

FINAL REPORT

Validation of Fluorine-free AFFF against Military Specification Performance Criteria

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14. ABSTRACT Twelve PFAS-free foams (PFFs) were tested against MIL-PRF-24385F specification for Class B fire suppressants. Two engineering solutions, namely compressed air foam (CAF) and ultra-high pressure (UHP) foam delivery, were tested to determine the improvement in firefighting performance of PFFs. The PFFs failed the ecotoxicity and biodegradability specification, generally being considered slightly toxic. These products failed some of the corrosion tests and some of the other physical property tests, especially spreading coefficient. All PFFs failed fire-extinguishment time specification, and a few failed the burnback time specifications, but CAF delivery significantly improved both for all PFFs. On average, the extinguishment time was reduced by about 40%, but still fell short of the specification. The CAF testing at medium-field (315-ft ²) scale showed that the extinguishment time was not significantly different than at Mil-Spec (28-ft ²) scale. The UHP technology also has shown considerable promise, but the demonstration of its true potential requires larger field-scale testing. Both CAF and UHP technologies help to significantly reduce the foam use, and thus the operating costs for extinguishing Type B fires.					
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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFCEC	Air Force Civil Engineer Center
AFFF	Aqueous Film-Forming Foam
ANSI	American National Standards Institute
ARFF	Aircraft Rescue and Fire Fighting
ASTM	American Society for Testing of Materials
BOD	Biological Oxygen Demand
CAF	Compressed Air Foam
CAFS	Compressed Air Foam System
CAS	Chemical Abstracts Service
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CO ₂	Carbon Dioxide
COD	Chemical Oxygen Demand
Co-PI	Co-Principal Investigator
COTS	Commercial Off-the-Shelf
DACS	Data Acquisition Control System
DI	Deionized Water
DoD	Department of Defense
DT ₅₀	50% Biodegradation Time
E0	Ethanol-free
E10	Gasoline with 10% Ethanol
EPA	Environmental Protection Agency
ER	Expansion Ratio
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Authority
FIRE	Fire Integrated Research and Engineering
GCR	General Corrosion Rate
gpm	Gallons per Minute
HNO ₃	Nitric Acid
HP	Horsepower
HRET	High-Reach Extendible Turret
IC ₂₅	Inhibition Concentration 25%
ICAO	International Civil Aviation Organization
IFT	Interfacial Tension
IMCOM	United States Army Installation Command

LC ₅₀	Lethal Concentration 50%
LED	Light Emitting Diode
LOEC	Lowest Observed Effect Concentration
MAJCOM	Major Air Command
NAVSEA	Naval Sea Systems Command
NDAA	National Defense Authorization Act
NFPA	National Fire Protection Agency
NOEC	No Observed Effect Concentration
PFAS	Perfluoroalkyl Substance
PFF	PFAS-free Foam
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctanesulfonic Acid
PI	Principal Investigator
POC	Point of Contact
PPE	Personnel Protective Equipment
PTO	Power Take-Off
RI	Refractive Index
ROM	Rough Order of Magnitude
RT	Room Temperature
Sb ₂ O ₃	Antimony Oxide
SDS	Safety Data Sheet
SERDP	Strategic Environmental Research and Development Program
SFT	Surface Tension
SnCl ₂	Stannous Chloride
TRL	Technology Readiness Level
TSCA	Toxic Substance Control Act
UHP	Ultra-High Pressure
UL	Underwriters Laboratory
US	United States
USAF	United States Air Force
USS	United States Ship
WWTP	Wastewater Treatment Plant

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The Principal Investigator (PI) was Dr. Satya P. Chauhan of Battelle. The members of the project team and their contributions are presented in the table below.

WP19-5299 Team

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Andrew McMeans	Battelle	Mil-Spec-scale and medium-size, field-scale fire testing; reporting
Julie Bryant	Battelle	Lab-scale fire and Mil-Spec-scale fire testing; reporting
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Kris Cozart	Battelle	Design and integration of CAF and UHP skids
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ABSTRACT

OBJECTIVE

The objectives of this proposed project were to (a) rigorously evaluate commercial off-the-shelf (COTS) perfluoroalkyl substance (PFAS)-free foams (PFFs) (previously referred to as fluorine-free aqueous film-forming foams [fluorine-free AFFFs or FF-AFFFs]) to determine where they fall short of MIL-PRF-24385F specifications; (b) determine whether commonly available firefighting engineering technology such as compressed air foam (CAF) or ultra-high pressure (UHP) and/or minor chemical modifications will allow the foams to meet the required standards of extinguishment and burnback times; and (c) demonstrate the CAF and UHP technologies at field scale.

TECHNOLOGY DESCRIPTION

Several COTS PFFs are available, but none of them currently meet the very stringent MIL-PRF-24385F specifications, especially for the extinguishment time (30 seconds maximum), and for some, the burnback time (360 seconds minimum). It is known that extinguishment and burnback times can be altered by affecting the quality of the foam produced. Both CAF and UHP are known to affect foam formation, and by adjusting the amount of air injection, pressure, and flow rates, one can choose the foam quality necessary (balancing spreadability with longevity) to extinguish a fire. PFF modifications can be (1) chemical (i.e., taking dry agents that cannot be used to combat fire alone and combining them with the PFFs); or (2) physical (e.g., delivering PFFs with UHP systems that can reach higher output pressures than traditional firefighting systems). Additionally, minor issues such as slightly higher than acceptable corrosion rates could be addressed by the manufacturer by simple formula changes, such as adding a corrosion inhibitor. By combining both the engineering and the chemical solutions, it was expected that one or more PFFs could be modified to meet the standards of MIL-PRF-24385F, thus allowing the United States (US) military to switch to a more environmentally friendly firefighting agent. Some branches of the US military were already advocating for brands/formulations of environmentally friendly COTS firefighting agents. By conducting this work, we have been able to comprehensively test and evaluate nine of the COTS PFFs against both MIL-PRF-24385F and each other, and determine which best fit the needs of the Department of Defense (DoD).

PERFORMANCE AND COST ASSESSMENT

The benefits to DoD from validating and demonstrating viable AFFF alternatives that are fluorine-free (especially PFAS-free) are (a) significant DoD operational and maintenance cost savings; and (b) a reduction in environmental risk. A preliminary economic analysis indicates that PFFs are ~10% to 20% cheaper than equivalent MIL-PRF-24385F grade fluorine-based concentrates. A 2011 study estimated that the DoD expends 157,000 gallons of AFFF concentrate per year, suggesting a potential DoD savings of \$1.4 million to \$2 million annually in foam purchase costs alone. Savings would also be realized on the reduced need for compliance and remediation. The estimated Technology Readiness Level (TRL) after completion of this project is 8/9, which should allow immediate implementation of the successful PFFs DoD wide, thus helping to meet the National Defense Authorization Act (NDAA) passed by Congress in 2020 requiring that the military assess and then implement foam alternatives that do not contain perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS). Additionally, this technology demonstration/validation will greatly help civil aviation reduce the environmental impact via use of fluorine-free PFFs that meet or exceed the performance of currently used fire suppressants.

IMPLEMENTATION ISSUES

The initial step in stakeholder acceptance of this technology is the inevitable release of the new Mil-Spec in October 2023. If it is determined that CAF or UHP, or a combination of both, is required for PFFs to achieve acceptable fire performance, modifications to existing systems will be required. Even if the new Mil-Spec can be met using conventional foam delivery, firefighters may choose to deploy CAF and UHP to reduce the quantity of foam required to extinguish fires. The United States Air Force (USAF) Aircraft Rescue and Fire Fighting (ARFF) fleet is already equipped with UHP vehicles but is not so widely equipped with CAF. The CAF and UHP technologies are tools that may be more effective in some scenarios and less in others. It may not be necessary (or indeed practical) to retrofit every firetruck with both delivery systems so long as both capabilities are distributed across the response fleet. In future procurements as the firefighting fleet is updated, it is expected that such technologies will become integrated as standard requirements, but lifecycle and sustainment analysis would have to be extensively completed ahead of an acquisition plan.

For trucks currently in the fleet, existing hardware could have trouble proportioning PFFs, as some of the new formulations are highly viscous. Regardless, every truck in the fleet that has operated with AFFF will need to be cleaned to remove the remaining fluorine. Furthermore, the firefighting techniques required to extinguish fires with PFFs are somewhat different than the techniques used with AFFF, so firefighters may have to be retrained.

PUBLICATIONS

The following publications resulted from this project:

Chauhan, S., “Assessment of Commercially Available PFAS-Free Foams,” SERDP/ESTCP Webinar #120, October 22, 2020.

Chauhan, S., “Progress in Enhancing Mil-Spec Performance of mature PFAS-Free Foams,” presented in Foams and Emulsions; PFAS-Free Foams and Understanding Bubbles, SERDP-ESTCP Symposium, Enhancing DoD’s Mission Effectiveness, December 1, 2020.

Chauhan, S., “Progress in Enhancing Performance of PFAS-Free Foams (PFFs) against Military Specification Criteria,” presented to Wisconsin Department of Natural Resources, October 15, 2021.

Chauhan, S. and A. McMeans, “Performance of Next Generation of Firefighting Agents against Military Specification Criteria,” presented at AFCEC/CXAE 2nd Annual Fire Protection Workshop, November 17, 2021.

Chauhan, S., “Demonstration of Selected Approaches for Enhancing Performance of PFAS-Free Foams,” presented at SERDP-ESTCP Symposium, Enhancing DoD’s Mission Effectiveness, December 1, 2021.

EXECUTIVE SUMMARY

INTRODUCTION

Aqueous film-forming foam (AFFF) is a robust Class B firefighting foam that has been widely used by militaries, municipal airports, and industrial sites since it was developed by the United States (US) Navy and the 3M Corp in the 1960s. The foam contains perfluoroalkyl substances (PFAS), whose unique surfactant properties make it a powerful and robust firefighting agent. Unfortunately, PFAS are also toxic, persistent, and have a propensity to bioaccumulate. Over the past two decades, the use of PFAS, primarily perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), has become increasingly regulated by governments across the world. In 2006, leading manufacturers of PFOA agreed to join a voluntary effort to phase out the use of this specific PFAS chemical. PFOA molecules in the AFFF formulation were replaced with smaller perfluorinated surfactants (i.e., 6-carbon chains as opposed to “C8” PFAS in the legacy foam). The replacement molecules in the C6 AFFF products, however, present comparable environmental persistence and potential hazards as the original AFFF. Increasing concerns over PFAS as a class of chemicals has led both the public and regulatory agencies to demand firefighting foam manufacturers discontinue the use of foams containing any perfluorinated-compounds in the formulation.

Pressure on the Department of Defense (DoD) to find a PFAS-free fire extinguishing agent has been increasing since the 2017 National Defense Authorization Act (NDAA), which directed the DoD to begin assessing potential replacements. More recently, the 2020 NDAA requires the DoD cease the use of AFFF (with the exception of use on maritime vessels) by October 1, 2024. Additionally, it is required that the Naval Sea Systems Command (NAVSEA) release an updated version of the Mil-Spec for PFFs by October 2023.

While many PFAS-free foams (PFFs) have emerged on the market over the past two decades, none of them are able to match the fire-extinguishment performance of AFFF. Engineered foam delivery methods such as ultra-high pressure (UHP) and compressed air foam (CAF) systems (CAFS) have previously been shown to improve the performance of AFFF. This project evaluated commercial off-the-shelf (COTS) PFFs against the MIL-PRF-24385F (Mil-Spec) and used CAF and UHP to evaluate their effect on the fire-extinguishment and suppression performance of various PFFs.

OBJECTIVES

The objectives of this proposed project were to (a) rigorously evaluate COTS PFFs to determine where they fall short of MIL-PRF-24385F specifications; (b) determine whether commonly available firefighting engineering technology such as CAF or UHP and/or minor chemical modifications will allow the foams to meet the required standards of extinguishment and burnback times; and (c) demonstrate the CAF and UHP technologies at field scale.

Performance objectives were based on evaluation against the Mil-Spec, including the engineering evaluation of PFFs with CAF and UHP on Mil-Spec (28-ft²) scale fires to validate the technology and allow for a down-select of PFF candidates before proceeding to large-scale fires in United States Air Force (USAF) relevant environments (i.e., Air Force Civil Engineer Center [AFCEC] fire test facility at Tyndall Air Force Base [TAFB]). **Table ES-1** covers the performance objectives and results for physical, corrosivity, and environmental properties. The objectives and results for firefighting properties are listed in **Table ES-2**.

Table ES-1. Performance Objectives and Results for Physical, Corrosivity, and Environmental Properties

Performance Objective	Data Requirement	Success Criteria	Result
Quantitative Performance Objective			
Physical properties testing (Section 4.7.1 – 4.7.4)*	Refractive index (RI)	RI: >1.3630	• None meet all requirements • Some PFFs are highly non-Newtonian • Some barely failed pH & RI • All fail spreading coefficient
	Viscosity	Viscosity: 25°C: >2 cSt 5°C: <20 cSt	
	pH	pH: 7.0<pH<8.5	
	Spreading coefficient	Spreading coefficient: >3	
Corrosivity testing (Section 4.7.7)	Low carbon steel (UNS G10100)	UNS G10100: < 1.5 milli in/yr	• 10 of 12 passed all • 2 others with partial failures
	Copper/Nickel (UNS C70600)	UNS C70600: <1.0 milli in/yr	
	Nickel/Copper (UNS NO4400)	UNS NO4400: <1.0 milli in/yr	
	Bronze (UNS C90500)	UNS C90500: <100 mg	
	Localized, corrosion resistant steel (CNS S30400)	CNS S30400: no pitting	
Environmental Impact (Section 4.7.13)	LC ₅₀ (Fathead minnows)	LC ₅₀ : <500 mg/L	• PFFs generally “slightly toxic” • All PFFs tested and C6 AFFF pass BOD₂₀/COD spec • All meet COD spec
	Chemical oxygen demand (COD)	COD: <1000K mg/L	
	Biological oxygen demand (BOD ₂₀)/COD	BOD ₂₀ /COD: >0.65	
Stability (Section 4.7.17)	Stratification	Stratification: No visible evidence	• 10 of 12 passed stratification requirements
	Precipitation	Precipitation: 0.05% by volume	

**Notations in brackets refer to the respective sections of the Mil-Spec.*

Optimal operating conditions for field testing were found via lab-scale and Mil-Spec-scale testing. The top-performing foams were tested in outdoor testing at a medium scale (i.e., 315-ft²) and a large scale (i.e., 6,504-ft²).

Table ES-2. Performance Objectives and Results for Firefighting Properties

Performance Objective	Data Requirement	Success Criteria	Result
Quantitative Performance Objective for 28-ft² Mil-Spec Scale, Gasoline Fires			
Foamability/ Drain Time	Expansion ratio (ER)	ER: ≥ 5	All PFFs pass
	25% foam drain time	25% drain time: ≥ 150 s	
90% Control	Heat flux	N/A to Mil-Spec	Measured
Fire Extinguishment	Stopwatch	Extinguishment time: ≤ 30 s	• No PFF passed with Mil-Spec nozzle (3 of 12 failed to extinguish) • 40% lower extinguishment time with CAF (1 of 12 failed to extinguish)
Burnback/ Cold Burnback	Stopwatch Heat flux	Burnback time: ≥ 360 s	• 6 of 12 passed with Mil-Spec nozzle • All 12 passed with CAF
Field-scale Performance Objective (315-ft² with Gasoline and Jet-A; 6,504-ft² with Jet-A)			
Extinguishment Time Handling/ Usability	Stopwatch Testing notes	Fire control and extinguishment	• Yes, for all 4 PFFs tested so far with CAF • Yes, for all 4 PFFs tested so far with UHP

TECHNOLOGY DESCRIPTION

PFAS-Free Foams (PFFs)

Non-fluorinated foams, like the original protein-derived firefighting foams that preceded AFFF, generally do not spontaneously form the vapor-suppressing films that allow for rapid fire extinguishment. Although some siloxane-based surfactants are contenders for rapid-film-forming behavior, none are yet able to meet the performance of traditional PFAS-reliant AFFF [1]. The majority of PFFs on the market utilize a blend of anionic and zwitterionic surfactants. Stabilizing agents used in these products can lead to them being very viscous; some rely on xanthan gum or polymer gels, which contributes to highly non-Newtonian behavior.

Compressed Air Foam (CAF) Delivery

Aspirating nozzles such as the Mil-Spec nozzle rely on the venturi effect to create foam. Just before the nozzle exit, there is a constricted area of flow, so the liquid pressure drops, forcing air into the foam matrix (**Figure ES-1**). Unlike conventional aspirating nozzles, CAFS inject air into the liquid line carrying the water/foam solution (**Figure ES-1**). There are three main zones in a CAFS: the air injection, development, and discharge zones. In the air injection zone, high pressure air is injected into a lower pressure liquid stream. The gas liquid mixture then moves through the development zone, where the flow through the plumbing of the system alters the foam structure to form a more uniform bubble distribution. In the discharge zone, foam is dispensed from a special nozzle that allows for little to no constriction upon exiting, which helps maintain the foam expansion.

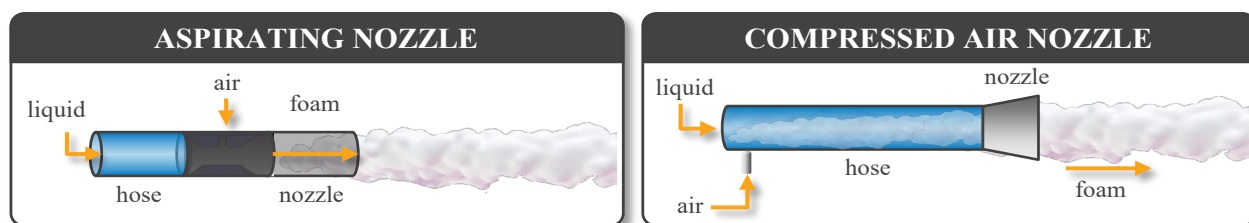


Figure ES-1. Foam Delivery Using an Aspirating Nozzle (Left Panel) vs. CAF (Right Panel)

Liquid foam is made up of gas bubbles entrapped within a liquid. As liquid drains from the foam structure, bubbles merge and gas diffuses between neighboring bubbles, causing the liquid to fall or drain out of the foam matrix, leaving behind a skeletal structure of larger bubbles encapsulated in thinner layers of liquid. Eventually, these remaining bubbles also rupture, and only the liquid remains. The rate of foam drainage is controlled by multiple factors. The rate that liquid escapes the foam matrix is driven by gravity and capillary action, which is driven by local changes in liquid pressure. Inside the foam matrix, drainage is countered by liquid holdup due to friction between descending liquid and ascending gas. As liquid leaves the foam matrix, the foam coarsens (i.e., the thin liquid layers between bubbles break, causing bubbles to merge); this is called coalescence. Over time, gas will move through the liquid layer between the bubbles in a process called differentiation.

CAFS typically produce foams that are more stable and slower-draining than foams from self-aspirating nozzles such as the Mil-Spec nozzle. This is due to the smaller, more uniform bubble distribution that CAF creates. After exceeding the optimal foam expansion, the liquid walls between bubbles become thin, increasing the rate of rupturing and drainage. Thus, the fire performance of over-expanded foams begins to taper off.

Ultra-High Pressure (UHP) Foam Delivery

UHP foam delivery is defined by the National Fire Protection Agency (NFPA) as foam delivered at 1100 psi or above. UHP has been shown to have a positive impact on firefighting, reducing the amount of AFFF needed to extinguish a fire by up to 33%. In this pressure range, the liquid agent forms extremely small droplets, on the scale of 90–100 μm upon release from the nozzle. This results in faster cooling due to increased surface area. UHP also allows for a more concentrated layer of AFFF to form at the surface of the fuel layer [2]. With increasing pressure, flow rates can be lowered to achieve the same extinguishment time. As delivery pressure increases, less agent is required to achieve the same extinguishment performance.

Table ES-3. COTS PFF Products Tested and Code Numbers

COTS PFF Vendor, Product	PFF No. or Foam No.
Phos-Chek®, 3–6% AFFF (C6) Baseline	0
FireAde®, Fluorine Free	1
Novacool®, UEF/ Novacool	2
Phos-Chek®, 1% Fluorine Free	4
Phos-Chek®, 3% Fluorine Free	5
Solberg, Re-Healing™ RH3	6
Fomtec®, Enviro USP 3%	7
BioEx, Ecopol A	8
BioEx, Ecopol A+	8.2
BioEx, F3HC	9
National Foam, Universal Green 3%	10
Pyrocool®, Pyrocool FEF	11
National Foam, Avio® Green KHC	12

PERFORMANCE ASSESSMENT

COTS PFFs

A total of 12 COTS PFFs (i.e., foams) shown in Table ES-3 were included in performance assessments. Each PFF was assigned a number for easier referencing in charts and tables. All PFFs were tested on a consistent basis for whatever performance testing was carried out. For field testing, a total of five PFFs were selected based on their fire-extinguishment performance at Mil-Spec (28-ft²) scale and due to budget limitations.

Environmental Fate and Toxicity

The acute and chronic toxicity results, for fathead minnows, for six PFFs are shown in Table ES-4. Based on the LC₅₀ data, obtained per ASTM E279, these products fit the EPA category of “slightly toxic.”

Table ES-4. Toxicity Results for Various COTS PFF Products

PFF	Acute LC₅₀ (mg/L)	Chronic NOEC (mg/L)	Chronic LOEC (mg/L)	Chronic IC₂₅ (mg/L)
PFF 1/ FireAde®	>120.0*	120.0	>120.0	>120.0
PFF 2/ Novacool®	56.6	20.0	40.0	37.8
PFF 4/ Phos-Chek® 1%	56.4	40.0	80.0	47.6
PFF 5/Phos-Chek® 3–6%	>80.0*	80.0	>80.0*	>80.0*
PFF 6/Solberg RH™3	66.2	40.0	80.0	52.9
PFF 7/Fomtec Enviro USP	70.7	40.0	80.0	55.1

*IC₂₅: Inhibition Concentration 25%; LC₅₀: Lethal Concentration 50%; LOEC: Lowest Observed Effect Concentration; NOEC: No Observed Effect Concentration. *=No LOEC was found.*

The BOD₂₀ and COD data for C6 AFFF (Foam No. 0) are shown in Table ES-5. BOD₂₀ values are based on a recently revised 20-day BOD test using a conditioned inoculum. As shown the biodegradability (BOD₂₀/COD) exceeds the 0.65 spec. Several values exceed the expected limit of 1.00 due to presence of nitrogen compounds that do not react well with the chemical oxidant but do cause BOD signal.

Table ES-5. BOD₂₀ and COD Results (mg/L) for Various COTS PFF Products

Foam Product	COD	BOD ₂₀	Biodeg Index
AFFF Mil-Spec ¹	575,300	514,800	0.89
PFF 1	407,000	678,824	1.67
PFF 2	734,000	1,028,393	1.40
PFF 4	605,000	499,950	0.83
PFF 5	229,300	1,631,110	7.11
PFF 6	521,600	525,300	1.01
PFF 7	372,700	356,850	0.96
PFF 8	378,600	881,043	2.33
PFF 8.2	446,300	323,900	0.73
PFF 9	300,700	877,318	2.92
PFF 10	456,000	1,071,344	2.35
PFF 11	570,000	NA	-
PFF 12	894,000	745,200	0.83

¹COD and BOD₂₀ are results from previous work done by AFCEC/CXAE technical team in program.

NA: Not measured.

Physical Properties

There were two most notable findings. First, the spreading coefficients of the PFFs ranged from 0.36 to -4.48 compared to 6.95 for C6 AFFF and a Mil-Spec value of at least 3. Thus, the PFFs are not film forming. Second, several PFFs are quite viscous and non-Newtonian, failing the 5C viscosity specification of 20 cp (max). Data for various physical properties are shown in Table ES-6.

Table ES-6. pH, Viscosity, RI, and Density Results for Various COTS PFF Products

Foam Product	pH	Viscosity 5C (cSt)	Viscosity 25 C (cSt)	RI	Density (g/cm3)
AFFF	8.05	6.99 (k)	3.29 (k)	1.367	1.01
PFF 1	6.66	47400 (b)	27900 (b)	1.335	1.04
PFF 2	7.02	99.8 (k)	47.7 (k)	1.3875	1
PFF 4	6.76	7.95 (k)	3.99 (k)	1.375	0.96
PFF 5	7.38	6770 (b)	5340 (b)	1.3605	1.08
PFF 6	7.33	45900 (b)	25100 (b)	1.6875	1.04
PFF 7	7.4	15400 (b)	13200 (b)	1.3715	1.26
PFF 8	7.95	4.12 (k)	2.33 (k)	1.334	0.99
PFF 8.2	8.01	26.20 (k)	11.36 (k)	1.3617	1.03
PFF 9	6.86	19100 (b)	13900 (b)	1.3335	1.1
PFF 10	7.31	4600 (b)	4190 (b)	1.332	1.1
PFF 11	7.74	12.7 (k)	8.74 (k)	1.325	1.1
PFF 12	8.33	145 (k)	60.1 (k)	1.3827	1

Key: k=kinematic viscometer, b=Brookfield viscometer (dynamic)

Corrosion Performance

Ten out of 12 COTS PFFs evaluated passed the corrosion requirements set out in the Mil-Spec (Table ES-7). The other two had partial failures, with PFF 11 only failing on the bronze coupon, and this limitation potentially can be addressed by the addition of a corrosion inhibitor. One product (i.e., PFF 2) was corrosive for all metal coupons except for Ni-Cu and may require reformulation to meet corrosion requirements of any current or future Mil-Spec.

Table ES-7. Corrosion Results for COTS PFF Products

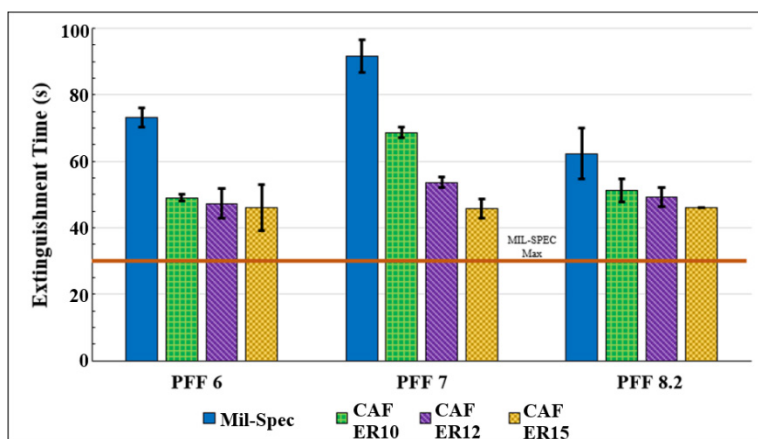
		Material Type			
		G10100 Steel	C70600 Cu-Ni	N04400 Ni-Cu	C90500 Bronze
Mil-Spec Max (mpy)		1.5	1	1	100 mg mass loss
Foam Product	AFFF	0.98	0.01	0.00	6.02
	PFF 1	0.36	0.41	0.01	45.66
	PFF 2	1.50	2.47	0.12	138.78
	PFF 4	0.81	0.98	0.00	85.26
	PFF 5	0.04	0.01	0.00	38.74
	PFF 6	0.18	0.02	0.02	17.98
	PFF 7	0.12	0.84	0.01	68.8
	PFF 8	0.23	0.16	0.04	56.14
	PFF 8.2	0.34	0.98	0.01	93.13
	PFF 9	0.13	0.16	0.04	30.38
	PFF 10	0.12	0.19	0.04	23.17
	PFF 11	1.02	0.84	0.01	131.84
	PFF 12	0.400	0.21	0.00	28.26

Red Values = Failing, Green Values = Passing

CAF Fire Testing

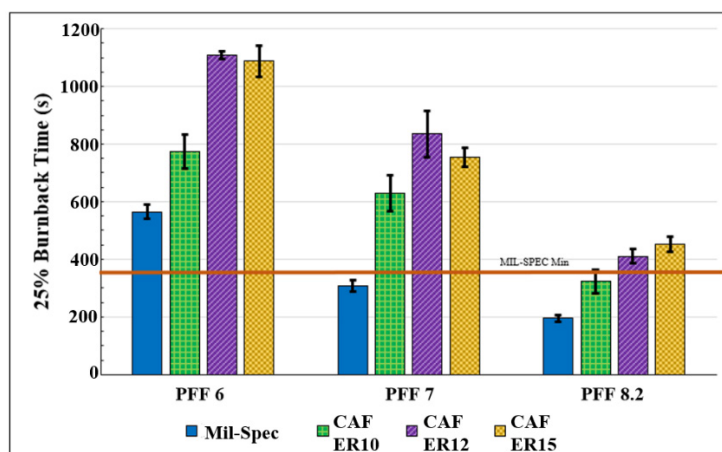
Fire testing with CAF was carried out at three scales: laboratory scale (0.4-ft²); Mil-Spec scale (28-ft²); and field scale (315-ft²). After some exploratory testing at the lab scale, extensive testing was carried out at Mil-Spec scale. Lab testing indicated that CAF performance depended on the foam expansion ratio (ER). Results of CAF optimization testing at Mil-Spec scale for ethanol-free (E0) gasoline (gas) are shown in Figure ES-2. The biggest enhancement in fire performance with CAF was at ER 10. Increasing the ER further from ER 10 to ER 12 only provided small improvement, averaging 9.7%, and from ER 12 to ER 15, exhibited a similar improvement, averaging 8.2%. It should be noted that the typical ER for these PFFs with a Mil-Spec nozzle is 6–8.

Figure ES-2. Effect of CAF ER on Extinguishment Time (28-ft², E0 Gas)



The effect of ER on burnback time can be seen in Figure ES-3. The same plateau in performance can again be observed when increasing from ER 12 to ER 15. Therefore, all subsequent CAF testing at Mil-Spec as well as at field scale was done at an ER 12.

Figure ES-3. 25% Burnback Times with CAF for 28-ft² E0 Gas Fires



The comparative CAF performance data for gas fires, for various PFFs at the optimum ER 12 are shown in Figure ES-4 (i.e., extinguishment time) and Figure ES-5 (i.e., burnback time). As seen, the use of CAF resulted in the extinguishment time being reduced by an average of 40% and the burnback time being increased by 100%, compared to the use of a Mil-Spec (self-aspirating) nozzle.

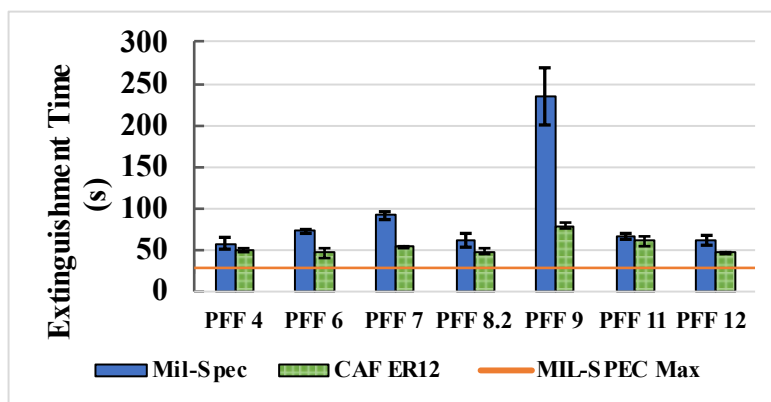


Figure ES-4. Comparison of Extinguishment Times for E0 Gas Fires for Mil-Spec Nozzle vs. CAF at ER 12

Based on the Mil-Spec-scale testing, the following four PFFs were down-selected for field-scale testing:

PFF 4 (Phos-Chek®, 1% Fluorine Free)

PFF6 (Re-Healing™ RH3)/ Solberg)

PFF 7 (Enviro USP 2–3%/ Fomtec®)

PFF 8.2 (Ecopol A+/ BioEx)

PFF 12 (Avio® Green KHC/ National Foam).

