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Design, Construction, and Testing of the PFAS Effluent Treatment System (PETS), a Mobile Ion Exchange–Based System for the Treatment of Per-, Poly-Fluorinated Alkyl Substances (PFAS) Contaminated Water

Scott A. Waisner, Victor F. Medina, Charles Ellison, Jose Mattei-Sosa, John Brasher, Jacob Lalley, and Chris Griggs

March 2022

Environmental Laboratory

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Final Report

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Abstract

Poly-,Per-fluorinated alkyl substances (PFAS) are versatile chemicals that were incorporated in a wide range of products. One of their most important use was in aqueous film-forming foams for fighting liquid fuel fires. PFAS compounds have recently been identified as potential environmental contaminants. In the United States there are hundreds of potential military sites with PFAS contamination.

The ERDC designed and constructed a mobile treatment system to address small sites (250,000 gallons or less) and as a platform to field test new adsorptive media. The PFAS Effluent Treatment System (PETS) has cartridge filters to remove sediments and a granular activated carbon (GAC) media filter to remove organic compounds that might compete with PFAS in the ion exchange process, although it may also remove PFAS too. The last process is an ion exchange resin specifically designed to remove PFAS to a target level of 70 ng/L or less (equivalent to the US Environmental Protection Agency (EPA) Drinking Water Health Advisory).

The system was tested at Hurlburt Field, a US Air Force facility in Florida and at Naval Support Activity (NSA) Mid-South in Millington, TN.

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Preface

This study was conducted for the National Defense Center for Energy and the Environment (NDCEE) under Military Interdepartmental Purchase Request (MIPR) 11285866. The project was titled "Design, Construction, Testing, and Application of the PFAS Effluent Treatment System (PETS) for Per-Poly-fluorinated Alkyl Substances (PFAS)." Mr. Adrian Salinas of the Army Environmental Command was the technical monitor for the project.

The work was performed by the Environmental Engineering Branch (EPE) of the Environmental Processes Division (EP), US Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). At the time of publication, Dr. Michael Rowland was the Branch Chief, CEERD-EPE; Mark Noel was Acting Division Chief, CEERD-EP. The Director of ERDC-EL was Dr. Edmund Russo.

COL Teresa Schlosser was Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

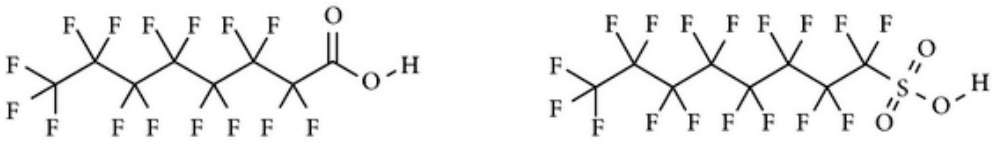
1.1 Background

1.1.1 PFAS (Per- and Polyfluorinated Alkyl Substances)

PFAS is the acronym used in general for per- and polyfluorinated alkyl substances. These compounds have been shown to create chronic health issues (including kidney, liver, and reproductive issues) and are a suspected carcinogen (Bilott et al. 2019; Sunderland et al. 2019). Consequently, the United States Environmental Protection Agency (USEPA) issued a very low Drinking Water Health Advisory (0.070 ng/L[1] PFAS). Because these compounds have been highly effective at suppressing fuel fires, they are commonly found in aqueous firefighting foams (AFFF)and therefore commonly found at military sites containing military aviation. The US Air Force has the most sites with PFAS contamination; however, all US Armed Services (Navy, Marine Corps, Army, and Coast Guard) also have contaminated sites. As a US Department of Defense (DoD) report indicated that the number of DoD and National Guard installations assessing PFAS use, or release increased from 401 to 651 in Fiscal Year 2019 (US Department of Defense 2020).

There are hundreds, perhaps thousands, of PFAS compounds. However, two in particular have been identified as problematic: perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) (figure 1).

Figure 1. Structures of perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA).



PFOA PFOS

1. For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

In addition to their presence at many military installations and facilities, PFAS are also found at industrial sites as spills or residuals from fires (Aly et al. 2020). They are also very challenging to degrade—particularly PFOS. For example, a study focusing on the use of advanced oxidation found that PFOA could be degraded by activated persulfate, but PFOS could not be (Park et al. 2016).

PFAS is a problematic contaminant for US military installations with firefighting training and maintenance areas. Our evaluation has indicated that there are sites and processes that have relatively small quantities (<250,000 gal [945,000 L) of PFAS contaminated water.[2] These include collection basins from firefighting training areas, equipment flushing and cleaning, and investigative derived waste (IDW) (that is, contaminated water pumped from wells). In these instances, a mobile treatment system could address these small-quantity sources. This project focused on the treatment of PFOS and PFOA, but other related PFAS will also be analyzed and assessed.

1.1.2 Small Military Sites

As mentioned above, the US Air Force, Navy, Marine Corps, and Army have numerous sources of small quantities of PFAS contaminated water (250,000 gal or less). Many of these facilities have recovery systems that collect the contaminated water. Although some of these can have large water volumes (>1 million gal), many of these systems are relatively small, ranging from 10,000 to 50,000 gal of water. These sites are too small to justify their own treatment systems, but the disposal costs of the collected water are still very high. A mobile system to periodically treat the contaminated water from these systems could, therefore, fill this need. The costs to produce such a system could be distributed across several sites and applied to each site as needed.

2. For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 345–7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

1.1.3 Requirements

The US Army Engineer Research and Development Center (ERDC) has identified several requirements applicable to contaminated water at US military installations:

1. In May 2016, the USEPA created a Lifetime Health Advisory (LHA) of 70 ppt (0.070 μg/L) for two PFAS compounds, PFOS and PFOA.
2. On 04 September 2018, Department of the Army Memorandum titled "Army Guidance for Addressing Releases of Per- and Polyfluoroalkyl Substances" indicated that potential PFAS contamination of soil and groundwater should be considered for army installations, base closure and realignment facilities, army national guard, and army reserve facilities, and sampling should be conducted if presence is likely. It also indicated that plans be developed for cleanup and response (Department of the Army 2018).
3. The US Air Force published the "Air Force PFOS/PFOA Snapshot," which indicated that, although the USEPA LHA is currently nonenforceable, under the Comprehensive Environmental Response, Compensation, and Liability Act[3] (CERCLA), the US Air Force will use this level to determine acceptable levels of PFOS and PFOA in drinking water (Department of the Air Force 2021).
4. On 14 February 2019, the USEPA prepared a PFAS action plan that committed to developing maximum contaminant levels for PFOA and PFOS, developing cleanup criteria for soil and groundwater, continual monitoring of contaminated areas, and evaluation of other PFAS forms for potential regulation (USEPA 2019a).
5. In October 2019 the USEPA prepared a public comment draft of the systematic review protocol for the PFBA, PFHxA, PFHxS, PFNA, and PFDA IRIS Assessments (USEPA 2019b).

1.1.4 The Decontamination Effluent Treatment System (DETS)

The DETS is an experimental water treatment system designed to treat contaminated water from mass personnel and vehicle decontamination activities resulting from CBRNE (chemical, biological, radiological, nuclear, explosive) events (figure 2). The DETS contains the following series of unit processes: sand filtration to remove sediments and particulates; an ion-exchange (IX) water softener to remove hardness; a

3. Comprehensive Environmental Response, Compensation, and Liability Act of 1980, 42 U.S.C. 103 § 9601 et seq. (7025).

granular activated carbon (GAC) media filter to remove bleach; surfactants, oils and grease, and other organic compounds; and a 5 μm sediment filter. The media filter processes are designed to be a pretreatment, removing constituents that could compromise the polishing and final processes, which is a six stage reverse osmosis (RO) system followed by a UV-disinfection unit. The RO system provides high rejection of organic and inorganic contaminants (Medina et al. 2012; Medina et al. 2015), including chemical warfare agents and radioisotopes. Detailed information on the DETS is provided in three previous publications (Dedeaux and Medina 2017; Medina et al., *Developing and Testing*, 2018; Medina et al., *Simulated Vehicle*, 2018; Medina 2019; Medina et al. 2019). The DETS was the inspiration for a mobile treatment system for PFAS.

Figure 2. The Decontamination Effluent Treatment System (DETS).

PFAS compounds are developed to be highly stable. The key aspect of these compounds is a spine of connected carbons, each bonded to fluorines to the external portions of the compound. The carbon:fluorine bond is one of the strongest chemical structures, with a bond dissociation energy of 544 kJ/mol (compared to 104.9, 83.7, 72.1, and 57.6 kJ/mol for carbon to hydrogen, chlorine, bromine, and iodine respectively, see Blanksby and Ellison 2003). So, it is not surprising that these compounds are very difficult to degrade by any means.

Our group conducted a series of studies evaluating activated persulfate (described in Park et al. 2016), Fenton's chemistry, and reductive:oxidative processes (not published). In each case, effective

degradation in terms of rate and ending concentrations were obtained for PFOA and another PFAS compound, 2:6 fluorotelmer sulfonate (2:6-FTS). No appreciable degradation was found for PFOS.

There have been efforts to degrade PFAS by biological processes and various abiotic means. In most of these studies, the same result was found: degradation of most PFAS compounds could be attained, including PFOA, but not for PFOS.

Some studies have found statistically supported degradation of PFOS. Sonolysis (Moriwaki et al. 2005) and boron-doped diamond electrodes have shown effective PFOS degradation (Carter and Farrell 2008; Liao and Farrell, 2009), but both have issues with cost-effective scale-up. Kingshott (2008) showed advanced oxidation could degrade PFOS but needed to use excessive reagents to accomplish it, beyond anything practicable for field use. Huang and Jaffe (2019) showed statistically significant biodegradation of PFOS, but the conditions of the experiment had concentrations several orders of magnitude higher than those found in the field, and the degradation leveled off at concentrations much higher than the 70 ng/L level.

Plasma destruction appears to have promise as an effective destructive PFAS technology (Mededovic Thagard n.d.; Singh et al. 2019). It has been shown to be able to destroy PFOS. Treatment rates are slow (for PFOA, 90% removal was achieved in 60 min), but plasma was developed for a pilot system that underwent field testing at Wright-Patterson Air Field (https://www.wpafb.af.mil/News/Article-Display/Article/2007997/air-force-tests-plasma-reactor-to-degrade-destroy-pfos-pfoa/).

1.1.6 Separation Technologies for PFAS Treatment

Because destructive technologies have been limited in their performance and applications, separation technologies have become the focus for treatment of PFAS. RO and membrane-separation technologies are generally effective for most contaminants. Studies on PFAS have shown that membrane treatments can effectively remove PFAS compounds, including PFOS. The ERDC team used the DETS system to demonstrate RO (Medina et al. 2019). The RO system on the DETS reduced PFOS levels from 30 μg/L to 8 ng/L.

However, RO produces a concentrate waste stream generally ranging 10%–50% of the volume. Many entities prefer not to have to address this concentrate. Because of this, granular media has become increasingly preferred as a separation media.

Granular activated carbon (GAC) has been used effectively and can be produced to have very high surface area, on the order of 800–1000 m^2/g (Medina 1994). This trait makes it a remarkable material for adsorptive removal of most contaminants (Helbig 1946; Terzyk and Gauden. 2002). The highest surface areas are found in coconut shell–based activated carbon, but coal-based activated carbons possess a greater range of pore spaces that allow water to move effectively within the particle and tend to be more effective for water treatment. Activated carbon can be made of many other materials, and activated biochar is an interesting material in terms of cost and effectiveness. Activated carbon is relatively inexpensive: it can cost up to $4.00/lb for the highest quality materials. However, GAC can have some issues that result in ineffective treatment. These include fouling, slow sorption kinetics for some contaminants (Weber and Morris 1963), and nonlinear sorption isotherms, which can limit effectiveness at high concentrations.

Ochoa-Herrera and Sierra-Alvarez (2008) compared sorptive removal of PFAS, including PFOS and PFOA, by GAC in water compared to zeolitic materials and sludge. They found that GAC had far more adsorption of PFAS compounds then the other materials, and they determined it a useful material for removal of PFAS in water.

Ion-exchange resins are another family material for physical removal of PFAS (Boodoo et al. 2017; Boodoo et al. 2018). Specialty resins designed to remove PFAS work by two mechanisms, adsorption and IX (PFAS compounds can weakly ionize in water). As such, these resins have been shown to be more efficient at PFAS removal than GAC and have a much higher removal capacity (Boodoo et al. 2017; Boodoo et al. 2018). As such, many treatment systems are now focusing on the use of IX to remove PFAS contaminants.

1.1.7 The PFAS Effluent Treatment System (PETS)

The PFAS effluent treatment system (PETS) (figure 3) resembles the DETS in that it is trailer mounted, media based, and has onboard power generation capability. The PETS differs from the DETS in that it does not

include an RO unit or UV disinfection unit, and it uses resins specifically designed to adsorb PFAS compounds from water (see section 2.2). Because the PETS does not have an RO unit, it does not produce a secondary waste stream requiring further treatment or disposal. Spent GAC, IX resin, and sediment filters are waste products generated from its operation.

Figure 3. PFAS Effluent Treatment System (PETS).

1.2 Objectives

This project sought to design, build, and demonstrate an effective mobile system for the treatment of PFAS-contaminated waters. The desired design parameters were outlined in a transition agreement with the Air Force Civil Engineering Center (AFCEC):

- Technical performance
  - Able to reduce PFAS concentrations from levels of approximately 400 ppb (µg/L) of combined PFOA and PFOS at Hurlburt Field to levels less than 70 ppt (ng/L)
  - Able to maintain a flow rate on average of 9 gpm
  - Able to reliably operate on average 8 h per day
- Cost
  - Produced for a capital cost not to exceed $120K

- Physical attributes
  - Trailer or skid-mounted system towed behind a V-8–powered, one-ton pickup truck
  - Units able to treat collected PFAS-contaminated water with a quantity ranging 100,000–250,000 gal
- Technology readiness level (TRL)
  - TRLs assist in decisions in the development and transfer of technology. The higher the TRL, the closer it is to transition.
  - The initial TRL was estimated at 6 (prototype development demonstration and validation). The goal was a completed TRL of 8 (prototype testing in an operational environment).

The USEPA-recommended drinking water health advisory was chosen as the treatment goal in the absence of any promulgated discharge regulations, waste disposal standards, remediation standards, or site-specific treatment goals.

A heavy-duty pickup truck was chosen as the design tow vehicle because of wide availability and lack of need for a specialized license to tow the system. This choice helps maintain a low mobilization cost for the developed system.

1.3 Approach

The challenge of a cost-effective treatment system for relatively small volumes of water contaminated with PFAS was addressed by designing a mobile treatment system (for use at several small sites) using highly effective IX and sorbent media.

1.4 Scope

The project scope consisted of design and construction of a mobile treatment system for PFAS-contaminated water (PETS) and field demonstrations of the prototype system (three at Hurlburt Field, Florida, and one at National Air Station (NAS) Memphis Millington Base Realignment and Closure (BRAC) site).

2 System Design

This section describes the thought process followed in the design of this mobile wastewater treatment system and provides a brief description of the components selected and incorporated into the system.

2.1 Basic Treatment Technology Selection

Review of treatment technologies developed at the time of this project indicated that no effective treatment technologies were currently available for destruction of PFAS compounds that can also be pulled behind a pickup truck (see section 1.1.1). For this reason, we considered two mature separation technologies: membrane separation and adsorption to solid media (see section 1.1.2).

Membrane separation technologies such as nanofiltration and RO are effective and were considered (see Medina et al. 2019, which includes a demonstration of the DETS system for PFAS treatment), but they both produce a significant secondary concentrated waste stream requiring disposal. While solid-phase adsorption also produces a waste stream in the form of spent media, modern IX resins developed specifically for PFAS treatment can produce a significantly lower unit volume of secondary waste than the liquid waste stream from a membrane separation process. Because the only viable destruction method currently available for PFAS-containing wastes is thermal destruction, volume reduction of waste is the key cost savings factor for treatment of waters containing PFAS.

2.2 Media Selection

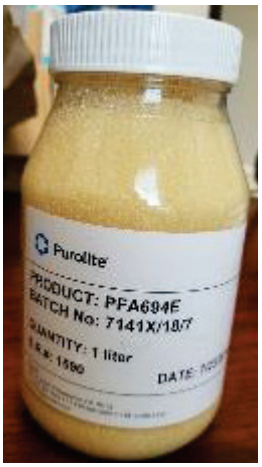
We based the choice of media on available design information and site studies from vendors. Using available information, we considered two types of media, GAC and IX resin.

Because this wastewater treatment unit is designed to treat relatively small volumes of less than 250,000 gal, we determined that regeneration of the media would not provide a significant cost savings. Regeneration of IX resin media using a solvent or brine fluid would further complicate and enlarge the system design, and it is likely to produce only a minimal volume reduction in the amount of media used and volume of waste

requiring disposal. Similarly, thermal regeneration of GAC media would not result in a significant reduction of media used.

Our studies led us to a resin produced by Purolite© called Purofine PFA 694E (figure 4, see https://www.purolite.com/product/pfa694e), a resin specially made for the removal of PFAS. We identified design data and operational results from field tests showing significantly greater PFAS binding capacity than GAC. Therefore, this resin was the adsorption media chosen for PFAS removal testing in our system.

Figure 4. Purlolite© Purafine PFA694E.



2.3 Pretreatment Technologies Selection

We selected three pretreatment steps for use with this system:

- screened suction strainers
- cartridge filtration
- GAC adsorption

2.3.1 Screened Suction Strainers

We attached strainers to the end of the intake hose for the system and used them to exclude large particulates before entering the system. We used two different and interchangeable suction strainers during demonstrations.

The first of the screens we selected was the 1.5 in (3.81 cm) model of the Dolphin Floating Suction Strainer by Megato (figure 5). It has a 1.5 in

(3.81 cm) barbed fitting to connect to the intake hose and is designed to float the hose slightly below the surface of the water.

Figure 5. Dolphin Floating Suction Strainer.

The second type we purchased from Dultmeier Sales (www.dultmeier.com/products/0.2623.2631/2461), item number EVRHS20 (figure 6). The manufacturer, brand, and model number of this device is unknown. This was a stainless steel cylinder with 3/8 in (0.95 cm) holes in the screen and a 1.5 in (3.81 cm) female NPT outlet port. We used a nylon mesh with 1.92 mm openings spaced at 11 per inchto cover the perforated sides to filter out smaller particles.

Figure 6. Dultmeier EVRHS 20 Suction Screen.

