using EPA Method 9056A (EPA, 2007) to assess fluorine (F) and chlorine (Cl) mass balances.

OTM-50 gas sampling was conducted measuring VFCs identified as PID. A list of compounds analyzed by OTM-50 is summarized in the SI, Table S4. Three tests were performed at 850 °C and one at 1150 °C, with the latter included as an additional test beyond the triplicate experiments. For these tests, a portion of the effluent was collected in an evacuated Summa canister (6 L volume) at a 15 mL/min flow rate to capture VFCs. The heated transfer line and FTIR spectrometer temperature were set at 191 °C to minimize condensation and maximize off gas transfer efficiency. Temperatures at critical points shown as TC1 to TC3 in Fig. 1 were monitored and recorded every 30 min to ensure they stayed above 190 °C.

Table 2 summarizes the experimental conditions for both high- and low temperature studies, which were designed to closely mimic typical MWC conditions. A recent study found that average municipal waste combustor temperatures in the U.S. ranged between 880 °C and 1230 °C (Giraud et al., 2021). MWCs in the EU are believed to operate at lower temperatures, with minimum temperatures of 850 °C required (Gehrmann et al., 2024). The 850 °C and 1150 °C tests were chosen to represent the average minimum and maximum temperatures in MWCs. Typically, municipal waste combustor operates with a residence time of approximately 2 s. To maintain consistent carrier gas to gasified sample ratios, the gas flow rate was held constant for both tests. This created different gas residence times at 1150 and 850 °C, respectively. Therefore, the gas flow rate was optimized such that the residence time was close to 2 s for both tests, as required by MWC guidelines. Furthermore, the concentrations of moisture, O_2, and CO_2 in the carrier gas were controlled to closely mimic those found in a typical municipal waste combustor.

2.1. Mass balance calculations

F and Cl mass balances were calculated based on the amount of PCTFE sample gasified and fluoride and chloride ions recovered from both main impinger set and 2nd impinger set using EPA method 9056A as shown below:

$$\text{F Mass Balance (\%)} = \frac{\text{Mass of F Recovered in (g)}}{\text{Mass of F Introduced in (g)}} \times 100 \quad (1)$$

where:

$$\text{Mass of F Recovered in (g)} = (\text{F}^- \text{ concentration in the main impinger in (mg/L)}) \text{ x } (\text{volume of main impinger sample in (L) x } 10^{-3} \text{ (g/mg)}) + (\text{F}^- \text{ concentration in the 2}^{\text{nd}} \text{ impinger in (mg/L)}) \times (\text{volume of the 2}^{\text{nd}} \text{ impinger sample in (L)} \times 10^{-3} \text{ (g/mg)}) \quad (2)$$

and.

Mass of F Introduced in (g) = (F Mass portion of PCTFE) x (Mass of PCTFE gasified in (g))

$$\text{F mass portion of PCTFE} = \frac{\text{Atomic Mass of three F}}{\text{Molecular Mass of PCTFE Monomer}} = \frac{19 \; x \; 3}{12 \text{ x } 2+19 \text{ x } 3+35.5 \text{ x } 1} = 0.489$$

Therefore,

$$\text{Mass of F Introduced in (g)} = 0.489 \times (\text{Mass of PCTFE gasified in (g)}) \quad (3)$$

$$\text{Cl Mass Balance (\%)} = \frac{\text{Mass of Cl Recovered in (g)}}{\text{Mass of Cl Introduced in (g)}} \times 100 \quad (4)$$

where:

$$\text{Mass of Cl}^- \text{ Recovered in (g)} = (\text{Cl}^- \text{ concentration in the main impinger in (mg/L)}) \text{ x } (\text{volume of main impinger sample in (L) x } 10^{-3} \text{ (g/mg)}) + (\text{Cl}^- \text{ concentration in the 2}^{\text{nd}} \text{ impinger in (mg/L)}) \times (\text{volume of the 2}^{\text{nd}} \text{ impinger sample in (L)} \times 10^{-3} \text{ (g/mg)}) \quad (5)$$

and

Mass of Cl Introduced in (g) = (Cl Mass portion of PCTFE) x (Mass of PCTFE gasified)

$$\text{Cl mass portion of PCTFE} = \frac{\text{Atomic Mass of three F}}{\text{Molecular Mass of PCTFE Monomer}} = \frac{35.5 \; x \; 1}{12 \text{ x } 2+19 \text{ x } 3+35.5 \text{ x } 1} = 0.305$$

Therefore,

$$\text{Mass of Cl Introduced in (g)} = 0.305 \times (\text{Mass of PCTFE gasified in (g)}) \quad (6)$$

Elemental analysis was conducted for the original PCTFE sample. The differences between the calculated values and the analytical results were minimal, within 2% of the calculated values. As the analysis was performed only once, without information on analytical variability, the calculated values were used for the mass balance calculations. The analytical results and their comparison with the calculated values are provided in the SI, Table S5.

