



AFCEC-CX-TY-TR-2022-0014

EVALUATION OF THE CHEMICAL AND PHYSICAL PROPERTIES OF COMMERCIAL FLUORINE FREE FOAMS

Rashelle McDonald, April Lumley, Glenn Johnson
Arctos Technology Solutions
1270 N. Fairfield Drive
Dayton, Ohio 45432

Sue Broxson, Heather Luckarift
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio 43201

Bridgett Ashley
Air Force Civil Engineer Center (AFCEC)
Airbase Technologies Branch (CXAE)
139 Barnes Drive, Suite 2,
Tyndall Air Force Base, Florida 32403

April 2022

**DISTRIBUTION STATEMENT A. Approved for public release; distribution
unlimited. AFCEC-20220025, 6 June 2022**

**AIR FORCE CIVIL ENGINEER CENTER
READINESS DIRECTORATE**

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the AFIMSC Public Affairs Office at Joint Base San Antonio-Lackland Air Force Base, Texas available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (<http://www.dtic.mil>).

AFCEC-CX-TY-TR-2022-0014 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//SIGNED//

Dr. Bridgett Ashley
Program Manager

//SIGNED//

Dr. Jeffery Owens
Technical Advisor

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YYYY) 01-04-2022		2. REPORT TYPE Technical Report		3. DATES COVERED (From - To) 1 March 2020-31 May 2022		
4. TITLE AND SUBTITLE EVALUATION OF THE CHEMICAL AND PHYSICAL PROPERTIES OF COMMERCIAL FLUORINE FREE FOAMS				5a. CONTRACT NUMBER FA8051-19-F-A020		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Rashelle McDonald, April Lumley, Glenn Johnson, Sue Broxson, Heather Luckarift, Bridgett Ashley				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Arctos Technology Solutions, 1270 N. Fairfield Drive Dayton, Ohio 45432 Battelle Memorial Institute, 505 King Avenue, Columbus, OH 43201				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Civil Engineer Center Readiness Directorate Requirements and Acquisition Division 139 Barnes Drive, Suite 1 Tyndall Air Force Base, FL 32403-5323				10. SPONSOR/MONITOR'S ACRONYM(S) AFCEC/CXA		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFCEC-CX-TY-TR-2022-0014		
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release; distribution unlimited. AFCEC-20220025, 6 June 2022						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The work herein analyzed and documented the physiochemical properties of commercial PFAS-free foams (PFF) in respect to the Military Specification (Mil-Spec) defined in MIL-PRF-24385F(SH). PFF (by definition) should be free of fluorinated surfactants, but contamination of new stock formulations from legacy fluorinated surfactants is possible due to carry over from manufacturing processes. Physical characteristics such as refractive index, viscosity, and pH were determined; these criteria are considered only as a comparison against the Mil-Spec, but results can be used in ranking candidate PFF when considered collectively with other test results. The change to more environmentally sustainable foam formulations is critical and as such, PFF were evaluated for environmental and health impact using standard comparative metrics. Standardized toxicological determinations included the lethal concentration (LC50) and inhibition concentration (IC25). These values estimate the effect of products on aquatic life, and predict extent that organisms are affected by the presence of new PFF formulations. Similarly, the biodegradability of a product is based on the combined chemical oxygen demand (COD) and biological oxygen demand (BOD) as a measure of environmental impact and						
15. SUBJECT TERMS per- and polyfluoroalkyl substances (PFAS), PFAS-free foams, aqueous film forming foam (AFFF), biological oxygen demand, chemical oxygen demand, biodegradability, Military Specification MIL-PRF-24385F(SH) (Mil-Spec), physiochemical						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Bridgett Ashley	
U	U	U	UU	31	19b. TELEPHONE NUMBER (Include area code) 850-283-6004	

Contents

LIST OF FIGURES	iii
LIST OF TABLES	iii
1. SUMMARY	1
2. INTRODUCTION	2
3. METHODS AND PROCEDURES.....	3
3.1. Test Objectives.....	3
3.2. Test Methods and Procedures	3
3.2.1. Refractive Index and Hydrogen Ion Concentration	3
3.2.2. Chemical Oxygen Demand, Biological Oxygen Demand, and Biodegradability	3
3.2.3. Quantitative PFAS and Fluorine Screening.....	5
3.2.4. Stability, Stratification, and Precipitation.....	5
3.2.5. Interfacial Tension, Surface Tension, and Spreading Coefficient	6
3.2.6. Combustion	6
3.2.7. Toxicity	7
3.2.8. Corrosion.....	7
3.2.9. Viscosity	8
3.2.10. Foamability and Foam Drainage Time	9
3.3. Candidate Foams for Evaluation.....	9
4. RESULTS AND DISCUSSION	10
4.1. Evaluation of Results	11
4.1.1. Refractive Index and Hydrogen Ion Concentration	11
4.1.2. Chemical Oxygen Demand, Biological Oxygen Demand, and Biodegradability	11
4.1.3. Quantitative PFAS and Fluorine Screening.....	12
4.1.4. Stability, Stratification, and Precipitation.....	13
4.1.5. Interfacial Tension, Surface Tension, and Spreading Coefficient	14
4.1.6. Combustion	14
4.1.7. Toxicity	15
4.1.8. Corrosion.....	16
4.1.9. Viscosity	16
4.1.10. Foamability and Foam Drainage Time	16
5. CONCLUSIONS.....	17
6. RECOMMENDATIONS	20
7. REFERENCES	23
LIST OF ABBREVIATIONS AND ACRONYMS	25

LIST OF FIGURES

	Page
Figure 1. Precipitation Vials after Centrifugation Steps	6
Figure 2. Example Exposure Depicting the Metal Coupons Suspended in Solution.....	8
Figure 3. FAA Foam Aging Tests.....	14

LIST OF TABLES

	Page
Table 1. Military Performance Standards from MIL-PRF-24385F	2
Table 2. Physical and Chemical Characterization of Non-Aged PFAS-Free Foams and Non-Aged AFFF	10
Table 3. Physical and Chemical Characterization of Aged PFAS-Free Foams and Aged AFFF. 11	11
Table 4. Environmental and Biological Effects of PFAS-Free Foams and Mil-Spec AFFF	12
Table 5. Alkyl Amidobetaine Derivatives in Candidate Foams	15

1. SUMMARY

The work herein analyzed and documented the chemical and physical properties of commercial PFAS-free foams (PFF) in respect to the Military Specification (Mil-Spec) defined in MIL-PRF-24385F(SH). Physical characteristics such as refractive index, viscosity, and pH were determined; these criteria are considered only as a comparison against the Mil-Spec, but results can be used in ranking candidate PFF when considered collectively with other test results. The change to more environmentally sustainable foam formulations is critical and as such, PFF were evaluated for environmental and health impact using standard comparative metrics. Standardized toxicological determinations included the lethal concentration (LC_{50}) and inhibition concentration (IC_{25}). These values estimate the effect of products on aquatic life, and predict extent that organisms are affected by the presence of new PFF formulations. Similarly, the biodegradability of a product is based on the combined chemical oxygen demand (COD) and biological oxygen demand (BOD) as a measure of environmental impact, and indicates how PFF may stimulate microbial activity in surface- and groundwater systems where chemicals may bioaccumulate. The biodegradation of PFF consumes oxygen, thus competing with aquatic species for the oxygen in the water.

PFF (by definition) should be free of fluorinated surfactants, but contamination of new stock formulations from legacy fluorinated surfactants is possible due to carry over from manufacturing processes. As such, the presence of fluorinated components, measured as total fluorine, was also targeted. Large-scale evaluations of foamability and drain time were also conducted to confirm the candidates would perform their basic function as a firefighting agent.

After manufacture, and during operational use, PFF products will likely be stored for extended periods of time until needed. As such, resistance to corrosion and storage stability is pertinent to practical performance. If the foam product corrodes the internal storage compartments, nozzles, or any part of a firetruck, it would render the firetruck unreliable in an emergency. In order to determine shelf-life and heat stability of products, aging qualities (e.g., evidence of stratification or formation of precipitates) were determined as pass/fail criteria for candidate products. The film formed by legacy aqueous film forming foam (AFFF) is the main mechanism of extinguishment, evidenced by a positive spreading coefficient that dictates how well a product can spread over a fuel source and affect fire extinguishment. The spreading coefficient of PFF was calculated from surface and interfacial tension measurements taken before and after aging of the samples and is one of the best predictive measurements for PFF performance.

None of the PFF products evaluated to date matched all parameters required to satisfy MIL-PRF-24385F(SH) or closely mimicked the currently-fielded AFFF. This document serves as a report of the results and preliminary interpretation of the importance of each of the parameters for practical application. The information may be used to rank and down-select PFF products that warrant further operational-scale fire-suppression tests. The physical characterizations may also provide background for formal documentation to guide transition to using PFF for fire suppression.

2. INTRODUCTION

Since the 1970s, the Department of Defense (DoD) and the civil aviation community have used Aqueous Film Forming Foam (AFFF) as a firefighting agent for the suppression of liquid fuel (Class B) fires, particularly in Aircraft Rescue and Firefighting (ARFF) vehicles. Legacy C8- and C6-based AFFF, however, contain per- and poly-fluoroalkyl substances (PFAS)—primarily perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS), perfluorohexane sulfonate (PFHxS), and perfluorohexanoic acid (PFHxA)—fluorinated surfactant compounds that have been shown to persist in the environment, and raise environmental and human health concerns.

Currently none of the commercial PFAS free foam (PFF) alternatives are able to meet the stringent fire performance criteria outlined in the military specification (Mil-Spec), specifically MIL-PRF-24385F(SH) (1). The Mil-Spec, in addition to fire testing, includes a variety of physical and chemical properties requirements. The Federal Aviation Administration (FAA) has a vested interest in finding an effective PFF to extinguish Class B hydrocarbon fires, continuity between DoD and civilian applications may improve operations safety. In response, the FAA used the laboratory capabilities of the Air Force Civil Engineer Center (AFCEC/CXAE) to test commercial off the shelf (COTS) PFF fire-fighting products and evaluate fundamental physical and chemical characteristics in order to assess their compliance against the Mil-Spec.

