EPA Federal Facilities Superfund Program
Using Lysimeters to Determine the Potential of PFAS to Leach from Soil to Groundwater

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The Department of Defense (DoD) began installing lysimeters at their installations to investigate per- and polyfluoroalkyl substances (PFAS). These devices were claimed to be appropriate for determining how PFAS move from soil to groundwater (Anderson, 2021). In response to questions from EPA staff about the applicability of these devices for PFAS, the Federal Facilities Restoration and Reuse Office (FFRRO) proposed that a team of EPA scientists review the available information and develop a summary document to help EPA staff when reviewing investigation documents proposing to use lysimeters.

This document was prepared by staff from FFRRO, the Groundwater Characterization & Remediation Division (GCRD) and the Technical Support Coordination Division (TSCD) in the Office of Research and Development (ORD), the Superfund and Emergency Management Division (SEMD) in Region 4, the Laboratory Services and Applied Science Division (LSASD) in Regions 8 and 10, and the Environmental Response Team (ERT) in the Office of Superfund Remediation and Technology Innovation (OSRTI).

In developing this document, we reviewed work plans and Quality Assurance Project Plans (QAPPs) for the Remedial Investigation (RI) of PFAS at federal facilities. The goal of this review was to develop a common understanding of how lysimeters are being used at federal facilities to determine the potential for PFAS in soils to impact groundwater. We also reviewed existing EPA guidance, a consensus standard, and select scientific publications to identify strengths, limitations, and concerns regarding the use of lysimeters for investigating PFAS.

The expectation is that this document will be updated as additional results from lysimeter studies and research on PFAS leaching protocols becomes available. The document represents a coordinated consensus on FFRRO's approach to addressing issues and challenges and is intended to help RPMs and technical support staff provide a consistent understanding and response across regions. This document is not intended to create new or revise existing policy and/or guidance.

<u>Table of Contents</u>

1. Purpose

This document provides an overview of suction lysimeters and their use for determining the potential of PFAS to leach from soils to groundwater. In addition, questions regarding the use of suction lysimeters are provided.

2. Existing Guidance

U.S. EPA, 1986. Permit Guidance Manual on Unsaturated Zone Monitoring for Hazardous Waste Land Treatment Units. EPA/530-SW-86-040. (Guidance on porewater monitoring including installation and sampling of lysimeters)

U.S. EPA, 1996. Soil Screening Guidance: Technical Background Document. EPA/540/R95/128. (Guidance on determining migration to groundwater screening levels using site data)

ASTM International, 2018. Standard Guide for Pore-Liquid Sampling from the Vadose Zone. D4696-18. (Consensus standard on equipment and procedures used for sampling water from the unsaturated zone) Link to the standard

U.S. EPA. 2019. Leaching Environmental Assessment Framework (LEAF) How-To Guide. Understanding the LEAF Approach and How and When to Use It. Link to the guide

3. Summary Statement on Use of Lysimeters for PFAS Investigations

A lysimeter is a device for measuring the movement of water through soil (percolation) and the concentration of soluble substances in soil water. Although there are many types of lysimeter devices, the suction lysimeter was the type specified in the work plans and QAPPs reviewed herein. Suction lysimeters collect soil water by vacuum (negative pressure) where the volume of soil sampled depends on soil texture and water content. Lysimeter sample results are typically not reproducible because water content is spatially and temporally variable, and soil texture is spatially variable. When used for PFAS investigations, the affinity of PFAS for the air-water interface confounds results, which makes the representativeness of one-time lysimeter samples suspect when evaluating impacts to groundwater over a season or from year-to-year. PFAS that accumulate at the air-water interface are redistributed as the soil moisture conditions change during the season in response to infiltration events and water-level fluctuations: as the air is displaced by water the PFAS that were at the interface may partition to soil and water. The samples collected using suction lysimeters are appropriate for qualitative comparisons of mass flux from soil to groundwater. However, suction lysimeters are not appropriate for making remedial decisions, such as whether to remove PFAS-contaminated soils or manage the soils in place, unless and until they are shown to yield reproducible and representative data that is pertinent at a specific site. At the Site Inspection (SI) and RI stage, leaching tests and soil results, along with groundwater results, are useful for identifying soil source areas, making removal action decisions, and developing site specific screening values. Lysimeters can then be used in temperate and semi-arid zones where most infiltration occurs through snow melt, when collocated and calibrated with leaching test, soil, and groundwater results, to monitor the performance of remedial actions such as capping or managing source areas in place. Care should be taken to ensure that lysimeter placement is above any permanent or transient capillary fringe associated with the groundwater table to ensure that the sample is from porewater in the vadose zone and not from the groundwater in the capillary fringe zone.

