# FINAL REPORT

## Enhanced Oxidative Destruction of PFAS in Investigation Derived Waste Soil and Water

SERDP Project ER18-1545

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**14. ABSTRACT**
Our team tested an ex-situ, on-site destructive technology for per- and polyfluoroalkyl substances (PFAS) present in soil and water investigation-derived waste (IDW). Our proof-of-concept study demonstrates that PFAS, including recalcitrant compounds such as PFOS and PFBA, can be destroyed by chemical oxidation with OxyZone® when combined with foamation/UV irradiation. The treatment is further aided by a low cost, patented non-toxic, biodegradable XCT® solution which promotes the desorption of PFAS from soil. Our approach not only addresses PFAS in soil and water but has also been found to degrade co-contaminants in prior studies, such as 1,4-Dioxane, polynuclear aromatics, chloroethenes, chloroethanes. Importantly, there is evidence that this technology also mineralizes a broad range of currently difficult to quantify PFAS compounds. Further, we examined the cost effectiveness, including potential limitations and risks of our treatment approach and compared it to current disposal methods, mainly incineration. Our estimates indicate that our technology likely is less costly and has a lower ecological footprint relative to incineration. However, no full-scale tests have been performed so far to back-up our estimates. Potential limitations of our combined soil/water treatment approach include: 1) soil treatment is not applicable to high organic content soils, such as peat or clayey soils 2) water treatment is not applicable to high salinity or high alkalinity water, and 3) treated water may not be discharged back into a drinking water supply aquifer, but could be discharged to the wastewater stream, depending on local regulations.

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**List of Acronyms**

| | |
|---|---|
| AFFF | Aqueous film forming foam |
| AOP | Advanced oxidation process |
| $C_0$ | Initial concentration |
| $C/C_0$ | Relative concentration |
| CVOC | Chlorinated volatile organic compounds |
| DoD | Department of Defense |
| DW | Distilled water |
| EEI | EnChem Engineering, Inc. |
| EPA | United States Environmental Protection Agency |
| GW | Groundwater |
| IDW | Investigation-derived waste |
| HDPE | High-density polyethylene |
| JBASWG | Joint Base Naval Air Station Willow Grove |
| LCMSMS | Liquid chromatography – Mass Spectrometer/Mass Spectrometer |
| LHA | Lifetime Health Advisor |
| MADEP | Massachusetts Department of Environmental Protection |
| MCP | Massachusetts Contingency Plan |
| NELAP | *National Environmental Laboratory Accreditation Program* |
| ORP | Oxidation-reduction potential |
| PAH | Polycyclic aromatic hydrocarbons |
| PFAA | Perfluoroalkylic acids |
| PFAS | Per- and polyfluoroalkyl substances (please see laboratory reports for abbreviation of individual PFAS compounds) |
| QSM | Quality Systems Manual |
| RPB | Remedial Project Managers |
| SERDP | Strategic Environmental Research and Development Program |
| TOP | Total Oxidizable Precursor |
| VOC | Volatile organic compounds |
| VPH | Volatile petroleum hydrocarbons |
| Uri | University of Rhode Island |
| UV | Ultraviolet light |
| WG | Willow Grove |
| XCT® | Extra Contact Technology |

**Keywords**

Investigation derived waste (IDW), PFAS, PFOS, PFOA, Remediation, Advanced oxidation process, OxyZone®, XCT®, Foam fractionation, UV irradiation, *ex-situ* treatment

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## Executive Summary

*Introduction*

In this study, we demonstrated the effectiveness of the OxyZone® ex-situ destructive technology for cost-effective and reliable on-site treatment of per- and polyfluoroalkyl substances (PFAS) present in soil and water investigation-derived waste (IDW). Based on PFAS contaminated IDW obtained from the Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN); in the following referred to as "Willow Grove" (WG) material, we demonstrated that PFAS can be mineralized to the degree that disposal might be possible.

The Department of Defense (DoD) has identified approximately 600 of fire/crash/training sites that are potentially PFAS contaminated (SERDP 2012). The presence of PFAS in soil and groundwater presents a liability and DoD has begun performing investigations to determine the extent of PFAS contamination across its installations. During the course of these investigations, large quantities of IDW are being (and will continue to be) generated. While incineration is a destructive treatment option for IDW waste disposal, this approach is costly. Hence, there is a critical need for alternative treatment technologies that are more economical and which permit unrestricted disposal, discharge, and/or reuse of IDW on-site.

OxyZone® technology is a patented advanced oxidation process (AOP) developed by EnChem Engineering Inc. (Newton, MA), which utilizes a proprietary blend of dissolved ozone, sodium persulfate, food grade phosphate-based buffers, and dilute hydrogen peroxide. In this oxidant blend, ozone and hydrogen peroxide (peroxone) are used as an activation agent to facilitate the production of hydroxyl (•OH) and sulfate radicals (•$SO_4^-$) and superoxide (•$O_2^-$); some of the strongest oxidants available (Table 1). As a result, OxyZone® is able to break down quickly organic contaminants through primary oxidation reactions, via ozone and persulfate molecules, as well as through more vigorous secondary oxidation reactions, via hydroxyl and sulfate radicals. The more advanced, patented XCT® (eXtra Contact Technology) and XCT-OxyZone processes contain a nontoxic, biodegradable desorbing compound that aides in the removal and destruction of PFAS.

*Objectives*

The overall objective of this project was to test an innovative, destructive treatment approach for the *ex situ*, on-site treatment of PFAS contaminated IDW soil and groundwater matrices. We postulated that in most cases, our technology permits the unrestricted disposal, discharge, and/or reuse of IDW

on-site. We conducted semi-bench scale studies followed by a proof-of-concept, larger volume study to demonstrate that the future on-site destruction of PFAS compounds with our patented peroxone activated persulfate oxidation process is possible and feasible. Our particular research questions and objectives were:

*Question I*: How fast and to what extent can a peroxone activated persulfate oxidant destroy PFAS compounds when applied to soil or water IDW or mixtures thereof?

*Objective*: Subjecting IDW material (soil, water) to a powerful, advanced oxidant to destroy PFAS contaminants.

*Question II*: Does this innovative IDW treatment approach reduce the environmental risk and cost when compared to conventional disposal methods?

*Objective*: Assessing the degree of IDW treatment by comparing before/after treatment contaminant concentration and determining if the treated material poses environmental risks that could prevent the unrestricted on-site disposal from a regulatory perspective.

*Question III*: What data must be acquired to develop a complete proposal for a more extensive follow-on study?

*Objective*: Acquiring scientific and economic data in support of technology upscaling under a variety of site conditions and contaminant inventories.

The data generated during the study clearly show that PFAS compounds can be destroyed and that up-scaling to a full-scale, on-site treatment system may be an cost effective alternative to current PFAS IDW treatments.

*Technical Approach*

Our experimental approach was organized by five tasks, namely:

*Task 1* Semi-Batch Experiments (PFAS amended distilled water (DW), IDW PFAS contaminated water*)*

*Task 2* Semi-Batch Experiments (IDW PFAS contaminated soil)

*Task 3* Design and Testing of Semi-Batch Scale Continuous Flow Gas Infusion Reactor for IDW Water and IDW Soil Slurry

*Task 4* System up-scaling: Pilot-Scale Gas Infusion Reactor Experiments for IDW Batch Mode Treatment

*Task 5* Report Preparation

During the initial stage of our experimental approach (Tasks 1 to 3) we performed laboratory experiments to adjust and optimize our treatment approach for the characteristics of the IDW (water/soil) waste that contains PFAS and, possibly, co-contaminants. Based on the initial optimization tests, we proceeded to pilot-scale testing (Task 4). All experiments were carried out in semi-batch mode for cost reasons. The studies were carried out largely in the EnChem Engineering, Inc. facilities in Newton, MA. The data collected along the way was used for studying design, cost, and implementation requirements for proposing a full-scale systems.

The PFAS analysis of solid and liquid samples was performed by BV Laboratories in Mississauga, ON, Canada. BV Laboratories (formerly Maxxam Analytics Laboratories) is NELAP accredited for the DoD QSM compliant method. The laboratory analyzes 23 (including two telomeres) PFAS by LCMSMS Compliant with QSM 5.1 Table B-15.

*Results and Discussion*

The treatment of IDW soil is a three-stage process, whereas only two stages are required for treating IDW water. After separating the fine (sand/silt/clay) from the coarse (gravel and larger) fractions of the IDW soil material, the (1) PFAS in the coarse fraction is rinsed off in a tumble reactor, possibly aided by the addition of our XCT solution which promotes desorption of PFAS from the mineral surfaces. The rinse water, either by itself or combined with IDW water, must be further treated. (2) The fine fraction of the IDW soil is rinsed with in a slurry reactor, again aided by XCT solution, until it meets soil standards for PFAS. The process water must be further treated. (3) The process water, either by itself or combined with IDW water, is treated by removing and concentrating PFAS from the solution via a stable foam of XCT solution. The concentrate is then subjected to ultraviolet light (UV) irradiation. This final treatment step leads to the mineralization of all 23 PFAS analyzed, except PFBA. The treatment endpoint for water was the current EPA Lifetime Health Advisor (LHA) concentration for PFAS (70 ng/L PFOS and/or PFOA) compounds in drinking water. Currently, no generally accepted method existed for determining the endpoint of treating PFAS contaminated soils. We addressed this issue by (1) developing a project-specific leachate testing procedure for formulating a possible treatment endpoint for soil and (2) relied on the Massachusetts Department of Environmental Protection (MADEP) for cleanup standards for PFAS in soil and groundwater, values for use in site-specific risk assessment, and notification criteria for soil and groundwater (www.mass.gov/lists/2019-proposed-mcp-revisions ). The Massachusetts Contingency Plan (MCP) Method 1 Soil Standards consider both the potential risk of harm resulting from direct exposure by

dermal contact and inhalation of soil particulates and the potential impacts of leaching to the groundwater at the disposal site. The MCP Method 1 groundwater standards consider human exposure to drinking water or exposure by environmental receptors by discharge to surface water. The soil standards are dependent on the applicable groundwater standards. The cleanup standards have recently been finalized and promulgated under the MCP. In Massachusetts, drinking water standards for PFAS have been proposed and are in the public comment phase.

*Implication for Future Research and Benefits*

Based on the data and results contained in this report, our team has demonstrated the proof of concept for the proposed ex-situ treatment of PFAS containing IDW soil by soil rinsing with a dilute XCT® solution and subsequent treatment of the process water; or treatment of IDW water. The proposed processes of soil rinsing followed by process water treatment or IDW water treatment are relatively low cost, on-site treatment alternatives compared to existing technology. Our technology should be tested and evaluated at field scale to assess those variables that can only be evaluated during a field scale pilot test, such as equipment size and site specific requirements. However, the end result of such a field scale test is not expected to change the overall results or outcome as compared to our current pilot scale testing.

During pilot scale testing, it is proposed that a soil slurry be first rinsed with XCT solution to remove PFAS to a very low residual concentration in the soil. The process water would then be treated using XCT® solution enhanced foam fractionation and UV enhanced OxyZone® process If there is any PFAS remaining in the soil, then it may be useful to use the OxyZone® process with the soil slurry after the rinse with XCT solution to investigate whether any PFAS residual can be further removed without adding any by-products. This second treatment is likely to provide an even lower PFAS concentration in the treated soil, although the added cost may not prove worthy. The results of bench scale testing reported here support this concept of sequential treatment, although not directly tested in the bench scale testing.

The following benefits of the proposed process are:

- The XCT® soil treatment process has the benefit that the proprietary rinsing agent is non-toxic and can bind to a broad range of PFAS, based on the published literature and from our results. It will also desorb a broad range of possibly co-contaminants, such as CVOC or PAH, which is well documented in the literature and from our own results. Furthermore, the

Team is not aware of any other soil treatment technology that uses a non-toxic rinsing solution (e.g. methanol is toxic and flammable) for PFAS removal from soil.

- Our IDW treatment is an *ex situ* process and therefore does not leave or create any toxic PFAS or their by-products in the subsurface.
- Our XCT® enhanced foam fractionation treatment step for process water or IDW water removes greater than 99.9% of PFAS, leaving a very low PFAS concentration nearing regulatory standards for drinking water after the foam is separated from the water.
- The separated foam containing the PFAS is concentrated by a factor greater than 10 times and is destroyed by our ultraviolet light (UV) enhanced OxyZone® process by greater than 99.9%.
- The Team is prepared to perform a field pilot test for *ex-situ* soil rinsing to remove PFAS from the soil followed by treatment of the process water (or IDW water, as needed) to demonstrate the process removes greater than 99.9% of the PFAS from the water.
- The technology is a viable cost effective on-site, *ex-situ* treatment alternative to incineration of soil and granular activated carbon or/resin technology for PFAS capture and treatment of IDW water.

# Abstract

*Introduction*: Our team tested an ex-situ destructive technology for cost-effective and reliable on-site treatment of per- and polyfluoroalkyl substances (PFAS) present in soil and water investigation-derived waste (IDW). The utilization of our treatment technology with a flexible chemistry and multi-stage treatment provides a high degree of certainty that PFAS and their potential chemical oxidation/reduction by-products and precursors are treatable on-site. This increases regulatory acceptance while simultaneously reduces the remediation time and expense as compared to current treatment technologies, such as off-site disposal or incineration. We conducted an initial series of semi-bench scale studies that lead to a proof-of-concept study, demonstrating that PFAS compounds can be destroyed under ex-situ, on-site conditions. Our treatment approach is based on chemically degrading the target contaminants via powerful sulfate, hydroxyl, and superoxide radical pathways in the presence of oxygen/ozone gas. The treatment is further aided by the non-toxic, biodegradable (XCT®) solution that promotes the desorption of PFAS from soil, forming a PFAS complex. Upon aeration, this complex forms a foam containing PFAS which can then be irradiated with the UV light enhanced OxyZone® processThis approach not only addresses PFAS, but has also been found to degrade co-contaminants and a broad range of currently difficult to quantify PFAS compounds. Some of which may be PFAS precursors. Particularly, we demonstrated that our technology is capable of degrading perfluorooctanesulfonic acid (PFOS), which is a notoriously difficult to destroy PFAS. We have designed and optimized our proof-of-concept system so that a future full-scale unit can be deployed easily, minimizing the spatial footprint and mobilization time and effort. Further, we compared the cost effectiveness of our approach to current disposal methods, mainly incineration of IDW PFAS containing soil, and we studied potential limitations and risks of our treatment approach. Our cost comparison indicates that our technology of soil rinsing of IDW soil, separation, and concentration of the PFAS from the rinse water by foam fractionation, followed by oxidative destruction of the PFAS concentrate is significantly cheaper than incineration of PFAS contaminated soil or water.

Potential limitations of our approach include: 1) the soil treatment is not applicable to high organic content soils, such as peat; or clayey soils 2) water treatment is not applicable to high salinity or high alkalinity water 3) treated water may not be discharged back into a drinking water supply aquifer, but could be discharged into other groundwater not used for drinking water, depending on local regulations.

*Objective*: Develop an innovative approach for the on-site treatment of investigation-derived waste that destroys PFAS compounds.

*Technical Approach*: Our treatment approach is based on chemically degrading the target contaminants via powerful sulfate ($\bullet SO_4^-$), hydroxyl ($\bullet OH$) and, possibly, superoxide ($\bullet O_2^-$) radical pathways in the presence of an ozone/oxygen gas mixture. We first conducted bench-scale studies that were followed by a proof-of-concept demonstration of our treatment approach at the pilot-scale, which is based on a patented peroxone activated persulfate oxidation process combined with the patented XCT® enhanced foam fractionation and UV /irradiation enhanced OxyZone® treatment.

*Results*: Over the funding period, we have conducted semi-bench scale studies followed by a proof-of-concept, larger volume study to demonstrate the on-site destruction of PFAS compounds. We postulated that in most cases, our technology permits the unrestricted disposal, discharge, and/or reuse of IDW on-site. The data generated during the study clearly show that PFAS compounds can be destroyed and that up-scaling to a full-scale, on-site treatment system may be a cost effective alternative to current PFAS IDW treatments with an XCT solution cost of $.04 per gallon (not including labor and equipment).

*Benefits*: Our efficient mobile on-site and ex-situ treatment technology for treatment of IDW from PFAS investigations can result in significant cost reductions compared to incineration and off-site disposal with legacy risks, which will greatly aid Department of Defense (DoD) Remedial Project Managers (RPMs) in the site management.

# 1. Objectives

The Department of Defense (DoD) is performing investigations to determine the extent of PFAS contamination across its installations. During the course of these investigations, large quantities of IDW are being (and will continue to be) generated. While incineration is a destructive treatment option for IDW waste disposal, this approach is costly. Hence, there is a critical need for alternative treatment technologies that are more economical and which permit unrestricted disposal, discharge, and/or reuse of IDW on-site.

The overall objective of this project was to test an innovative, destructive treatment approach for the *ex situ*, on-site treatment of PFAS contaminated IDW soil and groundwater matrices. We postulated that in most cases, our technology permits the unrestricted disposal, discharge, and/or reuse of IDW on-site. We conducted semi-bench scale studies followed by a proof-of-concept, larger volume study to demonstrate that the future on-site destruction of PFAS compounds with our patented peroxone activated persulfate oxidation process is possible and feasible. Our particular research questions and objectives were:

*Question I*: How fast and to what extent can a peroxone activated persulfate oxidant destroy PFAS compounds when applied to soil or water IDW or mixtures thereof?

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*Objective*: Acquiring scientific and economic data in support of technology upscaling under a variety of site conditions and contaminant inventories.

The data generated during the study clearly show that PFAS compounds can be destroyed and that up-scaling to a full-scale, on-site treatment system may be an cost effective alternative to current PFAS IDW treatments.

## 2. Background

Aqueous film forming foam (AFFF) formulations have been used by the DoD on many of its portfolio of sites. The predominantly used AFFF mixtures contained significant quantities of PFOS and related perfluoroalkyl sulfonates, such as PFHxS. To a lesser extent, DoD's legacy use of AFFF also included various fluorotelomer-based formulations. Because of their recalcitrance, PFAS are difficult to destroy with conventional treatment technologies. The U.S. Environmental Protection Agency (EPA) considers PFAS emerging contaminants with potential carcinogenic properties. It has recently issued drinking water health advisories for two common PFASs, namely PFOA and PFOS (0.07 µg/L individually or in total; EPA 2016) and many states are beginning to promulgate local drinking water standards.

The DoD has identified approximately 600 of fire/crash/training sites that are potentially PFAS contaminated (SERDP 2012). The presence of PFAS in soil and groundwater presents a liability and DoD has begun performing investigations to determine the extent of PFAS contamination across its installations. During the course of these investigations, large quantities of investigation derived wastes (IDW) are being (and will continue to be) generated. Often, the IDW also contains co-contaminants, for instance chlorinated solvents or 1,4-Dioxane. Current methods dictate landfilling of these wastes, but the DoD has a preference for destructive treatment technologies that minimize potential future environmental liabilities (SERDP 2017). While incineration is a destructive treatment option for IDW waste, this approach is costly. Hence, there is a critical need for alternative treatment technologies that are more economical and which permit unrestricted disposal, discharge, and/or reuse of IDW on-site.

| Oxidant | Standard oxidation potential (volts) |
|---|---|
| Hydroxyl radical ($\cdot OH$) | 2.8 |
| Sulfate radical ($\cdot SO_4^-$) | 2.5 |
| Ozone ($O_3$) | 2.1 |
| Superoxide ($\bullet O_2^- = O_2 + e^-$) | 0.18 |
| Persulfate ($S_2O_8^-$) | 2.0 |
| Hydrogen peroxide ($H_2O_2$) | 1.8 |
| Permanganate ($MnO_4^-$) | 1.7 |
| Chlorine ($Cl^-$) | 1.4 |
| Oxygen ($O_2$) | 1.2 |

**Table 1:** Commonly used oxidants. Bold: oxidants that are part of the OxyZone-XCT process. Sources: Huling and Pivetz (2006); Siegrist et al. (2001), Armstrong et al. (2013). Note: Superoxide can act as an oxidant or reductant.

One of the most promising PFAS treatment approaches is destruction by advanced oxidation processes (AOP). In AOPs, highly reactive free radicals attack and degrade otherwise recalcitrant compounds (Glaze et al, 1987), such as PFAS. The OxyZone® processis an AOP developed by EnChem Engineering (Newton, MA), which utilizes a proprietary blend of dissolved ozone, buffered sodium persulfate, food grade phosphate-based buffers, and dilute hydrogen peroxide. In this oxidant blend, ozone and hydrogen peroxide (peroxone) are used as an activation agent to facilitate the production of hydroxyl (•OH) and sulfate radicals (•$SO_4^-$) and superoxide (•$O_2^-$); some of the strongest oxidants available (**Table 1**). As a result, OxyZone® technology is able to break down organic contaminants through primary oxidation reactions, via ozone and persulfate molecules, as well as through more vigorous secondary oxidation reactions, via hydroxyl and sulfate radicals.

| **Property** | **Advantage** |
|---|---|
| No precipitation and clogging issues | Unlike other ISCO technologies, such as permanganate, precipitation and clogging issues in the treatment zone are avoided with the OxyZone® solution. This ensures (1) a stable flow field and (2) provides for contaminants to remain accessible to the oxidants. |
| Negligible heat and/or off gas emissions | Unlike Fenton's reagent and heat activated persulfate, very dilute concentrations of hydrogen peroxide make it safe to inject OxyZone® solution near and under buildings or subsurface utilities. |
| Environmentally safe | Treatment byproducts include sodium, sulfate, oxygen, small amounts of phosphate, and inert products such as water, and carbon dioxide. |
| Treatability of PFOS and PFOA | Most current soil/water PFAS regulations focus on treating PFOS and PFOA. Both compounds can be mineralized with our AOP. |
| Treatability of Co-Contaminants | Most likely PFAS co-contaminants are CVOC (such as Trichloroethene (TCE) or 1,1,1-Trichloroethane and associated 1,4-Dioxane stabilizer), gasoline compounds, and possibly PAH. All of them can be treated with our AOP. |
| Oxidation power persist longer than competing ISCO technologies | OxyZone® solution remains active for a few weeks rather than hours to days, such as peroxone (ozone and peroxide). Oxidant then completely disintegrates to benign products. Prolonged activity is advantageous because it limits contaminant rebound. |
| **Property** | **Potential Shortcomings** |
| Reactivity aboveground | Like most AOP technologies, the reactivity of the strong oxidants requires special handling and safety precautions aboveground. |
| Possible formation of by-products | Like with any competing AOP technologies, incomplete oxidation can lead to the formation of undesirable by-products (such as short-chain PFAS) |
| Cost and performance | Currently limited cost and performance data exist. Need for a field scale technology demonstration. |
| Soil oxidant demand (SOD) | Like with any competing AOP technologies, a fraction of oxidant will be consumed by organic matter naturally present in soil or by easy to oxidize co-contaminants that might be present at PFAS contaminated sites. |
| Inorganic co-contaminants | Contaminants that cannot be destroyed or converted by oxidation, such as most heavy metals or radiogenic isotopes, cannot be treated with our technology |

**Table 2:** Characteristics of the OxyZone® technology.

OxyZone® technology has already been field tested for the treatment of chlorinated solvents (Eberle et al., 2017). Studies under laboratory conditions demonstrate the this technology is also capable of destroying 1,4-Dioxane (Eberle et al. 2016) or petroleum hydrocarbons (Eberle 2012). **Table 2** summarizes the most important characteristics of this novel treatment approach.

For this project, a new approach was tested for treating investigation derived solid and aqueous waste (IDW) contaminated with PFAS. The treatment relies on the additive effects of multiple AOPs contained in OxyZone® combined with foamation/irradiation processes. The presence of nontoxic, biodegradable XCT® solution further aides in the destruction of PFAS.

## 2.1. Technical Approach

We already investigated the treatment of PFAS and co-mingled contaminants (Petroleum hydrocarbons, CVOC and 1,4-Dioxane) under both laboratory and field conditions (Eberle et al. 2016, 2017). Our data clearly demonstrate that all these compounds, including PFOS, can be treated with an advanced oxidant process developed by EnChem Engineering, Inc (EEI). of Newton, MA. This process exploits the strong oxidation potential of buffered persulfate when activated with ozone. The technology is commercialized by EEI under the brand name OxyZone®.

OxyZone® technology mineralizes PFOS and PFOA and many more PFAS compounds that are analyzable using a modified EPA Method 537. Another set of results shows that mineralization is a fast process, i.e. most aqueous phase PFAS can be destroyed by the OxyZone® process in a few hours. We also conducted Total Oxidizable Precursor (TOP) assays of PFAS contaminated site groundwater, which suggest that at least a fraction (i.e., any of those that are converted to one of the 23 quantifiable PFAS) of the PFAS precursors is converted and eventually destroyed or otherwise removed during treatment with the OxyZone® process. Our conclusions regarding PFAS mineralization are corroborated by fluoride anion recoveries, which show that fluoride (F-) is produced during the de-fluorination of PFAS compounds.