The Mil-Spec is based upon the properties and behavior of traditional fluorosurfactant-containing AFFFs, and consequently, the PFF products will not meet the Mil-Spec in its current form; however, it is fitting to obtain data that provides standard criteria for comparison. Table 1 lists the metrics set forth in the Mil-Spec for each of the analyses performed.

Table 1. Military Performance Standards from MIL-PRF-24385F

Table IV: Primary Performance Standards from API RP 2001			
CRITERIA		REQUIREMENT	METRIC
Toxicity	-	LC ₅₀	≥ 500 mg/L
		COD	≤ 1,000,000 mg/L
		BOD ₂₀ /COD	≥ 0.65
Environmental			
Foamability		Expansion Ratio	≥ 5:1
		25% Drainage Time	≥ 2.5 min
Corrosion	General	Steel	≤ 1.5 milli-inches/year
		Copper/Nickel	≤ 1.0 milli-inches/year
		Nickel/Copper	≤ 1.0 milli-inches/year
	Localized	Bronze	≤ 100 mg
		Corrosion Resistant Steel	No pits
Stability		Stratification	None visible
		Precipitation	None visible
Other Physical and Chemical Characteristics		Refractive Index	≥ 1.3630
		Viscosity	≤ 20 centistokes (at 5 °C)
			≥ 2 centistokes (at 25 °C)
		pH	7.0 to 8.5
		Spreading Coefficient	≥ 3
		Total Halides	≤ 500 ppm

The collected properties of a PFF are suggestive of its potential as a replacement for the legacy AFFF. For example, the spreading coefficient, a function of surface tension, is a good indicator of how the foam will spread on a fuel pool, extinguish, and suppress fire threats. The corrosivity

of the replacement foams is a critical characteristic to ensure there is no undue damage from prolonged contact of the PFF with equipment such as firetrucks. Aquatic toxicity and biodegradability readings provide insight to the potential environmental impact from use and release of the products. Foamability and drain time are relevant characteristics for PFF fire suppression in actual application.

3. METHODS AND PROCEDURES

3.1. Test Objectives

The project examines a series of PFF in order to define chemical properties with respect to the current standard fire suppression agent. The objective was met by analyzing PFF using the physical and performance standards in MIL-PRF-24385F. Initial material collection, test design, project management, and most physiochemical tests were performed by AFCEC/CXA (Tyndall AFB, FL). The corrosion, toxicity, viscosity, and total fluorine testing were performed by independent certified laboratories. Corrosion and viscosity testing were conducted by partners at Battelle Memorial Institute (Columbus, OH). Aquatic toxicity testing was accomplished by EnviroScience, Inc. (Stow, OH). Total fluorine determinations were done by Galbraith Laboratories, Inc. (Knoxville, TN).

3.2. Test Methods and Procedures

Standard laboratory processes referencing the corresponding Mil-Spec standards were performed in accordance to published guidance from ASTM International (formerly American Society for Testing and Materials (West Conshohocken, PA)); or the EPA (Environmental Protection Agency). Test procedures were derived using Standard Methods for the Evaluation of Water and Wastewater (22nd Edition) (2). All measurements were made using calibrated equipment and personnel used required personal protective equipment (PPE).

3.2.1. Refractive Index and Hydrogen Ion Concentration

Solution refractive indices (RI) were assessed according to Mil-Spec 4.7.1 using two analytical tools. The first trials used a Vee Gee C10 refractometer (Vee Gee Scientific, Vernon Hills, IL). Three drops of undiluted PFF liquid were placed on the site glass and then the line of refraction was determined by visual inspection. Replicate samples were analyzed for each PFF concentrate ($n=3$, 25 °C). Additionally, an Abbemat 3200 Refractometer (Anton Paar, Boynton Beach, FL) was used for RI determination. Three drops of each concentrate PFF were placed on the sapphire window and the RI was read against a light emitting diode (LED) light source. As before replicate samples were analyzed for each PFF concentrate ($n=3$, 25 °C). The Mil-Spec states use of a sodium vapor source lamp, the LED is considered the modern alternative, and provides consistent emission wavelength (3).

Hydrogen ion concentration (pH) was assessed according to Mil-Spec 4.7.3. Undiluted PFF product was placed in contact with the glass electrode while stirring, and measured against the reference electrode, using a digital pH meter ($n=3$, 25 °C) (Orion Star model A211, Thermo Fisher Scientific, Waltham, MA).

3.2.2. Chemical Oxygen Demand, Biological Oxygen Demand, and Biodegradability

The chemical oxygen demand (COD) limit for fire extinguishing agents is defined in the Mil-Spec section 4.7.12.2. The COD of all test products was done using the industry standard reagents and materials from the Hach Company (Loveland, CO). The principles and approach for COD determinations are provided in detail by Wayne (4). The specific steps and modifications for present work follow. Samples of the PFF and AFFF concentrates were mixed with deionized water (1:1000 w/v), 2 mL of the diluted preparations were added to an 824 Ultra high range COD reagent tube (Hach Company) and then incubated at 150 °C for 2 h, in accordance with manufacturer instructions. COD was determined (mg/L) using a Hach DR3900 Spectrometer and its associated analytical software package. Replicate samples ($n=3$) were prepared and analyzed for statistical reliability and then the COD for the 3% working solution extrapolated from the determined values.

The biological oxygen demand (BOD) was determined using standardized methodology and analysis for the Ultimate BOD test (20-d BOD or BOD₂₀) (5, 6). In order to find an appropriate test range to allow for reliable assessment of biodegradation, a series of diluted samples were prepared from stock solutions of each of the foam concentrates (1:1000 w/v in aerated, buffered water). Those samples were the subject in standard BOD tests, the trials needed to sustain a level of BOD above the background, but not so high that the test bottle oxygen concentrations became limiting for microbial activity. Specifically, dilutions that *consumed* at least 2 mg/L dissolved oxygen (DO) but did not drop *below* 1 mg/L DO in the test were considered best for the quantitative determination. Once the appropriate working concentration was determined, best representative dilutions ($n=1$) were prepared and used in the BOD₂₀ test.

All reagents, materials, and methodologies followed standard practices (2, 5, 6). The trials were done using sealed polyethylene test bottles (300-mL capacity). Samples were incubated in a controlled environmental chamber (20 °C, dark). The DO for each test bottle was determined at start, then at 5-d intervals (± 2 h) with final reading after 20 days incubation. The DO determinations were made using an Orion Star A216 Meter and RDO probe (Thermo Scientific, Waltham, MA). Buffered water, a negative control, and standard control (300 mg/L glucose/glutamic acid (Hach Company)) samples were done in parallel with all trials to monitor for systematic problems. The trials used raw wastewater (obtained from Advanced Wastewater Treatment Plant, Tyndall AFB, FL) as a representative inoculum (also known as “seed”) for testing agent biodegradation. Background oxygen consumption from materials present in the inoculum were also determined using standard methods (5). Those measurements define the seed correction factor (SCF), which was used in data analyses. Ultimate BOD for the 3% working solution was calculated from the experimentally determined BOD₂₀ and Equation 1 below, any dilutions done were factored into the calculation along with any re-aeration steps during test. BOD₂₀ and COD are both expressed as mg/L in the formula. Biodegradability index was then calculated using Equation 2 below.

$$\text{Ultimate BOD (BOD}_{20}) = |DO_{20} - (DO_i - SCF)| \quad (1)$$

$$\text{Biodegradability Index} = \frac{BOD_{20}}{COD} \quad (2)$$

3.2.3. Quantitative PFAS and Fluorine Screening

Starting with a 1% stock solution of each sample foam, 1:100 dilutions (v/v, DI water) underwent two filtration processes. The first was a pre-filtering step, using ENVI-carb (Supelclean, Milwaukee, WI) carbon resin through a syringe filter, then the samples were pulled through an additional cellulose acetate vacuum filtration step (Corning). Next, all samples were processed through solid phase extraction (SPE) on a Biotage Horizon SmartPrep automated cartridge extractor (Biotage US, Charlotte, NC) to concentrate the analytes. A Thermo LTQ XL mass spectrometer, liquid chromatograph (LC-MS) was employed to quantify PFOA, PFOS, PFHxS, and PFHxA following SPE processing as directed in EPA test method 537 (7). Total fluorine content of the PFF concentrates was quantified at Galbraith Laboratories Inc. (Knoxville, TN) using their documented standard method (8). Analysis proceeds by first converting the fluorine to fluoride by combustion of known sample (100-200 mg in buffer solution) in an oxygen rich atmosphere contained in a thick-walled oxygen flask, to withstand the pressure. An Orion fluoride ion selective electrode (Thermo Fisher Scientific, Waltham, MA) was then used to determine the total fluoride content of the concentrates. Single trials were ($n=1$) done for each of the test foams.

3.2.4. Stability, Stratification, and Precipitation

In accordance with Mil-Spec 4.7.10, material stability was tested by accelerated aging (65 °C, 10 days). Foam concentrate or a 3% solution (w/v), (1 L) were transferred to loosely-capped glass jars, as instructed in the Quality Systems Manual (QSM), 5.9.1 (9) ($n=1$). At completion, samples that passed the preliminary aging test were subjected to further analyses, including, surface tension measurements (4.7.4), stratification (4.7.14), and precipitation (4.7.15). Aged samples were inspected for the presence of stratification according to Mil-Spec 4.7.14, which describes a direct visual examination for liquid separation. After the aging step, 50 mL aliquots of foam concentrate and aged 3% solution samples were mixed 1:1 (v/v) with water-saturated toluene and 1 mL mineral oil added as a demulsifier. The sample tubes were inverted, vented, then centrifuged using a Koehler Centrifuge (Holtsville, NY) for 5 min at 500 RCF (relative centrifugal force), at 60 °C three times. Sample separations ($n=2$) were then determined in accordance with ASTM D96 (10). Figure 1 shows the results of three different results of the precipitation tests. All show a definite separation of the aqueous and organic layers with the demulsifier in the aqueous layer.

