Life Cycle Stage 4: PFAS Remediation

Remediation PFAS Guidance

***Goal:* Address PFAS contamination source to mitigate the identified risk(s) to human health and the environment through remedial activities.** Remedial activities include but are not limited to the treatment, destruction, or removal of PFAS-impacted environmental media, and/or engineering or institutional controls. The remedy selection process is discussed in the *Draft Guidelines Remedy Selection* (MPCA, 1998) guidance document and can be used to address PFAS and other contamination.

The remediation life cycle stage focuses on selecting and implementing remedies at contaminated Superfund sites, cooperative responsible party sites, or brownfields sites. Remedy selection begins after a thorough site investigation and risk assessment have been completed, and it has been determined that an unacceptable risk exists at the site. Using the site investigation data, remedial alternatives are developed that protect public health and the environment and can reduce the identified risk to an acceptable level.

Actions:

4.1 Risk management

Risk management utilizes the information gained during risk assessments but is considered a separate process. Risk assessment establishes whether a risk is present and if possible, the range or magnitude of that risk while risk management uses the results of a risk assessment and integrates it with other lines of information such as economic, technology, legal and other factors to reach a decision regarding the best management strategy for a site and response to address the risk. Purely health based RBVs, for example, do not take into consideration information such as the cost or feasibility of treatment; therefore, they represent only one line of information/evidence to consider during site cleanups. Risk managers also use the information gained from a risk assessment to communicate risk to stakeholders and affected communities. Risk-based values (RBVs, discussed in detail in the Risk Assessment section), along with ambient levels, detection limits or analytical limitations, technology limitations (e.g., using values derived based on best available treatment technology), economic/cost considerations, and other factors should be considered when establishing remedial/cleanup goals. The other factors include the following:

- Current/future site usage
- Results of risk assessment
- Remediation options
- Other information/lines of evidence

4.2 Remedy selection

This section is not a comprehensive remedy selection guidance. The purpose of this section is to provide an overview of some unique factors to consider when evaluating and selecting remedies related to PFAS contaminant releases. Determining when an unacceptable risk is present and when response actions are needed related to PFAS are addressed in previous chapters of this document.

4.2.1 PFAS uncertainties and remedy considerations

Due to the complex nature of PFAS contaminants and because regulations and treatment technologies for PFAS in environmental media are still evolving, it is prudent to use caution in implementing long-term remedies (ITRC, 2022). For additional information, see the Uncertainty Analysis discussion in the Risk Assessment Life Cycle stage. Some of the characteristics of PFAS that warrant special consideration when evaluating and implementing remedies for these contaminants include:

- Very high degree of permanence and resistance to degradation in most settings.
- Strong tendency for cross-media contamination due to the recalcitrant, stable nature, and mobility of many PFAS including their ability to move between air, soil, groundwater, leachate, and surface water.
- Tendency for some PFAS to bioaccumulate in plants, animals, and human tissue.
- Rapidly developing knowledge regarding toxicity, and physical fate and transport properties.
- Uncertainty due to rapidly developing regulations and limited disposal options for contaminated media.
- Stable and surfactant nature of PFAS making many treatment technologies ineffective, including those that rely on contaminant volatilization or bioremediation (ITRC, 2022).

The complex chemistry of PFAS also makes understanding and effectively managing or remediating these contaminants challenging. There are numerous PFAS compounds including metabolites of originally released compounds and precursors to PFAS chemical detected in the environment. Information on physical and chemical properties and toxicity for many of these compounds is very limited.

Analytical methods are only available for a relatively small number of PFAS and may only be able to identify and quantify a portion of PFAS chemicals where releases may consist of a complex mixture of many compounds including precursors to shorter chain PFAS detected downstream. This can make characterizing source areas and meeting cleanup objectives difficult.

Due to these uncertainties and the ability of many PFAS contaminants to persist in the environment and to travel long distance in surface water and groundwater, protection of drinking water sources and human health should be prioritized as a primary response action objective when evaluating potential remedial alternatives. At some sites, it might be reasonable to take short-term site stabilization actions with the intent of applying more robust and cost-effective technologies as these are developed (ITRC, 2022). At the same time, remedies involving more complete cleanups, or providing permanent destruction might be greater preference in some situations given these factors.