2.3.2 Cartridge Filters

For filtration of suspended matter, we chose Big Blue filter housings by Pentek for use with 20 in (50.8 cm) long by 4.25 in (10.8 cm) diameter disposable filter cartridges (figure 7). To achieve longer mean run times between cartridge changes and to lower the head loss across this stage of pretreatment, we used two filter housings in parallel and chose AMI (Applied Membranes Inc.) melt-blown polypropylene sediment-filter cartridges for use in the system. The filter cartridges have a graded pore structure with a defined final filter pore size. For this system, we chose three cartridges with different cutoff pore size ratings: 10, 5, and 1 μm.

Figure 7. Big Blue filter housing for sediment removal cartridges.

2.3.3 GAC Adsorption Media

We chose GAC as the final pretreatment step for removal of general organics and neutralization of possible oxidants such as chlorine and used two different types of GAC media during testing:

- Coconut shell–based, acid-washed mesh #12-40 (AMI #YMC1240AWCOCO)
- Anthracite coal–based mesh #12-40 (AMI #YMC1240RCOAL)

2.4 Pump Selection

We determined that the PETS should be able to treat water from a variety of water storage types and locations and should be able to feed water to the system using pumps supplied with the system. Some of the water storage types anticipated were surface waters, underground and aboveground storage tanks, and drums. Because the access ports to some of the storage locations may not be large enough to insert a submersible pump, we decided that the chosen pump be mounted on the system trailer, self-priming, and able to produce up to 13 psi (89.6 kPa) of suction. Further, we decided that the pump should have a variable flow rate and be capable of producing a flow rate up to 10 gpm (378 gpm) at a pressure of 100 psi (689.5 kPa).

After review of available pump types, a hose pump (sometimes referred to as a peristaltic pump) proved to be the most reliable type for our design needs. Using a hose pump also provided the capability to deal with some level of solids, and only the hose would come into contact with the

contaminated media. The chosen pump was a Bredel 40 by Watson Marlow (figure 8), which met all requirements. It is the same pump chosen for use on the DETS, and it has performed well for similar situations.

Figure 8. Bredel 40 Hose pump used in the PETS.

The pump uses 240V, three-phase power and requires a variable frequency drive (VFD) to control pump speed. At the recommendation from the pump vendor, we chose a 3 hp VFD from ABB (model #ACS255-03U-10A5-2+B063+F278) to control the pump.

We also selected a pulse dampener so as to reduce the pulsations from the hose pump and to reduce stress on the system. Again, at the recommendation of the vendor, we chose a Sentry bladder type pulse dampener from Blacoh Fluid Control (model #C911W-F). The pump was bolted to the decking material.

2.5 Media Tank Selection

The system used three media tanks, placed in series, with one tank for GAC and two tanks for the IX resin. Each tank had a gravel bed to support the granular media. In the selection of tanks, we considered several factors, including the following:

- media capacity (that is, empty bed volume)
- maximum flow rate greater than the minimum retention time recommended for the media (that is, bed volumes per hour, or BVH)
- approximate head loss at maximum flow rate
- approximate volume of water treated before capacity of media completely expended and requiring replacement

- form factor of tank and placement on trailer

Using knowledge of firefighting training sites that a minimum estimated treatment capacity before a requirement for media exchange should be about 200,000 gal (757,082 L) assuming a combined PFOA and PFOS influent concentration of about 100 µg/L, we also decided that the desired maximum flow rate should be about 10 gpm.

Purolite recommends 20 to 40 BVH maximum flow rate for acceptable performance for Purofine PFA694E point-of-entry applications. On the basis of this flow rate and a target maximum flow rate of 10 gpm (37.8 L/min), we calculated a range of estimated bed volume requirements using the following equation:

$$\frac{10\ \text{gal}}{\text{min}} \times \frac{1\ \text{hr}}{20\ \text{bed vol}} \times \frac{60\ \text{min}}{1\ \text{hr}} \times \frac{1\ \text{cu ft}}{7.48\ \text{gal}} = \frac{4.01\ \text{cu ft}}{\text{bed vol}} \quad (1)$$

From this calculation, we determined that the empty bed volume of each tank should be between 2 and 4 ft^3 (57–114 L).

Using the estimated required bed volume, we then determined that typical point-of-entry media tanks for home use would be sufficient and chose a 16 in (40.6 cm) diameter by 65 in (165.1 cm) height polyethylene-lined and fiberglass reinforced tank. This tank had a recommended media bed volume of 3.5 ft^3 (99.1 L). This recommended bed volume leaves sufficient headspace for bed expansion during backwash. For our applications, the data that suggested that the suspended solids were not excessive and the resin was single use, so we did not anticipate backwashing for these applications. Because of that, it was possible to increase the media bed volume to 4.5 or 5 ft^3 (127.4–141.6 L) for this application if required. A tank diameter of 16 in (40.6 cm) was sufficiently narrow to fit three tanks in a line across the width of the trailer bed. The tanks would be down flow, and the bed would not be fluidized.

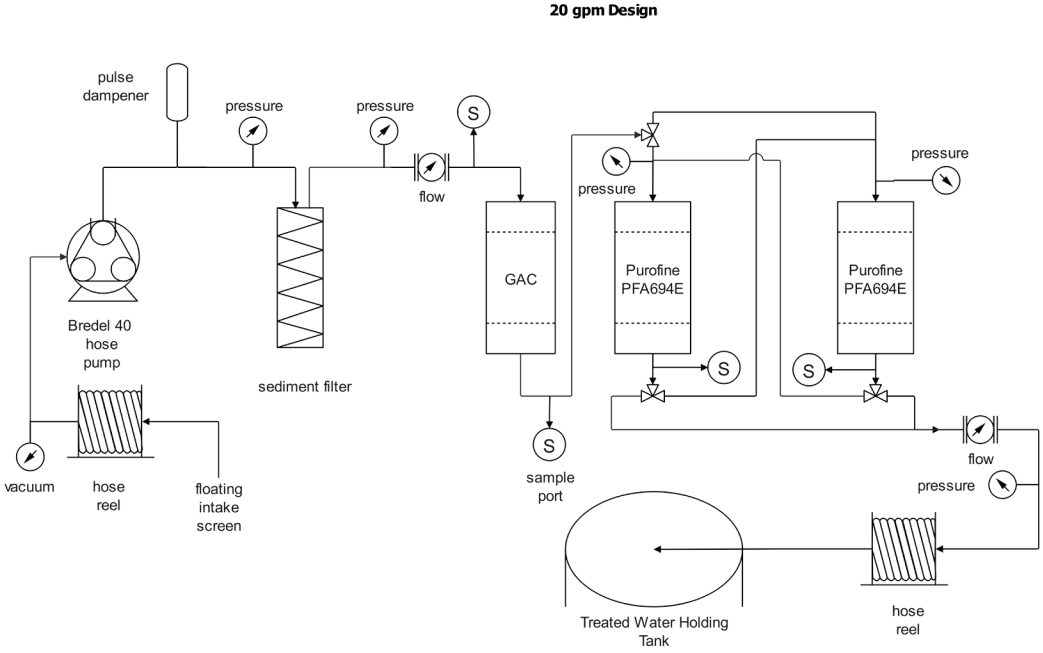
The total head loss across the resin bed of this tank was estimated to be 3.4 psi (23.4 kPa), which is sufficiently low for this application. This loss was based on a flow rate of 10 gpm (37.8 L/min) and a bed volume of 3.5 ft^3 (99.1 L). The cross-sectional area and height of the media bed will be 201 in^2 (1,296.8 cm^2) and 30.1 in (76.5 cm) respectively. This estimate

was based on pressure loss information provided in the product literature for Purofine PFA694E (https://www.purolite.com/product/pfa694e).

2.6 Process Flow Diagram

This basic process flow diagram created for the project will guide further development of the treatment system (figure 9).

Figure 9. Basic process flow diagram of the PETS.



2.7 Additional System Components

2.7.1 Sensing

We incorporated sensors into the system design to monitor flow rates into and out of the system and pressures at several locations in the system and used signals from these sensors to control the flow rate and pressures by varying the speed of the pump.

Identical flowmeters measured the flow rates. The first meter, placed between the sediment filters and the first media tank, monitored flow into the system. The second meter, placed between the last media tank and outlet hose reel, monitored flow out of the system. Both meters were Kobold Model DRG-1155N6C34P (figure 10). This meter type is a rotating vane (paddle wheel) sensor with an electronic display and transmitter. The

meter has a flow range of 1.5–23 gpm (5.7–465.6 L/min) and was configured to transmit a 4–20 mA output signal.

Figure 10. Kobold Model DRG-1155N6C34P Flowmeter used in the PETS.

Pressure transmitters measured pressures in seven locations and were placed before the pump, after the pump, after sediment filters, and after each media tank. A vacuum sensor before the pump monitored for possible plugging issues at the hose intake. The other pressure transmitters allowed monitoring of the pump pressure and calculation of head losses across the sediment filter and the media tanks. The transmitters selected were from ifm Electronic Gmbh. The vacuum sensor was model PX3229 with a pressure range of –14.5 to 0 psi (–99.9 to 0 kPa) and transmits a 4–20 mA signal. The pressure sensors were model PX3244 with a pressure range of 0–150 psi (0–1,034.2 kPa) and transmit a 4–20 mA signal.

2.7.2 Human Machine Interface (HMI) Process Controller

A human machine interface (HMI) with a touchscreen that could be programmed for easy monitoring and control of the system by the user and a programmable logic controller (PLC) for interface with the pump, valves, and sensors in the system we determined would be desirable features for the system. A combined touchscreen HMI panel and PLC from EZAutomation was selected, EZ Touch I/O model #EZ3-T10C-E-PLC-E (figure 11). The unit has a 10 in (25.4 cm) color TFT pressure-sensitive screen. The PLC can be configured with up to eight detachable input/output (I/O) modules for sending and receiving up to 64 I/O signals.

Figure 11. Human machine interface–programmable logic controller (HMI-PLC) unit used on the PETS.

2.7.3 Power

Because the system should be capable of both operating with line power or independently with a generator integrated with the system, we needed a generator with sufficient power and fuel capacity to allow at least three days of continuous system operation without requiring refueling. Further, we sought a generator with good noise suppression, since the generator would be collocated on the same trailer as the water treatment unit.

We decided that a WhisperWatt TLG8SSK4F2 manufactured by Multiquip would meet our requirements. This diesel generator has a 6 kW output, and we specified that it be coupled with a 40 gal (151.4 L) sub-base fuel tank. The manufacturer's estimated fuel consumption rates and estimated run times with 40 gal (151.4 L) of fuel are provided in table 1. Using these fuel consumptions rates, the generator could meet our three-day (72 hours of use) operational requirement at a 75% load. Our estimate is that the system power demand during normal operational conditions would be approximately a 50% load, which provides a continuous runtime capability of about 3.5 days.

Table 1. Generator estimated fuel consumption rates.

Load	Fuel consumption rate (gph, L/h)	Run time (h)
Full	0.68, 2.57	58
3/4	0.55, 2.08	73
1/2	0.48, 1.81	83
1/4	0.37, 1.40	108

We used a single-walled fuel tank for our unit because it reduced the dry weight by 400 lbs (181.4 kg) when compared to the double-walled tank. The dry weight of the generator and tank combined is 659 lbs (298.9 kg). The single-walled tank also reduced the footprint length of the fuel tank, which made the unit easier to fit on the trailer. The estimated wet weight of the unit full of fuel is 937 lbs (425 kg). The reduced weight also lowered our concern about a concentrated load on the trailer bed.

2.7.4 Trailer

For the mounting and transport of this system, we selected a Top Hat model THMP8316 utility trailer (figure 12). The trailer has a 6 ft 11 in wide by 16 ft long bed, tandem axels, electric brakes, and a gross vehicle weight rating (GVWR) of 7,000 lbs. The trailer was modified by the supplier so that it had four drop-leg jacks, one near each corner of the trailer bed, and a spare tire rack was welded to the front of the bed frame.

Figure 12. Trailer (Top Hat Model THMP8316) used for the PETS.

After purchase, we replaced the 2 × 6 lumber decking material with aluminum planks purchased from Direct Metals (www.directmetals.com). The planks had dimensions of 1.5 × 6 × 191 in (3.81 × 15.2 × 485.1 cm) and were punched with rectangular holes (figure 13). The replacement of decking material provided a very strong, rigid, and well-drained surface to which equipment could be mounted, and the material will not rot or suffer from corrosion when exposed to the environment for long durations.

However, the cost of this decking material doubled the finished overall cost of the trailer.

Figure 13. Aluminum planks installed on the PETS trailer.

2.7.5 Hose

For our major water lines on this system, we required a flexible hose with 1 in ID, capable of operating at pressures up to 100 psi (689 kPa), and we preferred a translucent material to allow easier monitoring of the liquid flow in the system. To that end, we selected a polyurethane tubing with braided reinforcement manufactured by Saint Gobain, Versilon C-544-A IB (part #AZY02064). The translucent nature of the hose material allowed us to see air bubbles in the lines and changes in fluid color. We noticed no degradation in the clarity of the hoses during our experiments.

2.7.6 Hose Reels

Hose reels for the influent and effluent lines would add significant benefit to mobile nature of this system, so we acquired two stainless-steel, spring-retractable reels for 1 in (2.54 cm) ID hose (Reelcraft Industries model #D9400 OLSSW). Each real has a capacity for 50 ft (15.2 m) of our selected hose.

2.7.7 Actuated Valves

Three-way actuated valves redirected flow between the media tanks and facilitated changing the order of flow between the second and third media tanks. For this step we chose Banjo model EV100SL (figure 14), a 12 VDC-actuated and -operated valve.

Figure 14. Banjo EV100SL Actuated three-way valve used in the PETS system.

2.7.8 Tank and Sediment Filter Frames

The support frames for holding the media tanks (figure 15) and the sediment filters (figure 16) were custom made by the ERDC welding shop. The tank frame was bolted directly to the trailer frame through the decking material, and the filter frame was bolted to the decking material.

Figure 15. Media tank support frame.

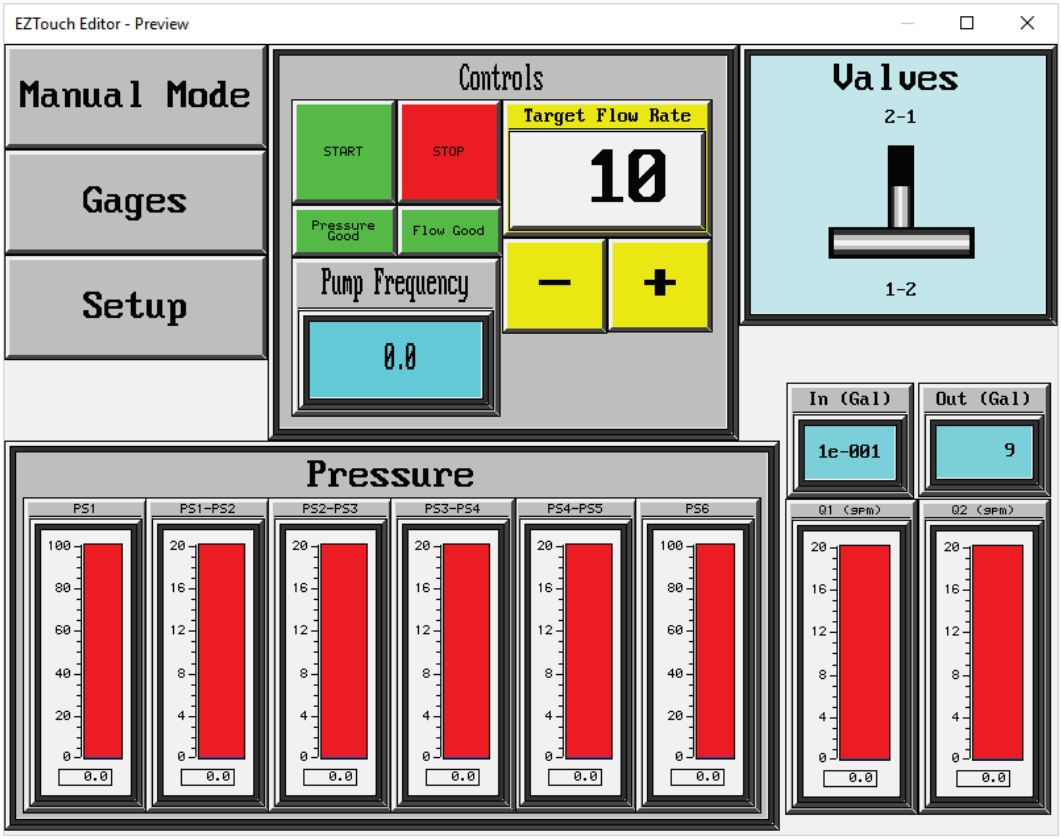
Figure 16. Sediment filters and support frame.

3 Process Control

3.1 Descriptions of Touchscreens

Process control occurs within the combined touchscreen HMI panel and PLC discussed in section 2.7.2 . The touch interface consists of four displays. The startup display, labeled *Auto Mode*, is illustrated in figure 17.