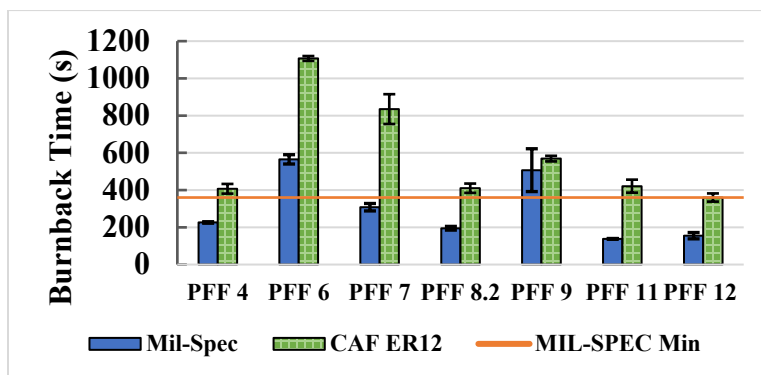


Figure ES-5. Comparison of Burnback Times for E0 Gas Fires for Mil-Spec Nozzle vs. CAF at ER 12

While other PFFs have potential as viable Mil-Spec PFF candidates, our budget only allowed testing five PFFs, so we selected the ones that had relatively better performance.

The Mil-Spec nozzle and CAF at ER 12 data for these down-selected PFFs, with E0 gas, are summarized in Table ES-8.

Table ES-8. Summary of 28-ft² E0 Gas Fire Test Data for PFFs Down-selected for Field-Scale CAF Testing

Product	Mil-Spec Nozzle		CAF (at ER 12)	
	Extinguishment Time, s	Burnback Time, s	Extinguishment Time, s	CAF Burnback Time, s
PFF 4	58±7	226±4	50±3	407±26
PFF 6	73±3	565±25	47±5	1107±13
PFF 7	92±5	308±20	54±2	835±80
PFF 8.2	62±8	195±10	49±3	410±25
PFF 12	63±6	155±17	48±1	360±22

Since the revised Mil-Spec for on-shore applications is likely to specify testing with Jet-A fuel as well as E0 gas, tests were also conducted with Jet-A on the down-selected PFFs. The extinguishment times for Jet-A fires at 28-ft² scale are shown in Figure ES-6.

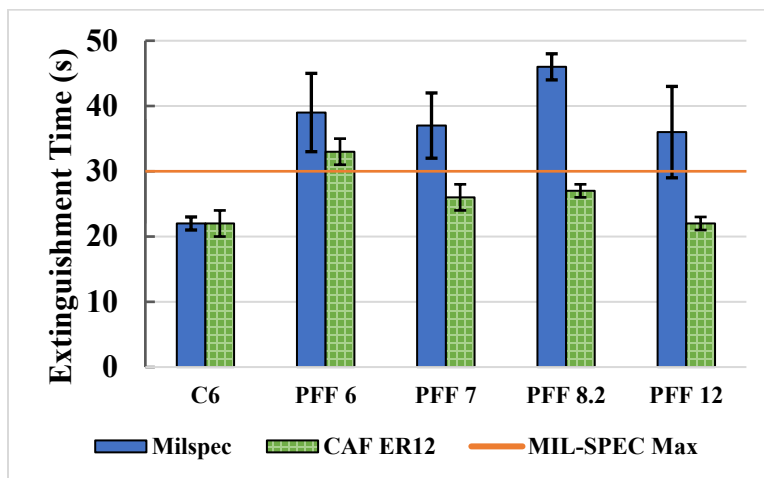


Figure ES-6. Extinguishment of 28-ft² Jet-A Fires with C6 and selected PFFs with Mil-Spec Nozzle vs. CAF (at ER 12)

CAF testing at medium-size field scale (i.e., 315-ft²) demonstrated that all PFFs selected for testing extinguished the Jet-A or the gas fires. CAF results with E0 gas fires for the four PFFs were quite comparable to C6 AFFF, as shown in Figure ES-7. The CAF performance at 315-ft² on Jet-A for all five down-selected PFFs was also quite comparable to C6 AFFF.

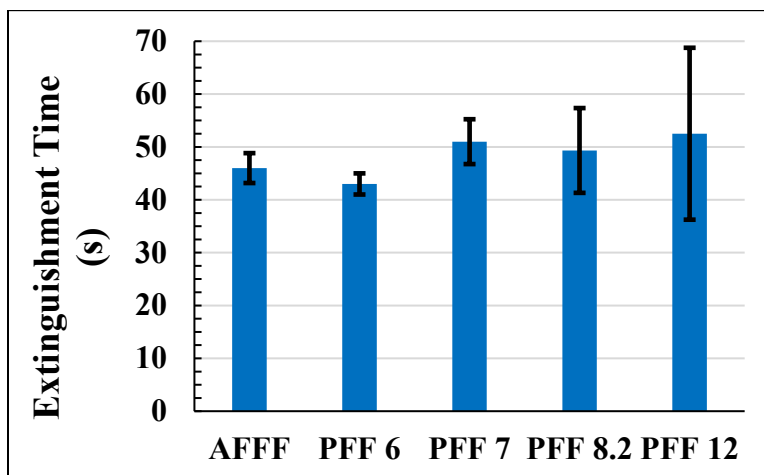


Figure ES-7. Extinguishment Time for 315-ft² E0 Gasoline Fires with CAF at ER 12

CAF fire testing with E0 gas was conducted at three separate scales with PFF 6, 7, 8.2, and 12. Each set of tests was conducted in triplicate at ER 12. Figure ES-8 shows a graphical comparison of extinguishment times. The average difference in extinguishment time between the lab scale and Mil-Spec scale was about 20%, mostly due to a significantly larger difference for PFF 12. The average difference in extinguishment time between the Mil-Spec scale and medium-size field (i.e., 315-ft²) scale was just 4%. This suggests that lab-scale testing can be used as a tool to screen PFFs before conducting much more expensive Mil-Spec scale testing.

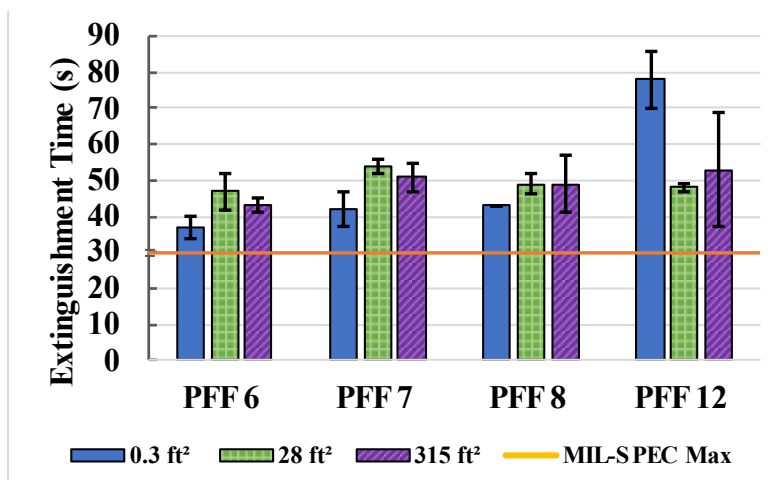


Figure ES-8. E0 Gasoline Fire Extinguishment Time for Lab-, Mil-Spec-, and Field-Scale with CAF @ ER 12

UHP Fire Testing

UHP testing was conducted with E10 gas at 28-ft² scale as well as with Jet-A at 315-ft² scale. The 28-ft² scale turned out to be too small to be able to control the foam delivery. This problem was corrected at the larger scale, and the results were quite promising.

PFFs 4, 6, 7, 8.2, and 12 were tested with UHP at 3% concentration and 20 gallons per minute (gpm) at the 315-ft² field scale. All PFFs were successful in extinguishing the Jet-A fires, while the use of water alone failed to extinguish the fire at this scale. The extinguishment times for PFF 6 and 8.2 were 50 seconds (Figure ES-9), as compared to 180 seconds at the 28-ft² scale. It is believed that the full potential of UHP technology can be further demonstrated at a yet larger field scale. Therefore, tests are planned for UHP testing, under the companion WP20-5335 project, at the 6,504-ft² scale.

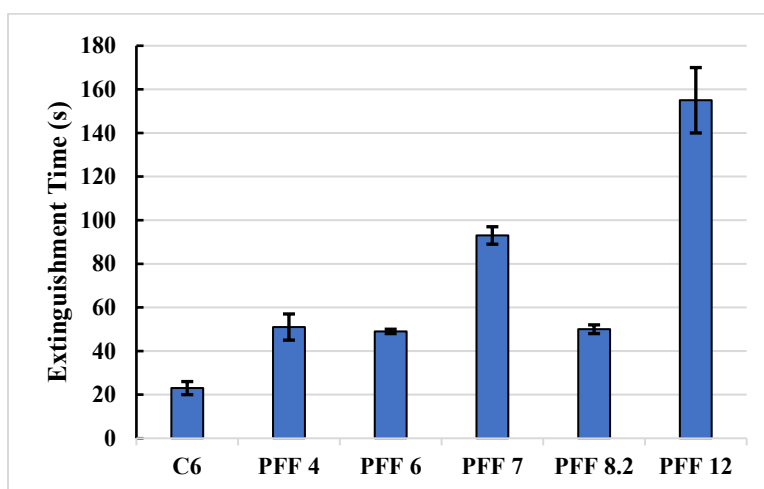


Figure ES-9. Extinguishment Time for Jet-A Fires with UHP at 315-ft²

COST ASSESSMENT

The NDAA mandate dictates that the shift to a PFF will be made regardless of cost. Accordingly, it is critical to estimate the extent that the shift to PFF will affect operating and equipment budgets. Initial projections have been made using present costs of the commercially available foams and estimated costs for retrofitting or replacing firefighting equipment with enhanced foam delivery systems such as CAF and UHP. There is potential for significant cost changes from the estimates. As the demand expands, an economy of scale or market competition may reduce costs.

A fire truck with CAFS is 10–20% more expensive than a standard platform. Currently, fire trucks can be retrofitted with a customized CAF system for \$30,000–\$50,000, eliminating the need to purchase a whole new fleet if CAF improvement of PFF performance merits the retrofit. The USAF currently fields a few UHP systems for flight line fires. The cost of retrofitting a larger truck to UHP is unknown, but the success of UHP research has encouraged development of UHP P-19s, which are available for purchase.

Both CAF and UHP have been previously shown to substantially reduce the amount of AFFF product needed to extinguish a fire. Testing with PFFs in this project showed that CAF helped reduce the extinguishment time by an average of 44%. Data were used to conduct a preliminary analysis of the foam cost savings from use of CAF over conventional (i.e., air-aspirating) nozzles. Since the large-tote selling prices for PFFs are not readily available, we looked at published prices of 5-gallon pails. Using these prices and the extinguishment times from trials, relative costs for using PFF with CAF and conventional foam delivery were calculated and are summarized in Table ES-9. The first estimates reveal an initial foam cost increase over AFFF. The absolute cost is dependent on a combination of the product price and the effectiveness.

Additional extrapolation of the data can be applied to rationalizing the transition to CAF on DoD platforms. A 2011 report estimated that the USAF used 2,826,000 gallons of AFFF per year at a cost of \$18 per gallon (\$22.32 in 2022 dollars, for total cost of ca. \$66 million). Applying the relative costs from Table ES-9, the foam cost using CAF is twice that total, and standard air aspiration three times that total. Realizing that savings would mean all platforms need to have that technology; the upgrade through retrofitting and replacing platforms is a complex and expensive proposition. It is estimated that there are substantial savings in PFF foam cost (i.e., of the order of \$60 million annually) possible via fleet-wide retrofitting with CAF.

Table ES-9. Relative Cost for Various PFFs for Fighting a 28-ft² Fire

PFF	Price/ Unit	Relative Price	Relative Quantity with CAF	Relative Quantity w/o CAF	Relative Cost with CAF	Relative Cost w/o CAF
1 & 15 (FireAde®/ FireBull)	\$118.75	0.94	1.64	2.60	1.54	2.43
4 (Phos-Chek® 1%)	\$166.50	1.31	1.67	1.94	2.19	2.55
5 (Phos-Chek® 3–6%)	\$95.00	0.75	2.84	4.88	2.13	3.65
6 (Solberg Re-Healing™ 3–6%)	\$120.00	0.94	1.58	2.44	1.49	2.31
7 (Fomtec® Enviro USP)	\$214.00	1.69	1.79	3.06	3.02	5.15
8.2 (Ecopol A+)	\$128.30	1.01	1.64	2.08	1.66	2.10
Average	\$140.43	1.11	1.66	2.83	1.98	3.03

The main savings provided by the shift from AFFF to PFFs will be reduced waste management burden and the associated long-term environmental restoration or remediation costs. Even with replacement of AFFF with PFFs, there will continue to be compliance costs related to handling wastewater. As such, a substantial reduction in compliance costs will result from foam usage reduction possible with the shift to CAF and UHP. A detailed payback analysis, including the cost of retrofitting and/or replacing existing Aircraft Rescue and Fire Fighting (ARFF) trucks with CAF and UHP, should be carried out when the costs for retrofitting are better known.

IMPLEMENTATION ISSUES

The initial step in stakeholder acceptance of this technology is the inevitable release of the new Mil-Spec in October 2023. If it is determined that CAF or UHP, or a combination of both, is required for PFFs to achieve acceptable fire performance, modifications to existing systems will be required. Even if the new Mil-Spec can be met using conventional foam delivery, firefighters may choose to deploy CAF and UHP to reduce the quantity of foam required to extinguish fires.

The USAF ARFF fleet is already equipped with UHP vehicles but is not so widely equipped with CAF. CAF and UHP technologies are tools that may be more effective in some scenarios and less in others. It may not be necessary (or indeed practical) to retrofit every firetruck with both delivery systems so long as both capabilities are distributed across the response fleet. In future procurements as the firefighting fleet is updated, it is expected that such technologies will become integrated as standard requirements, but lifecycle and sustainment analysis would have to be extensively completed ahead of an acquisition plan.

For trucks currently in the fleet, existing hardware could have trouble proportioning PFFs, as some of the new formulations are highly viscous. Regardless, every truck in the fleet that has operated with AFFF will need to be cleaned to remove the remaining fluorine. Furthermore, the firefighting techniques required to extinguish fires with PFFs are somewhat different than the techniques used with AFFF, so firefighters may have to be retrained.

1.0 INTRODUCTION

1.1 BACKGROUND

Aqueous film-forming foams (AFFFs) are robust Class B firefighting foam that have been widely used by militaries, municipal airports, and industrial sites since it was developed by the US Navy and the 3M Corp (Maplewood, MN) in the 1960s. The foam contains perfluoroalkyl substances (PFAS), whose unique surfactant properties make it a powerful and robust firefighting agent. Unfortunately, PFAS are also toxic, persistent, and have a propensity to bioaccumulate [3]. Over the past two decades, the use of PFAS, primarily perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) has become increasingly regulated by governments across the world. In 2006, leading manufacturers of PFOA agreed to join a voluntary effort called the “2010/2015 PFOA Stewardship program” to phase out the use of this specific PFAS chemical [4]. PFOA molecules in the AFFF formulation were replaced with smaller perfluorinated surfactants (6-carbon chains as opposed to “C8” PFAS in the legacy foam). The replacement molecules in the C6 AFFF products, however, present comparable environmental persistence and potential hazards as the original AFFF [5]. Increasing concerns over PFAS as a class of chemicals has led both the public and regulatory agencies to demand that firefighting foam manufacturers discontinue the use of foams containing any perfluorinated-compounds in the formulation.

While many PFAS-free foams (PFFs) have emerged on the market over the past two decades, none of them are able to match the fire-extinguishment performance of AFFF. Engineered foam delivery methods, such as ultra-high pressure (UHP) and compressed air foam (CAF) systems (CAFS), have previously been shown to improve the performance of AFFF [6–8]. This project evaluated commercial off-the-shelf (COTS) PFFs against the MIL-PRF-24385F (Mil-Spec) and then used CAF and UHP to evaluate their effect on the fire-extinguishment and suppression performance of various PFFs.

1.2 OBJECTIVE OF DEMONSTRATION

The objectives of this proposed project were to (a) rigorously evaluate COTS PFFs to determine where they fall short of MIL-PRF-24385F specifications, (b) to determine if commonly available firefighting engineering technology such as CAF or UHP, and/or minor chemical modifications, will allow the foams to meet the required standards of extinguishment and burnback times, and (c) to demonstrate the CAF and UHP technologies at field scale.

The first objective was to characterize and evaluate the PFFs using the criteria laid forth for AFFF in the Mil-Spec. Collected information included various properties, such as on corrosivity, aquatic toxicity, biological and chemical oxygen demand (BOD and COD), viscosity, surface and interfacial tension, and stability. Some of these data provide information on the ability to directly drop these replacements into use, without any modification to existing plumbing systems, such as viscosity, corrosivity, and aging. Some characteristics can also be used to make preliminary evaluations on environmental impact, such as toxicity and oxygen demands. Other information, including refractive index (RI) and pH, is used to characterize the foam products and solutions.

The second objective was to rigorously evaluate the effect of UHP and CAF on PFF fire suppression in standard strength, freshwater Mil-Spec fire tests. While the Mil-Spec demands 42 different 28-ft² fire tests, assessing variables such as use of seawater, agent concentration, dry chemical compatibility, and performance of aged solutions; the objective of this program was more oriented toward assessing the impact that delivery methods have on fire-extinguishment performance. Standard strength freshwater 28-ft² fires were the benchmark criteria used to judge fire performance.

The third objective was to demonstrate the fire-extinguishment performance at field scale, employing commercially available foam delivery equipment. Optimal operating conditions were found via lab-scale and Mil-Spec-scale testing and then the top-performing foams were tested in outdoors testing at a medium (315-ft²) and a large (6,504-ft²) scale.

1.3 REGULATORY DRIVERS

Pressure on the Department of Defense (DoD) to find a PFAS-free fire extinguishing agent has been increasing since the 2017 National Defense Authorization Act (NDAA), which directed the DoD to begin assessing potential replacements. More recently, the 2020 NDAA requires that the DoD ceases use of AFFF (with the exception of use on maritime vessels) by October 1, 2024. Additionally, it is required that the Naval Sea Systems Command (NAVSEA) release an updated version of the Mil-Spec for PFFs for shore-based applications by 2023.

In April 2021, the Environmental Protection Agency (EPA) established the EPA Council on PFAS to address contamination from this class of chemicals. In October of the same year, they released a “roadmap” encompassing plans to increase research, regulate use, and remediate contamination. The agency is currently in the rule-writing phase to regulate PFAS under the Toxic Substance Control Act (TSCA) and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). EPA has announced their regulatory decision for two PFAS chemicals (the 8-carbon PFOS and PFOA) and are in the process of implementing national primary drinking water regulations explicitly pertaining to those two molecules. The initial formal regulatory moves, however, may expand and affect the availability of other PFAS chemicals to manufacturers and further additions [9].

2.0 DEMONSTRATION TECHNOLOGY

The section provides a summary of the primary technologies utilized during this demonstration (Section 2.1), a history of that development (Section 2.2), and a discussion of the advantages and limitations of that technology in respect to the state of the art (Section 2.3).

2.1 TECHNOLOGY DESCRIPTION

2.1.1 PFAS-Free Foams (PFFs)

Non-fluorinated foams, like the original protein-derived firefighting foams that preceded AFFF, generally do not spontaneously form the vapor-suppressing films that allow for rapid fire extinguishment. Although some siloxane-based surfactants are contenders for rapid-film-forming behavior, none are yet able to meet the performance of traditional PFAS-reliant AFFF [1]. The majority of the PFFs on the market utilize a blend of anionic and zwitterionic surfactants. The stabilizing agents used in these products can lead to them being very viscous: some rely on xanthan gum or polymer gels which contributes to highly non-Newtonian behavior.

2.1.2 Compressed Air Foam (CAF) Delivery

Aspirating nozzles, such as the Mil-Spec nozzle rely on the venturi effect to create foam. Just before the nozzle exit, there is constricted area of flow, so the liquid pressure drops, forcing air into the foam matrix (Figure 1). Unlike conventional aspirating nozzles, CAFS inject air into the liquid line carrying the water/foam solution (Figure 1). There are three main zones in a CAFS: the air injection, development, and discharge zones. In the air injection zone, high pressure air is injected into a lower pressure liquid stream. The gas liquid mixture then moves through the development zone, where the flow through the plumbing of the system alters the foam structure to form a more uniform bubble distribution. In the discharge zone, foam is dispensed from a special nozzle that allows for little to no constriction upon exiting, which helps maintain the foam expansion [10].

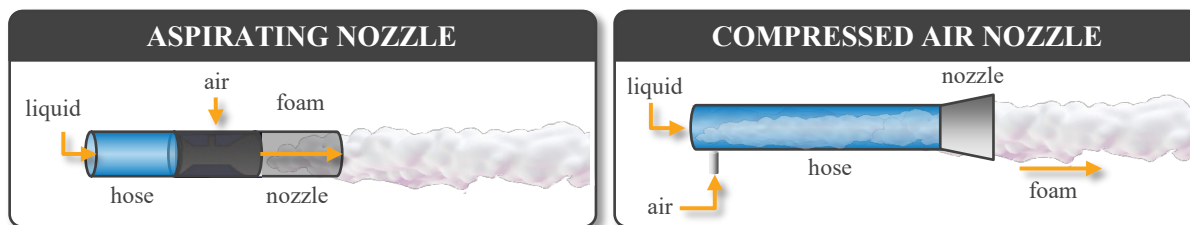


Figure 1. Foam Delivery Using an Aspirating Nozzle (Left Panel) vs. CAF (Right Panel)

A liquid foam is made up of gas bubbles entrapped within a liquid. As liquid drains from the foam structure, bubbles merge and gas diffuses between neighboring bubbles, causing the liquid to fall or drain out of the foam matrix, leaving behind a skeletal structure of larger bubbles encapsulated in thinner layers of liquid. Eventually, these remaining bubbles also rupture and only the liquid is left. The rate of foam drainage is controlled by multiple factors. The rate that liquid escapes the foam matrix is driven by gravity and capillary action, which is driven by local changes in liquid pressure [11]. Inside the foam matrix, drainage is countered by liquid holdup due to friction between descending liquid and ascending gas. As liquid leaves the foam matrix, the foam coarsens (i.e., the thin liquid layers between bubbles break, causing bubbles to merge); this is called coalescence.

Over time, gas will move through the liquid layer between the bubbles in a process called differentiation. A wide distribution of bubble sizes is characteristic of “differentiated” foam [12].

CAFS typically produce foams that are more stable and slower-draining than foams from self-aspirating nozzles, such as the Mil-Spec nozzle. This is due to the smaller, more uniform bubble distribution that CAF creates. After exceeding the optimal foam expansion, the liquid walls between bubbles become thin, increasing the rate of rupturing and drainage. Thus, the fire performance of over-expanded foams begins to taper off.

Foam generated using this method has both smaller bubble volume and size distribution [13], leading to an improvement in foam stability which affects fire performance [14]. The ability to control the rate of air injection leads to subsequent control over the Expansion Ratio (ER) (i.e., the ratio of expanded foam volume to unexpanded liquid volume), the inverse of which is the gas fraction, an important parameter in foam quality. CAF has been previously shown to improve the performance of AFFF on Class B fires. Compared to traditional systems, CAF uses up to 44% less agent to accomplish equivalent extinguishment times [15].

2.1.3 Ultra-High Pressure (UHP) Foam Delivery

UHP foam delivery is defined by the National Fire Protection Agency (NFPA) as foam delivered at 1100 psi or above. UHP has been shown to have a positive impact on firefighting, reducing the amount of AFFF needed to extinguish a fire by up to 33% [16]. In this pressure range, the liquid agent forms extremely small droplets, on the scale of 90–100 μm upon release from the nozzle. This results in faster cooling due to increased surface area [16]. UHP also allows for a more concentrated layer of AFFF film to form at the surface of the fuel layer [2]. With increasing pressure, flow rates can be lowered to achieve the same extinguishment time. As delivery pressure increases, less agent is required to achieve the same extinguishment performance.

2.2 TECHNOLOGY DEVELOPMENT

2.2.1 PFAS-free Foams

The first firefighting foams, developed in Russia in the early 20th century, were generated by reacting sodium bicarbonate with aluminum sulfate, producing carbon dioxide as a byproduct, and generating what is referred to as a chemical foam [17]. While foams can be used on structural and wildland fires (Class A, burning solids), they are essential in fighting Class B (liquid and vapor) fires. Water has a higher specific gravity than hydrocarbon fuels, making it an ineffective extinguishing agent for fuel fires, as it simply sinks below the burning liquid. Foam is lighter than both hydrocarbon liquids and water, allowing it to float on top of the liquid surface, forming a barrier between the liquid fuel and oxygen as well as absorbing heat. Today, most of the foams used for firefighting are made by agitating a surfactant solution, using the mechanical process to introduce air into the liquid agent. An exception to this is sodium bicarbonate handheld fire extinguishers. Early extinguishing agents included plant-based surfactants such as saponin and licorice roots that stabilized the mixture [17].

Over time, there was a shift toward fluorinated surfactants because of their film-forming characteristics, and in the 1960s, the US Navy and the 3M Corp patented AFFF that used PFOS and PFOA. In 1967, the United States Ship (USS) Forrester caught fire, costing 134 lives.

Shortly after this accident, the Navy dictated that all vessels carry AFFF on board. With this declaration, MIL-PRF-24385 was created. The current version of the Mil-Spec for AFFF foam has specifications that are more rigorous than comparable regulations such as International Civil Aviation Organization (ICAO) standards due to the lower application rate and more volatile fuel type. The DoD and Federal Aviation Authority (FAA) have both adopted the Mil-Spec to validate foam performance. The original version of the Mil-Spec, released in 1969, required a 28-ft² fire be extinguished in 84 seconds and a minimum 25% burnback of 240 seconds at an application rate of 0.10 gpm/ft². The current version of the Mil-Spec sets a maximum extinguishment time of 30 seconds and a minimum burnback time of 360 seconds at an application rate of 0.071 gpm/ft². It is interesting to note, that while the physical fire test specifications have largely remained unchanged, the passing criteria for extinguishment and burnback time have become more stringent as the AFFF formulation was further developed and matured.

The traditional chemistry of AFFF relies heavily on PFAS surfactants, whose highly stable character and low surface and interfacial tension contribute to rapid spreading and film-forming character on hydrocarbon fuels. These surfactants are amphipathic in nature due to their non-polar perfluorinated tails and polar head groups. When they encounter a hydrophobic fuel, the non-polar tails on the PFAS surfactants will align themselves toward the fuel, while the hydrophilic head groups align with the aqueous foam solution. Though these characteristics are positive for firefighting, it also makes PFAS nearly impossible to degrade naturally. They cannot be photolyzed, biodegraded, or thermally degraded at near-ambient conditions. Since PFAS are exceptionally stable, they persist in the environment, accumulate in living organisms and spread throughout the ecosystem. These chemicals are not exclusively used in firefighting products: the chemistry of PFAS makes them useful in a variety of consumer products, such as skincare products, grease-resistant paper (often used in food packaging), and non-stick coatings. Due to the ubiquity of products and the resilient nature of the PFAS, nearly everyone in the United States has detectable concentrations of these chemicals in their bodies [18]. Health concerns relating to PFAS first arose in the early 2000s, which led to regulations from governing agencies worldwide. Firefighting foam manufacturers no longer use PFOS and PFOA, and the market for PFFs has continued to grow especially as the GenX PFAS chemicals that replaced them were found to be problematic as well.

Many PFFs are already available as COTS products. To date, none of these foams pass the Mil-Spec, although some of these foams are certified by other standards, such as ICAO. PFFs use zwitterionic and anionic surfactants, the most common of which is diethylene glycol monobutyl ether (CAS number 112-34-5), which is present in most of the PFF products evaluated in this project, in concentrations ranging from 2.5–30%. This chemical is known to be an eye irritant and acutely toxic to aquatic life [19]. Many PFF blends also take advantage of thickening agents to form a more stable foam, including pseudo-plastic polymers such as xanthan gum. The chemical makeup of PFFs does not allow them to spread spontaneously or form films (discussed in Section 3.1.4); instead, they achieve extinguishment through heat absorption and by forming a physical barrier between fuel and oxidant.

2.2.2 CAF

CAFS were first produced in the 1940s, but they did not gain traction until the 1970s when firefighters in Texas began using CAFS to combat wildland fires. The firefighters found that the CAF adhered to surfaces better than self-aspirated foams, and the increased expansion also allowed them to use less of their scarce water supply. The same firefighters began employing CAFS to fight structural fires when called to neighboring municipalities and recognized the same benefits that they saw with wildland fires [8]. More recently, CAF technology has gained traction in combatting Class B fires, beginning in the mid-90s with use in aircraft hangers [6]. Multipurpose overhead CAFS and their Class B fire suppression performance has also been assessed in locations such as chemical storage facilities [6]. Many newer models of Aircraft Rescue and Fire Fighting (ARFF) trucks include CAFS as standard feature or at least an optional upgrade.

Crampton and Kim found that CAF improved the performance of both Class A foams and AFFF on heptane and gasoline in Underwriters Laboratory (UL) 162 tests for Foam Equipment and Liquid Concentrates; they found that at the same ER, CAF had improved fire performance across all areas including shorter extinguishment, longer burnback and drain time [7]. In a series of large-scale gasoline fires, the use of CAF in sprinkler systems was evaluated by Chen *et al.*, who found the optimal ER for AFFF in this application to be around 10:1 [20]. Additionally, it has proven to be more effective than foam and water, or water alone, at combatting Class A solid fuel fires [21].

2.2.3 UHP

The use of water mist in combatting fires initially gained interest in the 1990s [22] and is now used in sprinkler systems [23]. UHP firefighting technology is, essentially, a way to create a high velocity water mist [24] (a suspension of water particles in air) that can be used for truck-mounted firefighting. The USAF first employed this technology on vehicle-mounted systems to aid in the delivery of liquid CO₂. Live fire tests revealed that the CO₂ effect on fires was far less than that due to the UHP mechanism of extinguishment [25]. Later tests showed that UHP decreases necessary water consumption and requires one third of the volume of AFFF to extinguish a Class B fire. These tests led to the modification of P-19 trucks, fitted with UHP technology, being a fielded member of the USAF ARFF fleet.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.3.1 Class B Firefighting Foams

Generally, PFFs and AFFF use distinct physiochemical mechanisms for Class B fire suppression. Typically, PFF surface tensions are not low enough to spread spontaneously on hydrocarbon fuels (i.e., the PFFs are not “film-forming”). Instead, the PFF formulations will yield a stable foam to blanket the fuel source. The “architecture” of the PFF structure, however, does not prevent vapor transport as effectively as AFFF [26]. The phenomenon is quantified by the negative spreading coefficients and long drain times of PFFs. While PFFs have inferior fire-extinguishment performance compared to legacy AFFF, many products exhibit comparable or better 25% burnback performance (i.e., suppress the re-ignition of liquid fuels). While PFFs meet the defining characteristic (not containing PFAS), the consequences of use (and release) are unclear.

For example, standardized tests show the acute toxicities may be far higher than that of AFFF (discussed in Section 6.1.1). The environmental impact trade-offs require further evaluation. Also, many PFFs are non-Newtonian and highly shear-thinning fluids; properties that are likely to necessitate adjustments to the pumps and plumbing used in mobile systems to proportion the foam concentrate and deliver the solutions.

2.3.2 CAF

The use of CAF improves efficiency in fire control and extinguishment. This leads to increased safety for firefighting personnel, and a decrease in the amount of water and foam concentrate necessary to fight a fire. CAF is limited in its applications, however, in that it is not a compatible technology in every existing fire truck. CAF requires compressed air, which can be provided from a cylinder or air compressor. This leads to additional power and space requirements that can be expensive or impossible to add to existing fire trucks. However, CAF systems are currently commercially available from nearly every manufacturer of fire trucks.

