ESTCP

EXECUTIVE SUMMARY

Ex Situ Soil Washing to Remove PFAS Adsorbed to Soils from Source Zones

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ESTCP Project ER20-5258

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ACRONYMS AND ABBREVIATIONS

ADEC	Alaska Department of Environmental Conservation
AFB	Air Force Base
AFFF	aqueous film-forming foam
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CET	CleanEarth Technologies, Inc.
DoD	U.S. Department of Defense
ESTCP	Environmental Security Technology Certification Program
HAL	Health Advisory Level
ISM	incremental sampling methodology
OSD	Office of the Secretary of Defense
PFAS	per- and polyfluoroalkylated substances
PFBS	perfluorobutane sulfonic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
QSM	Quality Systems Manual
TOC	total organic carbon
USEPA	United States Environmental Protection Agency

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1.0 INTRODUCTION

This Final Report (Report) summarizes the implementation and results of the Environmental Security Technology Certification Program (ESTCP) Project ER20-B2-5258 (Project), which validates the field application of ex situ soil washing using a mobile pilot system to remove per- and polyfluoroalkyl substances (PFAS) adsorbed to soils from source zones at the Department of Defense's (DoD) Eielson Air Force Base (AFB), Alaska (the Site). The project was conducted by Arcadis U.S., Inc. (Arcadis) and CleanEarth Technologies Inc. (CET).

The current state of very low PFAS soil and groundwater standards, combined with recalcitrance of the carbon-fluorine bond and the likelihood of hazardous substance designation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), creates an exceptional challenge for practitioners and stakeholders when evaluating options for PFAS-impacted soil treatment. Soil treatment options are limited and expensive for PFAS-impacted soils. Current treatment options include excavation and landfill disposal, destructive technologies such as incineration and thermal desorption, and stabilization methods designed to limit leaching.

Landfilling is becoming more expensive as regulations and restrictions limit disposal options. Incineration has long been considered the gold standard for PFAS-containing waste destruction; however, recent public concern about incomplete treatment of off-gas emissions has led to a U.S. DoD moratorium on incineration of PFAS-containing wastes. Adsorption and stabilization can be effective for managing PFAS-impacted soil (McDonough et al. 2021), but it does not remove PFAS from soil, meaning that ongoing long-term management and monitoring are required. Soil washing could fill the gap in the market as a cost-effective mass removal and volume reduction technology that could be used to treat large volumes of PFAS-impacted soil.

2.0 TECHNOLOGY

Soil washing is a "catch-all" phrase that describes a range of physical/chemical techniques for soil remediation that involve processing soil through physical and chemical separation equipment connected in parallel or in series. Historically, soil washing processes have taken on one of three general forms:

1) Size separation processes that segregate the coarse-grained soil particles from the fine-grained to reduce the volume of impacted soil.
2) Size separation and density separation processes that both concentrate the chemical in the fine-grained soil and remove it by density separation from the coarser soil fractions.
3) Size and/or density separation combined with a chemically amended process water.

Soil washing has been used on a commercial scale in Europe since the mid-1980s through fixed facilities (Nunno and Hyman 1988), and in North America, a mobile soil washing system was tested for the United States Environmental Protection Agency (USEPA) in the 1980s (Scholz and Milanowski 1984; Griffiths 1995). Soil washing has been used to treat cyanide, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, and metals, but the treatment of PFAS-impacted soil using soil washing is a relatively new application.

Despite the limited pilot-scale trials on PFAS-impacted soils, the chemical properties of PFAS make it a good candidate chemical for treatment by soil washing. In a soil washing process, the high aqueous solubility of PFAS, along with the ability to control the pH of the process water, segregate the fine-grained fraction of the soil from the coarse-grained, and target the separation of organic compounds or other soil minerals from the bulk soil offer the ability to reduce the volume of impacted soil requiring further treatment or disposal. The coarse-grained soil can be treated to achieve single-digit parts per billion cleanup goals; if fine-grained soil concentrations exceed remediation standards, they can be managed using secondary treatment including incineration, thermal desorption, stabilization and adsorption, or specialized landfilling.

