Table 12-2. SOLIDS TECHNOLOGIES – REMEDIATION TECHNOLOGIES AND METHODS COMPARISON

This table belongs with the ITRC PFAS Tech Reg Document. The ITRC intends to update this table periodically as new information is gathered. This table has been updated (October 2021) to add a selection of new technologies and new references for some of the technologies presented in the April 2020 table version. The user should note that these additional references have transformed the third column into a selection of representative technologies of likely interest, and not a complete review of all of the references. The expanded body of research has made it too cumbersome to succinctly capture the PFAS and concentrations that were investigated for each reference and what removal efficiency was achieved. Many of these studies were novel at the time of original publication of this table and providing the PFAS and range of concentrations for the body of research was instructive at that time. The user should consult the references directly for additional information on the PFAS and concentrations that were researched.

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The mechanism of treatment (separation vs transformation) is listed under each Remediation Group.

Remediation Group	Remediation Technology (Includes PFAS-1 document section number for more information)	Chemicals Evaluated and Reported Removal Efficiencies for Select Studies	Strengths (Includes Co-Contaminants, Sustainability, Scalability)	Challenges/Limitations (Includes Co-Contaminants, Sustainability, Scalability)	Waste Management/Life Cycle	Future Data Needs	PFAS Demonstration Maturity (FI – Field Implemented, LA – Limited Application, D – Developing)	References
Sorption and Stabilization (Separation)	12.3.1 Stabilization (As an example, activated carbon blended with amorphous aluminum hydroxide, kaolin clay, and additives)	PFOS, PFOA, PFHxS, PFHxA, and 24 other PFAS analytes PFOS~1–376µg/L with 95–99% reduction in measurable PFOS concentration	Basic implementation technology (soil mixing, etc.) with proven independent studies since 2015. Tendency for hysteresis to limit desorption. Used at full-scale.	Competition for binding sites by organic co-contaminants.		Long-term stability not demonstrated.	🟩 🟩 🟩 🟩 FI	Birk 2015; Kempisty, Xing, and Racz 2018; Marquez et al. 2016; Stewart, Lawrence, and Kirk 2016; Stewart and McFarland 2017; Brusseau et al. 2019; Xiao et al. 2019
	12.6.1 Natural minerals (iron oxide, high iron sand, clay)	PFOS, PFHxS, PFOA, PFHxA PFOS~0.12–8.0 ppm	Enhance sorption by modifying surface. Adsorption isotherms vary for various minerals.	Potential for desorption and leaching of PFOS off surface. Influenced by soil chemistry (pH, ions, and organic carbon content). Relatively low surface area. Amendment dosage is high (>7%). The soil moisture content needs to be 60% of soil water-holding capacity.	May need to manage the sorbed media, particularly if potential desorption and leaching of PFAS is a concern.	Potential for PFAS to leach from soil after treatment. Further study needed to identify the sorption mechanism(s) involved.	⬜ ⬜ ⬜ 🟩 D	Johnson et al. 2007; Zhao et al. 2014

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	Surface-modified clay	Four soils with total PFAS of 1,827-59,783 µg/kg had a reduction of 95-99% of leachable anionic PFAS, including PFOS and PFOA, by amending contaminated soil with 0.5% to 5% by weight of surface-modified clay.	High affinity for a variety of PFAS; Commercially available media.	Effectiveness can vary depending on soil type and chemistry.	Ex situ stabilized soil must be disposed of by landfilling or the equivalent. Long-term stability of PFAS in soils amended with surface-modified clay in situ is currently under study.	Long-term stability of PFAS in soil amended with surface-modified clay.	⬜ ⬜ 🟩 🟩 LA	Kambala and Naidu 2013; Wang et al. 2021; McDonough et al. 2021; Willett and Geary 2021
Destruction	Ultrasound	PFOA, PFOS, PFBA, PFNA, PFHxA, PFHxS, 6:2 FTS, and PFBS	PFAS could be desorbed using a desorption solution and ultrasound, and then the desorbed PFAS are simultaneously destroyed by ultrasound.	Ultrasound is still at bench-scale level.	Dependent on target concentrations.	Pilot-scale to examine the technology for groundwater and soil from different DOD locations, because the type of soil, PFAS contamination, and groundwater chemistry can vary with location.	⬜ ⬜ ⬜ 🟩 D	Hui 2020
Soil Sieving/Washing	Separates soil by size fractionation and then removes PFAS from contaminated fraction by washing.	Up to 17 mg/kg PFOS.	Separation by size fractionation is a readily implementable technology, soil washing is an accepted soil remediation technology used on a wide range of contaminants.	Does not work on uniform material. Washing liquid must be treated. Requires treatability testing.	Will produce residuals that require additional treatment and/or disposal.	Applications tend to be site/soil specific. Need for improved PFAS desorption and treatment technologies.	🟩 🟩 🟩 🟩 FI	Ventia 2020; Grimison et al. 2018; Toase 2018; Torneman 2012