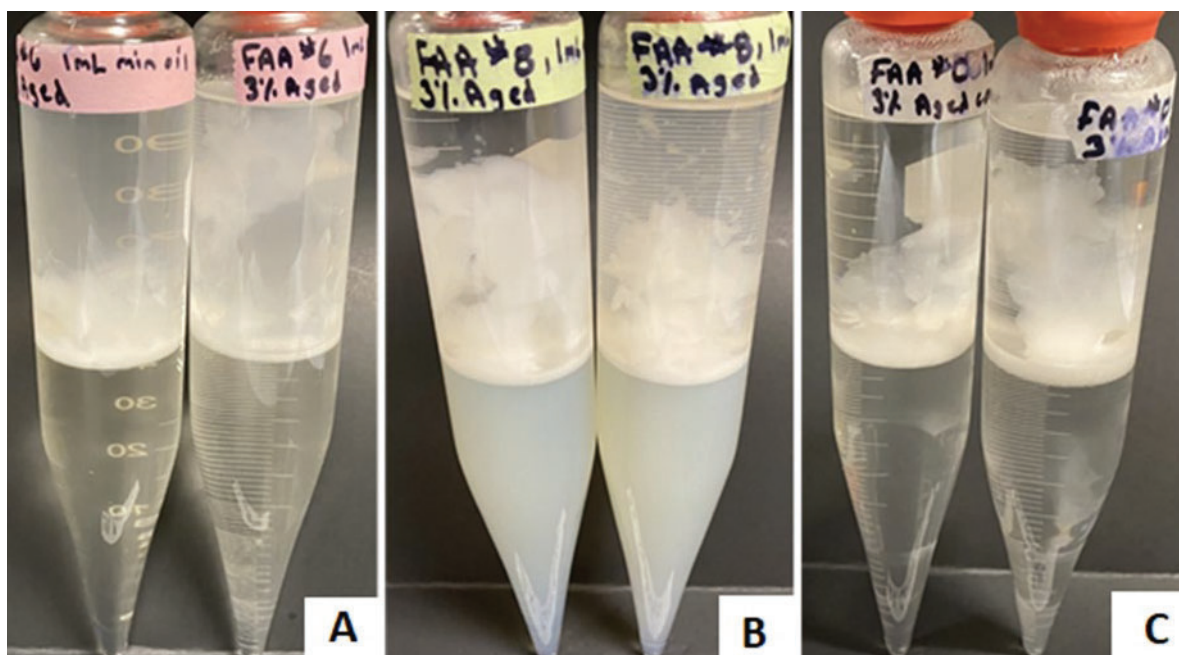


Figure 1. Representative Acceptable (Pass) Precipitation Tests

All examples pass (no visible precipitates), however, each sample looks different after centrifugation. A: FAA#6 shows distinct layering with slightly cloudy liquid layer; B: FAA#8 shows relatively dense foam layer and colloidal liquid phase; C: FAA#0 shows a limited layer of foam with the demulsifier clouding the liquid phase

3.2.5. Interfacial Tension, Surface Tension, and Spreading Coefficient

The Wilhelmy plate method was used to measure dynamic surface tension (SFT) using a Krüss K100C tensiometer (Matthews, NC). Samples ($n=3$) were prepared in 1-L aliquots of 3% solutions (w/v, in DI water), as listed in ASTM D1331 (11). Interfacial tension (IFT) was measured according to Mil-Spec 4.7.4.2. The samples were all done using 3% solutions (w/v, in DI water) and compared to cyclohexane as a standard hydrocarbon substrate (measured in house using the same method, with an average of 24.42, std dev 0.44). The spreading coefficient was calculated according to Mil-Spec 4.7.4. using the IFT and SFT data along with the measurements for cyclohexane; all analyses were done using the same equipment and accessories. Equation 3 was applied to calculate the spreading coefficient (S), from the surface tension of cyclohexane (γ_a), spreading coefficient of PFF (γ_b), and the interfacial tension between the two liquids, (γ_i) and was calculated for samples pre- and post-aging.

$$S(a/b) = \gamma_a - \gamma_b - \gamma_i \quad (3)$$

3.2.6. Combustion

The Mil-Spec was not defined in context of the PFF chemical composition; the new formulation, however, will affect how they behave and react in the environment. It is critical to know whether the thermal breakdown products of the PFF possess additional environmental or health risks. The thermal decomposition of foams is typically evaluated by combining Thermogravimetric Analysis, Differential Scanning Calorimetry, and Mass Spectroscopy (TGA-DSC-MS). Decomposition products of the known foam components were determined by a comprehensive

literature search, which were used to build the MS method. In order to determine thermal decomposition characteristics foam samples (10–25 mg diluted 1:50 (v/v) in DI water) were placed in a covered Al_2SiO_2 crucible for analysis. The sample was purged under nitrogen, then heated in a protective atmosphere from 35 °C–1500 °C (10 °C/min ramp rate). The temperature, sample mass, and heat flux were continuously recorded, the volatile combustion products were analyzed by using MS, screening for product masses predefined in the method. Preliminary trials were performed using the Netzsch model F3 TGA-DSC-Aeolos MS (Netzsch, Germany). Following the analytical process, the spectra were reviewed for presence of the known components, predicted breakdown products, and then queried using a commercial MS library.

3.2.7. Toxicity

In order to assess the PFF toxicity with respect to Mil-Spec 4.7.12.1, single samples of foam concentrates were analyzed by EnviroScience Inc. (Stow, OH) for acute and chronic toxicity to *Pimephales promelas* (fathead minnows). Initial acute toxicity tests determined the LC_{50} concentrations after 96-h exposure. Chronic toxicity tests defined the no observed effect concentration (NOEC) and specified growth inhibition concentrations (IC_{25}) after 168-h exposure to the test organisms.

Additional review of the PFF formulations was conducted in order to screen for the presence of other suspected toxic or deleterious components that are not explicitly defined in the Mil-Spec, specifically alylamidobetaine and its derivatives. Literature from the PFF product manufacturer data sheets and safety data sheets were reviewed for chemical composition and individual components. Specifically, search criteria for the product alylamidobetaine, or its derivatives, were noted based on recent reports (12, 13). The alylamidobetaine-based detergents are widely used in the emerging PFF alternatives and the predicted no effect concentration (PNEC) is extremely low in water and soil tests.

3.2.8. Corrosion

A 60-d corrosion analysis was performed according to Mil-Spec 4.7.7. and ASTM E527 (14) in order to evaluate general corrosion effects of PFF on four different metal coupons: a) G10100 – Steel; b) C70600 – Cu-Ni; c) N04400 – Ni-Cu; d) C90500 – Bronze. A fifth material (S30400 – Stainless Steel) was used in “localized corrosion” assessment. All metal coupons except sand-cast bronze (C90500) were acquired from Alabama Specialty Products (Munford, AL) and had nominal dimensions of 3” x ½” x 1/16”. The sand-cast bronze (C90500) was obtained from Franklin Bronze Plaques (Franklin, PA) and had nominal dimensions of 3” x ½” x 3/16”, confirmed with Vernier calipers. The coupons were cleaned (acetone / DI water), air dried, and initial weight recorded. The stainless steel coupons were passivated in a 10% HNO_3 solution for five minutes prior to immersion in foam samples. The PFF concentrates were diluted using artificial seawater (ASTM D1141 (15)) to a 10% (by volume) solution. Each coupon material type was contained in separate cells of foam solution to prevent cross-contamination of metal ions that might result from corrosion processes. During the standard tests, the test coupons ($n=5$) were suspended in the foam solutions by a nylon string attached to the containment cell lid (Figure 2-A) and spaced apart to prevent the contact of metal surfaces during the 60-d exposure. In the localized corrosion test stainless steel coupons were placed vertically against the sidewall of a 600 mL beaker with glass beads on the bottom, the beaker was covered with a watch glass to prevent evaporation (Figure 2-B). At the close of the 60-d exposure, each material coupon was

removed from its solution, rinsed with deionized water, scrubbed lightly with a nylon bristle brush, and rinsed again with deionized water. The coupons were separated by material type and stored in a desiccator. Prior to inspection and analysis, the materials were chemically descaled per ASTM G1/NACE TM-0169 (16, 17) with 20% HCl for 1–3 min on the C70600 - Cu-Ni, N04400 - Ni-Cu, and the C90500 – Bronze. The descaling varied for G10100 - Steel, utilizing (undiluted) HCl + 20 g/L SnCl₂ + 50g/L Sb₂O₃ for 1–25 min. Losses were determined based on change in mass. The standard density of each alloy was used to convert the recorded mass loss to a supposed change in profile of the coupon, i.e., milli-inches per year (mpy). The stainless steel localized corrosion specimens were not de-scaled in this way, but were observed at 10× magnification for localized corrosion occurrences. Determining the presence of corrosion product deposits was essential for categorizing the localized corrosive degeneration. The maximum allowable corrosion rates/mass losses for each material per the Mil-Spec are listed in Table 1.

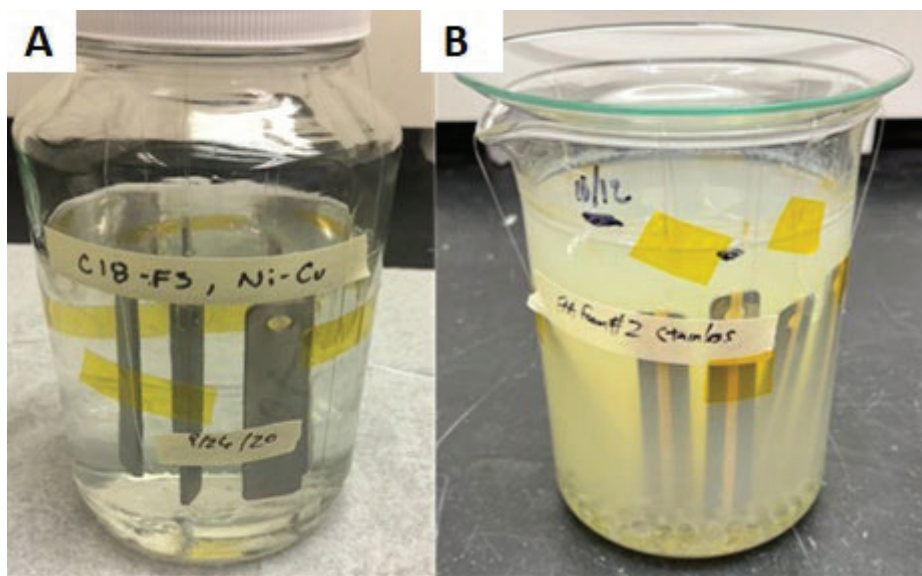


Figure 2. Example Exposure Depicting the Metal Coupons Suspended in Solution
A: General corrosion testing; B: Localized corrosion testing

3.2.9. Viscosity

Preliminary viscosity measurements were taken as defined in Mil-Spec 4.7.2. Undiluted foam samples (30–50 mL) were transferred to a Brookfield viscometer cell (Ametek Brookfield Engineering, Middleboro, MA) and viscosity estimated at 5°C and 25°C (+/- 0.1°C). Once the viscosity range of each PFF was defined in the preliminary test, all samples were set in a water bath to equilibrate. A glass capillary method (18) was used to rigorously define PFF viscosity. Samples ($n=3$) were transferred to either 50, 150, or 200-size Cannon-Ubbelohde-glass capillaries and flow time observed at both 5°C and 25°C (+/- 0.1°C). The appropriate capillary was selected using results of preliminary tests. When presented with thicker samples, the Brookfield viscometer cell fitted with a Helipath stand and a T-bar spindle modification were applied to obtain the viscosity measurement.