3.0 OBJECTIVES

The objective of the Project was to demonstrate and validate soil washing as a cost-effective mass removal and volume reduction technology that can be applied to treat PFAS-impacted coarse-grained soil in source zones. **Table ES-1** outlines the performance objectives of the field-scale demonstration. Regional screening levels for the Project discussed in **Table ES-1** are adopted from Alaska Department of Environmental Conservation (ADEC; 2016), ADEC 2019, and Office of the Secretary of Defense (OSD; 2021), which are presented in **Table ES-2**. 2022 USEPA and OSD screening levels were not used, as they were issued after the field demonstration was completed.

Table ES-1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria
1. Bench-scale testing to demonstrate site suitability and optimize treatment process and a field-scale trial to demonstrate performance	Particle size distribution, physico-chemical soil parameters, total concentration and leachable concentration of individual PFAS in soil, co-occurring chemicals and total organic carbon (TOC).	i) >99% removal of perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA), and perfluorobutane sulfonate (PFBS) and >99% removal of sum of 24 PFAS on the USEPA Method 537/DoD Quality Systems Manual (QSM) analyte list ii) Post-treatment soil concentrations and leachate concentrations < regional screening levels iii) Post-treatment water concentrations < USEPA Health Advisory Level (HAL)
2. Cost optimization and reduction of lifecycle costs	Treatment cost estimate in $180 to $210 USD/ton for different soil types	40 to 50% cost reduction relative to thermal treatment

Table ES-2. Regional PFAS Screening Levels

Screening Levels	PFOS	PFOA	PFOS + PFOA	PFBS
Soil migrating to groundwater (ADEC 2016)	3 µg/kg	1.7 µg/kg	-	-
Groundwater (ADEC 2019)/USEPA HAL	-	-	70 ng/L	-
Groundwater (OSD 2021, USEPA 2021)	40 ng/L	40 ng/L	-	600 ng/L

Notes:
µg/kg – micrograms per kilogram
ng/L – nanograms per liter

Although the Project had no performance criteria for non-target PFAS, the presence and removal efficiency of non-target PFAS in soil and process water were evaluated through extractable organofluorine analysis and adsorbable organofluorine.

4.0 TECHNOLOGY DESCRIPTION

4.1 SITE DESCRIPTION

PFOS/PFOA-impacted soil generated from construction projects at Eielson AFB was stockpiled at a centralized location on base (Landfill #3) to allow the construction projects to proceed as scheduled. Currently, there are approximately 150,000 cubic yards of PFOS/PFOA-impacted soil stockpiled on or near Landfill #3. These stockpiled soils consist predominantly of coarse-grained soil (gravel and sand). Fine-grained soil accounted for 6 to 33 percent of soil in each of the stockpiles; less than 10 percent of the total volume exhibited a fines content above 20 percent.

4.2 TEST DESIGN

The technology was tested at the bench scale, and the process was optimized based on initial results to achieve the performance criteria. The most successful treatment elements were carried forward to optimize the final design of the pilot-scale system, which was tested in the field at Eielson AFB. Soil tested during the bench-scale treatability testing and field demonstration contained both the average and highest concentration range of PFAS at Eielson AFB to evaluate the capabilities of the technology at Eielson AFB as well as the wider DoD portfolio.

4.3 BENCH-SCALE TREATABILITY TESTING

Testing was conducted on samples from three stockpiles at Eielson AFB: EIE393-1, EIE377-1, and EIE379-2. EIE393-1 was representative of soil from an aqueous film-forming foam (AFFF) source zone, and EIE377-1 and EIE379-2 were representative of construction stockpiles. The objectives of the bench-scale treatability trial were to evaluate the processes required to treat the soils and verify that the soil washing process could reduce PFAS concentrations in the coarse-grained soil to concentrations below ADEC screening levels and meet USEPA groundwater screening levels for leachate.