2.3.3 UHP

UHP technology creates very fine water droplets, which increases the liquid surface area, leading to improved cooling. The increased surface area means AFFF can more rapidly form a film over burning fuels. However, delivering foam as a mist will strip most of the air out of the mixture, meaning that foam delivered at UHP has a very low ER, and does not form a stable blanket on top of burning fuel. Thus, foam delivered by UHP is more likely to allow hydrocarbon fires to burnback and reignite. With AFFF, the use of UHP has been shown to significantly decrease the time, water, and foam required to extinguish a fuel fire. UHP is already widely used across the ARFF fleet. Like CAF, UHP also requires pressurized air from a cylinder or air compressor that cannot easily be retrofitted onto standard trucks.

3.0 PERFORMANCE OBJECTIVES

Performance objectives were based on evaluation against the Mil-Spec including the engineering evaluation of PFFs with CAF and UHP on Mil-Spec (28-ft²) scale fires to validate the technology and allow for a down-select of PFF candidates before proceeding to large-scale fires in USAF relevant environments (i.e., AFCEC fire test facility at Tyndall Air Force Base; AFB). Table 1 covers the performance objectives and results for physical, corrosivity, and environmental properties. The objectives and results for firefighting properties are listed in Table 2.

Table 1. Performance Objectives and Results for Physical, Corrosivity, and Environmental Properties

Performance Objective	Data Requirement	Success Criteria	Result
Quantitative Performance Objective			
Physical properties testing (Section 4.7.1 – 4.7.4)*	Refractive index (RI)	RI: >1.3630	• None meet all requirements • Some PFFs are highly non-Newtonian • Some barely failed pH & RI • All fail spreading coefficient
	Viscosity	Viscosity: 25°C: >2 cSt 5°C: <20 cSt	
	pH	pH: 7.0<pH<8.5	
	Spreading coefficient	Spreading coefficient: >3	
Corrosivity testing (Section 4.7.7)	Low carbon steel (UNS G10100)	UNS G10100: < 1.5 milli in/yr	• 10 of 12 passed all • 2 others with partial failures
	Copper/Nickel (UNS C70600)	UNS C70600: <1.0 milli in/yr	
	Nickel/Copper (UNS NO4400)	UNS NO4400: <1.0 milli in/yr	
	Bronze (UNS C90500)	UNS C90500: <100 mg	
	Localized, corrosion resistant steel (CNS S30400)	CNS S30400: no pitting	
Environmental Impact (Section 4.7.13)	LC ₅₀ (Fathead minnows)	LC ₅₀ : <500 mg/L	• PFFs generally “slightly toxic” • All PFFs tested and C6 AFFF pass BOD₂₀/COD spec • All meet COD spec
	Chemical oxygen demand (COD)	COD: <1000K mg/L	
	Biological oxygen demand (BOD ₂₀)/COD	BOD ₂₀ /COD: >0.65	
Stability (Section 4.7.17)	Stratification	Stratification: No visible evidence	• 10 of 12 passed stratification requirements
	Precipitation	Precipitation: 0.05% by volume	

**Notations in brackets refer to the respective sections of the Mil-Spec.*

Table 2. Performance Objectives and Results for Firefighting Properties

Performance Objective	Data Requirement	Success Criteria	Result
Quantitative Performance Objective for 28-ft ² Mil-Spec Scale, Gasoline Fires			
Foamability/ Drain Time	Expansion ratio (ER)	ER: ≥5	All PFFs pass
	25% foam drain time	25% drain time: ≥150 s	
90% Control	Heat flux	N/A to Mil-Spec	Measured
Fire Extinguishment	Stopwatch	Extinguishment time: ≤30 s	• No PFF passed with Mil-Spec nozzle (3 of 12 failed to extinguish) • 40% lower extinguishment time with CAF (1 of 12 failed to extinguish)
Burnback/ Cold Burnback	Stopwatch	Burnback time: ≥360 s	• 6 of 12 passed with Mil-Spec nozzle • All 12 passed with CAF
	Heat flux		
Field-scale Performance Objective (315-ft ² with Gasoline and Jet-A; 6,504-ft ² with Jet-A)			
Extinguishment Time Handling/ Usability	Stopwatch Testing notes	Fire control and extinguishment	• Yes, for all 4 PFFs tested so far with CAF • Yes, for all 4 PFFs tested so far with UHP

3.1 PHYSICAL PROPERTIES TESTING AGAINST THE MIL-SPEC

3.1.1 Hydrogen Ion Concentration, pH

The criteria for the hydrogen ion concentration, or pH, is described in Section 4.7.3 of the Mil-Spec. The permissible range of values is between 7.0 and 8.5 at 25°C.

3.1.2 Refractive Index (RI)

The criterion for RI is described in test Section 4.7.1. of the Mil-Spec and requires PFFs to exhibit RI measurements of greater than 1.3630 ct. RI can be used as a simple metric that can be used to check the foam concentration. The range of values determined for AFFF that relates to a proportioned concentration of 3% is at least 1.3580. Considering the chemical composition of AFFF and PFFs are vastly different, it is not surprising or relevant to firefighting performance that they vary from the current Mil-Spec requirement.

3.1.3 Viscosity

Viscosity is a measure of a fluid's ability to resist flow and has units of force over area. A Newtonian fluid has a viscosity that does not change as the force applied to it changes. Conversely, for non-Newtonian fluids, viscosity will change as more force is applied. Non-Newtonian fluids can be shear-thickening or shear-thinning (e.g., they exhibit a change in viscosity as force is applied). Non-Newtonian PFFs are shear-thinning and in practice, this translates to a fluid that requires more force to move but will flow readily once sufficient force has been applied. The Mil-Spec is only designed to test Newtonian fluids and does not require the appropriate tests to evaluate the shear-thinning concentrates. The method described in the Mil-Spec uses an Ubbelohde capillary viscometer, which is used to determine the length of time it takes for a fluid to fall from one point to another in the apparatus as it flows through a narrow section of glass tube, the capillary (Figure 2).

This time is then multiplied by a constant unique to the device that considers the cross-sectional area of the capillary. This method was used for the Newtonian foams being evaluated in this study, and a more applicable method using a rotational viscometer, made by Brookfield, was used for the non-Newtonian products. The rotational viscometer measures the torque, or angular force, required to move a spindle through the fluid and relates it to the viscosity. Section 4.7.2 of the Mil-Spec sets forth a minimum viscosity at ambient temperature and a maximum viscosity at low temperatures. The minimum viscosity at 25°C is 2 cSt, and the maximum at 5°C is 20 cSt. This test takes place at ambient and low temperatures because viscosity will change with temperature, and formulations still need to be usable at low ambient operating temperatures.

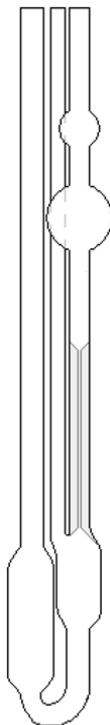


Figure 2. Ubbelohde Viscometer

3.1.4 Spreading Coefficient

Surface tension, caused by cohesion of particles in the bulk liquid media, is the measure of how much the surface layer can resist disturbance. The interfacial tension between two liquid layers is the amount of force that is required to break the interface between these two liquids. The spreading coefficient is determined as the difference between the interfacial tension, (IFT), of two different liquid media, and the surface tensions (SFT) of both of those media. A positive spreading coefficient implies that one media will spontaneously spread, or wet, the lighter media. Spreading coefficient is an important property for film-forming foams, as the film that spontaneously forms is a key factor for extinguishment. The minimum set forth for this value in the Mil-Spec is a spreading coefficient of 3 dynes.

3.2 CORROSIVITY TESTING

The corrosivity of an agent is an important consideration when determining compatibility with the materials in existing systems. The corrosion test, described in Section 4.7.7 of the Mil-Spec, requires that metal coupons be held in a 10% solution of foam concentrate in sea water for 60 days. The stringent sea water solvation reflects the fact that the Mil-Spec was originally written by NAVSEA for naval vessels.

3.3 ENVIRONMENTAL IMPACT

3.3.1 Aquatic LC₅₀ and IC₂₅

The lethal concentration (LC₅₀) is the amount of a material that will result in 50% reduction of a given aquatic population (species death) over a given period, usually 24 or 96 hours. The inhibitory concentration, IC₂₅, is the concentration that leads to a 25% reduction in a biological function (usually growth or reproduction); lower values relate to higher toxicity, as less material is required to illicit a biological response.

3.3.2 BOD₂₀ and COD

The chemical oxygen demand (COD) is the amount of dissolved oxygen consumed during reaction of a strong oxidant (typically potassium dichromate) and an aqueous sample of organic materials. The 20 day (sometimes noted as ultimate) biological oxygen demand (BOD₂₀) is the total amount of oxygen consumed by microbes during complete digestion of a specific sample. The Mil-Spec uses the value of 0.65 as the metric for this ratio, which is often cited in literature regarding standards for wastewater in treatment facilities. It should be noted that the ratio (BOD₂₀/COD) is not the same as a true biodegradability test, often reported as disappearance time or DT₅₀ (biodegradation half-life). Biodegradability is determined by measuring the amount of carbon dioxide produced as a sample is consumed by microbes in three media, typically soil, water, and sediment. Recently, it was discovered that the respirometric method used for estimating BOD₂₀, based on a 10-day test and a predicted value for an additional 10 days gives a significantly lower value than an ultimate BOD test run for full 20 days; so the BOD₂₀ values from this revised method, which is supported by NAVSEA, are reported here.

3.4 STABILITY OF PFF CONCENTRATE

The stability of an as-received PFF product (concentrate) is determined by criteria set forth in Section 4.7.11 of the Mil-Spec, and assessment consists of accelerated aging tests conducted on each PFF. Undiluted concentrate was held at 65°C for 10 days, then analyzed for precipitation, stratification, viscosity, and spreading coefficient of the dilute solution.

3.5 28-FT² FIRE PERFORMANCE

The comprehensive Mil-Spec testing of fire suppression foams includes a series of 42 extinguishment/ suppression tests on 28-ft² fires containing 10 gallons of gasoline; the test conditions include multiple agent concentrations, and flowrates. In the present work, however, all fire tests used standard strength solution (3%), in freshwater, and a fixed 2-gpm application rate. The results of those tests were compared and used to select the foams for tests at field scale.

The tests comprised evaluation of the foam expansion and 25% drain time of the agent used for fire extinguishment, the full extinguishment time, as well as the time it takes for 25% of the foam blanket to burn away after re-ignition. The performance requirements outlined in the Mil-Spec are extinguishment in fewer than 30 seconds and 25% burnback resistance greater than 360 seconds. When CAF and UHP delivery systems were evaluated, the fire size and flow rates remained constant. The first round of tests was completed with ethanol-containing gasoline, as this had historically been standard practice at the AFCEC test site. Subsequent tests used ethanol-free gasoline, to match current standard industry practices.

3.6 EASE OF USE

Notes on the product usability were taken at every point throughout the project. Characteristics included factors such as miscibility and pumping requirements of the concentrate itself. It also included notes from the firefighters conducting fire testing, particularly on their observations of product performance and handling and any difficulties noted during the firefighting operation. Comments from stakeholders in the ARFF community were taken during the field-scale (315-ft²) firefighting demonstration. The feedback from firefighters will be critical to incorporate into future training packages if the approach to using PFFs to meet the Mil-Spec fire performance requires specific nuance of technique in how to fight a fire.

4.0 SITE/PLATFORM DESCRIPTION

4.1 TEST PLATFORMS/FACILITIES

Fire testing was conducted at Tyndall AFB, FL at the Silver Flag Fire Training Facility and at facilities operated by AFCEC/CXAE, including a facility referred to as SkyX. Field testing consisted of fire suppression tests using an Air Force UHP P-34 Rapid Intervention Vehicle and commercial CAF firefighting platform, such as the Rosenbauer Panther, with hand line or turret delivery. Specifics of test platforms at these facilities are described in more detail below.

4.1.1 SkyX

The SkyX test facility at Tyndall AFB was used for all Mil-Spec scale fire tests. SkyX is a concrete hangar fitted with an overhead ventilation system that can effectively remove smoke after each test. A portable comfort station was brought to site when warranted for recovery of fire fighter personnel. The station includes seating and air conditioning so the firefighters and other staff can rehydrate and rest while the smoke clears the hangar between tests.

The SkyX site contains a 6-foot diameter test pan for liquid fuel fires (Figure 3). The pan has a drain for test effluent that can be pumped to a storage tank after each trial. The test pan is on a raised concrete pad that provides secondary containment for all test materials outside the pan. Materials that spill onto the concrete pad are subsequently pumped to the storage tank with the rest of the test effluent. Thermocouples and heat flux sensors are installed at specific locations around the pan to monitor and record fire output. During each test, the readings of each sensor are tracked using custom configured collection and control software. After tests are complete, the video data were analyzed to determine 90% control times and 25% burnback times.

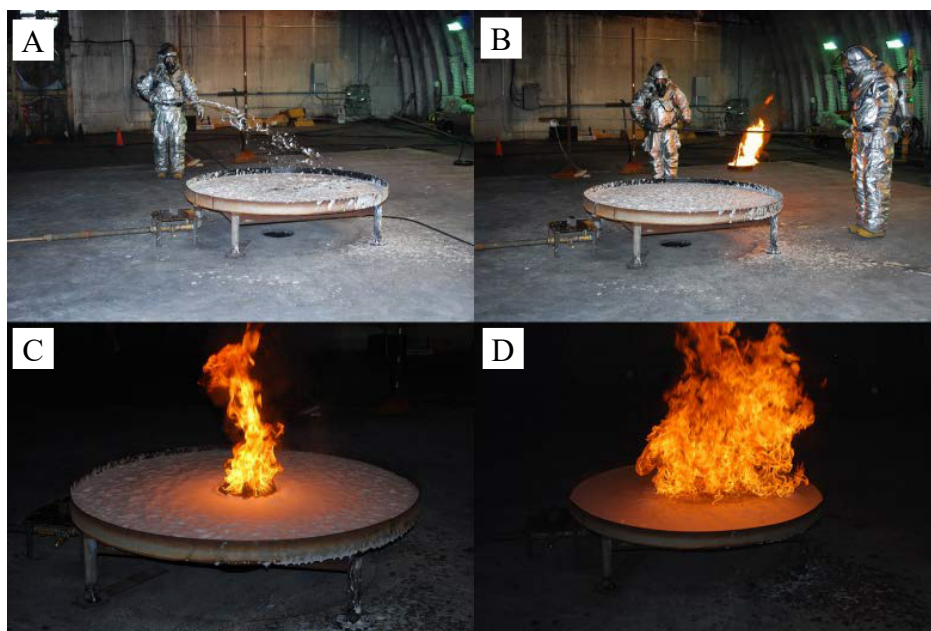


Figure 3. Mil-Spec 25% Burnback Test in SkyX Facility

Key: A) End of agent application, B) Insertion of burnback fire pan, C) Re-ignition of foam blanket, D) 25% of foam blanket is burning, time recorded

4.1.1.1 Mil-Spec-Scale CAF Skid

SkyX contains a Mil-Spec-scale CAF skid that was designed and built by AFCEC/Battelle personnel to deliver foam at the flowrate mandated by the Mil-Spec. The custom platform was required as testing specifications are not readily achievable using commercially available equipment. The CAF skid can be used to produce and deliver foam using compressed air or self-aspirating nozzles. The skid uses a single tank, so foam formulations are premixed and pumped into the tank. The tank is then pressurized with a gasoline-powered air compressor. This air compressor is also used to inject air to create CAF. The skid is connected to a control system, where compressed air and liquid foam flowrates can be manipulated independently and monitored. The control software tracks the volume of foam used in each test and the liquid level in the skid tank.

4.1.1.2 Lab-Scale Fire Testing System

The 0.31-ft² fire pan, lab-scale test apparatus, sometimes referred to as Mini-CAF system, is a down-sized CAFS built by Battelle/AFCEC (Figure 4). It allows the user to manipulate the flow rates of a foam solution and air at extremely low liquid flow rates, on the order of 80 mL/min, which corresponds to the Mil-Spec application rate of 0.071 gpm/ft². It can be used to conduct preliminary lab-scale tests on foam formulations and CAF input parameters. Due to the size of the apparatus, lab-scale tests can be completed in rapid succession while using limited quantities of foam, and because it is a fixed system does not require the presence of a trained firefighter.



Figure 4. Lab-Scale “Mini-CAF” System

Key: 1) Sample holder; 2) Peristaltic pump; 3) Pressure dampener; 4) Flow meter; 5) Flow controller; 6) Proportioning valve; 7) Air inlet and filter; 8) Air flow controller; 9) Mixing chamber liquid inlet; 10) Mixing chamber air inlet; 11) Foam tube; 12) Nozzle; 13) Fire pan

Liquid foam formulations are premixed in a container. The mixture is pumped through a pressure dampener with a peristaltic pump. The flowrate is controlled via a flow meter, controller, and proportioning valve. The liquid comes into contact with flow-controlled compressed air in a mixing chamber that contains steel wool to coarsen the foam with turbulent flow. The liquid flowrate can be set between 1.0–140.4 mL/min. The air injection rate can be set between 0–2 standard cubic feet per minute. The foam ER can be manipulated by setting the compressed air flowrate, so the system can create ERs that are typical of both aspirating nozzle, such as the one specified in the Mil-Spec, and CAFS at larger scales. However, the same nozzle and same method of generation of foam (i.e., by bubbling air in the tube filled with foam solution), is employed to simulate both a Mil-Spec nozzle

and CAF nozzle delivery. Mini-CAF data has shown that lab-scale fire testing does not linearly scale to Mil-Spec-scale fire tests, but Battelle/AFCEC has shown that mini-CAF data is consistent and can qualitatively compare foam formulations to aid in down-selection.

4.1.2 Silver Flag Training Facility

The Silver Flag Fire Training Facility (also known as the 9400 Test Area) has two 91-ft diameter pools used for fire training exercises for Air Force firefighters as well as research conducted by the Fire Integrated Research and Engineering (FIRE) group (Figure 5).



Figure 5. Aerial view of Silver Flag training site at Tyndall AFB

The fire pits can be used to conduct two-dimensional live fire tests (Figure 6). Circular stainless steel rings can also be placed into the pools to conduct test fires of any size, up to the full surface area of the pool. The same cooldown trailer that is used between tests at SkyX is used for rest, rehydration, and recovery between Silver Flag tests. Fuel can be pumped directly into test rings via control systems integrated into the Fire Training Facility fuel transfer system. After tests are completed, the remaining jet fuel in the test pool can be burnt off. Effluent water from tests in the fire pit is sent to an oil/water separator, where it is then stored in holding ponds and eventually evaporated to remove foam concentrate and other contaminants.



Figure 6. Silver Flag Fire Testing Pit

4.1.2.1 Large-Field-Scale (6,504-ft², 91-ft Diameter) ARFF Platforms

The Silver Flag ARFF inventory includes a Class 4 vehicle (Rosenbauer Panther) that is on loan to AFCEC/CXAE from the FAA as part of a collaborative extramural project. It is used for large-scale (up to 6,504-ft²) fires for research and demonstration. The Panther truck includes a Rosenbauer R-600 two stage centrifugal pump with automatic around-the-pump foam proportioning system, a dual-agent handline that can be used for non-aspirated application of PFF and dry chemical. The truck features a CAF handline (50–100 gpm, 100 psi), standard CAF discharge from the bumper turret is 600–1200 gpm and is 500–1000 gpm for the High-Reach Extendible Turret (HRET). These flow rates can be adjusted on the truck before a test begins. On board compressed air storage includes six, 400 standard ft³ compressed air cylinders. The AFCEC inventory also includes a Rosenbauer P-34 UHP Fire Truck that can deliver foam at UHP (1100+ psi). The truck includes a water CPK-5 Ultra-High Pressure 325 gpm pump, a bumper monitor (Elkhart UHP flow rate of 300 gpm) and a 210-gallon foam tank and 1600-gallon water tank. Tyndall AFB also has a P-19 UHP fire truck for research purposes.

4.1.2.2 Dual-Agent CAF Skid

For CAF testing at the larger scale, a CAF skid was designed and built by Burner Fire Control® (Broussard, LA) (Figure 7). This system was used for medium-scale fires at 315-ft². The skid includes a 200 lb. dry chemical tank, 80-gallon CAF foam tank with internal coating, a 100-ft discharge hose, four nitrogen cylinders (sufficient to completely discharge the system twice), a smooth-bore dual-agent handline for CAF and dry chemical (CAF discharge rate of 15–24 gpm) and an adjustable, dual-agent handline (straight stream and fog).



Figure 7. Dual-Agent CAF Skid for 315-ft² Fire Testing

4.1.2.3 CAF/UHP Trailer

To support testing, a dual CAF/UHP trailer was developed by AFCEC/Battelle to evaluate the effectiveness of CAF delivered in the UHP region. Although the skid is equipped to handle both operations simultaneously, it can also act as a test skid for UHP that can achieve the relatively low flow rates required for Mil-Spec-scale testing. The skid includes a 50-gallon foam tank with a centrifugal pump, a 250-gallon water tank with a centrifugal pump, a nitrogen cylinder to create CAF, a 200 ft handline with an orifice nozzle that can produce UHP and a control panel that can be used to control power to the pumps and monitor the liquid levels in the tanks, pump efficiency, and the pressure at the nozzle.

4.2 PRESENT OPERATIONS

Currently, AFFF can only be used to combat Class B fires in emergency scenarios, and during firefighter training, as per an operational use certification (Appendix A). It has not been used for training since July 2019. The use of firefighting foams with either CAF or HP systems is not broadly accepted or implemented across the DoD, even though both types of system are commercially available from major manufacturers of firefighting trucks and many of the newer ARFF firetruck models do have the option to come equipped with UHP and CAF. The techniques are being implemented in ARFF procedures, and are increasingly more common in structural firefighting, where they have been repeatedly shown to improve the performance of AFFF. Vehicles such as the P-34 UHP firefighting trucks are deployed Air Force wide for use in ARFF scenarios and again, have been repeatedly shown to improve performance of firefighting agents. As discussed herein, PFFs are not yet widely fielded in the USAF, but the NDAA mandate will rapidly see a need for integration (drop-in) replacement for current AFFF.

4.3 SITE-RELATED PERMITS AND REGULATIONS

In July of 2019, the Secretary of Defense issued a stop-use order for testing and training for all firefighting foams (Appendix B). A certification was acquired to allow for testing and training to occur at Tyndall AFB, with the requirement that effluent is not released into the environment.

5.0 TEST DESIGN

5.1 ECOTOXICITY TESTING

5.1.1 LC₅₀, IC₂₅

LC₅₀ and IC₂₅ testing was conducted on fathead minnows by a commercial testing facility (Test America) and is discussed in depth in a report submitted separately (Appendix C). Section 4.7.13.1 of the Mil-Spec describes the use of Killifish (*Fundulus herteroclitus*) in accordance with ASTM E279, but these were not readily available for testing. Thus, toxicity testing was conducted on fathead minnows (*Pimephales promelas*). Testing consisted first of an acute toxicity range finding test, followed by a 96-hour chronic toxicity test. Acute testing was performed according to the “Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms [27]” and chronic testing was performed according to the “Short-Term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Freshwater Organisms” [28].

5.1.2 Chemical Oxygen Demand (COD)

COD was measured according to Mil-Spec 4.7.13.2. Samples of PFF concentrate were prepared at 1% concentration, the COD of which was determined using a Hach TNT 824 Ultra-high range (g/L) COD kit on a Hach DR3900™ Spectrometer. The concentrates were diluted to bring the oxygen demand within the limit of detection, and the final value was determined by multiplying the sensor reading by the dilution factor.

5.1.3 Biological Oxygen Demand (BOD)

BOD measures how much oxygen is needed for microbial organisms to digest a sample media per unit volume. It is often used in wastewater treatment plants, in conjunction with the COD, as a measure of the biodegradability of the sample. The Mil-Spec requires the BOD₂₀, or ultimate BOD, be extrapolated from the results of the 5-day test, following the equation:

$$BOD_{20} = \frac{BOD_t}{(1 - e^{-kt})}$$

To do so, the rate constant k for solutions of PFFs must be known, but these values are not readily available for this specific media. Finding the ultimate BOD with these considerations required the use of a respirometric device (Hach BOD Trak II), which takes periodic measurements of oxygen concentrations in sealed BOD bottles. The BOD of the raw concentrates exceeded the range of detection for the device (700 mg/L), so the concentrates were diluted 1:100 to 1% by weight, and the dilution factor was included in the correction factor. The correction factor for the BOD readings also depended on the volume of the sample and was used to correct the instrument reading. Some concentrate solutions exhibited a time lag before they began to decay at a *second-order* rate. In these instances, the data selection was truncated so as not to include these regions.

To account for the two unknowns (the rate constant and ultimate BOD), the Fujimoto arithmetic method was employed. This method plots oxygen concentrations at t_1 vs t_{i+1} , and uses linear regression to find the equation for the first order line of best fit, and calculates the ultimate BOD as the value where the regression line, $BOD_{t+1} = A + B * BOD_t$ is equal to the line $y = x$. It should be noted that using different parameter estimation methods, or using a dilution as opposed to a respirometric method to measure BOD, will yield different results [29].

A new BOD₂₀ method, recently recommended by NAVSEA that involves an ultimate BOD determined over a 20-day test is now being utilized and only the results from this new method are reported here. For the present tests, a sample from the Tyndall AFB Advanced Wastewater Treatment Plant was used to inoculate mineral media containing a mixture of PFF concentrates as a mixed-nutrient source. The mixture was incubated and passed through a series of subcultures (10% subculture pass into fresh media every 48 h, 14-day total incubation). The microbial consortium obtained following the process was used to initiate the BOD₂₀ assays. The selected population was required to represent potential biodegradability in an exposed environment.

5.2 PHYSICAL PROPERTIES TESTING

5.2.1 SFT, IFT

SFT and IFT on cyclohexane were determined, and used to calculate the spreading coefficient, described in Section 4.7.4. of the Mil-Spec. The Wilhelmy plate method was used to determine the SFT, and the DuNoey ring method was used to determine the IFT, on a Krüss K100C tensiometer (Matthews, NC). Samples were prepared at their intended usage concentration (1 or 3%), as well as the aged concentrates, in water as listed in American Society for Testing of Materials (ASTM) D1331. The spreading coefficient was calculated as follows:

$$S_{\frac{a}{b}} = \gamma_b - \gamma_a - \gamma_i$$

Where:

$$S_{\frac{a}{b}} = \text{Spreading coefficient of a over b}$$

$$\gamma_b = \text{surface tension of cyclohexane}$$

$$\gamma_a = \text{surface tension of foam solution}$$

$$\gamma_i = \text{interfacial tension between foam solution and cyclohexane}$$

The SFT value for cyclohexane as a standard hydrocarbon substrate was found to have an average of 24.29 mN/m, std dev 0.44, and remained constant for each calculation.

5.2.2 Viscosity

Viscosity measurements were taken using an Ubbelohde viscometer as described in Mil-Spec for the Newtonian products. Some PFF products were highly non-Newtonian and were instead evaluated using a Brookfield viscometer cell (Ametek Brookfield Engineering, Middleboro, MA) at 5°C and 25°C (± 0.1 °C). When required, the Brookfield viscometer was fitted with a Helipath stand and a T-bar spindle modification, set at 12 RPM, to obtain the necessary viscosity measurement.

Dynamic viscosity, as measured by the Brookfield viscometer, was converted to kinematic viscosity by normalizing for the density of the concentrate, per the following equation:

$$\eta = \rho v$$

Where:

$$\eta = \text{dynamic viscosity, cP}$$

$$\rho = \text{density of fluid}$$

$$v = \text{kinematic viscosity, cSt}$$

5.2.3 Refractive Index (RI) and pH

The RI of foam solutions at the intended usage concentration was determined per Mil-Spec Section 4.7.1. Three drops of diluted PFF were placed on a Vee Gee C10 refractometer (Vee Gee Scientific, Vernon Hills, IL). Additionally, an Abbemat 3200 Refractometer (Anton Paar, Boynton Beach, FL) was used for collecting RI data. Three drops of each dilute PFF solution were placed on the sapphire window and the RI was read. The Mil-Spec requires a sodium vapor source lamp; however, the Light Emitting Diode (LED) is considered the modern alternative to provide consistent emission wavelength. The pH of the foam concentrates was determined as described in Mil-Spec 4.7.3. The measurements were done using an Orion Star A211 pH meter (Fisher Scientific, Pittsburgh, PA).

5.2.4 Stability (Advanced Aging, Stratification, and Precipitation)

Accelerated aging is tested by holding 1 L of foam concentrate, in a 65°C oven for ten days in a glass jar with the lids slightly loosened, as instructed in the Quality Systems Manual (QSM), 5.9.1 [30]. At completion, samples that passed the preliminary aging test were subjected to surface tension measurements (Mil-Spec Section 4.7.4), stratification (Mil-Spec Section 4.7.15), and precipitation (Mil-Spec Section 4.7.16) for further analyses. Aged samples were inspected for the presence of stratification according to Mil-Spec, which describes a direct visual examination for liquid separation. After the aging step, 100 mL aliquots of foam concentrate samples were mixed 50/50 by volume with toluene, then centrifuged using a Robinson Hand Crank Centrifuge (Broken Arrow, OK) for 5 min at 500 rpm (revolutions per minute), at 65°C. Sample separations were then determined in accordance with ASTM D96.

5.3 CORROSION TESTING

A 60-day corrosion analysis was performed according to Mil-Spec 4.7.7. and ASTM E527 in order to evaluate general corrosion effects of PFF on four different metal coupons: G10100 Steel, C70600 Cu/Ni, N04400 Ni/Cu, and C90500 Bronze. A fifth material (S30400 Stainless Steel) was used for the “localized corrosion” assessment, where only pitting was assessed. All metal coupons except sand-cast bronze (C90500) were acquired from Alabama Specialty Products (Munford, AL) and had nominal dimensions of 3-inch x ½-inch x 1/16-inch. The sand-cast bronze (C90500) was obtained from Franklin Bronze Plaques (Franklin, PA) and had nominal dimensions of 3-inch x ½-inch x 3/16-inch. The coupons were cleaned (acetone/deionized (DI) water), air dried, and the initial weight recorded. The stainless-steel coupons were passivated in a 10% HNO₃ solution for five minutes prior to immersion in test samples.

Sample PFF concentrates were diluted using artificial seawater (ASTM D1141) to a 10% (by vol) solution. Different coupon types were held in separate cells of foam solution. The coupons were suspended in the foam solutions by a nylon string attached to the containment cell lid and spaced to prevent the contact of metal surfaces. 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.

At the close of the 60-day exposure, each material coupon was removed from its solution, rinsed with DI water, scrubbed lightly with a nylon bristle brush, and rinsed again with DI 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 with 20% HCl for 1–3 cycles (min) on the C70600 Cu-Ni, N04400 Ni-Cu, and the C90500 Bronze. The descaling varied for G10100 Steel, by utilizing (undiluted) HCl + 20 g/L SnCl₂ + 50g/L Sb₂O₃ for 1–25 cycles (min). The stainless-steel localized corrosion specimens were not descaled in this way but were observed at 10X magnification for localized corrosion occurrences. Determining the presence of corrosion product deposits was essential for categorizing the localized corrosive degeneration.

5.4 FIRE TESTING

5.4.1 Lab-Scale Fire Testing (0.31-ft²)

Lab-scale fire testing was conducted with the mini-CAF described in Section 4.1.1.2. Tests were conducted in a 3.5-inch deep, 7.5-inch diameter test pan, which translates to a 0.31-ft² fire pan area. Foam solution was premixed to 3% and placed in a sample holder. The foam was pumped at 80 mL/min. The desired outlet ER was set by adjusting the inlet air flowrate and measuring expansion until the desired ratio was achieved. 60 mL of water was placed in the pan for each test, followed by 30 mL of ethanol-free gasoline. Next, the gasoline in the test pan was ignited and allowed to pre-burn for 30 seconds. After pre-burn, the test pan was moved under the center of the nozzle to begin extinguishment. The 90% and complete extinguishment times were recorded. Test effluent was then properly disposed of.