The equation for calculating kinetic viscosity is shown in equation 4, where ν is the viscosity of the sample in centistokes (cSt), C is the viscometer constant, and t is the time of flow in seconds:

$$v = C \times t \quad (4)$$

Equation 5 is used to calculate viscosity in centipoise (cP), where η is viscosity in cP, F is the factor, and R is the dial reading.

$$\eta = F \times R \quad (5)$$

The Mil-Spec requirements are defined in centistokes (cSt) and needed for sample comparisons. Equation 6 converts cP to cSt by dividing cP by the density of PFF (d , in g/cm³):

$$cSt = cP/d \quad (6)$$

3.2.10. Foamability and Foam Drainage Time

Foamability assessments (Mil-Spec Section 3.3.2.a) were conducted on all eight PFF candidates using methods defined in Mil-Spec Table 1 Section 4.7.5 and NFPA 412 (19). Briefly, foam concentrates and working solutions of the product (3% in municipal tap water) were incubated 10 days at 65°C (+/-2.0°C) to mimic aging during storage. Following incubation, the aged concentrate was mixed with tap water to provide a second working solution (3% v/v). The expansion ratio and 25% drainage time for all solutions were subsequently determined. Foam was generated using a specialized test nozzle based on specifications provided by the Naval Research Laboratory. The flow rate and inlet pressures were constant and identical settings used for all foam mixtures, 2-gpm and 100 psi, respectively. The nozzle was held at a 30-degree angle from hip height and foam directed onto a backboard (6 ft discharge distance). Foam was allowed to flow from the backboard to fill two 1000 mL graduated cylinders. After which, the expansion ratio was mathematically calculated from weight and 25% drainage time was evaluated by visual inspection for both samples collected. Foamability tests were done once for each 3% foam solution, the results were the simple average of the replicate cylinders.

$$Foamability = \frac{Foam\ volume}{Foam\ mass} \quad (7)$$

3.3. Candidate Foams for Evaluation

The representative PFF samples were provided by the FAA, the MilSpec AFFF was used from AFCEC inventory. The foams and manufacturer details are listed below.

- Foam 1: Bio-Ex Eco-Pol F3 HC 3%,
(Batch # 18K17C1, Bio-Ex, Montrottier, France.)
- Foam 2: Bio-Ex Eco-Pol A 3%,
(Batch # 17J28J0, Bio-Ex, Montrottier, France.)
- Foam 3: Fom-Tec Enviro USP 2-3%,
(Batch # 194311, Dafo Fomtec AB, Tyresö, Sweden.)
- Foam 4: National Foam Avio Green KHC 3%,
(Batch # 50-19, National Foam, Angier, NC.)
- Foam 5: Solberg Rehealing Foam RF3 3%,
(Batch # B1900530, Solberg Co, Green Bay, WI.)
- Foam 6: FireBull F3, Bio-Ex,
(Batch # 210904-FB-FF, EnforcerOne, LLC, Peachtree City, GA.)

Foam 7: EcoPol A 3+, Bio-Ex S.A.S.,
(Batch # 21D02F0, 5, Chemin de Clapeloup, Sainte-Consorce, France.)
Foam 8: Solberg Avigard 3B,
(Batch # N/A, Auxquima, S.A.U., Poligono Industrial de Bana, Asturias, Spain.)
Foam 0: PhosChek Foam 3% (AFFF MILSPEC),
(Batch # N/A, Perimeter Solutions LP, Rancho Cucamonga, CA.)

4. RESULTS AND DISCUSSION

Table 2 summarizes results for each of the assays of the non-aged PFF and the non-aged Mil-Spec reference foam. On assays that were only required for pass/fail, results are reported as such. For any test with sufficient replicates, the mean is shown. The color coding in Table 2 highlights the pass/fail value assigned to each candidate PFF for each Mil-Spec parameter evaluated. The baseline AFFF was not evaluated for corrosion or total fluorine in this study.

Table 2. Physical and Chemical Characterization of Non-Aged PFAS-Free Foams and Non-Aged AFFF

	Foam #1	Foam #2	Foam #3	Foam #4	Foam #5	Foam #6	Foam #7	Foam #8	AFFF	Mil-Spec Criteria
Refractive Index	1.357±0.003	1.358±0.000	1.369±0.000	1.381±0.000	1.382±0.000	1.378±0.000	1.362±0.000	1.391±0.000	1.367±0.000	> 1.3630
pH	6.9±0.009	7.8±0.008	7.6±0.005	8.5±0.017	7.0±0.000	6.8±0.008	8.2±0.005	7.9±0.005	8.1±0.017	7.0–8.5
Total Fluorine	87	30	<10	29	37	N/D ▼	N/D ▼	N/D ▼	N/A	Parts per million (ppm)
Spreading Coefficient	-5.14	-0.06	-0.71	-2.52	-5.83	-1.97	-0.83	-1.37	8.01	> 3 dynes/cm
Viscosity ^{5°C}	19082	4.31	21809	133	32075	20352	26.7	29.9	6.88	2–20 centistokes (cSt)
Viscosity ^{25°C}	16147	2.38	18762	53.9	24210	12402	11.9	14.5	3.32	
Localized Corrosion	Pass	1/10	Pass	Pass	Pass	Pass	Pass	2/10	Pass [†]	No visible pitting
G10100 Steel	0.13	0.22	0.16	0.15	0.24	0.22	0.29	0.03	Pass [†]	< 1.5 mpy
C70600 Cu-Ni	0.21	1.35	0.63	0.15	0.13	0.43	0.79	0.00	Pass [†]	< 1.0 mpy
N04400 Ni-Cu	0.01	0.01	0.02	0.01	0.02	0.00	0.04	0.00	Pass [†]	< 1.0 mpy
C90500 Bronze	24.22	107.71	70.19	15.48	17.71	45.22	45.36	2.02	Pass [†]	< 100 mg

[†]Corrosion values of AFFF are assumed

▼ Fluorine values of specified samples not done

Color Key for Table 2: Pass (green), Inconclusive (yellow), Fail (red). Not in Mil-Spec (gray)

Table 3 summarizes results for each of the assays of the aged PFF and aged Mil-Spec reference foam; all aged as both concentrate and as a 3% solution. On assays that were only required for pass/fail, results are reported as such. For any test with sufficient replicates, the mean is shown. The color coding in Table 3 highlights the pass/fail value assigned to each candidate PFF for each Mil-Spec parameter evaluated.

Table 3. Physical and Chemical Characterization of Aged PFAS-Free Foams and Aged AFFF

	Foam #1	Foam #2	Foam #3	Foam #4	Foam #5	Foam #6	Foam #7	Foam #8	AFFF	Mil-Spec Criteria
Aged Concentrate Spreading Coefficient	-6.37	-0.70	-0.78	-2.69	-6.32	-1.80	-0.63	-2.35	7.36	>3 dynes/cm
Stratification	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	No visible strata
Precipitation	Pass	Inconclusive	Pass	Pass	Pass	Pass	Pass	Pass	Pass	No visible precipitation
Foam 25% Drainage Time	9.34±0.26	6.15±0.01	10.58±0.08	9.57±0.03	23.65±0.01	15.70±0.22	3.72±0.19	2.94±0.02	3.63±0.02	> 2.5 min
Foam Expansion	7.8±0.2	6.9±0.3	6.3±0.2	8.1±0.2	8.2±0.3	7.7±0.2	6.3±0.0	5.3±0.1	6.6±0.2	> 5:1
Aged 3% Solution Spreading Coefficient	-4.51	-2.04	-1.86	-0.77	-6.73	-2.28	0.08	-0.98	7.86	>3 dynes/cm
Stratification	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	No visible strata
Precipitation	Pass	Inconclusive	Pass	Inconclusive	Pass	Pass	Inconclusive	Pass	Pass	Pass/Fail
Foam 25% Drainage Time	15.31*	6.15*	41.08*	9.57*	24.75*	14.32*	3.34*	2.93*	5.43±0.2	> 2.5 min
Foam Expansion	7.3*	6.8*	8.3*	6.7*	7.2*	7.0*	6.05*	5.1*	6.8±0.1	> 5:1

Color Key for Table 3: Pass (green), Inconclusive (yellow), Fail (red). Not in Mil-Spec (Gray)

*n=1 collected for these samples

4.1. Evaluation of Results

All results are reported by the respective analysis method, described in relation to the Mil-Spec, and compared to the characteristics of a currently fielded AFFF (PhosChek) as a baseline reference.