Our treatment approach is based on chemically degrading the target contaminants via powerful sulfate ($\bullet SO_4^-$), hydroxyl ($\bullet OH$) and possibly superoxide ($\bullet O_2^-$) radical pathways in the presence of an ozone/oxygen gas mixture (Cashman et al. 2019). This approach not only addresses PFAS and typical co-contaminants, but has also been found to degrade a broad range of PFAS compound. Some of which may be PFAS precursors. The initial strength of our oxidant solution is very high, i.e. >900 mV ORP and we can adjust the chemical formulation of our AOP solution to maintain pH condition

in the alkaline range (~pH 9) range, which we found advantageous for the oxidative destruction of most PFAS.

Our treatment technology addresses both water and soil IDW and relies on contacting the polluted IDW with XCT® solution and/or OxyZone® process in a staged system of treatment reactors. Soil and water are combined as a slurry. Materials that are difficult to suspend, i.e. coarser grained materials (gravel) or bulky IDW materials, such as rock cuttings, are removed from the treatment solution and treated separately. A conceptual schematic of the treatment system is shown in **Figure 1**.

For the semi-bench scale tests, we worked at scales of ~1 pound of soil or ~1 gallon water, respectively. Our experimental approach was organized by five tasks, namely:

*Task 1* –Semi-Batch Experiments (PFAS amended distilled water (DW), IDW PFAS contaminated water*)*

*Task 2*- Semi-Batch Experiments (IDW PFAS contaminated soil)

*Task 3* - Design and Testing of Semi-Batch Scale Continuous Flow Gas Infusion Reactor for IDW Water and IDW Soil Slurry

*Task 4*- System up-scaling: Pilot-Scale Gas Infusion Reactor Experiments for IDW Batch Mode Treatment

*Task 5* - Reporting

During the initial stage of our experimental approach (Tasks 1 to 3) we performed laboratory semi-bench scale and continuous flow treatment experiments to adjust and optimize our treatment approach for the characteristics of the IDW (water/soil) waste that contains PFAS and, possibly, co-contaminants. Based on the initial optimization tests, we proceeded to pilot-scale testing (Task 4). All experiments were carried out in batch mode only for cost reasons. The studies were carried out largely in the EEI facilities in Newton, MA. The data collected along the way was used for studying design, cost, and implementation requirements for possibly proposing a full-scale system.

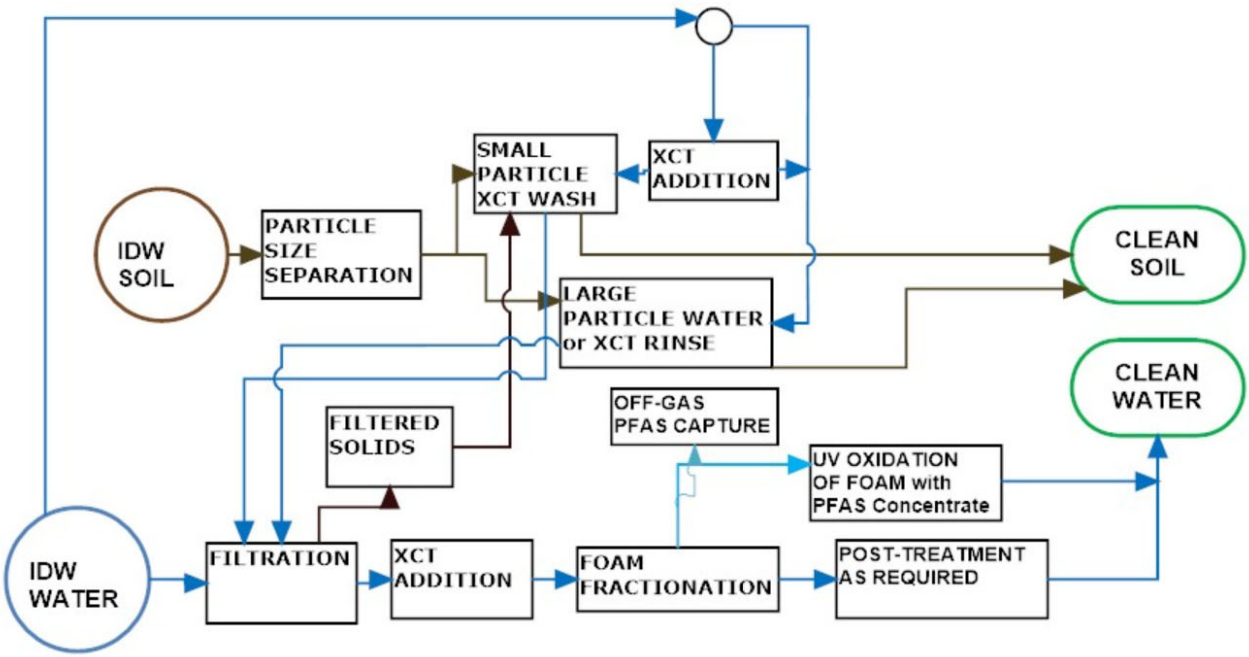



**Figure 1:** Schematic representation of the XCT® and OxyZone® treatment technology for PFAS contaminated IDW soil and water.

## 3. Materials and Methods

*3.1 IDW test material:* The IDW site material (soil and groundwater) investigated in this study originated from the Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN); in the following referred to as "Willow Grove" (WG) material. The soil samples were collected by a third party and transferred to EEI staff on-site. EEI personal collected the groundwater samples on-site. Upon receipt of the IDW soil and groundwater by EEI at their laboratories, a number of analyses were carried out. These and all subsequent PFAS analysis were carried out by Maxxam Analytics Laboratories, Ontario, Canada (Now: Bureau Veritas (BV) Laboratories). Inorganic analyses were performed New England Testing (NET) of Warwick, RI and in EEI 's Treatability Laboratory. Surface tension measurements were conducted in the Environmental Hydrogeology laboratory at the University of Rhode Island.

The IDW soil was analyzed for potential co-contaminants, including volatile organic compounds (VOC), volatile petroleum hydrocarbons (VPH), polycyclic aromatic hydrocarbons (PAH), and acid extractable metals. Site groundwater was tested for iron and manganese and VOC. After air-drying, the soil sample material was sieved to determine the percentage fraction of material <2 mm (sand, silt, and clay fraction) relative to larger grain seizes (fine gravel and greater).

OxyZone® was prepared from Klozur® sodium persulfate environmental grade obtained from PeroxyChem (Philadelphia, PA). Food grade-phosphate buffer and hydrogen peroxide (35% $H_2O_2$) were purchased from Mann Chemical, Warwick, RI and Acros Organics, respectively. Ozone was generated from pure oxygen using a Pacific Ozone LAB-12 generator which produced ozone concentrations between 6% to 8%.

*3.2 Sampling*: PFAS-free, high-density polyethylene (HDPE) containers with unlined caps made of HDPE or polypropylene were used for sample collection and preparation. Sample holding times for VOCs, PAH and metals were less than 28 days (EPA 2018). The test reactors were constructed of PVC or aluminum. Care was taken to decontaminate the reactor vessels after each experiment to avoid cross-contamination. Samples were collected and shipped in 50 to 250 ml HDPE bottles filled to the neck. Besides sample materials, blanks and duplicates were analyzed. Chain-of-Custody procedures were followed. For shipping, samples were placed in ice filled cooler and shipped to the laboratory.

*3.3 Analytics*: The PFAS analysis of solid and liquid samples was performed by BV Laboratories in Mississauga, ON, Canada. BV Laboratories (formerly Maxxam Analytics Laboratories) is NELAP accredited for the DoD QSM compliant method. The laboratory analyzes PFAS by LCMSMS Compliant with QSM 5.1 Table B-15. The 23 (including two telomers) PFAS compounds analyzed and the lab's detection limits are summarized in **Appendix 1**. Replicate analyses, controls, and blanks were analyzed to assure quality control. Total Oxidizable Precursor (TOP) assays on the raw and treated IDW water were carried out by BV Laboratories. TOP assay is a standardized hydroxyl radical based oxidation reaction in water samples designed to expose underlying PFAS precursors not amenable to standard laboratory identification and quantification. Precursors are transformed to dead-end perfluoroalkylic acids (PFAAs) in such reactions (Houtz and Sedlak, 2012). Hence, the increase in PFAS concentration is an indication of the amount of these precursors in the sample.

To determine if PFAS de-fluorination is occurring, fluoride ($F^-$) was analyzed in samples by EEI's Treatability Laboratory following ASTM D1179-04 (B) and Standard Methods 4500-F- C (21st edition). The method accurately quantifies fluoride with an ion selective electrode with a detection limit as low as 10 to 20 ppb. Replicate samples have also been sent to Maxxam and Eurofins for quality control evaluation.

Persulfate concentrations were determined by CHEMets® KIT Sodium Persulfate K-7870. The oxidation-reduction potential (ORP) was measured with an Thermo Orion 9157BM ORP electrode and a Thermo Orion 2115000 Dual Star pH Meter. The pH was determined with a Thermo Orion 2115000 Dual Star pH Meter and a Thermo Orion 9106BNWP electrode or Omega PHE-5460 pH electrode. Sulfate was analyzed by New England Testing of Warwick, RI utilizing method SM4500-S04-E, gravimetric followed by loss on ignition.

Aqueous phase ozone concentrations were measured with ATI_Q46-64 Dissolved Ozone electrode and Monitor. All instruments were frequently calibrated, following the manufacturer's instructions.

The formation of perchlorate, a potential treatment by-product, was tested in effluent samples and analyzed by a Eurofins Laboratories by EPA method SW-846 6850 1/2007.

The surface tension of six samples of Willow Grove site groundwater with and without XCT® was determined with a Fisher Surface Tensiomat Model 21 (operated manually). The concentrations of the active ingredient(s) in the XCT® solution was very low and ranged from 100 mg/L to 5,000 mg/L. The experiments were conducted at $20^0$C. Prior to any measurements, the tensiometer was calibrated

following the manufacturer's instructions. The surface tension of each sample was measured by transferring approximately 30 ml of aqueous sample into a 50 ml glass beaker, starting with the sample having the lowest XCT® concentration. Four measurements were conducted on each sample and the average of these readings are reported.

*3.4 Definition of Treatment Endpoint:* For aqueous matrices, we adopted the current EPA Lifetime Health Advisor (LHA) concentration for PFAS (70 ng/L PFOS and/or PFOA) compounds in drinking water (EPA 2016).

No generally accepted method existed for determining the endpoint of treating PFAS contaminated soil at the time this study was performed. We addressed this issue by developing a leachate testing procedure for formulating a possible soil treatment endpoint. Following typical leachate testing procedures, our project-specific leachate test was carried out as follows: treated IDW soil slurry was settled and centrifuged, followed by air-drying the "sludge" for 24 hrs. The dried soil sample (~20 gr) was then immersed in 0.4 L distilled water (DW) and tumbled for 24 hrs. After centrifuging and/or filtration, the water phase was analyzed for leached PFAS. The soil was considered treated when the total PFAS concentration in the leachate was less than 70 ng/L. This threshold concentration is the current EPA Lifetime Health Advisor (LHA) concentration for PFAS (PFOS and/or PFOA) compounds in drinking water.

In 2019, the Massachusetts Department of Environmental Protection (MADEP) proposed and promulgated the Massachusetts Contingency Plan (MCP) for cleanup standards for PFAS in soil and groundwater, values for use in site-specific risk assessment, and notification criteria for soil and groundwater (www.mass.gov/lists/2019-proposed-mcp-revisions ). The final PFAS-Related changes to the MCP were released on 2019-12-13 (**Table 3**) and promulgated on December 27, 2019. The MCP Method 1 Soil Standards consider both the potential risk of harm resulting from direct human exposure to hazardous material in the soil and the potential impacts on the groundwater at the disposal site. The applicability of a specific numerical Standard is thus a function of both the soil and the groundwater category identified. Six perfluoroalkyl substances have been added to the Method 1 Standards list – Perfluorodecanoic Acid (PFDA), Perfluoroheptanoic (PFHpA), Perfluorohexanesulfonic Acid (PFHxS), Perfluorooctanoic Acid (PFOA), Perfluorooctane Sulfonate (PFOS) and Perfluorononanoic Acid (PFNA). The promulgated MCP Method 1 Soil and Groundwater Standards represent levels of hazardous materials at which no further remedial response

actions would be required based upon the risk of harm posed by these chemicals. Assuming that treated IDW will not be deposited in areas of residential use or in drinking water aquifers (S-1 and GW-1, respectively), the likely applicable limits are S-2 or S-3 soil standards and GW-3 groundwater standards (Table 3). If treated IDW soil was placed in an area of residential use or a groundwater aquifer the S-1/GW-1 soil standard would most likely apply. Please see **Appendix 2** for definitions. Note that GW-2 standards for PFAS (individual and total) are not defined because PFAS is not volatile. For comparison, the finalized because PFAS is not volatile (non-GW-1 areas) standards are 500 µg/L for PFAS and 0.4 µg/g for each individual compound, respectively.

| **Compound** | **Groundwater-1 (µg/L = ppb)** | **Groundwater-3 (µg/L = ppb)** | **S-1, S-2 and S-3 Groundwater-1 conditions (µg/g = ppm)** | **S-1 Soil (non-Groundwater-1 Conditions) (µg/g = ppm)** | **S-2 or S-3 Soil (non-Groundwater-1 Conditions) (µg/g = ppm)** |
|---|---|---|---|---|---|
| PFAS | 0.02* | NA | NA | NA | NA |
| PFDA | 0.02 | 40,000 | 0.0003 | 0.3 | 0.4 |
| PFHpA | 0.02 | 40,000 | 0.0005 | 0.3 | 0.4 |
| PFHxS | 0.02 | 500 | 0.0003 | 0.3 | 0.4 |
| PFNA | 0.02 | 40,000 | 0.00032 | 0.3 | 0.4 |
| PFOS | 0.02 | 500 | 0.002 | 0.3 | 0.4 |
| PFOA | 0.02 | 40,000 | 0.00072 | 0.3 | 0.4 |

**Table 3**: MADEP MCP Method 1 groundwater and soil standards (April 2019). PFAS is defined as the sum concentrations of perfluorodecanoic acid (PFDA), perfluoroheptanoic acid (PFHpA), perfluorohexanesulfonic acid (PFHxS), perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), and perfluorononanoic acid (PFNA). Note: 0.4 µg/g = 400 µg/kg. * Individual or total of six PFAS. There are no GW-2 criteria since PFAS are not considered volatile. Source: www.mass.gov/doc/final-pfas-related-changes-to-the-mcp-2019-12-13

In the following sections, we are comparing our soil material treatment results to both the more stringent leaching test we developed and the proposed MADEP MCP soil standards.

*3.5 Methods by Tasks*: Tasks 1 to 3 (see Section 1) were performed at batch reactor and semi-batch reactor scale. In Task 4, a proto-type gas infusion reactor system was designed to treat IDW in batch mode.

*3.5.1. - Task 1* –Semi-Batch Experiments (PFAS amended distilled water, IDW PFAS contaminated water*)*

Prior to experimentation with actual soil and water IDW, solutions of spiked PFAS distilled water were tested in a custom-made plastic gas-infusion reactor. Buffered persulfate and ozone/oxygen gas was added to initiate destruction and de-fluorination of PFAS inside the gas infusion reactor. The ozone was generated from oxygen gas to reach the highest possible concentration (up to 8%). PFAS

in the off-gas was captured and concentrated in traps filled with distilled water in series. In general, samples were collected and analyzed from 15 minutes to 16 hours to determine the length of time needed for effective PFAS destruction. In addition to PFAS concentrations, pH, fluoride, and ORP were monitored.

Semi-batch experiments in the gas-infusion reactor were then repeated by replacing spiked water with IDW water (no solids). Treatment experiments were conducted at various retention times, oxygen/ozone sparging flowrates, and buffered persulfate concentrations to determine the optimum operating conditions. Additional experiments were performed at lower chemical concentrations to determine the lowest practical chemical concentration (i.e., persulfate from 60 g/l down to 6 g/l) and ozone gas flow rate for PFAS destruction in IDW water. Mole ratios of PFAS to oxidants were evaluated that achieve the required destruction efficiency. After optimum conditions were selected for treatment of IDW water, a duplicate experiment under the selected conditions was carried out with a control consisting of only distilled water. The contaminant treatment rates from this experiment were compared to the IDW water treatment rates to work out any IDW matrix interferences. The results from these semi-batch experiments with IDW water were expected to provide data on PFAS destruction effectiveness and rates and guided the actual procedures used in the subsequent tasks.

**Figure 2:** Tumbler for rinsing coarser IDW soil.

*3.5.2. - Task 2* - Semi-Batch Experiments (IDW PFAS contaminated soil)

The 'Willow Grove" soil IDW test material contained larger grain seizes (coarse gravel and larger) that would have been difficult if not impossible to suspend in a slurry. Hence, we separated the IDW soil material into three fractions: (1) coarse gravel (> 0.44"), (2) fine gravel (0.2 to 0.44 in) and (3) sand/silt/clay (<0.2 in). The largest sized grain fraction (> 0.44") was not studied, assuming that if the fine gravel fraction can be successfully treated, coarser material (larger gravel, pebbles) can be as well. Prior to treatment, samples of the fine gravel and the sand/silt/clay fraction were submitted

to BV Labs for duplicate analysis of 23 PFAS (including two fluorotelomers) to determine the initial PFAS concentrations.

Rinsing of the coarse IDW material was performed with either DI water, followed by XCT® solution (1,000 mg/L) or with just XCT® solution (5,000 mg/L). Others have also shown that the active ingredient(s) of XCT® enhances the absorption of PFAS desorbed from mineral grains (Xiao et al. 2017; Karoyo et al. 2015). Up to four rinses were performed, using a 50 g of soil and tumbling it in 0.2 L of rinsing solution for 15 minutes (**Figure 2**). Afterwards, samples of the rinsed IDW material and the rinsing solutions were analyzed for PFAS.

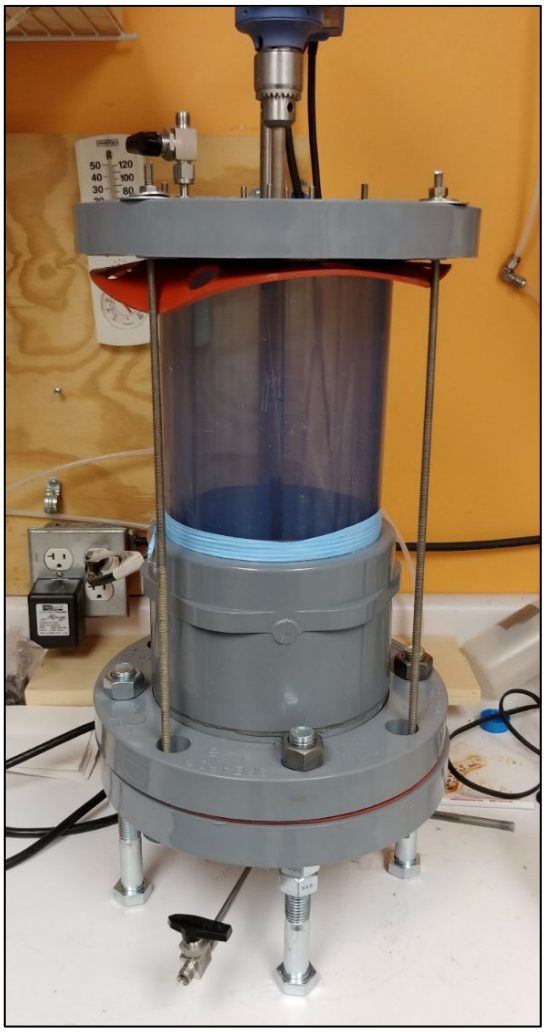


**Figure 3:** The sand/silt/clay IDW soil fraction was treated inside a 5 liter clear PVC slurry reactor.

The sand/silt/clay IDW soil fraction was treated inside a 5 liter clear PVC reactor slurry reactor (**Figure 3**). Originally, it was planned to use an air gas stream for holding the finer soil fraction in suspension. However, this approach proved impracticable. Instead, a stainless steel mixer was inserted through a lid covering the reactor and used to mix a 20% (wt/wt) soil slurry of the fine IDW fraction containing 5,000 mg/L XCT® solution. At that concentration level, the XCT® solution cost is $0.04 per gallon.

Water samples were collected at predetermined times and analyzed as in Task 1 for PFAS. Soil samples were collected before, during, and after the experiment and analyzed for PFAS. That time/concentration data set was used for calculating PFAS destruction rates. The results from these semi- batch experiments with IDW soil were expected to provide data on PFAS desorption and removal effectiveness and guided the actual procedures used in the subsequent tasks.

*3.5.3. - Task 3* - Design and Testing of Semi-Batch Scale Continuous Flow Gas Infusion Reactor for IDW Water and IDW Soil Slurry

The finer IDW soil fraction (sand/silt/clay) was treated inside a 5 liter clear PVC reactor slurry reactor (**Figure 4**). These finer soil materials were suspended by a stainless steel mixer inserted through a lid covering the reactor and, for OxyZone® testing, also the action of the oxygen/ozone sparging as well. These mechanical processes mix and keep in suspension the 20% (wt/wt) soil slurry of the fine IDW fraction and either solutions of XCT® or OxyZone®. With rinsing tests, the XCT® concentrations ranged from 1,000 to 5,000 mg/L.

**Figure 4:** A batch-scale foam fractionation reactor was build using plastic column material. The dimensions of the system were 3" diameter and 6' long

Slurry and decantate samples were collected at predetermined times and analyzed as in Task 1 for PFAS, pH, and ORP. Slurry sample concentrations were quantified by centrifuging the slurry to produce a decantate and sludge, separately extracting the PFAS from the decantate and sludge, and then combining the extracts for subsequent PFAS analysis. The results are therefore expressed as µg/l of the slurry. Treated soil samples were collected initially (when still dry) and after the experiments were finished (by centrifuging and drying the slurry) and analyzed for PFAS. That time/concentration data set was used for calculating PFAS destruction rates. The results from these semi- batch experiments with IDW soil provided data on PFAS destruction effectiveness and guided the actual procedures used in the subsequent tasks. Soil samples were collected before, during, and after the experiment and analyzed for PFAS.

This gas-infusion treatment system for IDW soil slurry and IDW water (including process water) was constructed based on Tasks 1 and 2 results (**Figure 4**). The reactor was also outfitted with an off-gas scrubber, ensuring capture of any PFAS that might possibly escape as aerosols. The IDW soil (fine fraction) was added (0.9 kg) to an OxyZone® solution (4.5 L). A mix of ozone/oxygen

(~1:15) was injected through the porous bottom of the reactor at a rate of ~1 to 2 L/min. Solution was mixed by the oxygen/ozone sparging and the paddle mixer. The initial pH of the test solution was adjusted to 11 with NaOH. PFAS samples of the aqueous and solid phases were collected at predetermined times. Leaching tests were performed on the centrifuged and dried soil after treatment.

Task 3 tests generated treatment rates for IDW water alone and for soil slurry from mixing IDW soil and (process) water. Expected outcomes was information about the feasibility of designing a mixed IDW waste treatment system at pilot-scale.

*3.5.4. - Task 4* - System up-scaling: Pilot-Scale Gas Infusion Reactor Experiments for IDW Batch Mode Treatment

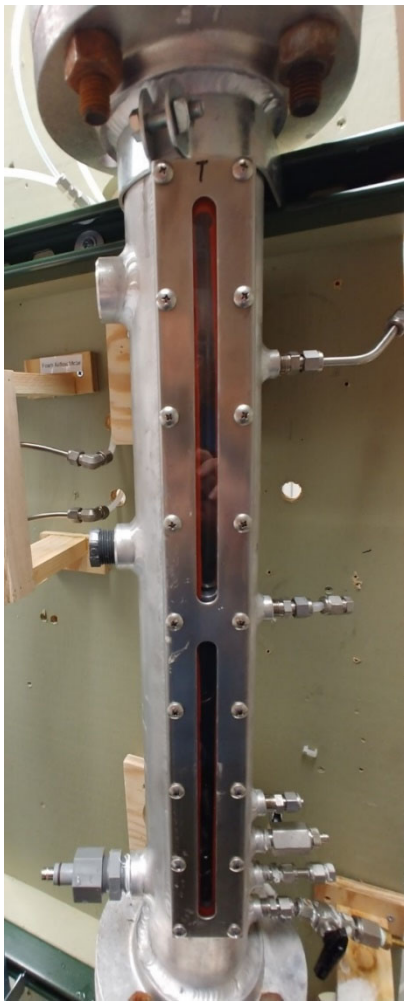


**Figure 5:** Pilot-scale UV-irradiation reactor**.**

Based on Tasks 1 to 3 data, we designed a pilot-scale gas infusion reactor system to treat IDW and process water in batches of ~2 liters (**Figure 5**). Building and testing a continuous mode treatment system was not anticipated within the constraints of this project.

