# Treatment Technologies and Methods for Per- and Polyfluoroalkyl Substances (PFAS)

## 1 Introduction

This fact sheet summarizes treatment technologies and methods for PFAS in environmental media. Additional information is available in the Guidance Document. Treatment technologies for PFAS are the focus of intense research and development and are evolving. The treatment technologies described in this fact sheet are categorized by degree of development and implementation history, as well as current confidence in the technology based on peer-reviewed literature, externally validated non-peer reviewed literature, and the professional judgment of the authors.

The unique stability and surfactant nature of PFAS make many conventional treatment technologies ineffective, including those that rely on contaminant volatilization at ambient temperature (for example, air stripping, soil vapor extraction) or bioremediation (for example, biosparging, biostimulation, bioaugmentation). Even aggressive technologies such as thermal treatment and chemical oxidation require extreme conditions beyond typical practices (for example, elevated temperatures, high chemical doses, very high pH) to be effective or partially effective in volatilizing or destroying PFAS. Because many conventional treatment technologies (other than those identified within this document) have shown to be inadequate, new technologies or innovative combinations of existing technologies are often required to treat PFAS.

ITRC has developed a series of fact sheets that summarize recent science and emerging technologies regarding PFAS. The information in this and other PFAS fact sheets is more fully described in the ***ITRC PFAS Technical and Regulatory Guidance Document (Guidance Document)*** (*https://pfas-1.itrcweb.org/*).

The purpose of this fact sheet is to:

- provide an overview of treatment technologies and methods for treatment of solids (soil or sediment) and liquids (groundwater, leachate, or storm water)
- discuss factors affecting PFAS treatment technology selection
- describe processes and considerations for the treatment of PFAS that are in general use
- reference a summary of other limited application and developing treatment technologies

### PFAS Remediation Technologies Overview

This fact sheet summarizes “field-implemented technologies” that have been demonstrated in full-scale operation for different applications by multiple parties at multiple sites and are well-documented in practice or peer-reviewed literature. At this time, full-scale treatment of PFAS-impacted liquids or solids is primarily achieved through ex situ sequestration technologies that remove or bind PFAS but do not destroy them.

This fact sheet also introduces “limited application technologies,” which have been implemented in full- or pilot-scale applications on a limited number of sites by a limited number of practitioners and may not have been documented in practice or peer-reviewed literature. “Developing technologies,” which are those that are developing through laboratory or bench-scale research but are not yet field demonstrated, are also included. For more detail, please refer to Section 12, including Tables 12.1 and 12.2, of the Guidance Document (see the External Data Tables on(https://pfas-1.itrcweb.org/).

The most commonly field-implemented water treatment technologies for PFAS treatment include separation/removal using granular activated carbon, ion exchange resin, or reverse osmosis (RO). The resulting residuals (spent activated carbon, resins, and RO concentrate) must be managed through further treatment, destruction, or disposal.

Treatment of solids (for example, soils, sediments) currently relies on stabilization, incineration, or disposal in a landfill. Incineration has received recent attention due to possible incomplete combustion and byproduct generation. As of April 2022, the Department of Defense had placed a temporary ban on incineration of PFAS-containing materials while ongoing research is completed to better understand the fate of PFAS and optimal operating conditions for complete destruction of PFAS. Please refer to the Guidance Document for the most current information on this topic. Solid and hazardous waste disposal outlets that are permitted and willing to accept PFAS waste are also limited in number and may not be in close geographic proximity, leading to recent focus on the development of alternative onsite and in situ stabilization and destruction technologies.

Air treatment is not included in this fact sheet because the current research is generally limited to liquid and soil treatment technologies.

### Factors Affecting Technology Selection

Selection of a remedy depends on a number of key factors, including site characteristics, the availability of proven treatment technologies, and the regulatory framework to measure progress and compliance. A well-prepared conceptual site model is fundamental to understanding and presenting the rationale and justification for the selected technology. At some sites, it might be reasonable and necessary to implement interim remedial actions to mitigate completed exposure pathways with the intent of applying more robust and permanent solutions as they are developed.

Development of regulatory standards continues and includes the identification of specific PFAS to be treated. These values are summarized in PFAS Water and Soil Values Table (https://pfas-1.itrcweb.org/fact-sheets/).