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Soil Sieving/Washing with Advanced Oxidative Process (AOP)	Multistep process to treat investigation-derived waste soil and water. Process steps are: sieve contaminated soils, wash with a proprietary desorbing agent, concentrate rinsate with foam fractionation to concentrate PFAS, and treat concentrate by AOP-enhanced oxidative destruction of PFAS using dissolved ozone, sodium persulfate, food-grade phosphate-based buffers, and dilute hydrogen peroxide.	23 PFAS treated in rinsate to Massachusetts Department of Environmental Protection (MADEP) cleanup standards for PFAS in soil and groundwater.	Can treat a variety of PFAS, CVOCs, and 1,4-dioxane.	Complex treatment process with multiple steps.	Intended to result in complete destruction with all waste streams meeting standards.	Field-scale testing at full-scale.	☐ ☐ 🟩 🟩 D	Boving and Ball 2018; Boving 2020
Thermal Desorption (Separation)	12.6.2 Thermal desorption, in situ and ex situ capture	Demonstrated on many PFAS compounds PFOS ~21,000µg/Kg, >99% removal at 400°C	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.	Generates waste stream (air) that still needs to be managed.	Field-scale demonstrations and assessment of volatilization of PFAS thermal conversion products, as well as hydrogen fluoride and production of hydrofluoric acid, need to be better understood.	☐ ☐ 🟩 🟩 D	Grieco and Edwards 2019; Crownover et al. 2019; DiGuiseppi et al. 2019; Barranco 2021; Hatton 2020; Burke 2019; Hatton et al. 2019; Iery 2020; NRC Alaska LLC 2019; Wehrmann 2020
Electron beam	High-energy electron beam with advanced oxidation reduction process.	Defluorination rates were reported as 95.7% for PFOA and 85.9% for PFOS.	Has the potential to be a permanent solution.	High energy, expensive. Uncertainty in complete destruction. Potential byproducts that could be generated.	Could potentially generate an air waste stream that needs to be managed.	Demonstrate treatment for a variety of different soils/media and optimize operational parameters. Develop pilot-scale treatment systems.	☐ ☐ ☐ 🟩 D	Pillai 2020

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Thermal Destruction	12.4 Off-site incineration	Soil, remediation waste–all concentrations	Has the potential to be a permanent solution	High energy, expensive. Uncertainty in required temperature and complete destruction and flu gas chemistry. Potential byproducts that could be generated.	Could potentially generate an air waste stream that needs to be managed.	Field demonstrated when used in conjunction with excavation. Assessment of volatilized PFAS thermal conversion products needs to be better understood.	☐ 🟩 🟩 🟩 FI	Watanabe et al. 2016; Aleksandrov et al. 2019
	In situ smoldering/combustion	Soil and water remediation PFOS, PFOA, PFHxS, PFNA, PFBS, PFHpA reduced soil concentrations to <0.4 ug/kg.	Has the potential to be a permanent solution.	The temperatures obtained through smoldering can be significant and exceed temperatures needed to destroy per- and polyfluoroalkyl substances (PFAS). Requires a surrogate fuel that can support the smoldering process to achieve temperatures (greater than 900°C) sufficient to destroy PFAS. Potential incomplete combustion and emissions. Heterogeneity reduces treatment effectiveness.	Generates HF gas and potential for emission of volatile PFAS.	Obtain complete mass balance and optimize PFAS emissions controls. Field-demonstrate technology.	☐ ☐ ☐ 🟩 D	Major 2019; Duchesne et al. 2020
Excavation and Disposal	12.3.2 Excavation and Disposal	Applies to all PFAS.	Proven technology.	Possible contribution to PFAS in landfill leachate. Some landfills refuse to accept PFAS-contaminated soils/materials.	Could potentially act as a secondary source, so long-term liability and leachability should be considered.	Ability to ensure landfilled materials do not contribute to PFAS in landfill leachate	🟩 🟩 🟩 🟩 FI	Lang et al. 2017

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