The design for the test consisted of three main stages: 1) size separation; 2) attrition scrubbing; and 3) advanced physical processing and chemical extraction. One sample was collected from each of the process streams generated from the process (gravel, sand, fines). Three rounds of testing were required to meet the treatment objectives. Round 1 evaluated different process conditions such as basic chemistry of the wash solution, temperature, retention time, liquid to solid ratios, and agitation. Round 2 included the most successful conditions from Round 1 and a chemical extraction step. Round 3 included the most successful conditions from the two previous rounds and a physical optimization step. During the bench-scale treatability testing, the organics were successfully treated without segregation from the fines. The pilot process therefore did not segregate the organic compounds.

4.4 DESIGN, LAYOUT, AND PROCESS FLOW OF PILOT SYSTEM

A modular 1- to 10-ton per hour pilot-scale soil washing system was designed to duplicate the unit treatment processes and sequence of treatment evaluated at the bench scale. The system consisted of two soil modules and a water treatment circuit. Each soil treatment module was built within a rectangular frame measuring 40 feet long by 8 feet wide and certified for shipment by road, rail, and ocean to create flexibility for mobilization to remote project sites. The process area footprint consisted of a 40-foot by 100-foot bermed, lined area that allowed space for equipment setup and stockpiling of untreated and treated soil.

4.5 FIELD TESTING

The pilot-scale process was shipped to Eielson AFB, with equipment arriving between August 13 to 20, 2021.Commissioning (consisting of site preparation, liner installation, placement of equipment, and connection of piping and electrical) was completed by August 24, 2021. The system was powered by a 185 kVA generator, and the system was filled with water from a lake at Eielson AFB (Mullins Pit), which was verified to be PFAS-free.

In total, 180 tons of soil were excavated and treated for the demonstration from three stockpiles. Stockpile EIE393-1 was representative of AFFF source-zone soil, and EIE382-5 and EIE385-4 were representative of construction stockpiles. Only the Round 1 treatment process was tested in the field. The Round 2 and Round 3 processes could not be evaluated due to the onset of freezing conditions in September 2021.

Soil samples were collected before and after treatment using two methods to validate the technology: batch sampling to evaluate the consistency in performance of each batch and the incremental sampling methodology (ISM) to evaluate mean treatment performance for each of the three stockpiles. One batch sample was collected for every batch (20 tons) of soil treated for each stockpile. One ISM sample was collected for each process stream and consisted of 30 increments (50 grams per increment), and each ISM sample was collected in triplicate. An untreated and treated water sample of the process water was also collected during the processing of each of the three stockpiles.

Soil and process water samples were sent to Pace Analytical in West Columbus, South Carolina for analysis of 25 target PFAS compounds via the USEPA Method 537 (modified)/US DoD (DoD, 2019) QSM 5.3 (2019) (Table B-15) plus heptadecafluoro-N-methyloctanesulphonamide (N-MeFOSA; list of 25 PFAS). Bench-scale treatability samples were analyzed for leaching via the Australian Standard Leaching Procedure by method AS 4439.3. Field demonstration samples were analyzed for leaching via the synthetic precipitation leaching procedure method SW-846 Test Method 1312.

5.0 PERFORMANCE ASSESSMENT

Results from the bench-scale treatability testing are presented in **Table ES-3**. Concentrations of PFBS and PFOA were initially low in untreated samples and often treated to concentrations below detection limits, meeting all performance goals at the end of the treatability process. PFOS was the driver for meeting performance goals, and discussion will focus on PFOS results.

For EIE377-1 and EIE379-2, the soil performance goals were achieved using the Round 1 process in coarse-grained soil in the bench-scale testing. For EIE393-1, the soil concentration performance goals were achieved after using the Round 3 processes. The bench-scale treatability trial indicated that, during the field demonstration, soil with lower PFAS concentrations could be successfully treated using the simpler Round 1 process conditions including basic water chemistry, size separation, and agitation. However, soil with higher PFAS concentrations would require chemical extraction and physical optimization steps included in the Round 2 and 3 processes.

