ESTCP

EXECUTIVE SUMMARY

ARFF Apparatus Disassembly and Characterization

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ESTCP Project ER21-7229

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ACRONYMS AND ABBREVIATIONS

ARFF	aviation rescue and firefighting
AFFF	aqueous film forming foam
ATL	Arcadis Treatability Laboratory
DoD	United States Department of Defense
PFAS	per- and polyfluoroalkyl substances
PFOS	perfluorooctanesulfonic acid
TOP	total oxidizable precursor
XPS	x-ray photoelectron spectroscopy

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1.0 INTRODUCTION

Aqueous film forming foam (AFFF) is known to contain per- and polyfluoroalkyl substances (PFAS), which are used in these products for their foaming, film forming, and heat-resistant properties. AFFF was first developed in the 1960s and was rapidly adopted as a superior alternative to previous protein based foams (Darwin 2004). In the United States, certified airports are required to maintain a minimum number of aircraft rescue and firefighting (ARFF) vehicles carrying AFFF and a foam discharge capacity based on their 'Airport Index' (FAA 2013). Many fire suppression systems, including ARFF vehicles, are impacted by residual entrained PFAS resulting from exposure to AFFF, which has been known to contain >10 g/L of total PFAS (Houtz et al. 2013).

Companies manufacture alternative PFAS-free firefighting formulations (Bioex 2024, Foam 2024, PerimeterSolutions 2024), and the U.S. Department of Defense (DoD) has published the Military Performance Specification for PFAS-free firefighting formulation use on land with fresh water (USDoD 2023). There are an increasing number of states and countries promulgating regulations around the manufacture, sale, release and/or use of PFAS containing AFFF (Washington 2018, Colorado 2019, Allan 2020, Colorado 2020, Congress 2021, Resources 2022, Alaska 2023).

PFAS residuals on wetted fire suppression system surfaces have complicated the foam transition process. These residuals have been shown to be present on materials that have been in contact with highly concentrated PFAS-containing materials like AFFF (Lang et al. 2022, Dahlbom et al. 2024). PFAS are known to self-assemble and coat surfaces at liquid/solid interfaces to form water resistant coatings and can therefore be difficult to fully remove from surfaces. If ARFF foam systems are not properly cleaned prior to replacement PFAS-free firefighting formulation being added, PFAS can dissolve from the surfaces of the system and release into the new PFAS-free firefighting formulation (Ross and Storch 2020). Lang et al. (2022) previously demonstrated that stainless steel AFFF concentrate pipe can amass approximately 10 $\mu g/cm^2$ of measurable surface-associated PFAS (post-total oxidizable precursor (TOP) assay). Dahlbom et al. (2024) demonstrated almost 100 $\mu g/cm^2$ of measured PFAS surface residuals on galvanized steel AFFF piping, 0.01 to 0.1 $\mu g/cm^2$ on an AFFF concentrate tank, almost 1 $\mu g/cm^2$ on a handheld fire extinguisher, and almost 10 $\mu g/cm^2$ on a fire hose (post-TOP assay) (Dahlbom et al. 2024).

The overall objective of this work was to characterize PFAS residual mass on the wetted surfaces of ARFF vehicle on-board fire suppression system components from the water, mixed foam, and foam concentrate systems with various geometries, materials of construction, and locations within the fire suppression system. ARFF vehicles typically have both a tank containing water and a tank containing AFFF concentrate. When foam is needed, the water and foam are piped to a proportioner where they are mixed at the appropriate ratios (e.g., 3% or 6%). Mixed foam is then piped to a variety of turrets or outlets for handlines. A more complete understanding of the extent of PFAS impacts in an on-board fire suppression system will provide information to determine the best course of action to achieve a substantially PFAS-free system and prevent future release to the environment.

2.0 OBJECTIVES

The objective of this project was to understand the PFAS composition within an ARFF apparatus on-board foam system and by:

- Characterizing PFAS distribution within individual components of an ARFF on-board foam system, including both system location (e.g., water, foam, mixed), part material (e.g., brass, stainless steel, etc.), and part shape (e.g., straight, bent).
- Determining the total costs for labor and materials associated with the complete replacement on the on-board foam system inclusive of the out-of-service time required for cleaning.
- Evaluating the extent of replacement needed to achieve successful PFAS removal from an on-board foam system.