4.1.1. Refractive Index and Hydrogen Ion Concentration

The RI of the eight PFF concentrates were evaluated. While all values were similar to the PhosCheck AFFF (averaging <3% difference), candidates 3-6 and 8 met the Mil-Spec requirement (min 1.3630) along with the baseline foam. Samples were tested in concentrate form as directed in the Mil-Spec. The RI is used as a reference measure of the liquid and is related to the concentration of various solutes. The formulations of the products differ widely, accordingly the RI will differ among products and are not relevant to usage or performance characteristics. The pH of PFF were determined; Foams 1 and 2 fall below the Mil-Spec acceptable range (less than 1%) of 7.0–8.5; Foam 7 is considered inconclusive because it is on the cusp of passing (less than 0.1% from Mil-Spec minimum). Again, samples were tested in triplicate as the commercial concentrate, as described for Mil-Spec test. Although pH can affect solution corrosivity, minor differences in the pH compared to the standard are inconsequential.

4.1.2. Chemical Oxygen Demand, Biological Oxygen Demand, and Biodegradability

The test results are summarized in Table 4. The COD determinations are consistent for all replicates (standard deviation all $<\pm 5\%$ of the average COD). The BOD is not an explicit value in the Mil-Spec, but needed to determine the relative biodegradability of a material. The BOD₂₀ determinations showed greater differences than COD, but were within industry tolerance ($\pm 30\%$). Differences are expected for biological catalysts versus the chemical permanganate oxidation. Control samples showed consistent and predicted values, adding confidence to determinations.

Table 4. Environmental and Biological Effects of PFAS-Free Foams and Mil-Spec AFFF

	Foam #1	Foam #2	Foam #3	Foam #4	Foam #5	Foam #6	Foam #7	Foam #8	AFFF	Mil-Spec Criteria
BOD₂₀	505,500	570,300	695,700	801,700	913,500	819,300	731,500	790,200	514,800	Not defined in Mil-Spec
COD	382,000 $\pm$ 1.5	351,000 $\pm$.5	2585,000 $\pm$ 6.8	1893,000 $\pm$ 1.6	4554,000 $\pm$ 9.5	1472,300 $\pm$ 5.1	1454,700 $\pm$.4	574,300 $\pm$.9	575,300 $\pm$ 5.1	< 1,000,000 mg/L
Biodegradability index	1.32	1.62	1.19	0.90	1.65	1.73	1.61	1.38	0.89	> 0.65
Toxicity										
LC₅₀ (mg/L)	1131	70.71	87.61	20.49	60.37	154.70	43.43	21.96	2213	> 500 mg/L
IC₂₅ (mg/L)	990.2	74.4	75.0	27.6	57.6	>100	15.4	13.5	1802	Not defined in Mil-Spec

The COD values reported in the Mil-Spec (4.7.12.2) reference those expected in a 3% foam solution. The formulation content required that each were diluted to 0.1% in order to make COD determinations with standard analytical reagents. The COD for the eight PFFs all fall below the 1 million mg/L limit defined in the Mil-Spec. The biodegradability index showed all foams were higher than the Mil-Spec threshold (0.65), thus susceptible to microbial oxidation processes. Notably the reference AFFF (0.89) met the Mil-Spec requirement, suggesting a valid approach and test methodology. The exceptionally high index for 7 of the 8 PFF is likely due to a combination of nitrogenous BOD demand and carbonaceous demand. Microbial oxidation of reduced nitrogenous compounds in the test samples from the surfactant composition and other additives will affect the BOD. Our earlier PFF biodegradation results reported to FAA (Summer 2021, not shown here) showed that AFFF and the PFF were not biodegradable using a standard commercial inoculum for BOD tests (Polyseed, Hach Company). Further scrutiny revealed the metabolic diversity in that inoculum was insufficient to reliably assess and evaluate foam biodegradability. By using an environmentally representative, and robust inoculum from a municipal wastewater treatment facility, the test revealed that the PFF are all biodegradable as defined by Mil-Spec criteria.

4.1.3. Quantitative PFAS and Fluorine Screening

The results from LC-MS analyses for PFAS in the PFF did not reveal PFAS in the samples. The analyses, however, were thoroughly scrutinized and those results were inconclusive. The PFF sample compositions produced excessive matrix interference that confounded detection of analytes. Additional extraction and filtration steps were done with aim to remove interfering materials and analytes. Those tests showed low recovery of the internal standards and poor quality, non-Gaussian chromatographs, accordingly there was no supporting data to quantify the

representative PFAS molecules, PFOS or PFOA. The complexity of the PFF sample matrix appears to severely affect chromatographic separation, spreading the analytes and internal standards well outside of their acceptable retention windows, as well as introducing nonlinear effects such as peak splitting, peak shouldering, and tailing. Further efforts to find better pretreatment processes, or analyzing samples at significantly higher dilutions (e.g., 1:10,000) could alleviate many of these conditions; however, there are risks to losing the analytes at such high dilutions, as well as elevating reporting limits to levels beyond usefulness.

As an alternative to quantifying individual PFAS molecules, total fluorine assays (organic and inorganic) were used as a quantitative measure of potential PFAS contamination. Both approaches may give indicators, but the total organic fluorine quantitation is likely best suited for this purpose. For this reason, additional samples were not evaluated for total fluorine content. Foam 1 contained the highest quantity of fluorine, 87 ppm. Foams 2, 4, and 5 all contained statistically equivalent concentrations (30, 29, 37 ppm, respectively). Foam 3 contained less than 10 ppm of fluorine, which was the lowest value of the tested PFF. The Mil-Spec did not list an acceptable range for fluorine, since it does not specifically address PFF, therefore, these values cannot be compared against the Mil-Spec directly. The target levels and recommendations must be made on the basis of documented regulations, that is, which molecule or class of molecules are regulated and what is the regulatory threshold. Values may be compared to known quantities of fluoride, such as allowable levels in city water, however with caution because some localities have higher natural fluoride contents; if used in manufacturing the PFF can exhibit skewed results. Until approved methods for measuring total organic fluoride are developed, caution must be used in interpreting results.

4.1.4. Stability, Stratification, and Precipitation

The accelerated aging study was designed to reveal whether and to what extent, PFF may degrade in storage. After the elevated temperature storage (65 °C, 10 days) all samples were inspected for signs of separation and changes from the original consistency and appearance. All PFF remained stable (no stratification) during the 10 days of the evaluation. Figure 3 shows examples of Foam 3 (left) and Foam 7 (right). As directed by the Mil-Spec, candidate foams that fail the aging portion are not evaluated for post-aging IFT or SFT; two candidate foams did undergo a repeated evaluation and showed no stratification after a second exposure. While these particular candidates did not separate, a color change was noted. Foam 3 darkened to a light amber from a relatively colorless starting material, and Foam 7 darkened from green to deep amber. These candidates were not pulled from further testing as they did not stratify, but the color change was recorded.

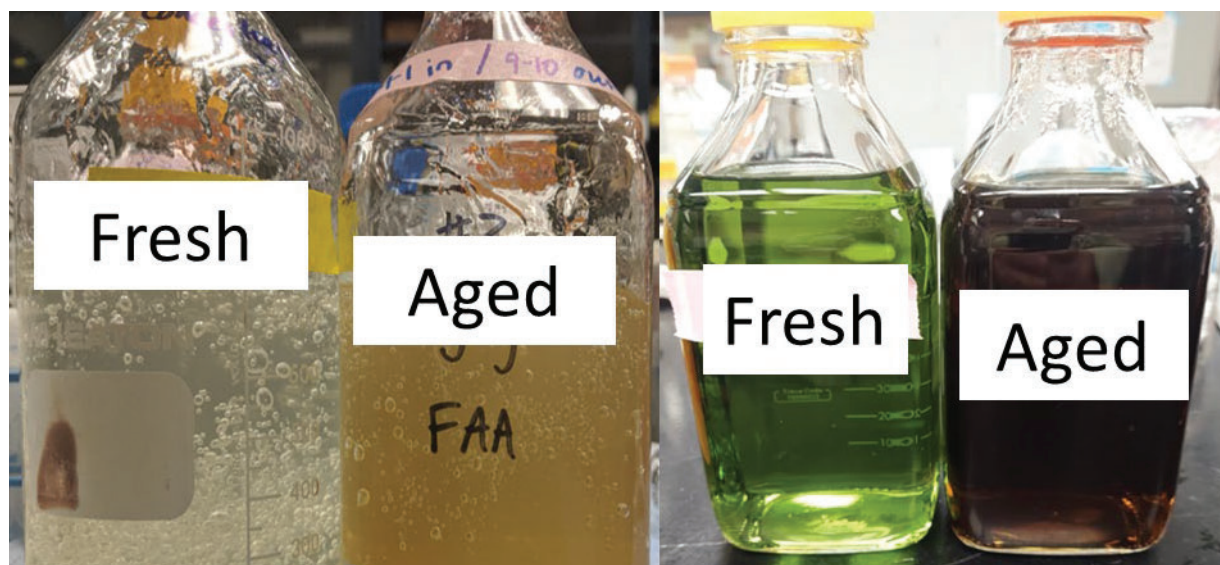


Figure 3. FAA Foam Aging Tests

Left Panel: FAA#3- from stock and post aging; Right Panel: FAA Foam #7- from stock and post aging

The precipitation evaluation consists of the appearance of any visible particulates after 5 minutes of centrifugation (500 RCF, 60 °C) (simple pass/fail designation). Precipitation tests were run on samples post-aging and in two different formats. The samples were either aged as a concentrate (then diluted to 3%) or a 3% solution, then precipitation protocol was applied. The AFFF standard passed the precipitation test, along with five of the PFF (samples 1, 3, and 5, 6, and 8). Candidates 2, 4, and 7 produced inconclusive results. Foam 2 separated into 2 almost indistinguishable, very milky layers in both the concentrate and 3% aged samples. Foams 4 and 7 formed a stable emulsion in the 3% aged sample, but produced a passing result in the aged as concentrate form.

Stability is an important criterion for shelf-life and storage. It is not necessarily a reason to down-select a candidate foam, because as long as you know a foam's shelf-life, you can simply work within the realm of its expiration for storage conditions such as time and temperature.

4.1.5. Interfacial Tension, Surface Tension, and Spreading Coefficient

The spreading coefficient is intended to represent how well a foam spreads to blanket a fuel source, such as a floating liquid fuel. The calculation includes measured values for foam samples and the standard hydrocarbon solvent, cyclohexane (24.42). None of the PFF reached the threshold "3" spreading coefficient defined in the Mil--Spec, meaning that no candidate exhibited a film-forming behavior utilized by the current standard AFFF. The spreading coefficient calculated for the tested PFF all show a negative value from $0 \geq -6$. The current candidate foams exhibit a different behavior (and vapor suppression mechanism) and will need to be evaluated against a different set of criteria since these new PFFs function very differently from the current Mil-Spec foam.