Table ES-3. Bench-Scale Treatability Testing Results

			PFOS		Sum PFAS	
			Soil	Leachate	Soil	Leachate
Stockpile	**Treatment Round**	**Soil Fraction**	**µg/kg**	**ng/L**	**µg/kg**	**ng/L**
EIE377-1 Construction Soil	Round 1	Untreated	15	450	20.24	687.5
		Gravel	**0.32 J**	**<0.95**	0.32 J	<DL
		Sand	**0.50 J**	**<1**	0.5J	<DL
		Fines	5.4	47	5.4	151.3
EIE379-2 Construction Soil	Round 1	Untreated	59	3300	62.85	4045.9
		Gravel	**<0.19**	**29**	<DL	147.8
		Sand	**0.42 J**	**2.2 J**	0.42 J	64
		Fines	9.6	7.8	11.9	116.7
EIE393-1 AFFF Source Soil	Round 1	Untreated	2,700	32,000	3,155	39,795
		Rock	88	200	97	270
		Gravel	27	620	32	803
		Sand	150	900	170	1,005
		Fines	2,400	530	2,822	1,123
	Round 2	Rock/Gravel	8.8	120	9.4	194
		Sand	12	75	14	181
	Round 3	Rock/Gravel/Sand	**0.34 J**	**36 J**	0.34 J	36 J
		Performance Goals	**3**	**40**	**--**	**--**

Notes:
<DL = No compounds were detected above the detection limit so Sum of PFAS could not be calculated.
J= estimated result, less than limit of quantitation and greater than detection limit.
Bold values achieved the performance goals. There were no soil or leachate concentration based performance goals for Sum PFAS.
Sum of PFAS = sum of 24 PFAS compounds on Table B-15, QSM 5.3 plus N-MeFOSA.

Table ES-4 presents the results from the field demonstration from ISM sampling for the three stockpiles. The soil performance goals were achieved for EIE382-5 and EIE385-4 using the Round 1 treatment process verified in the bench-scale treatability trial. Mean coarse-grained soil PFOS concentrations in these stockpiles ranged from below the detection limit to 0.9 µg/kg. Soil performance goals were also achieved in the fine-grained fraction for EIE382-5. This result highlights the potential for soil washing to achieve soil performance goals without requiring secondary treatment of the fines if untreated concentrations are relatively low. In Stockpile EIE393-1, the soil performance goals were not achieved, but this was expected because the Round 2 and 3 processes, which were required to achieve higher levels of PFAS removal at the bench scale, could not be completed due to freezing conditions. Based on the comparable performance of the Round 1 process at the bench and pilot scales, the project team expected that the pilot treatment unit or full-scale treatment would perform to meet soil performance goals.

Optimization of performance parameters in the full scale and confirmation of treatment performance related to Round 2 and 3 processes would be part of any future full-scale remediation effort in this regard.

Table ES-4. ISM Arithmetic Mean PFAS Results

Stockpile	Soil Fraction	PFBS		PFOA		PFOS		Sum PFAS	
		Soil µg/kg	Leachate ng/L	Soil µg/kg	Leachate ng/L	Soil µg/kg	Leachate ng/L	Soil µg/kg	Leachate ng/L
EIE382-5	Untreated	**<0.19**	**<10**	**0.2**	**10.0**	4.5	193	6	316
	Gravel	**<0.23**	**<10**	**<0.23**	**<10**	**<0.23**	**<10**	0.3	<DL
	Sand	**<0.23**	**<10**	**<0.23**	**<10**	**0.2**	**<10**	0.2	50
	Fines	**<0.24**	**<10**	**<0.24**	**<10**	**1.7**	56	**2**	109
EIE385-4	Untreated	**0.2**	**12**	**0.8**	**36**	8	430	16	825
	Gravel	**<0.20**	**<10**	**<0.20**	**<10**	**0.2**	**<10**	0.2	17
	Sand	**<0.20**	**<10**	**<0.20**	**<10**	**0.9**	**13**	1.3	66
	Fines	**<0.21**	**<10**	**0.2**	**16**	9	243	12	345
EIE393-1	Untreated	**1.4**	49	6.0	243	560	22000	675	25833
	Gravel	**<0.20**	**<10**	**0.4**	**19**	30	1500	35	1796
	Sand	**<0.20**	**<10**	**0.4**	**32**	31	840	38	1103
	Fines	**0.7**	**12**	2.2	88	330	12667	409	14780
Performance Goal		**1900**	**40**	**1.7**	**40**	**3**	**40**	**--**	**--**

Notes:
<DL = No compounds were detected above the detection limit so Sum of PFAS could not be calculated.
Bold values achieved the performance goals. There were no soil or leachate concentration performance goals for "Sum PFAS".
Sum of PFAS = sum of 24 PFAS compounds on Table B-15, QSM 5.3 plus N-MeFOSA.