A multiple lines of evidence approach, which might include a combination of lysimeters, leaching protocols, groundwater transects, and soils analysis, is preferred for developing site specific cleanup levels for PFAS. Results from leaching protocols are more representative of the seasonal PFAS concentrations that are generated from impacted soil.

Disclaimer: Research on air-water interface dynamics is active and the statement above represents the current thinking.

4. Summary of Lysimeter Use during Remedial Investigations

Work plans and QAPPs for RIs at the following installations were reviewed to better understand how lysimeters are being used at federal facilities:

- Eielson AFB, Fairbanks, Alaska
- Ellsworth AFB, near Rapid City, South Dakota
- Hill AFB, near Salt Lake City, Utah
- Luke AFB near Phoenix, Arizona
- Pease AFB, Portsmouth, New Hampshire
- Travis AFB, near Sacramento, California

These were the work plans made available to the team and do not represent the full range of climate, water infiltration, precipitation, or depth to groundwater found throughout the United States.

Most work plans stated that suction lysimeters were to be installed in areas with the highest PFAS soil concentrations. The exception was at Eielson AFB where lysimeters were to be used to monitor if PFAS could be left in place in areas where PFAS soil concentrations do not warrant removal. The stainless-steel suction lysimeters from Soil Measurement Systems were the most often specified. These were to be installed with 200 mesh silica flour as packing material around the porous membrane. Most work plans contained a standard operating procedure (SOP) for lysimeter installation and sampling. Some of the SOPs were by consultant firms such as AECOM, Arcadis, CH2M, and Wood (see Appendix A for a comparison of SOPs). The other work plans stated lysimeter installation will be based on manufacturer's instructions and the ASTM D4696-18 standard guide. Installation depths, where specified, ranged from 3 to 30 feet below ground surface (bgs), except at Hill AFB where suction lysimeters were to be installed as deep as practically possible or just above the water table which is 100 feet bgs in some areas. [Note: The maximum sample depth for a dual-chamber suction lysimeter is approximately 50 feet bgs, see Section 5.1] The overall objectives for using lysimeters was to evaluate and quantify the potential for PFAS in soil to impact groundwater. As described in the following section, the data quality objectives (DQOs) for each investigation varied from no stated objectives to using lysimeters in conjunction with leaching tests and soil concentrations, along with groundwater transects, to quantify the PFAS leaching from the source zone into groundwater.

4.1. Data Quality Objectives

The following are brief excerpts from Worksheet #11 of each QAPP showing the extreme range in DQOs.

Eielson AFB: DQO #4 – Source strength Evaluation

- "Determine the soil to groundwater concentration ratio to evaluate leachability of PFAS at the 13 validated source areas at Eielson AFB."
- "Determine the relationship between validated source area groundwater quality compared to upgradient and downgradient groundwater quality to determine contribution from a validated source area."

- Information inputs include “Source area soil, source area groundwater including immediately up and downgradient groundwater, Synthetic Precipitation Leaching Procedure (SPLP) data, cation exchange capacity (CEC) data, anion exchange capacity (AEC), total organic carbon (TOC), and hydrogeological information collected during previous investigations.”

Ellsworth AFB Data Gap Investigation: “Collection of site-specific soil porewater data using lysimetry may be a viable alternative to using SSLs as characterization screening levels. Porewater data from lysimeters can provide a definitive measurement of the spatially integrated in situ mass discharge of PFAS to groundwater, and account for all site-specific soil retention processes and rates.” Goal is to “Assess the concentrations of PFAS and pH, permeability, TOC, and anion and cation exchange capacity in vadose zone soil and concentrations of PFAS in porewater in FT001 (former FTA) to evaluate the potential for preferential leaching by compound of residual PFAS from soil to porewater; determine if specific residual PFAS concentrations in soil are being transported via porewater to groundwater.”

