Tool 4.1: Considerations for Selecting a Method of Ex Situ Water Treatment

LIMITATION: The following table represents the state of technologies as of January 2022. EPA, DoD, and other agencies are leading ongoing research and technology evaluation, and users of this guidebook should refer to those agencies for the most up-to-date information on technologies and their applicability to the remediation project in question.

Absorption / Adsorption Technologies

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)
Granular Activated Carbon (GAC) adsorption and disposal *Cost: Medium to High; Screening Status: Retain*
Description: ✓ Physical mass transfer from the aqueous phase onto solid phase carbon. Removal rates are governed by GAC properties (surface area, pore size, surface chemistry) and influent characteristics (flow rate, geochemistry, and other co-contaminants which may consume GAC adsorption sites). ✓ Commonly combined with different types of removal technologies (e.g. IX) in series to optimize removal rates and minimize treatment residuals. ✓ GAC removal does not involve chemical degradation or destruction. **Implementability:** ✓ Requires centralized treatment system, with access for large-scale GAC changeouts. Additional pre- and post-treatment (filtration, post-GAC polishing) could be required depending on contaminant and water quality parameters. ✓ The quantity of GAC required for PFAS can be significantly impacted by co-contaminants (e.g., volatile organic compounds [VOCs]). Analytical data required to select optimal GAC. ✓ GAC disposal or regeneration off-site required. Disposal costs increase significantly if GAC is classified as hazardous waste, rather than regenerated. However, some regulatory agencies may not approve use of regenerated carbon for potable systems; NSF/ANSI standards also include recommendations limiting regenerated carbon reuse (ITRC, 2021).

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)

Effectiveness:

✓ Effective at long-chain PFAS removal; inefficient (i.e., shorter breakthrough times) for removing shorter-chain PFAS compounds. Sulfonate and sulfonamide groups are more readily adsorbed than carboxylates (ITRC, 2021). Removal rates are particularly low (70-90%) for 6:2 FTS and 8:2 FTS (Tow et. al., 2021).

✓ The effectiveness of regeneration facilities (and incineration facilities) in removing PFAS from GAC and treating PFAS in the vapor stream is currently being assessed by EPA (Tow et. al., 2021).

Availability / Maturity:

✓ Commercially available, multiple vendors.

✓ Used for residential point-of-use systems.

✓ Becomes less economical at higher influent concentrations (>10-100 μg/L) (ITRC, 2021) and when short chain PFAS dominate.

Ion Exchange (IX)

Cost: Medium to High; Screening Status: Retain

Description:

✓ Physical mass transfer process from the aqueous phase onto a charged synthetic polymer or a specific resin designed to bind via hydrophobic and van der Waals interactions (Ross et al., 2018). IX can be single use (high or low concentration influent) or can be designed for multiple treatment cycles (i.e., regeneration system, high concentration influent) (ITRC, 2021).

✓ If a regeneration system is installed on-site, the process would generate a brine backwash with highly concentrated PFAS, requiring off-site disposal. Residence times are typically less than GAC. Co-contaminants and site geochemistry can compromise IX effectiveness.

✓ IX does not involve chemical degradation or transformation. There is ongoing research to develop treatment techniques for destruction of IX brines on-site.

Implementability:

✓ Would require centralized treatment system, with access for large-scale resin changeouts or management of regeneration brines. Additional pre- and post-treatment will likely be required.

✓ The type and quantity of resin required can be strongly impacted by the presence of organic and inorganic co-contaminants (e.g., VOCs, sulfates). Analytical data required to select optimal resins. If single-use resin is used, disposal is required off-site.

✓ If regeneration is performed on-site, additional processing and handling of brine is required on-site; solvent brine is flammable and only available from one vendor at this time (ITRC, 2021). Off-site disposal or destruction of brine would be required.

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)

Effectiveness:

✓ Effective at PFAS removal; depending on specific species present, a mixture of IX resins and/or IX and GAC may be required to optimize removal effectiveness.

Availability / Maturity:

✓ Commercially available, multiple vendors.

✓ Used for residential point-of-use systems.

✓ More expensive than GAC, more economical for higher influent concentrations (>10-100 µg/L) (ITRC, 2021).

Modified Zeolites
Cost: Medium to High; Screening Status: Retain

Description:

✓ Modified zeolites are minerals (clays, ash) which have been chemically enhanced to improve adsorption properties. Treatment effectiveness, like GAC and IX, varies with the composition of and performance specifications of the modified zeolite, system operating parameters, and influent water characteristics.

✓ Treatment does not involve chemical degradation or destruction.

✓ Use in combination with GAC may improve removal rates for shorter chain compounds (ITRC, 2021).

Implementability:

✓ Would require centralized treatment system, with access for large-scale zeolite changeouts. Additional pre- and post-treatment will likely be required.