4.1.6. Combustion

The combustion analysis outlined for the PFF (Section 3.2.6) was not completed and cannot be included in the present technical report. Existing AFCEC-CXAE instrumentation has limited capability for screening and identifying combustion products from the TGA. The MS resolution and throughput capacity was not adequate to characterize the combustion products produced from the foams. The requirement has been addressed and a solution is in progress. An advanced GC-MS platform will be coupled with the TGA presently on site, this will allow us to continuously screen and characterize foam combustion products. The instrumentation is scheduled to be in operation in November 2022. The candidate foams in this report may be analyzed then, as appropriate, along with any other PFF or suppression agents of interest.

4.1.7. Toxicity

Both acute and chronic toxicity evaluations used PFF concentrate samples as the starting material for assays. The Mil-Spec specifies *Fundulus herteroclitus* (killiefish) for the test species; the killiefish, however, was not available for contracted testing. *Pimephales promelas* (fathead minnow) was substituted for the tests. The fathead minnow is a freshwater species commonly used for toxicology tests, the substitution undoubtedly differs from the Mil-Spec standard species, but direct comparison in side-by-side tests with the legacy AFFF was decided to be sufficiently representative to gauge relative toxicity and guide down-selection of PFF products.

The LC₅₀ (96-h exposure) is a measurement of acute toxicity while the assay for long-term toxic effects increased exposure time to 168-h. The lower the value, the more toxic the compound for both acute and chronic toxicity evaluations (20). As reference the AFFF representative and PFF #1 showed an LC₅₀ greater than the Mil-Spec value for killiefish (500 mg/L). The LC₅₀ of the other PFFs were all over an order of magnitude lower based on the quantitative measure (Table 4). The relative differences were consistent for both acute and chronic exposure tests. The absolute values should not be directly applied against the Mil-Spec (due to substituted test organism), but all were within the EPA's acceptable toxicity limit, ranging between "practically non-toxic" to "slightly toxic" (21).

The safety data sheet (SDS) for each PFF product was examined for the inclusion of substances containing compounds from the generic class of alkyl betaines. The compounds are widely used in cleansing products, shampoos, and cosmetics; environmental studies revealed significant toxicological effect to fishes (12, 13). Various derivative of alkyl betaines are noted in footer below Table 3. While the SDS for each PFF does list chemical constituents, they may be incomplete, and are not required to list all forms or classifications of compounds by invoking proprietary concerns. Table 5 summarizes the compounds that may be considered environmentally toxic. Inspection and analysis of the PFFs revealed a form and relative percentage of alkyl betaine compounds in four of the eight foams.

Table 5. Alkyl Amidobetaine Derivatives in Candidate Foams

Foam	Designation	Concentration (wt/vol)	CAS Number
1	Alkyl sulfates	<2.5%	Mixture
2	Alkyl betaine, Amphoteric surfactants	<2.5%, <2.5%	86438-78-0
3	N/A	N/A	N/A
4	Lauryl dimethylamine oxide		1643-20-5

5	Cocamidopropyl hydroxysulfaine	<20%	61789-40-0
6	N/A	N/A	N/A
7	Alkyl betaine, unspecified	<2.5%	Not Specified
8	Amines, ocoalkyldimethyl, N-oxides	<5%	617-88-90-7

Examples of molecules included in inspection of foam formulations:

- Aylamidobetaine
- Cocamidopropyl betaine
- AMPHOSOL CG-50, {[3-(Dodecanoylamino)propyl](dimethyl)ammonio} acetate
- 2-[(3-Dodecanamidopropyl)dimethylaminio]acetate
---(all trade names for CAS 61789-40-0)
- Lauramidopropyl betaine (CAS 86438-78-0),
- Cocamidopropyl betaine (12)

4.1.8. Corrosion

A low magnification (10X) inspection of the coupon surface was examined for occurrences of localized corrosion (for the S30400 stainless steel samples only). Foams 2 and 8 presented with pitting on a fraction (1/10 and 2/10, respectively) of the coupons. Additionally, Foam 2 exhibited a greater than allowable corrosion content on the Cu-Ni coupons, where all other foams had an allowable mass loss, the measure of corrosion used for this analysis. These evaluations are critical to the overall performance of a candidate foam, as corrosion of equipment or storage containers could create an expensive problem for end users.

4.1.9. Viscosity

Due to the wide variations in the properties of each PFFs, it was necessary to calculate the viscosity of the samples differently, resulting in two different measurement types. Foams 2, 4, 7-8, and baseline AFFF were all able to be measured with capillary viscometers 50, 150, or 200. Foams 1, 3, and 5-6 were so viscous and gel-like they were unable to be run on a capillary viscometer. They were also strongly shear thinning, meaning the viscosity readings changed with more shearing. Those samples were measured with the Brookfield viscometer and Helipath Stand, which allowed the T-bar spindle to constantly cut through fresh material providing an undisturbed reading of the viscosity. The minimum viscosity was reached for 25 °C, but Foams 1, 3, 5, and 6 all exceeded the maximum allowable value at 5 °C.

The Mil-Spec states the samples must not exceed a maximum viscosity of 20 cSt at 5 °C and a minimum viscosity of 2 cSt at 25 °C. Only Foam 2 and AFFF baseline met the viscosity requirements defined in the Mil-Spec (minimum 2, maximum 20 cSt), all other candidates presented with higher viscosities. Many of the candidate foams evaluated presented as non-Newtonian and do not fit within the current Mil-Spec standards they were tested against.

4.1.10. Foamability and Foam Drainage Time

Foamability tests were conducted on all eight PFFs in two ways 1) a 3% freshwater solution of aged concentrate and 2) an aged 3% freshwater solution. All eight PFFs met the minimum values outlined by Table 1 for both expansion ratio (5:1) and the minimum 25% drainage time (150s). The ability of a PFF candidate to produce a foam and move across a fire at a specific rate show

its ability to suppress the fire. The foam's viscosity and spreading coefficient values may contribute to this data point.

5. CONCLUSIONS

The results available for each of the PFF candidates are summarized below. The PFAS content and combustion product analyses were equivocal or incomplete. The preliminary results for those two criteria are not included, but later tests can be considered when the methodology is refined or instrumentation is sufficient for thorough analysis. The report may be amended and information provided to sponsor agency if directed. Summaries for each foam product are noted below.

Foam 1 (Bio-Ex Eco-Pol F3 HC) The PFF presented with both RI and pH below the Mil-Spec limit, by less than 2% difference from the Mil-Spec minimum requirement. The refractive index indicates the solvent concentration in a sample; this PFF had an RI between water and AFFF. An acidic pH could indicate that the foam may be corrosive to equipment or degrade the foam concentration. The total fluorine content of this product is 87 ppm, the highest of samples tested herein. There is no value given for fluorine content in the Mil-Spec, as these fluorine-free foams are not specifically discussed in the reference document, however the lower fluorine content may be considered more desirable for overall environmental impact. Some fluorine may be carryover from past product production or municipal water supplies and the value may vary as production increases. The corrosivity of the candidate PFF was evaluated via exposure tests to quantify the PFF per the requirements of the Mil-Spec. The PFF met the Mil-Spec corrosion rate and mass loss requirements for both localized and general corrosion parameters. The PFF underwent accelerated aging in a 65 °C oven and was observed for stratification at the end of 10 days. This PFF stratified once and was retested as per Mil-Spec requirement; the second time the foam did not separate. This is considered a passing result. The pre-aging spreading coefficient was calculated from the interfacial and surface tension measurements using the equation in the Mil-Spec and the measured cyclohexane as the interface. The spreading coefficient was calculated as -5.81. Foams that do not form a film during the film formation test and do not have a positive spreading coefficient are not easily compared to the current Mil-Spec's film formation requirement (23). When considering the flow properties of the foam, the thickness was so much greater (5 °C and 25 °C) than the Mil-Spec viscosity that it had to be calculated using a different method with different units (cP; converted to cSt). This material presented as a non-Newtonian fluid. This sample underwent post-aging precipitation and no precipitate formed, passing the evaluation for both aged concentrate and aged 3% solution (both run as a 3% solution). Spreading coefficient was recalculated and is the same magnitude as unaged samples (-5.14, -6.37, and -4.51, respectively). The COD (Mil-Spec standard 1000 K) is $382 \text{ K} \pm 12 \text{ K mg/L}$, used in correlation with the BOD as a metric for the biodegradability of the PFF candidates. While not specified explicitly in the Mil-Spec, BOD is necessary to calculate the biodegradability and, as such, is also considered in the selection of a candidate product. The quotient of the $\text{BOD}_{20}/\text{COD}$ yields the biodegradability index, Foam 1, 1.32, is higher than the Mil-Spec minimum value of 0.65; this would indicate the candidate PFF would more readily enter the environment. The LC_{50} , acute toxicity value was 1131 mg/L. This is higher (less toxic) than the Mil-Spec (500 mg/L), and is considered practically non-toxic by the scale established by the EPA (21). This PFF was the sole product that met the Mil-Spec toxicity parameter.

Foam 2 (Bio-Ex Eco-Pol A) The PFF had a lower RI parameter, within 1% under the Mil-Spec minimum. The viscosity ($2.38 \geq 4.31$) and pH (7.8) properties of the sample fall within the Mil-Spec ranges (5 °C, 25 °C, 7.0–8.5 pH). The total fluorine content of this product is 30 ppm. There is no value given for fluorine content in the Mil-Spec, as these new fluorine-free foams are not specifically discussed in the specifications, however, lower values are considered more desirable. The sample was aged and observed for stratification at the end of 10 days and showed no signs of stratification, meaning the sample was stable under the accelerated aging test. The precipitation tests were inconclusive, as both aged sample types showed a milky emulsion. The spreading coefficient was calculated for both pre- and post-aged product and all measured negative, which are not on the same scale as the Mil-Spec value, 3. A negative spreading coefficient implies that the product will not spread in the same manner as AFFF over a fuel pool, altering performance in a fire (23). Corrosion rates outside of the Mil-Spec limits were observed for C70600 Cu-Ni and C90500 bronze coupons, as well as localized corrosion testing. The COD value 351 K is within an acceptable value of the Mil-Spec value (1000 K). The BOD, a necessary value to calculate the biodegradability index (quotient of BOD₂₀ and COD), is also considered in the selection of a candidate foam. The ratio gives 1.62, which is considered more biodegradable than the Mil-Spec expected value of 0.65, which means the foam has a higher oxygen removal rate in water, but it needs to be considered that the product could break down even while in storage. The LC₅₀ was 70.71 mg/L, which is a lower value than the Mil-Spec, but is still considered only slightly toxic by the EPA category for toxicity (21).