2.2. Quality Assurance and Quality Control (QA/QC)

Since this study aimed to investigate the possible emissions of PFAS arising from the incineration of PCTFE, it was critical to minimize background contaminants that may lead to false positives. Therefore, a series of Quality Assurance and Quality Control (QA/QC) measures were implemented.

Prior to each incineration test, a system blank run (an experimental run without sample introduction) was performed to verify that no PFAS were present in the system, including the sample introduction assembly, reactor, transfer line, and impinger sampling train. The PCTFE incineration experiments were conducted only after confirming a PFAS-free background. In addition, for each experiment, all major system components including the reactor, reactor flanges, and the manifold connecting the reactor to both the impinger sampling train and the FTIR heated transfer line were replaced with new parts. Before use, all components were thoroughly washed with laboratory glassware detergent and solvent rinsed. In addition, the source water used in the impinger sampling train and the sampling blank (i.e., the rinsate from the impinger sampling train collected prior to use) were analyzed for PFAS to confirm the absence of background contamination. These procedures

Table 3
F and Cl mass balance.

Test Description	Temperature (°C)	Ion	Sample Gasified (g)	Mass Fraction (g)	Total Ion Recovered (g)	Mass Balance[a] (%)
1st High Temperature Incineration Test	1150	F^-	0.4834	0.2365	0.2396	101.3
		Cl^-		0.1473	0.1310	88.9
2nd High Temperature Incineration Test		F^-	0.4683	0.2291	0.2306	100.6
		Cl^-		0.1427	0.1288	90.3
3rd High Temperature Incineration Test		F^-	0.4600	0.2251	0.2220	98.6
		Cl^-		0.1402	0.1185	84.5
4th High Temperature Incineration Test		F^-	0.4939	0.2417	0.216	89.2
		Cl^-		0.1505	0.124	82.5
1st Low Temperature Incineration Test	850	F^-	0.6248	0.3057	0.3071	100.5
		Cl^-		0.1904	0.1560	81.9
2nd Low Temperature Incineration Test		F^-	0.5767	0.2822	0.2724	96.6
		Cl^-		0.1757	0.1446	82.3
3rd Low Temperature Incineration Test		F^-	0.5864	0.2869	0.2822	98.4
		Cl^-		0.1787	0.1541	86.2

[a] Rounding errors may occur.

Table 4
PFAS Analysis ($\geq C_4$) in Units of ng/L.

Description	Temperature (°C)	PFBA	PFHxA	PFHpA	HFPO-DA
Blank	1150	ND	ND	ND	ND
1st High Temperature Incineration Test		1.13	1.78	ND	ND
Blank		ND	ND	ND	ND
2nd High Temperature Incineration Test		1.02	ND	ND	ND
Blank		ND	ND	ND	ND
3rd High Temperature Incineration Test		ND	1.65	ND	ND
Blank		ND	ND	ND	ND
4th High Temperature Incineration Test		ND	ND	ND	ND
Blank	850	ND	ND	ND	1.28
1st Low Temperature Incineration Test		ND	ND	ND	ND
Blank		ND	ND	ND	ND
2nd Low Temperature Incineration Test		ND	ND	ND	ND
Blank		ND	ND	ND	ND
3rd Low Temperature Incineration Test		ND	ND	0.985	ND

also allowed any potential PFAS background contamination to be traced to its source, if identified. An extensive summary of the QA/QC protocol is presented in the SI.