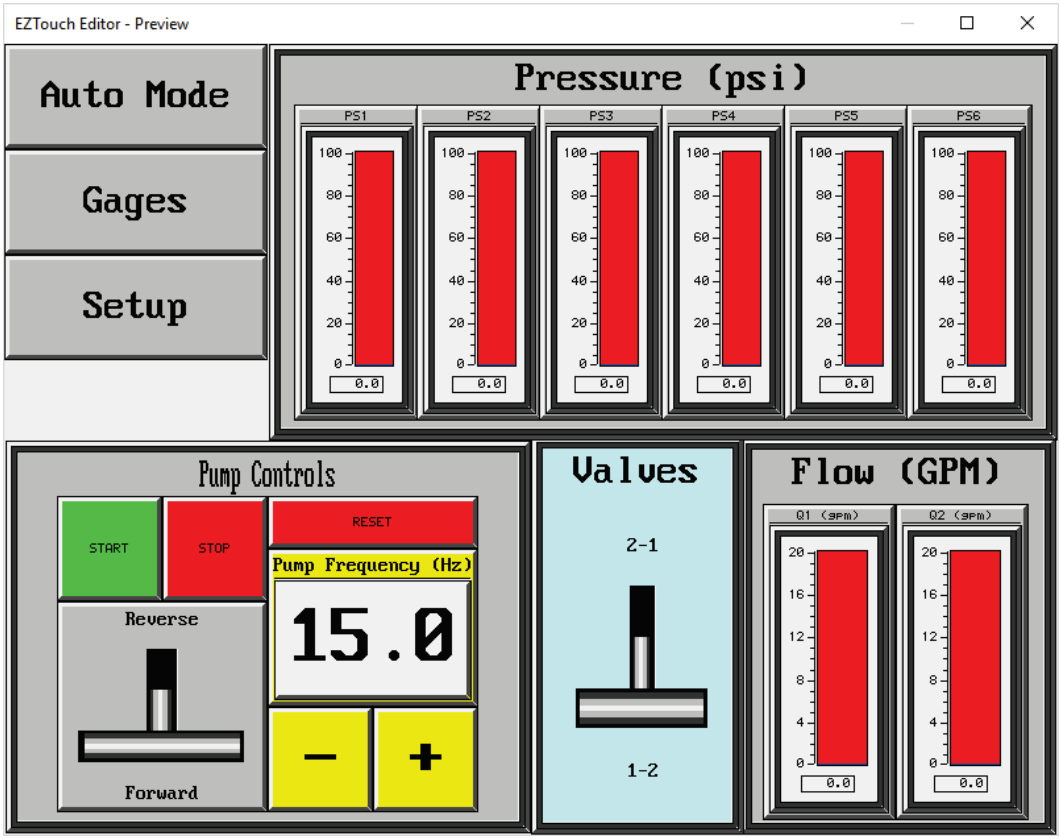
Figure 17. HMI Screen, Auto Mode display.



The Auto Mode display provides process controls in the top half of the screen and gages and other information sources in the bottom half of the screen. Available controls include start and stop buttons for the main process cycle, the ability to adjust the target flow rate for the proportional controller, and a switch to redirect flow between the second and third media tanks. Gages consist of input and output flow rates, flow counters, pressures at the pump and outlet, and the pressure drop across the various filter media.

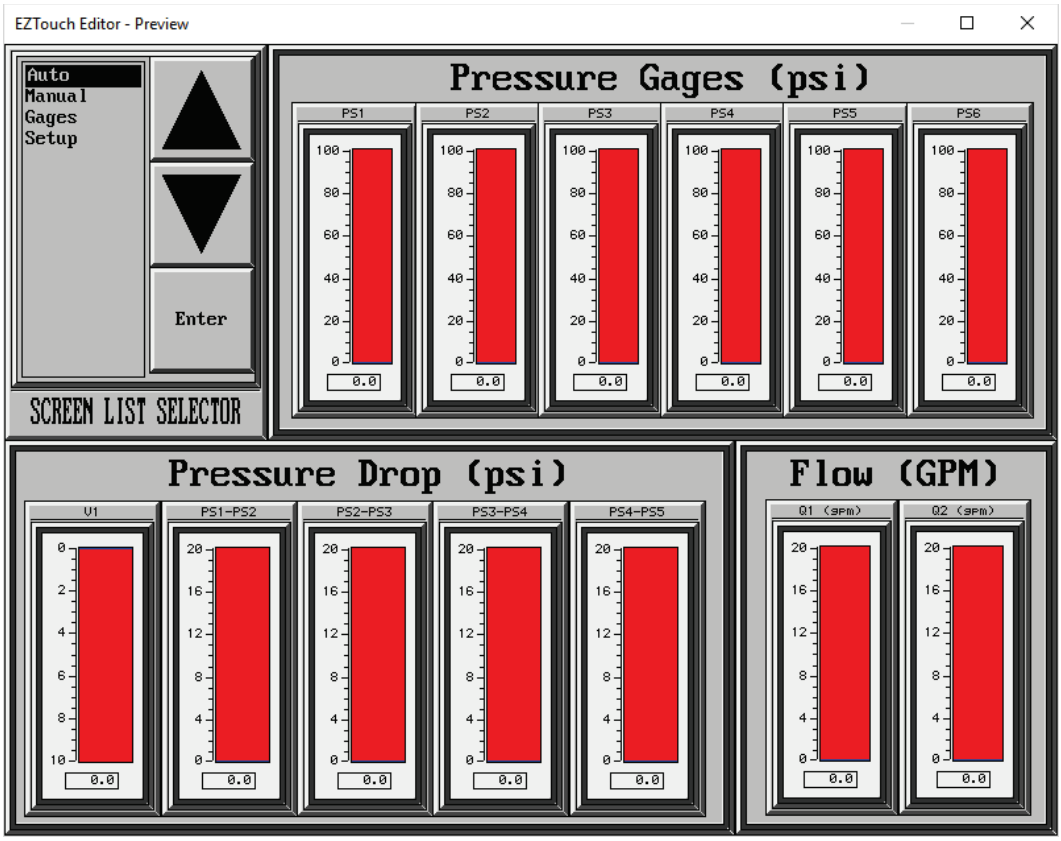
The upper-left corner of the screen provides access to additional displays, including a more manually oriented control screen (figure 18), a gage-focused screen (figure 19), and a setup screen (figure 20).

Figure 18. HMI Screen, Manual Mode display.



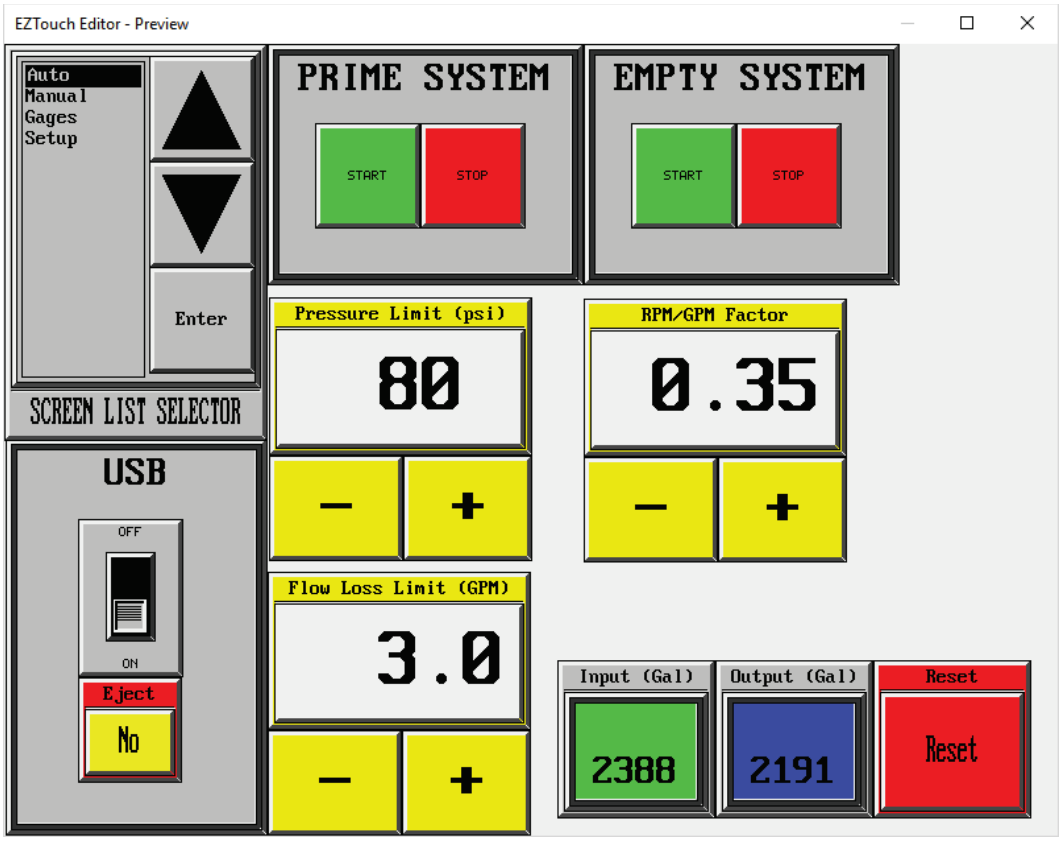
As the name suggests, the Manual Mode display focuses on direct manual control of the pump speed, including the ability to reverse pump flow. Gages on this display focus on the direct pressure readings at each pressure and flow gage.

Figure 19. HMI Screen, Gages display.



The Gages display removes all controls, providing more space for gages, including direct readings from all pressure and flow gages, and the pressure drop across all of the various filter media.

Figure 20. HMI Screen, Setup display.



The Setup display provides access to functions that will prime the system (run pump until output flow is equal to input flow) and empty the system (run pump until output flow drops to zero). This screen also provides control of the two safety shutoffs: (1) maximum acceptable pump pressure (that is, excessive backpressure) and (2) maximum deviation between input and output flow (that is, leak detection). Some of the automatic flow algorithms require an initial guess factor relating pump speed (rpm) to flow (gpm), and control of this factor is provided on the setup screen. Finally, USB-based datalogging controls and a reset for the flow counters are also provided on the setup screen.

3.2 Descriptions of Programming Logic

Like most PLCs, programming of the EZAutomation system is performed in ladder logic. The basic logic for the PETS system is summarized in figure 21, with further details of the three available automatic cycles illustrated in figure 22 through figure 24.

Figure 21. Main ladder logic diagram.

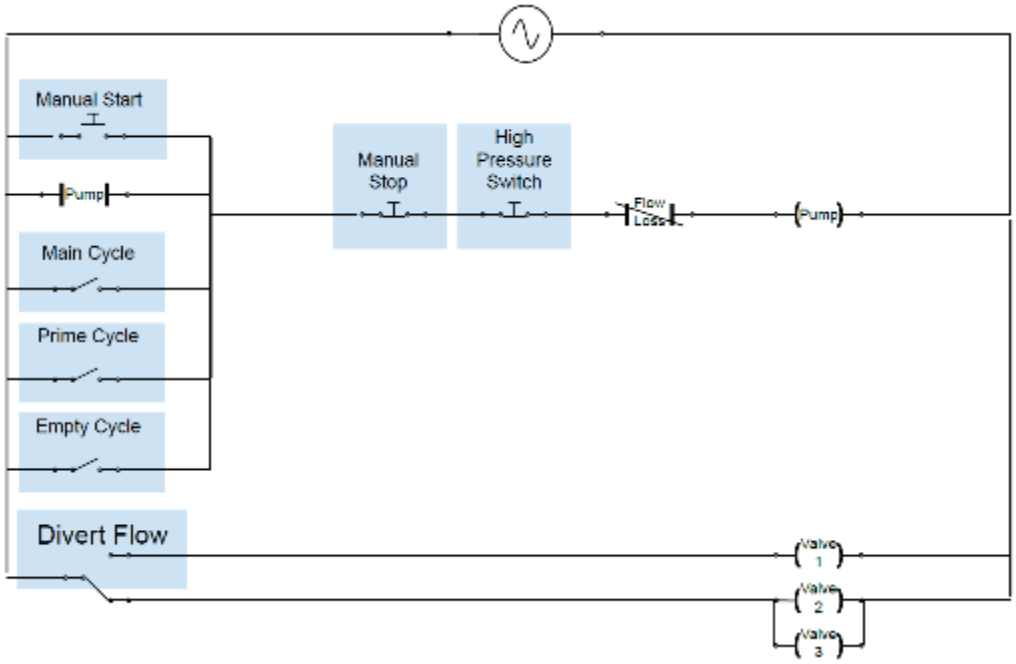


Figure 22. Main cycle logic.

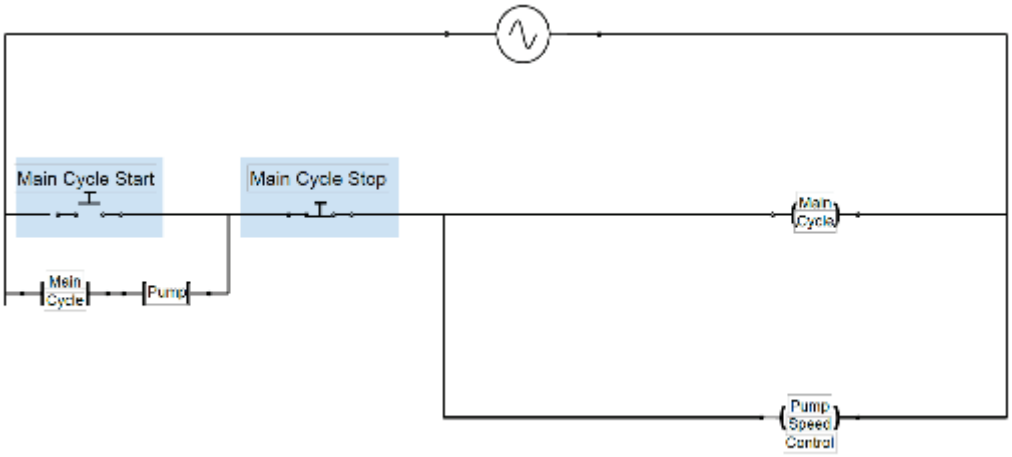


Figure 23. Prime cycle logic.

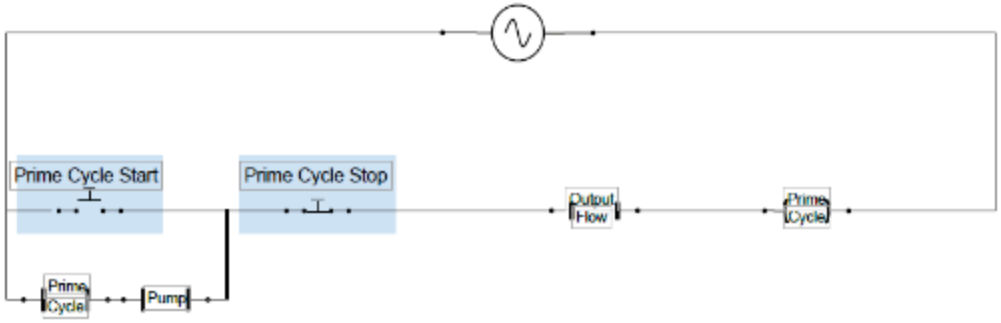
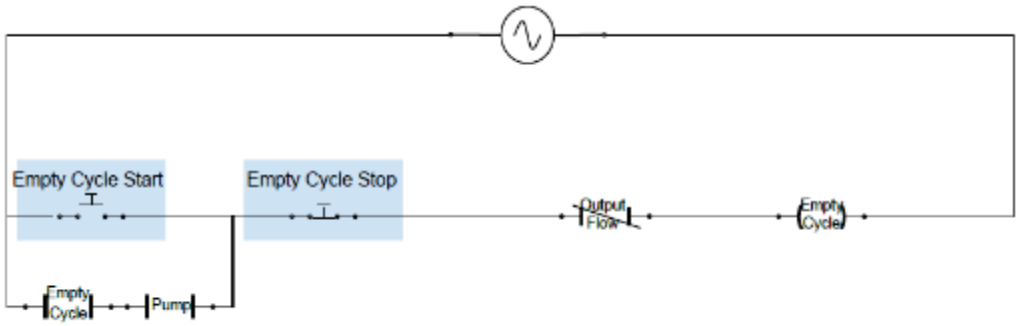


Figure 24. Empty cycle logic.



Automatic pump speed control is enabled when the main cycle is running and consists of a PID loop that attempts to maintain a user-selected flow rate. PID values include a proportional gain of 110, an integral time of 50, and a derivative time of 0. In response to the very large pressure fluctuations generated by the hose pump, the PLC maintains a 40 s rolling average for all gage inputs. This average is used within the pump speed control loop to prevent hunting behavior. The rolling average is also used on all gage displays to make them more readable.

4 Demonstrations

4.1 PFAS Analytical Methods

4.1.1 EPA Method

PFAS analyses were conducted by Eurofins TestAmerica using the USEPA and Standard methods listed in table 2.

Table 2. List analytical methods.

Method Number & Reference	Analyte(s)
SW846 Method 3535 (USEPA 2007)	solid phase extraction (SPE)
EPA Method 537 (USEPA 2008)	per- and poly-fluorinated alkyl substances (PFAS)
SM 2510B (Standard Methods 2018)	specific conductivity
SM 2540C (Standard Methods 2018)	total dissolved solids (TDS)
SM 2540D (Standard Methods 2018)	total suspended solids (TSS)
SM 4500 H+ B (Standard Methods 2018)	pH
SM 5310B (Standard Methods 2018)	total organic carbon (TOC)

Notes:

SM—Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF)
SW846—Test Methods for Evaluating Solid Waste: Physical/Chemical Methods (USEPA)
EPA Method—Analytical Methods for Drinking Water (USEPA)

PFAS compounds listed in EPA Method 537 M and their abbreviations are listed in table 3. A table with additional information on these compounds is included in appendix 2. The method detection limit and reporting levels were 1 and 2 ng/L for PFOA and PFOS.

Table 3. PFAS compounds and abbreviations in EPA Method 537M.

Compound	Abbreviations
N-ethylperfluorooctanesulfonamidoacetic acid	NEtFOSAA
N-methylperfluorooctanesulfonamidoacetic acid	NMeFOSAA
Perfluorobutanesulfonic acid	PFBS
Perfluorodecanoic acid	PFDA
Perfluorododecanoic acid	PFDoA
Perfluoroheptanoic acid	PFHpA
Perfluorohexanesulfonic acid	PFHxS
Perfluorohexanoic acid	PFHxA
Perfluorononanoic acid	PFNA
Perfluorooctanesulfonic acid	PFOS
Perfluorooctanoic acid	PFOA
Perfluorotetradecanoic acid	PFTA, PFTeA
Perfluorotridecanoic acid	PFTrDA, PFTriA
Perfluoroundecanoic acid	PFUnA

4.1.2 Adaptation of MBAS Method for Use in the Field

We investigated one expedient analytical method for use in the field. This method was necessary to estimate when PFAS compounds were breaking through the media tanks and was an adaptation of Hach Method TNT 874 for Anionic Surfactants. The adapted method was used during these demonstrations to give an approximation of long-chain PFAS concentrations. The primary goal of this field expedient test was not to provide a quantitative measure of PFAS compounds eluting from a tank but to provide a comparison of the PFAS levels into and out of the media tanks within a 24 h window.

Prior to analysis by the Hach colorimeter, the samples were concentrated by passing 500 mL of sample water through Agilent Bond Elut LMS solid phase extraction (SPE) cartridges (part #12255021). The PFAS where then eluted from the SPE cartridge with 5 mL of methanol. The methanol was then diluted as necessary with deionized water and analyzed using Hach TNT 874 tubes. We estimated that this method would provide a concentration factor of up to 100 and reduce the lower detection limit of the Hach method to 1 µg/L of sodium dodecylbenzene sulfonate (SDBS). Using the ratio of molecular weights this should equate to 1.4 µg/L of PFOS.