Foam 3 (FomTec Enviro USP) The PFF falls within the acceptable RI and pH range (1.369, 7.63). Fluid properties reveal this sample's thickness fails both viscosity boundaries (the foam could not be evaluated on the same instrument, as it has a consistency of honey). The total fluorine content of this product is <10 ppm, the lowest value for a candidate in this study; however, there is no Mil-Spec or baseline value for comparison. The corrosivity of the candidate was evaluated via exposure tests to quantify the PFF, per the requirements of the Mil-Spec. This PFF satisfied the Mil-Spec for both general and localized corrosion rate and mass loss requirements. The sample was aged (65 °C, 10 days) and no stratification or precipitation was noted. The spreading coefficient was calculated for both the pre- and post-aged PFF (both concentrate and 3% solution). However, based on the Mil-Spec value, both pre-aged (-0.71) and two post-aged (-0.78, -1.86) results vary from the desired value, 3. A negative spreading coefficient implies that the product does not respond the same as AFFF and will not spread in the same manner over a fuel, altering performance in a fire. The COD (585 K $\pm$ 17 K mg/L), within acceptable range. The ratio of BOD₂₀ to COD is 1.19, which meets the Mil-Spec expected value (0.65), defining the PFF as biodegradable. The LC₅₀ was 87.61 mg/L. This is lower (more toxic) than the Mil-Spec, but is only considered slightly toxic by EPA standard (21).

Foam 4 (National Foam Avio F3 Green) The PFF is inside the limits for RI (1.381) value. The candidate PFF holds at the upper limit of the maximum allowable pH (8.5). A higher pH indicates a more basic material, which could have an effect on storage containers, predominately the inside of a fire truck, if the foam is stored long term. The corrosivity of the candidate was evaluated via general and localized exposure tests to quantify the PFF per the requirements of the Mil-Spec and met the corrosion rate and mass loss requirements. The fluid properties show this foam is higher (133, 5 °C, and 53.9, 25 °C) than the allowable maximum viscosity requirements in the Mil-Spec, meaning the liquid will be thicker when mixing. The total fluorine content of

this product is 29 ppm. There is no value given for fluorine content in the Mil-Spec, as these new fluorine-free foams are not specifically discussed in this document. PFF 4 was aged and observed for stratification at the end of 10 days. This candidate foam did not show any signs of stratification, passing the aging requirement. However, the precipitation data gave inconclusive results, creating an emulsion in the aged 3% solution. The spreading coefficient was calculated for both pre- and both post-aged samples (-2.52, -2.69, and 0.77, respectively). However, based on the Mil-Spec value, 3, a negative spreading coefficient implies that the product will not spread properly over a fuel, altering fire performance. The COD is 893K mg/L, the highest of all candidates evaluated here, but is still considered a passing value as compared to the higher Mil-Spec value of 1000 K. The biodegradability ratio, 0.90, meets the Mil-Spec expected value (0.65). Due to the higher BOD and subsequent biodegradability results, this points to the candidate foam showing future concerns in the environment in regards to dissolved-oxygen content in the watershed, pointing to anaerobic conditions and aquatic life disruption. This is coupled with the LC₅₀, 20.49 mg/L, the lowest and most toxic of this study. Even though this is lower than the Mil-Spec requirement, it still does not exceed Fish and Wildlife's threshold for an acutely toxic substance (22), and the EPA lists this value as a slightly toxic product (21).

Foam 5 (Solberg Rehealing RF3) meets both RI (1.382) and pH (7.0 ± 0.01) range. The total fluorine content of this product is 37 ppm. There is no comparative value as, these fluorine-free foams are not specifically discussed in the Mil-Spec, however, as fluorine free products, the lower values are desired. Fluid properties reveal the highly non-Newtonian nature of this sample (32075, 5 °C, and 24210, 25 °C) with greater than the required viscosity allowable range (20 at 5 °C, and 2.0 at 25 °C). The sample was aged (65 °C, 10 days) and observed for stratification and precipitation; the candidate foam stratified once and was retested. The second attempt yielded a passing reading, while the precipitation passed both sets of aged samples. The pre-aging spreading coefficient was calculated from the interfacial and surface tension measurements using the equation in the Mil-Spec and the specified cyclohexane as the interface. The Mil-Spec value for spreading coefficient is 3, but this candidate's value was calculated as -5.83, -6.32, and -6.73 for non-aged, aged as concentrate, and aged solution. Foams that do not form a film during the film formation test and do not have a positive spreading coefficient fail the film formation requirement (23). Foam 5 passed the precipitation requirement on both aged sample types. The corrosivity of the candidate was evaluated via exposure tests to quantify the PFF per the requirements of the Mil-Spec and met the Mil-Spec corrosion rate and mass loss requirements. COD (554 K mg/L) was lower than the maximum allowable, 1000 K mg/L, Mil-Spec standard. The ratio between COD and BOD₂₀ is the biodegradability of the foams as the standard is 0.65, with this sample coming in 1.65, more biodegradable than AFFF. The LC₅₀ was 60.37 mg/L, lower (more toxic) than the Mil-Spec, but again does not reach the US Fish and Wildlife threshold (21) and maintains a slightly toxic EPA rating.

Foam 6 (Firebull F3) The PFF presents with an acceptable value for RI, while the pH (6.8) falls just below the minimum boundary (1%). Fluid properties reveal this sample's thickness fails both viscosity boundaries (the foam could not be evaluated on the same instrumentation, as it has a consistency of hair gel). The total fluorine content was not collected for this sample. The corrosivity of the candidate was evaluated via exposure tests to quantify the PFF per the requirements of the Mil-Spec and satisfied the Mil-Spec for both general and localized corrosion rate and mass loss requirements. The sample was aged (65 °C, 10 days) and no stratification or

precipitation was noted. The spreading coefficient was calculated for both pre- and post-aged (both concentrate and 3% solution). However, based on the Mil-Spec value, both pre-aged (-1.97) and two post-aged (-1.80, -2.28) results vary from the desired value, 3. A negative spreading coefficient implies that the product does not respond the same as AFFF and will not spread in the same manner over a fuel, altering performance in a fire. The COD (585 K $\pm$ 17 K mg/L), within acceptable range. The ratio of BOD₂₀ to COD is 1.73, which exceeds the Mil-Spec threshold value (0.65). The LC₅₀ was 154.7 mg/L. This is lower (more toxic) than the Mil-Spec, but is considered practically non-toxic by standard (21).

Foam 7 (BioEx ECOPol A3+) falls just below the minimum boundary (0.1%) for RI (1.362), but falls within the acceptable pH range (8.2). Both viscosity values fall within the Mil-Spec boundaries. The total fluorine content was not collected for this sample. The corrosivity of the candidate was evaluated via exposure tests to quantify the PFF per the requirements of the Mil-Spec and satisfied the Mil-Spec for both general and localized corrosion rate and mass loss requirements. The sample was aged (65 °C, 10 days) and no stratification or precipitation was noted. The spreading coefficient was calculated for both pre- and post-aged (both concentrate and 3% solution). However, based on the Mil-Spec value, both pre-aged (-0.83) and two post-aged (-0.63, 0.08) results vary from the desired value, 3. A negative spreading coefficient implies that the product does not respond the same as AFFF and will not spread in the same manner over a fuel, altering performance in a fire. The COD (454.7K mg/L), within acceptable range. The ratio of BOD₂₀ to COD is 1.61, which meets the Mil-Spec expected value (0.65). The LC₅₀ was 43.43 mg/L. This is lower (more toxic) than the Mil-Spec, but is only considered slightly toxic by standard (21).

Foam 8 (Solberg Avigard 3B) falls within the Mil-Spec values for RI (1.391) and pH (7.9). The 25 °C viscosity value (14.5 cSt) viscosity value falls within the Mil-Spec boundaries, but the 5 °C value (29.9 cSt) is 2% over the Mil-Spec value, which is closer than the majority of the candidates tested herein. The total fluorine content was not collected for this sample. The corrosivity of the candidate was evaluated via exposure tests to quantify the PFF per the requirements of the Mil-Spec and exhibited pitting calculated as 2/10 on the stainless steel, but the general corrosion coupons showed no effect from the foam. The sample was aged (65 °C, 10 days) and no stratification or precipitation was noted. The spreading coefficient was calculated for both pre- and post-aged (both concentrate and 3% solution). However, based on the Mil-Spec value, both pre-aged (-1.37) and two post-aged (-1.60, -0.98) results vary from the desired value, 3. A negative spreading coefficient implies that the product does not respond the same as AFFF and will not spread in the same manner over a fuel, altering performance in a fire. The COD (574.3K mg/L), within acceptable range. The ratio of BOD₂₀ to COD is 1.38, which meets the Mil-Spec expected value (0.65). The LC₅₀ was 21.96 mg/L. This is lower than the Mil-Spec, but is considered practically non-toxic by standard (21).