Concentrations of PFBS and PFOA were treated to concentrations below detection limits for the coarse fractions of EIE382-5 and EIE385-4, and this was sufficient to achieve soil concentration performance goals. In coarse fractions, PFOS removal ranged from 88.6 to 98.1 percent, and removal for the sum of 25 PFAS was generally higher (ranging from 91.7 to 99 percent), which indicated that the soil washing process was effective at removing other target PFAS. The goal of >99 percent PFOS removal was not achieved in the stockpiles; however, soil concentrations for PFOS in coarse-grained fractions of EIE382-5 and EIE385-4 achieved the performance goal, which was the primary driver for evaluating treatment performance. These results confirmed that the simple treatment process employed for these stockpiles was sufficient to achieve soil concentration targets, but Round 2 and Round 3 processes would be required to achieve >99 percent removal and achieve performance goals for EIE393-1.

PFAS leachate results correlated to the soil PFAS results for the untreated and treated soil fractions, commonly showing approximately one order of magnitude higher soil concentrations for PFOS compared to the leachate concentrations. Leachability was reduced in all coarse-grained fractions after treatment with similar levels of PFAS removal from the soil. The leachate concentration performance goals were achieved for EIE382-5 and EIE385-4, but not for EIE393-1.

Batch results indicated that treatment performance was consistent during the demonstration, and treatment variability was low. Batch samples reported concentrations similar to those of ISM samples, and all batch samples for the coarse soil fractions of EIE382-5 and EIE385-4 achieved the performance objectives, consistent with ISM results.

Untreated water results confirmed that PFAS adsorbed to soil was transferred to the aqueous phase. On average, more than 99.99 percent PFAS removal was achieved in treated water samples, indicating that PFAS was successfully adsorbed to granular activated carbon and ion exchange resin.

6.0 COST ASSESSMENT

The goal of this ESTCP project was to demonstrate that soil washing could be implemented at costs similar to landfilling in the lower 48 states, or approximately \$200 to \$400 per ton, including residuals management. The cost drivers for soil washing include:

1) Soil characteristics—grain size composition and fraction of fines, PFAS concentrations in soil, co-occurring chemicals, and organic content.
2) Regulatory requirements—performance goals for PFAS in soil and leachate.
3) Logistics related to residuals management—proximity to landfills, incinerators, and thermal desorption facilities.
4) Stakeholder objectives regarding disposition of residuals—whether landfilling or destructive treatment are required, or if stabilization and on-site management are acceptable.

These factors made it difficult to provide more than a general cost range without site-specific treatability testing results. As the demonstration site's remote location in Fairbanks, Alaska impacted the logistics and costs of the testing, particularly for residuals treatment and disposal, the project team framed the cost of soil washing based on drivers and scenarios to illustrate the potential savings related to the volume reduction approach below. Under this approach, the costs included treatment of the coarse fraction (gravel and sand) to meet regulatory limits via soil washing and treatment/disposal of the residuals (fines and organics).

Based on the treatability results, a relatively simple process (relying on water and aggressive attrition scrubbing) can be applied to meet performance goals in sand and gravel when total PFAS concentrations are low. For higher concentrations indicative of AFFF sources, advanced treatment using additives, surfactants, and other physical optimization steps would be required. This would increase the complexity of treatment, potentially reducing throughput of full-scale treatment, and ultimately increase the cost. An increased proportion of fines and organic compounds would require additional process equipment to segregate and dewater the residuals. Finally, endpoint objectives can range from a fraction of a µg/kg to tens of µg/kg for PFOA and PFOS and can be a major cost driver. These factors combine to a range of soil washing costs between approximately \$100 to \$200 per ton, excluding residuals treatment.