We employed similar experimental conditions as in the previous tasks. Varying flowrates at ozone gas concentration of 6% (reminder: oxygen) were sparged into the reactor containing intermittent peroxide, buffered persulfate at approximately constant pH (~9 pH) and IDW water. Samples were collected at predetermined times during treatment and analyzed for PFAS, possible by-products (perchlorate), and fluoride to determine the rate of PFAS destruction and final PFAS concentrations. The off-gas PFAS concentrate was collected and analyzed for PFAS. The treatment time and conditions (including amount of IDW and process water treated) was recorded for documenting the process effectiveness and for cost estimation purposes. All experiments were conducted at room temperature (18 to 21 ºC).

The results of these experiments are the basis for the sizing a full-scale reactor. The results also provided estimates of on-site treatment costs in relation to alternative disposal approaches.

# 4. Results and Discussion

*4.1. IDW Test Material Analysis*

IDW soil samples were obtained from the Joint Base Naval Air Station Willow Grove, PA. The chemical analysis of the soil by JBASWG is summarized in **Appendix 3**. Our confirmation analysis confirmed that PFAS were the principal contaminants in the sample material (**Appendix 4**). Of all PFAS, PFOS is the dominant compounds reported by JBASWG (96% of total PFAS analyzed), followed by PFOA and PFBS; both present at similar concentrations. Compared to the original JBASWG data set, the results obtained from 11 replicate analyses showed PFOS (Average: 1,220 µg/kg) concentrations were about one order of magnitude higher than reported by JBASWG (Maximum 126 µg/kg). Discussions with JBASWG base personal determined that the source of the sampled IDW soil was from the same area but not the same stockpile of excavated soil. In the following, we considered our soil confirmation analysis for PFAS (**Appendix 4**) as the baseline for determining the effectiveness of OxyZone® treatment process. In addition, the confirmation analysis revealed that non-PFAS co-contaminants (i.e. PAHs) were present but only at low levels near their respective detection limits. For this reason, we did not investigate these compounds further.

A composite sample of the site IDW groundwater collected on November 15, 2018 was analyzed for 11 times for PFAS (**Appendix 5**). The data showed that PFOS is the principal contaminant (Average: 104 µg/L), representing 74% of the total PFAS inventory in the aqueous phase. In addition, site groundwater was tested for VOC, iron and manganese. The concentrations of these compounds were all below detection limit (**Appendix 3**). Therefore, interferences with our treatment process potentially associated with these compounds were ruled out.

The TOP assay of the raw site groundwater (**Appendix 6A**) revealed that of the 12 PFAS identified in the analyses of the Willow Grove IDW water, seven compounds, i.e. shorter chained C:4 to C:6 PFAS, increased in concentration via the TOP Assay procedure from a total of 27 µg/L to 69 µg/L. This result indicates that there are precursor compounds present in the groundwater that can be transformed. Two other PFAS concentrations decreased, including PFOS (-17%).

A TOP assay of IDW water after OxyZone® treatment (including formation/irradiation for 5.3 hrs; see Tasks 3 and 4) showed that the total pre-oxidation PFAS concentration (8.3 µg/L) decreased to 5.3 µg/L post-oxidation (**Appendix 6B**). Only three PFAS compounds (PFHpA, PFBS, and PFOS) increased in concentration, albeit at minimal levels that may be within the accuracy of the analytical

procedure, (i.e. PFOS increased from 0.055 µg/L to 0.084 µg/L). The overall negligible conversion of precursors to PFAS suggests that the prior OxyZone® treatment had already converted and/or destroyed most precursors.

Besides testing the IDW test materials, we also investigated (1) how much persulfate was consumed during PFAS treatment, (2) how much sulfate was produced, and (3) if and how much perchlorate might have formed. In general, the initial mass of persulfate in solution was sufficiently high so that at the end of most OxyZone® tests, there was still between 85% and 50% of the amount of persulfate remaining. However, data collected during foam fractionation/irradiation treatment (Task 4) indicate that all persulfate was converted, suggesting that this treatment approach was highly effective in activating and converting persulfate.

The mole ratios of PFAS to persulfate ranged from approximately $1:10^5$ to $1:10^6$, depending on the experimental conditions. Hence, reactions were treated as pseudo-first order with respect to OxyZone®. Sources of sulfate in the treatment solutions can originate from impurities in the persulfate, naturally present sulfate in the IDW matrix, and can be produced from the mineralization of sulfonates. The Na-persulfate used for all experiments contained about 8% sulfate, resulting in initial sulfate concentrations in the OxyZone® treatment solution of around 470 mg/L. After treatment, the sulfate concentrations increased depending on the duration of treatment (e.g., breakdown of persulfate) and other experimental conditions, such as type of matrix treated or pH. For instance, during OxyZone® treatment of PFOS spiked distilled water (pH=9.3), the initial sodium persulfate concentration decreased from approximately 6000 mg/L to 3700 mg/L with a final sulfate concentration of 1180 mg/L. In all experiments, the contribution of sulfate produced from the mineralization of PFAS was considered insignificant relative to the other potential sulfate sources. With regards to perchlorate, we tested the original IDW groundwater and soil and detected none in either matrix. Also, none of the OxyZone® chemicals contained measurable perchlorate concentrations except persulfate, which contained 50 µg perchlorate per gram persulfate when dissolved in distilled water. The presence of perchlorate indicates that an alternative, perchlorate-free source of persulfate may need to be identified. We further investigated if the presence of chloride and/or dissolved iron and manganese in the aqueous phase might contribute to the creation of perchlorate from the action of persulfate. For example, chloride can be converted to perchlorate under favorable conditions (Rao et al. 2010) and both metals are known persulfate activators. Our data

indicate that even at comparatively high NaCl concentration (2 g/L) and in the presence of potential persulfate activators like iron and manganese, no additional perchlorate was produced in solutions containing 6g/L persulfate. In fact, when Fe and Mn were present in solution, perchlorate concentrations decreased slightly from 300 µg/L to 240 µg/L. An even more pronounced decrease in perchlorate (190 µg/L) was observed during the foam fractionation/irradiation treatment of PFAS with OxyZone® (see Tasks 3 and 4).

| Grain size | Sieve size | Perct. |
|---|---|---|
| Coarse gravel | >0.44" | 7.7% |
| Fine gravel | 0.44" to 0.19" | 6.0% |
| Coarse sand | 0.19" to 0.08" | 11% |
| Sand, silt and clay | <0.08" (2 mm) | 75% |

**Table 4**: IDW soil grain size analysis data. The fine gravel material is referred to as the "coarse fraction" whereas coarse sand and finer materials are referred to as the "fine Fraction.

The grain size distribution of the soil sample material (**Table 4**) revealed that the IDW test material consisted of 75% material with a grain size of medium sand or smaller.

Untreated IDW soil material was divided into two fractions for treatment experiments: (1) finer fraction (sand, silt and clay) and (2) coarser fraction (fine gravel). The course gravel was not tested but was presumed treatable in the same manner as the fine gravel. The fine gravel fraction represented 6% of the entire test material (**Table 4**). A sub-sample from each fraction, including the original bulk IDW sample material, was analyzed for PFAS concentration. The results shown in **Table 5** revealed that PFAS concentrations (primarily PFOS; 95%) were, as expected, higher (1,560 µg/kg) in finer fraction relative to coarser one (490 µg/kg).

| PFAS Detected in Willow Grove IDW Soil | UNITS | Proposed MADEP Soil Criteria, non-aquifer area | Bulk Soil | Fine Gravel fraction | Fine sand/silt fraction |
|---|---|---|---|---|---|
| 6:2 Fluorotelomer sulfonate | ug/kg | | 3.2 | 2.1 | 1.4 |
| 8:2 Fluorotelomer sulfonate | ug/kg | | < 3.3 | 0.60 | <3.3 |
| Perfluorobutane Sulfonate (PFBS) | ug/kg | | 0.33 | 1.2 | 1.4 |
| Perfluorobutanoic acid (PFBA) | ug/kg | | 1.5 | 1.4 | 2.3 |
| Perfluorodecane Sulfonate | ug/kg | | 17 | 3.9 | 4 |
| Perfluorodecanoic Acid (PFDA) | ug/kg | 300 | 1.1 | 0.37 | <3.1 |
| Perfluorododecanoic Acid (PFDoA) | ug/kg | | 0.47 | 0.31 | <1.9 |
| Perfluoroheptane sulfonate (PFHpS) | ug/kg | | 1.3 | 1.6 | 3.7 |
| Perfluoroheptanoic Acid (PFHpA) | ug/kg | 300 | 0.49 | 1.3 | <1.8 |
| Perfluorohexane Sulfonate (PFHxS) | ug/kg | 300 | 21 | 14 | 36 |
| Perfluorohexanoic Acid (PFHxA) | ug/kg | | 3.1 | 3.3 | 5.6 |
| **Perfluoro-n-Octanoic Acid (PFOA)** | **ug/kg** | **300** | **1.2** | **1.6** | **3.1** |
| Perfluorononanoic Acid (PFNA) | ug/kg | 300 | 2.1 | 1.2 | <1.5 |
| Perfluorooctane Sulfonamide (PFOSA) | ug/kg | | 2.7 | 1.2 | <1.9 |
| **Perfluorooctane Sulfonate (PFOS)** | **ug/kg** | **300** | **1,220** | **470** | **1,500** |
| Perfluoropentanoic Acid (PFPeA) | ug/kg | | 2.4 | 2.2 | 4.5 |
| Perfluoroundecanoic Acid (PFUnA) | ug/kg | | 1.7 | 0.49 | 1.6 |
| | **ug/kg** | TOTAL | **1,280** | **505** | **1,560** |

**Table 5**: PFAS concentration in untreated IDW soil test material by grain seize fractions, including bulk soil. PFAS concentrations (primarily PFOS) are higher in finer fraction (sand and finer) relative to coarser (fine gravel) grain seize fraction.

The Willow Grove groundwater had a native fluoride concentration of 123 µg/L (mean of 7 samples; range: 120 to 127 µg/L). Therefore, to detect an increase in fluoride from destruction and defluorination, only experiments that generated fluoride of at least 20-30 µg/L could be conclusively said to be releasing fluoride.

The Willow Grove soil has significant native fluoride background concentration, approximately 10 mg/kg. Therefore, slurries of WG soil up to one kilogram of soil in approximately 5 Liter contained ~1,000 µg/L of fluoride and the release of fluoride from destruction of the PFAS were typically not high enough to be detectable against this high background.

*4.2. Results by Tasks*

*4.2.1 - Task 1 –Semi-Batch Experiments (PFAS amended distilled water, IDW PFAS contaminated water)*

The purpose of the Task 1 tests was to investigate differences, if any, resulting from treating a real-world PFAS contaminated liquids versus distilled water spiked with PFAS. Experiments were performed in a custom-made plastic gas-infusion reactor filled with approximately 2.5 liter of

OxyZone®. PFAS, pH, fluoride and ORP were tested during treatment. The data indicate that PFAS were degraded and stoichiometric amounts of fluoride ($F^-$) were produced in proportion to the measured amount of PFAS destroyed (**Figure 6**).

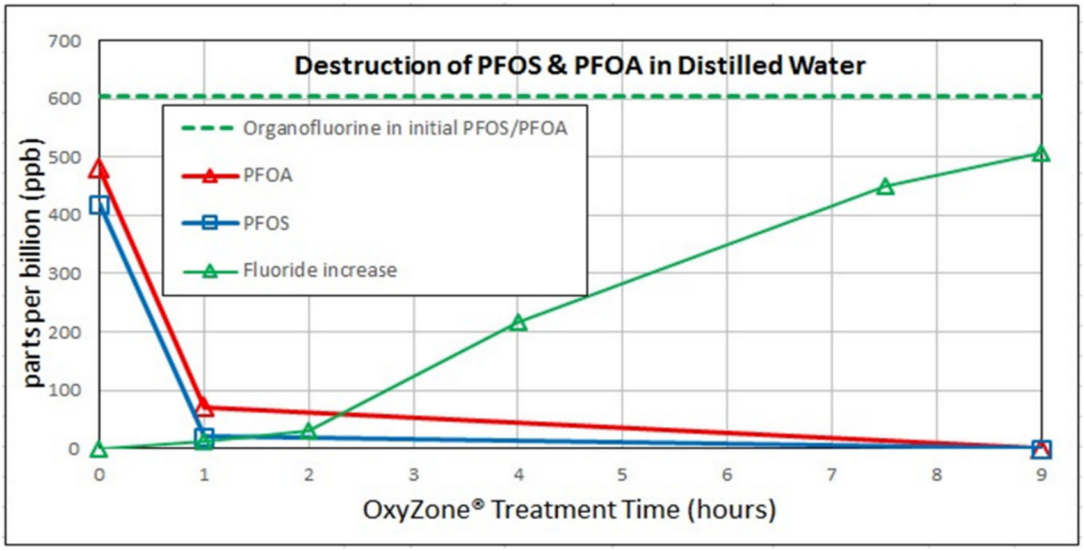



**Figure 6**: Destruction of PFAS (PFOA and PFOS) by OxyZone® and stoichiometric amount of Fluoride (F-) produced from the defluorination of those two PFAS compounds. The data indicates that PFAS was destroyed and fluoride produced. Further, while the parent PFAS compounds degraded rapidly, i.e. within approximately 2 hrs, the fluoride continued to accumulate over the following hours. The fluoride data indicate that the PFAS degradation process advances through intermediates but will eventually (after approximately after 12 hrs) result in complete defluorination.

After testing the OxyZone® treatment on PFAS dissolved in distilled water, actual IDW groundwater was treated. PFOS decreased by 70% and PFOA decreased by 42 % in 4 hours. The results of Task 1 demonstrate that treating aqueous phase PFAS with OxyZone® can achieve the desired levels of mineralization. However, the treatment duration to achieve low concentration is comparably long, i.e. it is in excess of the duration of an average workday.

*4.5.2. - Task 2- Semi-Batch Experiments (IDW PFAS contaminated soil)*

The main objective of Task 2 was to investigate the most feasible way to treat PFAS contaminated IDW soil. The untreated IDW test material was spilt into two fractions (coarse versus fine) for treatment testing. Two ways of agitating the soil were examined: (1) treatment of the coarse fraction in a tumbling reactor and (2) treatment of the fine fraction in a slurry reactor.

*4.5.2.1. Coarse Soil Treatment – tumbling and slurry*

Our previous tests showed that XCT® solution extracted more PFAS from packed soil columns than distilled water, especially for higher molecular weight PFAS compounds. That is, based on the mass amount of PFAS flushed, XCT® was always more effective at PFAS removal from soil than distilled

water, especially for seven carbon chain and greater PFASs. Overall, when considering removal of total PFAS or the six UCMR PFASs, XCT® solution removed significantly more PFAS than distilled water, 87-98% versus only 8-9% with distilled water. Further, we hypothesized that for larger soil particles, XCT® solution may extract sufficient PFAS to render the soil remediated without more expensive chemical oxidation. To test this hypothesis, soil rinsing experiments were performed with the fine gravel soil fraction, using DI water and/or XCT® solution.

The first tests focused on rinsing, in a tumbler (**Figure 2**), the coarse fraction of the IDW soil (40 g) with 200 ml DW water followed by two rinses with 200 ml each of dilute (1,000 mg/L) XCT® solution. The total PFAS concentrations in the tumbler treated soil was 45 µg/kg compared to the initial 490 µg/kg in the untreated IDW soil, i.e., % removal (**Appendix 7**). The results indicate that rinsing the coarse IDW fraction with XCT® solution more effectively transfers sorbed PFAS from the grain surfaces to the aqueous solution compared to rinsing with DW water. Further, the tests showed that rinsing with higher concentrated XCT® solution is more effective because it minimizes the quantities of rinse water to be processed later. In a second test, the soil was rinsed with 5,000 mg/L XCT® solution in a 20% slurry reactor for 15 minutes. The PFAS concentration in the coarse soil was reduced from 490 µg/kg to only 5 µg/kg (**Table 6**). Only 2 PFAS remained in the soil above the detection limit after this short slurry test. Treatment in a slurry is thought to be more effective than tumbling because the XCT® solution is in closer contact to the PFAS sorbed to the soil. Finally, and most importantly, compared to the MA DEP soil treatment criteria, the most stringent non-drinking water criterion (PFAS 300 µg/kg for S-1 soil) was easily met. From these results, it was concluded that rinsing the coarse IDW fraction with XCT® solution is sufficient to reduce PFAS concentrations to limits that might be acceptable for disposal.

| 11 | | | | | Treated by Tumbling | | Treated by Slurry, 5 g/l CD | |
|---|---|---|---|---|---|---|---|---|
| 12 | | UNITS | Lowest MADEP Soil Criteria, non-aquifer area | Mean of 5 results-fine gravel | 2x with DW, then 1x with CD- 1 g/l | Mean of 2 Analyses | 15 minute mixing | dupe analysis |
| 13 | 6:2 Fluorotelomer sulfonate | ug/kg | | 2.1 | 0.26 | <0.26 | <0.26 | <0.26 |
| 14 | 8:2 Fluorotelomer sulfonate | ug/kg | | 0.6 | <0.33 | <0.26 | <0.26 | <0.26 |
| 19 | Perfluorobutane Sulfonate (PFBS) | ug/kg | | 1.2 | 0.84 | <0.17 | <0.17 | <0.17 |
| 20 | Perfluorobutanoic acid | ug/kg | | 1.4 | <0.23 | <0.12 | <0.12 | <0.12 |
| 21 | Perfluorodecane Sulfonate | ug/kg | | 3.9 | <0.39 | <0.39 | <0.39 | <0.39 |
| 22 | Perfluorodecanoic Acid (PFDA) | ug/kg | 300 | 0.37 | <0.28 | <0.31 | <0.31 | <0.31 |
| 23 | Perfluorododecanoic Acid (PFDoA) | ug/kg | | 0.31 | <0.28 | <0.19 | <0.19 | <0.19 |
| 24 | Perfluoroheptane sulfonate | ug/kg | | 1.6 | <0.39 | <0.39 | <0.39 | <0.39 |
| 25 | Perfluoroheptanoic Acid (PFHpA) | ug/kg | 300 | 1.3 | <0.19 | <0.18 | <0.18 | <0.18 |
| 26 | Perfluorohexane Sulfonate (PFHxS) | ug/kg | 300 | 14 | 4.1 | 0.25 | <0.24 | 0.29 |
| 27 | Perfluorohexanoic Acid (PFHxA) | ug/kg | | 3.3 | 0.19 | <0.14 | <0.14 | <0.14 |
| 28 | **Perfluoro-n-Octanoic Acid (PFOA)** | **ug/kg** | **300** | **1.6** | **<0.25** | <0.25 | <0.25 | <0.25 |
| 29 | Perfluorononanoic Acid (PFNA) | ug/kg | 300 | 1.2 | <0.22 | <0.15 | <0.15 | <0.15 |
| 30 | Perfluorooctane Sulfonamide (PFOSA) | ug/kg | | 1.2 | 0.15 | <0.19 | <0.19 | <0.19 |
| 31 | **Perfluorooctane Sulfonate (PFOS)** | **ug/kg** | **300** | **468** | **39** | 4.7 | 1.2 | 8.2 |
| 32 | Perfluoropentanoic Acid (PFPeA) | ug/kg | | 2.2 | <0.25 | <0.10 | <0.10 | <0.10 |
| 35 | Perfluoroundecanoic Acid (PFUnA) | ug/kg | | 0.49 | <0.34 | <0.15 | <0.15 | <0.15 |
| 36 | TOTAL | ug/kg | **Total (sum)** | **505** | **45** | **5.0** | **1.2** | **8.5** |

**Table 6**: Results of rinsing the coarse fraction (fine gravel) of the IDW test soil with XCT® solution in both the tumbling reactor and the slurry reactor. Initial PFAS concentrations in each soil fraction and in the bulk soil are provided for reference. The most stringent non-drinking water aquifer Massachusetts Department of Environmental Protection (MA DEP) MCP limit for PFAS contaminated soils is 300 µg/kg (S-1 Soil Standard).

The rinsed fine gravel fraction from the tumbler test was also subjected to leachate testing procedure described above. The results of a leaching test indicate that PFOA concentration in the unfiltered leachate was below detection limit (<7.4 ng/L) and PFOS was at 72 ng/L, i.e. just barely exceeding the threshold of 70 ng/L (**Table 7**). Note that PFOS made up >95% of all PFAS in the untreated IDW test material. Further, it has been noted that the total PFAS concentration in the unfiltered leachate material is about twice as high for reasons unknown.

| IDW Soil (Willow Grove) | UNITS | LEACHATE - FILTERED | LEACHATE - UNFILTERED |
|---|---|---|---|
| Perfluorobutanoic acid | ug/L | <0.0070 | <0.0070 |
| Perfluoropentanoic Acid (PFPeA) | ug/L | 0.0046 | 0.0058 |
| Perfluorohexanoic Acid (PFHxA) | ug/L | 0.012 | 0.051 |
| Perfluoroheptanoic Acid (PFHpA) | ug/L | <0.0071 | <0.0071 |
| **Perfluorooctanoic Acid (PFOA)** | **ug/L** | **0.013** | **<0.0074** |
| Perfluorononanoic Acid (PFNA) | ug/L | <0.0049 | <0.0049 |
| Perfluorodecanoic Acid (PFDA) | ug/L | <0.0041 | <0.0041 |
| Perfluoroundecanoic Acid (PFUnA) | ug/L | <0.0043 | <0.0043 |
| Perfluorododecanoic Acid (PFDoA) | ug/L | <0.0068 | <0.0068 |
| Perfluorotridecanoic Acid | ug/L | <0.0069 | <0.0069 |
| Perfluorotetradecanoic Acid | ug/L | <0.0067 | <0.0067 |
| Perfluorobutanesulfonic acid | ug/L | <0.0051 | <0.0051 |
| Perfluorohexanesulfonic acid | ug/L | 0.015 | <0.0052 |
| Perfluoroheptanesulfonic acid | ug/L | <0.0033 | <0.0033 |
| **Perfluorooctanesulfonic acid (PFOS)** | **ug/L** | **0.22** | **0.072** |
| Perfluorodecanesulfonic acid (PFDS) | ug/L | <0.0072 | <0.0072 |
| Perfluorooctane Sulfonamide (PFOSA) | ug/L | <0.0066 | <0.0066 |
| EtFOSA | ug/L | <0.0090 | <0.0090 |
| MeFOSA | ug/L | <0.0035 | <0.0035 |
| EtFOSE | ug/L | <0.0094 | <0.0094 |
| MeFOSE | ug/L | <0.0066 | <0.0066 |
| 6:2 Fluorotelomer sulfonate | ug/L | <0.0059 | <0.0059 |
| 8:2 Fluorotelomer sulfonate | ug/L | <0.0073 | <0.0073 |
| **TOTAL:** | | **0.265** | **0.129** |

**Table 7**: Results of leachate testing performed on coarse fraction (fine gravel) of the IDW test soil. After tumbling treatment, PFOA concentrations in the unfiltered sample were below the proposed limit. PFOS slightly exceeded the leachate test threshold of 0.070 µg/L. It has been noted that for reasons unknown the PFAS concentration in the filtered leachate material were about twice as high.

Rapidly mixed soil slurry experiments of the coarse fraction of IDW soil and distilled water mixed with XCT® solution indicate that 98% of the total PFAS sorbed to the soil was removed from the soil including 98% of the PFOS. Leachate testing of the washed soil indicate that 4 out of the 5 PFAS compounds detected in the leachate were less than 70 ng/L with one compound (PFOS) was at 146 ng/L (mean of the filtered and unfiltered result). Given these results, PFAS soil leaching limits can likely be met during pilot-scale testing if the soil is either washed with XCT® solution for a longer time (to overcome possible rate limited dissolution).

*4.5.2.2. Fine Soil Slurry Treatment – by OxyZone®*

The soil investigated in this section was the finer fraction of the IDW test material (sand, silt and clay fraction). It is noted that the finer fraction contained higher total PFAS concentrations (1,564 µg/kg) relative to the coarser fraction (505 µg/kg). Several experiments were carried out in the slurry reactor shown in **Figure 3** to test which treatment approach is most effective for treating the IDW. The tests were conducted by making a 20% soil/aqueous slurry of Willow Grove soil, Willow Grove

groundwater (or distilled water) and OxyZone®. The first experiment tested the effectiveness of OxyZone® on Willow Grove soil in a slurry with DW. The initial pH of the solution was pH was 11; due to the conversion of persulfate, the final pH was 7. The slurry was agitated for 4 hrs. Samples of the aqueous phase were analyzed for PFAS (**Table 8**).

