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 rapidly 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 conventional treatment technologies other than those identified above have generally shown to be inadequate to treat PFAS, the unique chemical properties of PFAS often require new technologies or innovative combinations of existing technologies.

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. Full-scale (field-implemented) treatment of PFAS-impacted liquids or solids is currently limited to 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, as well as “developing technologies,” which are those that are developing through laboratory or bench scale research but are not yet field demonstrated. For more detail, please refer to Section 12, including Tables 12.1 and 12.2, of the Guidance Document.

At the time of publication, most treatment applications have focused on drinking water, and the most common water treatment technologies for PFAS treatment include separation/removal using granular activated carbon, ion exchange resin, or reverse osmosis. The resulting residue (spent activated carbon, resins, and concentrate) must be managed through further treatment and/or disposal. Treatment of solids (for example, soils, sediments) currently relies on stabilization, excavation and disposal, or incineration. Incineration has received recent attention due to possible incomplete combustion and by-product generation and is the topic of current study to better understand the fate of PFAS. Solid and hazardous waste disposal outlets are also limited, leading to recent focus on the development of alternative on-site and in-situ treatment and encapsulation alternatives. At some sites, it might be reasonable and necessary to implement interim remedial actions with the intent of applying more robust and permanent solutions as they are developed. 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, with confidence that treatment targets can be achieved, depends on a number of key factors, including site characteristics, the availability of proven remediation technologies, and the capacity and tools to measure progress and compliance with applicable regulatory criteria. A well-prepared Conceptual Site Model is fundamental to understanding and presenting the rationale and justification for the selected technology. Care in remedy selection is important because proven treatment technologies are limited. Site-specific evaluation is necessary to identify the best technology alternative for each application.

The regulatory standards for PFAS treatment continue to evolve, including which specific PFAS compounds are required to be treated. These values are summarized in tables of PFAS water values and PFAS soil values (https://pfas-1.itrcweb.org/fact-sheets/).

A summary of key factors affecting PFAS remedy selection include:

- **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.
- **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.

Factors specifically challenging for PFAS remediation include:

- Multiple ionic states
- Variable isomers
- Differing alkyl groups
- Past remediation effects
- Common co-contaminants
- Regulatory/stakeholder acceptance

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.

Key cost considerations for liquid treatment selection include:

- PFAS mix and competitive species
- pretreatment needs
- influent concentrations
- flow rate
- discharge criteria
- spent media disposal/regeneration
- treatment and disposal of RO concentrate

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 a specific PFAS compound. These include pH, ionic strength, nature and concentrations of organic co-contaminants (including naturally occurring organic matter), competing inorganic ions normally present (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. In general, the process technology that targeted to remove PFAS is placed at the end of the treatment train after co-contaminant removal for optimal efficiency.

Granulated Activated Carbon (GAC)

GAC adsorption is an established water treatment technology proven to effectively treat long-chain PFAS (such as PFOS, PFOA and PFNA). Individual PFAS have different GAC loading capacities and corresponding breakthrough times, which are typically defined as the number of bed volumes (the total volume of the treatment vessel that contains the treatment media) treated prior to detection in the effluent (Eschauzier et al. 2010). GAC removal capacity for PFOS is greater than PFOA, but both can be effectively removed (McLeaf 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 increased.

Temporary (mobile and skid-mounted) and permanent GAC systems can be rapidly deployed. Several different types of base materials for GAC are currently available and current data show that bituminous-based products are more effective for PFAS removal (McNamara et al. 2018; Westreich et al. 2018). Currently, spent GAC media can be disposed of by landfilling or incineration, or 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 resins are effective sorbents for a variety of contaminants and have historically been used for water treatment applications such as nitrate, perchlorate, and arsenic removal. 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 et. al. 2017). Single-use resins are used until breakthrough occurs at a pre-established threshold and are then removed from the vessel. Regenerable resins are used until breakthrough but are then regenerated on site using a regenerant solution to restore the resin's PFAS removal capacity. Currently, 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. Pretreatment may be necessary to preserve resin capacity for PFAS removal, particularly in the context of remediation where complex co-contaminant chemistry is expected.

Reverse Osmosis (RO)

RO membranes are effective in removing most organic and inorganic compounds from water solutions and 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, lowering operating pressures and reducing costs. 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 treatment media. Site-specific evaluation is always needed to identify the best technology for a given treatment scenario. There are currently two known field-implemented technologies for treating soil contaminated with PFAS: sorption and stabilization, and excavation and disposal.

Sorption and Stabilization

Sorption and stabilization, which are considered "immobilization" or "chemical fixation" technologies, may be selected based on a site-specific evaluation and provide a relatively quick, simple, and low-cost (relative to off-site disposal) 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 treat anionic, cationic, and zwitterionic long- and short-chain 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.

Excavation and Disposal

PFAS contaminated soils/solids may be excavated and disposed of in a landfill. Treatment with stabilizing agents can reduce PFAS leachability from excavated soils 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 nonhazardous waste landfills do not accept PFAS waste. Overall, issues related to disposal of PFAS in landfills are similar to issues commonly encountered with other contaminants.

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.

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 treatment time, the potential to generate products of incomplete combustion, stack gas analyses, deposition onto land, and other risk factors. When considering waste disposal options, transportation costs, energy costs, regulatory approvals, and final disposition of process waste residues should be evaluated, as these differ among incineration facilities.

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: • Ozone-based Systems • Catalyzed Hydrogen Peroxide (CHP)-based Systems • Activated Persulfate • Sonochemical Oxidation/Ultrasound • Photoloysis/Photochemical Oxidation • Electrochemical Treatment • Solvated Electrons (Advanced Reduction Processes) • Plasma Technology • Zero-Valent Iron (ZVI)/Doped ZVI • 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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