PROJECT NAME

PFAS Impacted Sediment Thermal Treatment Demonstration



This project demonstrates TerraTherm's ability to design, fabricate, operate, and adapt its high temperature thermal treatment system for PFAS-impacted soil and sediment. As part of ESTCP Project ER23-8372, TerraTherm completed a pilot-scale demonstration using a scaled down version of its patented IPTD® technology at Peterson Space Force Base in Colorado Springs, Colorado. The approximately 1.8-cubic-yard treatment system heated PFAS-impacted sediment to a target temperature of approximately 400°C while a patent-pending thermal catalyst treated the extracted high temperature vapor stream at approximately 600°C. Colorado School of Mines led the overall ESTCP project, with Geosyntec providing project coordination and oversight. The ESTCP project involved a side-by-side demonstration and evaluation of PFAS destruction technologies including: smoldering, thermal desorption (our thermal treatment system for PFAS-impacted media), soil washing, HALT, SCWO, UV/SGM. The project included a comprehensive testing and analysis framework for all the technologies that included pre and post target and non-target PFAS analyses, TF, other co-contaminants, and LEAF (PFAS leachability), and emissions testing using OTM-45, 50, and 55, and EPA method 26A for HF.

Target and non-target/suspect PFAS, including precursors, were non-detect for most compounds with only a few PFAS detected at low ng levels similar to detections in laboratory method blanks. Similarly, PFAS emissions from the thermal catalyst were de minimus at low ng levels below or similar to levels observed in the OTM field (proof) blank. The total-fluorine mass balance accounted for more than 99% of the starting fluorine in the system, with approximately 79% remaining in the treated sediment and 20% mobilized to the spent catalyst media as inorganic fluorine, likely present as inert CaF_2 in both the sediment and catalyst. These results indicate near complete mineralization of the PFAS using our patent-pending system for treatment of PFAS combining IPTD® with our specially design thermal catalyst.

LOCATION
Peterson Space Force Base, Colorado Springs, Colorado

CLIENT
Colorado School of Mines/ Environmental Security Technology Certification Program (ESTCP)

PROJECT START DATE
June 9, 2025

PROJECT COMPLETION DATE
July 30, 2025

VOLUME TREATED
Approx. 1.8 cubic yards

HEATING TECHNOLOGIES
In Pile Thermal Desorption (IPTD)

CONTAMINANTS TREATED
PFAS

Material Characteristics

The sediment was predominantly sand (61.4%), with approximately 26.6% silt, 11.2% clay, and 0.8% gravel. Pretreatment testing by Eurofins using standard USEPA Method 1633 analyses for 40 PFAS compounds identified a starting concentration of 68.12 µg/kg or 143 mg of total target PFAS in the sediment. The Colorado School of Mines also performed an extensive analytical program using high resolution mass spectrometry and suspect-screening methods in addition to USEPA Method 1633 analyses for an expended list.

Analysis	Soil and Catalyst	Condensate, NAPL, GAC	Vapors During Treatment	
	Pre and Post	Post	Before and After Catalyst	Stack / Emissions
Target PFAS & Precursors EPA Method 1633 (LC-MS/MS)	X	X		
Non-Target/Suspect PFAS & Precursors (LC-HRMS)	X			
Total Fluorine/Absorbable Organic Fluorine/Extractable Organic Fluorine (CIC)	X	X		
Extractable Fluoride EPA 9056A (IC)	X			
VOCs / SVOCs / TPH EPA Methods 8260 / 8270 / 8015	X			
TOC / Moisture Content	X			
Polar Semi-Volatile, Non-Polar Volatile, and Non-Polar Semi-Volatile PFAS, Precursors & Fluorinated Compounds OTM 45, 50 and 55				X
Hydrogen Fluoride EPA Method 26A				X
Target PFAS & Precursors PUF XAD Vapor Tubes EPA TO-13A mod. (LC-MS/MS)			X	X
O_2, CO, H_2S, LEL, VOCs, Benzene 4-Gas Meter, PID, Draeger Tube			X	X
LEAF - PFAS Leachability EPA Methods 1316 / 1633	Soil			

This expanded analytical approach evaluated 134 target and suspect PFAS compounds, including precursor compounds and fluorinated substances not routinely measured by commercial laboratories. The expanded Colorado School of Mines evaluation measured approximately 1,775 µg/kg total PFAS when both target and suspect compounds were included. These findings confirmed the presence of a substantial inventory of PFAS precursors and non-target fluorinated compounds that would not have been captured through conventional analytical approaches alone.