The absorbance of the resultant samples in the TNT 874 tubes was measured at 653 nm was converted to an estimated concentration of PFOS using the calibration provided in figure 25 (Hach 2016) and the ratio of molecular weights for PFOS and linear alkyl sulfonates (LAS).

Figure 25. Calibration of Hach TNT874 with linear alkyl sulfonates (LAS) (from Hach 2016).

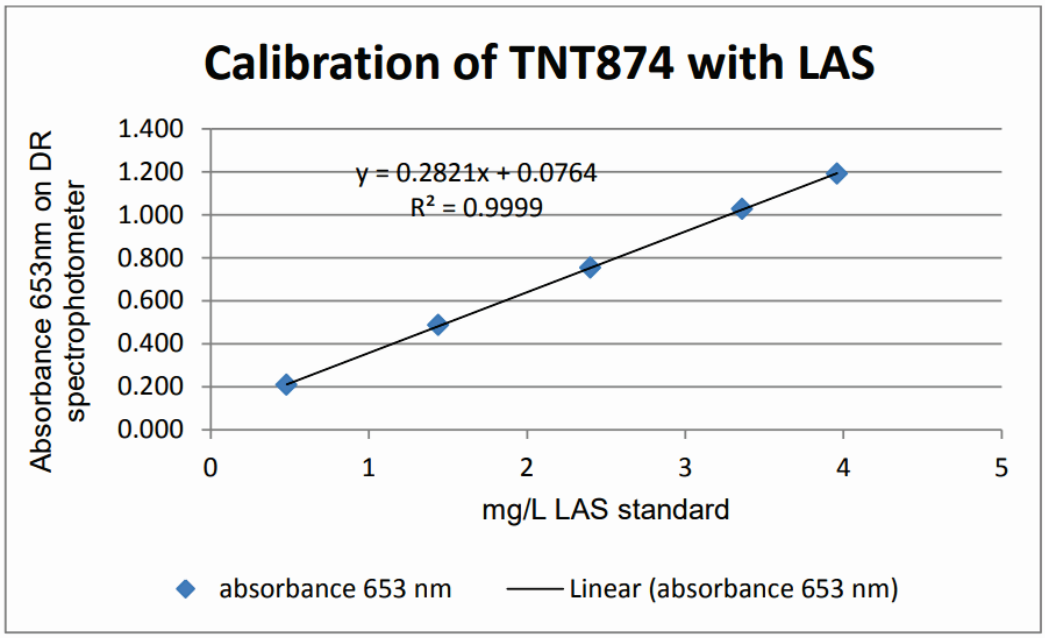


Figure 1: Calibration of TNT874 with LAS

The calibration formula is given by:
Conc. mg/L LAS = abs. 653 nm *3.54 – 0.26 (zero against air)

The method was used as a semiquantitative tool to monitor for breakthough. However, this approach could be developed with additional research and could possibly be an effective field measurement method.

4.2 Hurlburt Field Site and Demonstrations

Three demonstrations were conducted at Hurlburt Field, Florida, during the summer of 2019. These demonstrations occurred from 10–14 June, 29 July–6 August, and 26–30 August.

4.2.1 Site Description

Hurlburt Field is a US Air Force installation located in Okaloosa County, Florida, immediately west of the town of Mary Esther, and it is part of the greater Eglin Air Force Base reservation. A fire training facility was constructed at Hurlburt Field in the late 1990s. It is located toward the

north end of the runway on the east side. This facility consists of a circular area with a simulated aircraft fuselage in the center, a water recovery and conservation pond, and a simulated building infrastructure (figure 26). Both the training area and the pond were lined to protect the local groundwater. The training area has been graded such that water used in the training area drains toward the center and is collected in a sump and then pumped into the water conservation pond for reuse as quench water during training. To prevent overtopping of the pond, water is pumped to the sanitary sewer as needed and is treated at the on-base wastewater treatment facility.

Hurlburt Field's wastewater treatment facility currently treats approximately 600,000 gal (2.3 million liters) of water per day and is classified as an advanced biological nutrient removal facility because the treated water is released into a wetland. Therefore, in addition to removing solids and organics, nutrients that can have a detrimental effect to the wetland such as ammonia, phosphorus, and nitrogen must also be removed to extremely low levels. Treated water is disinfected with chlorine and is reclaimed for usage at wash racks and irrigation of a golf course and other recreational fields.

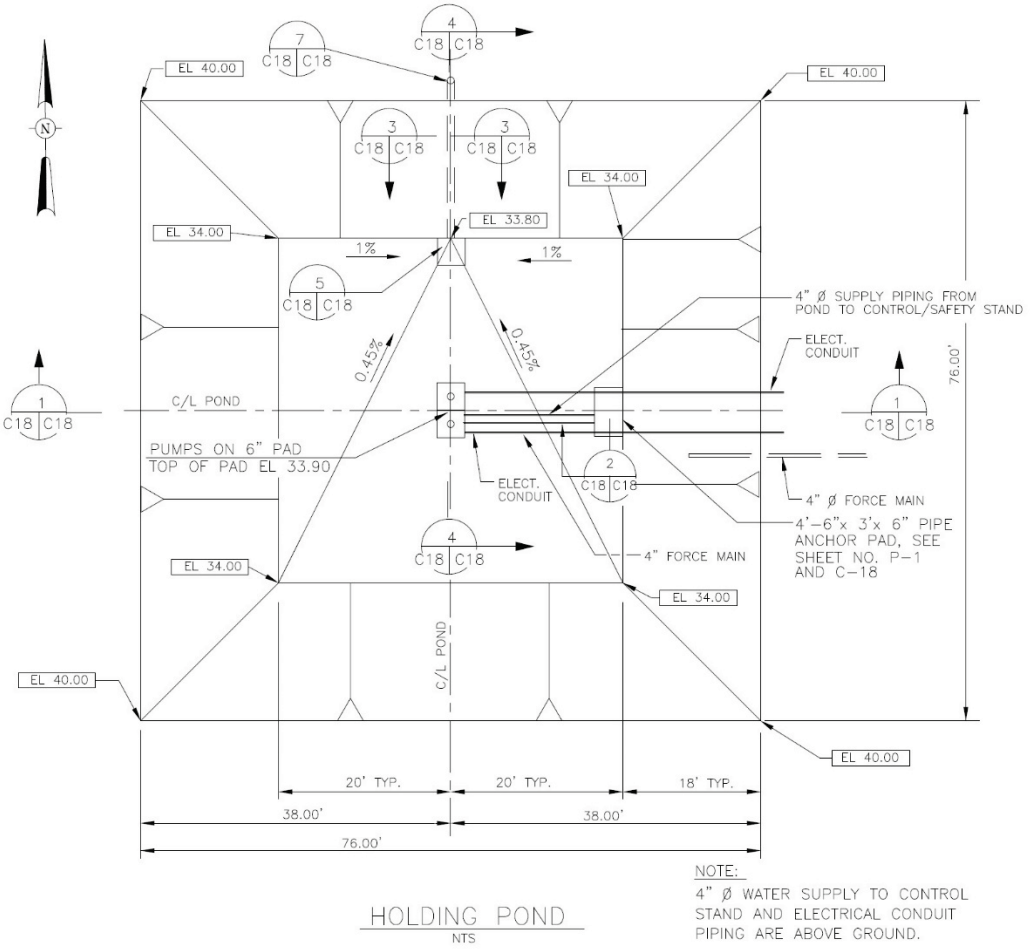
Figure 26. Aerial View of Fire training facility at Hurlburt Field.

Demonstrations described in this report were conducted with water from the water conservation pond. The PETS was parked adjacent to and at the southeast corner of the pond as shown in figure 27. Treated water during these demonstrations was either pumped back into the pond or into the existing water collection sump for the training facility and discharged to the sanitary sewer. When the PETS was not powered by the onboard generator, power was drawn from the training facility's local power distribution panel.

Figure 27. Aerial Photograph: Layout of demonstration area.

The maximum retention volume of the water conservation pond was estimated from design drawings developed during construction of the training facility (figure 28). The drawing used indicated the approximate shape of the pond to be a frustum of a pyramid. The bottom plane of the pond is a square 40 ft (12.1 m) on a side, giving it an area of 1,600 ft^2 (148.6 m^2), and the top plane of the pond is a square 76 ft (23.2 m) on a side, giving it an area of 5,776 ft^2 (536.6 m^2). The drawing indicates the depth of pond to be 6 ft. Using the formula shown in equation 2, the volume of the pond was estimated to be 20,832 ft^3 or 155,834 gal (589,858 L).

Figure 28. Design drawing of water conservation pond.



$$V = \frac{h}{3}\left(A_1 + A_2\sqrt{A_1 \times A_2} \right) \quad (2)$$

where

A_1: area of first plane
A_2: area of first plane
h: height between two planes

Estimated concentrations of PFAS compounds in the pond water were provided by Hurlburt Field and based on samples collected in December 2018. Analytical results from the pond water provided in table 4.

Table 4. Estimated PFAS concentrations in pond water.

Constituent	Concentration (ng/L)
Perfluorobutanesulfonic Acid (PFBS)	550
Perfluoroheptanoic Acid (PFHpA)	3,100
Perfluorohexanesulfonic Acid (PFHxS)	6,100
Perfluorononanoic Acid (PFNA)	1,800
Perfluorooctanesulfonic Acid (PFOS)	360,000
Perfluorooctanoic Acid (PFOA)	8,200

Base personnel indicated that the concentrations of PFAS increased and decreased in inverse proportion because of evaporation and precipitation in the area. Because the pond receives all the runoff from precipitation falling on the training area as well as the pond, precipitation has an exaggerated effect on the pond level. On the basis of design drawings for the training facility, it is estimated that the total area of the pond and lined area is approximately 29,800 ft^2 (2,768.5 m^2). From this it can be estimated that 1 in (2.54 cm) of precipitation will add 2,483 ft^3 or 18,574 gal (70,310.2 L) of water to the pond. This estimate indicates that the pond can be at capacity with approximately 8.4 in (21.4 cm) of precipitation. Estimates of rainfall were calculated using National Oceanographic and Atmospheric Administration (NOAA) records from a rain gauge located about 2 mi from this site in nearby Mary Esther, Florida.

In contrast to precipitation, 1 in (2.54 cm) of evaporation will remove a maximum of 481 ft^3 or 3,601 gal (13,631.3 L) of water. PFAS is described as minimally evaporative, so losses of this type are assumed to be minimal (MN DOH 2019). The best estimate of evaporation rates found for the area were taken from a NOAA report (NOAA 1982) with measurements from a station in Milton, Florida, which is approximately 25 mi to the northeast of Hurlburt Field. According to the records, the mean evaporation rates for June, July, and August are 7.08, 6.56, and 6.05 in (18.0, 16.7, and 15.4 cm) per month. This equates to daily average evaporation rates of 0.236, 0.212, and 0.195 in (0.60, 0.54, 0.50 cm) per day for the same months. Estimated average daily evaporative water losses for the pond for the months of June, July, and August are 850, 763, and 702 gal per day (224.5, 201.6, and 185.4 L).

The pond has not been cleaned since construction, and as a result a significant level of detritus from the nearby pine trees has accumulated in

the bottom. This organic material in the water has contributed to the growth of algae in the pond, and a significant algal mat in the bottom of the pond. However, pond water sampled away from the algae and the bottom of the pond was relatively clear and free of suspended solids.

4.2.2 Demonstration 1

The first demonstration at Hurlburt Field occurred 10–14 June 2019 and sought to test the road worthiness of the PETS, discover weaknesses in the design, and validate the system's capability of removing PFAS constituents from the water to produce effluent concentrations below the target of 70 ng/L. For this demonstration, the treated water was returned to the pond.

For this initial field test, two items had not been completed in the construction of the PETS. Owing to delays in the acquisition and delivery of the generator unit, the generator was not yet mounted on the trailer. The PETS was operated with line power provided at the fire training area for the duration of this demonstration. Additionally, the Masonite pegboard on which the three-way valves were mounted had not been replaced with a steel plate. The PETS as tested is shown in figure 29.

Figure 29. The PETS during demonstration 1 at Hurlburt Field.

At the time of this demonstration the pond, shown in figure 30, was filled to near its maximum capacity. Also visible in the photo are the influent and effluent lines in the pond. The Dolphin screened suction strainer (figure 5) was used for this test. The strainer was suspended at a level approximately 1 ft below the pond surface by keeping tension on the intake hose using a rope attached to the fence on the far side of the pond.

Figure 30. Firefighting training area water conservation pond—demonstration 1.

One significant issue was identified during the demonstration. The HMI screen froze after several hours of operation. This issue was first noticed on the morning of the second day of operation. On the basis of variations in the pump speed, flow rates read directly from the meters, and pressure displayed on the pulse dampener, it was apparent that the PLC was continuing to monitor and properly control the system. Because the cause of the issue and the effect of rebooting the system were unknown, it was decided to let the system continue to operate in its current status. Although the screen did not update the readings, it continued to function as programmed for the duration of the demonstration.

4.2.2.1 Results and Discussion

Water samples were collected from the pond on 13 June at approximately 15:00 for basic water-quality parameters. These data were only collected from the pond, since they were not indicators of actual treatment performance. However, they could affect treatment. Samples for TOC analysis were also collected at the same time from the PETS at two locations, after the GAC media and the effluent line from the system. These sample were analyzed for TOC. The results are provided in table 5. All levels were within levels expected not to affect treatment.

Table 5. Pond water-quality parameters—Hurlburt Field, demonstration 1.

	Pond	After GAC	Effluent
pH	8.2 Q		
TDS (mg/L)	140		
TSS (mg/L)	<3.2 U		
TOC (mg/L)	4.6	37	2.9
Specific conductance (µS/cm)	180		

Note:
Q: Sample held beyond the accepted holding time.
U: Indicates that the compound was analyzed for but not detected. Value shown is method detection limit.

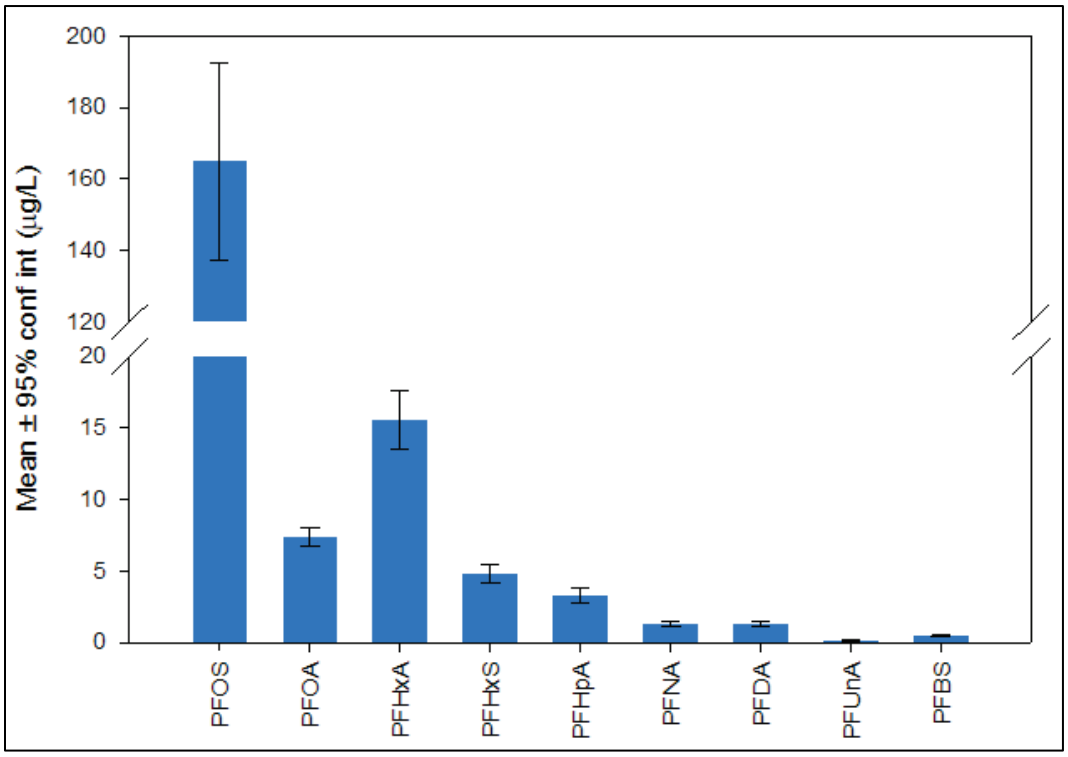
Samples of the influent (pond in table 5) were collected each day from the sample point on the PETS located just after the sediment filter, each associated by sample identification numbers I1 through I4. The results from the PFAS analyses are presented in table 6, and the mean concentrations of measurable compounds are presented graphically in figure 31. The three major constituents were PFOS, PFHxA, and PFOA, with average concentrations of 165, 17, and 7.4 µg/L, respectively. PFAS concentrations remained relatively consistent during the test. The relative standard deviation (RSD) of measurable PFAS compounds was 10% or less with the exception of PFUnA. The RSD for PFUnA was 22% and 18%, respectively. The measured values for PFUnA were very low, and with only one sample having detectable amounts.

Table 6. PFAS in influent—Hurlburt Field, demonstration 1. (All dates presented dd/mm/yy.)

Sample ID date/time	I1 11/6/19 15:25	I2 12/6/19 10:00	I3 13/6/19 14:30	I4 14/6/19 09:45
PFHxA (ηg/L)	17,000	15,000	14,000	16,000
PFHpA (ηg/L)	3,400	3,200	2,900	3,700
PFOA (ηg/L)	7,400	7,700	6,800	7,600
PFNA (ηg/L)	1,400	1,300	1,200	1,200
PFDA (ηg/L)	1,200	1,200	1,300	1,400
PFUnA (ηg/L)	<100 U	<100 U	150 I	<100 U
PFDoA (ηg/L)	<52 U	<52 U	<51 U	<51 U
PFTeA (ηg/L)	<27 U	<27 U	<27 U	<27 U
PFBS (ηg/L)	450	460	410	450
PFHxS (ηg/L)	4,900	4,700	4,300	5,300
PFOS (ηg/L)	160,000	160,000	150,000	190,000

Note:
U: Indicates that the compound was analyzed for but not detected. Value shown is method detection limit.

Figure 31. Mean influent PFAS concentrations—Hurlburt Field, demonstration 1.