The results indicate that the total PFAS concentration in the slurry water decreased by 82% over 4 hours (**Figure 7**). Other removal percentages were 96% for PFOS and 54% for PFOA. However, shorter chain PFAS (namely, PFBA, PFBS, PFPeA, PFHxA and PFHpA) were generated.

| **IDW soil (Willow Grove)** | **UNITS** | **T=0** | **T= 0.5 hrs** | **T=4 hrs** |
|---|---|---|---|---|
| Perfluorobutanoic acid | ug/L | <0.42 | <1.3 | 3.0 |
| Perfluoropentanoic Acid (PFPeA) | ug/L | 5.1 | 1.9 | 6.5 |
| Perfluorohexanoic Acid (PFHxA) | ug/L | 1.4 | 5.1 | 16 |
| Perfluoroheptanoic Acid (PFHpA) | ug/L | <0.43 | <1.3 | 1.2 |
| Perfluorooctanoic Acid (PFOA) | ug/L | 0.63 | <1.3 | 0.29 |
| Perfluorononanoic Acid (PFNA) | ug/L | 0.31 | <1.3 | <0.042 |
| Perfluorodecanoic Acid (PFDA) | ug/L | 0.33 | <1.3 | <0.035 |
| Perfluoroundecanoic Acid (PFUnA) | ug/L | 0.34 | <1.3 | <0.037 |
| Perfluorododecanoic Acid (PFDoA) | ug/L | <0.41 | <1.3 | <0.058 |
| Perfluorotridecanoic Acid | ug/L | <0.41 | <1.3 | <0.059 |
| Perfluorotetradecanoic Acid | ug/L | <0.40 | <1.3 | <0.057 |
| Perfluorobutanesulfonic acid (PFBS) | ug/L | <0.31 | <1.3 | 1.3 |
| Perfluorohexanesulfonic acid (PFHxS) | ug/L | 5.6 | 7.2 | 2.7 |
| Perfluoroheptanesulfonic acid (PFHpS) | ug/L | 0.65 | <1.3 | 0.088 |
| Perfluorooctanesulfonic acid (PFOS) | ug/L | 220 | 160 | 9.5 |
| Perfluorodecanesulfonic acid (PFDS) | ug/L | 0.89 | <1.3 | 0.064 |
| Perfluorooctane Sulfonamide (PFOSA) | ug/L | 0.46 | <1.3 | 0.23 |
| EtFOSA | ug/L | <0.54 | <1.3 | <0.077 |
| MeFOSA | ug/L | <0.21 | <1.3 | <0.030 |
| EtFOSE | ug/L | <0.56 | <1.3 | <0.080 |
| MeFOSE | ug/L | <0.40 | <1.3 | <0.056 |
| 6:2 Fluorotelomer sulfonic acid | ug/L | <0.35 | 2.4 | 1.4 |
| 8:2 Fluorotelomer sulfonic acid | ug/L | <0.35 | <1.3 | 0.10 |
| **TOTAL** | **ug/L** | **236** | **177** | **42** |

**Table 8**: Results of treating the finer IDW soil fraction (sand/silt/clay) with OxyZone® process for 4 hours.

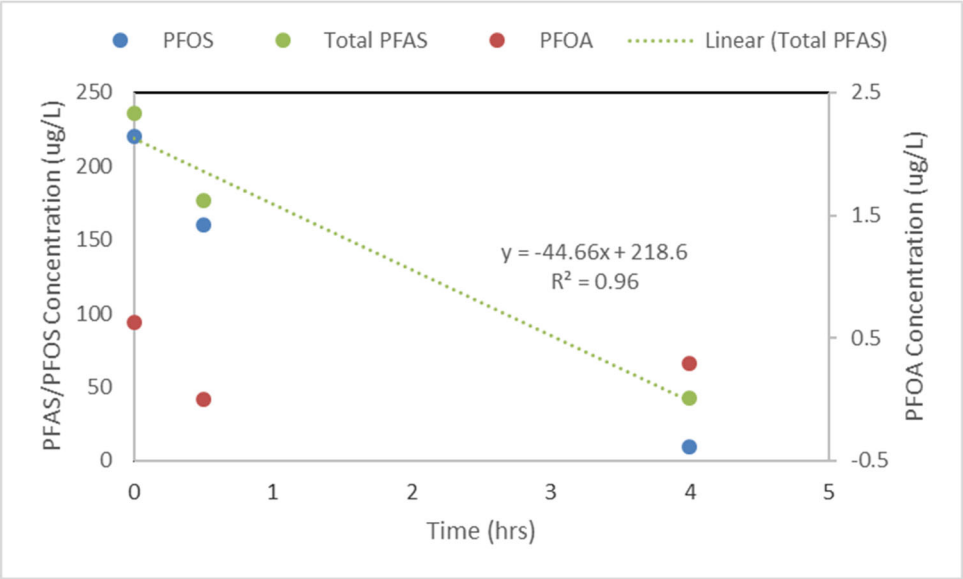



**Figure 7**: After 4 hrs of treatment of IDW soil slurry (fine fraction) with OxyZone® process, the total PFAS concentrations decreased by 82%. PFOS and PFOA reduction was 96% and 54%, respectively.

The previous test was repeated under similar conditions, except that the pH was held steady at 11 and the treatment time was extended to 6 hrs. Similar results were observed (Total PFAS removal 81%), indicating that keeping the pH steady had not major effect on the OxyZone® treatment process (Data not shown).

Another similar test was carried out for 6 hours during which hydrogen peroxide was added continuously to the slurry. This test resulted in an overall lower total PFAS treatment destruction (54%; data not shown). Based on these tests, it was concluded that treating the aqueous phase of the slurry does not require keeping the pH constant or adjusting the peroxide concentration of the treatment solution.

In a final OxyZone® slurry test, the slurry samples collected from inside the gas-infusion reactor over the duration of the treatment (16 hrs) indicate that PFOS concentration decreased by 66% in 11.5 hrs PFOA increased from an initial concentration of 2.8 µg/L to 8.7 µg/L. Four other compounds (PFNA, PFBS, PFHxA, and the 6:2 fluorotelomer) also increased during, suggesting that a fraction of PFAS precursors or unidentified PFAS compounds were being converted during the experiment.

| PFAS Detected in Willow Grove IDW Soil | UNITS | Proposed MADEP Soil Criteria, non-aquifer area | Bulk Soil | Fine Gravel fraction | Fine sand/silt fraction | | Leachate from fine fraction (sand/silt) and GW treated with OxyZone® in a slurry reactor (ug/l) |
|---|---|---|---|---|---|---|---|
| 6:2 Fluorotelomer sulfonate | ug/kg | | 3.2 | 2.1 | 1.4 | | 0.012 |
| 8:2 Fluorotelomer sulfonate | ug/kg | | < 3.3 | 0.60 | <3.3 | | < 0.0059 |
| Perfluorobutane Sulfonate (PFBS) | ug/kg | | 0.33 | 1.2 | 1.4 | | < 0.0051 |
| Perfluorobutanoic acid (PFBA) | ug/kg | | 1.5 | 1.4 | 2.3 | | < 0.007 |
| Perfluorodecane Sulfonate | ug/kg | | 17 | 3.9 | 4 | | < 0.0072 |
| Perfluorodecanoic Acid (PFDA) | ug/kg | 300 | 1.1 | 0.37 | <3.1 | | < 0.0041 |
| Perfluorododecanoic Acid (PFDoA) | ug/kg | | 0.47 | 0.31 | <1.9 | | < 0.0068 |
| Perfluoroheptane sulfonate (PFHpS) | ug/kg | | 1.3 | 1.6 | 3.7 | | 0.039 |
| Perfluoroheptanoic Acid (PFHpA) | ug/kg | 300 | 0.49 | 1.3 | <1.8 | | 0.047 |
| Perfluorohexane Sulfonate (PFHxS) | ug/kg | 300 | 21 | 14 | 36 | | 0.060 |
| Perfluorohexanoic Acid (PFHxA) | ug/kg | | 3.1 | 3.3 | 5.6 | | 0.036 |
| **Perfluoro-n-Octanoic Acid (PFOA)** | **ug/kg** | **300** | **1.2** | **1.6** | **3.1** | | **0.11** |
| Perfluorononanoic Acid (PFNA) | ug/kg | 300 | 2.1 | 1.2 | <1.5 | | < 0.0049 |
| Perfluorooctane Sulfonamide (PFOSA) | ug/kg | | 2.7 | 1.2 | <1.9 | | < 0.0066 |
| **Perfluorooctane Sulfonate (PFOS)** | **ug/kg** | **300** | **1,220** | **470** | **1,500** | | **0.34** |
| Perfluoropentanoic Acid (PFPeA) | ug/kg | | 2.4 | 2.2 | 4.5 | | < 0.0041 |
| Perfluoroundecanoic Acid (PFUnA) | ug/kg | | 1.7 | 0.49 | 1.6 | | < 0.0043 |
| | **ug/kg** | TOTAL | **1,280** | **505** | **1,560** | | **0.64** |

**Table 9**: Soil leachate results after treating the fine fraction (sand/silt/clay) of the IDW test soil with OxyZone®. Initial PFAS concentrations in each soil fraction and in the bulk soil are provided for reference. The most stringent of the proposed Massachusetts Department of Environmental Protection (MA DEP) MCP limit for PFAS contaminated soils is 300 µg/kg (S-1). Also shown are the results of the leachate test conducted on the treated soil. Based on this test, some of the PFAS exceeded the 0.070 µg/L leachate testing threshold.

After this OxyZone® treatment, the treated fine fraction was settled, centrifuged, washed and dried before being subjected to the leachate testing procedure. The results indicate that both PFOS (340 ng/L) and PFOA (110 ng/L) concentrations in the leachate exceeded the threshold of 70 ng/L. However, 15 other PFAS, including 4 of the 4 UCMR PFAS were below 70 ng/l (Total PFAS: 644 ng/L; **Table 9**).

Leaching tests on the 16-hour OxyZone treated fine fraction soil indicate that 4 PFAS (PFOS, PFHxS, PFHpA, and PFPeA) exceeded the 70 ng/L threshold in the leachate. **Table 10** compares the leachate concentrations measured after treatment by XCT® rinsing and OxyZone® destruction of the coarse and fine soil fractions, respectively. The PFAS compounds in the leachate after XCT® rinsing are considerably lower than after OxyZone® destruction.

Overall, the results suggests that gas infusion treatment of soil slurry material is not more effective than XCT® solution rinsing (see Task 2). Therefore, OxyZone® gas infusion should be considered a viable treatment for IDW material under the conditions tested.

| what treated | treatment | what was analyzed | # PFAS less than 70 ppt | PFAS RESULTS > 70 ppt | | | UCMR-6 | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | PFOS | PFOA | PFHxS | PFHxA | PFHpA | PFPeA |
| fine gravel-fraction containing 17 PFAS, in DW | 1 g/l CD tumbling for 15 minutes | 20x leachate > tumbling treated fine gravel - 15 min. - unfiltered | 16 PFAS', incl. 5 UCMR's | 0.072 | < 70 ppt | < 70 ppt | < 70 ppt | < 70 ppt | < 70 ppt |
| | | | | | | | | | |
| sand/silt fraction, containing 17 PFAS, in DW | OxyZone slurry for 4 hrs., pH 11, then 7, in DW | 20x leachate of treated and rinsed sand/silt-filtered | 15 PFAS', incl. 4 UCMR's | 0.34 | 0.11 | < 70 ppt | < 70 ppt | < 70 ppt | < 70 ppt |
| | | | | | | | | | |
| sand/silt fraction, containing 17 PFAS, in GW | OxyZone in slurry for 16 hrs., pH 11, w/ peroxide | 20x leachate of cleaned sand/silt - unfiltered | 14 PFAS', incl. 3 UCMR's | 3.2 | < 70 ppt | 0.53 | 0.28 | < 70 ppt | 0.11 |
| | | NOTE: the 6 UCMR PFAS are: | | PFOS | PFOA | PFHxS | PFHpA | PFNA | PFBS |

**Table 10:** Summary of soil leachate concentrations from soil treated by both XCT® rinsing and OxyZone®

*4.5.3. - Task 3* - Design and Testing of Semi-Batch Scale Continuous Flow Gas Infusion Reactor for IDW Water and IDW Soil Slurry

The results from Tasks 1 and 2 indicated that:

(1) the PFAS associated with the coarse soil fraction of the IDW test material is best treated separately from the finer fraction,

(2) rinsing the coarse fraction with XCT® solution produces a material that can be possibly considered remediated based on MADEP criteria

(3) the fine soil fraction can be treated to meet S-1/Groundwater-3 MADEP criteria when processed with OxyZone® in a slurry reactor, but failed our internal project-specific criterion (leachate test),

(4) the liquid phase separated from the slurry and rinsing the coarse IDW fraction requires further treatment.

The main objective of Task 3 was testing a modified soil/water treatment process (gas infusion) to speed up the PFAS treatment process of soil and water together. Towards this goal, we developed and investigated a gas-infusion treatment process at batch scale coupled with foaming as a means to concentrate PFAS. Subsequent tests were carried out in which PFAS enriched foam was irradiate with UV light.

*Testing for Aerosol Losses of PFAS*

An experiment was carried out to investigate the amount of PFAS entering the air phase during gas-infusion. A gas infusion reactor was constructed to treat IDW slurry (**Figure 4**). A mix of ambient air

and ozone (~10:1) was injected from the bottom of the reactor at a rate of 1 to 2 l/min. The reactor was outfitted with three in-series off-gas traps for capturing any PFAS transferred into the gas phase. The traps were filled with DI water. The amount of IDW soil inside the reactor was 900 g. The aqueous phase was OxyZone® solution (4.5 L). The initial and final pH was 11.0 and 11.2, respectively. There was no XCT® present in the solution. The experimental duration was 16 hrs. Afterward, the treated IDW material inside the reactor was recovered and dried. A fraction of the material was subjected to a leaching test. Another fraction of the treated soil was send to the laboratory for analysis.

The data from analyzing the off-gas traps demonstrate that PFAS transfer from the soil/aqueous phase (slurry) to the gas phase is comparatively small (1.1 % accumulated in off-gas traps) relative to the initial PFAS mass contained in the soil inside the reactor. The percentage of PFAS trapped varied per individual PFAS and ranged from 6% to 20% (**Table 11**). Of the total amount of PFAS trapped, the first trap was about two times more effective compared to the second trap and nine times more effective than the third. The third trap contained only 0.1% of the total PFAS initially in the reactor, suggesting that any amount of PFAS that could have escaped the system was negligible.

| BV Labs ID | | | KYQ513 | KYQ514 | KYQ515 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sampling Date | | | 10/3/19 | 10/3/19 | 10/3/19 | | | | |
| COC Number | | | n/a | n/a | n/a | | | | |
| | **ug in slurry at t=0** | | **TRAP#1 T=11.5 HR** | **TRAP#2 T=11.5 HR** | **TRAP#3 T=11.5 HR** | **UNITS (each trap is 1 L)** | **total ug in all 3 traps** | **% of t=0 mass in all 3 traps** | **% of mass in Trap #3 of total in all 3 traps** |
| Perfluorobutanoic acid (PFBA) | 6.9 | | 0.33 | 0.069 | 0.038 | ug/L or ug | 0.44 | 6.3% | 8.7% |
| Perfluoropentanoic Acid (PFPeA) | 14 | | 0.69 | 0.14 | 0.075 | ug/L or ug | 0.91 | 6.4% | 8.3% |
| Perfluorohexanoic Acid (PFHxA) | 35 | | 1.9 | 0.43 | 0.25 | ug/L or ug | 2.6 | 7.4% | 10% |
| Perfluoroheptanoic Acid (PFHpA) | 3.9 | | 1.1 | 0.15 | 0.15 | ug/L or ug | 1.4 | 36% | 11% |
| Perfluorooctanoic Acid (PFOA) | 14 | | 1.8 | 1.0 | 0.19 | ug/L or ug | 3.0 | 22% | 6.4% |
| Perfluorononanoic Acid (PFNA) | 0.9 | | 0.16 | 0.26 | 0.072 | ug/L or ug | 0.49 | 54% | 15% |
| Perfluorodecanoic Acid (PFDA) | < DL | | <0.0041 | 0.0059 | <0.0041 | ug/L or ug | < DL | < DL | < DL |
| Perfluoroundecanoic Acid (PFUnA) | 1.4 | | <0.0043 | <0.0043 | <0.0043 | ug/L or ug | < DL | < DL | < DL |
| Perfluorododecanoic Acid (PFDoA) | < DL | | <0.0068 | <0.0068 | <0.0068 | ug/L or ug | < DL | < DL | < DL |
| Perfluorotridecanoic Acid | < DL | | <0.0069 | <0.0069 | <0.0069 | ug/L or ug | < DL | < DL | < DL |
| Perfluorotetradecanoic Acid | < DL | | <0.0067 | <0.0067 | <0.0067 | ug/L or ug | < DL | < DL | < DL |
| Perfluorobutanesulfonic acid (PFBS) | 13 | | 0.048 | <0.0051 | <0.0051 | ug/L or ug | 0.048 | 0.36% | 5.5% |
| Perfluorohexanesulfonic acid (PFHxS) | 109 | | 4.0 | 1.0 | 0.37 | ug/L or ug | 5.4 | 4.9% | 6.9% |
| Perfluoroheptanesulfonic acid (PFHpS) | 13 | | 0.089 | 0.032 | 0.0086 | ug/L or ug | 0.13 | 1.0% | 6.6% |
| Perfluorooctanesulfonic acid (PFOS) | 1390 | | 1.7 | 2.2 | 0.23 | ug/L or ug | 4.1 | 0.30% | 5.6% |
| Perfluorodecanesulfonic acid (PFDS) | 3.6 | | <0.0072 | <0.0072 | <0.0072 | ug/L or ug | < DL | < DL | < DL |
| Perfluorooctane Sulfonamide (PFOSA) | 1.8 | | <0.0066 | 0.018 | <0.0066 | ug/L or ug | 0.018 | 1.0% | 12% |
| EtFOSA | < DL | | <0.0090 | <0.0090 | <0.0090 | ug/L or ug | < DL | < DL | < DL |
| MeFOSA | < DL | | <0.0035 | <0.0035 | <0.0035 | ug/L or ug | < DL | < DL | < DL |
| EtFOSE | < DL | | <0.0094 | <0.0094 | <0.0094 | ug/L or ug | < DL | < DL | < DL |
| MeFOSE | < DL | | <0.0066 | <0.0066 | <0.0066 | ug/L or ug | < DL | < DL | < DL |
| 6:2 Fluorotelomer sulfonic acid | 14 | | 0.036 | 0.047 | 0.021 | ug/L or ug | 0.10 | 0.72% | 20% |
| 8:2 Fluorotelomer sulfonic acid | 1.1 | | <0.0059 | 0.020 | <0.0059 | ug/L or ug | 0.020 | 1.8% | 11% |
| **TOTAL** | **1622** | | **12** | **5.4** | **1.4** | **ug/L or ug** | **19** | **1.1%** | **7.5%** |

**Table 11:** Amount of PFAS compounds accumulated in off-gas traps #1 to #3.

*Surface Tension Measurements*

The foam fractionation reactor takes advantage of the residual XCT® solution left-over from rinsing the IDW soil (Tasks 1 and 2). The XCT® solution creates a mild foam that remains stable for sufficiently long time to permit exposure to UV light. The stability of the foam can be adjusted based on the XCT® solution concentration and its effect on solution's surface tension. The surface tension of six samples of Willow Grove site groundwater with and without XCT® were determined (**Figure 8**). The XCT® concentrations ranged from 100 mg/L to 5,000 mg/L.

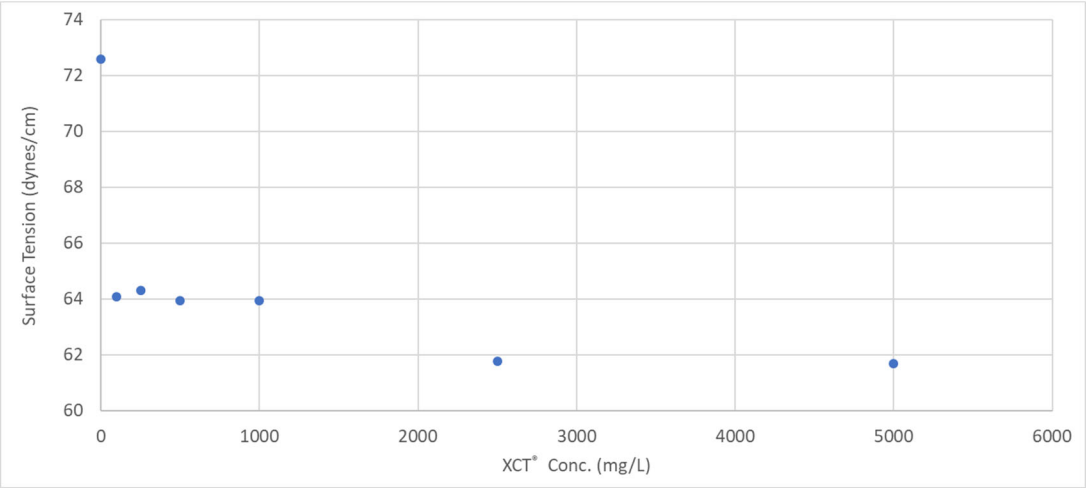



**Figure 8**: Surface tension dropped from 72.6 dynes/cm in site groundwater after adding as little as 100 mg/L XCT®. Although the surface tension further declined by adding increasing amounts of XCT® (up to 5,000 mg/L), the overall drop was less than 3 dynes/cm over the range of XCT® concentrations measured.

*Enhanced Foam Fractionation Reactor Tests*

Initial tests were carried out to characterize the XCT® solution as an enhanced foam fractionation agent. Subsequent tests demonstrated the effectiveness of foamation when irradiated with UV light. This task's objective was to produce a PFAS enriched, stable column of foam containing the PFAS for treatment in a reactor by UV irradiation of OxyZone®.

The following tests focused on measuring the effect of foam fractionation on PFAS concentration inside the foam fractionation reactor (**Figure 4**). During foam fractionation, air was bubbled through an aqueous solution of PFOS and PFOA ($C_o$ = 103 µg/L and 2.5 µg/L, respectively). The solution contained 1000 mg/L XCT® solution, but no oxidants or ozone gas. The foam created was skimmed from the top of the solution and collected in a plastic container. Samples from the liquid inside the foam fractionation reactor were collected at 0, 0.5 and 2 hours. At the end of the experiments, the

initial volume of liquid inside the reactor was reduced by about 10%, the collapsed foam being about 10% of the initial volume added to the reactor. The results are summarized in **Figure 9** and indicate that PFAS was effectively transferred from the aqueous to gas phase. That is, the PFOS and PFOA concentration in the liquid remaining inside the reactor dropped by at least 99.5%, respectively, within two hours of foam fractionation. Our results (**Figure 9**) confirmed, in fact exceeded, the results presented by Meng et al. (2008). The precise mechanism of PFAS transfer from the liquid to the foam was not studied further. However, the literature documents that three representative PFAS of varying carbon chain length, ranging from 8 to 4 carbons (i.e. PFOS, PFOA, and PFBA) are encapsulated by in the active ingredients of XCT® (Karoyo et al. 2015). We therefore hypothesize that PFAS encapsulated in XCT® compositions are concentrating is on the surface of the foam bubbles that from when XCT® solution is aerated.

The results of the batch-scale foam fractionation experiments indicate the concentration PFAS in a XCT®/foam phase is an efficient process to remove these compounds from water.