3. Results and discussion

For the high temperature test, PCTFE was mineralized to HF and HCl, with a fluorine mass balance between 99 % and 101 % except one experiment and a chlorine mass balance between 83 % and 90 %. All targeted short- (C_1–C_3) and long-chain ($\geq C_4$) PFAS were non-detect (ND) or below reporting limit (RL) for all tests. VFCs and CFCs were all ND. Therefore, it was concluded that targeted PFAS including any gas-phase fluorinated compounds were not emitted for PCTFE incineration at temperatures of 1150 °C. However, it should be emphasized that the PFAS analyses were targeted and therefore limited to the compounds specified in Table S2 and S3 in the SI. Specific gas-phase VFCs and CFCs that were analyzed are given in the SI, Table S4.

For the low temperature tests, the fluorine mass balance was between 97 % and 101 %, and the chlorine mass balance was between 82 % and 86 %. No targeted PFAS above C3 were emitted at 850 °C; however, significant amounts of perfluoroethanoic acid (CF_3COOH, trifluoroacetic acid (TFA)) and a small amount of perfluoropropanoic acid (CF_3CF_2COOH, PFPrA) were observed. Small amounts of trifluoromethane (CHF_3) and chlorotrifluoromethane ($CClF_3$) were emitted as PID. FTIR sampling also indicated the formation of COF_2 in addition to HF and HCl (see SI for more details of the FTIR detection of COF_2). Therefore, it was concluded that PCTFE incineration at a temperature of 850 °C and residence times of 2 s were not sufficient to fully mineralize the polymer. Additional details of the experimental results are provided in sections 3.1, 3.2, 3.3, and 3.4.

Table 5
Results of short-chain targeted PFAS (C_1 – C_3).

Description	Temperature (°C)	PFEtA (ng/L)	PFPrA (ng/L)
Blank	1150	<91.4[a]	<17.9
1st High Temperature Incineration Test		<96.6	<18.6
Blank		<99.1	<19.4
2nd High Temperature Incineration Test		<95.1	<18.6
Blank		<100	<19.6
3rd High Temperature Incineration Test		<144	<19.9
Blank	850	<100	<19.6
1st Low temperature Incineration Test		198000	142
Blank		<108	<19.2
2nd Low Temperature Incineration Test		228000	117
Blank		<99.2	<17.9
3rd Low Temperature Incineration Test		219000	133

[a] "<" indicates that the value was below RL.

3.1. F and Cl mass balancers

The results are summarized in Table 3. Nearly 100 % fluorine recovery was achieved in both the high- and low-temperature tests, except for the fourth high-temperature test, which showed slightly lower recovery (slightly below 90 %). COF_2 was generated at the lower temperature; however, it is expected to have quantitatively converted to HF upon contact with water in the impinger sampling train. As a result, the fluorine mass balance was near 100 % at both temperatures.

In contrast, chlorine recovery was lower, ranging between 82 % and 90 %. This outcome was somewhat unexpected, as the formation and transport of HCl in the experimental system was anticipated to be more quantitative than HF, which is known to react with quartz or glass surfaces. The gas-phase $CClF_3$ concentrations did not contribute to improve chlorine mass balance. A possible explanation for the low chlorine mass balances is as follows. Since the C–Cl bond (330 kJ/mol) is weaker than C–F bond (439 kJ/mol) in PCTFE-based polymers, it is expected to be broken first to generate a chlorine radical which could potentially combine/react with various other radicals/species present within the reactor. These combined species have neither been detected nor quantified due to lack of reference spectra in FTIR library. It is also unlikely that these chlorofluorocarbons would convert to HCl in the impingers. A more detailed overview on the mass balance calculations and the FTIR measurements can be found in the SI, Table S5–S7.

3.2. PFAS analysis ($\geq C_4$)

These results are summarized in Table 4, and only PFAS species above the method detection limit (MDL) are reported. ND denotes "non-detect" and indicates that the measured concentration was below MDL. The MDL varied by targeted PFAS compound and by individual analysis, although most values remained consistent, with only minor variations. As shown, all experimental runs, including blank runs, yielded PFAS

Table 6
VFCs Detected by OTM-50 (Unit in ppb).

Test Description	Temperature (°C)	CHF_3	$CClF_3$
4th High Temperature Incineration Test	1150	ND[a]	ND[b]
1st Low Temperature Incineration Test	850	3.85	50.4
2nd Low Temperature Incineration Test		5.06	54.7
3rd Low Temperature Incineration Test		4.97	49.0

[a] Below MDL, 0.471 ppb v/v.
[b] Below MDL, 0.440 ppb v/v.

concentrations either ND or below the RL in both the high-temperature and low-temperature studies. The RL is an analytical laboratory defined threshold below which concentrations are considered non-quantitative. For Method 537 M, the RL established by the analytical laboratory was 2 ng/L. These results confirm that the experimental system did not contain background PFAS and that the incineration tests did not emit the targeted PFAS at quantifiable levels.