5.4.2 Mil-Spec-Scale (28-ft²) Standard Nozzle Fire Testing

A 3% foam solution was mixed and pumped into the CAF skid tank. The Mil-Spec nozzle was attached to the line. The Mil-Spec nozzle is a self-aspirating nozzle. The skid tank was then pressurized to 120–150 psi. The Data Acquisition/Control System (DACS) was used to slowly open the liquid valve until the flowrate reads the desired flowrate (usually 2 gpm). Once the desired flowrate was achieved, the pressure was measured at the Mil-Spec nozzle. The desired pressure is 100 ± 5 psi. If the nozzle pressure was too high, the pressure on the skid tank was decreased until the desired nozzle pressure was achieved. If the nozzle pressure was too low, the pressure on the skid tank was increased until the desired nozzle pressure was achieved. The Mil-Spec ER and drain time procedures were then followed. Cylinders measuring 1 L were weighed and placed under a backboard. Foam was dispensed onto the backboard and allowed to drain into the cylinders. The filled cylinders were weighed again to calculate the ER. The foam in the cylinders was then monitored to determine the 25% drain time. A full version of these procedures can be found in Section 4.7.5 of the Mil-Spec.

Once the ER and drain time values were confirmed, water was transferred into the 6-ft fire test pan until the bottom of the pan was completely covered with a layer of water. Ten gallons of gasoline was then added to the test pan, and one gallon of gasoline was added to the burnback pan. The gasoline in the test pan was then ignited and allowed to pre-burn for 10 seconds. While the gasoline was pre-burning, the DACS was initiated to begin flowing foam. After the pre-burn, the firefighters in full personnel protective equipment (PPE) attempted to extinguish the fire with foam as expeditiously as possible. The extinguishment time was recorded, and the flow of foam continued after extinguishment until foam was discharged into the pan for a total of 90 seconds. Once foam flow was halted, the burnback pan was ignited and placed into the center of the foam blanket. The burnback pan was removed once it was no longer needed to sustain flames inside the pan. The 25% burnback time was recorded. Test effluent was pumped to a holding tank and disposed of according to site handling regulations.

5.4.3 Mil-Spec-Scale (28-ft²) CAF Fire Testing

The required volumes of foam concentrate, and water were mixed and transferred into the CAF skid tank. A smooth-bore nozzle was attached to the line. The skid tank was pressurized to 130–150 psi. The DACS was then used to slowly open the liquid and air valves until the flowrate reads the desired flowrate (usually 2 gpm) and input ER. Once the desired flowrate and ER were achieved, the Mil-Spec ER and drain time procedures were then followed. These procedures were briefly described in Section 5.4.2 of this document, and can be found in full in Section 4.7.5 of the Mil-Spec. If the outlet ER was lower than desired, the air and liquid valves were manipulated to produce a higher input ER. If the outlet ER was higher than desired, the air and liquid valves were manipulated to produce a lower input ER. This process continued until the desired output ER was achieved.

Once desired ER and drain time values were confirmed, water was transferred into the 6-ft fire test pan until the bottom of the pan was completely covered with a layer of water. Ten gallons of gasoline was then added to the test pan, and one gallon of gasoline was added to the burnback pan. The gasoline in the test pan was then ignited and allowed to pre-burn for 10 seconds. While the gasoline was pre-burning, the DACS was used to begin flowing foam. After the pre-burn, the firefighters in full PPE attempted to extinguish the fire with foam as expeditiously as possible. The extinguishment time was recorded, and the flow of foam continued after extinguishment until foam was discharged into the pan for a total of 90 seconds. Once foam flow was halted, the burnback pan was ignited and placed into the center of the foam blanket. The burnback pan was removed once it was no longer needed to sustain flames inside the pan. The 25% burnback time was recorded. Test effluent was pumped to a holding tank and disposed of according to site handling regulations.

Some foam formulations took longer than 90 seconds to extinguish the fire at this scale, thus there was more foam in the pan for the burnback test than was standard. To produce more standardized burnback results, “cold” burnback tests were conducted. For a cold burnback test, a layer of water was added to the pan followed by 10 gallons of gasoline. One gallon of gasoline was added to the burnback pan. Foam was then flowed onto the test pan for 90 seconds (no fire). The burnback pan was lit and placed in the center of the foam layer, and 25% burnback time was recorded for each test.

5.4.4 Medium-Size Field-Scale (315-ft²) UHP Fire Testing

Typically, only water goes into the P-34 firetrucks holding tank and foam concentrate goes into a separate foam tank to be proportioned. To avoid any variance and limitations associated with proportioning highly viscous PFFs, however, foam and water were premixed to 3% and pumped directly into the water tank. Next, foam was flowed and timed to determine the outlet flowrate. The nozzle was adjusted until the desired flowrate was achieved. 100 gallons of jet fuel was pumped into the steel ring for the 315-ft² fires. The fuel was then lit with a torch and allowed to pre-burn for 15 seconds once the full ring was involved. The fire was then extinguished as expeditiously as possible by two firefighter personnel holding the UHP handline, and the extinguishment time was recorded. The jet fuel that remained in the pit was burnt off and the remaining water and foam was treated in the closed-loop water treatment system.

5.4.5 Medium-Size Field-Scale (315-ft²) CAF Fire Testing

About 75 gallons of 3% foam solution was premixed and pumped into the CAF skid tank. The tank was sealed and pressurized by opening the CAF activation valve. The handline nozzle was then opened to prime the line and closed again after priming. 100 gallons of jet fuel was pumped into the steel ring for the 315-ft² fires. The fuel was lit with a torch and allowed to pre-burn for 15 seconds once the full ring was involved. The fire was then extinguished as expeditiously as possible by two firefighter personnel using the CAF handline, and the extinguishment time was recorded. The jet fuel that remained in the pit was burnt off and the remaining water and foam was treated in the closed-loop water treatment system.

5.4.6 Large-Size Field-Scale (6,504-ft²) CAF or UHP Fire Testing

Water and foam concentrate are pumped into the Rosenbauer's designated tanks. Foam is flowed while concentrations and flowrates are monitored with the truck's data acquisition system. Flow rate is adjusted until desired test inputs were achieved. About 1000 gallons of jet fuel is pumped into the fire pit for these tests. Two fire technicians walk around the perimeter of the pit to light the fire. The fuel is allowed to pre-burn for 15 seconds once the full pit was involved. The fire is then extinguished as expeditiously as possible with the equipment on the Rosenbauer truck, and the extinguishment time was recorded. The jet fuel that remains in the pit is burnt off and the remaining water and foam is treated in the closed-loop water treatment system. Note that these tests are still planned to be carried out under a companion ESTCP project and will be reported later.

6.0 PERFORMANCE ASSESSMENT

6.1 COTS PFFS

The 12 COTS PFFs (i.e., foams) shown in Table 3 were included in performance assessments. Numbering is consistent throughout the remainder of the report as well as the publications to date [31–35]. Note that a product called “Pinnacle Class A” (numbered PFF 3), was only tested for toxicity, before it was realized that it was not suited for Class B firefighting applications.

Table 3. COTS PFF Products Tested and Code Numbers

COTS PFF Vendor, Product	PFF No. or Foam No.
Phos-Chek®, 3–6% AFFF (C6) Baseline	0
FireAde®, Fluorine Free	1
Novacool®, UEF/ Novacool	2
Phos-Chek®, 1% Fluorine Free	4
Phos-Chek®, 3% Fluorine Free	5
Solberg, Re-Healing™ RH3	6
Fomtec®, Enviro USP 3%	7
BioEx, Ecopol A	8
BioEx, Ecopol A+	8.2
BioEx, F3HC	9
National Foam, Universal Green 3%	10
Pyrocool®, Pyrocool FEF	11
National Foam, Avio® Green KHC	12

Further descriptions of these PFFs and associated test results are provided in Appendix C.

6.2 ENVIRONMENTAL FATE AND TOXICITY

6.2.1 LC₅₀ and IC₂₅

Toxicity testing aims to find the threshold of exposure that does not result in adverse effects. To do so, the concentration at which there is no observed effect (i.e., NOEC) and the lowest concentration where an adverse effect is observed (i.e., LOEC) were noted (Table 4). The inhibition concentration 25% (IC₂₅) is the concentration at which reproductive effects are observed in 25% of the subsequent generation. For all PFF tested, the success criteria of LC₅₀ being >500 mg/L was not met; in fact, most PFFs were found to be an order of magnitude more toxic to aquatic life than the legacy AFFF.

Table 4. Toxicity Results for Fathead Minnows for Various COTS PFF Products

PFF	Acute LC ₅₀ (mg/L)	Chronic NOEC (mg/L)	Chronic LOEC (mg/L)	Chronic IC ₂₅ (mg/L)
PFF 1 / FireAde®	>120.0*	120.0	>120.0	>120.0
PFF 2 / Novacool®	56.6	20.0	40.0	37.8
PFF 4 / Phos-Chek® 1%	56.4	40.0	80.0	47.6
PFF 5 / Phos-Chek® 3–6%	>80.0*	80.0	>80.0*	>80.0*
PFF 6 / Solberg RH™3	66.2	40.0	80.0	52.9
PFF 7 / Fomtec Enviro USP	70.7	40.0	80.0	55.1

*IC₂₅: Inhibition Concentration 25%; LC₅₀: Lethal Concentration 50%; LOEC: Lowest Observed Effect Concentration; NOEC: No Observed Effect Concentration. *=No LOEC was found.*

The EPA defines various acute toxicity categories and associated acute concentrations in mg/L as shown in Table 5 [36].

Table 5. EPA Acute Toxicity Categories

EPA Toxicity Category	Acute Concentration (mg/L)
Very highly toxic	< 0.1
Highly toxic	0.1 – 1
Moderately toxic	>1 – 10
Slightly toxic	>10 – 100
Practically non-toxic	> 100

Based on the EPA terminology, most of the PFFs tested so far are considered “slightly toxic” while legacy AFFF is “practically non-toxic.”

PFAS surfactants in AFFF are moderately toxic to non-toxic but tend to bioaccumulate [37]. In comparison, PFF contain high levels of non-fluorinated surfactants, which due to high BOD, can be highly toxic to aquatic life. To decrease toxicity and bioaccumulation potential, non-fluorinated betaines are used in PFF, but their environmental impact is not well known. While PFF and their degradation products are expected to be less persistent than those containing the recalcitrant carbon-fluorine bond, PFF could be less efficient, meaning that higher amounts of active ingredients would be needed to reach fire extinguishing standards [38]. Further investigation would be needed to better understand the toxicity of non-fluorinated surfactants, and more extensive research is needed to fully evaluate the trade-off between acute and chronic toxicity of next-generation PFF.

A more detailed test report for the toxicity testing is provided in Appendix D.

6.2.2 BOD₂₀ and COD

Table 6 provides the data obtained from assessing biodegradability of selected PFFs. The COD and biodegradability index are identified within the Mil-Spec for fire suppression foams. All PFF tested met the COD pass-fail definition. BOD values obtained from extended tests using the conditioned inoculum show all PFF tested also exceed required biodegradability threshold for the Mil-Spec. In fact, the BOD was significantly greater than COD in 6 of 11 PFFs (Table 6). In most instances, COD is greater than BOD, as the chemical oxidant reacts with all dissolved organic matter. In some present samples, there is likely a high concentration of additional nitrogen containing organic molecules that do not react well with the chemical oxidant but do cause BOD signal. Accordingly, PFFs are readily biodegradable by the present criteria (index >> 0.65). Whether that relationship is appropriate assessment of the PFF environmental impact may be subject for further review and consideration.

Table 6. BOD₂₀ and COD Results (mg/L) for Various COTS PFF Products

Foam Product	COD	BOD ₂₀	Biodeg Index
<i>AFFF Mil-Spec¹</i>	575,300	514,800	0.89
PFF 1	407,000	678,824	1.67
PFF 2	734,000	1,028,393	1.40
PFF 4	605,000	499,950	0.83
PFF 5	229,300	1,631,110	7.11
PFF 6	521,600	525,300	1.01
PFF 7	372,700	356,850	0.96
PFF 8	378,600	881,043	2.33
PFF 8.2	446,300	323,900	0.73
PFF 9	300,700	877,318	2.92
PFF 10	456,000	1,071,344	2.35
PFF 11	570,000	NA	-
PFF 12	894,000	745,200	0.83

¹COD and BOD₂₀ are results from previous work done by AFCEC/CXAE technical team in program.

NA: Not measured.

6.3 PHYSICAL PROPERTIES

6.3.1 Spreading Coefficient

The results for spreading coefficient are provided in Table 7. A positive spreading coefficient is indicative of spontaneous film-formation and is an inherent character of PFAS-based foams in AFFF, but this characteristic is challenging to replicate without the use of fluorinated surfactants. As such, it is not surprising that PFFs are not able to meet this requirement because most PFF replacements are not designed to be film-forming foams, but rather rely on a thick foam blanket to smother the fire. Thus for PFFs, this is not a particularly useful metric by which to assess their viability as extinguishing agents. However, this is an aspect of the current Mil-Spec; therefore, it must be considered in its current form.

Table 7. Spreading Coefficient Results for Various COTS PFF Products

PFF	0	1	2	4	5	6
SFT n(mN/m) (Non-Aged)	16.34	26.60	24.90	26.20	26.80	27.00
IFT n(mN/m) (Non-Aged)	1.00	1.33	0.45	1.36	1.72	2.42
Spreading Coefficient (Non-Aged)	6.95	-3.64	-1.06	-3.27	-4.23	-5.13

PFF	7	8	8.2	9	10	11	12
SFT n(mN/m) (Non-Aged)	22.38	23.90	23.82	26.61	23.04	26.23	25.40
IFT n(mN/m) (Non-Aged)	1.55	0.97	NA	2.16	5.48	0.57	1.35
Spreading Coefficient (Non-Aged)	0.36	-0.58	NA	-4.48	-4.23	-2.51	-2.46

NA: Not analyzed

6.3.2 pH, Viscosity, RI, and Density

The results for physical properties such as pH, viscosity, RI, and density are provided in Table 8. While some PFFs are notably more viscous than AFFF, they do technically pass the minimum viscosity requirement of the Mil-Spec at 25°C. However, at 5°C the non-Newtonian products fail the maximum viscosity limit of 20 cSt (Table 8). Many manufacturers are aware of the concerns surrounding the viscosity of these products and are working to lower them, but due to the nature of their formulations they will likely never be as flowable as AFFF. The positive impact of the viscosity of these concentrates, however, can be observed in relation to the increased 25% drain and burnback times of these products (refer to Section 6.4). Solutions with higher viscosities experience more drag within the gas phase, which results in more liquid holdup and correlates with a lower foam drain rate; as discussed previously, increased drain time correlates with a concurrent improvement of burnback time.

The Mil-Spec does not include a specific density requirement, but the foam density is needed to convert the viscosity measurement of non-Newtonian foams to cSt for a meaningful comparison; therefore, densities were measured (Table 8).

While some products may not pass the RI test, this characteristic is mainly used as a benchmark to validate concentration of the product during use, and to ensure the foam concentrate proportioner is operating as intended and within an optimal working range. This metric is a legacy component of the Mil-Spec and is less important now that proportioning technology is more controllable.

Table 8. pH, Viscosity, RI, and Density Results for Various COTS PFF Products

Foam Product	pH	Viscosity 5C (cSt)	Viscosity 25 C (cSt)	RI	Density (g/cm3)
AFFF	8.05	6.99 (k)	3.29 (k)	1.367	1.01
PFF 1	6.66	47400 (b)	27900 (b)	1.335	1.04
PFF 2	7.02	99.8 (k)	47.7 (k)	1.3875	1
PFF 4	6.76	7.95 (k)	3.99 (k)	1.375	0.96
PFF 5	7.38	6770 (b)	5340 (b)	1.3605	1.08
PFF 6	7.33	45900 (b)	25100 (b)	1.6875	1.04
PFF 7	7.4	15400 (b)	13200 (b)	1.3715	1.26
PFF 8	7.95	4.12 (k)	2.33 (k)	1.334	0.99
PFF 8.2	8.01	26.20 (k)	11.36 (k)	1.3617	1.03
PFF 9	6.86	19100 (b)	13900 (b)	1.3335	1.1
PFF 10	7.31	4600 (b)	4190 (b)	1.332	1.1
PFF 11	7.74	12.7 (k)	8.74 (k)	1.325	1.1
PFF 12	8.33	145 (k)	60.1 (k)	1.3827	1

Key: k=kinematic viscometer, b=Brookfield viscometer (dynamic)

Lastly, the pH of some products may be slightly out of the current Mil-Spec pH range (table 8), but if deemed to be problematic, modifications can be made to a manufacturer's PFF to modify formulations accordingly. Density was included in physiochemical analysis to be able to convert between dynamic and kinematic viscosity measurements.

6.3.3 PFF Stability Testing

The effect of aging on spreading coefficient and stratification are provided in Table 9. Only two of the PFF products tested failed the stratification requirement of the Mil-Spec test; interestingly, both of these products likely contained xanthan gum, based on the Safety Data Sheets (SDS). While all other PFF products were able to pass the aging requirements, none of the remaining products had acceptable spreading coefficients. This is expected, as the un-aged PFF failed the spreading coefficient also (as shown in Table 7).

Table 9. Aging Test Results for COTS PFF Products

PFF	0	1	2	4	5	6
SFT n(mN/m)	16.33	Extreme Stratification	25.13	26.4	27.14	Stratification
IFT n(mN/m)	0.59		0.95	0.9	2.07	
Spreading coefficient	7.47		-1.79	-2.91	-4.82	

PFF	7	8	9	10	11	12
SFT n(mN/m)	24.72	23.62	26.61	23.12	26.61	24.98
IFT n(mN/m)	2.08	1.12	2.71	5.69	0.22	1.97
Spreading coefficient	-2.41	-0.35	-4.93	-4.42	-2.44	-2.56

Note: All specifications were measured on aged PFF concentrate unless otherwise noted.

The effect of aging on foamability was determined based on the ER and 25% drainage time. The testing of three of the four PFFs down-selected for large-fire testing was completed, and the results are shown in Table 10. As shown, aging does not seem to affect the ER, but the effect on 25% drainage time, which relates to foam stability and can be related to the effectiveness of firefighting for PFFs, is significantly reduced for two of the three PFFs tested.

Table 10. Aged Foamability Results for COTS PFF Products

		PFF 6	PFF 7	PFF 8.2
Un-aged	ER	8.3	8.6	6.3
	25% Drain Time (s)	1351.1	701.6	519.2
Aged Concentration	ER	8.0	8.8	6.7
	25% Drain Time (s)	1252.9	822.2	194.9
Aged Solution	ER	7.9	8.5	6.7
	25% Drain Time (s)	1138.2	306.9	66.4

6.4 CORROSION TESTING

Ten of the 12 COTS PFFs evaluated passed corrosion requirements set out in the Mil-Spec, as shown in Table 11. The other four had partial failures, with two (i.e., PFF 1 and PFF 7) only failing on the specific Cu-Ni alloy; this limitation potentially can be addressed by the addition of a corrosion inhibitor. One product (i.e., PFF 2) was corrosive for all metal coupons except for Ni-Cu and may require reformulation to meet corrosion requirements of any current or future Mil-Spec. Another product (i.e., PFF 11) only failed on the bronze coupon. A detailed report is provided in Appendix E.

Table 11. Corrosion Results for COTS PFF Products

		Material Type			
		G10100 Steel	C70600 Cu-Ni	N04400 Ni-Cu	C90500 Bronze
Mil-Spec Max (mpy)		1.5	1	1	100 mg mass loss
Foam Product	AFFF	0.98	0.01	0.00	6.02
	PFF 1	0.36	0.41	0.01	45.66
	PFF 2	1.50	2.47	0.12	138.78
	PFF 4	0.81	0.98	0.00	85.26
	PFF 5	0.04	0.01	0.00	38.74
	PFF 6	0.18	0.02	0.02	17.98
	PFF 7	0.12	0.84	0.01	68.8
	PFF 8	0.23	0.16	0.04	56.14
	PFF 8.2	0.34	0.98	0.01	93.13
	PFF 9	0.13	0.16	0.04	30.38
	PFF 10	0.12	0.19	0.04	23.17
	PFF 11	1.02	0.84	0.01	131.84
	PFF 12	0.400	0.21	0.00	28.26

Red Values = Failing, Green Values = Passing

6.5 FIRE TESTING AT MIL-SPEC SCALE (28-FT²)

6.5.1 CAF Fire Testing with E10 Gas

The fire performance of PFF products was tested initially using the Mil-Spec requirements of a self-aspirating nozzle compared to CAF technology using E10 gas. All CAF tests were conducted at ER 10. Results are shown in Figure 8.

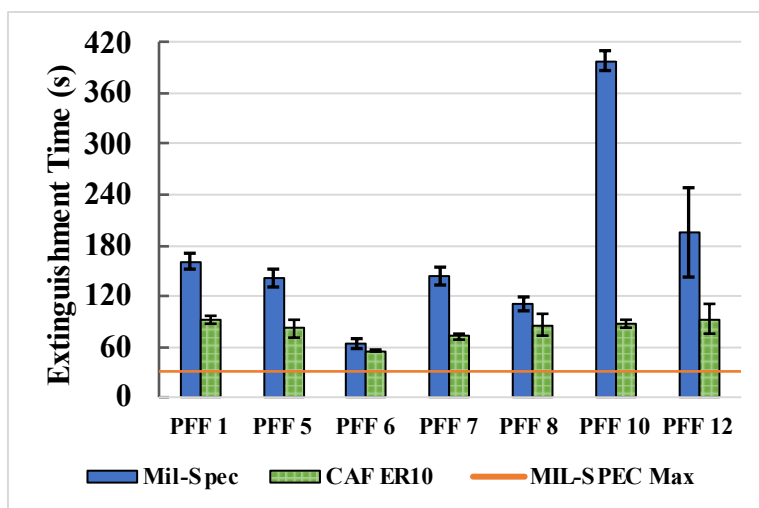


Figure 8. Results for 28-ft² E10 Gas Fires with Mil-Spec Nozzle vs. CAF (at ER 10)

The use of CAF improved the extinguishment time of the PFFs by an average of 36.6% compared to the Mil-Spec air-aspirating nozzle. However, the extinguishment time improvement provided by CAF was not sufficient for any PFF to pass the Mil-Spec extinguishment time of 30 seconds. Interestingly, results show that CAF equalizes the performance of PFFs (i.e., the difference between lesser-performing PFFs and top-performing PFFs is significantly decreased when using CAF). The relative standard deviation of average extinguishment times was 62.6% when using the Mil-Spec air-aspirating nozzle. In comparison, the relative standard deviation for extinguishment times decreased to 16.8% for fire tests with CAF. Note that PFF 2 failed to extinguish the fire with either nozzle type.

As described previously, in an attempt to normalize burnback measurements, a “cold” burnback approach was used in which a preset layer of PFF was delivered onto the fuel pan prior to the burnback test. This eliminates any variability introduced by the depth of the layer of foam during testing. The data in Figure 9 show ubiquitous improvement in burnback time with the use of CAF. Burnback time increased by an average of 33.6%, ranging between 7.1% and 75.0%. There was no equalizing effect between PFF foams with burnback time, as seen with extinguishment time; this is attributed to the varying blanket thickness that arises from different extinguishment times for each PFF. The relative standard deviation of the average burnback time with the Mil-Spec air-aspirating nozzle was 36.5%, while CAF had a relative standard deviation of 32.1%.

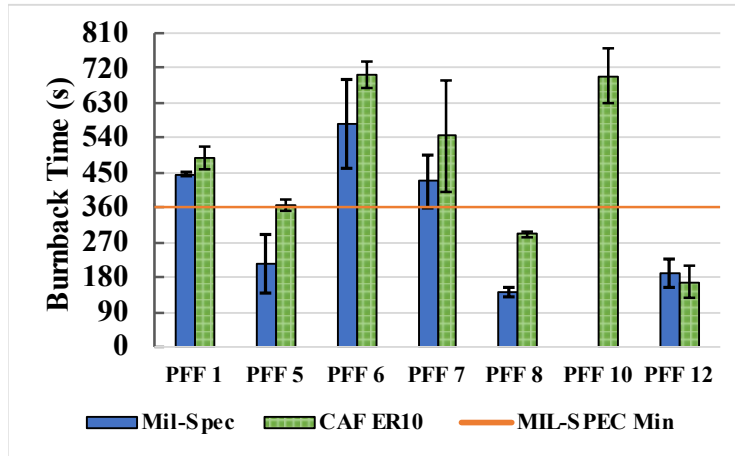


Figure 9. Cold Burnback Time with E10 Gas for Mil-Spec Nozzle vs. CAF (at ER 10)

6.5.2 CAF Fire Testing with E0 Gas

Within Class B fires, alcohol and polar solvent fires are considered even more challenging than non-polar hydrocarbon liquid fires. In a non-polar hydrocarbon and aqueous foam system, the foam phase and hydrocarbon phase are immiscible, and there is little mass transfer at the foam-fuel interface. In an alcohol fire, the aqueous foam solution is also soluble in the alcohol, and there is significant mass transfer at the foam-fuel interface, making development of a foam blanket more challenging, and the fires are more difficult to combat. Some foam formulations claim to be “alcohol-resistant,” and are specifically designed to fight alcohol-containing fuel fires.

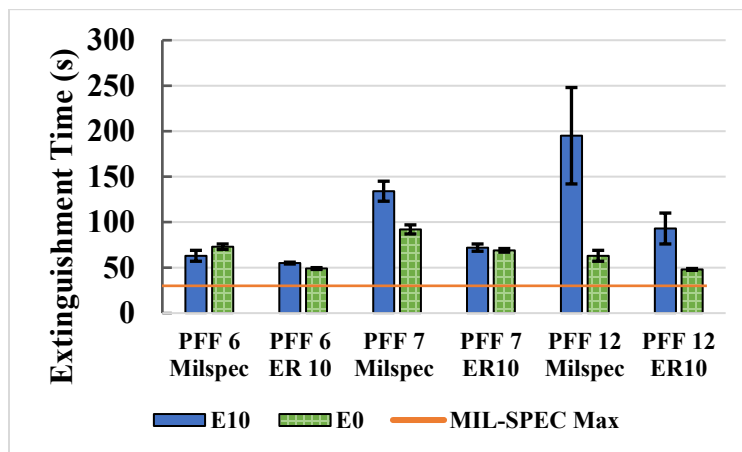


Figure 10. Extinguishment Time for 28-ft² Fire for E10 Gas vs. E0 Gas for Mil-Spec Nozzle and CAF (at ER 10)

PFFs 6 and 7 were tested with the Mil-Spec air-aspirating nozzle at ER 10 with both E0 and E10 gasoline. As shown in Figure 10, the use of E0 gas slightly decreased the extinguishment time for PFF 6 and PFF 7 with CAF. With the Mil-Spec nozzle, the reduction in extinguishment time was large for PFF 7, and somewhat longer for PFF 6. The use of E0 gas marginally improved burnback performance of both foams with CAF and marginally worsened the burnback performance of both foams with the Mil-Spec nozzle, as shown in Figure 11.

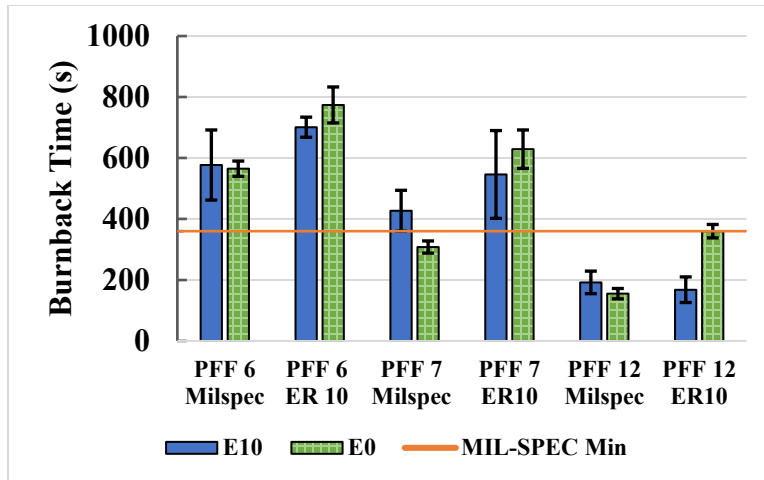


Figure 11. 25% Burnback time E10 vs. E0 Gas for Mil-Spec Nozzle and CAF (at ER 10)

6.5.3 Effect of CAF ER on Firefighting Performance

The coverage of foam delivered by CAFS inherently impacts the fire-extinguishment performance in fuel pool fires, and the coverage rate is governed by the ER of the CAF. The effect of ER on performance of CAF is demonstrated in Figure 12 for three PFF products. The combined average extinguishment time for each of the three foams improved by 30.8% with CAF at an ER 10 compared to the self-aspirating Mil-Spec nozzle. Note that PFFs 6 and 7 are non-Newtonian, whereas PFF 8.2 is Newtonian, so the viscosity of the products does not appear to greatly impact the relationship between performance enhancement by CAF and ER.

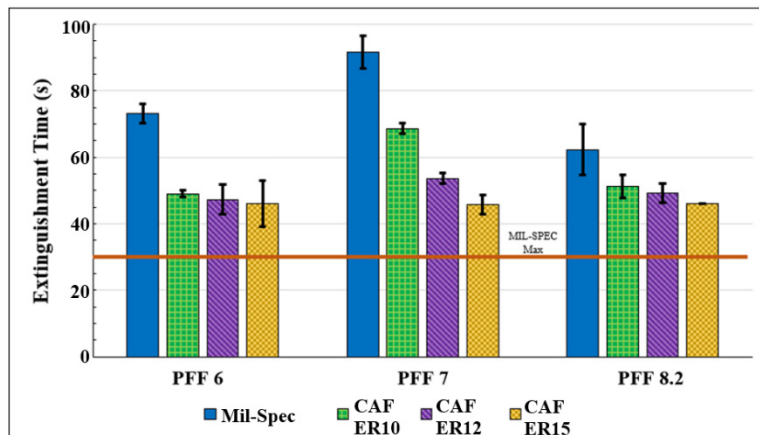


Figure 12. Effect of CAF ER on Extinguishment Time (28-ft², E0 Gas)

The biggest enhancement in fire performance with CAF was at ER 10. Increasing the ER further from ER 10 to ER 12 provided only small improvement (i.e., averaging 9.7%), and from ER 12 to ER 15 exhibited a similar improvement (i.e., averaging 8.2%). This may lead to the conclusion that the “optimum” ER is 15 or greater, but at higher ER, we begin to observe a negative effect on 25% drain time (Figure 13). Foam drain time increases with ER until an optimum drain time is reached.

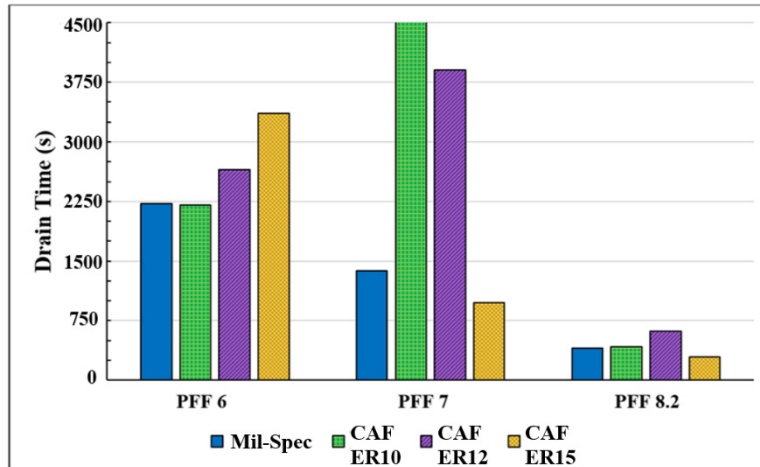


Figure 13. 25% Foam Drain Times at Increasing ER for CAF vs. Mil-Spec Nozzle

The optimum ER varies between foams but is typically at ER 12. The 25% drain times at ER 10 were an average of 77.8% higher than drain times with the self-aspirating Mil-Spec nozzle. The 25% drain times at ER 12 were an average of 18.0% higher than drain times at ER 10. At ER 15, 25% drain times were an average of 33.7% lower than the drain times at ER 12. The decrease after that optimum point is attributed to the fact that over-expanding the foam eventually destabilizes the mixture.