4.2.2 MPCA Remediation Division general remedy selection policy

The primary missions of the MPCA Remediation Division programs are to protect human health, public welfare, and the environment by conducting or overseeing investigations and response actions related to releases of hazardous substances and pollutants to the environment in order to return land to economic or other beneficial use under the authority of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and the Minnesota Environmental Response and Liability Act (MERLA, including the Land Recycling Act). Responding to releases of PFAS contaminants into the environment falls under this authority.

In accordance with MERLA, remedy decisions also may incorporate concepts of cost-effectiveness, pollution prevention, and natural resources damages. The MPCA Remediation Division mission supports evaluation of potential remedies ranging from those that thoroughly destroy contaminants to those that include the use of engineering controls and institutional controls, depending upon site specific circumstances (MPCA, 1998).

4.2.3 MN remedy selection process

The remedy selection process follows site characterization and a risk assessment where it has been determined that an unacceptable risk exists at the site and response actions are needed. Information about the nature and extent of the releases along with site characterization data are used to construct a conceptual site model and to develop potential remedial alternatives designed to protect public health and welfare and the environment (MPCA, 1998).

The remedy selection process can vary depending on the size and complexity of the site (including the extent of contamination and impacted receptors), and if the cleanup work is being conducted and funded by a responsible or voluntary party. The remedy selection process for state remediation sites is described in the Draft Guidelines Remedy Selection, Minnesota Pollution Control Agency Site Remediation Section (MPCA, 1998). This guidance document includes a description of appropriate variations for streamlining or abbreviating the process based on the size and complexity of the project.

A Remedial Investigation/Feasibility Study (RI/FS) process is often used for remediation projects to investigate a release and to evaluate potential remedial actions. The RI/FS is used to develop a conceptual site model and response action objectives and to screen and evaluate potential remedial alternatives.

For PFAS sites, even for small sites being remediated by a responsible party (RP) or voluntary party (VP), special consideration must be given to the unique transport, storage, and potential transformation of PFAS, and the limited options for remediation and disposal. At some sites, it might be reasonable to take interim response actions (discussed later in this section) with the intent of applying more robust and cost-effective technologies as these are developed (ITRC, 2022) . For PFAS sites, a primary objective is to reduce or eliminate migration of contaminants into groundwater or surface water and protection of drinking water.

For remediation sites the following balancing criteria and other considerations must be evaluated when selecting a remedy. These are described in detail in the MPCA Remedy Selection Guidance Document (MPCA, 1998) and MPCA Generic RFRA (MPCA, 1998).

- Required balancing criteria:
  - Short Term Risk
  - Long-Term Effectiveness
  - Project Implementability
  - Cost Effectiveness
  - Community Participation
- Other required considerations
  - Compliance with Regulation
  - Planned Use of the Property
  - Institutional Controls

This same general framework must be used for state remediation sites with PFAS contamination. The unique characteristics of PFAS chemicals, such as their persistence in the environment, mobility in water, complex chemistry, and limited options for treatment and disposal should also be evaluated.

The remedy selection process for remediation sites with federal oversight and/or funding, such EPA led National Priorities List (NPL) superfund sites or Great Lakes National Program Office (GLNPO) led sediment remediation sites must be consistent with the remedy selection process as described in the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) and CERCLA. The 1990 NCP at 55 FR **8719-2.3** describes how the detailed analysis of alternatives is to be performed using these criteria. Chapter 7 of the "Interim Final Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA" (EPA, 1988) provides further detail on the process.

For remediation projects that are being led or funded by the federal government, the remedy selection process must be consistent with the detailed remedy selection approach described in the NCP and CERCLA. Some of the primary steps included in the federal superfund remedy selection process under CERCLA include:

- Remedial Investigation/Feasibility Study (RI/FS)
  - Remedial Investigation and Risk Assessments
  - Development of Response Action Objectives
  - RI/FS Detailed Analysis of Remedial Alternatives using comparative analysis of nine standard threshold and balancing criteria
  - Selection and Development of Proposed Plan

- Public Notice of Proposed Plan
- Evaluation and Implementation of Modifying Criteria
- Issuing Record of Decision and Public Notice

4.2.4 State of MN Streamlined Remedy Selection Options

The remedy selection process for state remediation sites is described in Draft Guidelines Remedy Selection, Minnesota Pollution Control Agency Site Remediation Section (MPCA, 1998). This guidance document includes a description of appropriate variations for streamlining or abbreviating the process based on the size and complexity of the project.