A summary of key factors affecting PFAS remedy selection includes:

- **characteristics of PFAS**. The wide-ranging chemical and physical characteristics of PFAS, such as recalcitrance to common technologies due to the strength of the carbon-fluorine bond, ionic state, types of ionic groups (sulfonate or carboxylate), chain length, and total concentration, impact treatment effectiveness.
- **changes in PFAS properties**. Naturally occurring processes or past/current remedial actions for other (commingled) contaminants, such as chlorinated solvents and petroleum hydrocarbons, can affect PFAS distribution and mobility in groundwater (McGuire et al. 2014).
- **co-contaminants, organic matter, and geochemistry.** The presence of co-contaminants, total organic carbon, natural organic matter, minerals, cations, and anions can significantly affect treatment efficacy; pretreatment for these other constituents may be critical to efficiently and effectively remove PFAS.
- **community acceptance.** Stakeholders, including community members, are often faced with trade-offs in terms of cost, cleanup effort, and residual contamination as part of remediation efforts.

## 2 Field-Implemented Liquids Treatment Technologies

Liquid treatment technologies in this section may be applied to a variety of PFAS-impacted media, including drinking water, groundwater, surface water, wastewater, or landfill leachate. At this time, the “field-implemented” technologies are ex situ treatment systems, meaning PFAS-impacted liquids are extracted and treated. Although some technologies described here have been applied in situ, such applications are not considered field-implemented at this time.

### Sorption

Sorption on granular activated carbon and ion exchange media has been proven effective at full scale. A number of influent water parameters can impact the sorption effectiveness and efficiency for specific PFAS. These include pH, ionic strength, nature and concentrations of organic co-contaminants (including naturally occurring organic matter), competing inorganic ions (for example, sulfate, nitrate, bicarbonate, and chloride), and any suspended solids or potentially precipitating impurities (for example, iron, manganese, calcium) that can foul and degrade the performance of the media. Pretreatment steps, such as coagulation, precipitation, filtration, pH adjustment, or oxidant removal, may be necessary to remove interfering constituents to optimize the performance of sorbent media. Certain pretreatment steps may result in additional waste streams. In general, the process technology for removal of PFAS is placed at the end of the treatment train after co-contaminant removal for optimal efficiency. These treatment systems are typically configured with lead-lag vessels and redundant treatment trains to allow for continuous operation.

#### *Granulated Activated Carbon (GAC)*

GAC adsorption is an established water treatment technology proven to effectively remove long-chain PFAS. Individual PFAS have different GAC loading capacities and corresponding breakthrough times, which are typically defined as the number of bed volumes treated prior to detection in the effluent (Eschauzier et al. 2012). GAC removal capacity for PFOS is greater than PFOA, but both can be effectively removed (McCleaf et al. 2017). In general, shorter chain PFAS have lower GAC loading capacities and faster breakthrough times but could be effectively treated if changeout frequency is determined based on the breakthrough of these short-chain PFAS.

Temporary (mobile and skid-mounted) and permanent GAC systems can be rapidly deployed. Several different types of base materials for GAC are available, and data show that bituminous-based products are more effective for PFAS removal than other forms of GAC, such as coconut husk (McNamara et al. 2018; Westreich et al. 2018). Currently, spent GAC media can be disposed of by landfilling or incineration, or potentially reactivated for reuse, with each option potentially requring regulatory approval. For incineration and reactivation, additional studies are needed to investigate the fate of PFAS.

### *Ion Exchange (IX)*

IX resin options for removal of PFAS include single-use and regenerable resins. IX resins have been shown to have high capacity for many shorter chain PFAS (Woodard, Berry, and Newman 2017). Single-use resins are used until breakthrough occurs at a pre-established threshold and are then removed from the vessel and replaced with new media. Regenerable resins are used until breakthrough but are then regenerated on site using a regenerant solution to restore the resin's PFAS removal capacity. As of June 2022, spent IX media can be disposed of by landfilling or incineration, or regenerated for reuse, with each option potentially requring regulatory approval. The regeneration process generates a waste that must be managed. Temporary and permanent IX systems can be rapidly deployed.

### *Reverse Osmosis (RO)*

RO membranes have been shown to be highly effective in removing measurable PFAS (Appleman et al. 2014; Tang et al. 2006; Tang et al. 2007). In recent years, new polymer chemistry and manufacturing processes have improved efficiency, lowered operating pressures, and reduced costs associated with operating RO systems. As a result, RO membranes are increasingly used by industry to concentrate or remove chemicals. RO membranes are susceptible to fouling (loss of production capacity) because of accumulation of material on the membrane surface, so effective pretreatment to remove suspended solids is a necessity for any RO system. The reject stream will contain PFAS-enriched concentrate, which needs to be appropriately managed through treatment, permitted discharge, or disposal.