The sediment also contained diesel- and motor-oil-range hydrocarbons, multiple PAHs, and 38,000 mg/kg TOC. The moisture content of the sediment ranged between 17.3% and 25%.

The unexpectedly high organic content became a major operating consideration. As the sediment heated, organic material pyrolyzed and oxidized, producing lower-molecular-weight hydrocarbons, resulting in collection of approximately 1.1 gallons of NAPL in the vapor extraction manifold and condensate collection system.

These materials increased vapor-system pressure loss and required modifications to vapor conveyance and condensate management during operations.

Approach and Design Specifics

IPTD® Heated Box and Extraction Network

TerraTherm designed and built a nominal 2-foot-deep by 5-foot-wide by 6-foot-long carbon-steel heated box with capacity for approximately 1.8 cubic yards of sediment. The insulated box contained five heater wells, three multi-point temperature-monitoring locations, two air-injection wells, and three vapor-extraction wells. The box or treatment demonstration unit was designed to represent a scaled down version of a full-scale IPTD® system. A four-inch layer of clean coarse sand above the sediment surrounded the vapor-extraction wells and served as a vapor-collection plenum. Silicon-controlled rectifiers modulated heater output, and a power meter recorded real-time and totalized energy use.

Patent-Pending Thermal Catalyst

The extracted high temperature vapor stream was routed through a stainless-steel thermal catalyst vessel containing a proprietary blend of inert media and calcium hydroxide. The vessel heated the catalyst and vapor to approximately 600°C. Moisture-rich vapors generated during the boiling and sediment drying phase bypassed the catalyst; after dry-out, the vapor stream was redirected through it. The catalyst served to mineralize volatilized PFAS and related thermal-decomposition products (e.g., PIDs and VFCs) extracted from the sediment and capturing the fluorine generated as inert calcium fluoride, minimizing emission of HF.

Vapor Conditioning, Controls, and Monitoring

Equipment downstream of the treatment unit and thermal catalyst included noncontact water-cooled heat exchangers, moisture separators, a condensate sump and pump, a process blower, vapor-phase activated carbon, and a discharge stack. The vapor phase carbon beds served as backup polishing and treatment of organics related to the breakdown of the high TOC (e.g., benzene and ketones). A PLC-based system provided automation, alarms, local HMI control, remote data acquisition, and remote-control capability through satellite telemetry. The modular system was preassembled and commissioned at TerraTherm's shop and was reassembled and operational in the field within approximately three days after delivery.



Sampling and Performance Verification

The analytical program included pre-treatment equipment wipe and rinsate sampling; pre-treatment sediment, sand, and catalyst-media sampling; weekly low-volume PUF/XAD process-vapor sampling; formal OTM-45, OTM-50, and OTM-55 stack testing at the 100°C/boiling and high-temperature phases (i.e., sediment temperatures ranging between 250 and 300°C); EPA Method 26 HF testing; condensate and NAPL sampling; spent GAC and catalyst-media sampling; post-treatment sediment sampling; and total-fluorine and extractable-organic-fluorine analyses. The program also evaluated

associated field, media, laboratory, and equipment blanks, as well as OTM vapor sampling-train proof blanks.

Leaching Environmental Assessment Framework (LEAF) testing using USEPA Method 1316 was also performed by Texas Tech University to evaluate whether PFAS remaining in the treated sediment could leach into groundwater after treatment. The objective was to determine whether thermal desorption not only reduced total PFAS concentrations in the sediment but also reduced the potential for residual PFAS to migrate to groundwater or surface water following beneficial reuse or disposal.