Samples of the effluent were collected each day from the sample point located just after the last media tank on the PETS, each associated by sample identification numbers E1 through E4. The results are presented in

table 7. The only PFAS compound measured above 2 µg/L in the effluent was PFOS. A plot of PFOS and total PFAS concentrations in the influent and effluent are presented graphically in figure 32 and figure 33.

Table 7. PFAS in effluent—Hurlburt Field, demonstration 1. (All dates presented dd/mm/yy.)

Sample ID date/time	E1 11/6/19 16:45	E2 12/6/19 10:00	E3 13/6/19 14:40	E4 14/6/19 09:50
PFHxA (ηg/L)	<0.54 U	<0.53 U	<0.54 U	0.90 I
PFHpA (ηg/L)	<0.23 U	<0.23 U	<0.23 U	0.30 I V
PFOA (ηg/L)	<0.80 U	<0.77 U	<0.79 U	1.2 I
PFNA (ηg/L)	<0.25 U	<0.25 U	<0.25 U	<0.26 U
PFDA (ηg/L)	<0.29 U	0.55 I	0.50 I	0.89 I
PFUnA (ηg/L)	<1.0 U	<1.0 U	<1.0 U	1.1 I
PFDoA (ηg/L)	<0.52 U	0.85 I	0.82 I	1.6 I
PFTeA (ηg/L)	<0.27 U	<0.26	0.50 I V	0.46 I V
PFBS (ηg/L)	<0.19 U	<0.18 U	<0.19 U	<0.19 U
PFHxS (ηg/L)	0.54 I V	0.32 I V	0.54 I V	1.0 I V
PFOS (ηg/L)	18	28	33	62

Note:

I: The reported value is between the laboratory method detection limit and the laboratory practical quantitation limit.
U: Indicates that the compound was analyzed for but not detected. Value shown is method detection limit.
V: Indicates that the analyte was detected at or above the method detection limit in both the sample and the associated method blank and the value of 10 times the blank value was equal to or greater than the associated sample value.

Figure 32. PFOS results—Hurlburt Field, demonstration 1. Brown dashed lines are 95% confidence limits, and blue dashed line is best fit trend.

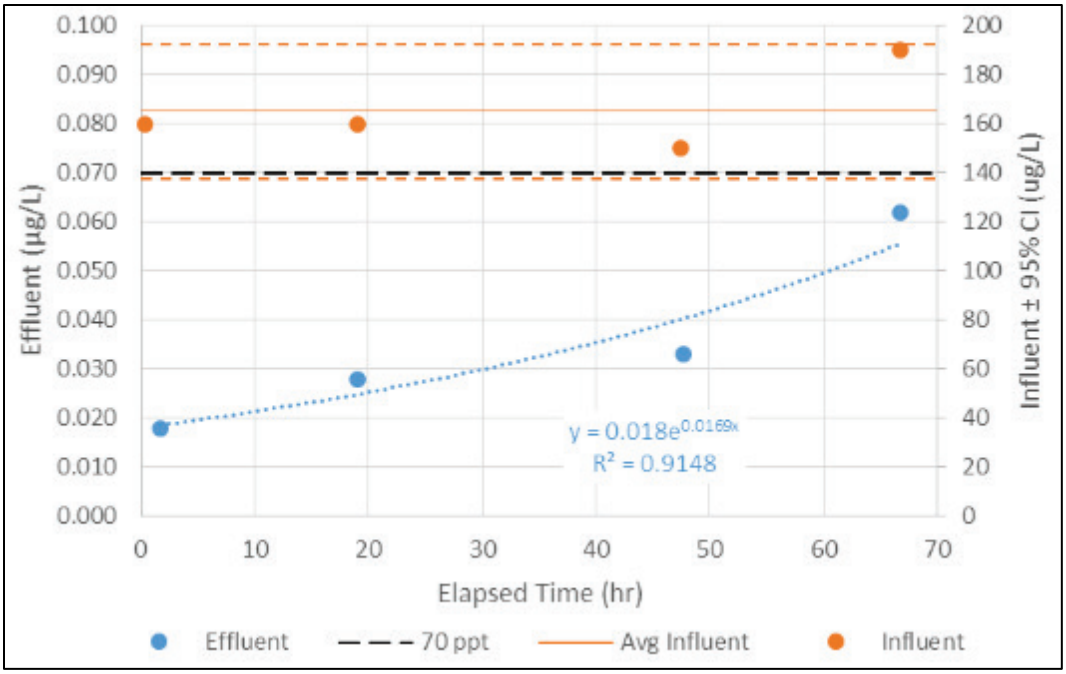
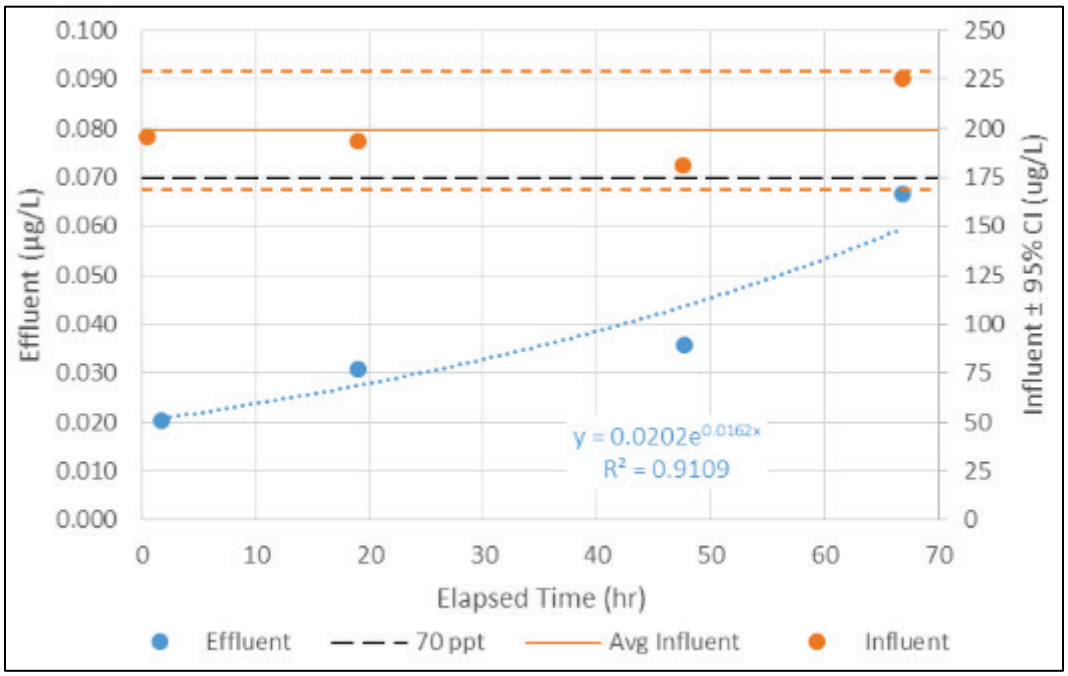


Figure 33. Total PFAS results—Hurlburt Field, demonstration 1. Brown dashed lines are 95% confidence limits and blue dashed line is best fit trend.



PFOS and total PFAS concentrations in the effluent were below the goal of 70 ng/L for all samples. Effluent PFAS concentrations did increase steadily and exhibited exponential growth, as is typically seen during the

initial stages of breakthrough in an adsorption system. The fact that PFAS concentrations broke through both media tanks and showed exponential growth at such an early stage of operation is an indication that a mass transfer zone extends across or nearly across both tanks, which means that contact times were too short. Options available to address this issue are decreasing the flow rate, adding a third tank of IX media, increasing the amount of media in the existing tanks, or some combination of these options.

It was hypothesized that the nonresponsive HMI system was the result of overheating because of direct sunlight on the enclosure. An umbrella was added over the housing to reduce heating due to direct sunlight. At the conclusion of the demonstration, the system was drained by removing the intake hose from the pond and the power disconnected. After power was reapplied, the PLC rebooted, and the HMI functioned normally.

During this demonstration the PETS was operated continuously for 67.5 h at an average flow rate of 10.7 gpm (40.5 L/min) and approximately 43,350 gal (164,097.6 L) of water were treated and returned to the pond. The results demonstrated that the PETS could be operated continuously for extended periods of time and treat relatively high concentrations of PFAS contaminated water to below the 70 ng/L treatment goal.

4.2.3 Demonstration 2

The second demonstration at the Hurlburt Field Fire Training Facility occurred between 29 July and 6 August. This demonstration sought to evaluate the use of the system while using power from the onboard generator and to determine approximate runtime on a tank of fuel. The demonstration at Naval Support Activity Mid-South was conducted between this demonstration and the first demonstration at Hurlburt Field. No exchange of media in the media tanks occurred between the first demonstration and this demonstration.

Upon returning to the site, we observed that the pond was again almost full. According to NOAA records, the area received approximately 7.92 in (20.11 cm) of precipitation since the last demonstration was completed. This level of precipitation would add approximately 147,106 gallons (556,856 L) of water to the pond. According to average monthly evaporation rates for the area (NOAA 1982), an estimated 9.91 inches (25.2 cm) of evaporation likely occurred and resulted in a loss of 35,682

gallons (135,071 L) from the pond. Combining these gives an estimated gained volume of approximately 111,400 gallons (421,694 L) of water. A photograph of the pond and placement of the suction strainer at the beginning of demonstration is provided in figure 34.

Figure 34. Pond at beginning of demonstration—Hurlburt Field, demonstration 2.

On the basis of results from the earlier demonstration in June, when the final concentration almost exceeded our goal of 70 ng/L, we decided that the flow rate for this demonstration would be reduced to 7 gpm for this test to allow a longer contact time with the media.

Three operational issues were encountered during this demonstration. The first issue was with the HMI system, and it occurred repeatedly. The HMI display would freeze during extended periods of operation. This issue did not extend to the PLC system, which continued to monitor and operate the PETS properly. However, the frozen HMI did prevent the PLC from accurately logging the total volumes of water treated by the system. Rebooting the HMI/PLC system did unfreeze the HMI, but the display would freeze again after several hours of operation.

The second issue occurred on the third day of operation, 1 August. Upon returning to the site in the morning, we discovered that the unit was not pumping. The HMI indicated that a leak was detected. The pump was restarted to determine the location of the leak. There was not a leak in the system, but it was found that the pump was drawing in air from the pond, which was interpreted as leak by the PLC, which then stopped the pump. Upon further inspection we noticed that the Dolphin strainer (see section 2.3.1) in the pond was not floating correctly because of the lowering of the pond level. To avoid a repeat of the issue, the suction strainer shown in figure 6 was used for the duration of the test.

The third issue was the failure of some PVC fittings due to repeated oscillating motion of the tubing between the pulse dampener and the sediment filters. The first failure occurred on the fourth day of operation, 2 August. Sometime before 09:00 both nipples connecting the two-way valves to the sediment filters broke off. The pump continued to run, but the system was turned off by base personnel by turning the generator off. The PVC nipples were replaced with ones made of steel, the media tanks were purged, and the system was restarted. The second failure occurred at approximately the sixth day of operation, 4 August. At approximately 23:00 one of the hose barb fittings connecting the hose to one of the two-way valves broke. This time the PLC detected the leak and stopped the pump. Both PVC hose barbs were replaced the following morning with galvanized steel fittings, the media tanks were purged, and the system was restarted.

4.2.3.1 Results and Discussion

Water samples were collected from the pond daily for basic water-quality parameters from 30 July to 2 August, each associated by sample identification numbers Pond1 through Pond4. The results are provided in table 9. All water-quality parameters were relatively stable over the course of four days, except for the pH reading on the second day. The pH reading of 4.4 is most likely an error of some kind, as it is unreasonable that the pH on a significant body of water could fluctuate down and up 4 standard pH units over the course of two days. Other than the one anomalous pH reading, all levels were within the normal range for surface fresh waters.

Table 8. Pond water quality parameters—Hurlburt Field, demonstration 2.
(All dates presented dd/mm/yy.)

Sample ID date/time	Pond1 30/07/19 14:55	Pond2 31/07/19 10:35	Pond3 01/08/19 10:55	Pond4 02/08/19 15:45
pH	8.4 HF	4.4 HF	8.4 HF	8.7 HF
TDS (mg/L)	140	130	140	130
TSS (mg/L)	<3.2 U	<3.2 U	5.0	<3.2 U
TOC (mg/L)	5.8	5.0	5.2	5.3
Specific conductance (µS/cm)	190	190	190	190

Note:
HF: Field parameter with a holding time of 15 minutes. Test performed by laboratory at client's request.
U: Indicates that the compound was analyzed for but not detected. Value shown is method detection limit.

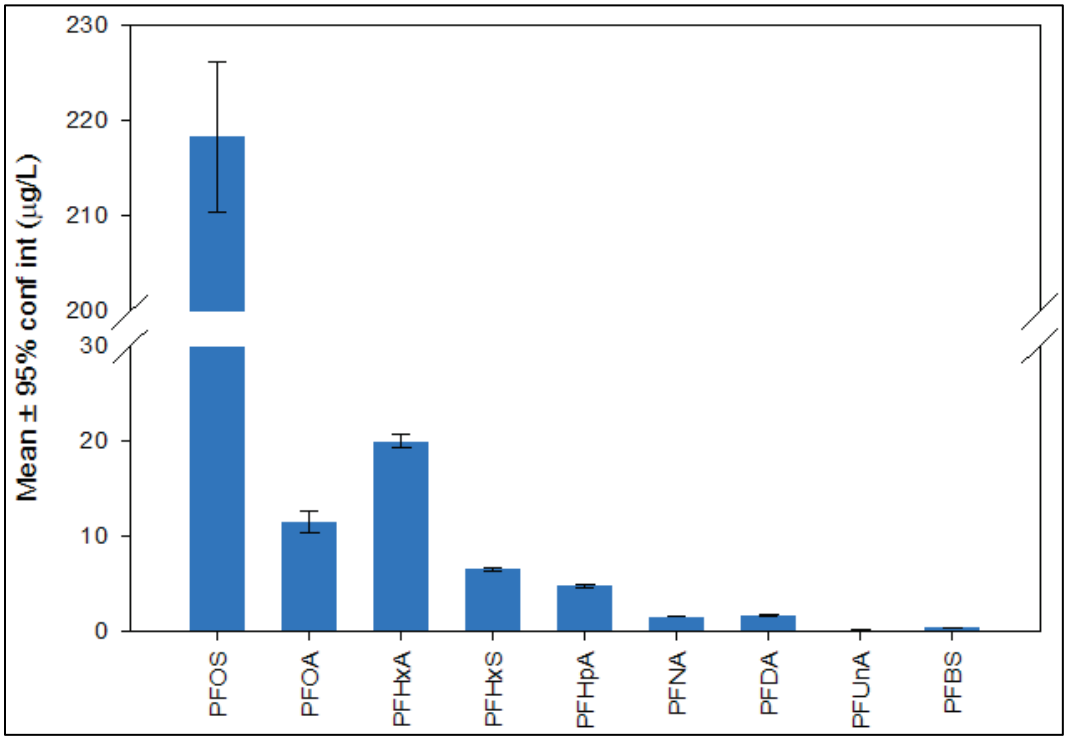
Samples of the influent were collected each day from the sample point on the PETS located just after the sediment filter, and the results are presented in table 10. Six influent samples were collected over the testing period, each associated by sample identification numbers I1 through I6. The mean concentrations of measurable compounds are presented graphically in figure 35. The three major constituents were PFOS, PFHxA, and PFOA with average concentrations of 220, 20, and 10 µg/L, respectively. PFAS concentrations were relatively consistent during the test. The relative standard deviation (RSD) of measurable PFAS compounds was 5% or less with the exception of PFOA and PFUnA. The RSD for PFOA and PFUnA were 9% and 18%, respectively. The measured values for PFUnA were very low, and most were below the practical quantitation limit.

Table 9. PFAS in influent—Hurlburt Field, demonstration 2. (All dates presented dd/mm/yy.)

Sample ID date/time	I1 30/07/19 14:55	I2 31/07/19 13:00	I3 01/08/19 11:10	I4 02/08/19 15:35	I5 03/08/19 19:10	I6 04/08/19 17:27
PFHxA (ng/L)	20,000	20,000	20,000	19,000	20,000	21,000
PFHpA (ng/L)	4,700	4,600	4,900	4,900	4,900	4,900
PFOA (ng/L)	10,000	13,000	12,000	12,000	11,000	11,000
PFNA (ng/L)	1,700	1,700	1,700	1,600	1,600	1,500
PFDA (ng/L)	1,700	1,700	1,900	1,800	1,800	1,800
PFUnA (ng/L)	110 I	170	160 I	160 I	200	170
PFDoA (ng/L)	<49 U	<47 U	<48 U	<48 U	<47 U	<47 U
PFTeA (ng/L)	<26 U	<25 U	<25 U	<26 U	<25 U	<25 U
PFBS (ng/L)	460	440	450	460	480	470
PFHxS (ng/L)	6,300	6,800	6,600	6,800	6,500	6,300
PFOS (ng/L)	220,000	220,000	220,000	230,000	210,000	210,000

Note:
I: The reported value is between the laboratory method detection limit and the laboratory practical quantitation limit.
U: Indicates that the compound was analyzed for but not detected. Value shown is method detection limit.

Figure 35. Mean influent PFAS concentrations—Hurlburt Field, demonstration 2.



Samples of the effluent were collected each day from the sample point located just after the last media tank on the PETS, each associated by sample identification numbers E1 through E6. The results are presented in table 11. The only PFAS compound measured above 3 µg/L in the effluent was PFOS. A plot of PFOS and total PFAS concentrations in the influent and effluent are presented graphically in figure 36 and figure 37.

Table 10. PFAS in effluent—Hurlburt Field, demonstration 2. (All dates presented dd/mm/yy.)

Sample ID date/time	E2 31/07/19 13:10	E3 01/08/19 11:20	E4 02/08/19 15:25	E5 03/08/19 19:15	E6 04/08/19 17:26
PFHxA (ηg/L)	0.70 I	1.3 I	1.2 I	0.97 I	0.88 I
PFHpA (ηg/L)	0.22 I	0.33 I	0.29 I	0.24 I	0.23 I
PFOA (ηg/L)	0.75 I	1.0 I	0.79 I	0.93 I	0.92 I
PFNA (ηg/L)	<0.23 U	0.35 I	<024 U	0.49 I	0.43 I
PFDA (ηg/L)	1.1 I	1.4 I	1.0 I	2.3	2.4
PFUnA (ηg/L)	1.0 I	1.8	1.4 I	2.2	2.7
PFDoA (ηg/L)	1.8	2.2	2.9	2.9	3.0
PFTeA (ηg/L)	0.45 I	0.52 I	0.56 I	<0.27 U	0.96 I
PFBS (ηg/L)	<0.17 U	<0.17 U	<0.18 U	<0.19 U	<0.18 U
PFHxS (ηg/L)	0.42 I V	0.67 I V	0.49 I V	0.54 I V	0.44 I V
PFOS (ηg/L)	35	140	47	55	49

Note:

I: The reported value is between the laboratory method detection limit and the laboratory practical quantitation limit.