## 3 Field-Implemented Solids Treatment Technologies

The technologies in this section may be applied to a variety of PFAS-impacted media, including soil, sediments, sludge, or spent treatment media. There are currently two known field-implemented technologies for treating soil contaminated with PFAS: sorption/stabilization and excavation/disposal.

### Sorption and Stabilization

Sorption and stabilization may be selected based on a site-specific evaluation and provide a relatively quick and simple way to reduce ongoing PFAS contamination transport from source zones to waterways and groundwater. This approach does not remove the PFAS from the source area, but immobilizes it, thereby reducing the risk of further transport or migration. For some amendments, established test methods have projected/modeled long-term stability of immobilized PFAS in amended soils (Stewart and MacFarland 2017). Amendments that have been demonstrated in the field include activated carbon and composite materials such as a blend of aluminum hydroxide, kaolin, and carbon specifically designed to affix PFAS. Different delivery methods, such as injection or in situ mixing, may provide different results and may be applied depending on geology and treatment objectives.

**Soil Containment**

Containment is not listed as a specific technology but is commonly utilized for other contaminants and may be suitable for PFAS depending on site-specific conditions.

Containment could include capping to prevent infiltration or exposure, construction of a slurry wall (or similar isolation barrier), addition of sorptive media to prevent migration, or landfill disposal. Containment options will depend on site specific considerations, nature of PFAS materials, and local regulatory requirements.

### Excavation and Disposal

PFAS contaminated soils/solids may be excavated and disposed of in a permitted landfill. Treatment of excavated soils (for example, stabilization) can reduce PFAS leachability and could be considered prior to landfilling. Rapidly changing regulations regarding the hazardous classification for PFAS can complicate implementation of this option, and disposal costs will increase if PFAS-impacted media must be disposed of as hazardous/regulated waste. Case-by-case inquiries to regulators and landfill facility owners is likely the best course of action. Some landfills do not accept PFAS waste.

## 4 Incineration

Incineration is defined as destruction (mineralization) of chemicals using heat. Heat is applied directly to the PFAS-contaminated solids (soil/sediment/spent adsorbents/waste) or liquids (water/wastewater/leachate/chemicals). Vaporized combustion products can be further oxidized and/or captured (precipitation, wet scrubbing) and/or further oxidized at elevated temperature.

Incineration is one of only a few technologies that can potentially destroy PFAS. However, at the time of publication, this is an active area of research to evaluate effective destruction temperatures and operating parameters, the potential to generate products of incomplete combustion, stack gas analyses, deposition onto land, and other risk factors.

## 5 Limited and Developing Treatment Technologies

A review of limited application technologies and developing technologies can be found in the Guidance Document. The technologies discussed are listed in Table 1.

**Table 1. Limited and Developing Treatment Technologies**

| Limited Application | Developing |
|---|---|
| Colloidal Activated Carbon (in situ treatment) | Coated Sand |
| Precipitation/Flocculation/Coagulation | Zeolites/Clay Minerals (Natural or Surface-Modified) |
| Surface Activation Foam Fractionation | Biochar |
| Deep Well Injection | Nanofiltration |
| Sorption and Stabilization/Solidification (for solids) | Redox Manipulation (Transformation), including:<br>• Ozone-based Systems<br>• Catalyzed Hydrogen Peroxide (CHP)-based Systems<br>• Activated Persulfate<br>• Sonochemical Oxidation/Ultrasound<br>• Photoloysis/Photochemical Oxidation<br>• Electrochemical Treatment<br>• Solvated Electrons (Advanced Reduction Processes)<br>• Plasma Technology<br>• Zero-Valent Iron (ZVI)/Doped ZVI<br>• Alkaline Metal Reduction |
| | Biodegradation |
| | High-energy Electron Beam (eBeam) |
| | Thermal Desorption (Separation) |

## 6 References and Acronyms

The references cited in this fact sheet and further references can be found at https://pfas-1.itrcweb.org/references/. The acronyms used in this fact sheet and in the Guidance Document can be found at https://pfas-1.itrcweb.org/acronyms/.

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