These results highlight the trade-offs at higher ERs with respect to a foam's ability to spread on the fire. Highly expanded foams may have problems in larger scale fires that are not immediately apparent at Mil-Spec scale. Highly expanded foam is much lighter since these foams capture more air per unit volume. This means that the foam may be more easily disrupted by wind or updrafts created during large-fire events and will be more impacted by buoyancy on the fuel layer. For these reasons, ER 12 was chosen for subsequent Mil-Spec-scale and field-scale CAF testing to provide a standardized ER for comparative testing (Section 6.4.5). ER and 25% drain time data for all PFFs are provided in Appendix F. As noted in the appendix, the typical ERs for these PFFs with a Mil-Spec nozzle are ERs 6–8.

The effect of ER on burnback time is shown in Figure 14. The same plateau in performance can be observed when increasing from ER 12 to ER 15. The average burnback time for CAF with an ER 10 was 61.8% higher than the average burnback time using the air-aspirating Mil-Spec nozzle. By comparison, ER 12 resulted in an average of 36.2% longer burnback times than ER 10, and ER 15 resulted in no significant change in burnback times compared to ER 12.

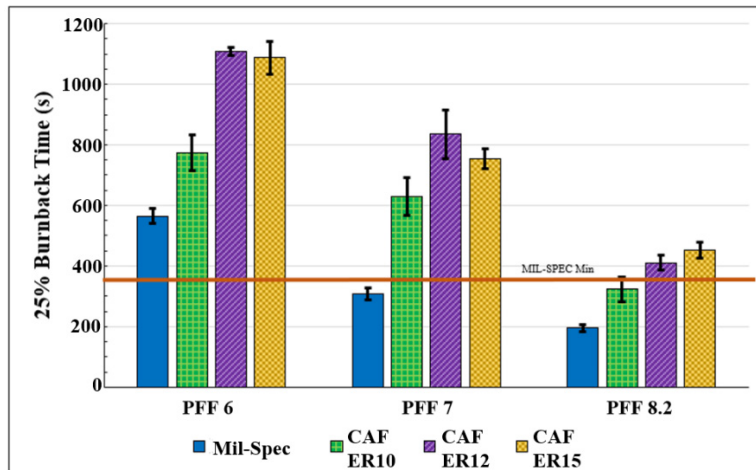


Figure 14. 25% Burnback Times for 28-ft² E0 Gas Fires

6.5.4 Comparative PFF 28-ft² Fire Performance Data at Optimum CAF ER 12

The comparative CAF performance data for various PFFs at the optimum ER 12 are shown in Figure 15 (i.e., extinguishment time) and Figure 16 (i.e., burnback time).

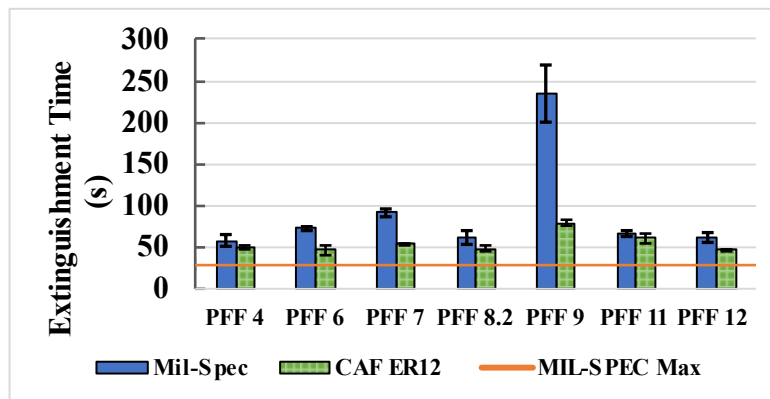


Figure 15. Comparison of Extinguishment Times for E0 Gas Fires with Mil-Spec Nozzle vs. CAF (at ER 12)

Based on Mil-Spec-scale testing, the following five PFFs were down-selected for field-scale testing:

PFF 4 (Phos-Chek®, 1% Fluorine Free)

PFF 6 (Re-Healing™ 3% (RH3)/ Solberg)

PFF 7 (Enviro USP 2–3%/ Fomtec®)

PFF 8.2 (Ecopol A+/ BioEx)

PFF 12 (Avio® Green KHC/ National Foam) (same as Jet Foam/Angus Fire).

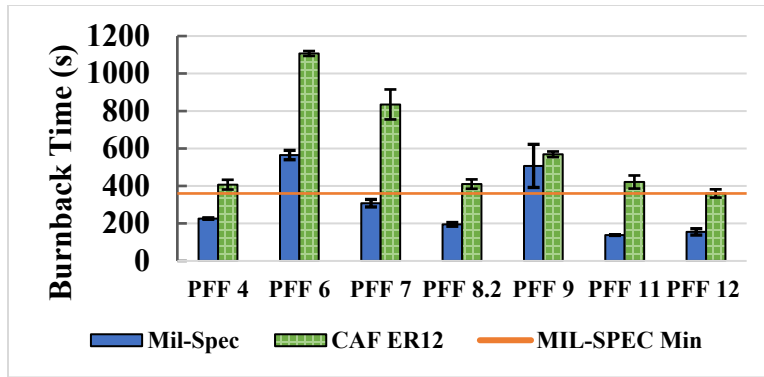


Figure 16. Comparison of Burnback Times for E0 Gas Fires with Mil-Spec Nozzle vs. CAF (at ER 12)

While other PFFs have potential as viable Mil-Spec PFF candidates, our budget only allowed testing five PFFs, so we selected the ones that had relatively better performance.

The Mil-Spec nozzle and CAF at ER 12 data for 28-ft² scale testing with E0 gas for these down-selected PFFs are summarized in Table 12.

Table 12. Summary of 28-ft² E0 Gas Fire Test Data for PFFs Down-selected for Field-Scale CAF Testing

Product	Mil-Spec Nozzle		CAF (at ER 12)	
	Extinguishment Time, s	Burnback Time, s	Extinguishment Time, s	CAF Burnback Time, s
PFF 4	58±7	226±4	50±3	407±26
PFF 6	73±3	565±25	47±5	1107±13
PFF 7	92±5	308±20	54±2	835±80
PFF 8.2	62±8	195±10	49±3	410±25
PFF 12	63±6	155±17	48±1	360±22

6.5.5 CAF Results for Jet-A Fuel Fires

The current Mil-Spec provides specifications for extinguishment and burnback times for E0 gas. However, the revised Mil-Spec for on-shore applications is likely to also include specifications for Jet-A fuel. Therefore, the PFFs down-selected for large-fire testing were also tested for effectiveness with Jet-A fires. Results for extinguishment time and burnback time for the four down-selected PFFs and C6 AFFF are shown in Figures 17 and 18, respectively. While none of the PFFs in this project were able to meet the Mil-Spec extinguishment time of 30 seconds with gas at the 28-ft² scale, three of the four PFFs tested were able to extinguish Jet-A fires in less than 30 seconds.

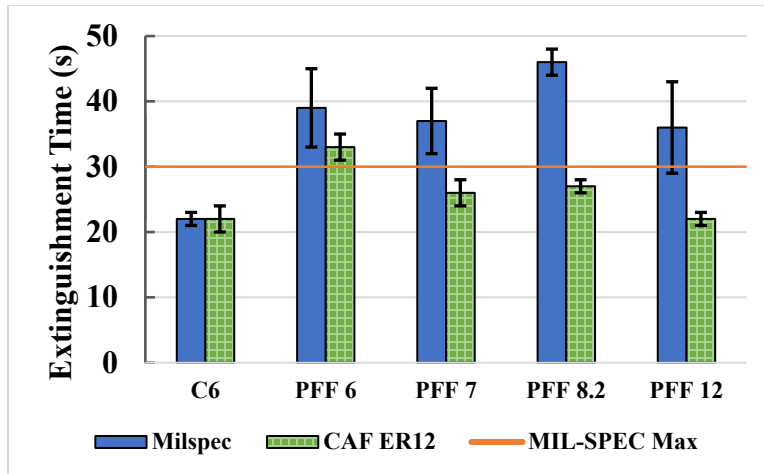


Figure 17. Extinguishment of 28-ft² Jet-A Fires with C6 AFFF and selected PFFs with Mil-Spec Nozzle vs. CAF (at ER 12)

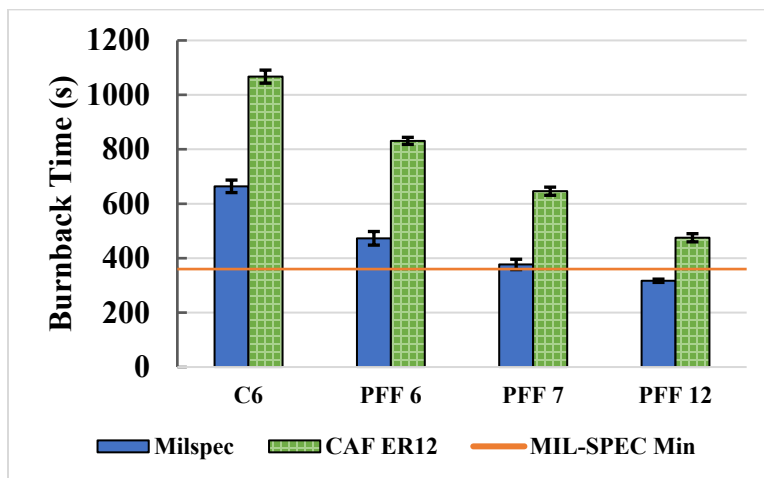


Figure 18. 25% Burnback Time for 28-ft² Jet-A Fires with C6 AFFF and selected PFFs with Mil-spec Nozzle vs. CAF (at ER 12)

Jet-A is less of a challenging fuel to extinguish than gas, as it is less volatile and not as explosive as gas. Results of Jet-A testing at 28-ft² along with comparisons to the gas extinguishment times at the same scale, ERs, and flowrate are shown in Figure 19.

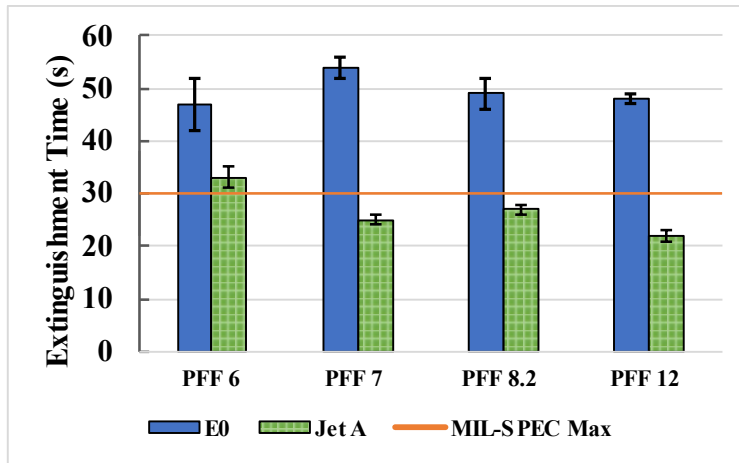


Figure 19. Extinguishment of 28-ft² E0 Gas and Jet-A Fires with selected PFFs and CAF (at ER 12)

6.5.6 UHP Testing at 28-ft² Scale

UHP testing presents a challenge for testing at the small scale (i.e., 28-ft²). The velocity of the agent stream disrupts the fuel surface and can literally push the fuel and foam outside of the capture pan, thereby impacting the effectiveness and variability in determining extinguishment times for new foam formulations. As a result, UHP extinguishment times at this scale were longer than the Mil-Spec extinguishment times for all but two of the foams tested, as shown in Figure 20. Interestingly, the two foams that improved with UHP were the two lowest-performing foams with the air-aspirating Mil-Spec nozzle. The use of UHP almost eliminated any difference in extinguishment time between PFF products tested. In fact, extinguishment time with water alone was statistically similar to extinguishment times using PFF. The relative standard deviation of the average extinguishment time for each PFF and the water baseline was less than 10% (9.18%). It was decided to retest the down-selected PFFs with UHP at medium-size field scale to determine whether that helps demonstrate the true potential of UHP reported in literature.

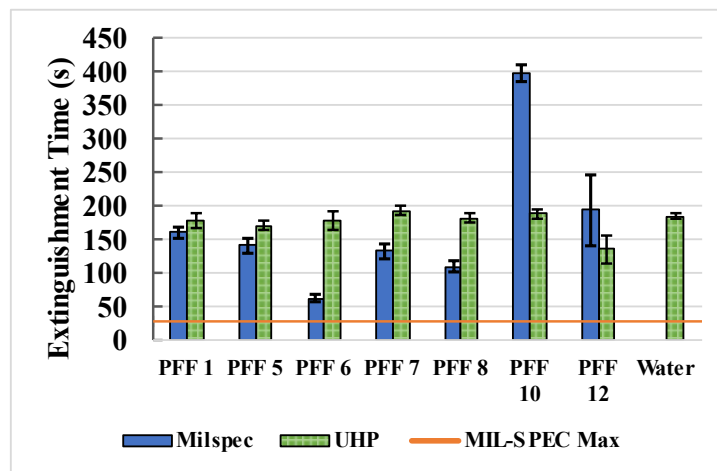


Figure 20. Extinguishment Time for 28-ft² E10 Gas Fires with Mil-Spec Nozzle vs. UHP Nozzle

6.6 FIRE TESTING AT MEDIUM-SIZE FIELD SCALE (315-FT²)

6.6.1 Scale-up of CAF to 315-ft² Field-Scale Fires

Based on the Mil-Spec-scale testing, PFFs 6, 7, 8.2, and 12 were selected for medium-size field-scale CAF testing. A CAF skid was procured to deliver foam at ER 12 and 20 gpm, which correlates to the same application rate (0.071 gpm/ft²) as the Mil-Spec requirement. Both Jet-A and E0 gas were used for tests at this scale.

6.6.1.1 CAF Testing at 315-ft² Scale with Jet-A Fires

Initial testing was conducted with Jet-A fuel, and extinguishment time results for the five PFFs are shown in Figure 21. All five products successfully extinguished the fire in 25–35 seconds. Three tests for each PFF were conducted, with fairly good reproducibility, with results being comparable to C6 AFFF.

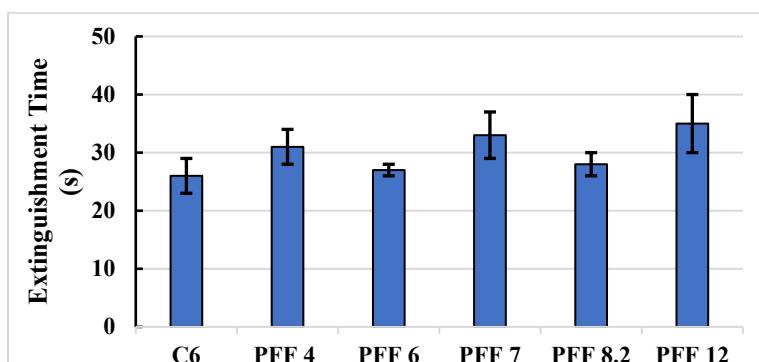


Figure 21. Extinguishment Time for 315-ft² Jet-A Fires with CAF (at ER 12)

6.6.1.2 Fire Scale Comparison for CAF with Jet-A

PFFs 6, 7, and 8.2 were tested with Jet-A at both the 28-ft² scale (i.e., Mil-Spec) and 315-ft² scale. All three PFFs were tested at ER 12 at the large scale. At the 28-ft² scale, PFFs 6 and 7 were tested at ER 15, and PFF 8.2 was tested at ER 12. Results are shown in Figure 22.

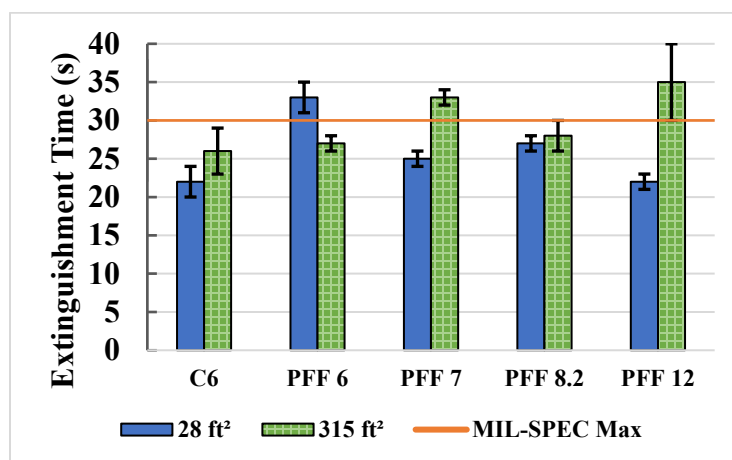


Figure 22. Extinguishment Time for CAF at 28-ft² vs. 315-ft² for Jet-A Fires

For PFFs 6 and 8.2, extinguishment times were about the same at both scales. However, for PFFs 7 and 12, extinguishment times were significantly higher at the 11X larger (i.e., medium-field) scale, as compared to Mil-Spec scale (i.e., 28-ft²).

Some differences between scales include the force at which the foam lands in the pan, the relative distance firefighters can traverse during the test, and the weather conditions of each test. The Mil-Spec-scale and field-scale tests were conducted several months apart, with the Mil-Spec-scale tests being conducted in a hangar, while the field tests were performed outdoors. The volatility of the fuel is largely dependent on temperature, and the stability of the foam blanket can be affected by gusts. To establish a more accurate scale-up relationship with respect to average extinguishment time, more tests would need to be conducted in multiple weather conditions.

6.6.1.3 CAF Testing at 315-ft² Scale with E0 Gas Fires

CAF testing at medium-size field scale was conducted with PFFs 6, 7, 8.2, and 12. All PFFs successfully extinguished the E0 gas fires. The average extinguishment times, based on three tests for each PFF, are shown in Figure 23. Extinguishment times for PFFs were comparable to C6 AFFF.

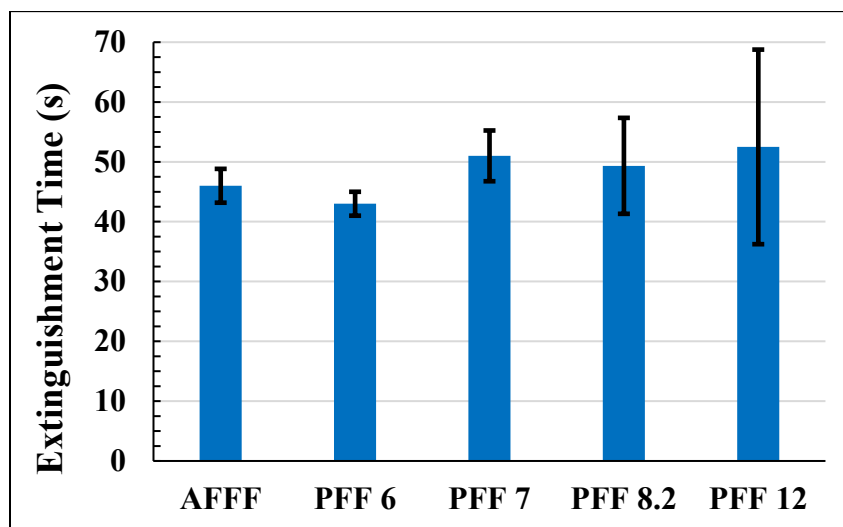


Figure 23. Extinguishment Time for a 315-ft² for E0 Gas Fire with CAF at ER 12

6.6.1.4 Fire Scale Comparison for CAF with E0 Gas

CAF fire testing with E0 gas was conducted at three separate scales with PFFs 6, 7, 8.2, and 12. Each set of tests was conducted in triplicate at ER 12. Figure 24 shows a graphical comparison of extinguishment times. Data from these tests are also summarized in Table 13. The average difference in extinguishment time between the lab scale and Mil-Spec scale was about 20%, mostly due to a significantly larger difference for PFF 12. The average difference in extinguishment time between the Mil-Spec scale and medium-size field scale (i.e., 315-ft²) was just 4%. This suggests that lab-scale testing can be used as a tool to screen PFFs before conducting the much more expensive Mil-Spec scale testing, and not as a tool to predict the exact firefighting performance at field scales.

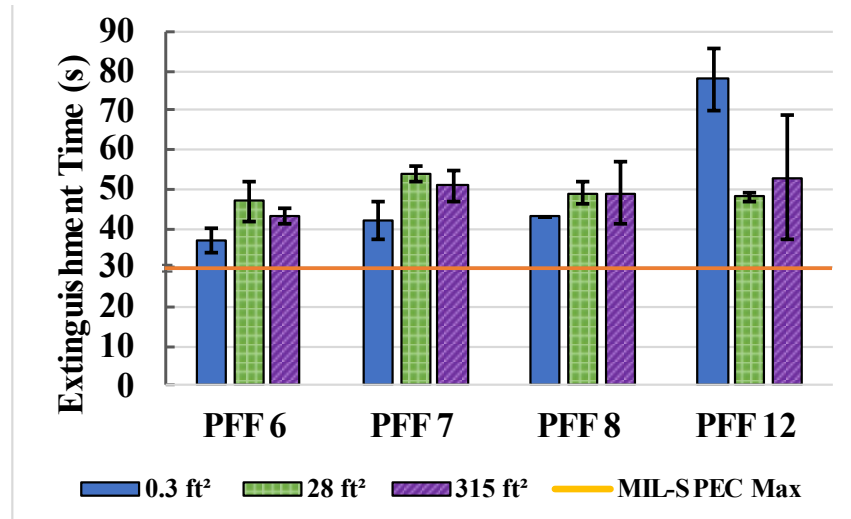


Figure 24. E0 Gas Fire Extinguishment Time for Lab-, Mil-Spec-, and Field-Scale with CAF at ER 12

Table 13. Extinguishment Times (in seconds) for E0 Gas Fires for Four PFFs with CAF (at ER 12) Tested at Lab-, Mil-Spec-, and Field-Scale

Fire Scale	PFF 6	PFF 7	PFF 8.2	PFF 12
Lab-scale (0.3-ft ²)	45.0	41.3	43.0	78.0
Mil-Spec-scale (28-ft ²)	47.3	53.7	49.3	48.0
Medium-Field-scale (315-ft ²)	43.0	51.0	49.3	52.5

6.6.2 Exploratory CAF Testing at 454-ft² Field-scale with Jet-A Fires

Several exploratory tests were also conducted at 454-ft² with Jet-A to observe the effect of a lower application rate than specified in the Mil-Spec on CAF firefighting performance. For both PFFs 6 and 7, the ER was set to 12, but the application rate was 0.05 gpm/ft². Extinguishment time results from these tests are compared with the tests at 315 ft², but at an application rate of 0.07 gpm/ft². As shown in Figure 25, PFF 7 had a significantly shorter extinguishment time at the decreased application rate, while PFF 6 was statistically the same. Further evaluations of application rates at field scale were outside of the scope of this project, but it is a topic that warrants investigation.

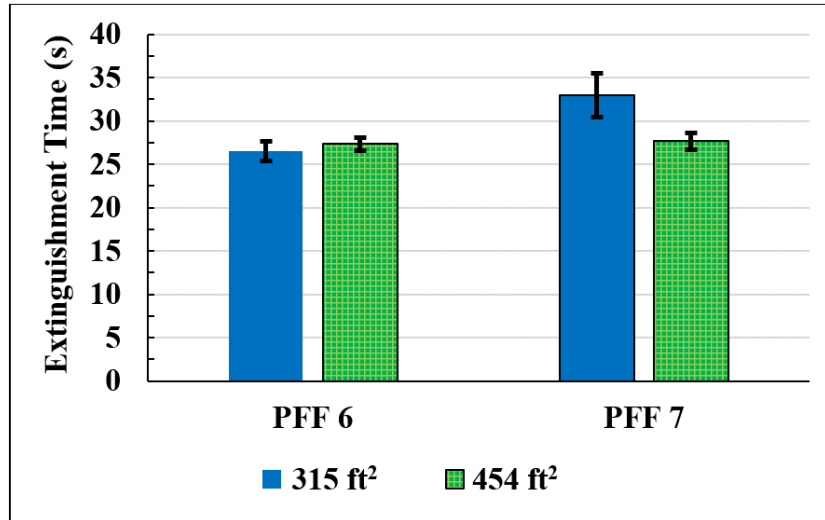


Figure 25. Application Rate Comparison for Jet-A Fires with CAF at ER 12
 (315-ft² @ .071 gpm/ft², 454-ft² @ 0.05 gpm/ft²)

6.6.3 Medium-Size Field Scale (315-ft²) Jet-A Fire Testing with UHP

PFFs 6, 7, 8.2, and 12 were tested with UHP at 3% concentration and 20 gpm at the 315-ft² field scale. All PFFs were successful in extinguishing the Jet-A fires, while the use of water alone failed to extinguish the fire at this scale. Extinguishment times for PFFs 6 and 8.2 were about 50 seconds, as shown in Figure 26, as compared to about 180 seconds at the 28-ft² scale. Initial testing was conducted with PFF 12, where the extinguishment times were much higher than desired, but these improved significantly with subsequent testing of other PFFs, as the UHP firefighting technique was refined. These results are quite encouraging regarding the potential of the UHP foam delivery technique. It is believed that the full potential of UHP technology can be further demonstrated at a yet larger field scale. Therefore, tests are planned for UHP testing under the companion WP20-5335 project at the 6,504-ft² scale.

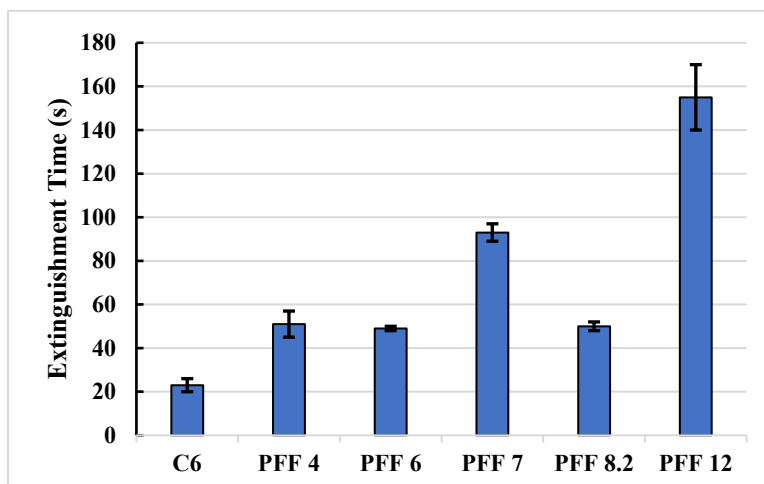


Figure 26. Extinguishment Time for Jet-A Fires with UHP at 315-ft²

6.6.4 Comparison of C6 AFFF with Selected PFFs at 315-ft² Scale

C6 AFFF was used to conduct baseline tests at the medium-size field scale. Baselines were conducted with both CAF and UHP. A comparison of C6 with the four PFFs is provided in Figure 27. As shown, C6 is only slightly better than the PFFs when tested with CAF. It is worth noting, however, that AFFF provided superior burnback protection compared to the PFFs. Burnback values were not recorded for these tests, but the remaining gas was burnt off between tests. Technicians found it much more difficult to ignite the remaining gas after C6 tests were conducted. Another observation worth noting is that the sustained winds were relatively high during the C6 tests. Wind speeds were a sustained 10 mph, and gusts were several mph higher.

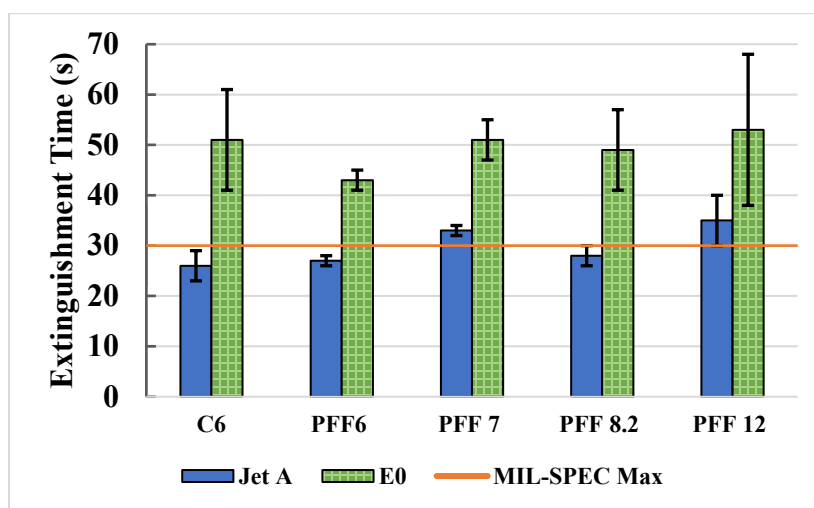


Figure 27. CAF Results for C6 AFFF vs. PFFs for Jet-A and E0 Gas Fires at 315-ft² (at ER 12; 20 gpm Application Rate)

C6 baselines were also conducted with UHP and Jet-A. These baselines resulted in the fastest extinguishment times achieved in this project, as shown in 26. The C6 extinguishment time averaged 23 seconds. There were high sustained winds for these tests as well (i.e., 10 mph), but the foam overcame the conditions and outperformed the next-best PFF by over 25 seconds. None of the PFFs provided any noticeable burnback prevention when delivered with UHP. However, the film provided by C6 delivered with UHP still provided a layer of burnback protection, even with low-quality foam.

6.7 PFF INTERCOMPATIBILITY

To determine whether mixing of different PFFs affects firefighting performance, three PFFs down-selected for field testing (i.e., PFF 6, 7, and 8.2), were mixed 50:50 by volume, so each PFF contributed 1.5% of concentrate in the diluted foam solution. There was no difficulty in obtaining a homogeneous solution. Fire testing was performed in the laboratory scale (i.e., mini-CAF) system at an application of 0.071 gpm/ft² employing CAF at ER 12. As shown in Table 14, the extinguishment time was no worse than for the unmixed PFF.

Table 14. Effect of Mixing PFFs (Each with 1.5% Concentrate in Diluted Foam) on E0 Gas Fire-Extinguishment Time (in seconds) with CAF at ER 12 (0.3-ft² Fire)

First PFF	Mixed with PFF 6	Mixed with PFF 7	Mixed with PFF 8.2
PFF 6 (Non-Newtonian)	37±3 (No Mixing)	35±1	35±1
PFF 7 Non-Newtonian)	35±1	42±5 (No Mixing)	39±4
PFF 8.2 (Newtonian)	35±1	39±4	43±0 (No Mixing)

6.8 SUMMARY OF PERFORMANCE ASSESSMENT

The performance testing with 12 PFFs against the Mil-Spec has shown the following:

- (1) None of the 12 PFFs tested so far meets the Mil-Spec.

Viscosity of several products is very high; these may have to be reformulated to reduce viscosity, which is the current trend, but may still require equipment changes to reduce handling problems.

Ten of 12 products passed all five corrosion tests; two products had partial failures, so these will require some additional corrosion inhibitors.

Based on the aquatic, acute toxicity testing on fathead minnows so far, the PFFs are “Slightly Toxic,” according to EPA classification.

All products appear to pass the biodegradability specification.

- (2) All PFFs fail the fire-extinguishment time requirement, and 6 out of 12 tested fail burnback time requirement.

Extinguishment times for E0 gas fires decreased with CAF by an average of 40%.

Burnback times increased with CAF by an average of 100%, making all six marginal PFFs meet the Mil-Spec.

Based on testing at Mil-Spec-scale, four PFFs (i.e., PFFs 6, 7, 8.2, and 12) were down-selected for field-scale testing, which have extinguishment times of 45–50 seconds for E0 gas fires and 22–30 seconds for Jet-A fuel fires.