3.3. Short-chain PFAS analysis ($C_1 - C_3$)

Table 5 summarizes the analytical results for short-chain targeted PFAS ($C_1 - C_3$). As with the long-chain targeted PFAS analysis, blank run samples collected prior to each incineration test were also analyzed. The RL values used for interpretation are provided in the SI, Table S3. As shown in Table 5, the results for all blank runs indicate PFAS concentrations below the RL, confirming that no quantifiable PFAS was present in the system.

For the high-temperature study (1150 °C), no short-chain PFAS above the RL were detected, indicating that incineration under these conditions did not emit quantifiable levels of short-chain PFAS. In contrast, the low-temperature study (850 °C) yielded significant concentrations of TFA (approximately 200–230 μg/L) and detectable concentrations of PFPrA (approximately 120–140 ng/L). Given that no quantifiable short-chain PFAS were detected in the blank runs, these findings clearly demonstrate that both TFA and PFPrA may be emitted during the PCTFE incineration at this lower temperature, and with standard residence times of 2 s. More detailed information can be found in the SI, Table S8.

3.4. VFC measurements

VFC measurements were conducted in triplicate at 850 °C; a single measurement was also conducted at 1150 °C. VFCs were not detected at 1150 °C. $CClF_3$ and CHF_3 were detected in each test at 850 °C. The data for quantified VFCs is summarized in Table 6. The RL and MDL varied for each analysis. The RL ranged from 1.70 to 3.14 ppb v/v, except for fluoromethane and hexafluoropropylene oxide in the high-temperature test, where it was 6.28 ppb v/v. The MDL ranged from <1 ppb v/v to 2.13 ppb v/v, with the same exceptions for fluoromethane and hexafluoropropylene oxide at the high-temperature test (6.28 ppb v/v).

3.5. PFAS destruction efficiency

The PFAS destruction efficiency (DE) calculations were conducted using the following equation:

$$PFAS\ DE = (1 - \Sigma\ PFAS_{out}/\Sigma\ PFAS_{in})^{\times}\ 100 \quad (7)$$

The Σ $PFAS_{out}$ was determined from the analytical results obtained from the impinger sampling for each test condition. This included LC-MS-MS analysis for both short- ($C_1 - C_3$) and long-chain PFAS ($\geq C_4$). For the majority of the method analyte species, no target was detected. Non-detectables were treated as MDL values for this analysis. The Σ $PFAS_{in}$ was a value determined from the measured amount of PCTFE gasified over the duration of the experiment, which is shown in Table 1, and the assumption that the PCTFE sample was pure with no additional sources of fluorine or non-polymeric PFAS present. Elemental analysis of PCTFE samples validated the first assumption, see Table S9 in the SI. The fundamental assumption in the PFAS DE calculation (Eqn (7)) was that all PCTFE could theoretically form PFAS during the combustion process. The PFAS DE calculations were normalized to the F content of input PCTFE and output PFAS measurements. The details of these calculations are given in the SI, Table S10.

PFAS DEs at 1150 °C were greater than 99.9999%. The average mass of PFAS measured across the three high temperature runs was 148 ng. PFAS DEs at 850 °C were 99.9%. The average mass of PFAS measured across the three low temperature runs was 180 μg, much higher than observed during the high temperature runs. The formation of TFA at lower temperature was responsible for the nearly a 1000-fold increase in PFAS mass and the 1000-fold decrease in PFAS DE.

Gehrmann et al. (2024) reported an identical PFAS DE calculation in their pilot-scale studies of the incineration of a FP mixture. Their calculation was denoted as a Reduction Rate for PID (R2PID). They reported R2PID values of >99.99 % at both 860 °C and 1095 °C. The values reported here indicate a higher level of PFAS destruction at elevated temperatures but a lower level of destruction at 850 °C compared to the Gehrmann et al. (2024).