3.0 TECHNOLOGY DESCRIPTION

This technology comprised a combination of established rinsing and extraction techniques to determine PFAS impacts in the components of an ARFF vehicle foam system. This project ultimately calculated PFAS residuals on the interior surfaces of individual ARFF vehicle foam system components. Data on PFAS residuals on specific components of the ARFF vehicle foam system would assist the DoD with determining whether cleaning or replacement of individual components would be more cost effective.

Methanol has been demonstrated to effectively remove PFAS from surfaces in laboratory soil extraction experiments (Washington, et al. 2008). The Arcadis Treatability Laboratory (ATL), located in Durham, North Carolina, systematically exposed the wetted components to methanol to extract PFAS. Analysis of the PFAS content in samples were sent to SGS AXYS and measured via Environmental Protection Agency Method 1633 with and without undergoing a TOP assay. A subset of components was submitted to subcontracted laboratories for combustion ion chromatography analysis to quantify total organic fluorine, particle-induced gamma emission spectroscopy to quantify fluorine content remaining on part, and x-ray photoelectron spectroscopy (XPS) to measure surface elemental composition, including percent fluorine.

The specific on-board foam system evaluated in this study was on an Oshkosh T-1500 (ARFF apparatus) with a 210-gallon plastic foam tank and 1,500-gallon polypropylene water tank located at Red River Army Depot in Texarkana, Texas. The fire suppression system on the ARFF vehicle contained three distinct zones: water supply (“water”), foam concentrate only (“foam”), and mixed fire water (“mixed”). For the current system evaluated, forty percent of components were constructed of stainless steel, but there were also several composed of plastic and brass. There were a variety of geometries including the foam and water tanks, hoses, straight pipes, valves, and elbows. Additionally, components were distributed among the foam, mixed, and water systems. Although the exact same components may not translate to all ARFF on-board foam systems, trends within the part types and locations may be more broadly applied.

The ATL received 82 unique catalogued components from the ARFF's on-board firefighting formulation delivery system as well as the foam and water tanks, which were split up into multiple baffles. A major advantage of characterizing PFAS composition for individual components was that rather than having to completely replace all 82 components within the foam system, components could be prioritized based on PFAS mass loading. For the current system evaluated, replacing just three specific elements (two hoses and one valve) would result in a 50% decrease in PFAS mass. Expanding this approach to include other critical components including the water tanks and components within the foam system would result in greater than 90% of the total PFAS mass reduction. This tactic not only offered a cost-effective alternative to comprehensive system replacement but also allowed for the optimization of PFAS de-impact efforts for foam transitions and enhanced operational sustainability.

4.0 PERFORMANCE ASSESSMENT

In characterizing PFAS impacts within the ARFF vehicle foam system, the performance objectives centered on the determination of PFAS residuals on individual components and the distribution among component types and location within the system. Most of the results and data from the system flushing and component PFAS characterization will be published in Anderson et al. (submitted 2024; Appendix B).

The initial ARFF vehicle rinsing procedures demonstrated moderate effectiveness at the removal of PFAS from system components (Table ES-1). The baseline rinsing event showed significant removal of PFAS in the foam-only portion of the system, indicating successful flushing of PFAS. The presence of PFAS in the rinse of the water-only system, albeit at much lower levels, suggested the potential for cross-impact between the water, mixed, and foam systems. This raised concern about unintended dispersion of PFAS into areas where they were not intended, possibly exacerbating impact levels. While the rinsing procedures demonstrated promise in reducing PFAS mass on system components, residual PFAS remaining after rinsing highlighted the need for more comprehensive cleaning protocols or altogether replacement of ARFF vehicle components.

Table ES-1. ARFF Vehicle Results of total PFAS Measured in Water and Foams Systems During the Baseline and Final Rinsing Events.