- (3) There was no significant change in observed extinguishment times for the four down-selected PFFs on scale-up of CAF to 315-ft² size, either for Jet-A or E0 gas fires, which is a very encouraging result. Testing at about 1000-ft² scale will provide a better correlation between extinguishment time and fire size.
- (4) Based on limited testing with CAF, the mixing of PFFs does not significantly impact fire-extinguishment time.
- (5) UHP data at 315-ft² scale look promising, as all four down-selected PFFs were able to extinguish fires. Two PFFs had extinguishment times below 50 seconds for Jet-A fires. One potential concern with UHP is that the burnback time is low, which may require application of a short-duration non-UHP application after over 90% fire control with UHP. Testing at larger scale will show the true potential of UHP, especially with respect to reducing the foam application rate.
- (6) Both CAF and UHP can provide significant savings in operating cost and waste-foam disposal costs due a considerably reduced foam usage for controlling and extinguishing Type B fires.

7.0 COST ASSESMENT

7.1 TRANSITION TO CAF OR UHP

As described in the 1994 technical report “Evaluation of NDI Compressed Air Foam System (CAFS) Applied as a Retrofit,” it is only feasible to retrofit trucks if there is a universal kit available [39]. Since 1994, multiple manufacturers/companies have begun to offer options to retrofit CAFS onto existing trucks. These include modular retrofit kits, such as those offered by ACAF Systems Inc., which produce up to 64 gpm per unit and are intended for handlines [40]. Fire truck manufacturers also offer their services to retrofit trucks [41, 42].

The key requirements for CAFS are the nominal compressed air, a foam proportioner, a mixing chamber, and sufficient power and space on the truck for these components. Size is a limiting factor, particularly for the inclusion of an air compressor. Generating CAF requires 1.4 cubic feet of air per gallon of flow rate. Thus, the maximum flow rate of CAF that a truck can produce is limited by the size of the compressor it is able to house. Air cylinders are used in some trucks, but these can only hold a set volume and can be difficult to maintain and are not the best option for robust and reliable response in the field. Additionally, if the truck’s available power is not sufficient for the trucks operations with the addition of a CAFS, modifications to the engine/power take-off (PTO) would also be required. The CAFS will also need to be incorporated with the rest of the trucks control system.

The USAF fields six core sets of fire and emergency response vehicles, each of which contains a certain number of structural pumpers, rescue vehicles, water tankers, crash trucks, rapid intervention vehicles, and HazMat vehicles [43]. Of these, the candidates for retrofit are the P-22 pumper, P-24 pumper, P-23 crash truck, and P-34 rapid intervention vehicle. There are numerous factors that lead to difficulty in estimating the cost of retrofitting a fleet. The first is lack of data: there are more options for CAF retrofits now than there were 25 years ago, but they are still not common. The second is the wide variety of firetrucks encompassed within the USAF fleet. The class of fire truck (P-22, P-34, etc.) is not indicative of uniformity. Rather, different makes and models of trucks that fit the performance requirements are designated against that “class” of vehicle. Different trucks vary in the key requirements discussed above, namely: power and space.

In order to develop a realistic cost estimate, a comprehensive survey of all the vehicles in the fleet that are candidates for retrofit would need to be amassed, and this is outside of the scope of the current work. Contractors/ manufacturers of the retrofit systems should be consulted for estimates on material and labor cost for representative trucks, which could then be extrapolated out to the fleet. It is possible that it may be more efficient to simply replace some models, if CAF is determined to be necessary. Foam proportioning systems may also require modifications to be compatible with more viscous foam concentrates, if those products are determined to be fit for use.

7.2 COST ANALYSIS AND COMPARISON

The NDAA mandate dictates that the shift to a PFF will be made regardless of cost. Accordingly, it is critical to estimate the extent that the shift to PFF will affect operating and equipment budgets.

Initial projections have been made using present costs of the commercially available foams and estimated costs for retrofitting or replacing firefighting equipment. There is potential for significant cost changes from the estimates. As the demand expands, an economy of scale or market competition may reduce costs. The approach and assumptions for the present cost estimates and projections are discussed below.

Both CAF and UHP have been shown to reduce the amount of foam product needed to extinguish a fire. The testing with PFFs in this project showed that CAF helped reduce the extinguishment time by an average of 44% compared to standard air aspiration. The data were used to do a preliminary analysis of the operational cost savings from use of CAF over conventional nozzles. The bulk price for PFFs (e.g., 300 gallon tote) are not readily available, so for comparison the published prices of 5-gallon pails were used for calculations. Market checks showed the C6-based AFFF is \$127 for 5-gallon pail [44]. Using that price and the extinguishment times from trials relative costs for using PFF with CAF and conventional (air aspiration) were calculated and are summarized in 15. The first estimates reveal an initial materials cost increase. The absolute cost is dependent on a combination of the product price and the effectiveness. As seen from Table 15, the present values indicate that material cost for PFF will increase compared to the Mil-Spec AFFF.

Table 15. Relative Cost for Various PFFs for Fighting a 28-ft² Fire

PFF	Price/unit [Reference]	Relative Price	Relative Quantity with CAF	Relative Quantity w/o CAF	Relative Cost with CAF	Relative Cost w/o CAF
1/15 (FireAde®/ FireBull)	\$118.75 [45]	0.94	1.64	2.6	1.54	2.43
4 (Phos-Chek® 1%)	\$166.50 [46]	1.31	1.67	1.94	2.19	2.55
5 (Phos-Chek® 3-6%)	\$95 [47]	0.75	2.84	4.88	2.13	3.65
6 (Solberg Re-Healing™ 3-6%)	\$120 [48]	0.94	1.58	2.44	1.49	2.31
7 (Fomtec® Enviro USP)	\$214 [49]	1.69	1.79	3.06	3.02	5.15
8.2 (Ecopol A+)	\$128.30	1.01	1.64	2.08	1.66	2.1
Average	\$140.43	1.11	1.66	2.83	1.98	3.03

Additional extrapolation of the data can be applied to rationalizing the transition to CAF on DoD platforms. A 2011 report estimated that the USAF used 2,826,000 gallons of AFFF per year at a cost of \$18 per gallon (\$22.32 in 2022 dollars, for total cost of ca. \$66 million). Applying the relative costs from Table 15, the foam cost using CAF is twice that and standard air aspiration three times that total. Realizing that savings would mean all platforms need to have that technology, the upgrade through retrofitting and replacing platforms is a complex and expensive proposition. It is estimated that there are substantial savings in PFF foam cost, of the order of \$60 million annually, are possible via fleet-wide retrofitting with CAF.

A fire truck with CAFS is 10–20% more expensive than a standard platform. Currently fire trucks can be retrofitted with a customized CAF system for \$30,000–\$50,000, eliminating the need to purchase a whole new fleet if CAF improvement of PFF performance merits the retrofit.

The Air Force currently fields a few UHP systems for flight line fires. The cost of retrofitting a larger truck to UHP is unknown, but the success of UHP research has encouraged development of UHP P-19s, which are available for purchase.

The main savings provided by the shift from AFFF to PFFs will be reduced waste management burden and the associated long-term environmental restoration or remediation costs. The DoD currently treats any emergency response where AFFF is used as a hazardous material release. Hazardous waste remediation following a single crash rescue response costs ca. \$5 million to clean up after AFFF dispersal. The category applies to the legacy C8-based product *and* the C6 replacement, the transition to the more environmentally friendly PFF will save the DoD tens of millions annually in those instances. Current reports show the Air Force spent \$974 million on PFAS-related actions to date [50]. Preliminary studies outline details for the great costs from management and remediation of PFAS contaminated sites and waters. The Air Force alone is expected to spend more than \$2 billion to clean up PFOS and PFOA contamination and safely dispose waste, accordingly the DoD responsibilities will be even greater. Any estimates, however, are highly speculative. There are no technologies to practically address full remediation at the scales and scope of the problem. In addition, the endpoint (acceptable level of exposure/contamination) has not been consistently defined, so the extent of treatment or number of sites that ultimately will require remediation is presently unknown and costs may be even higher.

A payback analysis including the cost of retrofitting and/or replacing existing ARFF trucks with CAF and UHP should be carried out in future when the costs for retrofitting are better known.

8.0 IMPLEMENTATION ISSUES

8.1 STAKEHOLDERS AND TECHNOLOGY ACCEPTANCE

The initial step in stakeholder acceptance of this technology is the inevitable release of the new Mil-Spec in October 2023. If it is determined that CAF or UHP, or a combination of both, is required for PFFs to achieve acceptable fire performance, modifications to existing systems will likely have to take place. The USAF ARFF fleet is already equipped with UHP vehicles but is not widely equipped with CAF. If every truck is required to be equipped with CAFS, that widespread implementation will likely be more challenging and expensive than only one truck in the fleet for a certain core vehicle set requiring CAFS.

8.2 PROCUREMENT ISSUES

CAF and UHP technologies are tools that may be more effective in some scenarios and less in others. It may not be necessary (or indeed practical) to retrofit every firetruck with both delivery systems as long as both capabilities are distributed across the response fleet. In future procurement as the firefighting fleet is updated, it is expected that such technologies will become integrated as standard requirements, but lifecycle and sustainment analysis would have to be extensively completed ahead of an acquisition plan.

8.3 PLANNED TECHNOLOGY TRANSFER EFFORTS

Battelle/AFCEC will write a Guidance Document on implementation of PFF and will provide recommendations on how CAF and UHP may be added to training schedules for ARFF. Documentation will consist of recommended practices for design and delivery of PFF, guidance in training firefighters to use the new technology, lessons learned from the ESTCP qualification testing, and lifecycle and cost analysis. It will require consultation of the stakeholders and regulatory advisors, however, to determine how to implement changes broadly across agencies, including DoD, FAA, and other agencies. Transition of PFF products will occur by channeling successful products into the technology transfer process that ultimately leads to certification by NAVSEA and addition to QPL-24385 of best performing agents. We anticipate Navy advisors will propose amendments of MIL-PRF-24385F in the near-term. Battelle will solicit administrative policy guidance for fire emergency services operations, fire prevention, and command and control from AFCEC/CXF. The Group are advisors to Fire and Emergency Services Working Group, AF Fire Panel/Major Air Commands (MAJCOMs) and FAA.

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APPENDIX A POINTS OF CONTACT

A list of the important points of contact (POCs) involved in this demonstration project is provided below.

POC Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Dr. Satya Chauhan (PI)	Battelle 505 King Avenue Columbus, OH 43201	Phone: 614-424-4812 Fax: 614-458-4812 E-mail: chauhan@battelle.org	Project planning and execution; reporting
Malena Maraviglia	Battelle 505 King Avenue Columbus, OH 43201	Phone: 202-422-2622 E-mail: N/A	Lab-scale fire and Mil-Spec-scale fire testing; reporting
Andrew McMeans	Battelle 505 King Avenue Columbus, OH 43201	Phone: 678-267-7842 E-mail: N/A	Mil-Spec-scale and small, field-scale fire testing; reporting
Julie Bryant	Battelle 505 King Avenue Columbus, OH 43201	Phone: 443-569-9216 E-mail: bryantj@battelle.org	Mil-Spec-scale and small, field-scale fire testing; reporting
Steven Wells	Battelle 505 King Avenue Columbus, OH 43201	Phone: 850-527-1621 E-mail: wellss@battelle.org	Large, field-scale fire testing; CAF expert
Kris Cozart	Battelle 505 King Avenue Columbus, OH 43201	Phone: 850-774-6566 E-mail: cozartk@battelle.org	Design and integration of CAF and UHP skids
Sue Broxson	Battelle 505 King Avenue Columbus, OH 43201	Phone: 850-596-2821 E-mail: broxson@battelle.org	Physical property testing coordination
Dr. Heather Luckarift	Battelle 505 King Avenue Columbus, OH 43201	Phone: 850-348-7213 E-mail: luckarift@battelle.org	Fire testing coordinator; reporting
Dr. Bridgett Ashley (co-PI)	AFCEC Tyndall AFB, FL	Phone: 850-283-6004 E-mail: bridgett.ashley.1@us.af.mil	Co-PI; CAF and UHP expert; test site oversight
Jonathon Torres	FAA	Phone: N/A E-mail: Jonathan.torres@faa.gov	Advisor
William Kavanaugh	ARMY IMCOM	Phone: +49-(0)611-9744-2975 E-mail: william.j.kavangh@usace.army.mil	Advisor; tech transfer
Marc Mills	EPA	Phone: N/A E-mail: N/A	Advisor; regulatory review
Jeff Eichler	Navy	Phone: N/A E-mail: Jeffery.eichler@navy.mil	Advisor; tech transfer

APPENDIX B PROHIBITION OF TESTING AND TRAINING WITH FLUORINATED AFFF



ASSISTANT SECRETARY OF DEFENSE

3500 DEFENSE PENTAGON
WASHINGTON, DC 20301-3500

September 18, 2020

SUSTAINMENT

MEMORANDUM FOR ASSISTANT SECRETARY OF THE ARMY (INSTALLATIONS,
ENERGY AND ENVIRONMENT)
ASSISTANT SECRETARY OF THE NAVY (ENERGY,
INSTALLATIONS AND ENVIRONMENT)
ASSISTANT SECRETARY OF THE AIR FORCE
(INSTALLATIONS, ENVIRONMENT AND ENERGY)
DIRECTOR, DEFENSE LOGISTICS AGENCY (INSTALLATION
MANAGEMENT)
DIRECTOR, PROGRAMS AND RESOURCES/COMPTROLLER,
NATIONAL GUARD BUREAU

SUBJECT: Prohibition of Testing and Training with Fluorinated Aqueous Film Forming Foam

This memorandum provides guidance for implementing Sections 323 and 324 of the National Defense Authorization Act for Fiscal Year 2020 that prohibit, respectively, the uncontrolled release of fluorinated Aqueous Film Forming Foam (AFFF) and its use for training exercises, at military installations. All testing of equipment and training of personnel with fluorinated AFFF is prohibited at Department of Defense (DoD) installations, except the following locations:

- Naval Air Weapons Station China Lake, CA
- The Naval Research Laboratory – Chesapeake Bay Detachment, MD
- Tyndall Air Force Base, FL
- Marine Corps Air Station Cherry Point, NC
- Marine Corps Air Station Camp Pendleton, CA

The installations listed above have documented containment systems, processes, and procedures in place to ensure AFFF is not released into the environment. Additionally, the pier side testing of ship's AFFF systems, to include repairs and demonstrations to validate "safe-at-sea" readiness are permitted by this policy. All PFAS wastes from the training or testing at the installations listed, or from pier side ship testing, must be handled, contained, and disposed of in accordance with all applicable policies and environmental regulations, including all DoD-wide, service specific, and locally applicable requirements. Where an AFFF release occurs as part of an emergency response, spill response procedures shall be implemented.

My point of contact is Lt Col Chad Gemeinhardt, ODASD(ENV), at 571-372-6889 or chad.a.gemeinhardt.mil@mail.mil.

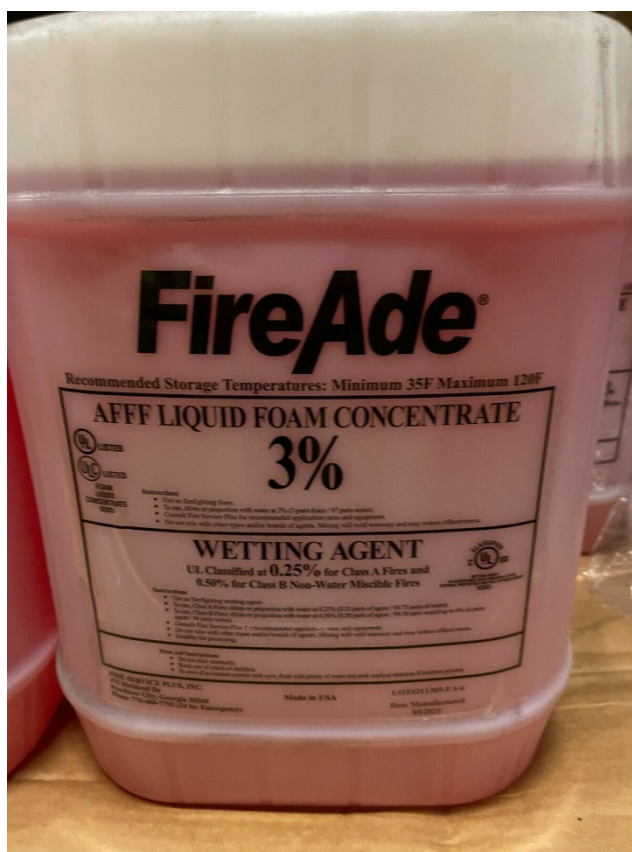
W. Jordan Gillis

APPENDIX C PFF-SPECIFIC PRODUCT DETAILS AND RESULTS

APPENDIX C-1: MIL-PRF-24385F TEST RESULTS FOR PFF 1, FIREADE 3% FLUORINE FREE

1.0 Firefighting Agent Details

FireAde® 3% Fluorine Free, made by Enforcer 1. NFPA 18-2017 certified wetting agent. UL-162 AFFF. Red gel-like concentrate; Manufacturer rebranded and reformulated, is now FireBull, included in WP20-5335 ESTCP project (PFF 15).



The Safety Data Sheet (SDS) can be found by making a request through the following link:
<https://pro.fireade.com/products/fireade/>

2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental	
LC ₅₀ (mg/L): >500 mg/L	>100
COD (mg/L)	407,000
BOD ₂₀ (mg/L): <1,000 mg/L	678,824
Biodegradability (BOD ₂₀ /COD): >0.65	1.67
Other Physical Properties	
Spreading coefficient; > 3	-3.64
pH (concentrate); 7.0<pH<8.5	6.14
Viscosity 5 C (cSt); <20 cSt	47,400
Viscosity 25 ;C (cSt); >2 cSt	27,900
Refractive Index; >1.3630	1.335
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.36
UNS C70600: <1.0 milli in/yr	0.41
UNS NO4400: <1.0 milli in/yr	0.01
UNS C90500: <100 mg	45.66
CNS S30400: no pitting	Some pitting
Stability	
Spreading coefficient; > 3	Not measured
Stratification; No visible evidence	Extreme stratification
Precipitation: 0.05% by volume	Not tested

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in the table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-containing gasoline (E10); 2 gpm				
Mil-Spec	7.7	1020	161± 9	446± 5
CAF	10.2	1260	92±4	488±29
UHP	2	804	178±11	7±4

4.0 Testing Observations

This product was not selected for further testing because the manufacturer had rebranded and reformulated their product, which was included in the companion, WP20-5335 project. FireAde (PFF 1) was a highly viscous concentrate. The new product was significantly less viscous with improved fire performance.

APPENDIX C-2: MIL-PRF-24385F TEST RESULTS FOR PFF 4, PHOS-CHEK 1% FLUORINE FREE

1.0 Firefighting Agent Details

Produced by Perimeter Solutions; Light green, low-viscosity concentrate; UL 162/ULC S654 Listed, ANSI/NFPA 18 Approved, EN1568-3:2018 Approved, LASTFIRE Batch Tested.

The Safety Data Sheet (SDS) can be found at this link: https://store.danko.net/files/documents/SDS_PC-1-Fluorine-Free-OSHA-WHMIS-GHS_2019-09-13_EN-25.pdf



2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	56.4
COD (mg/L); <1,000 mg/L	605,000
BOD ₂₀ (mg/L)	499,950
Biodegradability (BOD ₂₀ /COD): >0.65	0.83
Other Physical Properties	
Spreading coefficient; > 3	-3.27
pH; 7.0<pH<8.5	6.76
Viscosity 5 C (cSt); <20 cSt	7.95
Viscosity 25 ;C (cSt); >2 cSt	3.99
Refractive Index; >1.3630	1.375
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.81
UNS C70600: <1.0 milli in/yr	0.98
UNS NO4400: <1.0 milli in/yr	0.00
UNS C90500: <100 mg	85.26
CNS S30400: no pitting	Somepitting
Stability	
Spreading coefficient; > 3	-2.91
Stratification; No visible evidence	No visible evidence
Precipitation: 0.05% by volume	

3.0 Firefighting Performance

The Mil-Spec (28-ft²) scale data for the following three foam delivery methods are provided in the table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-free gasoline; 2 gpm				
Mil-Spec	7	345	58±7	226±4
CAF	12	365	50±3	407±26
315-ft² Jet-A Fuel; 20 gpm				
CAF	11.7		31±3	N/A
UHP			51±6	N/A

4.0 Testing Observations

This product was a low-viscosity product. It has been down-selected for field-scale testing in an on-going, companion project.

APPENDIX C-3: MIL-PRF-24385F TEST RESULTS FOR PFF 5, PHOS-CHEK 3% FLUORINE FREE

1.0 Firefighting Agent Details

Produced by Perimeter Solutions; UL 162, EN 1568-3:2008, EN 1568-4:2008, approved by LASTFIRE; Milky non-Newtonian concentrate.



The Safety Data Sheet (SDS) can be found by making a request through this link: <https://www.perimeter-solutions.com/en/request-a-safety-data-sheet/>

2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	>80.0
COD (mg/L); <1,000 mg/L	229,000
BOD ₂₀ (mg/L)	1,631,110*
Biodegradability (BOD ₂₀ /COD); BOD20/COD: >0.65	7.11*
Other Physical Properties	
Spreading coefficient; > 3	-4.23
pH; 7.0<pH<8.5	7.38
Viscosity 5 C (cSt); <20 cSt	6,770
Viscosity 25 ;C (cSt); >2 cSt	5,340
Refractive Index; >1.3630	
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.04
UNS C70600: <1.0 milli in/yr	0.01
UNS NO4400: <1.0 milli in/yr	0.00
UNS C90500: <100 mg	38.74
CNS S30400: no pitting	No pitting
Stability	
Spreading coefficient; > 3	-4.82
Stratification; No visible evidence	No visible evidence
Precipitation; 0.05% by volume	

**This test needs to be repeated later.*

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in the table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-containing (E10) gasoline; 2 gpm				
Mil-Spec	6.8		142±11	215±74
CAF	10.1		82±11	366±14
UHP	1.7		172±6	13±5
28 ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	7		146±26	198±34
CAF	12		54±1	377±13

4.0 Testing Observations

This product was not selected for further testing because the manufacturer had a better-performing product (PFF 4) that was also tested (see Appendix C-2).

APPENDIX C-4: MIL-PRF-24385F TEST RESULTS FOR PFF 6, SOLBERG RE-HEALING RH3, 3% FOAM CONCENTRATE

1.0 Firefighting Agent Details

Produced by Solberg; UL 162, FM Standard 5130, EN Standard 1568, ICAO B/C; Thick, brown non-Newtonian concentrate.



The Safety Data Sheet (SDS) can be found by making a request through this link: <https://www.perimeter-solutions.com/en/request-a-safety-data-sheet/>

2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data are provided below. The first column shows the Mil-Spec requirements and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	66.2
COD (mg/L); <1,000 mg/L	521,600
BOD ₂₀ (mg/L)	525,300
Biodegradability (BOD ₂₀ /COD); >0.65	1.01
Other Physical Properties	
Spreading coefficient; > 3	-5.13
pH; 7.0<pH<8.5	7.33
Viscosity 5 C (cSt); <20 cSt	45,900
Viscosity 25;C (cSt); >2 cSt	25,100
Refractive Index; >1.3630	1.6875
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.18
UNS C70600: <1.0 milli in/yr	0.02
UNS NO4400: <1.0 milli in/yr	0.02
UNS C90500: <100 mg	17.98
CNS S30400: no pitting	No pitting
Stability	
Spreading coefficient; > 3	Not conducted
Stratification; No visible evidence	Stratified
Precipitation; 0.05% by volume	Not conducted

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in Table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

This PFF was tested with field-scale fires, so the extinguishment data for the same are also provided in the Table.

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-containing (E10) gasoline; 2 gpm				
Mil-Spec	7.1	2220	63±6	577±115
CAF	10.1	>3600	55±1	701±33
UHP	1.9	760	180±10	3±1
28-ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	7		73±3	565±25
CAF	10	2210	49±1	774±59
CAF	12	2650	47±5	1107±13
CAF	15	3360	46±7	1088±54
CAF @ 0.5X	11.6	2378	47±5	688±8
28-ft² Jet-A fuel; 2 gpm				
Mil-Spec	8.3	1351	39±6	473±25
CAF	12.4	2074	33±2	831±13
CAF	15	3360	34±2	793±11
315-ft² E0 gasoline; 20 gpm				
CAF	12.3	43	43±2	N/A
315-ft² Jet-A fuel; 20 gpm				
CAF	12		27±1	N/A
UHP			49±1	N/A
454-ft² Jet Fuel A; 20 gpm				
CAF	12		27±1	N/A

4.0 Testing Observations

Good extinguishment times and burnback protection were observed. There are usability concerns due to the highly non-Newtonian behavior of this product. A lower viscosity product is planned to be tested under a companion. ESTCP WP20-5335 project.

APPENDIX C-5: MIL-PRF-24385F TEST RESULTS FOR PFF 7, FOMTEC ENVIRO USP 3%

1.0 Firefighting Agent Details

Produced by Fomtec; EN 1568 Parts 1/2/3; ICAO B, UL 162 (7th edition), FM 5130, IMO, and GESIP approved; Thick, non-Newtonian milky concentrate.



The Safety Data Sheet (SDS) can be found at this link:
https://publish.almego.com/getfile/129B8129-6B94-4C2A-BC84-8C73753F07D5/html/5644/5644_Dafo%20Fomtec%20AB_Fomtec%20Enviro%203%25_12-3360-XX_GB-en_v1_0

2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	70.7
COD (mg/L); <1,000 mg/L	372,700
BOD ₂₀ (mg/L)	356,850
Biodegradability (BOD ₂₀ /COD); BOD ₂₀ /COD: >0.65	0.96
Other Physical Properties	
Spreading coefficient; > 3	0.36
pH; 7.0<pH<8.5	7.4
Viscosity 5 C (cSt); <20 cSt	15,400
Viscosity 25; C (cSt); >2 cSt	13,200
Refractive Index; >1.3630	1.3715
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.12
UNS C70600: <1.0 milli in/yr	0.84
UNS NO4400: <1.0 milli in/yr	0.01
UNS C90500: <100 mg	68.8
CNS S30400: no pitting	Minor pitting
Stability	
Spreading coefficient; > 3	-2.41
Stratification; No visible evidence	No visible evidence
Precipitation; 0.05% by volume	

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in Table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

This PFF was also tested with field-scale fires, so the extinguishment data for the same are also provided in the Table.

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-containing (E10) gasoline; 2 gpm				
Mil-Spec	6.2	1380	134±11	427±67
CAF	10	>3600	72±4	546±144
UHP	1.8	402	193±7	N/A
28-ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	6.2		92±5	308±20
CAF	10	4550	69±2	629±63
CAF	12	3910	54±2	835±80
CAF	15	975	46±7	755±32
28-ft² Jet-A fuel; 2 gpm				
Mil-Spec	8.6	701.6	37±5	377±19
CAF	12.1	886.3	25±1	646±15
CAF	15	975	33±3	805±47
315-ft² E0 gasoline; 20 gpm				
CAF	11.5		51±4	N/A
315-ft² Jet-A fuel; 20 gpm				
CAF	12.2		33±1	N/A
UHP			93±4	N/A
454-ft² Jet-A fuel; 20 gpm				
CAF			28±3	N/A

4.0 Testing Observations

This product was selected for large-field scale demonstration. There are usability concerns due to the high viscosity of PFF 7, but a newer, lower-viscosity product has been introduced, which is being tested under a companion project.

APPENDIX C-6: MIL-PRF-24385F TEST RESULTS FOR PFF 8, BIOEX

1.0 Firefighting Agent Details

BioEx EcoPol A; ICAO and EN1568-3 certified; Light green, Newtonian concentrate.



The Safety Data Sheet (SDS) can be found by making a request through this link: <https://www.bio-ex.com/en/our-products/product/ecopol-a-plus/>

2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data for PFF 8 are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	Not measured
COD (mg/L); <1,000 mg/L	378,600
BOD ₂₀ (mg/L)	881,043
Biodegradability (BOD ₂₀ /COD); BOD ₂₀ /COD: >0.65	2.33
Other Physical Properties	
Spreading coefficient; > 3	-0.58
pH; 7.0<pH<8.5	7.44
Viscosity 5 C (cSt); <20 cSt	4.12
Viscosity 25 ;C (cSt); >2 cSt	2.33
Refractive Index; >1.3630	1.334
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.23
UNS C70600: <1.0 milli in/yr	0.16
UNS NO4400: <1.0 milli in/yr	0.04
UNS C90500: <100 mg	56.14
CNS S30400: no pitting	No pitting
Stability	
Spreading coefficient; > 3	-0.35
Stratification; No visible evidence	No visible evidence
Precipitation; 0.05% by volume	

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in Table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-containing (E10) gasoline; 2 gpm				
Mil-Spec (PFF 8)	6.6	165	110±8	142±12
CAF	10.1	910	86±12	291±8
UHP	2	340	183±8	12±2

4.0 Testing Observations

EcoPol A (PFF 8) was selected for field-scale demonstration. But, before we began field-scale tests, BioEx released EcoPol A3+, designated by Battelle as PFF 8.2. The new product was tested at Mil-Spec scale to confirm performance. Performance was similar (see Appendix C-7), so EcoPol A3+ was used for field-scale testing. This product is a well-performing low-viscosity PFF.

APPENDIX C-7: MIL-PRF-24385F TEST RESULTS FOR PFF 8.2, BIOEX COPOL A3+

1.0 Firefighting Agent Details

BioEx EcoPol A3+; ICAO and EN1568-3 certified; Light green, Newtonian concentrate.



The Safety Data Sheet (SDS) can be found by making a request through this link: <https://www.bio-ex.com/en/our-products/product/ecopol-a-plus/>

2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data for PFF 8.2 are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	Not tested
COD (mg/L); <1,000 mg/L	446,300
BOD ₂₀ (mg/L)	323,900
Biodegradability (BOD ₂₀ /COD); >0.65	0.73
Other Physical Properties	
Spreading coefficient; > 3	Not tested
pH; 7.0<pH<8.5	8,01
Viscosity 5 C (cSt); <20 cSt	26,20
Viscosity 25 ;C (cSt); >2 cSt	11.36
Refractive Index; >1.3630	1.3617
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.34
UNS C70600: <1.0 milli in/yr	0.98
UNS NO4400: <1.0 milli in/yr	0.01
UNS C90500: <100 mg	93.13
CNS S30400: no pitting	No pitting
Stability	
Spreading coefficient; > 3	Not tested
Stratification; No visible evidence	No visible evidence
Precipitation; 0.05% by volume	

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in Table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

This PFF was also selected tested for field-scale fires, so the extinguishment data for the same are also provided in the Table.

Delivery Method (PFF Version #)	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	6.8	400	62±8	195±10
CAF	10	420	51±4	323±40
CAF	12	620	49±3	410±25
CAF @ 2X Conc.	12		61±1	422±40
CAF	15	290	46±0	451±26
28-ft² Jet-A fuel; 2 gpm				
Mil-Spec	6.3		46±2	
CAF	12		27±1	
315-ft² E0 gasoline; 20 gpm				
CAF	12.2		49±8	N/A
315-ft² Jet-A fuel; 20 gpm				
CAF	12.2		28±2	N/A
UHP			50±2	N/A

4.0 Testing Observations

This product is a well-performing low-viscosity PFF.