A streamlined selection approach is appropriate at smaller and less complex cleanup sites where:

- The volume of contaminated media is low
- A proven effective treatment is available
- The impacted area is small and confined to one or a small number of properties. Off-site migration is not occurring, and off-site receptors are not impacted
- The remedy is non-controversial and has little or no impact on the surrounding community
- The cleanup is being conducted and paid for by a responsible or voluntary party
- The remedy is acceptable to the RP/VP

For simple remedies such as this, only a brief Remedial Action Plan (RAP) may be needed to describe how the remedial action will be conducted for MPCA staff review and approval.

A more comprehensive remedy selection process that more closely follows all steps in the MPCA Remedy Selection Guidance Document (MPCA, 1998) should be used for non-federal sites with more significant volumes of contaminated material, more complex technical issues, and/or have land use or other community issues that must be addressed. Two or more remedial options are generally evaluated to assess the effectiveness and cost of the different strategies and to provide alternatives in addressing the broader issues posed by t these types of sites. When evaluation of more than one remedial alternative is performed, the MPCA recommends conducting a focused feasibility Study (FFS) following the MPCA Remedy Selection Guidance Document (MPCA, 1998) or the remedy selection process outlined in CERCLA (EPA, 1997) to compare remedies and to document the selection process.

The FFS describes the remedial alternatives, evaluates each alternative in relation to balancing criteria, and provides the rationale for selection of the proposed remedy. With the FFS, the remedial alternatives or combination of alternatives that meet the needs of the RP/VP, MPCA, and the community can be selected.

Complex and state fund-financed sites:

The most complicated state RP/VP and state fund-financed sites may require a higher level of evaluation and documentation and stakeholder and public participation in order to select a remedy. These sites may have numerous areas and/or types of contamination, off-site contaminant migration impacted receptors and greater community-related concerns.

A more comprehensive remedy selection using an RI/FS process consistent with EPA remedy selection guidance (EPA) is typically used at larger more complex sites, sites listed on the MN Permanent List of Priorities (PLP), sites NPL sites, or other sites under federal oversight by the EPA superfund program or Department of Defense (DoD). Examples of situations where a comprehensive remedy selection process generally adhering to the traditional Superfund remedy selection process as outlined in the NCP is required or is appropriate include:

- State-lead sites where the MPCA is conducting the site investigation and cleanup because there is no identified or viable RP to do so. In these cases, the MPCA generally adheres to the traditional Superfund remedy selection process as outlined in the NCP to maximize the opportunity for recovery of MPCA's costs from RPs at a future date under federal Superfund law (42 U.S.C. § 9607(4)(A)) The actions taken by the MPCA must be "not inconsistent" with the NCP.
- When an RP/VP wishes to ensure their ability to pursue a cost recovery action under federal Superfund law. For example, an RP/VP may choose to begin site investigation and cleanup even though there are

other persons that are legally responsible for participating in the costs of site investigation and/or cleanup but are unwilling to do so. In this case, in order to pursue a future cost recovery action under federal Superfund law (42 U.S.C. § 9607(4)(B)), the RP/VP should follow a RI/FS process that is "consistent with" the NCP.

- In cases where the MPCA uses its authority to issue a Request for Response Action (RFRA) to an RP, the MPCA may require the RP to follow the RI/FS remedy selection process. The MPCA must issue a RFRA and a Determination of Inadequate Response (DIR) if it intends to spend state Superfund money for site cleanup where the RPs are unwilling or unable to do so.

Detailed information about the traditional RI/FS remedy selection process can be found in Attachments A and B to the MPCA's Generic RFRA (MPCA, 1998).

4.3 Interim response actions

In some cases, interim response actions may be needed to mitigate unacceptable risk to human health in a timely manner. For example, interim response actions may be needed if unacceptable levels of PFAS are found in drinking water, or if a spill or direct release of PFAS occurs.

Should environmental conditions require mitigation to immediately reduce unacceptable risks to human health or the environment, the Agency may require an Interim Response Action (IRA) prior to or parallel with the RI/RA process. The purpose of an IRA is to provide an expedited response which will reduce or eliminate the identified unacceptable risk. While an IRA may take any number of forms, further discussion is warranted on two specific scenarios that are particularly relevant to PFAS.

First, IRAs may be required in case of a release or imminent release of PFAS or PFAS-containing substance. While IRAs of this nature are not unique to PFAS, note that an intentional release of PFAS-containing AFFF as a fire suppressant (i.e., consistent with the product's intended use) may also require an IRA similar in scope to a spill response. Within this context, an IRA may likely include soil excavation to reduce human risks via direct soil contact and/or to reduce total PFAS mass and mobility.