✓ Zeolite disposal off-site required.

✓ Other limitations assumed to be like GAC. Testing required to select optimal zeolites.

Effectiveness:

✓ Effective PFAS removal; surface area is usually less than GAC, would have less capacity per pound of media (ITRC, 2021). Assessment on a broader suite of PFAS compounds required; only tested on sulfonates at this time (ITRC, 2021).

Availability / Maturity:

✓ Variable; modified zeolites in various stages of development.

✓ One marketed modified zeolite is currently available.

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)

Cyclodextrins

Cost: TBD, Screening Status: Do not Retain

Description:

✓ Made from cornstarch, this engineered adsorbent targets PFAS with selectivity based on polymer structure. Manufacturers are currently pilot testing media for municipal water treatment (Dichtel, 2020).

✓ Treatment does not involve chemical degradation or destruction. However, cyclodextrin is regenerable (ITRC, 2021).

Implementability:

✓ Would require centralized treatment system, with access for large-scale media changeouts. Additional pre- and post-treatment will likely be required.

✓ Cyclodextrin disposal off-site required.

Effectiveness:

✓ Effectiveness for PFAS removal appears promising in bench and pilot scale studies.

Availability / Maturity:

✓ At pilot scale; scale up underway.

✓ Limitations/ interferences TBD.

Metal Organic Frameworks (MOF)

Cost: TBD; Screening Status: Do not Retain

Description:

✓ MOFs are crystalline 3D structures with a high internal surface area. The structures can be designed for selective adsorption of PFAS. Currently research-scale for UiO-66 and two analogs of MIL-101.

✓ Treatment does not involve chemical degradation or destruction.

Implementability:

✓ Would require centralized treatment system, with access for large-scale media changeouts. Additional pre- and post-treatment will likely be required.

✓ MOF disposal off-site required.

Effectiveness:

✓ Effectiveness for PFAS removal appears promising in bench and pilot scale studies.

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)
Availability / Maturity: ✓ Research / pilot scale ✓ Limitations/ interferences TBD.
Biochar *Cost: TBD; Screening Status: TBD*
Description: ✓ A charcoal-like material made from agricultural or forestry wastes, adsorbs contaminants like GAC. However, biochar is not widely available, and therefore biochar properties are highly variable (Xiao, 2017). ✓ Treatment does not involve chemical degradation or destruction. **Implementability:** ✓ Would require centralized treatment system, with access for large-scale media changeouts. Additional pre- and post-treatment will likely be required. ✓ Biochar disposal or regeneration off-site required. ✓ Other limitations assumed to be like GAC. **Effectiveness:** ✓ Biochar appears to be effective at PFAS removal in pilot scale studies due to high surface area; overall effectiveness is affected by variations in biochar production. **Availability / Maturity:** ✓ Not commercially available, pilot studies only. ✓ Limitations/ interferences TBD.

Filtration / Precipitation Techniques

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)
Reverse Osmosis (RO) and Nanofiltration (NF) *Cost: Medium to High; Screening Status: Retain*
Description: ✓ RO/NF techniques remove compounds from water solutions by passing pressurized water across a semipermeable membrane. Treated water (permeate) passes through the membrane and rejected water (concentrate) is collected for disposal or discharge, depending on the compounds present. Rejected flow may be up to 10% of initial flow rate (ITRC, 2021). ✓ RO/NF membranes are susceptible to fouling. Concentrations and flow rates determine RO/NF configuration/design. ✓ Treatment does not involve chemical degradation or destruction. **Implementability:** ✓ Would require centralized treatment system, with access for membrane maintenance and concentrate management. Additional pre- and post-treatment will likely be required. ✓ Design and operation requirements are significantly impacted by source water quality (TSS, salts, temperature fluctuations) (ITRC, 2021). ✓ RO/NF systems have higher energy requirements than adsorption-type remediation systems (CRCCARE, 2018). Concentrate disposal off-site required. **Effectiveness:** ✓ Effective PFAS removal. High flux membranes would provide 99% rejection efficiency at low-strength PFOS solutions; however, high concentration solutions would not be sustainable. Multi-stage membrane arrays can be used to improve removal efficiencies (ITRC, 2021).
✓ Commercially available ✓ Used for residential point-of-use systems.

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)

Precipitation / Flocculation / Coagulation

Cost: TBD; Screening Status; Do not Retain

Description:

✓ Common pretreatment approach in wastewater treatment plants to remove particles and dissolved constituents. Upon solid formation, constituents such as PFAS can be physically incorporated into, or sorbed onto, the flocculated particulate (known as co-precipitation). The precipitated solids are then separated from the water by sedimentation or filtration processes. Sediment and residual solids require subsequent management/disposal.

✓ Chemical additives may precipitate PFAS and include powdered activated carbon. Sedimentation and filtration processes can then be used to separate and concentrate PFAS-impacted sediments.