U: Indicates that the compound was analyzed for but not detected. Value shown is method detection limit.

V: Indicates that the analyte was detected at or above the method detection limit in both the sample and the associated method blank and the value of 10 times the blank value was equal to or greater than the associated sample value.

Figure 36. PFOS concentrations—Hurlburt Field, demonstration 2. Brown dashed lines are 95% confidence limits.

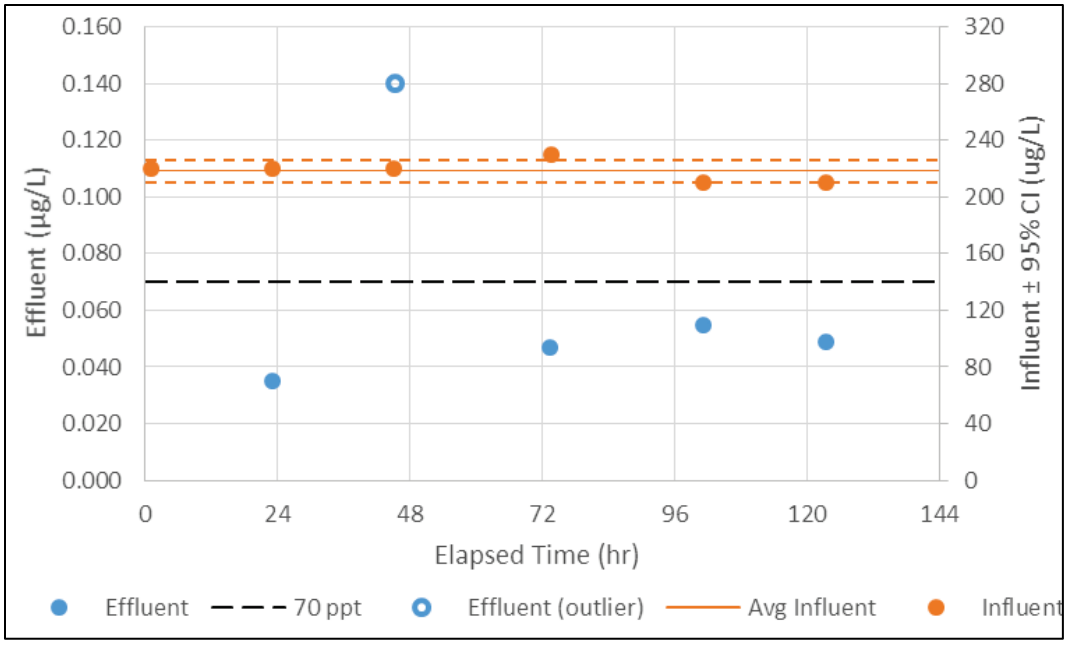
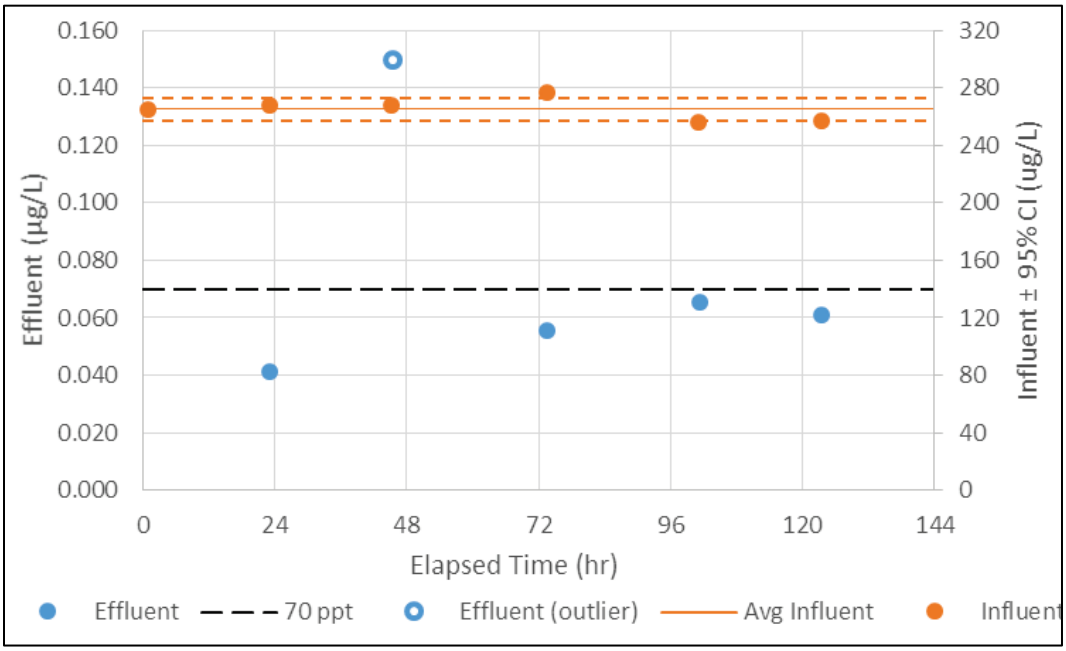


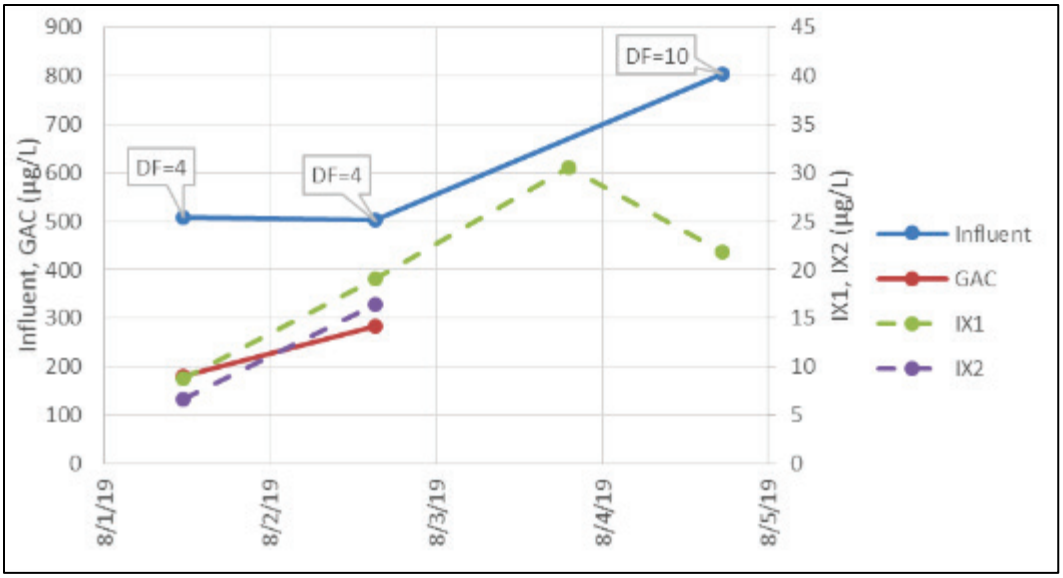
Figure 37. Total PFAS concentrations—Hurlburt Field, demonstration 2. Brown dashed lines are 95% confidence limits.



PFOS and total PFAS concentrations in the effluent were below the goal of 70 ng/L for four of the five samples (the exception being the one collected on 1 August 2019, which was 140 and 150 ng/L for PFOS and total PFAS, respectively). The sample on 1 August was collected after the system was restarted following an intake of air into the system. The high PFAS levels were therefore likely a result of short-circuiting due to entrained air in the media. PFAS concentrations returned to below the 70 ng/L goal again by the following day, but PFAS concentrations did continue to increase and were approaching the 70 ng/L treatment goal by the end of the demonstration.

Samples were collected from multiple points in the system and analyzed for PFAS with the adapted MBAS method described previously in section 4.1.2 (figure 38 for results). The results did show a positive correlation to results obtained from the EPA method; however, the absolute values were off significantly. The values for the influent, which should have remained consistent, were affected by the level of dilution of the methanol extract, which is shown on the graph, before use in the Hach method tubes. This inconsistency is a sign that PFAS concentrations of the diluted sample placed in the tube are beyond the range of the linear calibration curve. This field method holds promise for use in monitoring breakthrough in adsorption columns, but significant development remains to be done to make this technique a viable qualitative field method.

Figure 38. Adapted MBAS method results. Influent was collected just before the GAC column.



The PETS was operated for a total of approximately 130 h and treated approximately 67,000 gallons (253,622 L) of water. The generator was run for approximately 67 h and shut off with an estimated 1/8 tank of fuel remaining. This run time indicates that the system should be able to operate three days continuously on a full tank of fuel. The pond level was significantly lowered. Figure 39 shows the pond near the end of the demonstration.

Figure 39. Pond at end of demonstration—Hurlburt Field, demonstration 2.

This demonstration revealed three issues with the PETS needing attention. The first issue was with fittings on the PETS between the pump and the sediment filters breaking. The fittings and possibly the valves need to be made of a stronger material than PVC, such as steel or brass. The tubing in the same location also needs be secured to an immovable object to stop the repeated stress on the fittings. Another possible remedy is to add a pressure relief valve to reroute high pressure pulses of water back to the pump intake.

The second and third issues with the PETS have to do with the HMI/PLC control system. Although the repeated freezing of the HMI screen did not affect the operation and performance of the PETS, it did prevent accurate monitoring of the system during operation. The failure of the PLC to detect the complete rupture of the flow when both nipples broke off of the sediment filter housings illustrated that additional code needs to be added to detect a sudden and complete loss of flow into the system.

Finally, encountering heavy sediment loads near the bottom of the pond required frequent changes of the sediment filters. The current suction screens are designed to exclude particulates several millimeters in diameter. The system may require a high surface–area box covered with a geotextile material to completely drain water bodies with high sediment loads in the bottom.

This project evaluated the PETS system, so the processes in the pond itself were outside of the range of the project. However, in looking over the photograph in figure 39, the image shows that the retention pond was a complex environment. Studying other retention ponds in the future would increase understanding of the distribution of the PFAS in a pond environment. We also recommend studying the algae to explore whether they preferentially take up PFAS and the sediment to explore whether this environment was a PFAS sink. Finally, analyzing the liner material for concentrated PFAS would also prove interesting.

4.2.4 Demonstration 3

The third and final demonstration at the Hurlburt Field Fire Training Facility occurred 26–31 August 2019. Operation of the system began on 27 August and concluded on the 31 August 2019. The primary objective of this third demonstration was to evaluate durability improvements made to the PETS during extended operation. The secondary goal was to draw the water level down as low as possible to allow Hurlburt Field to clean the detritus out of the pond. A limited number of samples were collected for PFAS analysis during this demonstration, one influent and two effluents.

Upon returning to the site, we observed that the pond appeared to be about half full. According to NOAA records, the area received approximately 2.50 in (6.35 cm) of precipitation since the last demonstration. The precipitation added approximately 46,435 gallons (175,775 L) of water to the pond. The volume of water lost to evaporation is estimated to be 14,742 gal (55,804 L). It is also estimated that 1.04 in (2.74 cm) of rain and 0.98 in (2.49 cm) of evaporation occurred during the demonstration, which added approximately another 15,800 gallons (59,810 L) of water. This sum gives an estimated gained volume of approximately 47,500 gallons (179,807 L) of water.

We made a few changes to the PETS before this demonstration. The media in the GAC and IX1 tanks were exchanged for fresh media. The order of

flow through the IX tanks was changed to IX2 followed by IX1. The hose between the pulse dampener and sediment filters was secured to the trailer railing to reduce movement of the hose due to pulsations from the pump. An additional algorithm was added to the PLC programming to detect a rupture in the flow path. This algorithm calculated the flow according to the speed of the pump and compared it to the flow meter readings. Unfortunately, this algorithm continued to produce an error and stopped the pump. In order to proceed with the demonstration, the PETS had to be operated in a manual mode, which did not cause any operational issues.

An issue did occur with the pump. It was discovered that the pump was leaking lubricant from the gear box. The source of the leak was determined, and the remaining lubricant was drained from the gear box and replaced with an oil meeting the specifications of the manufacturer.

4.2.4.1 Results and Discussion

Water samples were collected from the pond toward the end of the demonstration on 30 August at approximately 08:15 for basic water-quality parameters. The results are provided in table 11. All levels were within the normal range for surface fresh waters.

Table 11. Pond water quality parameters—Hurlburt Field, demonstration 3.

Sample ID	Pond
pH	8.0 Q
TDS (mg/L)	140
TSS (mg/L)	4.0 I
TOC (mg/L)	6.1
Specific Conductance (µS/cm)	140

Note:
Q: Sample held beyond the accepted holding time.
I: The reported value is between the laboratory method detection limit and the laboratory practical quantitation limit.

One sample of the influent was collected for PFAS analysis on the second day of operation from the sample point on the PETS located just after the sediment filter, and the results are presented in table 12. The concentrations of measurable compounds are also presented graphically in figure 40. The three major constituents were PFOS, PFHxA, and PFOA, with average concentrations of 120, 14, and 6.3 µg/L, respectively. PFAS

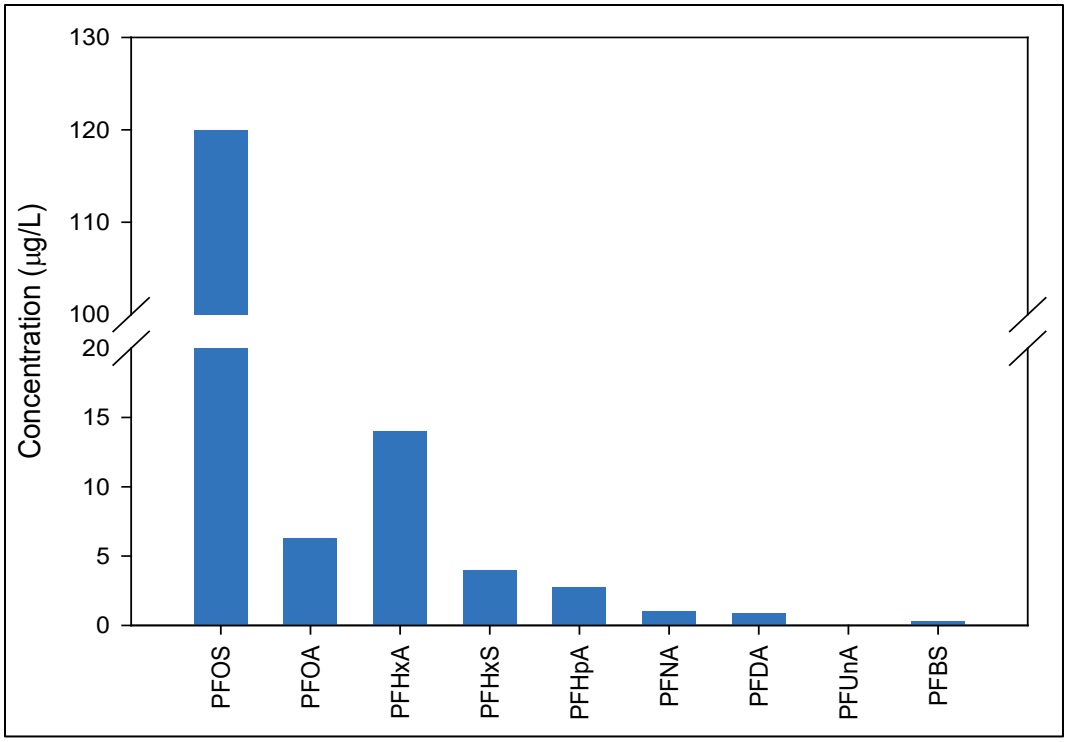
concentrations remained relatively consistent during the test. The relative standard deviation (RSD) of measurable PFAS compounds was 5% or less, with the exception of PFOA and PFUnA. The RSD for PFOA and PFUnA were 9% and 18%, respectively. The measured values for PFUnA were very low, and most were below the practical quantitation limit.

Table 12. PFAS in influent—Hurlburt Field, demonstration 3.
(All dates presented dd/mm/yy.)

Sample ID Date/Time	I1 28/08/19 08:15
PFHxA (ηg/L)	14,000
PFHpA (ηg/L)	2,800
PFOA (ηg/L)	6,300
PFNA (ηg/L)	1,000
PFDA (ηg/L)	890
PFUnA (ηg/L)	11 I
PFDoA (ηg/L)	<5.1 U
PFTeA (ηg/L)	<2.7 U
PFBS (ηg/L)	290
PFHxS (ηg/L)	4,000
PFOS (ηg/L)	120,000

Note:
I: The reported value is between the laboratory method detection limit and the laboratory practical quantitation limit.

Figure 40. Influent PFAS concentrations—Hurlburt Field, demonstration 3.



Samples of the effluent were collected each day from the sample point located just after the last media tank on the PETS, and the results are presented in table 13. The only PFAS compound measured above 3 µg/L in the effluent was PFOS. A plot of PFOS and total PFAS concentrations in the influent and effluent are presented graphically in figure 41 and figure 42.

Table 13. PFAS in effluent—Hurlburt Field, demonstration 3.
(All dates presented dd/mm/yy.)

Sample ID date/time	E1 28/08/19 8:15	E2 30/08/19 12:30
PFHxA (ηg/L)	14	13
PFHpA (ηg/L)	1.4 I	1.1 I
PFOA (ηg/L)	2.1	1.6 I
PFNA (ηg/L)	0.54 I	0.31 I
PFDA (ηg/L)	1.6 I	1.0 I
PFUnA (ηg/L)	1,3 I	1.3 I
PFDoA (ηg/L)	1,7 I	1.8 I
PFTeA (ηg/L)	1.2 I J	0.91 I
PFBS (ηg/L)	<0.19 U	<0.19 U
PFHxS (ηg/L)	0.77 I V	0.52 I V
PFOS (ηg/L)	85	48

Note:
I: The reported value is between the laboratory method detection limit and the laboratory practical quantitation limit.
J: Estimated value; value may not be accurate.
U: Indicates that the compound was analyzed for but not detected. Value shown is method detection limit.
V: Indicates that the analyte was detected at or above the method detection limit in both the sample and the associated method blank and the value of 10 times the blank value was equal to or greater than the associated sample value.