Ellsworth AFB Basewide Investigation: “Source Strength and Mass Flux: Suction lysimeters will be installed within each PFAS source area during the adaptive phase of the investigation to evaluate PFAS mass loading to groundwater at each source area.” “Source strength and mass loading of the PFAS Source Areas will be evaluated using a combination of soil sampling for circum-neutral synthetic precipitate leaching procedure (SPLP) in addition to the lysimeter porewater samples.” “Vertical aquifer profile (VAP) groundwater sampling will be completed to evaluate the mass flux of PFOA/PFOS/PFBS in groundwater migrating from the source areas…” “A VAP transect will be installed downgradient of each source area…”

Hill AFB: Proposed Study Question 1: Are source areas present that continue to contribute to an ongoing release of PFAS to groundwater?

- “If PFAS are detected in soil, then the area will be included as a location where a PFAS source might be contributing to an ongoing release of PFAS to groundwater. Evaluation of whether a potential area is contributing to ongoing release of PFAS will also include consideration of other lines of evidence (soil concentrations with depth, depth to groundwater, spatial groundwater concentration trends and lysimeter/pore water data from select areas).”
- “Up to three subsurface suction lysimeters will be installed at three different locations to collect pore water samples for analysis of PFAS...” “The pore water data will be screened against site specific pore water screening levels developed in accordance with EPA guidance…”

Luke AFB: “…there are no DQOs associated with lysimeters but AF wants to use the data to assess the soil to groundwater factor and to determine whether any soil removal actions are needed during the FS.”

Pease AFB: “…pressure-vacuum lysimeters will be used to evaluate PFAS contamination in soil and transport via porewater to groundwater, impacts on precipitation and PFAS leaching, provide data for fate and transport modeling and evaluate mass discharge of contaminants in surface soil to subsurface soils.”

Travis AFB: “Lysimetry will be used to sample pore water with the objective of assessing site-specific mass flux.”

4.2. Potential Additional DQOs

The following DQOs could be considered when using lysimeters to measure and investigate hydrological, chemical, and biological processes:

- measure energy balance of water and soil
- water quality measurements of micro-contaminants
- compound specific isotope analysis to demonstrate contaminant transformation
- study water balances

5. Overview of Lysimeters

A lysimeter is a device for measuring the movement of water through soil (percolation) and the removal of soluble substances (leaching losses) from a column of soil under controlled conditions (SSSA, 2008). There are many types of lysimeters, and they can be classified by the tension applied and type of water collected (macropore water, micropore water, water at zero potential or gravitational water) (Singh et al., 2018). If zero tension is applied during soil water extraction, porewater is only collected when saturated conditions persist above the collection device (gravitational flow). Common samplers that operate under zero tension are: drainage lysimeters or soil columns, pan lysimeters, and ion exchange resin bags. Applying tension (or vacuum) to soil results in the extraction of soil water from capillaries and micropores. The most widely used samplers in this category are wick lysimeters, suction cup lysimeters, and suction plate samplers.

As noted previously, suction lysimeters with silica flour packing material around the porous membrane were most often specified in the reviewed work plans/QAPPs.

5.1. Suction Lysimeter

A suction lysimeter consists of a hollow, porous section attached to a suction line (single chamber) or sample collection reservoir (dual chamber) (ASTM International, 2018). The porous section is installed at the subsurface depth from which a porewater sample is to be collected. Porewater is collected by applying a vacuum to the porous section, which can be made of ceramic or sintered stainless-steel. The vacuum level applied depends on the air-entry pressure of the water-saturated porous section (i.e., bubbling pressure), higher vacuum levels can be used with ceramic compared to sintered stainless-steel. When collecting a sample using suction lysimeters, the tension or vacuum applied should mimic the surrounding soil matric potential as indicated by a tensiometer installed adjacent to the sampling area (Singh et al., 2018).

The depth from which a sample can be collected depends on the type of suction lysimeter installed. The single-chamber suction lysimeter has a maximum depth of approximately 25 feet bgs, and the dual-chamber, or pressure-vacuum lysimeter, has a maximum depth of approximately 50 feet bgs (ASTM, 2018). The dual-chamber stainless-steel suction lysimeters from Soil Measurement Systems are recommended for depths greater than 10 feet bgs (SMS Inc., 2022).

There is a higher chance of failure to collect a porewater sample for suction lysimeters compared to other types of lysimeters if they are not installed carefully (Singh et al., 2018). Good hydraulic contact between the porous section and the soil is needed, especially in coarse-textured soils. To ensure proper installation, a slurry of native fine soil or silica flour (further discussed below) is poured into the annular space between the borehole and the porous section. Native soils collected from the respective interval of the soil boring/well should be used to backfill the borehole. A sodium bentonite seal near the ground surface is used to prevent water flow vertically down the borehole to the porous section.