6. RECOMMENDATIONS

Due to environmental and human health concerns about the fluorinated surfactants used in AFFF, the FAA is required (Title 14 Code of Federal Regulation (CFR) Part 139) to find a suitable non-fluorinated foam for use in class B aircraft fire scenarios. The current standard for AFFF used by the United States Department of Defense and the FAA is MIL-PRF-24385, with updated standards (2019). This contains requirements not just for fire testing performance, but

also selected physical and chemical properties of the fire-fighting foam. The physical and chemical properties of selected commercial PFF were examined using the current version of the Mil-Spec and compared to PhosCheck 3% as a standard AFFF baseline material. If a commercial PFF product satisfied all criteria outlined in the present standard, the transition could be a simple exchange of AFFF with a replacement PFF. The chemical properties of PFF, however, are distinct because they have very different formulations. Moreover, the fire suppression mechanisms of PFF and AFFF are distinct. Due to all those collective factors, a direct, drop-in, substitution is not realistic. Instead, the detailed results of the comparison reveal physical attributes that may be considered for new guidelines or shortcomings in PFF formulations that must be addressed in order to make transition from AFFF. Additionally, there are no standardized methodologies for evaluation of the PFF for direct comparison of results across organizations. For candidate PFF to be considered, test methods need to be created to assist in the uniform evaluation of products.

None of the representative PFF satisfy the entire list of relevant Mil-Spec designations. The basic physiochemical and toxicological properties tested here may assist the FAA in making preliminary selections for replacement options. The properties may not correlate specifically to utility in fire suppression or extinguishment. The AFFF Mil-Spec is an appropriate guide for the initial physiochemical characterization of the PFF. Using the strict values established for AFFF for each factor may not necessarily be appropriate or relevant to evaluation. For example, the refractive index for AFFF is intended to estimate the concentration of the “active ingredients” of the agent. The PFF are chemically distinct from the legacy AFFF concentrate; accordingly, one should not expect a characteristic like refractive index to match in the final product. Measuring and comparing the indices is reasonable, but not to consider as a pass/fail factor for selection. Viscosity is another characteristic that may need additional context. The suppression agent’s viscosity will affect mixing, proportioning, and delivery of a working solution. Significant differences will block a PFF as a drop-in replacement in present equipment. Modification or replacement of select components in the delivery platform could accommodate a PFF concentrate with significantly different viscosities. Other physical characteristics like spreading and toxicity are relevant indicators for suppression performance and safety—critical for utility and release of any firefighting agent. Nonetheless, even those criteria may be modified in light of the new product class. Comparisons to other industrial and consumer chemicals should be considered to aid in the evaluation of these PFF. For example, the toxicity of all foams tested qualify as “slightly toxic” or less according to EPA guidance (22), which can facilitate incorporation.

The standardized methods show the PFF materials and AFFF standard are all “biodegradable” as qualified under Mil-Spec. Biodegradability is a critical issue for products that when used as intended are directly released to the environment (e.g., pesticides, herbicides, some cleaning products). The persistence of chemicals in the environment is strongly associated with their susceptibility to microbial breakdown. Accordingly, the products are classified and regulated to limit environmental effects. An inoculum including a microbial community that readily adapts or has metabolic versatility to breakdown surfactants is needed for reliable determination of biodegradability of fire extinguishing agents. The exceptionally high BOD should be noted as a potential environmental impact in the event of direct release to environment (e.g., effect on DO content in surface waters).

Fire suppression tests using PFF were not performed as part of this project but are obviously necessary in the search to determine the next generation of foam fire suppression agents. Projects including “live-fire” evaluation are active at AFCEC-CXAE, its partners, and other service laboratories and agencies. The practical performance results will be balanced with the results of the environmental and toxicological effects in order to find whether an acceptable option is available from commercial or developmental products. The balance is a challenge but the regulations will be directed by NDAA (24). Final ranking and potential selection of the PFF will blend the— physical, chemical, and practical (performance) properties based on input and discretion of FAA and other user communities.

7. REFERENCES

1. Performance Specification, Fire Extinguishing Agent, Aqueous Film -Forming Foam (AFFF) Liquid Concentrate, For Fresh and Sea Water Mil-Spec MIL-PRF-24385F(SH), w/INT. AMENDMENT 3, (7 May 2019).
2. Rice, E.W., Baird, R.B., Eaton, A.D. and Clesceri, L.S., 2012. Standard methods for the examination of water and wastewater, American Public Health Association. American Water Works Association, Water Environment Federation.
3. Light Emitting Diode (LED) vs High pressure Sodium/Low Pressure Sodium Comparison. Stouch Lighting Staff, 03/11/2016. Stouch Lighting, 525 Turner Industrial Way, Aston, PA 19014. <https://www.stouchlighting.com/blog/led-vs-hps-lps-high-and-low-pressuresodium#:~:text=Sodium%20vapor%20bulbs%20contain%20metals,are%20the%20modern%20day%20equivalent> (accessed 04/27/2021).
4. Wayne, B., 1997. The science of chemical oxygen demand technical information series. *Hach Company, USA*, p.22.
5. Young, J.C. et al (editors). 2012. 5210-Biochemical Oxygen Demand (BOD). Standard Methods for the Examination of Water and Wastewater, 21st edition, American Public Health Association-American Water Works Association-Water Environment Federation, Washington, USA, pp.5-4.
6. Young, J.C. et al (editors). 2012. 5210C-Ultimate (20-Day) Biochemical Oxygen Demand (BOD). Standard Methods for the Examination of Water and Wastewater, 21st edition, American Public Health Association-American Water Works Association-Water Environment Federation, Washington, USA, pp.5-12.
7. Shoemaker, J. and Tettenhorst, D., 2018. Method 537.1: determination of selected per- and polyfluorinated alkyl substances in drinking water by solid phase extraction and liquid chromatography/tandem mass spectrometry (LC/MS/MS). National Center for Environmental Assessment, Washington, DC.
8. Galbraith Laboratories Inc., Determination of Total Fluorine by Oxygen Flask Combustion and Ion-Selective Electrode. Method Summary E9-3, Rev 15.
9. Quality Control Procedures, QSM 5.9.1., Laboratory Quality System Requirements, US Environmental Protection Agency. Revision 3.0 (Nov 5, 2007).
10. ASTM D96-88(1998), Standard Test Methods for Water and Sediment in Crude Oil by Centrifuge Method (Field Procedure) (Withdrawn 2000), ASTM International, West Conshohocken, PA, 1998.
11. ASTM D1331-14, Standard Test Methods for Surface and Interfacial Tension of Solutions of Paints, Solvents, Solutions of Surface-Active Agents, and Related Materials, ASTM International, West Conshohocken, PA, 2014.
12. Belsito, D.V., Hill, R.A., Klaassen, C.D., Liebler, D.C., Marks Jr, J.G., Shank, R.C., Slaga, T.J. and Snyder, P.W., 2017. Safety Assessment of Alkyl Sulfates as Used in Cosmetics. https://www.cir-safety.org/sites/default/files/alkbet032014final_0.pdf
13. The use of PFAS and fluorine-free alternatives in fire-fighting foams, 2020, final draft. European Commission DG Environment and European Chemicals Agency.
14. ASTM E527-16, Standard Practice for Numbering Metals and Alloys in the Unified Numbering System (UNS), ASTM International, West Conshohocken, PA, 2016.
15. ASTM D1141-98(2013), Standard Practice for the Preparation of Substitute Ocean Water, ASTM International, West Conshohocken, PA, 2013.

16. ASTM G1-03(2017)e1, Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens, ASTM International, West Conshohocken, PA, 2017.
17. ASTM G31-21(2021)/ NACE TM0169-2021, Standard Guide for Laboratory Immersion Corrosion Testing of Metals, ASTM International, West Conshohocken, PA, 2017.
18. ASTM D445-19a, Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity), ASTM International, West Conshohocken, PA, 2019.
19. NFPA 412: Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment, 2020 Edition. In *NFPA National Fire Codes Online*. Retrieved from <http://codesonline.nfpa.org>
20. USEPA, 2019. Technical Overview of Ecological Risk Assessment-Analysis Phase, Ecological Effects Characterization.
21. Risks of Naled Use to Federally Threatened California Red Legged Frog (*Rana aurora draytonii*) Pesticide Effects Determination Environmental Fate and Effects Division Office of Pesticide Programs, U.S.EPA, 2008, Washington, D.C. 20460
22. Johnson, W.W. and Finley, M.T., 1980. Handbook of acute toxicity of chemicals to fish and aquatic invertebrates: Summaries of toxicity tests conducted at Columbia National Fisheries Research Laboratory, 1965-78 (Vol. 137). US Department of the Interior, Fish and Wildlife service.
23. Understanding Foam Results Series - Film Formation & Spreading Coefficient. Dyne, September 2016. <https://www.dyneusa.com/understanding-foam-results-series-film-formation-spreading-coefficient-september-2016>.
24. National Defense Authorization Act for Fiscal Year 2020.S. 1790 116th Cong. (2019). <https://www.govtrack.us/congress/bills/116/s1790/text/es>

LIST OF ABBREVIATIONS AND ACRONYMS

AFCEC/CXAE	Air Force Civil Engineer Center
AFFF	aqueous film forming foam
ARFF	Aircraft Rescue and Fire Fighting
ASTM	American Society for Testing and Materials
BOD	biological oxygen demand
COD	chemical oxygen demand
CFR	Code of Federal Regulation
COTS	commercial off the shelf
cP	centipoise
cSt	centistokes
DI	deionized water
DO	dissolved oxygen
DOD	Department of Defense
DSC	differential scanning calorimetry
EPA	US Environmental Protection Agency
FAA	Federal Aviation Administration
PFF	PFAS-free foam
IC ₂₅	25% inhibition concentration -toxicant concentration that affects noted action or characteristic in 25% of the test population
IFT	interfacial tension
LC ₅₀	50% lethal concentration -toxicant concentration that kills 50% of the test population following exposure period
LC	liquid chromatograph
MPY	milli-inches per year
Mil-Spec	Military Specification MIL-PRF-24385F(SH)
MS	mass spectrometer
NOEC	no observed effect concentration
PFAS	per- and polyfluoroalkyl Substances
PFF	PFAS-free foam
PFHxA	perfluorohexanoic acid
PFHxS	perfluorohexane sulfonate
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonate
pH	hydrogen ion concentration
PNEC	predicted no effect concentration
PPE	personal protective equipment
QSM	Quality Systems Manual
RI	refractive index
RCF	relative centrifugal force
S	spreading coefficient
SCF	seed correction factor
SDS	safety data sheet
SFT	dynamic surface tension
SPE	solid phase extraction
TGA	thermogravimetric analysis