Gehrmann et al. (2024) measured values of 24.6 ng/m^3 and 29.5 ng/m^3 at the post-combustor chamber exit for temperatures of 860 and 1095 °C, respectively. The PFAS emission concentrations from the PCTFE tests reported here were 67,468 ng/m^3 and 51.2 ng/m^3 at 850 and 1150 °C, respectively. The larger emission concentrations in this work at 850 °C were due to the formation of TFA. Gehrmann et al. (2024) also measured for TFA in their pilot-scale study, but the results were not detected at both temperatures tested. The reported detection limits for TFA in the Gehrmann et al. (2024) tests were a factor of 5 to 50 times higher than this study (500 – 5000 ng/L), so these higher detection limits may partially explain the lower TFA emissions from the 860 °C tests conducted during their study. However, they did report well-mixed combustion conditions in the post combustion chamber for all tests. This may also be a factor that helps explain the lower PFAS emissions from the 860 °C tests, compared to the 850 °C tests reported here.

A post-combustion zone temperature of 850 °C is a minimum regulatory requirement in the EU for full-scale incinerators. However, except for sewage sludge incinerators, MWCs in the EU operate at post-combustion temperatures which exceed 1000 °C (Gehrmann et al., 2024; Aleksandrov et al., 2019). While TFA and PFPrA were emitted in significant concentrations in the 850 °C bench-scale tests reported here, it is highly unlikely that TFA or PFPrA would be emitted from a full-scale MWC operating with turbulent flow, strong waste-air mixing, and flame temperatures that exceed 1200 °C. These conditions currently represent the best-available technology. The bench-scale tests reported here attempt to mimic post-combustion oxidation in full scale systems. However, we fully expect that the bench-scale tests do not generate a flame and do not have turbulent conditions in the gas flow, as would be expected in a full scale facility. Furthermore, both TFA and PFPrA are highly acidic liquids at ambient conditions and can be safely quenched with an aqueous base, if needed.

3.6. Regulatory impact

US-EPA's recent interim guidance document (EPA, 2024) reports that incineration may be a viable PFAS destruction technology if done under certain conditions. Research on thermal treatment of PFAS fed as a liquid suggests that the minimum conditions for PFAS destruction include well mixed environments with temperatures greater than 1100 °C and optimized combustion stoichiometry (Shields et al., 2023). Recent full-scale tests on solid materials including AFFF, contaminated soils and spent activated carbon reported DREs of >99.99 % with the absence of PIDs (Labaye et al., 2025). These tests were performed with secondary combustion chambers temperatures above 1100 °C and PIDs were measured using EPA Method OTM-50. These full-scale tests provide further evidence that temperatures above 1100 °C may adequately destroy PFAS and minimize PIDs. Another recently reported full-scale test of AFFF and waste spiked with various PFAS as pure compounds also indicated that temperatures above 1100 °C may adequately destroy PFAS and minimize PIDs (Troxler et al., 2025). Neither of the two full-scale tests analyzed for TFA, due to a lack of a standardized analytical method. The potential emission of other semivolatile fluorinated compounds was also noted in these two tests.

The results of this study incinerating polymeric PCTFE demonstrated that temperatures of 1150 °C produced high PFAS DE (>99.9999%) and

the absence of PIDs. These results, and the recent tests of other solid PFAS contaminated materials at full-scale, support US-EPA's guidance that temperatures of 1100 °C or greater achieve complete mineralization of PFAS waste materials.

The European Chemical Agency (ECHA) is considering exemptions from PFAS regulations for manufacturing and certain materials including FPs (ECHA, 2024). In this analysis, ECHA is proposing PFAS emission factors for the incineration of FPs (ECHA, 2025). Emission factors (g PFAS/g FP fed) of 0.01 and 0.0001 are being considered for incineration temperatures of 850 °C and 1150 °C, respectively. Two recent studies, including this one, have generated much lower PFAS emission factors. The emission factors for this study (normalized to F content) are $2.2x10^{-4}$ and $3.1x10^{-7}$ for temperatures of 850 °C and 1150 °C, respectively. The recent study of Gehrmann et al. (2024) generated values of $1.8x10^{-8}$ and $2.0x10^{-9}$ for incineration tests at 860 °C and 1090 °C, respectively. This new data should be considered as ECHA finalizes their assessment of the impact of FP incineration on PFAS emissions, and the European Commission should take all information into account when drafting the final Annex XVII restriction.