			Total Measured Mass Removed (mg)*			
			Rinse 1	**Rinse 2**	**Rinse 3**	**Total**
Baseline Event	**Water System**	**Pre-TOP**	0.67	0.57	0.44	1.7
		Post-TOP	2.4	13	7.8	23
	Foam System	**Pre-TOP**	930	78	8.8	1020
		Post-TOP	19000	510	55	19600
Final Event	**Water System**	**Pre-TOP**	0.020**	0.021	0.024	0.065
		Post-TOP	0.029	0.032	0.047	0.108
	Foam System	**Pre-TOP**	0.035	0.033	0.045	0.113
		Post-TOP	0.089	0.092	0.072	0.253

* Total measured mass removed calculated as the sum of the PFAS concentrations in the bulk rinsing water times the volume of rinsing water

**Final event masses demonstrated as the sum of the average individual PFAS concentrations

Prioritizing critical components for replacement based on PFAS mass loading offered a strategic approach to achieving substantial reductions in overall PFAS impact levels. The results from this project successfully demonstrated significant differences in PFAS mass loadings among both system locations and component materials. Components from the foam and mixed systems had greater PFAS levels than components in the water only system. In all systems, the individual PFAS in greatest abundance were perfluorooctanesulfonic acid (PFOS) and 6:2 FtS, although there were differences in the relative amounts of these two compounds among system types. Components made of rubber and brass generally had greater PFAS concentrations than stainless steel and plastic components, indicating that there was a variation of PFAS loading based on material composition.

Some components with significantly larger surface areas, like the foam and water tanks, contained higher overall PFAS residuals (Table ES-2) despite their lower PFAS concentration, highlighting the importance of considering surface area when addressing PFAS impact in system components.

Table ES-2. Total Mass of PFAS Residual Measured on Components Removed from Each Section of the ARFF Fire Suppression System.

System	Pre-TOP Total Mass (mg)	Post-TOP Total Mass (mg)
Water	1.5	2.6
Mixed	25.0	62.0
Foam	18.0	51.0
Total	**44.0**	**120**

Surface total fluorine composition may also play a role in assessing PFAS impact levels and distribution within an ARFF system. While it was limited as a direct proxy for PFAS concentration due to variations among component materials, XPS analysis of total fluorine offered valuable insights with evaluating components of the same material type. The significantly higher percentage of fluorine on components from the foam system compared to the mixed or water systems indicated potential differences in PFAS impact across system components, as confirmed by Method 1633 analysis. Monitoring surface fluorine reductions after extraction with XPS provided a practical method for evaluating PFAS extraction efficiency. By tracking changes in surface fluorine content before and after extraction procedures, practitioners could gauge the effectiveness of cleaning protocols in removing PFAS chemicals of concern. In general, XPS detection limits could range from 0.1-1 atomic percent. Understanding surface fluorine composition through XPS analysis can enable the development of targeted cleaning strategies to enhance mitigation efforts in ARFF operations, particularly during foam transitions. By leveraging XPS insights, operators can optimize cleaning procedures, assess impact levels accurately, and implement tailored approaches to manage PFAS risks effectively in ARFF systems.

The final rinsing event conducted after the new components were installed had significantly reduced PFAS mass removal (>99%) compared to the baseline rinsing event (Table ES-1). However, there were still low level PFAS concentrations in samples from both the foam only and water only portions of the ARFF vehicle. The total PFAS concentrations in the rinsates for the water and foam systems both exceeded 70 ng/L (Pre-TOP: 87.7–141 ng/L; Post-TOP: 147–318 ng/L). Some of that PFAS was likely a result of the water provided for the rinsing, although even taking that into account, the total PFAS concentrations were still around or above 70 ng/L.

Assuming the system was at one time completely full, if all the residual PFAS mass from the water and foam systems post-baseline flushing had been successfully flushed in a follow-up event, the total PFAS concentration for the water and foam systems would have been 3,500 ng/L and 640,000 ng/L, respectively. These results indicated that achieving less than 70 ng/L may be hard to achieve even using brand new components.