Second, given the mobility of PFAS in groundwater, IRAs may be required in case of current or imminent human health risks via drinking water wells. In the case of private drinking water wells, the presumptive IRA may include mitigation by providing alternative water sources or point of use/point of entry treatment (POUT/POET). Proposed POUT/POET systems for IRAs will be evaluated by the Agency for system effectiveness (i.e., ability to meet the relevant risk threshold), the technology maturity and feasibility, cost-effectiveness, and other criteria where appropriate. All POUT/POET systems require regular maintenance and the following POUT/POET options can be effective at removing PFAS from drinking water when properly installed and maintained:

- **Reverse osmosis** systems use energy to push water through a membrane that stops many contaminants while allowing water to pass. Reverse osmosis systems are more practical as a POUT system than a POET system.
- **Granular activated carbon filtration** systems pass water through a bed or cartridge of activated carbon, which is known to have a high adsorption affinity for many PFAS.
- **Ion exchange resins** for PFAS removal is a newer technology relative to reverse osmosis and activated carbon. However, it too has become well-established. Effective PFAS-selective resins are now commercially available.
- **Temporary drinking water supply (e.g., bottled water)** can be provided until a long-term solution is identified and implemented.

4.4 Documenting a cleanup decision

State listed Superfund sites, (i.e., sites on the permanent list of priorities (PLP), which includes both non-cooperative responsible parties and fund-financed sites) have a Minnesota Decision Document (MDD) per Minn. Stat. § 115B.17. This presents the selected cleanup action(s) and cleanup levels. Sites with a cooperative responsible party do not have an MDD. Instead, the cleanup decision is presented in a Remedial Action Plan and/or in a Response Action Plan (RAP) that is approved by MPCA staff.

MDDs and RAPs contain the following information:

- A statement of purpose
- A description of the problem, including site history, investigations conducted, and extent and magnitude of contamination
- A description of response actions already completed
- Documents that have been reviewed
- An Evaluation of Response action alternatives. This includes information found from the Focused Feasibility Study (FFS) or Conceptual Site Model (CSM).
- A description of the RAOs and what the cleanup levels are
- A description of the selected remedy
- SMART goals (ITRC 2011)

Remedies achieve the following three performance standards:

- Protect human health and the environment based on reasonably anticipated land use(s), both now in the future.
- Achieve media-specific cleanup objectives that address media cleanup levels (chemical concentrations), points of compliance (where cleanup levels should be achieved), and remediation time frames (time to implement the remedy and achieve cleanup levels at the point of compliance).
- Remediate the source(s) of releases to eliminate or reduce further releases to the environment.

MDDs also have an opportunity for public input prior to finalization; the document is typically available for a 30-day comment period. MPCA staff take received comments into consideration for deciding the final remedy.

For RCRA corrective action sites, a Cooperative Action Agreement (CAA) is similar to the RAP and MDD. However, it is not a required document. Instead, these sites follow MN 7045 which outlines hazardous waste management rules.

Sites on the national list of priorities (NPL) have a Record of Decision (ROD) but this document does not cover RODs. For more information, please visit EPA's website.

4.4.1 Milestone: Assess remedial technologies

Data on remedial approaches for PFAS are emerging and remain an area of continuous learning. As the fate and transport of PFAS are better understood and technologies are updated, the available options may increase. Due to the nature of PFAS contaminants being stable and surfactants, it has been documented that many existing treatment technologies (e.g., volatilization or bioremediation) are generally inadequate for effective PFAS treatment (ITRC, 2022). As a result, there has been focused attention from the environmental community to develop new technologies or innovative combinations of existing technologies for PFAS treatment. To date, approaches to PFAS treatment have included sequestration/separation technologies that remove or bind PFAS, as well as technologies that are focused on transformation and/or destruction of PFAS (ITRC, 2022). The types of technologies currently being evaluated as candidates for PFAS treatment include, but are not limited to, the following:

- Separation
  - Flocculation/Coagulation
  - Membrane Filtration

    - Sorption
    - Stabilization
    - Thermal Desorption
    - Foam Fractionation
- Transformation/Destruction
    - Biodegradation
    - Redox Manipulation
    - Thermal Destruction

Additional information regarding specific examples of remediation technologies within each of the above referenced technology types is included in the Table of Liquid Treatment Technologies and the Table of Solid Treatment Technologies. The tables do not present a complete list of all available technologies but are provided as examples of the types of technologies currently being evaluated for PFAS treatment.