Figure 41. PFOS concentrations—Hurlburt Field, demonstration 3.
Blue dashed line is best fit trend.

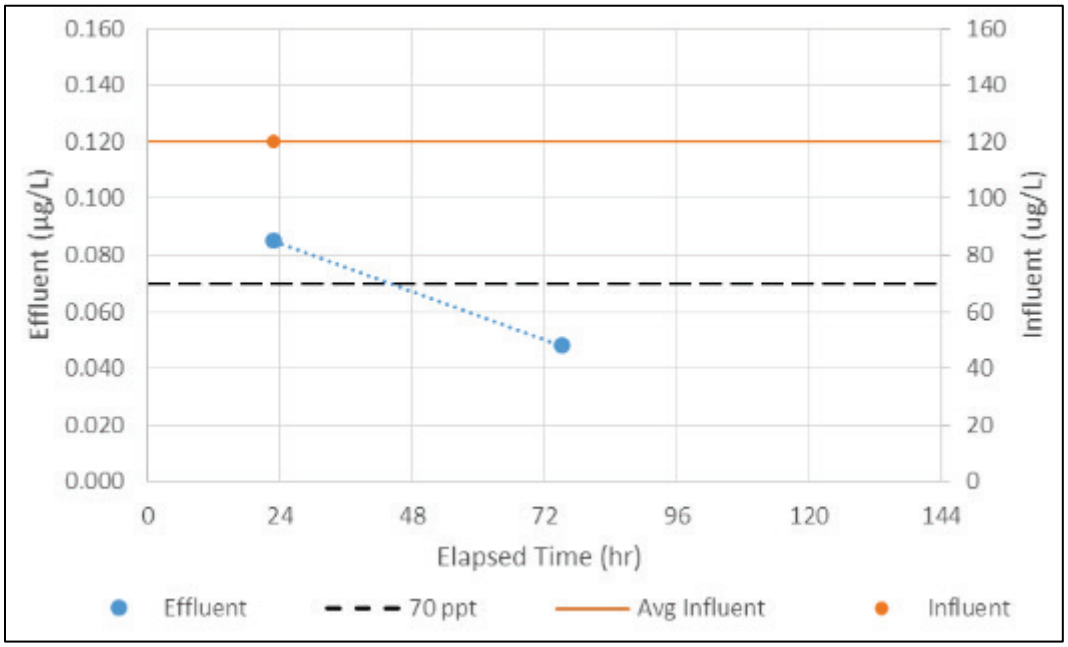
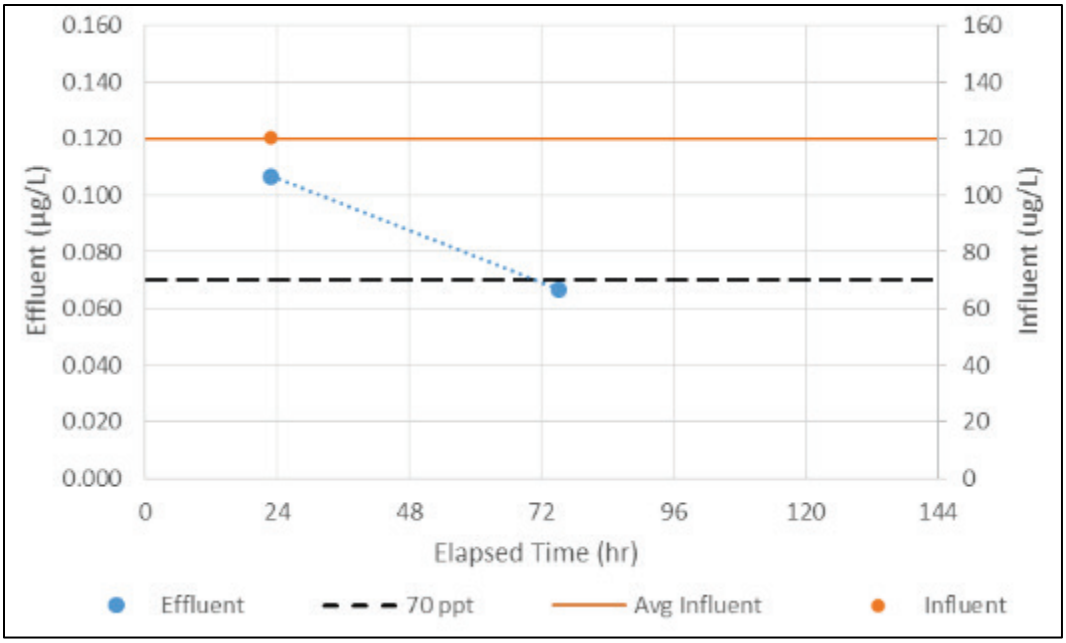


Figure 42. Total PFAS concentrations—Hurlburt Field, demonstration 3.
Blue dashed line is best fit trend.



The initial effluent sample collected after approximately one day of operation exceeded our goal of 70 ng/L, and the second sample collected after approximately three days of operation was below our treatment goal. An obvious reason for the high result of the first sample could not be determined. A sediment filter replacement was conducted about 10 min before the sample was collected. It is possible that some air was entrained in the media and caused short-circuiting of the media.

The PETS was operational for about 93 h at an average flow rate of approximately 7 gpm (26.5 L/min). In all, 39,200 gal (148,388 L) of water were treated by the end of the demonstration. The issue of the HMI screen freezing did not occur during this demonstration with the system operating in manual mode. Other than the pump requiring gearbox oil and several changes of sediment filters, no other significant issues occurred.

Several drums of detritus, primarily algae and pine needles, were removed from the pond. After the drums were filled, detritus was raked up onto the liner to dry. Base personnel created a screened box to filter out sediment, intended to allow us to further drain the pond (figure 43), but unfortunately, the screen material did not remove enough of the fine sediment to succeed. The box was useful for draining the detritus: it was filled to capacity and left on the pond liner above the waterline to dry (figure 44). Figure 45 shows the pond at the completion of the demonstration.

Figure 43. Screened box for sediment filtering.

Figure 44. Filled sediment filtering box at end of demonstration 3.

Figure 45. Pond at end of demonstration—Hurlburt Field, demonstration 3.

The final disposition of the collection pond was not a goal of this project. However, after discussing the issue with Hurlburt staff, we planned to pump out the sludge material for staff to dispose of it, presumably by incineration. Then, the pond was to be retired. The site had not used PFAS-containing foams for a couple of years, so they were hopeful that PFAS accumulation would be below levels requiring management.

4.3 NAS Mid-South Site and Demonstration

4.3.1 Site Description

NAS Mid-South (formerly NAS Millington) is located in Millington, Tennessee, and is a BRAC facility. The former station conducted flight and training operations. Our demonstration was conducted at a waste storage area located on the base, which is shown in the background of figure 46.

Figure 46. NAS Mid-South waste storage area.

4.3.2 Demonstration

One demonstration was conducted at Naval Support Activity Mid-South (NSA Mid-South) on 18 July 2019. This demonstration occurred between the first and second demonstrations at Hurlburt Field. No exchange of media occurred between the first demonstration at Hurlburt Field and this demonstration. There were three objectives for this demonstration:

- road test of the PETS trailer with the generator loaded onto it
- evaluation of the PETS running under generator power
- demonstration of the efficacy of PETS for treating small quantities of PFAS-contaminated water

The water containing PFAS to be treated was in a total of five containers, shown in figure 47. From left to right in the photograph, we identified the containers 200G-IN, 250G-IN, Drum#1-IN, and Drum#2-IN. The blue drum on the front of the trailer appeared to be empty.

Figure 47. Containers of investigative derived waste (IDW).

Because of the small volume of water to be treated, the PETS was operated in manual mode, and the flow rate was set at 5 gpm (18.9 L/min). Once the system was pulled onto the site, setup required about 10 min. Because it requires about 100 gal (378 L) to fill the hoses and media tanks on the PETS, filling and purging the media tanks required about 20 min.

The tank identified as 250G-IN was treated first, and the treated water was placed in a similar 250 gal (946 L) tote, which we identified as 250G-OUT #1. This tote was provided by base personnel, who indicated that the tote had been rinsed and was clean. After emptying 250G-IN, we began treatment of 200G-IN. 250G-IN was relabeled as 250G-OUT #2 and was rinsed several times with treated water. Each batch of rinse water was retreated. When 250G-OUT #1 became full, treated water was then placed in 250G-OUT #2. After treatment of 200G-IN was complete, DRUM#1 and DRUM#2 were treated in order. Following treatment of all containers, air was pumped through the system, which drained the water from the PETS into 250G-OUT #2.

The suction hose was placed in the containers without a suction screen connected so that it fit inside all the containers. Container 250G-IN had an unanticipated layer of sludge in the bottom of the tank, which almost immediately plugged the sediment filters and necessitated a filter change. After that incident, care was taken to keep the end of the hose just below the surface of the water until the sludge blanket was reached.

4.3.3 Results and Discussion

Water-quality samples were collected from each of the containers and are presented in table 14. The water was not mixed in the containers prior to sampling, so the analysis is indicative of the well-settled water. The containers showed significant variations in water quality, but none of the parameters was extreme. Both 250G-IN and 200G-IN were translucent containers and contained a large amount of algae. Since these waters were collected from different groundwater sampling events, it is not surprising that variations occurred in some of the water-quality parameters.

Table 14. Water-quality parameters—NSA Mid-South demonstration.
(All dates presented dd/mm/yy.)

Sample ID date/time	250G-IN 18/07/19 09:55	200G-IN 18/07/19 10:35	DRUM#1-IN 18/07/19 11:52	DRUM#2-IN 18/07/19 12:07	250G-OUT #1 18/07/19 11:00	250G-OUT #2 18/07/19 12:30
pH	10.6 HF	9.4 HF	8.2 HF	7.8 HF	7.5 HF	8.0 HF
TDS (mg/L)	180	160	260	300	210	210
TSS (mg/L)	<3.2 U	7.0	17	370	<3.2 U	8.0
TOC (mg/L)	8.8	7.6	1.7	4.7	4.5	1.8
Specific conductance (µS/cm)	290	220	370	410	220	250

Note:
HF: Field parameter with a holding time of 15 minutes. Test performed by laboratory at client's request.
U: Indicates that the compound was analyzed for but not detected. Value shown is method detection limit.

Samples from each of the containers were collected and analyzed for PFAS compound. The results are presented in table 15. The four major constituents found in all containers were PFOS, PFHxS, PFHxA, and PFOA.

Table 15. PFAS in influent—NSA- Mid-South demonstration.
(All dates presented dd/mm/yy.)

Sample ID date/time	250G-IN 18/07/19 09:55	200G-IN 18/07/19 10:35	DRUM #1-IN 18/07/19 11:52	DRUM #2-IN 18/07/19 12:07
PFHxA (ηg/L)	530	160	300	360
PFHpA (ηg/L)	110	42	110	140
PFOA (ηg/L)	230	120	160	180
PFNA (ηg/L)	14	8.1	20	19
PFDA (ηg/L)	6.1	3.1	0.20	0.96 J
PFUnA (ηg/L)	2.1 I	<1.1 U	<1.0 U	<1.1 U
PFDoA (ηg/L)	<0.53 U	<0.54 U	<0.52 U	<0.53 U
PFTeA (ηg/L)	<0.28 U	<0.28 U	<0.28 U	<0.28 U
PFBS (ηg/L)	190	75	150	170
PFHxS (ηg/L)	1,700 B	690 B	1.800 B	2,000 B
PFOS (ηg/L)	5,000	1,500	2,400	2,200

Note:
B: Compound was found in the blank and sample.
I: Value is EMPC (estimated maximum possible concentration).
J: Result is less than RL but greater than or equal to MDL and the concentration is an approximate value.
U: Indicates the analyte was analyzed for but not detected.

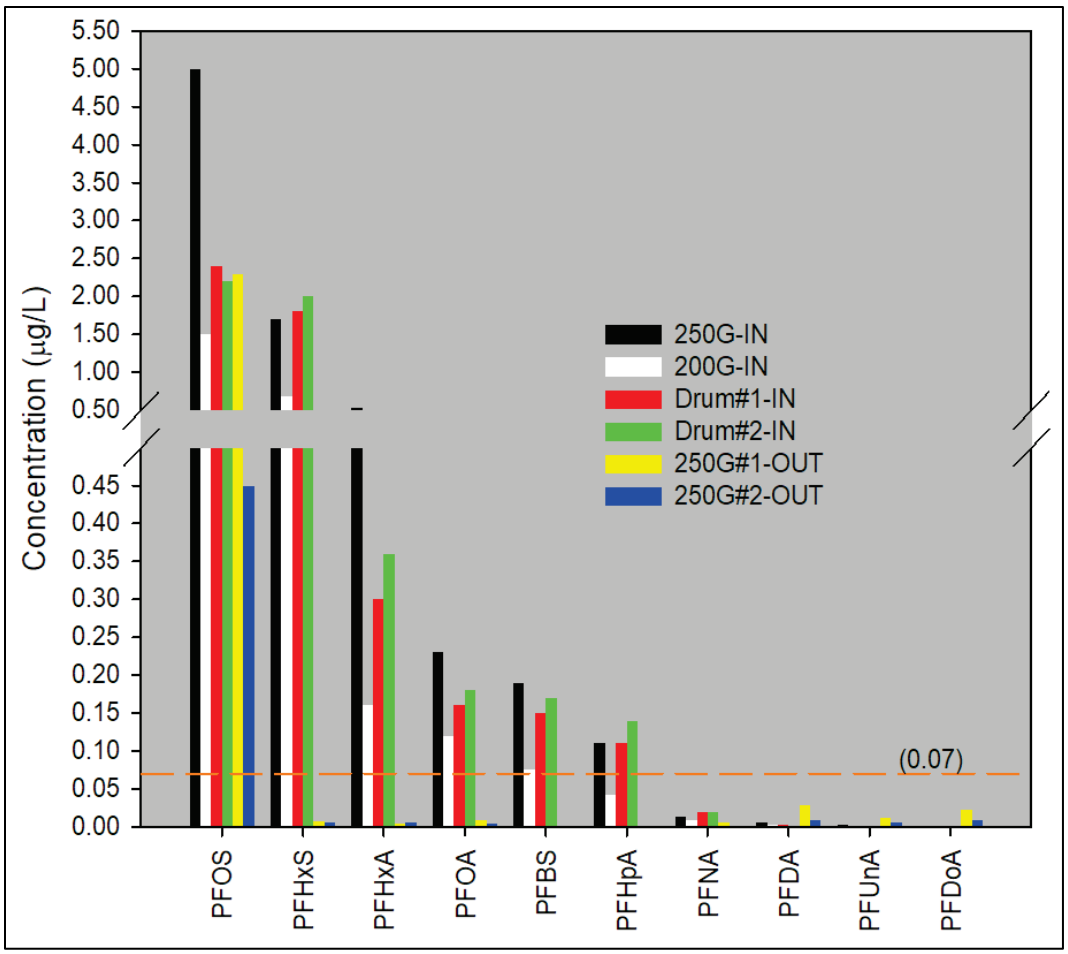
Samples were also collected from both of the effluent containers after they were filled, and the results are presented in table 16. A graphical comparison of influent and effluent concentration of PFOS and total PFAS are presented in figure 48.

Table 16. PFAS in effluent—NSA Mid-South demonstration.
(All dates presented dd/mm/yy.)

Sample ID date/time	250G #1 18/07/19 11:00	250G #2 18/07/19 12:30
PFHxA (ηg/L)	3.9	6.3
PFHpA (ηg/L)	1.8	1.3
PFOA (ηg/L)	9.0	4.3
PFNA (ηg/L)	6.3	1.3 J
PFDA (ηg/L)	29	8.0
PFUnA (ηg/L)	12	5.5
PFDoA (ηg/L)	22	8.1
PFTriA (ηg/L)	1.2 J	<1.2 U
PFTeA (ηg/L)	3.0	<0.27 U
PFBS (ηg/L)	<0.19 U	0.49 J
PFHxS (ηg/L)	7.0 B	5.2 B
PFOS (ηg/L)	2,300	450

Note:
B: Compound was found in the blank and sample.
J: Result is less than RL but greater than or equal to MDL and the concentration is an approximate value.
U: Indicates the analyte was analyzed for but not detected.

Figure 48. PFAS results—NSA Mid-South demonstration.



The results showed that the system failed to meet the treatment goal of 70 ng/L for PFOS. Two likely explanations are possible and likely for these results: rollover (stripping of previously adsorbed or exchanged contamination) or contaminated containers used to store the treated water.

The first explanation is rollover, likely caused by a change in water quality between the Hurlburt Field demonstration site and the IDW at this site. The media was not changed out between the two demonstrations, and the PFAS concentrations at Hurlburt were 25 times higher than this site. The significantly higher pH in this water, approximately two pH units, is the water-quality parameter that appears most likely to be a cause of rollover. Two pieces of evidence support this theory. First, the concentrations in the first container filled with treated water were higher for all measurable compounds than the container filled second. Second, the concentrations of a few compounds are higher in the effluent than the influent.

The second explanation is that the containers used to store the effluent were previously used to store PFAS-contaminated water. Although the containers were rinsed well, they were not tested to confirm that they were free of PFAS compounds. While this may have contributed to the PFAS levels in the effluent, it is very unlikely to be the cause of the high levels that were measured.

The PETS pulled and rode well with the generator mounted on the trailer. The demonstration was conducted running under power from the generator, and approximately 500 gal of water was treated at a flow rate of approximately 5 gpm. The entire demonstration, excluding shipment of samples, was completed in a little over two hours, which included setting up and repacking the system.

5 Conclusions

On the basis of these demonstrations, the PETS proved effective as a mobile treatment system for PFAS-contaminated waters to below 70 ng/L total PFAS and was towed more than 2,500 mi (~4,000 km) with a heavy-duty pickup truck. The system demonstrated the capability to be operated off of line power or continuously for 72 h using the onboard generator and a full tank of fuel. The system requires approximately 10 min to set up and can be completely operational and producing treated effluent in 30 min.

Over the course of the three demonstrations at Hurlburt Field, the PETS successfully treated 150,000 gal (~570,000 liters) of PFAS-contaminated water and operated over 290 h. These totals were accomplished with 15 ft^3 (425 L)of GAC and IX media, which resulted in a greater than 1,300:1 volume reduction of waste requiring disposal. Total PFAS concentrations in the influent ranging 149–277 µg/L were treated to below the goal of 70 ng/L except for one anomalous result.