APPENDIX C-8: MIL-PRF-24385F TEST RESULTS FOR PFF 9, BIOEX F3HC

1.0 Firefighting Agent Details

BioEx F3HC; EN1568-3 certified. PFF 9

The Safety Data Sheet (SDS) can be found at this link:

<https://www.fs.fed.us/rm/fire/wfcs/products/msds/foam/Bio-Ex%20Ecopol-F%20SDS.pdf>

2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	Not tested
COD (mg/L); <1,000 mg/L	300,700
BOD ₂₀ (mg/L)	877.318
Biodegradability (BOD ₂₀ /COD); >0.65	2.92
Other Physical Properties	
Spreading coefficient; > 3	-4.48
pH; 7.0<pH<8.5	6.86
Viscosity 5 C (cSt); <20 cSt	19,100
Viscosity 25 ;C (cSt); >2 cSt	13,900
Refractive Index; >1.3630	1.3335
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.13
UNS C70600: <1.0 milli in/yr	0.16
UNS NO4400: <1.0 milli in/yr	0.04
UNS C90500: <100 mg	30.38
CNS S30400: no pitting	No pitting
Stability	
Spreading coefficient; > 3	-4.93
Stratification; No visible evidence	No visible evidence
Precipitation; 0.05% by volume	

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in Table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	7.5	560	235±35	507±115
CAF	12	1890	79±4	569±15

4.0 Testing Observations

This product was not selected for further testing because of poor extinguishment performance in Mil-Spec fire test, and because another product from this vendor, PFF 8.2 performed well in Mil-Spec scale testing.

APPENDIX C-9: MIL-PRF-24385F TEST RESULTS FOR PFF 10, NATIONAL FOAM UNIVERSAL^{F3} GREEN 3%

1.0 Firefighting Agent Details

National Foam Universal^{F3} Green 3%; UL-Listed, Lastfire. Light cream, Non-Newtonian Concentrate.



The Safety Data Sheet (SDS) can be found at this link: https://nationalfoam.com/wp-content/uploads/sites/4/NMS510-Universal-Green-3-3-AR-Syn-Concentrate_09242021.pdf

2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	Not tested
COD (mg/L); <1,000 mg/L	456,000
BOD ₂₀ (mg/L)	1.071,344
Biodegradability (BOD ₂₀ /COD); >0.65	2.35
Other Physical Properties	
Spreading coefficient; > 3	-4.23
pH; 7.0<pH<8.5	6.79
Viscosity 5 C (cSt); <20 cSt	4,600
Viscosity 25 ;C (cSt); >2 cSt	4,190
Refractive Index; >1.3630	1.332
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.12
UNS C70600: <1.0 milli in/yr	0.19
UNS NO4400: <1.0 milli in/yr	0.04
UNS C90500: <100 mg	23.17
CNS S30400: no pitting	No pitting
Stability	
Spreading coefficient; > 3	-4.42
Stratification; No visible evidence	No visible evidence
Precipitation; 0.05% by volume	

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in Table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	6.9	>3600	398±12	N/A
CAF	9.9	>7200	87±4	698±71
UHP	1.5	N/A	189±8	4±2

4.0 Testing Observations

This product was not selected for further testing because of poor extinguishment performance in Mil-Spec fire testing, and because this vendor had a better performing product (PFF 12; see Appendix C-11).

APPENDIX C-10: MIL-PRF-24385F TEST RESULTS FOR PFF 11, PYROCOOL FEF

1.0 Firefighting Agent Details

Pyrocool FEF

The Safety Data Sheet (SDS) can be found at this link: <http://princeton-mn.safeschoolssds.com/document/repo/ae092c6e-7cbd-40d7-8e2b-326db4c9ee42>



2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	
COD (mg/L); <1,000 mg/L	570,000
BOD ₂₀ (mg/L)	Not tested
Biodegradability (BOD ₂₀ /COD); >0.65	
Other Physical Properties	
Spreading coefficient; > 3	-2.51
pH; 7.0<pH<8.5	7.74
Viscosity 5 C (cSt); <20 cSt	12.7
Viscosity 25 ;C (cSt); >2 cSt	8.7
Refractive Index; >1.3630	1.325
Corrosion	
UNS G10100: < 1.5 milli in/yr	1.02
UNS C70600: <1.0 milli in/yr	0.84
UNS NO4400: <1.0 milli in/yr	0.01
UNS C90500: <100 mg	131.84
CNS S30400: no pitting	Some pitting
Stability	
Spreading coefficient; > 3	-2.44
Stratification; No visible evidence	No visible evidence
Precipitation; 0.05% by volume	

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in Table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

If the PFF was tested with field-scale fires, the extinguishment data for the same are also provided.

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	6	260	67±3	138±2
CAF	12	335	62±6	421±35

4.0 Testing Observations

This product was not one of the 4 selected for field-scale testing because of budget limitations but may be worth exploring further in the companion ESTCP project.

APPENDIX C-11: MIL-PRF-24385F TEST RESULTS FOR PFF 12, NATIONAL FOAM AVIO^{F3} GREEN KHC

1.0 Firefighting Agent Details

National Foam Avio^{F3} Green KHC; ICAO Level C certified, Passes Boeing D6-17487. Clear Newtonian Concentrate.



The Safety Data Sheet (SDS) can be found at this link: <https://nationalfoam.com/wp-content/uploads/sites/4/NMS515-Avio-Green-KHC-3-FF.pdf>

2.0 Environmental, Physical, and Corrosion Performance

The environmental, physical, and corrosion performance data are provided below. The first column shows the Mil-Spec requirements, and the second column shows the results for the PFF.

Mil-Spec Requirements	Results for the PFF
Environmental Impact	
LC ₅₀ (mg/L); >500 mg/L	Not tested
COD (mg/L); <1,000 mg/L	894,000
BOD ₂₀ (mg/L)	745,200
Biodegradability (BOD ₂₀ /COD); >0.65	0.83
Other Physical Properties	
Spreading coefficient; > 3	-2.46
pH; 7.0<pH<8.5	8.33
Viscosity 5 C (cSt); <20 cSt	145
Viscosity 25 ;C (cSt); >2 cSt	60.1
Refractive Index; >1.3630	1.3827
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.10
UNS C70600: <1.0 milli in/yr	0.21
UNS NO4400: <1.0 milli in/yr	0.00
UNS C90500: <100 mg	28.26
CNS S30400: no pitting	No pitting
Stability	
Spreading coefficient; > 3	-2.56
Stratification; No visible evidence	No visible evidence
Precipitation; 0.05% by volume	

3.0 Firefighting Performance

The Mil-Spec (28-ft²) Scale data for the following three foam delivery methods are provided in Table below:

Mil-Spec nozzle, listed as “Mil-Spec”

Compressed Air Foam (CAF)

Ultra-High Pressure (UHP)

This PFF was also tested with field-scale fires, so the extinguishment data for the same are also provided in the Table.

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² ethanol-containing (E10) gasoline; 2 gpm				
Mil-Spec	6.4	250	195±53	192±37
CAF	9.9	330	93±17	168±42
UHP	1.6	140	137±21	5±4
28-ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	6.4		63±6	155±17
CAF	12		48±1	360±22
28-ft² Jet-A Fuel; 2 gpm				
Mil-Spec	6.7	190	36±7	317±6
CAF	11.6	385	22±1	475±15
315-ft² E0 gasoline; 20 gpm				
CAF	12.1		53±16	N/A
315-ft² Jet-A Fuel; 20 gpm				
CAF	12		35±5	N/A
UHP			155±15	N/A

4.0 Testing Observations

This product was selected for field-scale evaluations because of its relatively lower viscosity and good firefighting performance with CAF and UHP at the Mil-Spec scale.

APPENDIX D TOXICITY TESTING REPORT

AQUATIC TOXICOLOGY REPORT

Project Name: BATTELLE
Location: TYNDALL AFB, FLORIDA

Prepared by: Eurofins TestAmerica - Corvallis

1100 NE Circle Boulevard, Suite 310
Corvallis, Oregon 97330
541-243-6137



Oregon Environmental Laboratory Accreditation Program #OR100022 (NELAP)
State of Washington DOE Environmental Laboratory Accreditation Program, Lab ID C556
California State Environmental Laboratory Accreditation Program, Certificate No.: 1726

Report Date: November 26, 2019 Released by: Brett Muckey

Eurofins TestAmerica – Corvallis Lab I.D. No. B4522

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INTRODUCTION

Eurofins TestAmerica – Corvallis (ET-C) Aquatic Toxicology Laboratory conducted toxicity testing on samples from Battelle.

Testing was initiated on: October 24, 2019

The test(s) were conducted using:

- the fathead minnow (*Pimephales promelas*)

Testing was done with a preliminary “range finding” acute test. These tests were all conducted with a broad range of test concentrations (a ‘0.1 dilution series’ = 0.01, 0.1, 1, 10, and 100 mg/L) to identify the rough level of toxicity for each sample.

Based on the results of the acute testing, chronic test concentrations were identified using a more precise 0.5 dilution series (such as 5, 10, 20, 40, and 80 mg/L). Both the chronic test data and the 96 hour acute data were calculated from these results.

SUMMARY OF TEST RESULTS

Exhibits 1 and 2 provide a summary of the final test results.

EXHIBIT 1

Summary of Acute “Rangefinding” Test Results

Sample ID	Acute	
	LC ₅₀ (mg/L)	
Foam 1	> 100	Estimated @ 117
Foam 2	31.6	
Foam 3	2.82	
Foam 4	31.6	
Foam 5	33.7	
Foam 6	32.3	
Foam 7	32.3	

Note: acronyms are as defined below.

More detailed information is provided in the Results and Discussion section.

EXHIBIT 2
Summary of Chronic Test Results

Sample ID	Acute LC₅₀ (mg/L)	Chronic NOEC (mg/L)	Chronic LOEC (mg/L)	Chronic IC₂₅ (mg/L)
FIREAID Florine Free	> 120	120	> 120	> 120
Baum's Novacool UEF	56.6	20.0	40.0	37.8
Pinnacle Class A Foam	5.48	4.0	8.0	4.48
Phos-Chek 1% Florine Free – [UNIPOL-FF1]	56.4	40.0	80.0	47.6
Phos-Chek 3/6 Florine Free – [UNIPOL-FF 3/6]	> 80.0	80.0	> 80.0	> 80.0
RE-HEALING FOAM RF# 3%	66.2	40.0	80.0	52.9
Fomtec Enviro USP	70.7	40.0	80.0	55.1

Note: acronyms are as defined below.

More detailed information is provided in the Results and Discussion section.

ACRONYM DEFINITIONS (from EPA guidance):

NOEC = No Observed Effect Concentration: The highest test concentration that causes no observable adverse effects on the test organisms (i.e. no statistically significant reduction from the control).

LOEC = Low Observed Effect Concentration: The lowest test concentration that does cause an observable adverse effect on the test organisms (i.e. is statistically significant reduction from the control).

LC₅₀ = Lethal Concentration (50%): A point estimate of the test concentration that would cause death in 50 percent of the test population.

IC₂₅ = Inhibition Concentration (25%): A point estimate of the test concentration that would cause a 25 percent reduction of a non-quantal biological measurement (i.e. growth, reproduction, etc.) for the test population.

METHODS AND MATERIALS

TEST METHODS

The acute test methods were performed according to: *Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms*, USEPA Office of Water (2002), EPA-821-R-02-012.

The chronic test methods were performed according to: *Short-Term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Freshwater Organisms*, Fourth Edition, (2002), EPA-821-R-02-013.

Additional guidance was provided by:

- *Method Guidance and Recommendations for Whole Effluent Toxicity (WET) Testing* (40 CFR Part 136), (EPA July 2000), EPA 821-B-00-004.

DEVIATIONS FROM PROTOCOLS

Deviations from required procedures in the test methods:

- None noted.

Deviations from recommended procedures in the test methods:

- None noted.

TEST DESIGN

The following summarizes the conditions used for both overall testing and the specifics for each test (observations and notations can be found on the datasheets in Appendix A):

Overall Test Design:

- Acute Range finding tests: 0.01, 0.1, 1, 10, and 100 mg/L sample + dilution water for the control.
- Chronic tests (with Acute dual-endpoint): concentrations tested vary by sample. A 0.5 dilution series based on the acute test results + dilution water for the control.

Test Organism Conditions:

- All organisms tested were fed and maintained during culturing, acclimation, and testing as prescribed by the EPA (2002).
- The test organisms appeared vigorous and in good condition prior to testing.

P. promelas acute test (renewal):

- Source: Aquatox Inc., Hot Springs, Arkansas
- Age: 1 to 14 days old, within a 24 hour age range
- Design: Four test vessels per concentration, Ten organisms per vessel

- Test Solution Renewal: Daily (i.e. static-renewal test)
- Monitoring:
 - o Daily: Survival, DO, pH, and temperature; all concentrations.
 - o Pre and Post Renewal solutions: DO and pH, all concentrations.
 - o Test Initiation, with each new sample use, and Termination:
 - Conductivity, control and highest concentration (EPA)
- Termination: 96 hours.
- Endpoints: Survival (at termination)

P. promelas chronic test:

- Source: Aquatox Inc., Hot Springs, Arkansas
- Age: Less than 48 hours old and within an 24 hour age range
- Design: Four test vessels per concentration, ten organisms per vessel
- Test Solution Renewal: Daily
- Monitoring:
 - o Daily: Survival
 - o Daily: DO and pH in pre and post-renewal solutions, all concentrations
 - o Daily: Temperature in pre-renewal solutions, all concentrations
 - o With each new sample: Conductivity in post-renewal solutions, control and highest sample concentration
- Termination: 7 days after test initiation.
- Endpoints: Survival and Growth (average dry weight per organism added @ initiation)
- Acute Dual-Endpoint: 96 hour Survival (from the 4 day chronic exposure data)

DILUTION WATER

The dilution water used was the standard culture water used by ET-C:

- Reconstituted, moderately hard water (as per EPA protocol) with a total hardness of 75 to 105 mg/L as CaCO₃ and an alkalinity of 50 to 75 mg/L as CaCO₃.

SAMPLE COLLECTION AND STORAGE

Samples were collected by Battelle personnel. The samples were accepted as scheduled by ET-C. Chain of Custody and Sample Receipt Records are provided in Appendix C.

- The sample was received at ambient temperature.
- Following receipt, the samples were stored ambient room temperature (~ 21 °) until test solutions were prepared and tested.

SAMPLE PREPARATION

Samples used during these tests were:

- Test solutions were made by diluting the sample into dilution water.
- Temperature adjusted prior to test initiation and each daily renewal.

DATA ANALYSIS

The statistical analyses performed for the acute tests were those outlined in *Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms*, USEPA Office of Water, Fifth Edition (2002), EPA-821-R-02-012, using CETIS.

The statistical analyses performed for the chronic tests were those outlined in *Short-Term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Freshwater Organisms*, USEPA Office of Water, Fourth Edition (EPA 2002), EPA-821-R-02-013, using CETIS.

- The specific statistical analysis and CETIS version used for each endpoint evaluation is listed with the statistical outputs included with each test in Appendix A.

RESULTS AND DISCUSSION

Data for each sample tested is presented in two tables:

- The results of the acute range finding test
 - o 96 hour LC₅₀ value, with 95% confidence limits
- The results of the chronic test, with acute dual-endpoint
 - o 96 hour LC₅₀ value, with 95% confidence limits
 - o 7 day NOEC value
 - o 7 day LOEC value
 - o 7 day IC₂₅ value, with 95% confidence limits

Unless noted with the individual tests below:

- Dissolved oxygen concentrations remained at 4.0 mg/L or greater throughout the test period.
- Test temperatures remained in the range of 25±1 °C.
- The tests proceeded without any noted deviations or interruptions that could have affected test results.
- The testing should be considered “valid”.

The raw data sheets for all tests are presented in Appendix A.

FIREAID Florine Free

Table 1 summarizes the survival data for the *P. promelas* acute test.

Table 1 Summary of Range Finding Results- <i>P. promelas</i> FIREAID Florine Free	
Sample Concentration (mg/L)	Acute (96 hour) Percent Survival
Control	100
0.01	100
0.1	100
1	100
10	97.5
100	55.0

- $LC_{50} > 100$ mg/L (estimated @ 117) (95% CI = 74.9 to 263.4 mg/L)

The *P. promelas* acute test meets Test Acceptability Criteria (TAC) of a minimum 90 percent control survival. The testing should be considered “valid”.

Table 2 summarizes the survival and growth data for the *P. promelas* chronic test.

Table 2 Summary of Chronic Results - <i>P. promelas</i> FIREAID Florine Free			
Sample Conc. (mg/L)	Acute (96 hour) Percent Survival	Chronic (7 day) Percent Survival	Chronic (7 day) Mean Dry Weight Per Organism Added (mg)
Control	100	100	0.646
7.5	100	100	0.701
15	100	100	0.689
30	100	100	0.648
60	100	100	0.702
120	100	97.5	0.734
^a Indicates a statistically significant difference from the control at alpha = 0.05.			

- $LC_{50} > 120$ mg/L (95% CI = not available)
- NOEC = 120 mg/ L
- LOEC > 120 mg/ L
- $IC_{25} > 120$ mg/ L (95% CI = not available)

The *P. promelas* chronic test meets Test Acceptability Criteria (TAC) for a minimum 80 percent control survival and a minimum weight of 0.250 mg per surviving control organism. The testing should be considered “valid”.

Baum's Novacool UEF

Table 3 summarizes the survival data for the *P. promelas* acute test.

Table 3 Summary of Range Finding Results- <i>P. promelas</i> Baum's Novacool UEF	
Sample Concentration (mg/L)	Acute (96 hour) Percent Survival
Control	97.5
0.01	100
0.1	100
1	100
10	100
100	0.0

- LC_{50} = 31.6 mg/L (95% CI = 10 to 100 mg/L)

The *P. promelas* acute test meets Test Acceptability Criteria (TAC) of a minimum 90 percent control survival. The testing should be considered “valid”.

Table 4 summarizes the survival and growth data for the *P. promelas* chronic test.

Table 4 Summary of Chronic Results - <i>P. promelas</i> Baum's Novacool UEF			
Sample Conc. (mg/L)	Acute (96 hour) Percent Survival	Chronic (7 day) Percent Survival	Chronic (7 day) Mean Dry Weight Per Organism Added (mg)
Control	100	100	0.659
5	100	100	0.723
10	100	100	0.678
20	100	100	0.638
40	100	100	0.507 ^a
80	0.0	0.0 ^a	0.000

^a Indicates a statistically significant difference from the control at alpha = 0.05.

- LC_{50} = 56.6 mg/L (95% CI = 56.6 to 56.6)
- NOEC = 20 mg/ L
- LOEC = 40 mg/ L
- IC_{25} = 37.8 mg/ L (95% CI = 26.4 to 43.6)

The *P. promelas* chronic test meets Test Acceptability Criteria (TAC) for a minimum 80 percent control survival and a minimum weight of 0.250 mg per surviving control organism. The testing should be considered “valid”.

Pinnacle Class A Foam

Table 5 summarizes the survival data for the *P. promelas* acute test.

Table 5 Summary of Range Finding Results- <i>P. promelas</i> Pinnacle Class A Foam	
Sample Concentration (mg/L)	Acute (96 hour) Percent Survival
Control	100
0.01	100
0.1	95.0
1	100
10	0.0
100	0.0

- LC_{50} = 2.82 mg/L (95% CI = 2.40 to 3.31 mg/L)

The *P. promelas* acute test meets Test Acceptability Criteria (TAC) of a minimum 90 percent control survival. The testing should be considered “valid”.

Table 6 summarizes the survival and growth data for the *P. promelas* chronic test.

Table 6 Summary of Chronic Results - <i>P. promelas</i> Pinnacle Class A Foam			
Sample Conc. (mg/L)	Acute (96 hour) Percent Survival	Chronic (7 day) Percent Survival	Chronic (7 day) Mean Dry Weight Per Organism Added (mg)
Control	100	100	0.569
0.5	97.5	97.5	0.552
1	100	100	0.542
2	100	100	0.548
4	95.0	90.0	0.506
8	0.0	0.0 ^a	0.000
^a Indicates a statistically significant difference from the control at alpha = 0.05.			

- LC_{50} = 5.48 mg/L (95% CI = 5.21 to 5.76)
- NOEC = 4 mg/ L
- LOEC = 8 mg/ L
- IC_{25} = 4.48 mg/ L (95% CI = 3.58 to 4.86)

The *P. promelas* chronic test meets Test Acceptability Criteria (TAC) for a minimum 80 percent control survival and a minimum weight of 0.250 mg per surviving control organism. The testing should be considered “valid”.

Phos-Chek 1% Florine Free – [UNIPOL-FF1]

Table 7 summarizes the survival data for the *P. promelas* acute test.

Table 7 Summary of Range Finding Results- <i>P. promelas</i> Phos-Chek 1% Florine Free – [UNIPOL-FF1]	
Sample Concentration (mg/L)	Acute (96 hour) Percent Survival
Control	92.5
0.01	94.4
0.1	90.0
1	100
10	100
100	0.0

- LC_{50} = 31.6 mg/L (95% CI = 10 to 100 mg/L)

The *P. promelas* acute test meets Test Acceptability Criteria (TAC) of a minimum 90 percent control survival. The testing should be considered “valid”.

Table 8 summarizes the survival and growth data for the *P. promelas* chronic test.

Table 8 Summary of Chronic Results - <i>P. promelas</i> Phos-Chek 1% Florine Free – [UNIPOL-FF1]			
Sample Conc. (mg/L)	Acute (96 hour) Percent Survival	Chronic (7 day) Percent Survival	Chronic (7 day) Mean Dry Weight Per Organism Added (mg)
Control	97.5	97.5	0.513
5	95.0	90.0	0.470
10	95.0	95.0	0.523
20	97.5	97.5	0.550
40	100	100	0.561
80	0.0	0.0 ^a	0.000

^a Indicates a statistically significant difference from the control at alpha = 0.05.

- LC_{50} = 56.4 mg/L (95% CI = 55.9 to 56.9)
- NOEC = 40 mg/ L
- LOEC = 80 mg/ L
- IC_{25} = 47.6 mg/ L (95% CI = 45.6 to 47.6)

The *P. promelas* chronic test meets Test Acceptability Criteria (TAC) for a minimum 80 percent control survival and a minimum weight of 0.250 mg per surviving control organism. The testing should be considered “valid”.

Phos-Chek 3/6 Florine Free – [UNIPOL-FF 3/6]

Table 9 summarizes the survival data for the *P. promelas* acute test.

Table 9 Summary of Range Finding Results- <i>P. promelas</i> Phos-Chek 3/6 Florine Free – [UNIPOL-FF 3/6]	
Sample Concentration (mg/L)	Acute (96 hour) Percent Survival
Control	92.5
0.01	97.2
0.1	100
1	100
10	97.5
100	5.0

- $LC_{50} = 33.7 \text{ mg/L}$ (95% CI = 30.8 to 36.8 mg/L)

The *P. promelas* acute test meets Test Acceptability Criteria (TAC) of a minimum 90 percent control survival. The testing should be considered “valid”.

Table 10 summarizes the survival and growth data for the *P. promelas* chronic test.

Table 10 Summary of Chronic Results - <i>P. promelas</i> Phos-Chek 3/6 Florine Free – [UNIPOL-FF 3/6]			
Sample Conc. (mg/L)	Acute (96 hour) Percent Survival	Chronic (7 day) Percent Survival	Chronic (7 day) Mean Dry Weight Per Organism Added (mg)
Control	95.0	95.0	0.534
5	100	100	0.559
10	100	96.7	0.573
20	100	96.7	0.541
40	92.5	92.5	0.399
80	100	100	0.608
^a Indicates a statistically significant difference from the control at alpha = 0.05.			

- $LC_{50} > 80 \text{ mg/L}$ (95% CI = not available)
- NOEC = 80 mg/ L
- LOEC > 80 mg/ L
- $IC_{25} > 80 \text{ mg/ L}$ (95% CI = not available)

The *P. promelas* chronic test meets Test Acceptability Criteria (TAC) for a minimum 80 percent control survival and a minimum weight of 0.250 mg per surviving control organism. The testing should be considered “valid”.

RE-HEALING FOAM RF# 3%

Table 11 summarizes the survival data for the *P. promelas* acute test.

Table 11 Summary of Range Finding Results- <i>P. promelas</i> RE-HEALING FOAM RF# 3%	
Sample Concentration (mg/L)	Acute (96 hour) Percent Survival
Control	100
0.01	100
0.1	100
1	100
10	100
100	0.0

- LC_{50} = 32.3 mg/L (95% CI = 32.3 to 32.3 mg/L)

The *P. promelas* acute test meets Test Acceptability Criteria (TAC) of a minimum 90 percent control survival. The testing should be considered “valid”.

Table 12 summarizes the survival and growth data for the *P. promelas* chronic test.

Table 12 Summary of Chronic Results - <i>P. promelas</i> RE-HEALING FOAM RF# 3%			
Sample Conc. (mg/L)	Acute (96 hour) Percent Survival	Chronic (7 day) Percent Survival	Chronic (7 day) Mean Dry Weight Per Organism Added (mg)
Control	97.5	97.5	0.485
5	100	100	0.533
10	97.5	97.5	0.569
20	100	100	0.566
40	95.0	95.0	0.571
80	25.0	25.0 ^a	0.206

^a Indicates a statistically significant difference from the control at alpha = 0.05.

- LC_{50} = 66.2 mg/L (95% CI = 58.2 to 74.0)
- NOEC = 40 mg/ L
- LOEC = 80 mg/ L
- IC_{25} = 52.9 mg/ L (95% CI = 46.5 to 64.3)

The *P. promelas* chronic test meets Test Acceptability Criteria (TAC) for a minimum 80 percent control survival and a minimum weight of 0.250 mg per surviving control organism. The testing should be considered “valid”.

Fomtec Enviro USP

Table 13 summarizes the survival data for the *P. promelas* acute test.

Table 13 Summary of Range Finding Results- <i>P. promelas</i> Fomtec Enviro USP	
Sample Concentration (mg/L)	Acute (96 hour) Percent Survival
Control	100
0.01	100
0.1	100
1	100
10	100
100	0.0

- LC_{50} = 32.3 mg/L (95% CI = 32.3 to 32.3 mg/L)

The *P. promelas* acute test meets Test Acceptability Criteria (TAC) of a minimum 90 percent control survival. The testing should be considered “valid”.

Table 14 summarizes the survival and growth data for the *P. promelas* chronic test.

Table 14 Summary of Chronic Results - <i>P. promelas</i> Fomtec Enviro USP			
Sample Conc. (mg/L)	Acute (96 hour) Percent Survival	Chronic (7 day) Percent Survival	Chronic (7 day) Mean Dry Weight Per Organism Added (mg)
Control	100	97.5	0.507
5	100	100	0.534
10	100	97.5	0.533
20	92.5	92.5	0.531
40	95.0	95.0	0.548
80	35.0	30.0 ^a	0.243
^a Indicates a statistically significant difference from the control at alpha = 0.05.			

- LC_{50} = 70.7 mg/L (95% CI = 59.0 to 92.9)
- NOEC = 40 mg/ L
- LOEC = 80 mg/ L
- IC_{25} = 55.1 mg/ L (95% CI = 46.5 to 87.6)

The *P. promelas* chronic test meets Test Acceptability Criteria (TAC) for a minimum 80 percent control survival and a minimum weight of 0.250 mg per surviving control organism. The testing should be considered “valid”.

REFERENCE TOXICANT TESTS

Reference toxicant (reftox) testing is performed to document both initial and ongoing laboratory performance of the test method(s). While the health of the test organisms is primarily evaluated by the performance of the laboratory control, reftox test results also may be used to assess the health and sensitivity of the test organisms. Reftox test results within their respective cumulative summary (Cusum) chart limits are indicative of consistent laboratory performance and normal test organism sensitivity.

The results of the reftox tests indicate that the test organisms were within their respective cusum chart limits based on EPA guidelines. This demonstrates ongoing laboratory proficiency of the test methods and suggests normal test organism sensitivity in the associated client testing.

The *P. promelas* acute reftox test was conducted using sodium chloride. The *P. promelas* chronic reftox test was conducted using potassium chloride.

The data sheets for the reference toxicant tests are provided in Appendix B.

Tables 15 and 16 summarize the reference toxicant test results and Cusum chart limits.

Table 15		
Acute Reference Toxicant Tests (g/L)		
Species	LC₅₀	Cusum Chart Limits
<i>P. promelas</i> - October	7.7	6.0 to 8.9

Table 16		
Chronic Reference Toxicant Tests (g/L)		
Species	IC₂₅	Cusum Chart Limits
<i>P. promelas</i> (survival) - October	0.57	0.52 to 0.68
<i>P. promelas</i> (growth) - October	0.58	0.45 to 0.73
<i>P. promelas</i> (survival) - November	0.54	0.52 to 0.68
<i>P. promelas</i> (growth) - November	0.56	0.45 to 0.73

APPENDIX E CORROSION TESTING REPORT: MIL-F-24385F CORROSION TESTING AT BATTELLE OF SELECTED PFAS-FREE FOAMS (PFFS)

PURPOSE

This report covers the procedure and results obtained from the exposure study of eight (8) different aqueous film forming foams (AFFF) with respect to the requirements of military specification (Mil-Spec) MIL-F-24385F – “Fire Extinguishing Agent, Aqueous Film-forming Foam Liquid Concentrate, for Fresh and Sea Water”.

BACKGROUND

Battelle selected eight (8) distinct PFFs for qualification of the corrosivity against the above-reference Mil-Spec. The following list contains the nomenclature used for each foam (also referred to as PFF) tested:

Foam 1 (PFF 1): FireAde®

Foam 2 (PFF 2): Novacool® UEF

Foam 4 (PFF 4): Phos Chek® 1%

Foam 5 (PFF 5): Phos Chek® 3-6%

Foam 6 (PFF 6): Solberg RH™3

Foam 7 (PFF 7): Fomtec® Enviro USP

Foam 8 (PFF 8): BioEx “Foam A”

Foam 9 (PFF 9): BioEx “Foam B”

Originally there were nine (9) foams proposed for the study, but “Foam 3” was not sent to Battelle-Columbus (BCO) and so was omitted from the matrix. The “Foam #” identifier will be maintained throughout results reporting.

Per the Mil-Spec, the following materials were involved in the general corrosion exposure study:

G10100 Steel

C70600 Cu-Ni

N04400 Ni-Cu

C90500 Bronze

A fifth material was utilized for localized corrosion assessment:

S30400 Stainless Steel

The overarching objective of these exposure tests was to characterize and quantify the corrosivity of the AFFFs per the requirements of the Mil-Spec.

PROCEDURE

Materials Handling

The metal coupons/specimens were acquired via Alabama Specialty Products, with the exception of the sand-cast bronze (C90500), which required a bespoke supplier. The nominal dimensions of the material specimens were 3”L x ½”W x 1/16”T, per the Mil-Spec. These standard dimensions were not attainable for the sand-cast C90500, so their overall dimensions were independently measured with digital calipers upon receipt.



Figure E-1. Example Exposure Depicting the Material Coupons Suspended in Solution.

For the general corrosion test coupons, initial weights of each of the specimens were recorded prior to introduction to the exposure environment. Per the Mil-Spec, the stainless-steel coupons were also passivated prior to introduction to their containment cells.¹ Each coupon was suspended in the foam solutions by nylon string attached to containment cell lid. These tethers were spaced apart to prevent the contact of metal surfaces during the 60-day exposure.

Test Setup

Each provided AFFF was diluted with artificial seawater to a 10% solution. 750 mL glass jars were utilized for the matrix of exposures. The AFFF containment cells were all filled with 600 mL of the 10% solutions and marked with the time of exposure start on the side. Labels for the cells also marked the material type and foam # for proper record-keeping. Each material type per AFFF was contained in its own exposure cell to prevent cross-contamination of free metal ions that might result from corrosion processes. This amounted to 32 separate cells containing five (5) replicate material coupons for the general corrosion rate studies and eight (8) additional cells, each containing ten (10) stainless steel replicates, for the localized corrosion study.

¹ Pre-exposure weights were taken after passivation for the stainless steel coupons.



Figure E-2. AFFF Exposure Containment Cells – General Corrosion Rate Study.

Post-exposure Handling

At the close of the 60-day exposure, each group of specimens was removed from its containment cell. The material coupons were individually rinsed with de-ionized water, followed by a light mechanical scrub with a nylon bristle brush and then rinsed again. The groups of coupons were stored in a desiccator until all the exposures could be torn down. The next step in the post-test procedure was chemical de-scaling. Major alloy types have unique chemistries for de-scaling per ASTM G1/NACE TM-0169. Those regimens are tabulated below.