Due to the heterogeneity of contaminated sites across Minnesota, combined with the constantly evolving body of scientific literature regarding PFAS treatment, specific treatment technologies are listed here to serve as information only. Any remediation decisions should be evaluated on a case-by-case basis using professional judgement and the most up-to-date information. The referenced tables are intended to provide an overview of PFAS treatment technologies including a brief description of the technology, the maturity of the technology and general advantages and disadvantages of each. The information presented is based solely on published literature and/or guidance as of the date of this published guidance. Considering that many non-measurable PFAS can be present and the probability of converting these non-measurable PFAS into measurable target PFAS is still largely unknown, this document provides screening-level technology selection guidance based on the current understanding of target PFAS treatment technologies, their applicability, published literature and/or guidance, maturity, and technical effectiveness for removal of PFAS in water/liquid and solids.

As PFAS treatment technologies are evolving rapidly, any evaluation of PFAS treatment technology should not be limited to a review of this guidance document and should include a review of other technical publications (i.e., ITRC Treatment Technologies [12 Treatment Technologies – PFAS — Per- and Polyfluoroalkyl Substances (itrcweb.org)]), guidance documents, state and federal regulations, and consultation with technology service providers, as applicable.

Remedy selection for sites impacted with PFAS in Minnesota will follow existing MPCA guidance that requires the evaluation of alternatives using the balancing criteria previously described. As with any contaminant, evaluation of PFAS treatment technologies should include consideration of defined remedial action objectives, a well understood conceptual site model (CSM), site-specific PFAS characteristics, occurrence of co-contaminants, geochemistry and other factors as detailed by the ITRC.

The appropriate method for addressing PFAS contamination at a given site will be evaluated through completion of the feasibility study. As noted, the maturity of treatment technologies varies and while some technologies have demonstrated effectiveness in field demonstrations, the MPCA will likely require additional testing and documentation through completion of subsequent focused feasibility studies, treatability studies, pilot studies and/or bench tests prior to approval of emerging treatment technologies. Public acceptance of any selected approach will be determined during the public comment period of the decision document.

