Treatment Technologies for Per- and Polyfluoroalkyl Substances (PFAS)

1 Introduction

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 for treatment of solids (soil or sediment) and liquids (groundwater, leachate, or storm water)
- discuss factors affecting PFAS treatment technology selection
- describe specific technical considerations for PFAS treatment

This fact sheet summarizes treatment technologies 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 U.S. Department of Defense Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) provide extensive funding for research of PFAS treatment technologies (https://www.serdp-estcp.org). Active or recent SERDP/ESTCP projects are listed in the Guidance Document. The treatment technologies described 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 ITRC 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 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. Most successful PFAS treatment applications will contain a concentration or separation step, followed by a disposal or destruction step in a treatment train approach.

PFAS Remediation Technologies Overview

This fact sheet summarizes "field-implemented technologies" that have been demonstrated in full-scale operation by multiple parties at multiple sites and are well-documented in practice or peer-reviewed literature.

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 Table 12-1 of the Guidance Document (see https://pfas-1.itrcweb.org/).

The most commonly field-implemented water treatment technologies include separation/removal using granular activated carbon, ion exchange resin, or high-pressure membranes (for example 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) includes stabilization, incineration, soil washing or disposal in a landfill. Incineration has received recent attention due to possible incomplete combustion and byproduct generation. In April 2022, the Department of Defense (DOD) placed a temporary moratorium on incineration of PFAS-containing materials. Subsequently, in July 2023, the temporary moratorium was lifted and incinceration of PFAS containing waste could be considered as a disposal alternative, pending additional planning and coordination (USDOD 2023, Ref# 2852, 2856). Please refer to the Guidance Document for the more information on this topic. Solid and hazardous waste disposal outlets that are permitted and willing to accept PFAS waste are 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.

PFAS in stack emissions may be reduced by conventional air pollution control or thermal treatment, though effectiveness is not well understood. Sampling stack emissions and performing adequate analysis is an active area of research and will need to be a part of assessing adequate treatment of any stack emissions thought to contain PFAS. Current treatment of PFAS in air emissions is discussed in the Guidance Document.

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 Regulatory and Guidance Values Table Excel file (https://pfas-1.itrcweb.org/#1_3).

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.

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, PFAS removal systems are 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).

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. The regeneration process generates a waste that must be managed. Temporary and permanent IX systems can be rapidly deployed.

High-Pressure Membranes

High-pressure membranes (nanofiltration [NF] and RO) 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 high-pressure membrane systems. As a result, high-pressure membranes are increasingly used by industry to concentrate or remove chemicals. High-pressure 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 high-pressure membrane system. The reject stream will contain PFAS-enriched concentrate, which needs to be appropriately managed through treatment, permitted discharge, or disposal.

Foam Fractionation

Foam fractionation is a physical separation process that traditionally uses air and turbulence to generate bubbles rising through a water column to strip amphiphilic substances, such as PFAS, from the bulk liquid (Lemlich & Lavi 1961; Lemlich 1962). PFAS preferentially adsorb to the surface of the bubbles as they rise upwards, accumulate at the top of the column as a concentrated foamate, and are then removed for further treatment or disposal. This process has been implemented at field-scale worldwide. Foam fractionation is effective at removing PFOS and PFOA and long chain PFAS (Burns et al. 2021; Newman 2022; Burns et al. 2022; Smith et al. 2022) to single digit parts per trillion levels, but its performance at removing PFAS with fewer than six perfluorinated carbons remains mixed.

Colloidal Activated Carbon (CAC)

Injecting CAC into an aquifer is intended to take dissolved contaminants migrating in groundwater out of solution, in addition to adsorbing contaminants back-diffusing from lower permeability zones, reducing plume migration. Performance is subject to geochemical variables such as dissolved organic carbon, presence of competing anions and cations, and concentrations of co-contaminants. CAC may be injected using direct push or vertical wells using a grid pattern in source zones to immobilize contaminants or in a transect perpendicular to the plume to mitigate contaminant flux. Injected CAC has been successfully used on project sites in North America, Europe, Middle East and Asia (for example, McGregor 2020; Carey et al. 2022). Carey et al. (2022) presented performance data on 16 field-scale CAC projects, in which PFAS at nine of the sites were reduced to concentrations at or below detection levels.

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.

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

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.

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.

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.

Soil Washing

Soil washing is an ex situ on- or off-site, above-grade treatment process that uses physical separation and chemical desorption/extraction to remove adsorbed PFAS mass from soil. Soil washing systems operate on the principle that most contaminants bind to the finer soil fraction, consisting of clays, silts, and fine organic matter, as opposed to the coarser sand and gravel fraction. Physical size separation techniques are used to separate the finer grained from the coarser grained soil particles, thereby concentrating and reducing the PFAS-impacted soil volume that must be further treated or disposed. Soil washing systems utilize a wash solution usually consisting of water, but surfactant and/or an extraction solvent can also be used to dissolve and concentrate PFAS. Soil washing has been used at field scale in Australia and Canada in ex situ treatment facilities. Results for PFAS treatment by soil washing demonstrated in the U.S. indicate variable performance (ESTCP 2022 Ref#2839; Becker 2022 Ref#2772).

4 Incineration

Incineration is the 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 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, including literature references and case studies, where available. These technologies may advance over time to become field-implemented technologies based on published literature and the degree of confidence in implementation.

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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