5.0 COST ASSESSMENT

The operational costs associated with an ARFF apparatus on-board foam system complete replacement involves the transportation of the truck, the labor and expertise required for the disassembly and inventory management of individual components and acquisition of new components, particularly for custom or retroactively fitted components, the material cost for the replacement components, the labor and expertise required for the reassembly of the system, time cost for the truck being out of operation during replacement, and disposal costs for original components and potentially hazardous materials.

An itemized cost breakdown of labor and individual components was not provided by the DoD, but the total costs associated with labor were $110,502.58 and material costs were $263,626.84, for a total cost of approximately $363,000. Given the results from this study, a significant reduction in total costs could be achieved by targeting critical components within the system for replacement. For the current system, just five components (two hoses from the mixed system, one brass valve from the foam system, the water tank, and one stainless-steel part from the foam system) could be replaced rather than all 82 components, and it would still result in the removal of 90% of the total residual PFAS.

6.0 IMPLEMENTATION ISSUES

Analytical issues encountered during the ARFF baseline rinse analysis and component characterization included high detection limits, poor oxidation of some TOP assay samples, and extended turnaround times. The high detection limits were a result of dilution factors needed to accommodate high concentrations of PFOS and 6:2 FtS. In the most extreme case, concentrations in the mg/L range were reported as estimated data because of the high dilution factors. The lab turnaround times for Method 1633 were on average 4 months, and in some cases, as high as 10 months.

Some components were too large to extract as a whole part, and were not able to be cut down, so they required alternative extraction methods. Methanol wipe extractions previously demonstrated good performance and agreement with typical methanol extractions. However, in the current project there were significant issues with wipe extraction efficiencies resulting in an underestimation of PFAS and decreased statistical power due to wipe sample exclusions. Although previous work had demonstrated good agreement between wipe extractions and MeOH extractions, the poor recoveries here indicated that wipe extractions were not always suitable and may be dependent on material type.

This project also ran into several logistical issues involved in the procurement and installation of new components. These issues are identified below:

1. There were many components that were out of stock and required fabrication.
2. Some components that were custom manufactured for the truck and were no longer available.
3. Some components were provided by the manufacturer, but despite having the correct part number were manufactured to revised specifications that were not compatible with the T-1500 disassembled.
4. Some components in the system were not initially identified by the manufacturer for replacement. These were retrofitted components that were not provided by the original equipment manufacturer and thus were not included on any schematics/part lists.

The challenges associated with acquiring new components resulted in the truck sitting out of service for 15 months before being decommissioned, making a rebound test impossible.

7.0 RECOMMENDATIONS

The execution of this project provided a unique opportunity to view the complexities of managing a foam transition process. Specific to this project was the goal to completely replace the wetted system inside a vehicle to remove PFAS and prepare the vehicle to operate without PFAS impact derived from AFFF. As was observed from characterization of parts removed from the ARFF apparatus, a three times water rinse was not sufficient to remove PFAS from the wetted surfaces of an apparatus in the water or foam systems. Further, with PFAS observed in the post-reassembly rinse process, full replacement of a wetted system may not serve to rid the vehicle of all PFAS since use of PFAS in the manufacturing process or as a manufacturing aid could impart PFAS onto the newly manufactured surfaces of a vehicle.

Because of the complexity of a program replacing a full system worth of components, an abbreviated program consisting of replacing a small subset of components that represent approximately 90% of PFAS present in the system would serve to reduce the overall cost and downtime related to transition by focusing the supply chain on a smaller number of parts that could be acquired more quickly. This small list of parts identified in the report are: a pilot valve sensing hose, a hose in the brass manifold box, brass valve downstream of the foam fill riser, a stainless steel part upstream of the discharge and foam metering manifold, and the water tank.

The data generated in this study does provide information that a partial system replacement coupled with a single water rinse may provide an acceptable alternative to full system replacement for DoD equipment foam transition. With a combined strategy may come additional project challenges that would threaten its viability, including, but not limited to: availability of replacement parts, protracted lead time for identified and unavailable parts, extent of disassembly required to access, remove, and replace identified parts, and the cost of replacement of parts identified. The extent of the effectiveness of a partial system replacement and single water rinse strategy would require additional work to be completed to characterize a system subjected to this treatment process.

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