Table 4-1: Treatment technologies for PFAS impacted aqueous media

Type		Technology Description	Technology Examples[1]	Advantages	Disadvantages	Waste Consideration	Technology Maturity
SEPARATION TECHNOLOGIES	Coagulation/ Flocculation	Approach utilizes coagulation and flocculation methods in succession to remove suspended solids from liquid. The first step 'coagulation' involves addition of a coagulent (chemical or electrical) to the water that serves to destabilize the colloids (small particles) that are in suspension allowing them to group together. Flocculation is the process in which a polymeric substance is added to the water as it is slowly mixed to facilitate 'clumping' of smaller/fine particles into larger "floc" that can subsequently be separated from the water. The flocs are typically removed from water via filtration or sedimentation. Coagulation and flocculation is intended to reduce PFAS concentrations through removal of solids from suspension under the assumption that the suspended solids contain or have PFAS sorbed to their surfaces.	Chemical Coagulation (alum, ferric salts, polyaluminum chlorides, polymeric coagulents)	- Conventional technology. - Widespread use in traditional water/wastewater treatment. - Ease of scalability. - Potential for use in pre-treatment.	- Potentially ineffective for low level contamination - Potential limitation as initial or pre-treatment technology. - Will likely require polishing.	Solids dewatering and disposal	**Developing**
			Electrocoagulation	- Documented use in water/wastewater treatment. - Potential for use in pre-treatment.	- Potentially ineffective for low level contamination - Potential limitation as initial or pre-treatment technology. - Will likely require polishing. - Higher energy consumption.	Solids dewatering and disposal	**Developing**
	Foam Fractionation	Foam fractionation is the process by which PFAS are adsorbed onto the surface of bubbles rising through water. When exposed to the air-water interface, the bubbles form foam containing PFAS that can subsequently be separated. The separated foam can then be "collapsed" or concentrated for additional treatment.	Foam Fractionation	- Coupling separation with destructive approaches (e.g., ozofractionation) can enhance treatment. - Removal of long-chain PFAS	- Needs testing at various sites; - Removal efficiency depends on foam depth, ionic strength of solution, and aeration rates. - Low removal efficiency of short-chain PFAS.	Generates PFAS concentrated wastewater that requires additional treatment/disposal	**Developing**
	Sorption	Sorption technologies utilize two mechanisms (adsorption or ion exchange) to remove PFAS from water. Adsorption is a physical mass transfer process that use forces to bind PFAS to adsorptive media such as granular activated carbon. Ion exchange works for PFAS treatment through exchanging ions of the same charge. Ion exchange targets the functional end of the PFAS molecule and in exchange releases a benign ion (such as chloride) into the water in its place. Sorption technologies have been used for both in situ and ex situ water treatment applications; however, most in situ applications are still considered developing technologies.	Granular activated carbon (GAC)	- Conventional technology with regulatory acceptance. - Demonstrated effectiveness for both short- and long-chain PFAS. - Design flexibility to increase removal. - Simple operation. - Multiple vendors. - Off-site reactivation/regeneration available for PFAS.	- Need to evaluate breakthrough of different PFAS; faster breakthrough times for shorter chain versus longer chain PFAS under certain influent and other conditions. - Cost increases relative to influent concentrtions. - Challenges of co-contamination/competitive adsorption. - Presence of precursors and other PFAS not analyzed for may increase GAC loading and accelerate changeout frequencies and associated cost. - No destruction of PFAS, unless the GAC is reactivated. - Pretreatment may be required.	Spent activated carbon must be removed for offsite disposal, or reactivation / regeneration.	**Mature**
			Colloidal activated carbon (In Situ)	- Applied to eliminate migration and potential exposure to PFAS. - No operation and maintenance. - No waste generated. - Longevity projected to be Multiple decades with single injection. - Can be reapplied. - Highly sustainable with very low carbon footprint.	- PFAS contaminants are immobilized, not destroyed. - Presence of co-contamination may reduce efficacy of media.	None	**Developing**
			Anionic exchange resins (AEX or IX)	-Higher demonstrated loading capacity for PFAS versus activated carbon. - Design flexibility to increase removal. - Simple to operate without regeneration. - On-site solvent-brine regeneration is commercially available.	- Possible faster breakthrough times for shorter chain versus longer chain PFAS under certain influent and other conditions. - Virgin media costs twice as much as activated carbon, but less media replacement is needed. - Removal efficiencies are compound specific. - Payback for on-site regeneration may be long, but requires cost-benefit compared to GAC dur to higher loading capacities. - PFAS not destroyed unless resins are incinerated.	Spent resin must be removed for off-site disposal or on-site regeneration. Solvent-brine, which is flammable, is only demonstrated solution for on-site regeneration. On-site destruction technologies for concentrated regeneration brine are currently under development.	**Mature**
			Biochar	- Possible alternative to GAC. - effectiveness increases with surface area.	- Only proven effective on ultrapure water. - Natural organic matter reduces effectiveness. - Slow reaction kinetics.	Off-site disposal required for spent biochar.	**Developing**