Suction samplers can account for temporal and spatial variability of soluble chemicals when installed in large numbers at a site (Singh et al. 2018). However, suction samplers are not designed to capture macropore flows. During heavy precipitation events, porewater can easily bypass the suction lysimeter installed in coarse textured and well-structured soils. In fact, some investigators state that suction lysimeters are not suitable for measuring the flux of dissolved contaminants from soil to groundwater (Barkle et al., 2014).

5.2. Silica Flour Packing Material

Silica flour is often used to fill the annular space between the porous section and the borehole and represents another material that PFAS must travel through before reaching the lysimeter sample collection reservoir. No information on the potential for PFAS to adsorb to silica flour was found other than one anecdotal report by Schaefer et al. (2022) stating that parallel laboratory testing showed negligible sorption of PFOS to silica flour. Not only could PFAS adsorb to silica flour or other components that adsorb to high-surface area silica flour (e.g., dissolved organic carbon), but PFAS will partition to the air-water interfacial area in silica flour. Thus, the concentration of PFAS in samples collected from lysimeters using silica flour as a packing material are likely to be lower than what is present in the porewater of the unsaturated zone. However, there are no studies that confirm this possibility.

5.3. Overview of Guidance on Suction Lysimeters

There are two existing guidance documents on the installation and sampling of suction lysimeters: EPA's guidance document on monitoring the unsaturated zone at permitted hazardous waste land treatment units (U.S. EPA, 1986) and the ASTM's consensus standard on sampling porewater from the vadose zone (ASTM International, 2018). These documents offer a wealth of information where the following bullets provide some key points:

- The inherent heterogeneities of unsaturated porewater movement limit the degree to which samples collected with suction lysimeters can be considered representative. Suction lysimeter samples are good for qualitative comparisons, they cannot be used for quantitative analysis unless the variabilities of the parameters involved are established (ASTM § 7.6.2.1).
- The volume of soil sampled by a suction lysimeter depends on soil texture and water content (ASTM § 7.5.2.5 and § 7.5.2.6).
- A primary goal of porewater sampling is to detect fast moving hazardous constituents (EPA § 4.8.2).
- Sampling of suction lysimeters should occur immediately after infiltration events such as rainstorms, spring melts, or irrigations to capture higher porewater and contaminant flow rates (EPA § 4.8.1 and ASTM § 7.5.2.8).
- Installing samplers at interfaces between coarse and fine materials can capture perched porewater (ASTM § 7.5.2.8).
- Sample volume is greatly reduced under very dry conditions and long sample collection times may cause air to enter the porous membrane which restricts further water movement into the sampler due to hysteresis (EPA § 4.8.1 and ASTM § 7.6.1.1).
- A porewater sample from a suction lysimeter should be considered an average of the total flux past the sampler during the sampling interval (ASTM § 7.6.1.6).
- Pan lysimeters may be more suitable at sites where macropore flow is expected (EPA § 4.8.2 and ASTM § 7.6.1.6).

- Contaminant interactions with lysimeters should be determined by laboratory studies before installing at a site (EPA § 4.8.3.2).

6. Overview of Soil Leaching Protocols

Leaching protocols involve mixing soil with set volumes of liquid to determine the concentration of contaminants released from soil to water. These results are used to estimate contaminant mobility in soil. The chemistry of PFAS, such as the potential for sorptive loss onto common materials used in laboratory equipment, can complicate the analysis of dissolved concentrations and result in an underestimation of actual leaching potential. As a result, caution should be exercised when drawing conclusions from these laboratory leaching tests. The use of leaching protocols for PFAS in soil is an active area of research and guidance is expected soon. In the interim, the following provides a brief overview of the protocols likely to be used to determine PFAS mobility in soil.

6.1. Synthetic Precipitation Leaching Procedure (SPLP), SW-846 Method 1312 (U.S. EPA, 1994)

The SPLP is a batch equilibrium test in which a minimum of 100 g of soil sample is prepared by initially filtering through a 0.7-0.8 µm glass fiber filter using positive pressure or vacuum (if the “as-received” sample contains a liquid phase), followed by addition of a mildly acidic leaching solution to the solids in a 1:20 solid-to-solution ratio and mixed end-over-end at 30 rpm for 18 hours at ambient temperature (21 to 25 °C). After tumbling, the leaching solution is separated from the solids again by vacuum or pressure filtration and combined with any initial filtrate so long as they are mutually miscible. These combined filtrates, defined as the SPLP extract, may then be tested for organic and/or inorganic constituents. Samples are subjected to specific, separate handling procedures when volatile organic chemicals are of interest. The concentrations in the SPLP extracts are reported in aqueous concentration units without normalizing to the initial solids mass. According to EPA’s soil screening guidance, the SPLP test results can be used to calculate a site-specific soil to groundwater screening levels (U.S. EPA, 1996).