The LEAF method evaluates PFAS leaching behavior under increasing water-contact conditions by exposing sediment samples to PFAS-free water at a series of liquid-to-solid (L/S) ratios and measuring PFAS concentrations released into the resulting leachate. Pre-treatment and post-treatment sediment samples were tested and compared to assess changes in PFAS mobility resulting from treatment.

Challenges

High Organic Carbon and NAPL Formation

The sediment contained 38,000 mg/kg TOC, substantially more organic material than anticipated. Pyrolysis and oxidation of the TOC generated hydrocarbon vapors and NAPL and the NAPL accumulated in the sand plenum, vapor-extraction wells, and external piping, increasing pressure loss.

TerraTherm used an adaptive, data-driven operating strategy to maintain vapor collection, and complete the demonstration:

- Cleaned the vapor-extraction wells and piping after pressure profiling identified organic fouling near the heated-box outlet.
- Added a drip leg and condensate drum ahead of the thermal catalyst to remove condensed organic material.
- Modified the air inlet wells to include active air inject and added co-located heaters to the vapor extraction wells to increase oxidation rates of the hydrocarbons that accumulated in the vapor plenum.
- Extended the high temperature operating period to allow sufficient time to remove the hydrocarbons by volatilization, oxidation, and extraction.
- Used vapor oxygen, carbon dioxide, LEL, and PID data to track oxidation rates and determine when the hydrocarbons were removed.
- Temperature data, vapor flows and pressures, and PFAS, hydrocarbon, and combustion data on vapors extracted from the treatment unit were used to track treatment progress and document system performance.



Results and Outcome

Pilot system operations commenced on June 9, 2025. Active heating continued for 51 days before system shutdown on July 30, 2025. The planned operations schedule was for 35 days, and was extended 16 days to accommodate treatment of the hydrocarbons produced from the high TOC content.
The process blower remained in operation for approximately two additional weeks to cool the system prior to sediment sampling and demobilization. Peak average temperatures at the three post-treatment vertical-composite sampling locations ranged from 350 to 400°C.

Post-treatment sediment results demonstrated substantial PFAS removal. Three vertical-composite sediment samples representing the range of temperatures observed in the treatment unit and the sand-plenum sample were non-detect for all target PFAS analyzed except for a few PFAS compounds that were detected at low ng levels, similar to detections in field and laboratory method blanks. The post-treatment overall composite samples from the unit were also generally non-detect, with only estimated concentrations comparable to associated field and equipment blanks. Post-treatment sediment was also non-detect for analyzed VOCs, SVOCs, TPH, and TOC at the reported detection limits.



Eurofins Method 1633 analyses reported pretreatment concentrations of 68.12 µg/kg total target PFAS. Using a post-treatment concentration of 0.051 µg/kg PFOA, comparable to concentrations of PFOA detected in field and equipment blanks, the calculated destruction and removal efficiency (DRE) was 99.93%, substantially exceeding the ESTCP performance objective of 90% removal.

Colorado School of Mines' advanced analytical program, which screened 134 target and suspect PFAS compounds, measured a reduction in total target and suspect PFAS concentrations from approximately 1,775 µg/kg to 6.7 µg/kg, corresponding to a 99.6% DRE. Results showed near-complete removal of precursor compounds and unidentified PFAS species that can serve as long-term sources of PFAS formation. Only trace concentrations of a small number of compounds remained following treatment, with residual PFAS concentrations generally below 1 µg/kg.

LEAF testing demonstrated that thermal desorption also substantially reduced PFAS leaching potential. PFHxA and PFOS concentrations in leachate were reduced to below analytical detection limits, and associated mass-release curves showed significantly lower cumulative PFAS release than untreated sediment. Thermal desorption achieved the greatest reduction in PFHxA and PFOS leaching among the three sediment treatment technologies evaluated during the demonstration, indicating a significant reduction in future PFAS mobility.