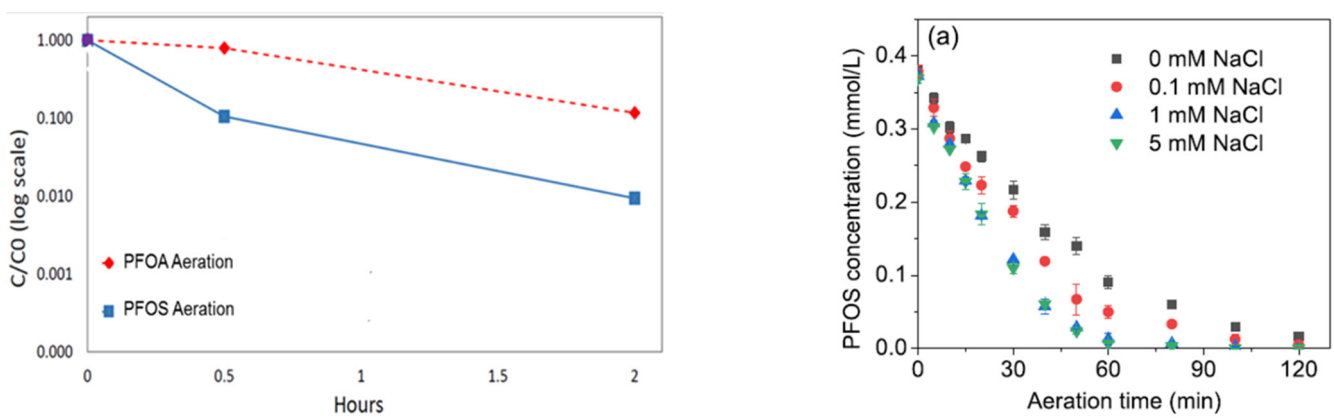



**Figure 9:** (Left) Results of transferring PFAS from an aqueous solution containing XCT® solution into foam (log scale). (Right) Removal of PFOS by foam fractionation using solutions of increasing ionic strength as presented by Meng et al. (2008).

*4.5.4. - Task 4* - System up-scaling: Pilot-Scale Gas Infusion Reactor Experiments for IDW Batch Mode Treatment

The results from Tasks 1 to 3 indicate that an OxyZone® reactor system can be constructed for the treatment of PFAS contaminated IDW soil and water.

At full-scale, such a system consists of treatment stages:

(1) rinsing of the coarse fraction of IDW soil,

(2) fine fraction soil slurry treatment, and

(3) aqueous phase (process water and/or IDW water) treatment by foam fractionation/irradiation.

Note that stage (3) is the only one required if treating IDW water only (no IDW soil). All tests were conducted at room temperature.

The main Task 4 objective was to conduct a proof-of-concept batch reactor experiment to demonstrate the treatment of the aqueous phase by foamation/irradiation. This treatment stage produces a PFAS enriched, stable column of foam that is then separated and treated by in a reactor by UV irradiation of OxyZone®. It is the final stage of our treatment train, resulting in the mineralization of PFAS in the IDW water and/or process water. The treated water exits the reactor and is discharged after validation.

The results from Tasks 1 to 3 indicate that a treatment system as shown in **Figure 1** can be constructed for the treatment of PFAS contaminated IDW soil and ground water at the pilot-scale. First, PFAS is rinsed off the IDW soil material. The soil rinsing is aided by XCT® solution which promotes desorption of PFAS from the mineral surfaces. The treated IDW soil meets the MADEP soil standards and can likely disposed. To meet the more stringent leachate test, additional rinses with fresh XCT® solution might be required. The rinse liquid, either by itself or combined with IDW water, must be further treated. Our data indicate that simple volatilization from a gas-infusion reactor is insufficient to reach the treatment goal. However, if PFAS are stripped from the solution via XCT enhanced foam fractionation, separated, and the stable XCT® foam issubjected to UV irradiation enhanced OxyZone®, the 23 target PFAS can almost entirely be mineralized. The goal of Task 4 was to test an aeration and foam collection and treatment reactor intended for treating XCT®-amended aqueous solutions (process water and actual IDW water, no soil). The gas infusion reactor creates a foam rich in PFAS. Inside the same reactor, the foam is irradiated with UV light, resulting in the destruction PFAS by oxidant radials produced from the OxyZone® process The treated water exits the reactor and is discharged after validation.

*Foam fractionation/UV Irradiation Reactor*

There is evidence in the literature (Bao et al. 2018) that PFAS can be degraded by UV light. However, most of the references describe comparably slow degradation rates. In this part of our study, we investigated if and how much OxyZone® can aide in the destruction of PFAS by UV irradiation. For this, we constructed a UV irradiation reactor at batch scale (**Figure 5**). A low pressure amalgam UV lamp (Model T6 GCL from Light –Sources, Inc. New Orange, CT) with an effective peak wavelength

between 185 - 254 nm was installed inside a plastic column. Two tests were performed) at room temperature, lasting 4 hours each, by adding XCT® solution to Willow Grove IDW water and treating the foam in the reactor with OxyZone®.

A combined foam fractionation/irradiation reactor was designed and built from aluminum and other inert parts (**Figure 5**). Process water and/or IDW ground water is pumped into the reactor (Volume= 3 L). Process water from rinsing IDW soil contains residual XCT® solution but IDW groundwater will not. Hence, XCT® solution is added as needed to the liquid to optimize foam formation. A mixture of oxygen and ozone gas (~15:1) is injected from the bottom of the foam collection chamber, resulting is the formation of foam inside the reactor. The stability of the foam can be adjusted by manipulating the solution's XCT® concentration. A 4 micron glass wool "screen" in the column annular space was inserted to minimize the escape of PFAS aerosols. A recent study by Brusseau (2019) suggests that PFAS tend to concentrate on at the air-water interface. Although not investigated, we further postulate that the presence of the XCT® further aides in the accumulation of PFAS at the foam surface. As the PFAS enriched foam rises, it envelopes a UV lamp. The UV light interacts with the OxyZone® solution to generate both hydroxyl and sulfate radicals, and possibly other ones, as demonstrated by Cashman et al. (2019). These radicals cause the mineralization of the PFAS. Any PFAS not destroyed is recycled back into the reactor solution to be converted to foam again. The treatment process proceeds until PFAS is degraded to below applicable thresholds, i.e. 70 ng/l. As needed, XCT® solution is added to maintain a stable foam.

*Experimental conditions*: The reactor used in this test was newly fabricated from aluminum and had never been exposed to IDW PFAS before. Prior to use, the reactor was rinsed several times with warm DI water. Then, a test was conducted to determine any interactions between the reactor and the Willow Grove IDW water.

Inside the reactor, 2 liters of Willow Grove IDW water was amended with buffered OxyZone® and XCT® solution. Because XCT® solution is being degraded during the experiments, additional XCT® was added throughout the test to keep the concentration steady (~6 g/hr). The initial pH was 9.1 and kept between 8 and 10 by addition of sodium hydroxide solution during the experiment. Oxygen/Ozone (~15:1) was sparged through the porous bottom of the reactor. The sparge rate was calibrated to ensure foam stability and height without foam existing the reactor via the off-gas traps. Samples of the liquid inside the reactor were periodically collected and analyzed for fluoride and

PFAS. The experiment lasted for 6 hrs. Afterward, samples were also collected from the three in-series off-gas traps and analyzed for PFAS. Samples of the aqueous phase were collected at 0, 0.5, 1, 2, 4 and 6 hours and analyzed for PFAS. The data is summarized in **Table 12**.

| | UNITS | 0 hr | 0.5 hr | 1 hr | 2 hr | 4 hr | 6 hr |
|---|---|---|---|---|---|---|---|
| Perfluorobutanoic acid (PFBA) | ug/L | 1.65 | 3.3 | 3.2 | 3.2 | 3.9 | 1.5 |
| Perfluoropentanoic Acid (PFPeA) | ug/L | 2.4 | 1.2 | 0.65 | 0.69 | 0.097 | 0.0081 |
| Perfluorohexanoic Acid (PFHxA) | ug/L | 8.95 | 1.7 | 0.68 | 0.69 | <0.02 | <0.0064 |
| Perfluoroheptanoic Acid (PFHpA) | ug/L | 0.67 | 0.17 | 0.068 | 0.11 | <0.022 | <0.0071 |
| Perfluorooctanoic Acid (PFOA) | ug/L | 2.2 | 0.17 | 0.03 | 0.025 | <0.023 | <0.0074 |
| Perfluorononanoic Acid (PFNA) | ug/L | <0.28 | <0.015 | <0.016 | <0.015 | <0.015 | <0.0049 |
| Perfluorodecanoic Acid (PFDA) | ug/L | <0.26 | <0.012 | <0.014 | <0.013 | <0.013 | <0.0041 |
| Perfluoroundecanoic Acid (PFUnA) | ug/L | <0.22 | <0.013 | <0.014 | <0.013 | <0.013 | <0.0043 |
| Perfluorododecanoic Acid (PFDoA) | ug/L | <0.17 | <0.020 | <0.022 | <0.021 | <0.021 | <0.0068 |
| Perfluorotridecanoic Acid | ug/L | <0.24 | <0.021 | <0.023 | <0.021 | <0.021 | <0.0069 |
| Perfluorotetradecanoic Acid | ug/L | <0.23 | <0.020 | <0.022 | <0.021 | <0.021 | <0.0067 |
| Perfluorobutanesulfonic acid (PFBS) | ug/L | 2.35 | 0.89 | 0.46 | 0.57 | 0.029 | 0.0066 |
| Perfluorohexanesulfonic acid (PFHxS) | ug/L | 15 | 3 | 0.84 | 0.87 | <0.016 | 0.0072 |
| Perfluoroheptanesulfonic acid (PFHpS) | ug/L | 2.1 | 0.16 | 0.02 | 0.01 | <0.01 | <0.0033 |
| Perfluorooctanesulfonic acid (PFOS) | ug/L | 95.5 | 2.9 | 0.15 | 0.11 | <0.016 | <0.0052 |
| Perfluorodecanesulfonic acid (PFDS) | ug/L | <0.22 | <0.022 | <0.024 | <0.022 | <0.022 | <0.0072 |
| Perfluorooctane Sulfonamide (PFOSA) | ug/L | <0.27 | <0.020 | <0.022 | <0.020 | <0.020 | <0.0066 |
| EtFOSA | ug/L | <0.28 | <0.027 | <0.030 | <0.028 | <0.028 | <0.0090 |
| MeFOSA | ug/L | <0.35 | <0.011 | <0.012 | <0.011 | <0.011 | <0.0035 |
| EtFOSE | ug/L | <0.20 | <0.028 | <0.031 | <0.029 | <0.029 | <0.0094 |
| MeFOSE | ug/L | <0.27 | <0.020 | <0.022 | <0.020 | <0.020 | <0.0066 |
| 6:2 Fluorotelomer sulfonic acid | ug/L | 2.55 | 0.076 | <0.019 | <0.018 | <0.018 | <0.0059 |
| 8:2 Fluorotelomer sulfonic acid | ug/L | <0.28 | <0.018 | <0.019 | <0.018 | <0.018 | <0.0059 |

**Table 12**: Results from foam fractionation/irradiation experiment treating IDW water with OxyZone® technology.

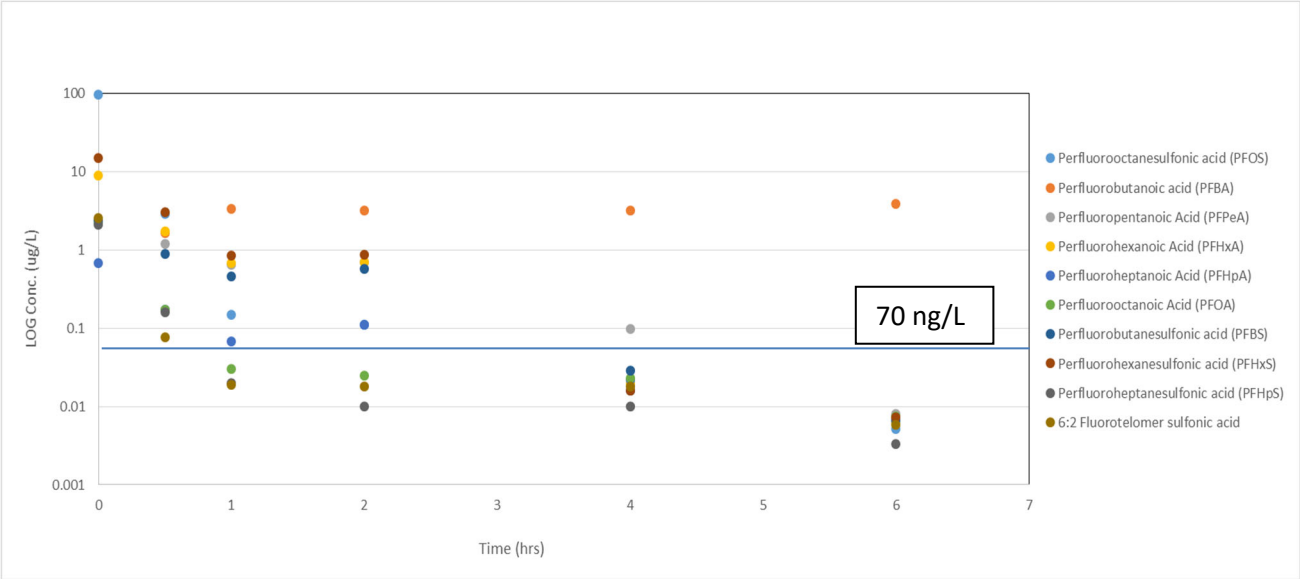



**Figure 10**: Concentrations (log µg/L) of initially present PFAS in response to foam fractionation/irradiation treatment of aqueous phase IDW. All PFAS, except PFBA declined to below the 70 ng/L treatment end-point threshold.

The data from the foam fractionation/irradiation experiment clearly demonstrate that all PFAS (except PFBA) initially detected in the IDW water can be mineralized to below the 70 ng/L threshold within 4 to 6 hrs (**Figure 10**).

Based on the initially present PFAS, the organofluorine concentration in the IDW water was 133 µg/l at t=0. It decreased to 1.7 µg/l after 6 hours of treatment, indicating that about 191 µg organofluorine was mineralized to fluoride ($F^-$). **Figure 11** illustrates that fluoride concentrations increased at a comparatively steady rate. Over 6 hours, more than 400 µg of fluoride were released or about 2 times the decrease in organofluorine expected from the initially detected PFAS. This suggests that a significant amount of other, non-detectable PFAS in the Willow Grove groundwater were also mineralized.

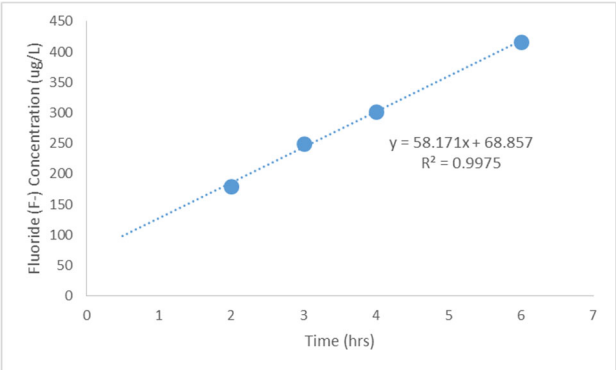
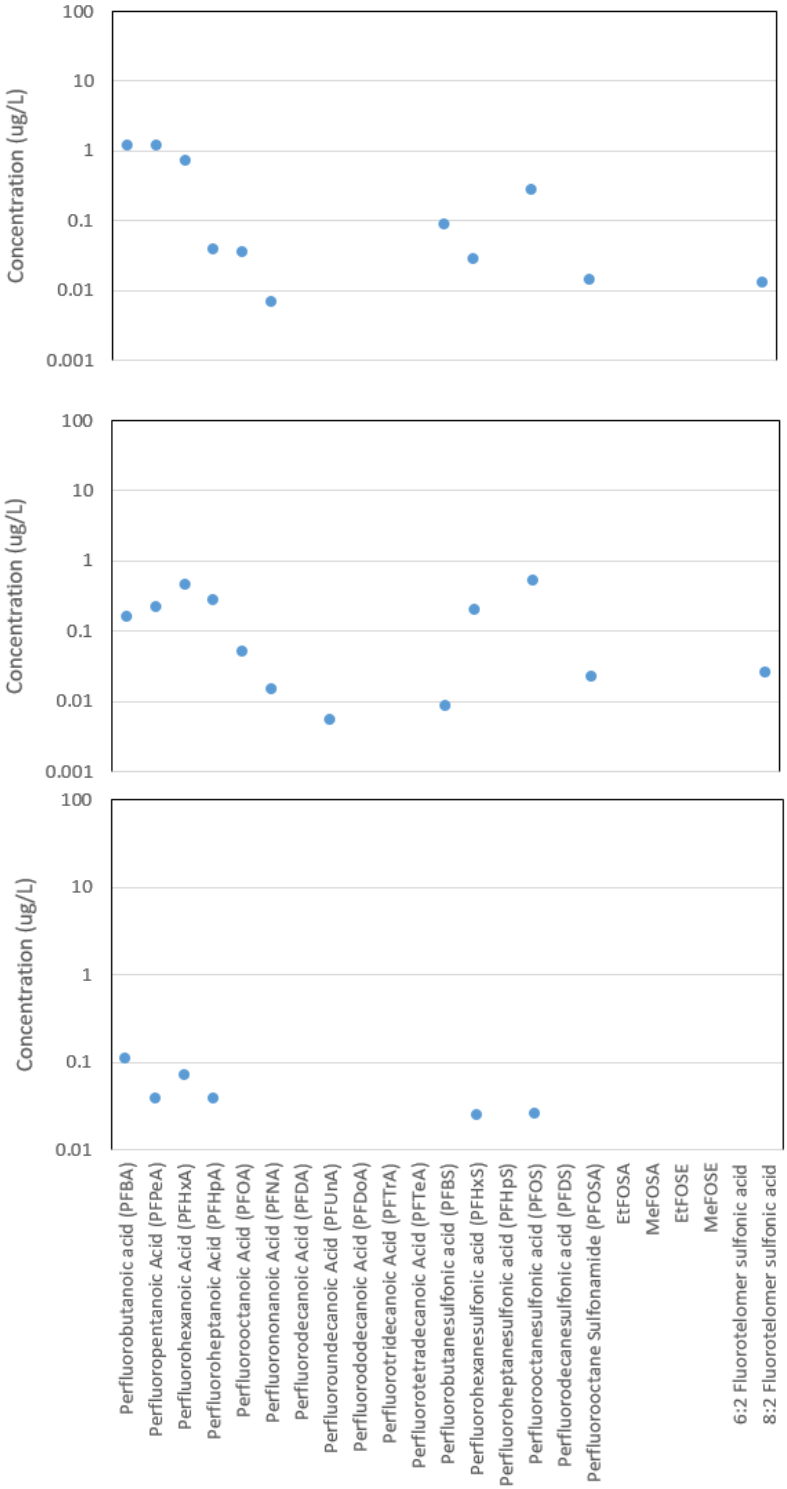



**Figure 11:** Observed fluoride (F-) concentration measured during foam fractionation/irradiation treatment with the OxyZone® process No samples were analyzed at 0.5 and 1 hr.

The untreated Willow Grove IDW water contained 10 detectable PFAS. After 1 to 4 hrs of treatment, eight PFAS were <70 ng/L. PFPeA required 4 to 6 hours to reach that threshold. PFHpS decreased to non-detect in 1-3 hours. Only PFBA increased in concentration during the experiment, although its final (6 hr) concentration was lower than initially. Presumably, other PFAS are breaking down into this 4-carbon PFAS and it appears that it takes longer than 6 hours to mineralize PFBA eventually.




**Figures 12a to 12c:** PFAS concentrations in off-gas traps 1 to 3 (top downward) after 6 hrs of foam fractionation/irradiation treatment with the OxyZone® process

*Transfer of PFAS from reactor to off-gas traps:* As shown in **Figures 12a** to **12c**, of the 10 detectable PFAS in the untreated IDW water, 8 were detected in traps #1 and #2, respectively and 6 in trap #3. Not detected in the traps #1 and #2 were PFHpS and 6:2 Fluorotelomer sulfonic acid. Hence, it can be assumed that they were fully mineralized inside the reactor. Breakthrough in trap #3 was observed for PFHpA and PFHxS and partial breakthrough (<10% compared to trap #1) for 4 others (**Figure 12c**). Additionally, three other PFAS (namely: PFNA, PFOSA, and 6:2 Fluorotelomer sulfonic acid), not even detected in the original IDW water, were detected in the traps #1 and #2; presumably they were produced in the reactor as breakdown products of other PFAS, and then partially transferred to the traps. There was a noticeable difference between the amount of PFAS that was transferred out of the reactor. Of the 5 to 7-carbon carboxylic acids, 10% to 42% were transferred to the exhaust. For all the longer chained PFAS, both acids and sulfonates, 1% to 10% were transferred out of the reactor. This lead to the conclusion that the remainder of the higher carbon PFAS must have been destroyed.

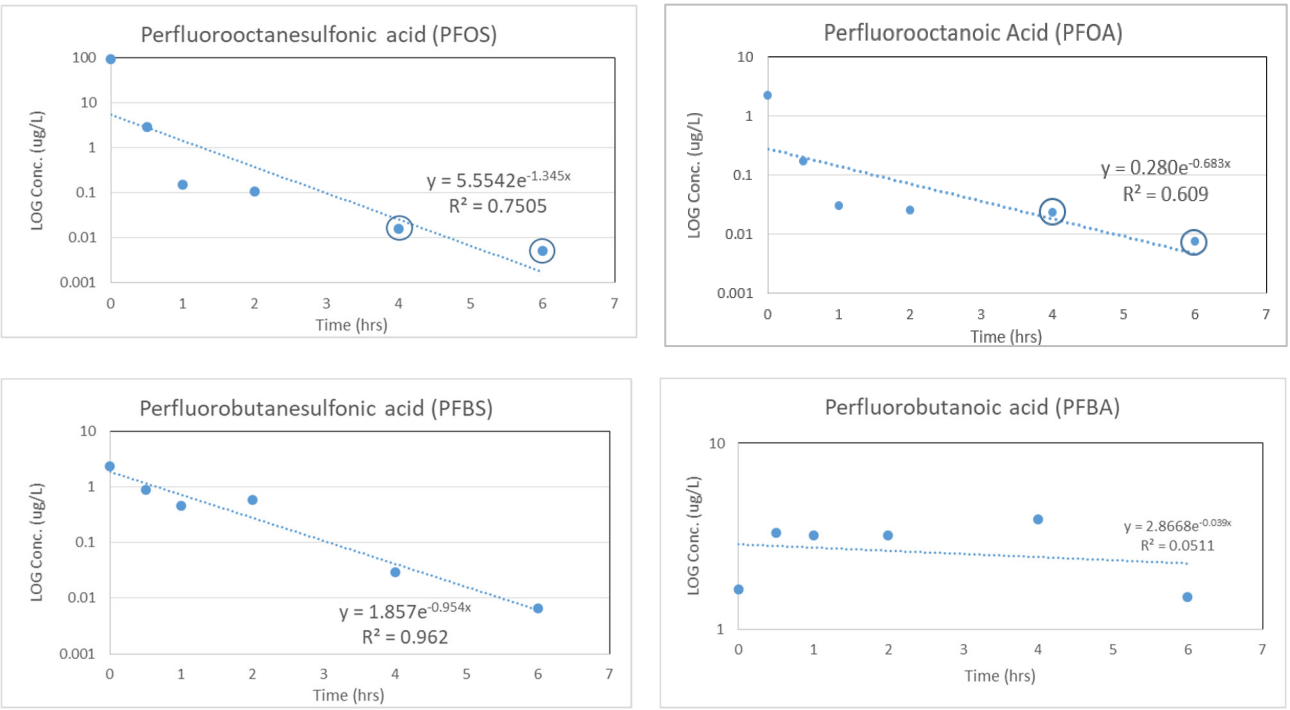



**Figure 13**: Concentrations (Log µg/L) of select PFAS as observed during foam fractionation/irradiation treatment of aqueous phase IDW. Circled data points (PFOS and PFOA) are concentrations below detection limit that are reported at the corresponding detection limit for illustration purpose.

**Figure 13** present four data sets (PFOS, PFOA, PFBS and PFBA) for closer inspection (see Appendix 8 for other PFAS). The PFBS graph reveals that the concentration is declining in a predictable (log-linear) fashion. This trend was observed for all PFAS compounds shown in **Figure 13**, except for PFOS and PFOA. The data for these two compounds suggest two separate stages of decline in the concentration profile: the first stage (0 to 1 hours) is fast, while the second stage (>1 hr) is slower. With the caveat of relying on the transformation of concentrations reported to be below the concentration to those at the detection limit, the profile might suggest that PFOS and PFOA are produced from precursors. However, destruction rates apparently exceeded production rates since both compounds were non-detectable after 2 hrs. Finally, the only PFAS compound that resisted our treatment was PFBA. However, since the trend line through the PFBA data is almost flat, it appears that this compound did not accumulate either, as was observed during treatment of PFAS with plasma (Holsen 2019). Additional tests have to be conducted to further investigate if PFBA truly is resisting treatment or if it is destroyed as fast as it might be produced via the degradation of longer-chained PFAS compounds.

*Interferences*: Prior to the foam fractionation/irradiation experiment, we tested the reactor vessel for any interferences, such as sorption of PFAS or other processes that could possibly add or remove PFAS. After filling the reactor with untreated IDW water and letting it sit undisturbed for 14 hrs at room temperature, all initially present PFAS compounds in the untreated IDW water decreased in concentration, from 5% to 20%, with a weighted average of 18%. While this amount of loss is not considered problematic during actual full-scale operation, it does detract from a good mass balance presentation. However, the amount of PFAS mineralization during the actual treatment, >99% for all PFAS (other than PFBA) over 6 hours or less, is much greater than the loss observed over 14 hours.