Implementability:

✓ Would require centralized treatment system, with access for tank maintenance and management and solids management. Additional pre- and post-treatment will likely be required.

✓ Solids disposal off-site required.

Effectiveness:

✓ Developing technology; currently being reviewed for effectiveness.

Availability / Maturity:

✓ Limitations/ interferences TBD.

Electrochemical Techniques

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)
Electrochemical Oxidation *Cost: TBD; Screening Status: Do not Retain*
Description: ✓ Electrochemical oxidation uses electrodes to complete mineralization of PFAS. PFAS are destroyed via direct electron transfer on "non- active" anodes under room temperature and atmospheric pressure. ✓ Commercial versions of this approach are being developed, with a focus on groundwater, wastewater, and IX brines. ✓ PFOS and PFOA mineralization has been reported; transformation pathways proposed or documented (ITRC, 2021). Initial results from early studies of this technology indicate high degradation rates of multiple PFAS. **Implementability:** ✓ Theoretically implementable. Would require centralized treatment system. Additional pre- and post-treatment will likely be required. **Effectiveness:** ✓ The technology is innovative, and effectiveness has not been demonstrated for a wide range of PFAS. Perchlorate or bromate may be formed as byproducts depending on electrolyte solution used. **Availability / Maturity:** ✓ At pilot scale; scale up underway. ✓ Electrode costs may be high and not scalable (ITRC, 2021). ✓ Limitations/ interferences TBD.

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)

Ozofractionation

Cost: High; Screening Status: Do not Retain

Description:

✓ Use of multi-stage ozonation columns to generate high-surface area ozone bubbles. PFAS collects on the ozone bubbles, which are then collected as concentrated foam fractionates, which can be separated from the treated water.

✓ Concentrations in the treated water are significantly lower concentrations (Tow et. al., 2021). While no spent media are generated, concentrate will require subsequent treatment.

✓ Multiple manufacturers have commercial systems which can be implemented for PFAS treatment.

Implementability:

✓ Ozofractionation has been adapted from other water treatment processes. Would require centralized treatment system. Additional pre- and post-treatment (e.g., nanofiltration) will likely be required (McDonough, 2019).

✓ High energy requirements.

Effectiveness:

✓ Effective at PFAS removal. Other gases are being evaluated for effectiveness (McDonough, 2019).

Availability / Maturity:

✓ At pilot scale; scale up underway.

✓ Limitations/ interferences TBD.

Plasma Destruction

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)
Sonochemical Oxidation / Sonolysis / Ultrasound *Cost: TBD; Screening Status: Do not Retain*
Description:
✓ High frequency ultrasound is used to create cavitation (microbubbles); as these collapse, PFAS are thermally destroyed and hydroxyl radicals generated. Sonolysis success significantly affected by contact with or adsorption to the microbubble surface (Ross, 2018), initial concentration, power density, solution temperature, and ultrasound frequency (Foote, 2020).
Implementability:
✓ Theoretically implementable. Would require centralized treatment system. Additional pre- and post-treatment will likely be required.
✓ High energy requirements.
Effectiveness:
✓ The technology is innovative, and effectiveness has not been demonstrated at field scale.
✓ Reaction rates may be adversely affected by inorganics (e.g., bicarbonate) (ITRC, 2021).
Availability / Maturity:
✓ At research/ pilot scale.
✓ Limitations/ interferences TBD.

Catalyzed Photolysis

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)
MOF and UV Treatment *Cost: High; Screening Status: Do not Retain*
Description: ✓ MOFs can incorporate catalysts (like titanium) into their structure. As PFAS are captured, UV-catalyzed oxidation degrades PFAS in the MOF structure. **Implementability:** ✓ Theoretically implementable. Would require centralized treatment system. Additional pre- and post-treatment will likely be required. **Effectiveness:** ✓ Demonstrated in laboratory/research scale. **Availability / Maturity:** ✓ Emerging (some commercially available, most still in research). ✓ Limitations/ interferences TBD.

Advanced Reduction Processes

Ex Situ Water Treatment Technologies (Presuming Groundwater Extraction)
Solvated Electrons *Cost: High; Screening Status: Do not Retain*
Description: ✓ Ultrasound, UV, microwaves, or electron beams are used with reducing agents, to generate radicals, resulting in reductive defluorination of PFAS (ITRC, 2021).

Implementability:

✓ Theoretically implementable. Would require centralized treatment system. Additional pre- and post-treatment will likely be required.

Effectiveness:

✓ Early demonstration in laboratory/research scale. The mechanisms of reactions and destruction need to be understood to demonstrate in situ treatment effectiveness (ITRC, 2021).

Availability / Maturity:

✓ Emerging (some commercially available, most still in research).

✓ Limitations/ interferences TBD.

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