Performance testing of the vapor treatment system using the PUF XAD resin vapor sampling tubes (EPA Method TO13A modified / LC-MS/MS) showed effective destruction of vapor-phase PFAS. Paired inlet and stack samples collected on June 30, 2025, produced a calculated 99.98% DRE across the thermal catalyst.

Results and Outcome

Two formal OTM-45 source-testing events were conducted during the demonstration: one during the 100°C drying phase and a second during the 400°C treatment phase. Although low concentrations of target PFAS were reported in some OTM-45 stack samples, many measured concentrations were comparable to those found in the proof blanks, media blanks, and laboratory blanks, creating uncertainty regarding whether detections represented actual stack emissions or analytical background contamination. OTM-50 and OTM-55 analyses conducted during both the 100°C and high temperature tests reported no detections of volatile fluorinated compounds (VFCs) or non-polar semi-volatile PFAS.

Overall, the OTM-45, OTM-50, OTM-55, EPA Method 26, and vapor-treatment performance data indicate that operation of the IPTD® system and patent-pending thermal catalyst produced negligible PFAS emissions, no detectable VFC emissions, and very low HF concentrations. Measured HF concentrations during the 100C and high-temperature sampling events were 0.11 ppmv and 0.015 ppmv, respectively.

The total-fluorine mass balance identified approximately 79% of the starting fluorine remaining in the treated sediment and approximately 20% in spent catalyst media, likely present as inorganic fluorine and mineral fluorides (e.g., CaF2). Only trace fluorine was observed in condensate and recovered NAPL, while approximately 0.35% of the starting fluorine was measured in stack vapor as HF. No target PFAS were detected in spent GAC except for an estimated PFOA concentration comparable to associated blanks, and total fluorine in spent GAC was non-detect at the reported detection limit.

Summary

Testing of TerraTherm's patent pending thermal treatment system for soils and sediments impacted with PFAS at Peterson Space Force Base in Colorado Springs, CO as part of ESTCP project ER23=8273, demonstrated the following:

- TerraTherm's IPTD® technology is effective at heating soil and sediment to the temperatures needed to destroy and remove PFAS to very low non-detect ng/g levels.
- During heating of the soil and sediment up to target temperatures of 350° to 400°C in the IPTD® system:
  - A significant percentage (e.g., 40-70%) of the PFAS, precursors, and fluorinated compounds present in the soil/sediment are directly mineralized via naturally occurring mineralizing agents present in the soil and sediment (e.g., calcium, magnesium, iron and other alkaline minerals) and the fluorine captured as inert inorganic fluorine minerals such as CaF2 or FeF3,
  - Short chained PFAS and precursors are volatilized,
  - Longer chained PFAS and precursors are degraded through naturally occurring mineralizing agents present in the soil and sediment (e.g., calcium, magnesium, iron and other alkaline minerals) and
  - The products of incomplete degradation (PIDs) and volatile fluorinated compounds (VFCs) are volatilized.
- Use of a thermal catalyst incorporating Ca(OH)2 and heated to 600°C is highly effective at treating volatized PFAS, precursors, PIDs, VFCs, and other fluorinated compounds extracted from the soil and temperatures, with de minimus emissions of PFAS and HF as measured using OTM 45, 50, 55 and EPA Method 26A.
- Production of secondary waste streams requiring treatment for PFAS are minimized, with only 2% of the

starting PFAS mass observed in the collected condensate and no PFAS detected in the GAC polishing beds, indicated around 98% destruction and mineralization of PFAS, precursors, PIDs, VFCs, and other fluorinated compounds through the combined treatment steps of the IPTD® system and thermal catalyst.

- Other contaminants present in the soil/sediment (e.g., VOCs, SVOCs, PAHs, and TPH) are also effectively treated to non-detect levels.
- TerraTherm's patent pending thermal treatment system for PFAS-impacted sediments and soils treats today's regulated PFAS as well as tomorrow's, avoiding the long term risks and liabilities associated with off-site transport and disposal, while minimizing the potential for emissions of PFAS or other fluorinated compounds.