## 5. Cost Effectiveness and potential limitations

*5.1. Cost effectiveness*

This project focused on treating IDW under semi-batch and pilot-scale conditions. Therefore, only limited data was generated to assess the cost effectiveness of a future full-scale treatment system. A preliminary cost estimate of our treatment approach was compared to incineration (land filling is not an option in many jurisdictions) of PFAS contaminated IDW soil and ground water matrices. The estimate suggests that our approach will be much less costly.

In addition to the OxyZone® treatment process, there are a number of PFAS IDW treatment technologies in the early stages of development (e.g., soil rinsing, plasma and electrochemical treatment). However, these technologies require further development to demonstrate technical merit and commercial feasibility for use (EPA 2018, GHD 2019). Therefore, a direct cost comparison with these evolving technologies is impossible at this time.

*5.2. Potential limitations and risks of treatment approach*

Our research demonstrates that the treatment of PFAS contaminated IDW soil and water matrices with OxyZone® technology is possible. Given the nature of IDW, our treatment approach is exclusively an *ex situ* process. That is, it cannot be transferred to treating PFAS pollution under *in situ* condition. However, *ex-situ* treatment is advantageous because it limits the risk of losing control over the treatment solution and escape of untreated PFAS.

Like any other advanced oxidation process, caution needs to be taken when handling strong oxidants involved in the PFAS mineralization process.

In addition, currently there is uncertainty regarding the regulatory framework under which PFAS contaminated soil and groundwater is administered. That is, the government and individual states are actively working on setting standards for treatment and disposal of PFAS contaminated matrices. In consequence, more or less time and effort might have to be spent to treat PFAS matrices in different jurisdictions.

*5.3. Comparison to alternative disposal/treatment approaches*

Landfilling of PFAS contaminated IDW is difficult if not impossible because of the lack of binding disposal standards. Sometimes, PFAS-impacted soil is stabilized or solidified before disposal into a landfill (ITRC 2019). Hazardous waste incineration may not be the most cost-effective disposal

method for PFAS wastes, but currently it still ranks as the Best Demonstrated Available Technology (BDAT) for generators concerned with the potential risks. Some states may require PFAS-contaminated solids to be treated at a Resource Conservation and Recovery Act (RCRA) permitted incinerator. The incineration of the contaminated soil is energy intensive, i.e. the estimated temperature to destroy specific PFAS varies widely, from around 300º to greater than 1,000ºC (IRTC 2019). Overall, incineration is problematic and prohibitively costly for generators, such as the Department of Defense, that have large volumes of IDW. Hence, many of these generators are managing these media by temporary storage or containment (GHD 2019).

In comparison, OxyZone® treatment mineralizes PFAS by exploiting strong chemical radicals. These radicals are produced at ambient temperature using commonly available chemical compounds and UV light. Therefore, the carbon footprint of this technology is likely much lower compared to incineration. Most important, the effluent of this treatment process results in comparably low dosages of benign chemicals (mostly sulfate and fluoride) that should not stand in the way of disposing the treated matrices.

## 6. Conclusions and Implications for Future Research

This proof-of-concept study demonstrated that IDW soil and groundwater contaminated with PFAS can be *ex-situ* treated with equipment that can be quickly and inexpensive mobilized at a given field site. We showed that PFAS can be mineralized to the degree that disposal might be possible.

Our particular research questions and objectives were:

Question I: How fast and to what extent can a peroxone activated persulfate oxidant destroy PFAS compounds when applied to soil or water IDW or mixtures thereof?

*Observations*: Peroxone activated persulfate (OxyZone®) is effective at destroying PFAS in IDW soil when applied in a soil slurry, although not as effective at mineralizing PFAS in soil as XCT® solution rinsing followed by treating the process water. Peroxone activated persulfate is effective at destroying PFAS in IDW water, but the treatment is even more effective when enhanced by foam fractionation/irradiation.

Question II: Does this innovative IDW treatment approach reduce the environmental risk and cost when compared to conventional disposal methods?

*Observations*: Our on-site and ex-situ treatment technology for the full mineralization of PFAS contaminated IDW promises to reduce cost compared to incineration and to lower the environmental risk associated with off-site disposal of IDW with legacy risks. These advantages will greatly aid DoD Remedial Project Managers in the site management. However, a full-scale study of our treatment approach would be needed to generate more concrete cost data.

Question III: What data must be acquired to develop a complete proposal for a more extensive follow-on study?

*Observations*: In this proof-of-concept study, we tested soil and water IDW from one particular site. Although the IDW material was typical in its mineralogical make-up and the degree of PFAS contamination, it is likely that materials from other sites require more or less treatment effort. During a follow-up study we would want to investigate if certain site characteristics might limit the implementation of our technology.

In addition, our Team believes that the proposed treatment train approach that we have tested herein is very cost effective due to the low cost of XCT® solution at $0.04 per gallon and the low concentration of 0.1 to 0.5 % required to remove PFAS from soil. Treatment of process water by XCT

®enhanced foam fractionation to remove the XCT®-PFAS complex is also inexpensive due to the low cost of aeration of water without the need for any additional chemicals other than the XCT®solution which is already present in the wash water from the soil rinsing step. In addition, there is the added benefit that the enhanced foam fractionation concentrates the XCT®-PFAS complex in a separate stream of foam by a factor of greater than 10 time and potentially 100 times in an optimized system. This makes for a very small volume of PFAS water to be treated, reducing the equipment size of the UV reactor and ozone generator units, and the electrical energy needed for UV light and ozone generation. The net result is a very effective and economical overall PFAS treatment process.

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# 8. Appendix

Appendix 1: List of PFAS analyzed, their detection limits and limits of quantification (Source: Maxxam Laboratories; http://maxxam.ca/ ).

Maxxam
A Bureau Veritas Group Company

Maxxam Analytics
6740 Campobello Road
Mississauga, ON, L5N 2L8

**QAPP Worksheet #15**

Matrix: Water  Analytical Group: Per- and Polyfluoroalkyl Substances (PFAS)  Concentration Level: Low

| Analyte | Acronym | CAS Number | Project Action Limit (ug/L) | Project Quantitation Limit Goal (ug/L) | Analytical Method[1] | | Achievable Laboratory Limits[2] | |
|---|---|---|---|---|---|---|---|---|
| | | | | | MDLs (ug/L) | Method QLs (ug/L) | LODs (ug/L) | LOQs (ug/L) |
| Perfluorobutanoic acid | PFBA | 375-22-4 | | | 0.0055 | 0.02 | 0.015 | 0.02 |
| Perfluoropentanoic acid | PFPeA | 2706-90-3 | | | 0.0075 | 0.02 | 0.018 | 0.02 |
| Perfluorohexanoic acid | PFHxA | 307-24-4 | | | 0.0035 | 0.02 | 0.010 | 0.02 |
| Perfluoroheptanoic acid | PFHpA | 375-85-9 | | | 0.0074 | 0.02 | 0.015 | 0.02 |
| Perfluorooctanoic acid | PFOA | 335-67-1 | | | 0.0033 | 0.02 | 0.010 | 0.02 |
| Perfluorononanoic acid | PFNA | 375-95-1 | | | 0.0087 | 0.02 | 0.018 | 0.02 |
| Perfluorodecanoic acid | PFDA | 335-76-2 | | | 0.0061 | 0.02 | 0.015 | 0.02 |
| Perfluoroundecanoic acid | PFUnA | 2058-94-8 | | | 0.0025 | 0.02 | 0.010 | 0.02 |
| Perfluorododecanoic acid | PFDoA | 307-55-1 | | | 0.0050 | 0.02 | 0.010 | 0.02 |
| Perfluorotridecanoic acid | PFTrDA | 72629-94-8 | | | 0.0038 | 0.02 | 0.010 | 0.02 |
| Perfluorotetradecanoic acid | PFTeDA | 376-06-7 | | | 0.0027 | 0.02 | 0.010 | 0.02 |
| Perfluorobutanesulfonic acid | PFBS | 375-73-5 | | | 0.0054 | 0.02 | 0.015 | 0.02 |
| Perfluorohexanesulfonic acid | PFHxS | 355-46-4 | | | 0.0056 | 0.02 | 0.015 | 0.02 |
| Perfluoroheptanesulfonic acid | PFHpS | 375-92-8 | | | 0.0080 | 0.02 | 0.018 | 0.02 |
| Perfluorooctanesulfonic acid | PFOS | 1763-23-1 | | | 0.0060 | 0.02 | 0.015 | 0.02 |
| Perfluorodecanesulfonic acid | PFDS | 335-77-3 | | | 0.0060 | 0.02 | 0.015 | 0.02 |
| Perfluorooctane sulfonamide | PFOSA | 754-91-6 | | | 0.0034 | 0.02 | 0.010 | 0.02 |
| N-methylperfluorooctanesulfonamide | MeFOSA | 31506-32-8 | | | 0.013 | 0.04 | 0.030 | 0.04 |
| N-ethylperfluorooctanesulfonamide | EtFOSA | 4151-50-2 | | | 0.010 | 0.04 | 0.030 | 0.04 |
| N-methylperfluorooctanesulfonamidoethanol | MeFOSE | 24448-09-7 | | | 0.012 | 0.04 | 0.030 | 0.04 |
| N-ethylperfluorooctanesulfonamidoethanol | EtFOSE | 1691-99-2 | | | 0.0079 | 0.04 | 0.030 | 0.04 |
| N-Methylperfluorooctanesulfonamidoacetic acid | MeFOSAA | 2355-31-9 | | | 0.0029 | 0.02 | 0.010 | 0.02 |
| N-Ethylperfluorooctanesulfonamidoacetic acid | EtFOSAA | 2991-50-6 | | | 0.0033 | 0.02 | 0.010 | 0.02 |
| 6:2 Fluorotelomersulfonic acid | 6:2-FTS | 27619-97-2 | | | 0.0066 | 0.02 | 0.015 | 0.02 |
| 8:2 Fluorotelomersulfonic acid | 8:2-FTS | 39108-34-4 | | | 0.0066 | 0.02 | 0.015 | 0.02 |

[1]Analytical MDLs and QLs are those documented in validated methods.

[2]Achievable MDLs and QLs are limits that an individual laboratory can achieve when performing a specific analytical method. *Laboratory Generated Limits are subject to change, the laboratory will use the most current limits at the time of analysis.*

Appendix 2: Promulgated standards (Method 1) chemical-specific cleanup standards for use under the Massachusetts Contingency Plan (MCP). The MCP Method 1 Standards represent levels of oil or hazardous materials at which no further remedial response actions would be required based upon the risk of harm posed by these chemicals.

## Method 1 Standards

The MCP Method 1 Standards represent levels of oil or hazardous materials at which no further remedial response actions would be required based upon the risk of harm posed by these chemicals. The standards are protective of public health, public welfare, and the environment (i.e., represent a condition of "no significant risk"), given the exposures assumed, and are measurable.

Method 1 standards are, by nature, generic, and are derived in a manner to be protective at a wide range of disposal sites across the state. The use of such generic standards is one risk characterization option in the Massachusetts Contingency Plan. It is important to remember that the flexibility exists under the MCP to use more site-specific risk characterization approaches under Methods 2 and 3.

### Categories of Standards

The criteria that determine the applicability of the groundwater standards are described in regulation at 310 CMR 40.0932. Click on the link below for more information on the specific groundwater standards, including the methodology to derive the standards.

Category GW-1 : Concentrations based on the use of groundwater as drinking water, either currently or in the foreseeable future.

Category GW-2 : Concentrations based on the potential for volatile material to migrate into indoor air.

Category GW-3 : Concentrations based on the potential environmental effects resulting from contaminated groundwater discharging to surface water.

The criteria that determine the applicability of the soil standards are described in regulation at 310 CMR 40.0932. Click on the link below for more information on the specific soil standards, including the methodology to derive the standards.

Category S-1 : Concentrations based on sensitive uses of the property and accessible soil, either currently or in the foreseeable future. Additional criteria are established for the protection of groundwater, based on the leaching potential of the contaminated soil.

Category S-2 : Concentrations based on property uses associated with moderate exposure and accessible soil, either currently or in the foreseeable future. Additional criteria are established for the protection of groundwater, based on the leaching potential of the contaminated soil.

Category S-3 : Concentrations based on restricted access and property with limited potential for exposure, either currently or in the foreseeable future. Additional criteria are established for the protection of groundwater, based on the leaching potential of the contaminated soil.

Appendix 3: IDW sample characteristics provided by Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN), designated point of contact (POCs) Mr. Jason Speicher.

## IDW Groundwater

**NAVY SITE 1 PFAS DATA FROM SOURCE WELL - LOCATED IN MID-ATLANTIC REGION**

| | BMWM-15-42 | | | BMWM-15-67 | | BMWM-15-99 | |
|---|---|---|---|---|---|---|---|
| | 4/27/2016 | 8/30/2017 | 8/30/2017* | 4/27/2016 | 8/30/2017 | 4/27/2016 | 8/30/2017 |
| **PFAS CHEMICAL** | **PFAS Compounds ug/L** | | | | | | |
| Perfluorobutanoic acid (PFBA) | NA | NA | NA | NA | NA | NA | NA |
| Perfluorooctanoic acid (PFOA) | 2.16 | 2.01 | 1.94 | 1.83 | 1.49 | 1.02 | 2.37 |
| Perfluorooctanesulfonic acid (PFOS) | 86.1 | 99.5 | 126 | 75.8 | 67.2 | 28.8 | 10.3 |
| Perfluoropentanoic acid (PFPeA) | NA | NA | NA | NA | NA | NA | NA |
| Perfluorohexanoic acid (PFHxA) | NA | 3.35 | 3.45 | NA | 2.55 | NA | 1.08 |
| Perfluoroheptanoic acid (PFHpA) | 0.694 | 0.519 | 0.552 | 0.584 | 0.414 | 0.265 | 0.278 |
| Perfluorononanoic acid (PFNA) | < 0.19 U | 0.0402 J | < 0.15 U | < 0.21 U | 0.0333 J | 0.0178 J | 0.0457 |
| Perfluorodecanoic acid (PFDA) | NA | < 0.063 U | < 0.29 U | NA | < 0.060 U | NA | 0.0165 |
| Perfluoroundecanoic acid (PFUnA) | NA | < 0.063 U | < 0.29 U | NA | < 0.060 U | NA | < 0.0063 U |
| Perfluorododecanoic acid (PFDoA) | NA | < 0.063 U | < 0.29 U | NA | < 0.060 U | NA | < 0.0063 U |
| Perfluorobutanesulfonic acid (PFBS) | 2.53 | 2.97 J | 1.92 J | 2.09 | 2.03 | 0.929 | 0.507 |
| Perfluorohexanesulfonic acid (PFHxS) | 14.9 | 15.2 | 16.3 | 14.3 | 10.6 | 5.02 | 3.69 |
| Perfluoroheptanesulfonic Acid (PFHpS) | NA | NA | NA | NA | NA | NA | NA |
| Perfluorodecane Sulfonic acid | NA | NA | NA | NA | NA | NA | NA |
| N-Ethyl perfluorooctane sulfonamidoacetic acid | NA | < 0.17 U | < 0.77 U | NA | < 0.16 U | NA | < 0.017 U |
| N-Methyl perfluorooctane sulfonamidoacetic acid | NA | < 0.17 U | < 0.77 U | NA | < 0.16 U | NA | < 0.017 U |
| Perfluorotetradecanoic Acid (PFTA) | NA | < 0.063 U | < 0.29 U | NA | < 0.060 U | NA | < 0.0063 U |
| Perfluorotridecanoic Acid (PFTrDA) | NA | < 0.063 U | < 0.29 U | NA | < 0.060 U | NA | < 0.0063 U |
| | | | | | | | |
| | **Field Parameters** | | | | | | |
| pH (su) | 6.69 | 6.63 | 6.63 | 6.6 | 6.63 | 6.85 | 6.88 |
| Conductivity (uS/cm) | 0.374 | 0.236 | 0.236 | 0.394 | 0.243 | 0.559 | 0.329 |
| Dissolved Oxygen (mg/L) | 1.81 | 2.00 | 2.00 | 1.83 | 1.78 | 1.34 | 1.30 |
| Temperature (celcius) | 19.42 | 15.44 | 15.44 | 19.10 | 15.72 | 19.46 | 15.96 |
| ORP (mV) | 340.0 | 54.0 | 54.0 | 346.0 | 122.0 | 333.0 | 28.0 |
| Turbidity (NTU) | 121.0 | 2.8 | 2.8 | 103.00 | 5.50 | 21.4 | 0.70 |
| | **Other Compounds ug/L** | | | | | | |
| Alkalinity, Total (as CaCO3) | NA | NA | NA | NA | NA | NA | NA |
| Hardness (as CaCO3) | NA | NA | NA | NA | NA | NA | NA |
| Total Dissolved Solids | NA | NA | NA | NA | NA | NA | NA |
| Total Organic Carbon (415.1) | NA | NA | NA | NA | NA | NA | NA |
| | **Metals Compounds ug/L** | | | | | | |
| Calcium, Total (SW6010B) | NA | NA | NA | NA | NA | NA | NA |
| Iron, Total (SW6010B) | NA | NA | NA | NA | NA | NA | NA |

Notes:
NA - not analyzed
* - dupilicate sample

# IDW Soil

Preliminary Waste Characterization Data Results
PFAS Soil Removal, Former NASJRB Willow Grove, Horsham, PA

| Location | | WC1-111518 | WC2-111518 |
|---|---|---|---|
| Sample ID | | NAS-JRB-WillowGr-A1-WC1-111518<br>Composite Soil (NV) | NAS-JRB-WillowGr-A1-WC2-111518<br>Composite Soil (NV) |
| Sample Depth (ft) | | 0 - 0 | 0 - 0 |
| Sample Date | | 11/15/2018 | 11/15/2018 |
| Analyte | Units | | |
| 537_MOD QSM 5.1 table B-15 (UG_KG) | | | |
| Perfluorobutanesulfonic acid (PFBS) | UG_KG | 1.8 | 1.6 |
| Perfluorooctane Sulfonate (PFOS) | UG_KG | 190 | 120 |
| Perfluorooctanoic acid (PFOA) | UG_KG | 5.7 | 5.6 |
| TCLP Metals 1311/6010D (MG_L) | | | |
| Arsenic | MG_L | 0.0250 U | 0.0250 U |
| Barium | MG_L | 0.356 B | 0.398 B |
| Cadmium | MG_L | 0.0025 U | 0.0056 |
| Chromium | MG_L | 0.0094 J | 0.0113 U |
| Lead | MG_L | 0.0094 J | 0.0113 U |
| Selenium | MG_L | 0.0375 U | 0.0375 U |
| Silver | MG_L | 0.0075 U | 0.0075 U |
| TCLP Mercury 1311/7470A (MG_L) | | | |
| Mercury | MG_L | 0.00010 U | 0.00010 U |
| 8015D (MG_KG) | | | |
| C8-C40 | MG_KG | 50 | 240 |
| Total TPH | MG_KG | 50 | 240 |
| TCLP Pesticides 1311/8081B (MG_L) | | | |
| Gamma BHC - Lindane | MG_L | 0.000020 U | 0.000020 U |
| Chlordane | MG_L | 0.0016 U | 0.0016 U |
| Endrin | MG_L | 0.00010 U | 0.00010 U |
| Heptachlor | MG_L | 0.000040 U | 0.000040 U |
| Heptachlor Epoxide | MG_L | 0.000036 U | 0.000036 U |
| Methoxychlor | MG_L | 0.00040 U | 0.00040 U |
| Toxaphene | MG_L | 0.010 U | 0.010 U |
| 8082A (MG_KG) | | | |
| Aroclor-1016 | MG_KG | 0.012 U | 0.012 U |
| Aroclor-1221 | MG_KG | 0.012 U | 0.012 U |
| Aroclor-1232 | MG_KG | 0.019 U | 0.019 U |
| Aroclor-1242 | MG_KG | 0.012 U | 0.012 U |
| Aroclor-1248 | MG_KG | 0.012 U | 0.012 U |
| Aroclor-1254 | MG_KG | 0.012 U | 0.012 U |
| Aroclor-1260 | MG_KG | 0.012 U | 0.012 U |
| Aroclor-1262 | MG_KG | 0.012 U | 0.012 U |
| Aroclor-1268 | MG_KG | 0.012 U | 0.012 U |
| TCLP Herbicides 1311/8151A (MG_L) | | | |
| 2,4-D | MG_L | 0.032 U | 0.032 U |
| 2,4,5-TP (Silvex) | MG_L | 0.0020 U | 0.0020 U |
| TCLP VOCs 1311/8260C (MG_L) | | | |
| Benzene | MG_L | 0.010 U | 0.010 U |
| 2-Butanone | MG_L | 0.020 U | 0.020 U |
| Carbon Tetrachloride | MG_L | 0.010 U | 0.010 U |
| Chlorobenzene | MG_L | 0.010 U | 0.010 U |
| Chloroform | MG_L | 0.010 U | 0.010 U |
| 1,2-Dichloroethane | MG_L | 0.010 U | 0.010 U |
| 1,1-Dichloroethene | MG_L | 0.010 U | 0.010 U |
| Tetrachloroethene | MG_L | 0.010 U | 0.010 U |
| Trichloroethene | MG_L | 0.010 U | 0.010 U |

| Location | | WC1-111518 | WC2-111518 |
|---|---|---|---|
| | | NAS-JRB-WillowGr-A1-WC1-111518 | NAS-JRB-WillowGr-A1-WC2-111518 |
| Sample ID | | Composite Soil (NV) | Composite Soil (NV) |
| Sample Depth (ft) | | 0 - 0 | 0 - 0 |
| Sample Date | | 11/15/2018 | 11/15/2018 |
| Analyte | Units | | |
| Vinyl Chloride | MG_L | 0.010 U | 0.010 U |
| TCLP SVOC 1311/8270D (MG_L) | | | |
| 1,4-Dichlorobenzene | MG_L | 0.005 U | 0.005 U |
| 2,4-Dinitrotoluene | MG_L | 0.010 U | 0.010 U |
| Hexachlorobenzene | MG_L | 0.001 U | 0.001 U |
| Hexachlorobutadiene | MG_L | 0.005 U | 0.005 U |
| Hexachloroethane | MG_L | 0.010 U | 0.010 U |
| 2-Methylphenol | MG_L | 0.005 U | 0.005 U |
| 4-Methylphenol | MG_L | 0.005 U | 0.005 U |
| Nitrobenzene | MG_L | 0.005 U | 0.005 U |
| Pentachlorophenol | MG_L | 0.010 U | 0.010 U |
| Pyridine | MG_L | 0.020 U | 0.020 U |
| 2,4,5-Trichlorophenol | MG_L | 0.005 U | 0.005 U |
| 2,4,6-Trichlorophenol | MG_L | 0.005 U | 0.005 U |
| SW-846 Chapter 7.3 | | | |
| Cyanide (Reactivity) | MG_KG | 48.2 U | 48.3 U |
| SW-846 Chapter 7.3 | | | |
| Sulfide (Reactivity) | MG_KG | 143 U | 143 U |
| 40 CFR 261.21 | | | |
| Ignitability | | Not Ignitable | Not Ignitable |
| 9045D (MG_KG) | | | |
| pH | pH unit | 7.33 | 6.86 |

**Notes:**
NA = Not analyzed
J = The analyte was positively identified: the associated numerical value is the approximate concentration of the analyte in the sample.

U = The analyte was analyzed for, but was not detected above the reported sample quantitation limit.
B = The analyte was detected in an associated blank.
Results are reported on a dry weight basis.
**Bold -- Analyte was detected**

# Appendix 4: Confirmation analyzes of IDW soil

EnChem Engineering, Inc.