6.2. Liquid-Solid Partitioning as a Function of Extract pH, SW-846 Method 1313 (U.S. EPA, 2017)

Method 1313 is a batch equilibration test in which replicate subsamples of a solid are equilibrated with an aqueous leaching solution at a 1:10 solid to solution ratio either at its natural/unadjusted pH, which may vary depending on the material, or at a pH adjusted to a range of values between 2 and 13. Liquid-solid equilibration is then achieved by mixing end-over-end at 28±2 rpm at ambient temperature (21 to 25 °C). Initial solid sample mass and equilibration times specified in the method depend on the particle size of the solid sample. After equilibration, liquid-solid separation is achieved by filtering through a 0.45 µm particle filter, and the concentrations of constituents in the aqueous leaching solutions are then determined at each measured pH value.

6.3. Liquid-Solid Partitioning as a Function of Liquid-to-Solid Ratio in Solid Materials, SW-846 Method 1316 (U.S. EPA, 2017).

Method 1316 is a batch equilibration test in which replicate subsamples of a solid are equilibrated with an aqueous leaching solution at its unadjusted/natural pH across a range of liquid to solid ratios from 10:1 to 0.5:1. As with method 1313, initial solid sample mass and equilibration times depend on particle size, and this method uses the same approach to liquid-solid equilibration and phase separation. The concentrations of constituents in the aqueous leaching solutions are then determined as a function of liquid to solid ratio.

6.4. Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials Using An Up-Flow Percolation Column Procedure, SW-846 Method 1314 (U.S. EPA, 2017)

Method 1314 is an up-flow column percolation test in which a solid sample is dried and size reduced, as needed, and packed into a column through which reagent water is pumped at a flow rate of 0.5-1 mL of aqueous solution per dry gram of solid. Eluate fractions are collected at defined liquid-to-solid (L/S) ratios ranging from approximately 0.2:1 to 10:1, which are then analyzed for the constituents of interest to provide a profile of leachate concentration as a function of L/S ratio.

Methods 1313, 1314, and 1316 are part of the Leaching Environmental Assessment Framework (LEAF). The LEAF methods have only been validated for inorganic constituents. EPA is currently in the process of demonstrating and validating a corresponding set of LEAF methods with process changes to ensure compatibility with organic constituents including PFAS. According to EPA's LEAF how-to guide, the outputs of the methods can be used to provide an estimate of source term, i.e., as a concentration or release rate, for each constituent that can be used as inputs in a fate and transport model along with site-specific conditions or hypothetical management scenarios. For example, estimated groundwater concentration resulting from each soil could be determined using the maximum concentration observed ($C_{leach, max}$) divided by the groundwater dilution attenuation factor (DAF) (U.S. EPA, 2019, Section 4.4.7).

7. Review of Lysimeter Results from the Ellsworth AFB Data Gap Investigation

Quarterly sampling results from suction lysimeters at the Ellsworth AFB fire training area (FTA) were the only results made available for this review (see Anderson et al., 2022). The investigation involved 12 lysimeter pairs installed in June of 2021 at depths of approximately 3 and 10 feet bgs and within 4 feet of each other. The deeper depths were in the most transmissive zones based on hydraulic profiling tool logs. Collocated soil samples were collected for soil texture, permeability, cation and anion exchange capacity, pH, total organic carbon, moisture content, and 16 PFAS. The lysimeters were sampled in June, October, and December of 2021 and in April of 2022.