3.7. Environmental implications

There are three environmental implications of this study: PFAS emissions, greenhouse gas emissions and PID emissions that impact stratospheric ozone. The high temperature tests, where full-scale combustors are expected to operate, yielded PFAS emission factors of 3.1 x 10^{-7} g PFAS/g PCTFE incinerated (average of three tests). Using the value of 6800 tonnes of PCTFE manufactured annually, this converts to a mass emission of 2.7 kg PFAS with the conservative assumption that all PCTFE generated annually is incinerated. This indicates that incineration of PCTFE is not a significant source of PFAS to the environment. The greenhouse gases $CClF_3$ and CHF_3 were observed from the low temperature tests but not from the high temperature tests. The global warming potential of $CClF_3$ and CHF_3 are 16,200 and 14,600, respectively (Masson-Delmotte et al., 2021). The mass ratio of $CClF_3$ to CO_2 in the low temperature (850 °C) tests was 3.4 x 10^{-6}. Similarly, the mass ratio of CHF_3 to CO_2 in the same tests was 1.6 x 10^{-7}. These very small mass ratios of greenhouse gas emissions for $CClF_3$ and CHF_3 multiplied by their GWPs yield GWP impacts of 0.2 % and 5.4 % relative to CO_2 for our experimental conditions.

A laboratory scale incineration study of pure PCTFE homopolymer was conducted to identify and quantify any potential PFAS species released when products containing PCTFE are incinerated at end-of-life under typical MWC conditions. Thermal gasification at 850 °C (low temperature) and 1150 °C (high temperature) was selected based on different technologies and guidance in the US and EU.

Ozone depletion potential (ODP) of these PIDs is also of environmental concern. The ODP for CHF_3 is near zero and the ODP for $CClF_3$ is ca. 1, similar to CFC-11 (trichlorofluoromethane), the baseline case (EPA, 2025b). When compared to $CClF_3$ global emissions from impurities, fugitive emissions, and aluminum smelting operations (Vollmer et al., 2018), incineration of materials containing PCTFE at 850 °C results in annual $CClF_3$ emissions that are a factor of 643,000 times lower (See Table S10), indicating minimal impact on stratospheric ozone.

4. Conclusions

A laboratory scale incineration study of pure PCTFE homopolymer was conducted to identify and quantify any potential PFAS species emitted to the environment when products containing PCTFE are incinerated at end-of-life under typical MWC conditions. Our study investigated byproduct emissions from PCTFE that were thermally gasified and incinerated at 1150 °C (high temperature) and 850 °C (low temperature).

For the high temperature condition, PCTFE was mineralized to HF and HCl, with a fluorine mass balance between 99 % and 101 %, except for one sample which showed a slightly lower recovery of 89 % and a chlorine mass balance between 83 % and 90 %, based on aqueous sample analyses. All PFAS analytes for the methods used were ND or below RL for all aqueous samples using 537 M as well as C_1 – C_3 PFAS analysis. Gas sample analysis using OTM-50 also showed that volatile, gas-phase fluorinated compounds were all ND. Therefore, it was concluded that no PFAS including any gas-phase fluorinated compounds were emitted for PCTFE incineration at temperatures of 1150 °C.

For the low temperature test, PCTFE generated COF_2 in addition to HF and HCl, as observed in FTIR gas monitoring. The aqueous sample fluorine mass balance was between 97 % and 101%, and the chlorine mass balance was between 82 % and 86 %. Aqueous sample analysis indicated that no PFAS, whose carbon number is above three, was emitted at 850 °C; however, it generated significant amount of TFA and small amount of PFPrA at 850 °C. The gas phase sample also showed that small amounts of CHF_3 and $CClF_3$ were emitted as PID. Therefore, it was concluded that PCTFE incineration at a temperature of 850 °C was not sufficient to fully mineralize the polymer.

These results should be used by regulators to understand the potential emission levels and species, along with the risk, associated with disposal of fluoropolymers in municipal waste incinerators.

CRediT authorship contribution statement

Takahiro Yamada: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Moshan Kahandawala:** Supervision, Project administration, Funding acquisition. **Yuk Yu Law:** Validation, Resources, Methodology, Investigation. **Thenappan Alagappan:** Validation, Methodology, Investigation. **Philip H. Taylor:** Validation, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2026.144908.

Data availability

Data will be made available on request.

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