Maxxam Job Number: B8U7825
Report Date: 2018/11/30

Site Location: SERDP #2-3
Sampler Initials: AM

**RESULTS OF ANALYSES OF SOIL**

| Maxxam ID | | | IIC769 | IIC769 | IIC770 | IIC771 | |
|---|---|---|---|---|---|---|---|
| Sampling Date | | | 2018/11/15 13:00 | 2018/11/15 13:00 | 2018/11/15 12:00 | 2018/11/15 11:00 | |
| COC Number | | | n/a | n/a | n/a | n/a | |
| | **UNITS** | **mean** | **PA-S-F** | **PA-S-F Lab-Dup** | **PA-S-G** | **PA-S-H** | |
| Fraction of Organic Carbon | g/g | 0.021 | 0.022 | N/A | 0.02 | N/A | |
| Fraction of Organic Carbon | % | 2.1% | 2.2% | N/A | 2.0% | N/A | |
| Moisture | % | 20.5 | 20 | N/A | 21 | 20 | |
| Total Organic Carbon | mg/kg | 21,000 | 22000 | N/A | 20000 | N/A | |
| 6:2 Fluorotelomer sulfonate | ug/kg | 3.2 | 4.3 | 4.9 | 0.48 | <2.6 | the mean ignores the < values |
| Perfluorobutane Sulfonate (PFBS) | ug/kg | 0.3 | <1.7 | <1.7 | 0.33 | <1.7 | the mean ignores the < values |
| Perfluorobutanoic acid | ug/kg | 1.5 | <2.3 | <2.3 | 1.5 | <2.3 | the mean ignores the < values |
| Perfluorodecane Sulfonate | ug/kg | 17 | 19 | 15 | 17 | 15 | |
| Perfluorodecanoic Acid (PFDA) | ug/kg | 1.1 | <2.8 | <2.8 | 1.1 | <2.8 | the mean ignores the < values |
| Perfluorododecanoic Acid (PFDoA) | ug/kg | 0.5 | <2.8 | <2.8 | 0.47 | <2.8 | the mean ignores the < values |
| Perfluoroheptane sulfonate | ug/kg | 1.3 | <3.9 | <3.9 | 1.3 | <3.9 | the mean ignores the < values |
| Perfluoroheptanoic Acid (PFHpA) | ug/kg | 0.5 | <1.9 | <1.9 | 0.49 | <1.9 | the mean ignores the < values |
| Perfluorohexane Sulfonate (PFHxS) | ug/kg | 21 | 28 | 26 | 6.7 | 23 | |
| Perfluorohexanoic Acid (PFHxA) | ug/kg | 3.1 | 4.8 | 3.8 | 1.1 | 2.8 | |
| Perfluoro-n-Octanoic Acid (PFOA) | ug/kg | 1.2 | <2.5 | <2.5 | 1.2 | <2.5 | the mean ignores the < values |
| Perfluorononanoic Acid (PFNA) | ug/kg | 2.1 | 2.6 | <2.2 | 1.4 | 2.4 | |
| Perfluorooctane Sulfonamide (PFOSA) | ug/kg | 2.7 | 3.5 | 3.4 | 1.7 | 2.2 | |
| Perfluorooctane Sulfonate (PFOS) | ug/kg | 1,218 | 1700 | 1500 | 370 | 1300 | |
| Perfluoropentanoic Acid (PFPeA) | ug/kg | 2.4 | 2.9 | <2.5 | 1.9 | <2.5 | the mean ignores the < values |
| Perfluoroundecanoic Acid (PFUnA) | ug/kg | 1.7 | <3.4 | <3.4 | 1.7 | <3.4 | the mean ignores the < values |
| **TOTAL** | | **1,268** | **1765** | **1553** | **408** | **1345** | the mean ignores the < values |
| | % PFOS | 96% | 96% | 97% | 91% | 97% | |

RDL = Reportable Detection Limit
QC Batch = Quality Control Batch
Lab-Dup = Laboratory Initiated Duplicate
N/A = Not Applicable

**Results relate only to the items tested.**

PAH concentrations in IDW soil collected at the Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN). Analysis by Maxxam Laboratories.

**O.REG 153 PAHS (SOIL)**

| Maxxam ID | | INE583 | INE583 | | | |
|---|---|---|---|---|---|---|
| Sampling Date | | 2018/11/15 | 2018/11/15 | | | |
| COC Number | | n/a | n/a | | | |
| | UNITS | PA-S-F | PA-S-F Lab-Dup | RDL | MDL | QC Batch |
| Moisture | % | 20 | 18 | 1.0 | 0.50 | 5887917 |
| Methylnaphthalene, 2-(1-) | ug/g | <0.071 | N/A | 0.071 | N/A | 5881671 |
| Benzo(e)pyrene | ug/g | 0.98 | N/A | 0.050 | N/A | 5890911 |
| Acenaphthene | ug/g | 0.13 | N/A | 0.050 | 0.020 | 5890911 |
| Acenaphthylene | ug/g | 0.18 | N/A | 0.050 | 0.010 | 5890911 |
| Anthracene | ug/g | 0.32 | N/A | 0.050 | 0.010 | 5890911 |
| Benzo(a)anthracene | ug/g | 1.3 | N/A | 0.050 | 0.020 | 5890911 |
| Benzo(a)pyrene | ug/g | 1.4 | N/A | 0.050 | 0.010 | 5890911 |
| Benzo(b/j)fluoranthene | ug/g | 2.0 | N/A | 0.050 | 0.020 | 5890911 |
| Benzo(g,h,i)perylene | ug/g | 0.96 | N/A | 0.050 | 0.040 | 5890911 |
| Benzo(k)fluoranthene | ug/g | 0.69 | N/A | 0.050 | 0.020 | 5890911 |
| Chrysene | ug/g | 1.3 | N/A | 0.050 | 0.020 | 5890911 |
| Dibenz(a,h)anthracene | ug/g | 0.21 | N/A | 0.050 | 0.040 | 5890911 |
| Fluoranthene | ug/g | 4.0 | N/A | 0.050 | 0.010 | 5890911 |
| Fluorene | ug/g | 0.21 | N/A | 0.050 | 0.010 | 5890911 |
| Indeno(1,2,3-cd)pyrene | ug/g | 1.0 | N/A | 0.050 | 0.040 | 5890911 |
| 1-Methylnaphthalene | ug/g | 0.059 | N/A | 0.050 | 0.010 | 5890911 |
| 2-Methylnaphthalene | ug/g | <0.050 | N/A | 0.050 | 0.010 | 5890911 |
| Naphthalene | ug/g | 0.061 | N/A | 0.050 | 0.010 | 5890911 |
| Phenanthrene | ug/g | 2.1 | N/A | 0.050 | 0.010 | 5890911 |
| Pyrene | ug/g | 3.1 | N/A | 0.050 | 0.010 | 5890911 |
| Biphenyl | ug/g | <0.050 | N/A | 0.050 | N/A | 5890911 |
| Perylene | ug/g | 0.33 | N/A | 0.050 | N/A | 5890911 |
| Surrogate Recovery (%) | | | | | | |
| D10-Anthracene | % | 112 | N/A | N/A | N/A | 5890911 |
| D14-Terphenyl (FS) | % | 111 | N/A | N/A | N/A | 5890911 |
| D8-Acenaphthylene | % | 109 | N/A | N/A | N/A | 5890911 |

RDL = Reportable Detection Limit
QC Batch = Quality Control Batch
Lab-Dup = Laboratory Initiated Duplicate
N/A = Not Applicable

Volatile Petroleum Hydrocarbon (VPH) concentrations in IDW soil collected at the Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN). Analysis by New England Testing Laboratory, Inc., West Warwick, RI.

**Volatile Petroleum Hydrocarbons**
**Sample: PA Soil Composite (8L13074-01)**

**SAMPLE INFORMATION**

| | | | |
|---|---|---|---|
| Matrix | Soil | | |
| Containers | Satisfactory | | |
| Sample Preservation | Aqueous | NA | |
| | Soil or Sediment | Preserved with methanol and/or in an air-tight container | ml methanol per gram soil: 1:1 +/- 25% |
| | | Methanol preserved (covering sample) | |
| | | Received in air-tight container | |
| Temperature | Received on Ice Received at: 4+/-2 C° | | |

**VPH ANALYTICAL RESULTS**

| | | |
|---|---|---|
| Method for Ranges: MADEP VPH-18-2.1 | Client ID | PA Soil Composite |
| Method for Target Analytes: EPA Method 8260C | Lab ID | 8L13074-01 |
| VPH Surrogate Standards: | Date Collected | 12/13/18 |
| PID: 2,5-Dibromotoluene | Date Received | 12/13/18 |
| FID: 2,5-Dibromotoluene | % Moisture | 19.70 |

| RANGE/TARGET ANALYTE | Elution Range | Dilution | RL | Units | Result | Analyzed |
|---|---|---|---|---|---|---|
| Unadjusted C5-C8 Aliphatic Hydrocarbons [1] | NA | 50X | 4.3 | mg/kg | <4.3 | 12/18/18 18:16 |
| Unadjusted C9-C12 Aliphatic Hydrocarbons [1] | NA | 50X | 4.3 | mg/kg | **6.1** | 12/18/18 18:16 |
| Benzene | C5-C8 | 50X | 0.4 | mg/kg | <0.4 | 12/18/18 18:16 |
| Ethylbenzene | C9-C12 | 50X | 0.4 | mg/kg | <0.4 | 12/18/18 18:16 |
| Methyl t-butyl ether (MTBE) | C5-C8 | 50X | 0.09 | mg/kg | <0.09 | 12/18/18 18:16 |
| Naphthalene | NA | 50X | 0.9 | mg/kg | <0.9 | 12/18/18 18:16 |
| Toluene | C5-C8 | 50X | 0.4 | mg/kg | <0.4 | 12/18/18 18:16 |
| m&p-Xylene | C9-C12 | 50X | 0.9 | mg/kg | <0.9 | 12/18/18 18:16 |
| o-Xylene | C9-C12 | 50X | 0.9 | mg/kg | <0.9 | 12/18/18 18:16 |
| Total xylenes | | 50X | 0.9 | mg/kg | <0.9 | 12/18/18 18:16 |
| C5-C8 Aliphatic Hydrocarbons [1,2] | NA | 50X | 4.3 | mg/kg | <4.3 | 12/18/18 18:16 |
| C9-C12 Aliphatic Hydrocarbons [1,3] | NA | 50X | 4.3 | mg/kg | **6.1** | 12/18/18 18:16 |
| C9-C10 Aromatic Hydrocarbons [1] | NA | 50X | 4.3 | mg/kg | <4.3 | 12/18/18 18:16 |
| 2,5-Dibromotoluene-PID | | | | % | 82.8 | 12/18/18 18:16 |
| 2,5-Dibromotoluene-FID | | | | % | 101 | 12/18/18 18:16 |
| Surrogate Acceptance Range | | | | % | 70-130 | |

[1] Hydrocarbon Range data excludes concentrations of any surrogate(s) and/or internal standards eluting in that range
[2] C5-C8 Aliphatic Hydrocarbons exclude the concentration of Target Analytes eluting in that range
[3] C9-C12 Aliphatic Hydrocarbons exclude conc of Target Analytes eluting in that range AND concentration of C9-C10 Aromatic Hydrocarbons

Extractable Petroleum Hydrocarbon concentrations in IDW soil collected at the Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN). Analysis by New England Testing Laboratory, Inc., West Warwick, RI.

**Extractable Petroleum Hydrocarbons**
**Sample: PA Soil Composite (8L13074-01)**

**SAMPLE INFORMATION**

| | |
|---|---|
| Matrix | Soil |
| Containers | Satisfactory |
| Aqueous Preservatives | NA |
| Temperature | Received on Ice Received at: 4+/-2 C° |
| Extraction Method | EPA Method 3546 |

**EPH ANALYTICAL RESULTS**

| | | | | | | |
|---|---|---|---|---|---|---|
| Method for Ranges: MADEP EPH 4-1.1 | | | | Client ID | PA Soil Composite | |
| Method for Target Analytes: MADEP EPH 4-1.1 | | | | Lab ID | 8L13074-01 | |
| EPH Surrogate Standards:<br>Aliphatic: Chlorooctadecane<br>Aromatic: o-Terphenyl | | | | Date Collected | 12/13/18 | |
| | | | | Date Received | 12/13/18 | |
| | | | | Date Thawed | NA | |
| | | | | Date Extracted | 12/14/18 | |
| EPH Fractionation Surrogates:<br>(1) 2-Fluorobiphenyl<br>(2) 2-Bromonaphthalene | | | | Percent Moisture | 19.70 | |
| **RANGE/TARGET ANALYTE** | | **Dilution** | **RL** | **Units** | **Result** | **Analyzed** |
| Unadjusted C11-C22 Aromatic Hydrocarbons [1] | | 1X | 8.11 | mg/kg | **61.5** | 12/18/18 00:07 |
| Diesel PAH Analytes | Naphthalene | 1X | 0.40 | mg/kg | <0.40 | 12/18/18 00:07 |
| | 2-Methylnaphthalene | 1X | 0.40 | mg/kg | <0.40 | 12/18/18 00:07 |
| | Phenanthrene | 1X | 0.40 | mg/kg | **1.55** | 12/18/18 00:07 |
| | Acenaphthene | 1X | 0.40 | mg/kg | <0.40 | 12/18/18 00:07 |
| Other Target PAH Analytes | Acenaphthylene | 1X | 0.40 | mg/kg | <0.40 | 12/18/18 00:07 |
| | Fluorene | 1X | 0.40 | mg/kg | <0.40 | 12/18/18 00:07 |
| | Anthracene | 1X | 0.40 | mg/kg | **0.42** | 12/18/18 00:07 |
| | Fluoranthene | 1X | 0.40 | mg/kg | **3.25** | 12/18/18 00:07 |
| | Pyrene | 1X | 0.40 | mg/kg | **2.93** | 12/18/18 00:07 |
| | Benzo(a)anthracene | 1X | 0.40 | mg/kg | **1.22** | 12/18/18 00:07 |
| | Chrysene | 1X | 0.40 | mg/kg | **1.54** | 12/18/18 00:07 |
| | Benzo(b)fluoranthene | 1X | 0.40 | mg/kg | **1.87** | 12/18/18 00:07 |
| | Benzo(k)fluoranthene | 1X | 0.40 | mg/kg | **0.65** | 12/18/18 00:07 |
| | Benzo(a)pyrene | 1X | 0.40 | mg/kg | **1.19** | 12/18/18 00:07 |
| | Indeno(1,2,3-cd)pyrene | 1X | 0.40 | mg/kg | **0.61** | 12/18/18 00:07 |
| | Dibenz(a,h)anthracene | 1X | 0.40 | mg/kg | <0.40 | 12/18/18 00:07 |
| | Benzo(g,h,i)perylene | 1X | 0.40 | mg/kg | **0.48** | 12/18/18 00:07 |
| C9-C18 Aliphatic Hydrocarbons [1] | | 1X | 16.2 | mg/kg | <16.2 | 12/17/18 22:57 |
| C19-C36 Aliphatic Hydrocarbons [1] | | 1X | 16.2 | mg/kg | **16.4** | 12/17/18 22:57 |
| C11-C22 Aromatic Hydrocarbons [1,2] | | 1X | 8.11 | mg/kg | **45.8** | 12/18/18 00:07 |
| Chlorooctadecane (Sample Surrogate) | | | | % | 61.0 | 12/17/18 22:57 |
| o-Terphenyl (Sample Surrogate) | | | | % | 68.4 | 12/18/18 00:07 |
| 2-Fluorobiphenyl (Fractionation Surrogate) | | | | % | 93.8 | 12/18/18 00:07 |
| 2-Bromonaphthalene (Fractionation Surrogate) | | | | % | 87.7 | 12/18/18 00:07 |
| Surrogate Acceptance Range [3] | | | | % | 40 - 140 | |

[1] Hydrocarbon range data excludes area counts of any surrogate(s) and/or internal standards eluting in that range.
[2] C11-C22 Aromatic Hydrocarbons excludes the concentration of Target PAH Analytes.
[3] See the case narrative in cases where a dash (-) is entered in the surrogate recovery block.

VOC concentrations in IDW soil collected at the Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN). Analysis by New England Testing Laboratory, Inc., West Warwick, RI.

## Results: Volatile Organic Compounds

**Sample: PA Soil Composite**
**Lab Number: 8L13074-01 (Soil)**

| Analyte | Result | Qual | Reporting Limit | Units | Date Prepared | Date Analyzed |
|---|---|---|---|---|---|---|
| **Acetone** | **1410** | | 369 | ug/kg | 12/15/18 | 12/16/18 |
| Benzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Bromobenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Bromochloromethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Bromodichloromethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Bromoform | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Bromomethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| **2-Butanone** | **7180** | | 369 | ug/kg | 12/15/18 | 12/16/18 |
| tert-Butyl alcohol | ND | | 369 | ug/kg | 12/15/18 | 12/16/18 |
| sec-Butylbenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| n-Butylbenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| tert-Butylbenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Methyl t-butyl ether (MTBE) | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Carbon Disulfide | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Carbon Tetrachloride | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Chlorobenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Chloroethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Chloroform | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Chloromethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 4-Chlorotoluene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 2-Chlorotoluene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,2-Dibromo-3-chloropropane (DBCP) | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Dibromochloromethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,2-Dibromoethane (EDB) | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Dibromomethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,2-Dichlorobenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,3-Dichlorobenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,4-Dichlorobenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,1-Dichloroethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,2-Dichloroethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| trans-1,2-Dichloroethene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| cis-1,2-Dichloroethene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,1-Dichloroethene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,2-Dichloropropane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 2,2-Dichloropropane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| cis-1,3-Dichloropropene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| trans-1,3-Dichloropropene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,1-Dichloropropene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,3-Dichloropropene (cis + trans) | ND | | 147 | ug/kg | 12/15/18 | 12/16/18 |
| Diethyl ether | ND | | 369 | ug/kg | 12/15/18 | 12/16/18 |
| 1,4-Dioxane | ND | | 36900 | ug/kg | 12/15/18 | 12/16/18 |
| Ethylbenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Hexachlorobutadiene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 2-Hexanone | ND | | 369 | ug/kg | 12/15/18 | 12/16/18 |
| Isopropylbenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |

# Results: Volatile Organic Compounds (Continued)

**Sample: PA Soil Composite (Continued)**
**Lab Number: 8L13074-01 (Soil)**

| Analyte | Result | Qual | Reporting Limit | Units | Date Prepared | Date Analyzed |
|---|---|---|---|---|---|---|
| p-Isopropyltoluene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Methylene Chloride | ND | | 369 | ug/kg | 12/15/18 | 12/16/18 |
| 4-Methyl-2-pentanone | ND | | 369 | ug/kg | 12/15/18 | 12/16/18 |
| Naphthalene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| n-Propylbenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Styrene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,1,1,2-Tetrachloroethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Tetrachloroethene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Tetrahydrofuran | ND | | 369 | ug/kg | 12/15/18 | 12/16/18 |
| **Toluene** | **181** | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,2,4-Trichlorobenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,2,3-Trichlorobenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,1,2-Trichloroethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,1,1-Trichloroethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Trichloroethene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,2,3-Trichloropropane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,3,5-Trimethylbenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,2,4-Trimethylbenzene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Vinyl Chloride | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| o-Xylene | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| m&p-Xylene | ND | | 147 | ug/kg | 12/15/18 | 12/16/18 |
| Total xylenes | ND | | 147 | ug/kg | 12/15/18 | 12/16/18 |
| 1,1,2,2-Tetrachloroethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| tert-Amyl methyl ether | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| 1,3-Dichloropropane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Ethyl tert-butyl ether | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Diisopropyl ether | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Trichlorofluoromethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |
| Dichlorodifluoromethane | ND | | 74 | ug/kg | 12/15/18 | 12/16/18 |

| Surrogate(s) | Recovery% | Limits | | |
|---|---|---|---|---|
| *4-Bromofluorobenzene* | *95.4%* | *70-130* | 12/15/18 | 12/16/18 |
| *1,2-Dichloroethane-d4* | *92.9%* | *70-130* | 12/15/18 | 12/16/18 |
| *Toluene-d8* | *103%* | *70-130* | 12/15/18 | 12/16/18 |

Appendix 5: Confirmation analyzes of IDW groundwater collected at the Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN). PFAS analysis conducted by Maxxam Laboratories.

EnChem Engineering, Inc.

Maxxam Job Number: B8U7823
Report Date: 2018/11/30

Site Location: EXP. #1-9

**RESULTS OF ANALYSES OF WATER**

| Maxxam ID | | | IIC766 | IIC766 | IIC767 |
|---|---|---|---|---|---|
| Sampling Date | | | 2018/11/15 14:00 | 2018/11/15 14:00 | 2018/11/15 15:00 |
| COC Number | | | n/a | n/a | n/a |
| | **UNITS** | **mean of GW-A** | **PA-GW-A** | **PA-GW-A Lab-Dup** | **PA-GW-B** |
| 6:2 Fluorotelomer sulfonate | ug/L | 2.6 | 2.6 | 2.8 | 2.3 |
| 8:2 Fluorotelomer sulfonate | ug/L | 0.24 | 0.24 | <0.22 | <0.22 |
| Perfluorobutanoic acid | ug/L | 0.70 | 0.72 | 0.72 | 0.65 |
| Perfluorobutane Sulfonate (PFBS) | ug/L | 2.0 | 2 | 2.2 | 1.9 |
| Perfluoroheptanoic Acid (PFHpA) | ug/L | 0.80 | 0.83 | 0.81 | 0.75 |
| Perfluoroheptane sulfonate | ug/L | 2.9 | 3 | 3 | 2.7 |
| Perfluorohexanoic Acid (PFHxA) | ug/L | 3.9 | 4 | 3.9 | 3.7 |
| Perfluorohexane Sulfonate (PFHxS) | ug/L | 15.3 | 15 | 16 | 15 |
| Perfluorooctane Sulfonamide (PFOSA) | ug/L | 0.43 | 0.43 | 0.42 | <0.31 |
| Perfluoropentanoic Acid (PFPeA) | ug/L | 1.2 | 1.3 | 1.2 | 1.1 |
| Perfluoro-n-Octanoic Acid (PFOA) | ug/L | 2.1 | 2.1 | 2.2 | 1.9 |
| Perfluorooctane Sulfonate (PFOS) | ug/L | 102 | 110 | 100 | 96 |
| **TOTAL** | **ug/L** | **134** | **142** | **133** | **126** |
| | % PFOS | 76% | 77% | 75% | 76% |
| | | | | | |
| **Surrogate Recovery (%)** | | | | | |
| 13C2-6:2 Fluorotelomer sulfonate | % | | 106 | 105 | 108 |
| 13C2-8:2 Fluorotelomer sulfonate | % | | 111 | 106 | 104 |
| 13C2-Perfluorodecanoic acid | % | | 102 | 101 | 102 |
| 13C2-Perfluorododecanoic acid | % | | 87 | 85 | 88 |
| 13C2-Perfluorohexanoic acid | % | | 101 | 103 | 103 |
| 13C2-perfluorotetradecanoic acid | % | | 55 | 54 | 56 |
| 13C2-Perfluoroundecanoic acid | % | | 99 | 91 | 99 |
| 13C4-Perfluorobutanoic acid | % | | 96 | 96 | 96 |
| 13C4-Perfluoroheptanoic acid | % | | 102 | 104 | 104 |
| 13C4-Perfluorooctanesulfonate | % | | 108 | 102 | 106 |
| 13C4-Perfluorooctanoic acid | % | | 105 | 106 | 108 |
| 13C5-Perfluorononanoic acid | % | | 103 | 106 | 106 |
| 13C5-Perfluoropentanoic acid | % | | 106 | 108 | 108 |
| 13C8-Perfluorooctane Sulfonamide | % | | 106 | 105 | 102 |
| 18O2-Perfluorohexanesulfonate | % | | 110 | 103 | 103 |
| D7-MeFOSE | % | | 113 | 113 | 112 |
| D9-EtFOSE | % | | 105 | 103 | 105 |

RDL = Reportable Detection Limit
QC Batch = Quality Control Batch
Lab-Dup = Laboratory Initiated Duplicate
N/A = Not Applicable

**Results relate only to the items tested.**

VOC concentrations in IDW groundwater collected at the Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN). Analysis by New England Testing Laboratory, Inc., W Warwick, RI.