Type		Technology Description	Technology Examples[1]	Advantages	Disadvantages	Waste Consideration	Technology Maturity
SEPARATION TECHNOLOGIES	**Membrane Filtration (Separation)**	Pressure-driven technologies that utilize semipermeable membrane filters or membrane filters with nanosized pores to physically filter out PFAS molecules from water.	Reverse osmosis	- Established technology.	- Demonstrated for drinking water applications only	Generates a high volume (~10% of flow) of concentrate (reject water) that must be managed.	**Mature**
			Nanofiltration	- Established technology.		Generates a concentrate that must be managed.	**Developing**
			Ultrafiltration	- Low pressure filtration process - Applicable under wide range of pH (2 to 13 SU)	- May require pretreatment. - Temperature affects water density and viscosity, which directly corresponds to flow rate across filter membranes. - Insufficient data to demonstrate efficacy		**Developing**
TRANSFORMATION TECHNOLOGIES	**Redox Manipulation**	Redox manipulation includes multiple subcategories including chemical oxidation and reduction technologies. Chemical oxidation includes the delivery of liquid, slurry or gaseous oxidants from a reactive oxidant to the target PFAS. This technology essentially decomposes PFAS through introduction of additives, light, sound, or electricity to highly reactive, oxidative, or reductive species.	Light (UV/solvated electrons, Photolysis/photochemical oxidation, Photocatalytic treatment with BOHP/BiPO4, UV irradiation (hydrated electron) with electrochemical reduction)	PFAS Compounds almost completely destroyed under specific conditions. Photocatalytic treatment with BOHP/BiPO4, UV irradiation (hydrated electron) with electrochemical reduction are Energy-efficient compared to other UV only treatment systems.	- Certain methods do not work well under various conditions (acidic, high temperature, high reductant dosage, and high solution pH). - Energy intensive.	No waste generated, but incomplete reactions may produce PFAAs.	**Developing**
			Redox additives (Catalyzed hydrogen peroxide based systems, activated persulfate, ozone based, zero valent iron)	- Scalable - Energy efficient - Potential to combine with other technologies	- May result in production of less reactive PFAS species. - Does not treat all PFAS. - pH and temprature dependent	No waste generated, but incomplete reactions may produce PFAAs.	**Developing**
			Electrochemical	- Degradation is not affected by dissolved organic carbon. - Can be combined with other treatment technologies. - Demonstrated to be effective for treatment of short chain, long-chain PFAAs as well as PFAA precursors in remediation-derived waste streams	- May consume high energy - High cost of electrodes, limited scalability. - Limited full-scale applications for any contaminant types.	No waste generated, but incomplete reactions may produce PFAAs.	**Developing**
			Plasma	- Effectively degrades PFAS ina short time period. - Environmentally friendly - no demand on pressure or temperature and does not require significant input of chemicals. - Degradation rate not affected by co-contaminants.	- Higher cost - Some conversion of longer chain to shorter chain PFAS	No waste generated, but incomplete reactions may produce PFAAs.	**Developing**
			Sonochemical Oxidation/Ultrasound	- PFAS are thermally destroyed and hydroxyl radicals are generated for destruction of cocontaminants. - Demonstrated in bench studies.	- Rate of reaction decreases above certain power level. - Inorganics such as bicarbonate decrease reaction rate. - High energy requirement.	No waste generated, but incomplete reactions may produce PFAAs.	**Developing**
	Biodegradation	Degradation and transformation of PFAS through biochemical processes through the introduction of certain strains of bacteria, fungi, or species of flora to the contaminated water.	Fungal/Bacterial Enzymes	- Green solution if proven effective - Process would likely be effective on organic cocontaminants. - Variety of carbon sources could be biostimulants for co-metabolism	- Limited evidence of effectiveness. - May be sensitive to environmental changes (e.g., temperature, pH).	None	**Developing**
			Phytoremediation	- Green solution if demonstrated effective.	- Limited evidence of effectiveness.	None	**Developing**

Notes:
1 - Technology examples presented do not represent all technologies currently in development. Refer to ITRC for additional technologies and the recent information.