The PETS demonstration at the small-volume NSA Mid-South site did not meet the 70 ng/L goal. The failure most likely resulted from rollover of PFAS loaded on the media during the initial demonstration at Hurlburt Field. This rollover was likely caused by the significantly higher pH in the first two vessels treated at NSA Mid-South. This demonstration highlighted the need to use fresh media when changing sites, particularly if the water-quality parameters differ significantly. This result also highlights the need for the addition of a small-tank design for smaller sites, since small volumes of water do not warrant the use and disposal of 9 ft^3 of media.

5.1 Return on Investment

A cost estimate and ratio of treatment costs were calculated using information gained through the three demonstrations at Hurlburt Field. Few options exist for disposing of PFAS-contaminated water. In this case, the water cannot be left in place indefinitely, because it would eventually overflow and contaminate the environment. The water could not be discharged directly into the wastewater treatment plant, because the treatment processes do not effectively treat PFAS. The water could not be safely landfilled or similarly disposed of, because current regulations do not allow these forms of management. Therefore, the current management

option would be to pump out the pond, containerize the wastes, and incinerate the water, destroying the PFAS in the process. So, our comparison was based on incineration as the option. Some basic assumptions were made in the estimate:

- PETS will be operated 24 h per day
- two operators are used, working 8 h per day
- power will be drawn from the generator
- the unit cost of incineration of media and water is the same (costs have been quoted as $3.80/gal, $4.00/gal, and in Okinawa, $10.00/gal)
- the flow rate will be limited to 7 gpm
- 150,000 gal of water will be treated continuously in one deployment

Figure 49. Cost estimates and ratio of treatment costs.

Assumptions		
Waste Incineration (including shipping)	$ 3.80	per gallon
Mobilization/Demobilization Time	2	days
Work day	8	hrs/day
Labor (2 person team, fully burdened)	$ 200.00	per hour
Time to Operate PETS/pumpout to drums	2	
Volume of contaminated water	150,000	Gallons
Volume of media/tank	3.5	cu ft/vessel
Number of medial tanks	3	vessels
Flow rate	7.0	gpm
Fuel consumption rate (PETS)	0.560	gph
Fuel consumption rate (towing)	10	mpg
Roundtrip travel distance	662	miles
Diesel	$ 2.50	per gallon
PETS operational time	357	hours
Time on site	15	days

	PETS	Incineration
Onsite labor	$ 27,200.00	$ 16,000.00
Tranporation Fuel Cost	$ 165.50	
PETS Fuel Cost	$ 500.00	
Incineration Costs	$ 298.45	$570,000.00
Total Costs	$ 28,163.95	$586,000.00

Ratio of Treatment Costs	20.81

The calculation shows that treatment costs of PFAS-contaminated water at small sites can be reduced by a factor of about 20 when compared to incineration of the collected water, the other proposed solution for Hurlburt Field. The cost to procure a mobile treatment system based on the PETS design is approximately $120,000. Assuming four sites of similar size to Hurlburt Field would be treated in a regional area on an annual basis and a five-year operational life for all major system components, the return on investment would be almost 100 to 1.

5.2 Small Flow Design

We designed the PETS to allow racks with different-sized media tanks to be used on the system, with the goal of tailoring the amount of media used to the volume of water to be treated. Tanks on the PETS are mounted on a detachable rack, which is attached to the trailer with four bolts through the base of the rack. Plumbing to and from the tanks is connected through two hoses with quick-release fittings, and all electrical connections to the racks are connected through one cable. This setup allows the rack of tanks to be swapped out in about one hour for another rack having the same footprint with the use of an overhead crane or a large forklift. Corresponding programming for a tank rack can be uploaded to the HMI/PLC system in a couple of minutes.

Originally, we intended to use a small tank design for small sites such as the IDW at NSA Mid-South. Unfortunately, due to constraints of time, scheduling, and funding, the small-tank rack system was not completed before this demonstration. However, development of this design has continued, and a demonstration has been planned. Figure 50 shows the small-tank rack under development.

Figure 50. PETS small-tank development.

6 Recommendations

6.1 Redesign of Large Tank Configuration

On the basis of the results from the demonstrations, breakthrough of PFAS started soon after operations began. This breakthrough indicates that residence times in the IX resin were too short. The tanks currently used are about 16 in in diameter and are only about half full with media and a bedding material of gravel. This extra space allows for room for expansion of the media during backwash operations. However, if the source water has relatively low sediment and organic matter, there would not be any reason to backwash single-use adsorptive media. The bed volume of media in these tanks can be safely increased from 3.5 to 5 ft^3 of media, which would increase the total bed volume of the ion exchange resin from 7 to 10 ft^3.

If media tanks 14 in in diameter and the same height as the current tanks were used, four tanks could replace the current three tanks in the same location on the trailer. Up to 4.25 ft^3 of media could be placed in each of these tanks, which would increase the total bed volume of the IX resin from 7 to 12.75 ft^3. This modification would improve the system performance the most, but it would also require a more complicated valve nest to rotate the order of flow between the three tanks as media is replaced.

6.2 Continuous or onsite monitoring of PFAS

A method of monitoring breakthrough of PFAS concentrations is a significant need to operate a mobile system on small sites. When planning to design and operate large static treatment systems for long-term operation and very large quantities of water, conducting laboratory column tests with site water to develop breakthrough curves is easily justified. These breakthrough curves allow the operator to predict with confidence when breakthrough of PFAS compounds will reach established limits. However, on small sites the cost of conducting these laboratory tests can be relatively expensive because of analytical costs and the time required. This higher relative cost makes development of a field-expedient qualitative method of great value.

The colorimetric field method used in this study for qualitative PFAS concentrations holds promise for use in monitoring breakthrough in adsorption columns, but significant development remains to make this technique a viable qualitative field method. Developmental work needed includes calibration curves, effect of methanol concentrations on the results when diluting samples and determining other water-quality parameters that may affect results. This or an alternative field technique should be developed.

6.3 Improved Operating System

The system was operated and monitored by an inexpensive screen HMI-PLC device (figure 10). When properly functioning, this system proved an inexpensive means for providing simple control of the system while also providing effective monitoring of flow and operating pressures. However, in two of the demonstrations (demo 1 and 2 at Hurlburt Field), the HMI-PLC froze. The PETS was able to maintain operation, but operation could not be conducted from the HMI-PLC and it was not able to monitor the system. The HMI-PLC returned to functionality once the system was shut down.

We hypothesize the reason for the system freeze was excessive heat. However, our effort to address this suspected cause using an umbrella was not effective. An upgrade to the HMI-PLC to a more heat-resistant system would be worthwhile.

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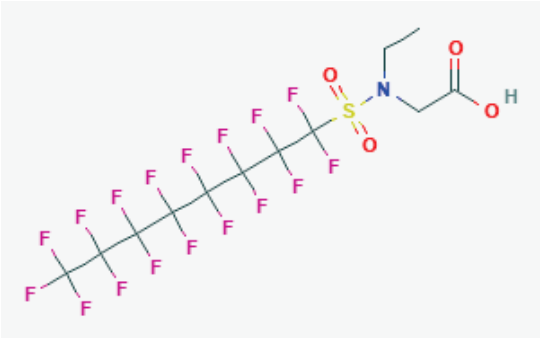
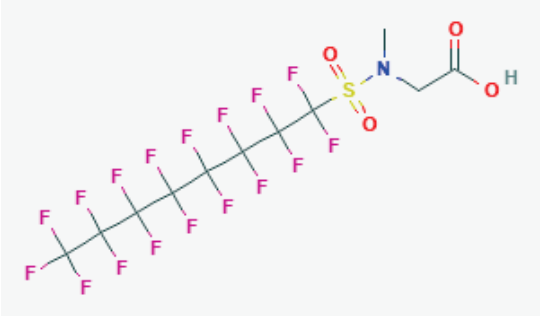
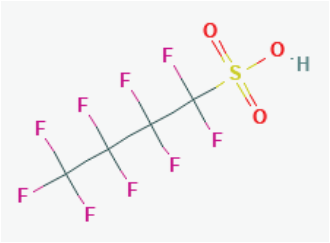
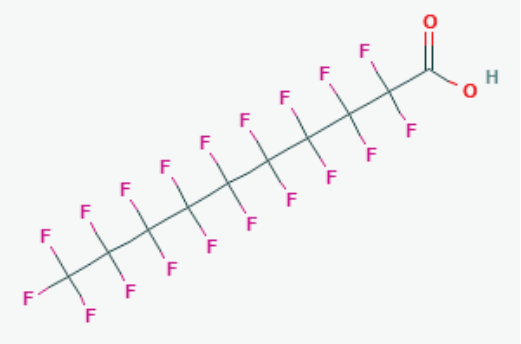
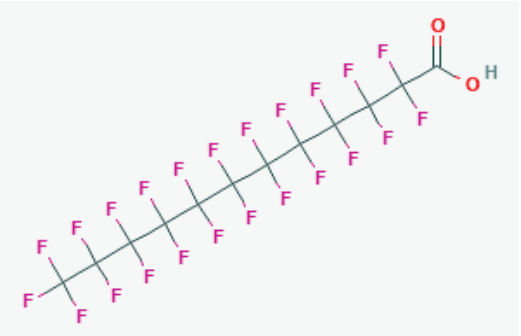
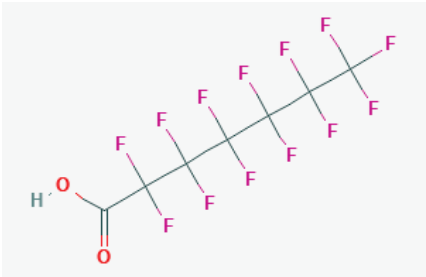
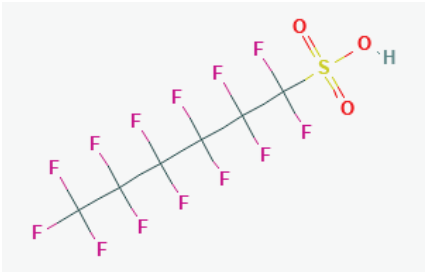
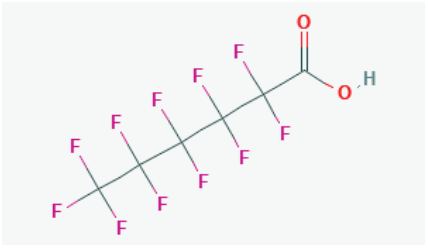
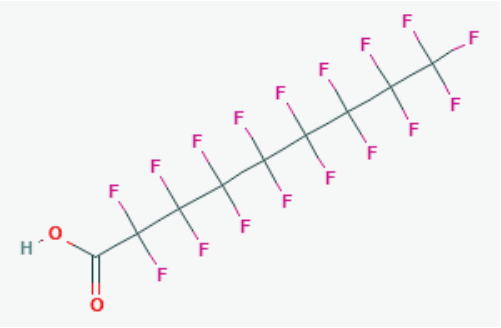
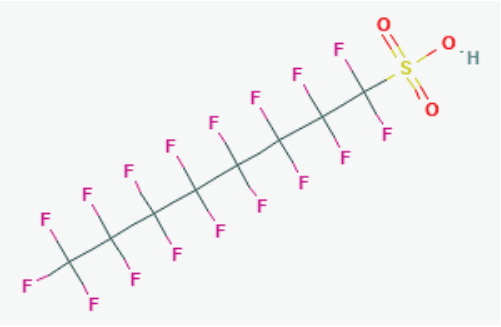
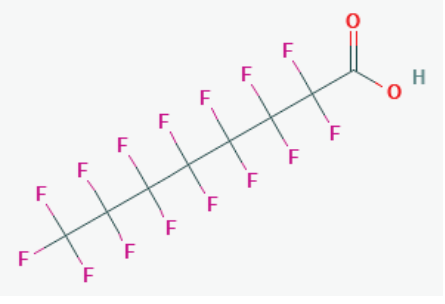
Acronyms and Abbreviations

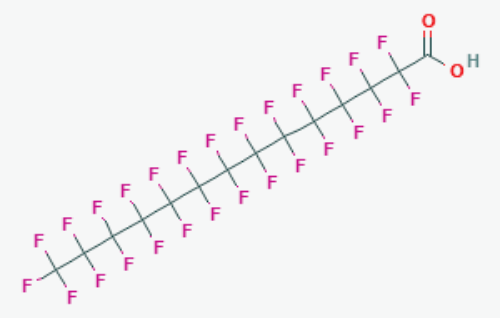
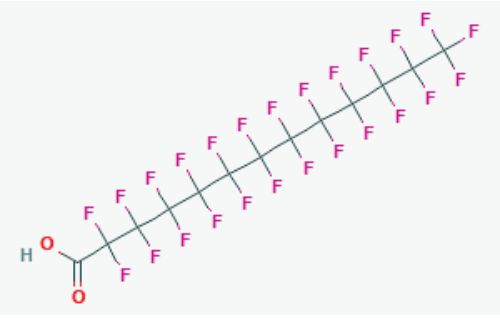
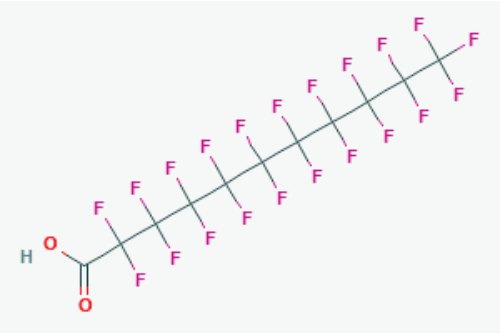
AFCEC	Air Force Civil Engineering Center
AFFF	Aqueous Firefighting Foam
BRAC	Base Realignment And Closure
CBRNE	Chemical, Biological, Radiological, Nuclear, Explosive
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DETS	Decontamination Effluent Treatment System
EL	Environmental Laboratory
ERDC	Engineer Research and Development Center
EPE	Environmental Engineering Branch
GAC	Granular Activated Carbon
IDW	Investigative Derived Wastes
LAS	Linear Alkylbenzene Sulfonate (a common surfactant form)
LHA	Lifetime Health Advisory
MIPR	Military Interdepartmental Purchase Request
NAS	Naval Support Activity
NDCEE	National Defense Center for Energy and the Environment
PETS	PFAS Effluent Treatment System
PFAS	Per-,Poly-fluorinated Alkyl Substance(s)
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
ppt	parts per trillion
TSS	Total Suspended Solids
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
µS	microsiemens

Appendix: PFAS compound information

Compound abbreviations CAS #, EC #	Carbon chain length	Fluorinated carbon chain	Molecular weight	Molecular formula 2D molecular structure
N-ethyl perfluorooctanesulfonamidoacetic acid, NEtFOSAA 2991-50-6 221-061-1	8	8	585.24	C12H8F17NO4S 
N-methyl perfluorooctanesulfonamidoacetic acid NMeFOSAA 2355-31-9 ————	8	8	571.21	C11H6F17NO4S 
Perfluorobutanesulfonic acid PFBS 375-73-5 206-793-1	4	4	300.1	$C_4HF_9O_3S$ 

Compound abbreviations CAS #, EC #	Carbon chain length	Fluorinated carbon chain	Molecular weight	Molecular formula 2D molecular structure
Perfluorodecanoic acid PFDA 335-76-2 206-400-3	10	9	514.08	$C_{10}HF_{19}O_2$ 
Perfluorododecanoic acid PFDoA 307-55-1 206-203-2	12	11	614.1	$C_{12}HF_{23}O_2$ 
Perfluoroheptanoic acid PFHpA 375-85-9 206-798-9	7	6	364.06	$C_7HF_{13}O_2$ 
Perfluorohexanesulfonic acid PFHxS 355-46-4 206-587-1	6	6	400.12	$C_6HF_{13}O_3S$ 

Compound abbreviations CAS #, EC #	Carbon chain length	Fluorinated carbon chain	Molecular weight	Molecular formula 2D molecular structure
Perfluorohexanoic acid PFHxA 307-24-4 206-196-6	6	5	314.05	$C_6HF_{11}O_2$ 
Perfluorononanoic acid PFNA 375-95-1 206-801-3	9	8	464.08	$C_9HF_{17}O_2$ 
Perfluorooctanesulfonic acid PFOS 1763-23-1 217-179-8	8	8	500.13	$C_8HF_{17}O_3S$ 
Perfluorooctanoic acid PFOA 335-67-1 206-402-4	8	7	414.07	$C_8HF_{15}O_2$ 

Compound abbreviations CAS #, EC #	Carbon chain length	Fluorinated carbon chain	Molecular weight	Molecular formula 2D molecular structure
Perfluorotetradecanoic acid PFTA, PFTeA 376-06-7 206-803-4	14	13	714.11	$C_{14}HF_{27}O_2$ 
Perfluorotridecanoic acid PFTrDA, PFTriA 72629-94-8 276-745-2	13	12	664.1	$C_{13}HF_{25}O_2$ 
Perfluoroundecanoic acid PFUnA 2058-94-8 218-165-4	11	10	564.09	$C_{11}HF_{21}O_2$ 

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Design, Construction, and Testing of the PFAS Effluent Treatment System (PETS), a Mobile System for the Treatment of Per-,Poly-Fluorinated Alkyl Substances (PFAS)

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14. ABSTRACT

Poly-,Per-fluorinated alkyl substances (PFAS) are versatile chemicals that were incorporated in a wide range of products. One of their most important use was in aqueous film-forming foams for fighting liquid fuel fires. PFAS compounds have recently been identified as potential environmental contaminants. In the United States there are hundreds of potential military sites with PFAS contamination.

The ERDC designed and constructed a mobile treatment system to address small sites (250,000 gallons or less) and as a platform to field test new adsorptive media. The PFAS Effluent Treatment System (PETS) has cartridge filters to remove sediments and a granular activated carbon (GAC) media filter to remove organic compounds that might complete with PFAS in the ion exchange process, although it may also remove PFAS too. The last process is an ion exchange resin specifically designed to remove PFAS to a target level of 70 ng/L or less (equivalent to the US Environmental Protection Agency (EPA) Drinking Water Health Advisory).

15. SUBJECT TERMS

PFAS	Remediation	Perfluorinated chemicals – Groundwater – Pollution	Water quality
Water Treatment	Perfluorinated chemicals – Soil pollution	Perflourinated chemicals – Water – Pollution	Military bases

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