Table ES-5 presents scenarios of low-cost ($100/ton), medium-cost ($150/ton), and high-cost ($200/ton) soil washing alternatives combined with options for residual management as a function of percentage of fines/organics in the soil. For the purposes of this analysis, the project team assumed that the volume of soil requiring treatment would be at least 25,000 cubic yards, such that there would be economies of scale tipping the balance toward equipment mobilization versus transportation of soils to centralized disposal or treatment facilities. The assumption for the low-cost scenario for residuals would be landfilling at $200/ton; medium- and high-cost scenarios would use thermal desorption at $300/ton. The combined costs per ton resulting under these scenarios are summarized in **Table ES-5**, applying unit costs for soil washing to the entire volume for treatment of the coarse fraction and separation of fines for treatment and unit costs for landfilling and thermal desorption to the fines fraction.

By design, the low-cost scenario would be compared to landfilling at $200/ton, and the medium- and high-cost scenarios would be compared to thermal desorption at $300/ton. Here the project team considered fines percentages up to 50 percent as a practical limit. At 10 percent fines, the cost savings as a percentage range between 40 percent for the low-cost scenario and 23 percent for the high-cost scenario. Even at 30 percent fines, the savings range between 20 and 13 percent, indicating that the volume reduction approach inherent in soil washing offers cost advantages. While best value is obtained when the soils have limited fines/organics content, stakeholders that are risk-averse or seek to maximize sustainability could do so with this combined treatment approach. By minimizing the residual wastes that require expensive, high-energy destructive technologies, or by implementing thermal desorption to eliminate landfilling, individual stakeholders can achieve these goals based on their priorities and sensitivity to incremental cost.

Table ES-5. Soil Washing Cost Scenarios (per ton) Compared to Landfilling and Thermal Desorption

Scenario		**Soil Composition**				
	Fines:	**5%**	**10%**	**20%**	**30%**	**50%**
	Coarse:	**95%**	**90%**	**80%**	**70%**	**50%**
Low-Cost		**$110**	**$120**	**$140**	**$160**	$200
Medium-Cost		**$165**	**$180**	**$210**	**$240**	$300
High-Cost		**$215**	**$230**	**$260**	**$290**	$350

Notes:
Bold values are less than cost of landfilling at $200/ton (low-cost scenario) or thermal desorption at $300/ton (medium- and high-cost scenarios).
Low-Cost: treatment of coarse soil using soil washing ($100/ton) and landfilling of fines ($200/ton).
Medium-Cost: treatment of coarse soil using soil washing ($150/ton and thermal desorption of fines ($300/ton).
High-Cost: treatment of coarse soil using soil washing ($200/ton) and thermal desorption of fines ($300/ton).

7.0 IMPLEMENTATION ISSUES

Due to manufacturing delays, the field demonstration did not start until August 2021 and freezing conditions in September 2021 meant that the Round 2 and Round 3 treatment processes could not be conducted on Stockpile EIE393-1.

7.1 CONSIDERATIONS FOR IMPLEMENTING SOIL WASHING AT PFAS SOURCES

The chemical properties of PFAS make it a good candidate chemical for treatment via volume reduction by soil washing. The volume reduction approach has demonstrated treatment of the sand and gravel soil fractions down to the low part per billion levels; however, as soil cleanup goals become more stringent, it is anticipated that more advanced soil washing processes will be needed to consistently treat the coarse-grained soil fractions to a PFAS concentration less than 1 part per billion. In anticipation of these new cleanup goals, continued research is required to demonstrate that optimization of the physical separation approach combined with chemical treatment can achieve these levels in the coarse-grained soil as well as a portion of the fine-grained soil fraction.

When evaluating soil washing as a treatment alternative, one should consider a systematic approach to feasibility assessment and predesign studies. The USEPA has published step-by-step guides outlining a systematic approach to designing and implementing treatability studies (USEPA 1992) along with guidance on planning-level process feasibility evaluations specific to physical separation for volume reduction for a range of chemicals (USEPA 1999). Section 8.3 of the full report outlines steps that should be taken specifically for implementing soil washing at PFAS sources.

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