One key observation was that the lysimeters often did not yield enough sample volume for analyses. Less than 5 mL of sample was obtained after 48 hours from 11 of the 12 shallow (3 feet bgs) and 2 of the 12 deep (10 feet bgs) suction lysimeters. Low sample volume was also noted during the investigation at Camp Grayling and was overcome by irrigating the site to yield enough sample for analysis (Quinnan et al., 2021). In addition, for lysimeters at the Ellsworth AFB FTA that yielded water, the volume collected from each lysimeter was highly variable, ranging from 5 to 415 mL. This may indicate that, due to differences in soil properties between lysimeter locations, the volume of soil sampled at each lysimeter was not consistent between locations or over time, which is one of the limitations of lysimeters (Singh et al., 2018). The variability in sample volumes was acknowledged as increasing the potential for sampling error, however, the lack of a trend between the variance in PFAS concentrations and sample volumes was suggested to demonstrate there was no measurable effect on porewater concentrations (Anderson et al., 2022).

Additionally, and of note, was that the porewater data collected during the study were too highly variable to make any quantitative conclusions. As such, one of EPA's primary comments on the *Ellsworth AFB Data Gap Investigation for PFAS (Lysimeter Study)* report was that refining the soil to groundwater protection values from the most current EPA regional screening levels could not be supported by the lysimeter study.

Another key observation was that the analytical limits of detection (LODs) for the lysimeter porewater samples were in the 1,000 to 10,000 ng/L range. This was due to the lysimeters being installed in locations with the highest PFAS soil concentrations resulting in porewater concentrations in the 1,000,000 ng/L range. This meant PFAS porewater concentrations below the 1,000 to 10,000 ng/L were reported as not detected which limited the utility in defining the extent of contamination.

8. Possible Questions Regarding Use of Lysimeters

The following questions were developed based on the review of the above information, the Ellsworth case study, and the available information on lysimeters. These questions could be considered when reviewing project plans that propose using lysimeters to investigate PFAS. Technical support staff should be consulted in the review process, such as regional Superfund and Technology Liaison (STL). If technical support staff are not available, reach out to your team lead for advice.

- Are site conditions conducive to the use of lysimeters to meet project DQOs?
    - In addition to physical soil properties (e.g. lithology, heterogeneity, etc.), depth to groundwater, and climate considerations, are there co-located contaminants or previous remediation efforts that may affect PFAS transport or have caused PFAS transformation?
- Are additional lines of evidence planned to demonstrate that the suction lysimeter samples are reproducible and representative of site conditions?
    - Duplicate analysis of lysimeter samples provides information about analytical accuracy, not information on reproducibility or representativeness of a lysimeter sample.
    - Will a transect of groundwater samples be used to estimate the flux of PFAS migrating from soil in both the vertical and horizontal planes?
    - If soil-water partitioning coefficients or ratios are calculated (i.e., K_d values), how do they compare to the range of values tabulated in Rovero et al. (2021) for selected PFAS?
    - How will it be determined that the residual water introduced during lysimeter installation is removed prior to sample collection (e.g., bromide tracer)?
- How will PFAS concentrations in samples be normalized to account for the different volumes of water that are likely to be collected at each suction lysimeter location so that results can be compared between locations and over time?
- What procedures will be used if a suction lysimeter fails to yield enough sample volume for analysis?
    - What is the minimum volume of sample acceptable for analysis? Note, most analysis methods specify a minimum sample volume in the 250 to 500 mL range.
- During sample collection, how will the vacuum be adjusted to account for the soil texture and water content present at the suction lysimeter location?
- How will the appropriate number and location of suction lysimeters be determined?
- In calculating the flux of PFAS to groundwater,
    - How will the infiltration or groundwater recharge rate be determined (e.g., infiltrometer)?
    - How will the concentration of PFAS in the macropore water be accounted for since suction lysimeters primarily sample from micropore water?
    - Are there enough lysimeters installed to account for PFAS in the infiltration area?

9. Collocated Soil Geochemical Parameters

Collocated soil samples should be collected during lysimeter installation from the depth at which the porous section is placed and analyzed for the geochemical parameters given in Table 1.

Table 1 - Recommended Geochemical Parameters for Collocated Soil Samples

Parameter	**Purpose**
TOC, organic carbon	PFAS sorption/desorption; transport and fate analysis (Anderson et al., 2019; Li et al., 2018; Rovero et al., 2021)
pH	PFAS sorption/desorption; transport and fate analysis (Campos Pereira et al., 2018; Nguyen et al., 2020)
Particle Size	Drainage; sorption; Conceptual Site Model (Anderson et al., 2019; Gnesda et al., 2022)
Moisture content	Drainage & PFAS mobilization; Conceptual Site Model (Gnesda et al., 2022)
CEC, cation exchange capacity	Measure of the total negative charge within the soil that can adsorb cations (e.g., Ca, Mg, Na, K, Fe); method is routine (Anderson et al., 2019; Li et al., 2018; Rovero et al., 2021)
AEC, anion exchange capacity	Measure of the total positive charge within the soil that can adsorb anions (e.g., negatively charged PFAS); method less routine compared to CEC (Li et al., 2018)
NOTES	Sample collection in HDPE, PFAS-free materials. Another parameter that has been noted in studies is "extractable iron concentration", related to iron mineralogy and potential sorption sites for PFAS. (Gao and Chorover, 2012)