| **NETLAB Case Number: 9L17056** | | **Willow Grove GW** | | **Groundwater from WG** | | **Trip Blank** | | |
|---|---|---|---|---|---|---|---|---|
| **Lab Sample Number:** | | **9L17056-01** | | **9L17056-02** | | **9L17056-03** | | |
| Date Sampled: | | 12/13/2019 12:00 | | 12/13/2019 9:00 | | 12/16/2019 14:00 | | |
| Date Received: | | 12/17/2019 13:29 | | 12/17/2019 13:29 | | 12/17/2019 13:29 | | |
| Parameter | CAS Number | Sample Result | Reporting Limit | Sample Result | Reporting Limit | Sample Result | Reporting Limit | Units |
| | | | | | | | | |
| **Volatile Organic Compounds** | | | | | | | | |
| Acetone | 67-64-1 | ND | 14 | ND | 14 | ND | 14 | ug/l |
| Benzene | 71-43-2 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Bromobenzene | 108-86-1 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Bromochloromethane | 74-97-5 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Bromodichloromethane | 75-27-4 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Bromoform | 75-25-2 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Bromomethane | 74-83-9 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 2-Butanone | 78-93-3 | ND | 8 | ND | 8 | ND | 8 | ug/l |
| tert-Butyl alcohol | 75-65-0 | ND | 5 | ND | 5 | ND | 5 | ug/l |
| sec-Butylbenzene | 135-98-8 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| n-Butylbenzene | 104-51-8 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| tert-Butylbenzene | 98-06-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Methyl t-butyl ether (MTBE) | 1634-04-4 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Carbon Disulfide | 75-15-0 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Carbon Tetrachloride | 56-23-5 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Chlorobenzene | 108-90-7 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Chloroethane | 75-00-3 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Chloroform | 67-66-3 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Chloromethane | 74-87-3 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 4-Chlorotoluene | 106-43-4 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 2-Chlorotoluene | 95-49-8 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,2-Dibromo-3-chloropropane (DBCP) | 96-12-8 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Dibromochloromethane | 124-48-1 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,2-Dibromoethane (EDB) | 106-93-4 | ND | *1* | ND | *1* | ND | *1* | ug/l |
| Dibromomethane | 74-95-3 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,2-Dichlorobenzene | 95-50-1 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,3-Dichlorobenzene | 541-73-1 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,4-Dichlorobenzene | 106-46-7 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,1-Dichloroethane | 75-34-3 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,2-Dichloroethane | 107-06-02 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| trans-1,2-Dichloroethene | 156-60-5 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| cis-1,2-Dichloroethene | 156-59-2 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,1-Dichloroethene | 75-35-4 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,2-Dichloropropane | 78-87-5 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 2,2-Dichloropropane | 594-20-7 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| cis-1,3-Dichloropropene | 10061-01-5 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| trans-1,3-Dichloropropene | 10061-02-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,1-Dichloropropene | 563-58-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,3-Dichloropropene (cis + trans) | 542-75-6 | ND | 2 | ND | 2 | ND | 2 | ug/l |
| Diethyl ether | 60-29-7 | ND | 5 | ND | 5 | ND | 5 | ug/l |
| 1,4-Dioxane | 123-91-1 | ND | *500* | ND | *500* | ND | *500* | ug/l |
| Ethylbenzene | 100-41-4 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Hexachlorobutadiene | 87-68-3 | ND | *1* | ND | *1* | ND | *1* | ug/l |
| 2-Hexanone | 591-78-6 | ND | 5 | ND | 5 | ND | 5 | ug/l |
| Isopropylbenzene | 98-82-8 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| p-Isopropyltoluene | 99-87-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Methylene Chloride | 75-09-2 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 4-Methyl-2-pentanone | 108-10-1 | ND | 5 | ND | 5 | ND | 5 | ug/l |
| Naphthalene | 91-20-3 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| n-Propylbenzene | 103-65-1 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Styrene | 100-42-5 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,1,1,2-Tetrachloroethane | 630-20-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Tetrachloroethene | 127-18-4 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Tetrahydrofuran | 109-99-9 | ND | 15 | ND | 15 | ND | 15 | ug/l |
| Toluene | 108-88-3 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,2,4-Trichlorobenzene | 120-82-1 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,2,3-Trichlorobenzene | 87-61-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,1,2-Trichloroethane | 79-00-5 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,1,1-Trichloroethane | 71-55-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Trichloroethene | 79-01-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,2,3-Trichloropropane | 96-18-4 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,3,5-Trimethylbenzene | 108-67-8 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,2,4-Trimethylbenzene | 95-63-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Vinyl Chloride | 75-01-4 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| o-Xylene | 95-47-6 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| m&p-Xylene | 1330-20-7 | ND | 2 | ND | 2 | ND | 2 | ug/l |
| Total xylenes | 1330-20-7 | ND | 2 | ND | 2 | ND | 2 | ug/l |
| 1,1,2,2-Tetrachloroethane | 79-34-5 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| tert-Amyl methyl ether | 994-05-8 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| 1,3-Dichloropropane | 142-28-9 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Ethyl tert-butyl ether | 637-92-3 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Diisopropyl ether | 108-20-3 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Trichlorofluoromethane | 75-69-4 | ND | 1 | ND | 1 | ND | 1 | ug/l |
| Dichlorodifluoromethane | 75-71-8 | ND | 1 | ND | 1 | ND | 1 | ug/l |

Iron and manganese concentrations in groundwater collected at the Joint Base Naval Air Station Willow Grove (JBASWG), PA (USN). Analysis by New England Testing Laboratory, Inc., W Warwick, RI.

## Results: Total Metals

**Sample: A+B PA Willow - Total**
**Lab Number: 8L20003-04 (Water)**

| Analyte | Result | Qual | Reporting Limit | Units | Date Prepared | Date Analyzed |
|---|---|---|---|---|---|---|
| Iron | ND | | 0.05 | mg/L | 12/21/18 | 12/27/18 |
| Manganese | ND | | 0.005 | mg/L | 12/21/18 | 12/27/18 |

Appendix 6A: TOP assay on untreated IDW groundwater.

| BV Labs ID<br>BV Labs Job Number: B9G4033 | | JZZ624 | | |
|---|---|---|---|---|
| **Sampling Date** | | **6/14/2019** | | |
| **Client Sample ID** | | **RAW Willow Grove GROUNDWATER** | | |
| **Parameter** | **Units** | **Pre Oxidation Concentration** | **Post Oxidation Concentration** | **Difference in Pre and Post Oxidation Concentration** |
| Perfluorobutanoic acid (PFBA) | µg/L | 0.84 | 7.8 | 7.0 |
| Perfluoropentanoic Acid (PFPeA) | µg/L | 1.4 | 9.5 | 8.1 |
| Perfluorohexanoic Acid (PFHxA) | µg/L | 3.8 | 27 | 23 |
| Perfluoroheptanoic Acid (PFHpA) | µg/L | 0.80 J | 1.1 | 0.3 |
| Perfluorooctanoic Acid (PFOA) | µg/L | 2.3 | 3.3 | 1.0 |
| Perfluorononanoic Acid (PFNA) | µg/L | 0.28 U | 0.80 U | <RDL |
| Perfluorodecanoic Acid (PFDA) | µg/L | 0.26 U | 0.80 U | <RDL |
| Perfluoroundecanoic Acid (PFUnA) | µg/L | 0.22 U | 0.80 U | <RDL |
| Perfluorododecanoic Acid (PFDoA) | µg/L | 0.17 U | 0.80 U | <RDL |
| Perfluorotridecanoic Acid | µg/L | 0.24 U | 0.80 U | <RDL |
| Perfluorotetradecanoic Acid | µg/L | 0.23 U | 0.80 U | <RDL |
| Perfluorobutanesulfonic Acid (PFBS) | µg/L | 2.7 | 3.0 | 0.3 |
| Perfluorohexanesulfonic Acid (PFHxS) | µg/L | 16 | 18 | 1.5 |
| Perfluoroheptanesulfonic Acid (PFHeS) | µg/L | 2.4 | 2.3 | -0.15 |
| Perfluorooctanesulfonic Acid (PFOS) | µg/L | 96 | 79 | -17 |
| Perfluorodecanesulfonic Acid | µg/L | 0.22 U | 0.80 U | <RDL |
| Perfluorooctane Sulfonamide (PFOSA) | µg/L | 0.53 J | 0.80 U | <RDL |
| EtFOSA | µg/L | 0.28 U | NR | NR |
| MeFOSA | µg/L | 0.35 U | NR | NR |
| EtFOSE | µg/L | 0.20 U | NR | NR |
| MeFOSE | µg/L | 0.27 U | NR | NR |
| 6:2 Fluorotelomer sulfonic Acid | µg/L | 2.9 | 0.80 U | decreased |
| 8:2 Fluorotelomer sulfonic Acid | µg/L | 0.28 U | 0.80 U | NR |
| | TOTAL | 128 | 150 | 24 |
| | Precursors only | 27 | 69 | |

RDL = Reportable Detection Limit
QC Batch = Quality Control Batch
U = Undetected at the limit of quantitation
J = Estimated concentration between the MDL & RDL
Sum of Differences in Pre and Post Assay

**Results relate only to the items tested.**

**Notes:** The change in PFAS concentration was calculated by subtracting the pre oxidation concentration from the post oxidation concentration.
A negative change indicates a decrease in the PFAS concentration after oxidation.
If the concentration of a parameter was <RDL either prior to or post oxidation, the concentration was treated as "zero" for the difference calculation.
Difference calculation performed using raw data. The rounding of final results may result in an apparent difference.
Not reported (NR) due to high volatility under the conditions used for oxidation.
Approximately 20% of PFOSA is known to be lost due to volatility under the conditions used for oxidation.
Oxidation was performed adhering to the protocol as described by Houtz, E.F. and Sedlak, D.L. (2012). *Environ. Sci. Technol*., 46, 9342-9349.
Due to high concentrations of target analytes, the sample required dilution prior to oxidation.
PFOS: The pre and post oxidation concentrations are within the acceptable laboratory tolerance limits for reproducibility.

Appendix 6B: TOP assay on IDW groundwater treated by OxyZone® foam fractionation/ irradiation (Duration: 5.3 hrs)

| **BV Labs ID**<br>**BV Labs Job Number: B9G4033** | | BV Labs Job Number: B9X4750 | | **LKR121** |
|---|---|---|---|---|
| | | Report Date: 2019/12/24 | | |
| **Sampling Date** | | **11/26/2019** | | |
| **Client Sample ID** | | **OxyZone treated (5.3 hrs. foam and UV) WG GROUNDWATER** | | |
| **Parameter** | **Units** | **Pre Oxidation Concentration** | **Post Oxidation Concentration** | **Difference in Pre and Post Oxidation Concentration** |
| Perfluorobutanoic acid (PFBA) | µg/L | 4.3 | 1.5 | -2.8 |
| Perfluoropentanoic Acid (PFPeA) | µg/L | 1.4 | 1.2 | -0.2 |
| Perfluorohexanoic Acid (PFHxA) | µg/L | 0.82 | 0.73 | -0.1 |
| Perfluoroheptanoic Acid (PFHpA) | µg/L | 0.10 | 0.13 | 0.03 |
| Perfluorooctanoic Acid (PFOA) | µg/L | 0.024 | <0.040 | UNK |
| Perfluorononanoic Acid (PFNA) | µg/L | 0.0055 | <0.040 | UNK |
| Perfluorodecanoic Acid (PFDA) | µg/L | <0.0041 | <0.040 | <RDL |
| Perfluoroundecanoic Acid (PFUnA) | µg/L | <0.0043 | <0.040 | <RDL |
| Perfluorododecanoic Acid (PFDoA) | µg/L | <0.0068 | <0.040 | <RDL |
| Perfluorotridecanoic Acid | µg/L | <0.0069 | <0.040 | <RDL |
| Perfluorotetradecanoic Acid | µg/L | <0.0067 | <0.040 | <RDL |
| Perfluorobutanesulfonic Acid (PFBS) | µg/L | 1.1 | 1.2 | 0.10 |
| Perfluorohexanesulfonic Acid (PFHxS) | µg/L | 0.46 | 0.46 | 0.00 |
| Perfluoroheptanesulfonic Acid (PFHeS) | µg/L | 0.013 | <0.040 | UNK |
| Perfluorooctanesulfonic Acid (PFOS) | µg/L | 0.055 | 0.084 | 0.029 |
| Perfluorodecanesulfonic Acid | µg/L | <0.0072 | <0.040 | <RDL |
| Perfluorooctane Sulfonamide (PFOSA) | µg/L | <0.0066 | <0.040 | <RDL |
| EtFOSA | µg/L | <0.0090 | <0.040 | <RDL |
| MeFOSA | µg/L | <0.0035 | <0.040 | <RDL |
| EtFOSE | µg/L | <0.0094 | <0.040 | <RDL |
| MeFOSE | µg/L | <0.0066 | <0.040 | <RDL |
| 6:2 Fluorotelomer sulfonic Acid | µg/L | 0.027 | <0.040 | UNK |
| 8:2 Fluorotelomer sulfonic Acid | µg/L | <0.0059 | <0.040 | <RDL |
| | TOTAL | 8.3 | 5.3 | -2.9 |
| | Precursors only | 1.3 | 1.4 | |

RDL = Reportable Detection Limit
QC Batch = Quality Control Batch
U = Undetected at the limit of quantitation
J = Estimated concentration between the MDL & RDL
Sum of Differences in Pre and Post Assay

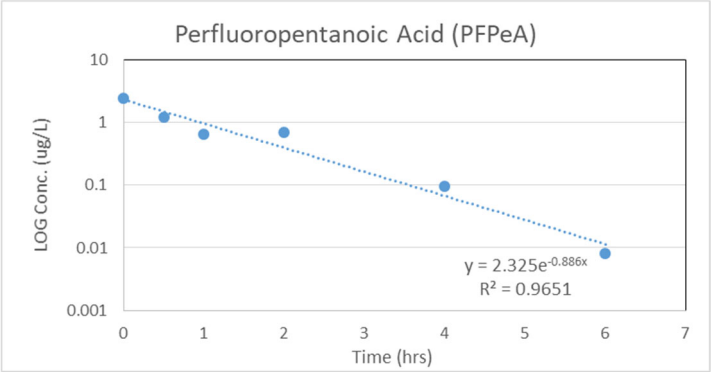
**Results relate only to the items tested.**

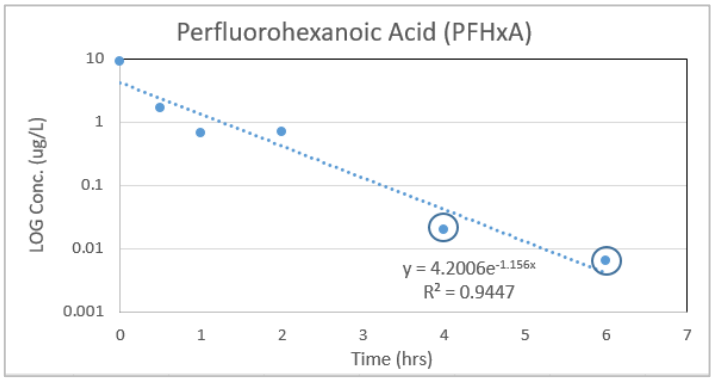
**Notes:** The change in PFAS concentration was calculated by subtracting the pre oxidation concentration from the post oxidation concentration.
A negative change indicates a decrease in the PFAS concentration after oxidation.
If the concentration of a parameter was <RDL either prior to or post oxidation, the concentration was treated as "zero" for the difference calculation.
Difference calculation performed using raw data. The rounding of final results may result in an apparent difference.
Not reported (NR) due to high volatility under the conditions used for oxidation.
Approximately 20% of PFOSA is known to be lost due to volatility under the conditions used for oxidation.
Oxidation was performed adhering to the protocol as described by Houtz, E.F. and Sedlak, D.L. (2012). *Environ. Sci. Technol*., 46, 9342-9349.
Due to high concentrations of target analytes, the sample required dilution prior to oxidation.
PFOS: The pre and post oxidation concentrations are within the acceptable laboratory tolerance limits for reproducibility.

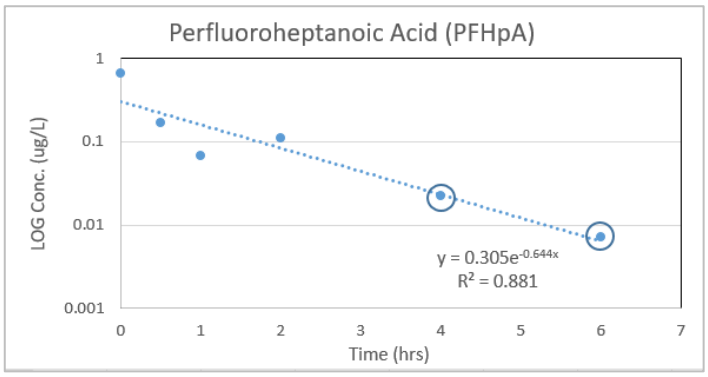
Appendix 7: Test results from rinsing, in a tumbler, the coarse fraction (fine gravel) of IDW soil (40 g) with 200 ml DI water followed by two rinses with 200 ml each of dilute (1,000 mg/L) XCT® solution.

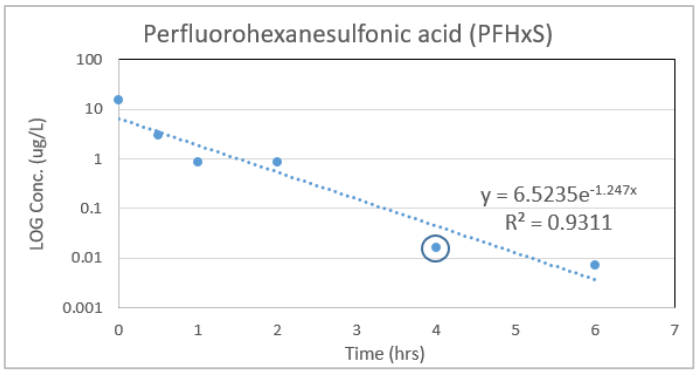
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sampler Initials: AM | | | | | | | | | |
| **RESULTS OF ANALYSES OF SOIL** | | | | | | | | | | | |
| Maxxam ID | | IOH174 | IOH174 | | IOH168 | IOH168 | | IOH169 | IOH169 | | |
| Sampling Date | | 2018/12/13 14:00 | 2018/12/13 14:00 | | 2018/12/13 17:15 | 2018/12/13 17:15 | | 2018/12/13 17:30 | 2018/12/13 17:30 | | |
| COC Number | | 254091 | 254091 | | 254091 | 254091 | | 254091 | 254091 | | |
| | **UNITS** | **PA#2 SOIL** | **PA#2 SOIL Lab-Dup** | mean | **CD RINSED PA-SOIL#2** | **CD RINSED PA-SOIL#2 Lab-Dup** | mean | **DW-CD2 RINSED PA-SOIL#2** | **DW-CD2 RINSED PA-SOIL#2 Lab-Dup** | mean |
| Moisture | % | 2.4 | N/A | 2.4 | 4.7 | N/A | 4.7 | 6.7 | N/A | 6.7 |
| Dry wt. soil basis | grams | | | 39.04 | | | 38.12 | | | 37.32 |
| | | **Initial total PFAS concentration in IDW soil** | | | **PFAS concentration in soil after 1st rinse with CD** | | | **PFAS concentration in soil after 3rd rinse** | | |
| 6:2 Fluorotelomer sulfonate | ug/kg | 1.6 | 1.9 | 1.8 | <0.26 | 0.34 | 0.30 | <0.26 | <0.26 | <0.26 |
| 8:2 Fluorotelomer sulfonate | ug/kg | <0.33 | 0.60 | 0.47 | <0.33 | <0.33 | | <0.33 | <0.33 | |
| Perfluorobutane Sulfonate (PFBS) | ug/kg | 1.5 | 1.7 | 1.6 | 0.19 | 0.27 | 0.23 | 1.5 | <0.17 | 0.8 |
| Perfluorobutanoic acid | ug/kg | 0.77 | 0.70 | 0.74 | <0.23 | <0.23 | | <0.23 | <0.23 | |
| Perfluorodecane Sulfonate | ug/kg | 5.5 | 4.3 | 4.9 | 1.3 | 1.2 | 1.3 | <0.39 | <0.39 | <0.39 |
| Perfluorodecanoic Acid (PFDA) | ug/kg | 0.34 | <0.28 | 0.31 | <0.28 | <0.28 | | <0.28 | <0.28 | |
| Perfluoroheptane sulfonate | ug/kg | 1.2 | 1.3 | 1.3 | <0.39 | <0.39 | | <0.39 | <0.39 | |
| Perfluoroheptanoic Acid (PFHpA) | ug/kg | 0.68 | 0.59 | 0.64 | <0.19 | <0.19 | | <0.19 | <0.19 | |
| Perfluorohexane Sulfonate (PFHxS) | ug/kg | 15 | 16 | 16 | 2.2 | 2.6 | 2.4 | 7.5 | 0.76 | 4.1 |
| Perfluorohexanoic Acid (PFHxA) | ug/kg | 2.8 | 2.8 | 1.5 | 0.27 | 0.32 | 0.30 | 0.24 | <0.14 | 0.19 |
| Perfluoro-n-Octanoic Acid (PFOA) | ug/kg | 1.1 | 1.0 | 1.1 | <0.25 | 0.36 | 0.31 | <0.25 | <0.25 | <0.25 |
| Perfluorononanoic Acid (PFNA) | ug/kg | 0.68 | 0.6 | 0.64 | <0.22 | <0.22 | | <0.22 | <0.22 | |
| Perfluorooctane Sulfonamide (PFOSA) | ug/kg | 0.86 | 0.74 | 0.80 | <0.14 | <0.14 | <0.14 | <0.14 | 0.16 | 0.15 |
| Perfluorooctane Sulfonate (PFOS) | ug/kg | 440 | 470 | 455 | 70 | 81 | 75.5 | 57 | 21 | 39 |
| Perfluoropentanoic Acid (PFPeA) | ug/kg | 1.5 | 1.5 | 1.5 | <0.25 | <0.25 | | <0.25 | <0.25 | |
| Perfluoroundecanoic Acid (PFUnA) | ug/kg | 0.58 | 0.46 | 0.52 | <0.34 | <0.34 | | <0.34 | <0.34 | |
| TOTAL | ug/kg | | | **488** | | | **80** | | | **44** |
| Total PFAS mass in soil sample | ug | | | **19.1** | | | **3.1** | | | **1.7** |
| Perct. PFOS of total PFAS | ug | | | **93%** | | | **94%** | | | **88%** |
| Total PFAS removed | % | | | | | | **84%** | | | **91%** |

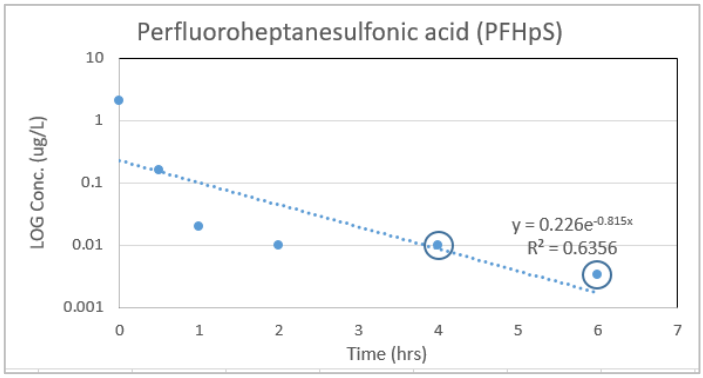
Appendix 8: Concentrations of PFAS not included in Figure 13. Data observed during foam fractionation/irradiation treatment of aqueous phase IDW. Circled data points are concentrations below detection limit that are reported at the corresponding detection limit for illustration purpose.

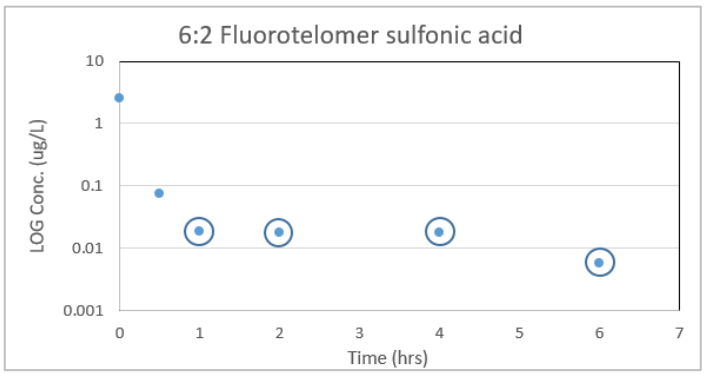



Perfluorohexanesulfonic acid (PFHxS)
LOG Conc. (ug/L)
100
10
1
0.1
0.01
0.001
0
1
2
3
4
5
6
7
Time (hrs)
y = 6.5235e-1.247x
R² = 0.9311


Perfluoroheptanesulfonic acid (PFHpS)
LOG Conc. (ug/L)
10
1
0.1
0.01
0.001
0
1
2
3
4
5
6
7
Time (hrs)
y = 0.226e-0.815x
R² = 0.6356


6:2 Fluorotelomer sulfonic acid
LOG Conc. (ug/L)
10
1
0.1
0.01
0.001
0
1
2
3
4
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7
Time (hrs)

## 9. Work products

Boving, T.B., Ball, R., 2018. Innovative Treatment of Investigation-Derived Waste Polluted with Per- and Polyfluoroalkyl Substance Contaminants and Other Co-Contaminants. Poster presented at the SERDP/ESTCP Symposium, Washington, DC, Nov. 27-29, 2018.

Boving, T.B., Ball, R., 2019. Innovative Treatment of Investigation-Derived Waste Polluted with Per- and Polyfluoroalkyl Substance Contaminants and Other Co-Contaminants. Poster presented at the SERDP PFAS Workshop, San Diego, CA, July 29 to Aug. 01, 2019.