Table 4-2:Treatment technologies for PFAS impacted solid media

Type		Technology Description	Example Technology	Advantages	Disadvantages	Waste Consideration	Technology Maturity
SEPARATION TECHNOLOGIES	Sorption and Stabilization	Sorption and stabilization are intended to reduce the potential for PFAS to leach or migrate from the surface of the impacted soil into groundwater. A variety of materials have been used to bind PFAS compounds including Portland cement, activated carbon, kaolinite clay and others. The materials are used to cement the subsurface materials and solidify/stabilize the PFAS and render it immobile. Technology is highly dependent on site-specific considerations such as PFAS concentrations, soil type, moisture content, treatment objectives, etc. Changing conditions following stabilization may also result in additional leaching from immobilized media. Long term monitoring plans are highly recommended to evaluate effectiveness of stabilization technologies.	Stabilization (Soil Mixing)	- Basic implementation technology (soil mixing etc.) with proven results for other contaminants of concern. - Mature technology with use at full-scale	- PFAS contamination not treated or destroyed - Effectiveness will vary depending on soil type and chemistry. - Changes in site conditions (ph, ionic strength etc.) may result in leaching from immobilized media. - Effectiveness evaluated through long-term monitoring programs	None	**Mature**
			Natural minerals (iron oxide, high iron sand, clay)	- Enhance sorption by modifying surface. - Adsorption isotherms vary for various minerals.	- PFAS contamination not treated or destroyed - Effectiveness will vary depending on soil type and chemistry. - Changes in site conditions (ph, ionic strength etc.) may result in leaching from immobilized media. - Effectiveness evaluated through long-term monitoring programs	Sorbed media	**Developing**
			Surface-modified clay	- High affinity for a variety of PFAS - Commercially available media.	- PFAS contamination not treated or destroyed - Effectiveness will vary depending on soil type and chemistry. - Changes in site conditions (ph, ionic strength etc.) may result in leaching from immobilized media. - Effectiveness evaluated through long-term monitoring programs	Ex situ stabilized soil	**Developing**
	Thermal Desorption	Utilizes high temperatures to remove PFAS from soil surface through the process of desorption and separates the PFAS into a vapor phase that can then be captured.	Thermal desorption, in situ and ex situ capture	Can remove other volatile co-contaminants	Due to high heat demand, in situ treatment may not be cost-effective. May have potential to be applied as an in-situ technology.	Air emissions	**Developing**
	Soil Sieving/ Washing	Physically removes PFAS from the surface of soil after its been fractionated by grain size.	Separates soil by size fractionation and then removes PFAS from contaminated fraction by washing.	- Accepted remedial technology for a wide range of contaminants.	- Relatively high cost and energy intensive. -Requires use of washing solvents that require treatment/disposal. -Efficacy of washing solvents needs further evaluation/site-specific testing.	Wastewater	**Mature**
DESTRUCTION TECHNOLOGIES	Soil Sieving/Washing with Advanced Oxidative Process (AOP)	A multi-step treatment approach using a combination of soil washing, foam fractionation and AOP to treat the resultant wastewater. PFAS from the surface of fractionated soil is removed through washing. The soil wash rinsate water is then subject to foam fractionation to concentrate the PFAS. The concentrate generated by foam fractionation is then treated using highly oxidative species through the incorporation of various additives (dissolved ozone, sodium persulfate, food-grade phosphatebased buffers, and dilute hydrogen peroxide).	Soil Washing/Treatment using innovative approaches of combining technologies to separate and then treat/destroy PFAS.	- Effective for PFAS and co-contaminants. - Treatment of waste intended to result in complete destruction of all waste streams.	- Complex treatment process with multiple steps. - High cost and energy intensive	None	**Developing**
	Thermal Destruction	Utilizes high temperatures to degrade PFAS compounds sorbed to the surface of soil.	Off-site incineration	- Proven technology. - Applicable to all PFAS	- High energy consumption and associated cost. - Uncertainty in complete destruction due to potential for air emissions.	Air emissions	**Mature**
	Excavation and Disposal	Remove PFAS from locations where it poses a threat to human health or the environment and relocate it to a qualified landfill.	Excavation and Disposal	- Proven technology. - Applicable to all PFAS	- Possible contribution to PFAS in landfill leachate. - Regulatory acceptance may be subject to change. - Landfills may be changing acceptance rules for PFAS impacted waste.	Excavated material needs offsite disposal	**Mature**

Notes: Technology examples presented do not represent all technologies currently in development, and there may be other advantages or disadvantages for the technologies listed. Refer to ITRC for additional technologies and the recent information.

References and Resources

ITRC. 2018. *LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies*. LNAPL-3. Washington, D.C.: Interstate Technology & Regulatory Council. LNAPL Update Team. https://lnapl-3.itrcweb.org.

ITRC. 2022. Treatment Technologies and Methods for Per- and Polyfluoroalkyl Substances (PFAS). Interstate Technology and Regulatory Council. https://pfas-1.itrcweb.org/wp-content/uploads/2022/09/TreatmentTech_PFAS__FactSheet_082522_508.pdf

ITRC. 2023. Treatment Technologies. Interstate Technology and Regulatory Council. https://pfas-1.itrcweb.org/12-treatment-technologies/#:~:text=Full-scale%20treatment%20of%20PFAS-impacted%20liquids%20or%20solids%20is,Table%2012-1%2C%20provided%20as%20separate%20PDF%2C%20for%20references%29

MPCA. 1998. Draft Guidelines Risk Based Site Characterization and Sampling Guidance. Minnesota Pollution Control Agency. https://www.pca.state.mn.us/sites/default/files/sitechar.pdf

Minnesota Legislature. 1983. Chapter 115B, Environmental Response and Liability Act. 1983. Office of the Revisor of Statutes. https://www.revisor.mn.gov/statutes/cite/115B.01

USEPA. 1997.Rules of Thumb for Superfund Remedy Selection, United States Environmental Protection Agency, (EPA 540-R-97-013 OSWER 93655.0-69 PB97-963301 (August, 1997): https://www.epa.gov/superfund/Key Principles of Superfund-Remedy-Selection

USEPA. 1990. Quick Reference Fact Sheet: A Guide to Selecting Superfund Remedial Actions. United States Environmental Protection Agency, Office of Solid Waste and Emergency Response (Directive: 9355.0-27FS (April, 1990): https://semspub.epa.gov/work/HQ/174406.pdf