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Appendix A Standard Operating Procedure Overview

Table A-1: Lysimeter Type and Installation

Author	Lysimeter	Borehole	Packing	Backfill
Arcadis	Ceramic cup	2- to 4-inch diameter borehole for greater than 3 feet bgs	Lower ceramic cup into borehole and then tremie in 5 feet of 200 mesh silica flour slurry with 3 feet of slurry above ceramic cup.	Bentonite grout as backfill to surface for deep installations and sifted soil at shallow locations.
AECOM	Stainless steel (dual chamber)	Borehole diameter not specified	Tremie in 10 kg of 200 mesh silica flour with 150 mL of PFAS-free water or use soil from the bottom of the borehole. Lower pre-wetted lysimeter into the borehole and gently press into slurry. Add additional slurry until one foot above the porous section.	Add 6 inches of sand filter pack followed by 6 inches of bentonite tablets or chips. Add PFAS-free water to wet bentonite. Backfill to surface with grout or native material.
CH2M	Single or dual chamber (material not specified)	3 inches greater than porous cup	Tremie in 3-inch depth of silica flour slurry (one-part distilled water to three parts silica flour). Lower pre-wetted lysimeter into borehole with augers in place. Tremie in silica slurry to 1.5 feet above porous cup and then remove auger.	Add a 6-inch layer of No.1 grade silica sand followed by hydrated bentonite pellet seal with thickness of 2 feet. Backfill with portland cement-bentonite mix (20:1) to ground surface.
Wood	Stainless steel (single or dual chamber)	2-inch diameter auger or 4-inch diameter for rocky soil	Tremie in 1 pound of 200 mesh silica flour with 150 mL of laboratory supplied PFAS-free water slurry into 2-inch diameter hole. Lower pre-wetted lysimeter into slurry with 3 inches of slurry below and 1.5 feet of slurry above the porous section.	Add 6 inches of sieved native soil from same depth followed by 6 inches of bentonite to isolate lysimeter. Backfill to surface with native material free of pebbles and rocks
ASTM D4696-18	Ceramic cup, stainless steel, or PTFE*	4- to 5- inch diameter for 2-inch diameter lysimeter (§ 7.4.2.4)	Lower lysimeter filled with distilled water into borehole (§ 7.4.2.5) and then tremie in 200 mesh silica flour with 150 mL of distilled water to 30 cm (11.8 inches) above the lysimeter body (§ 7.4.2.6)	Add 15 cm (5.9 inches) of hydrated bentonite plug above silica and backfill to surface with native material (§ 7.4.2.6)

*PTFE is not recommended when sampling for PFAS

Table A-2 - Lysimeter Sample Collection

Author	Lysimeter	Vacuum	Rewetting	Collection Vessel
Arcadis	Ceramic cup	0.6 bar for 24 to 48 hours	Add 250 mL of deionized water down the sample line to rewet the ceramic cup if necessary.	Not specified.
AECOM	Stainless steel (dual chamber)	0.3 bar in sandy soils or 0.5 bar in loams and gravelly clay loams from 1 to 24 hours	Not specified	250 mL sample container not otherwise specified
CH2M	Single or dual chamber (material not specified)	Sampling may begin 24 hours after installation and development. Use vacuum per manufacturer's recommendation.	Not specified	Not specified
Wood	Stainless steel (single or dual chamber)	0.3 bar in sandy soils or 0.5 bar in loams and gravelly clay loams from 1 to 24 hours	Not specified	250 mL sample container not otherwise specified
EPA	Ceramic cup or PFTE*	Evacuate samplers 2-3 days prior to sample collection to obtain fresh sample. 0.6 bar for minimum of 24 hours.(§ 4.7)	Install tensiometer to verify enough water present. Reinstall lysimeter if enough water is present per tensiometer.	Not specified

*PTFE is not recommended when sampling for PFAS