Table E-1. Chemical De-scaling Details per ASTM G1/NACE TM-0169

Material Type	Chemistry	Cycle
G10100 - Steel	(undiluted) HCl + 20g/L SnCl ₂ + 50g/L Sb ₂ O ₃	1 to 25 min @ RT
C70600 - Cu-Ni	20% HCl	1 to 3 min @ RT
N04400 - Ni-Cu	20% HCl	1 to 3 min @ RT
C90500 - Bronze	20% HCl	1 to 3 min @ RT

The stainless steel, localized corrosion specimens were not de-scaled in this way as tracking the corrosion product deposits was essential for categorizing the localized attack suffered.

Once cleaned and/or de-scaled properly, the specimens were analyzed for corrosion resistance in their respective foams. For the general corrosion coupons, a rate of mass loss due to corrosion was generated, and for the stainless steel, a low magnification inspection of the coupons elucidated occurrences of localized corrosion. The results are documented in the following section.

RESULTS

It is prudent to break down the results presentation into two categories. Namely, general corrosion and localized corrosion as they are distinct mechanisms and require varying analyses for reporting per the Mil-Spec.

General Corrosion

General corrosion is a mechanism characterized by a uniform dissolution of substrate material into corrosion product. Analysis results in a general corrosion rate (GCR), which is gravimetric in nature. The weights prior to the exposure are compared to the weights post-exposure. Knowing the surface area and density of the material allows for the calculation of a GCR for each test coupon. Per the Mil-Spec, the maximum allowable corrosion rates/mass losses for each subject material are as follows:

G10100 Steel – 1.5 milli-inches per year (mpy)

C70600 Cu-Ni – 1.0 mpy

N04400 Ni-Cu – 1.0 mpy

C90500 Bronze – 100 mg gross mass loss

The overall material averages are presented in the following figure followed by breakdowns by Foam # and specific alloy.

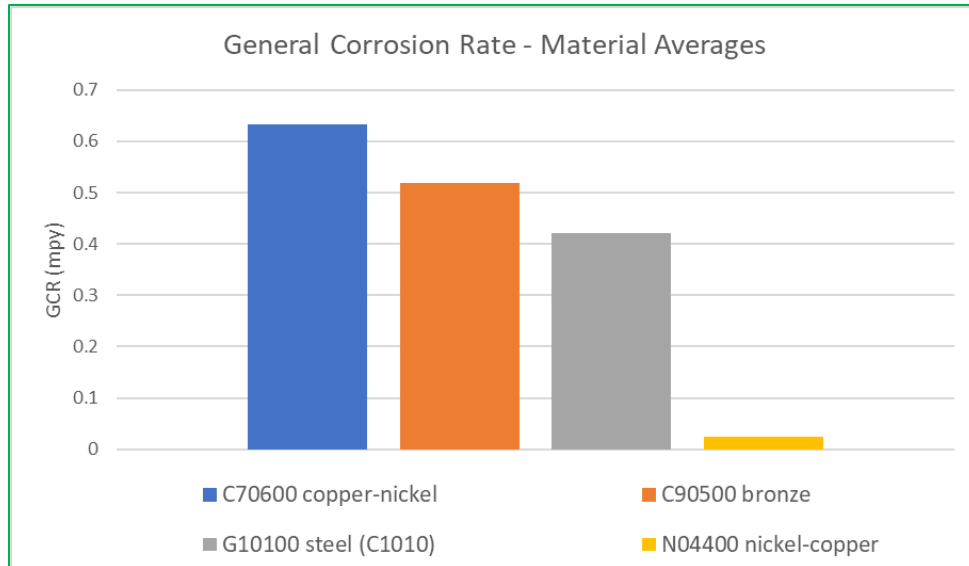


Figure E-3. Average Corrosion Rates Summed Over the Entirety of the Field of Coupons Regardless of Foam# Exposure.

More granular results are presented by Foam # and by Material Type in the following sets of plots. This first set tabulates the GCR of all subject materials with respect to individual foam chemistries. For the C90500 Bronze coupons, the change in weight is superimposed on each GCR plot.

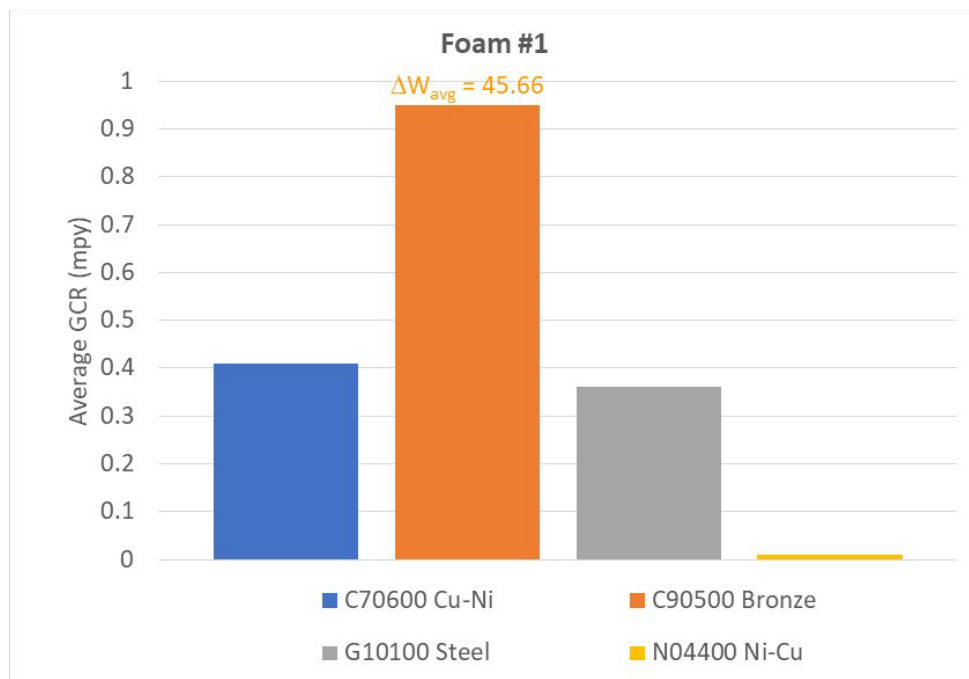


Figure E-4. Average Corrosion Rate by Material with Respect to Foam #1 Exposure.

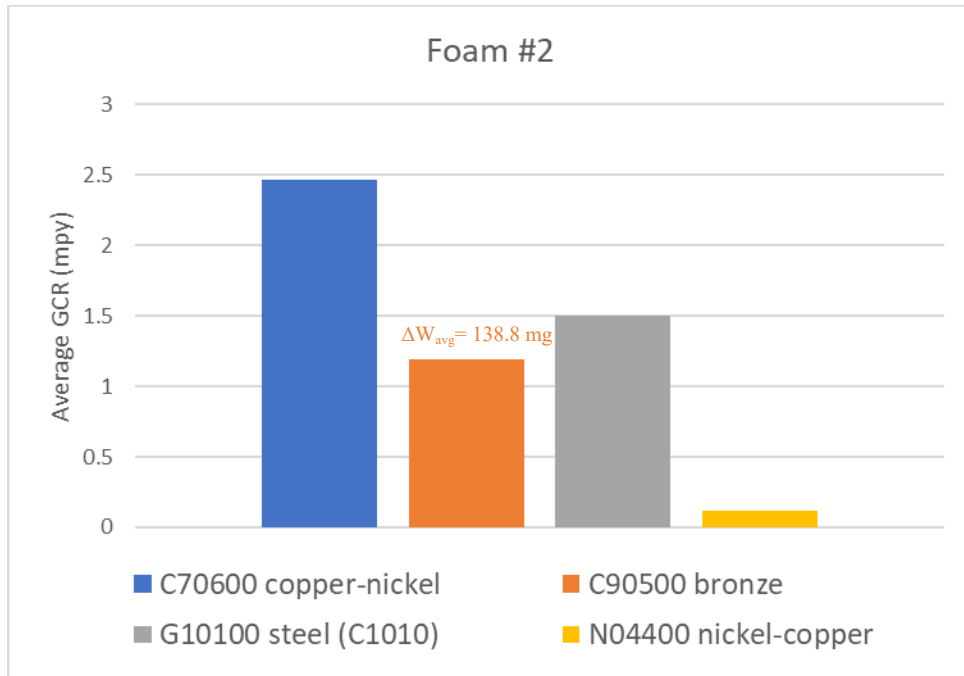


Figure E-5. Average Corrosion Rate by Material with Respect to Foam #2 Exposure.

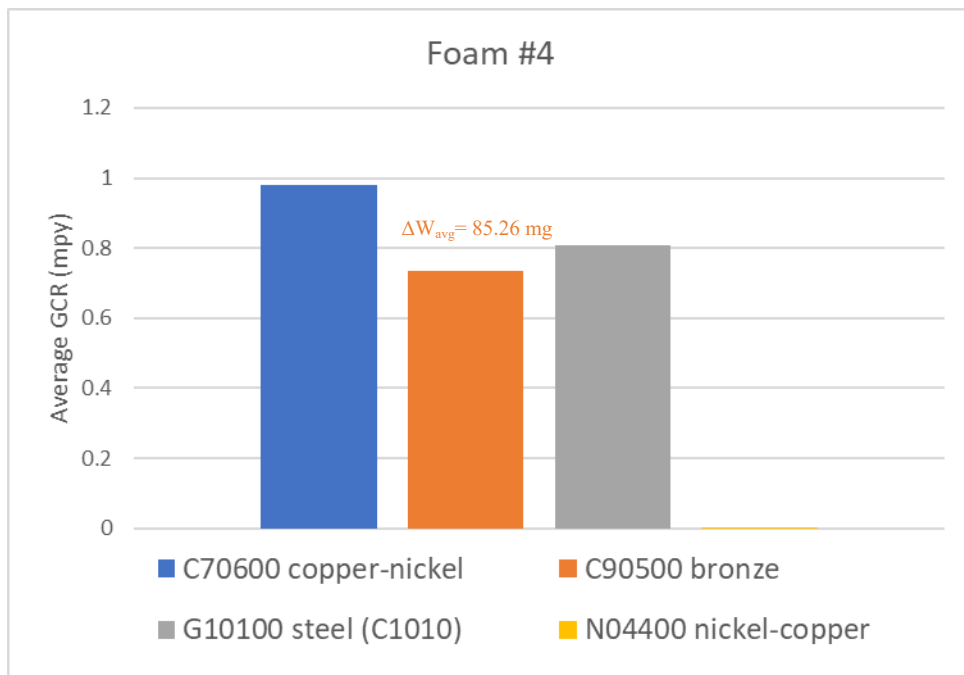


Figure E-6. Average Corrosion Rate by Material with Respect to Foam #4 Exposure.

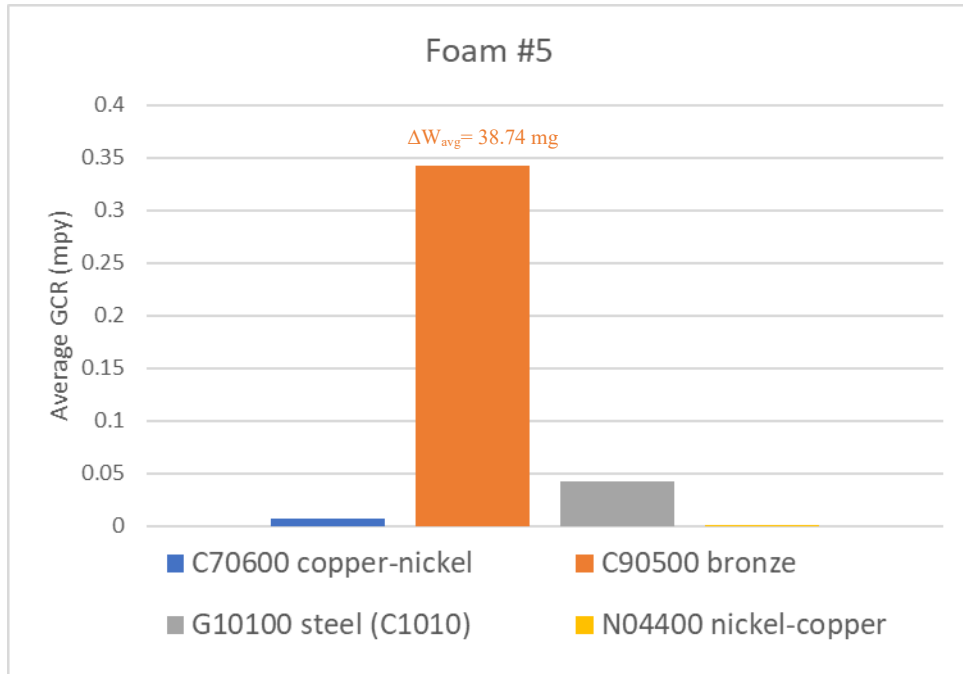


Figure E-7. Average Corrosion Rate by Material with Respect to Foam #5 Exposure.

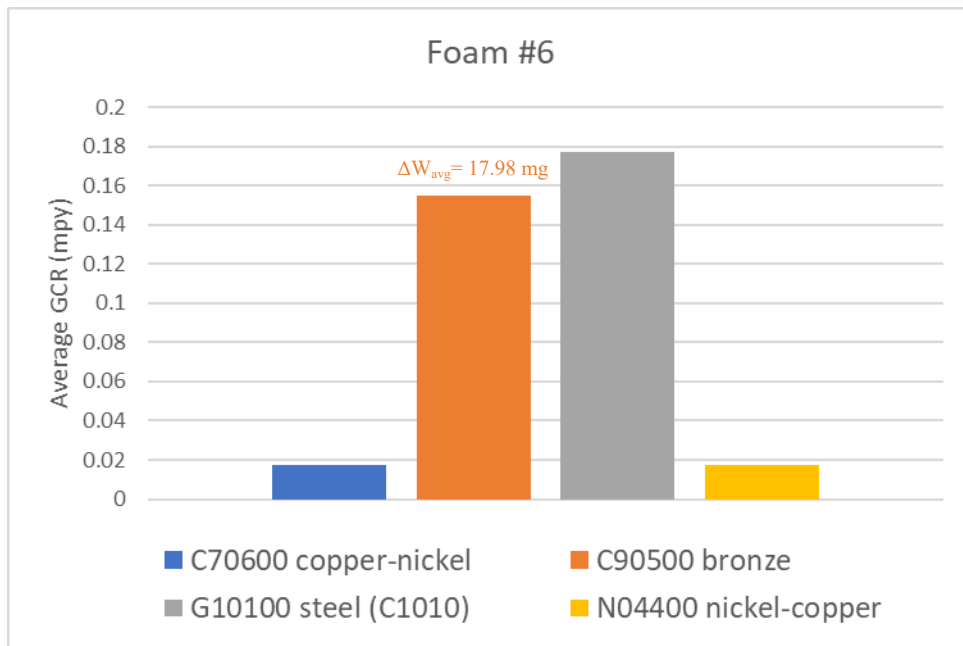


Figure E-8. Average Corrosion Rate by Material with Respect to Foam #6 Exposure.

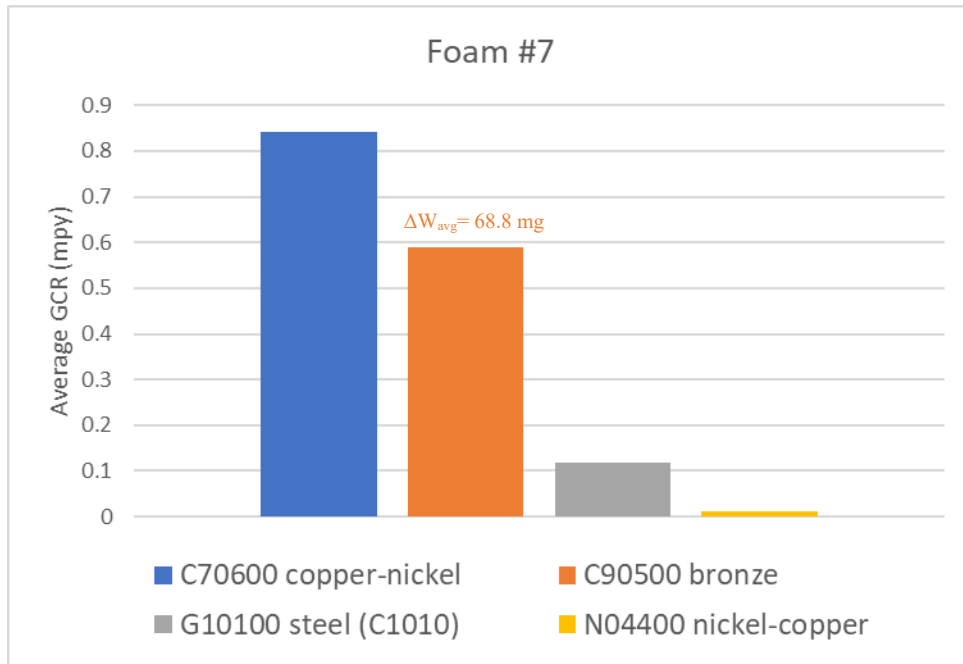


Figure E-9. Average Corrosion Rate by Material with Respect to Foam #7 Exposure.

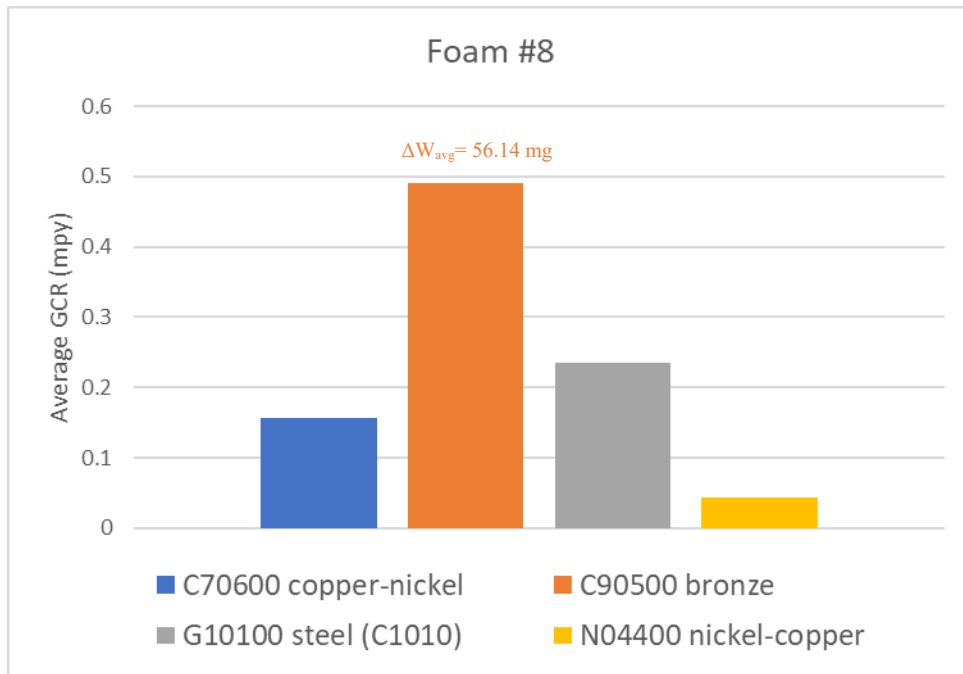


Figure E-10. Average Corrosion Rate by Material with Respect to Foam #8 Exposure.

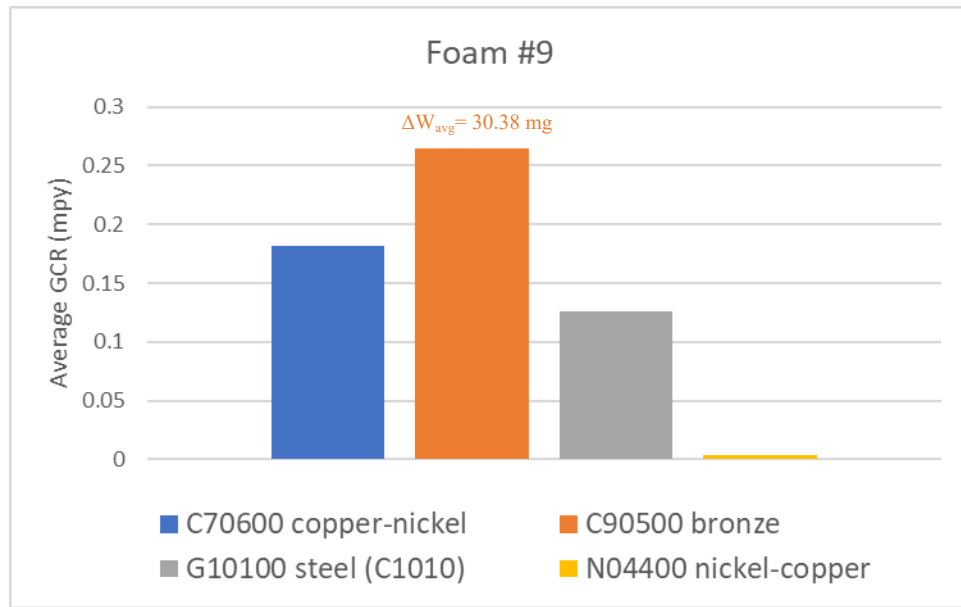


Figure E-11. Average Corrosion Rate by Material with Respect to Foam #9 Exposure.

The next set of plots examines the foam chemistry in which each material is most susceptible to general corrosion breakdown. The maximum allowable corrosion rate per the Mil-Spec is superimposed for each subject material.

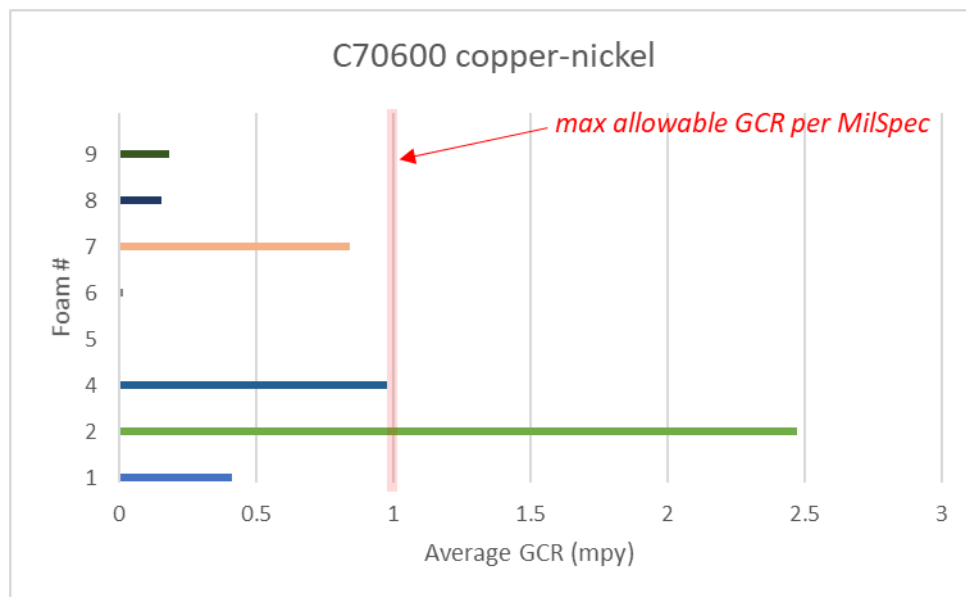


Figure E-12. Average Corrosion Rate of C70600 with Respect to Foam #.

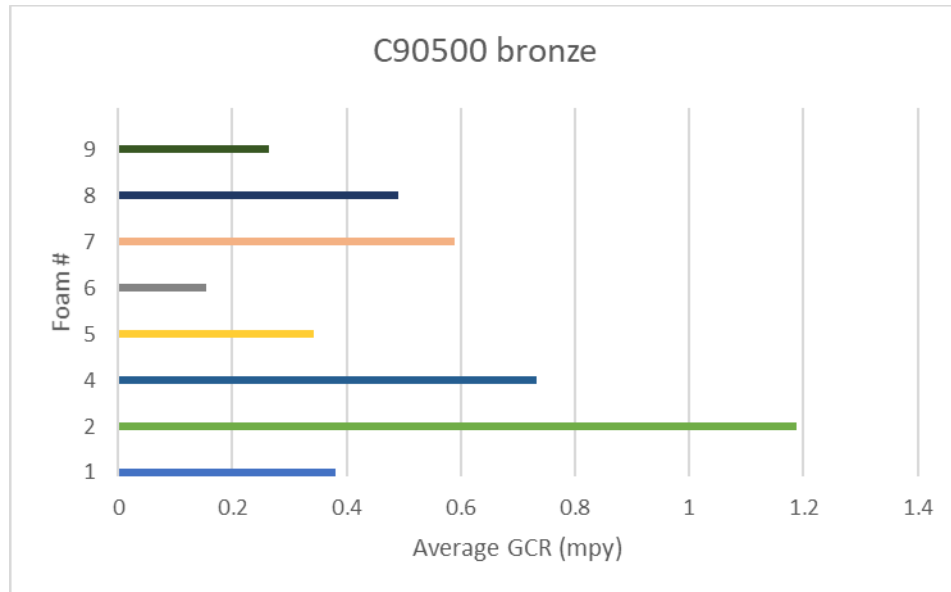


Figure E-13. Average Corrosion Rate of C90500 with Respect to Foam #.

The Mil-Spec calls for the C90500 specimens to be ranked based on total mass loss as opposed to the calculated GCR. That data is presented in the following figure.

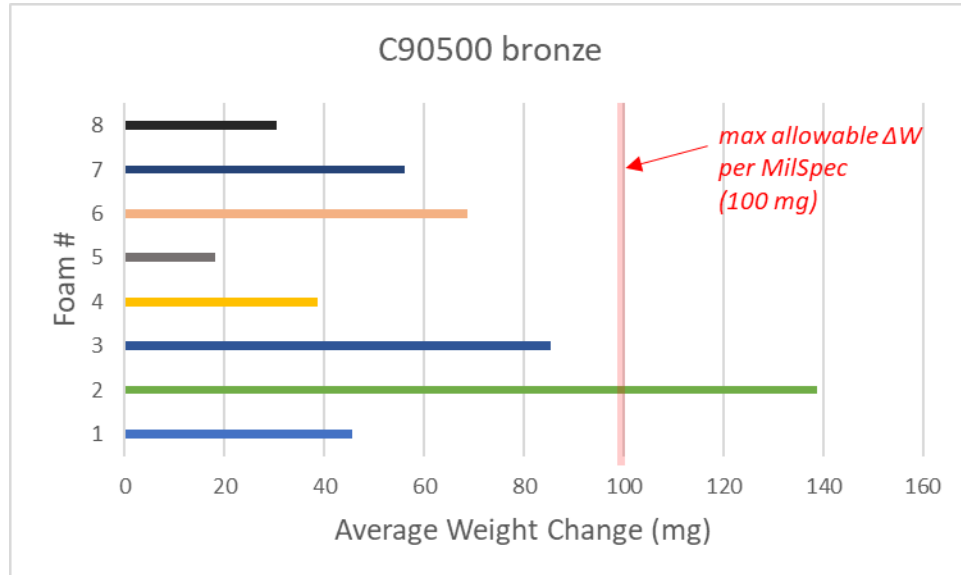


Figure E-14. Average Change in Weight of C90500 with Respect to Foam #.

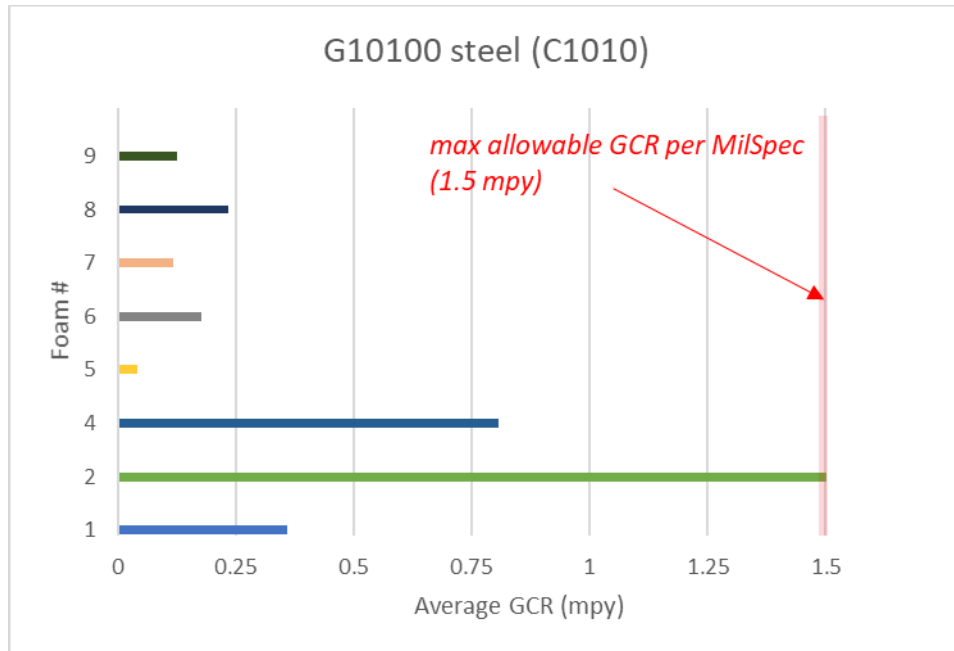


Figure E-15. Average Corrosion Rate of G10100 with Respect to Foam #.

For the N04400 coupons, the maximum allowable GCR per the Mil-Spec (1.0 mpy) is far to the right of the x-axis boundaries, therefore is not pictured as a superimposition on the following chart.

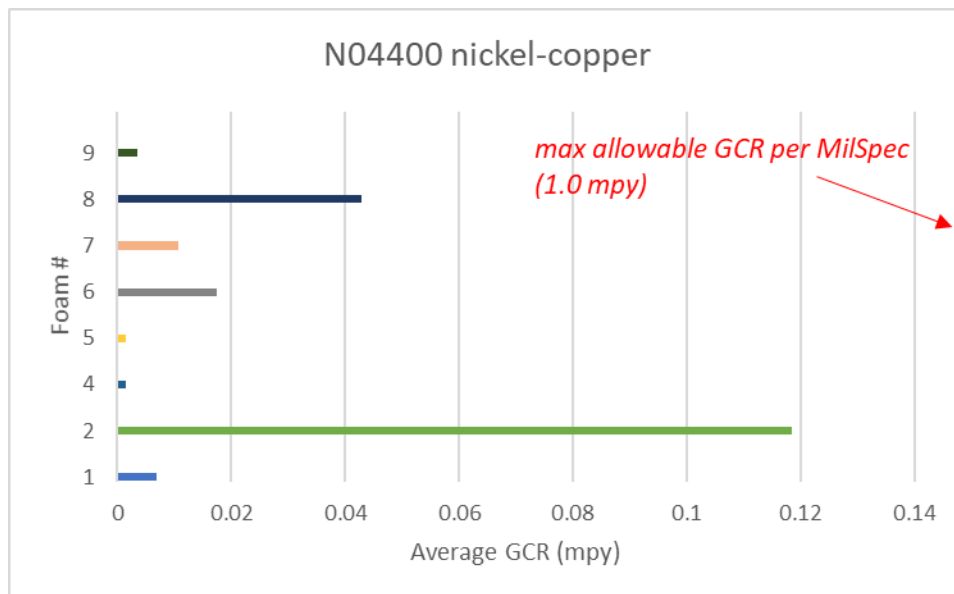


Figure E-16. Average Corrosion Rate of N04400 with Respect to Foam #.

Localized Corrosion

The stainless-steel coupons were utilized for the localized corrosion susceptibility study. They were nominally the same dimensions as the general corrosion material coupons with the addition of a band of gum rubber affixed lengthwise over the coupon as a crevice former. The results reporting for localized corrosion per the Mil-Spec is observational in nature. To provide some additional detail, the observations are classified into coded categories of attack:

Pitting (P) – isolated pits observed on the broad faces of the coupon

Crevice (C) – crevice attack observed under the gum rubber band

Edge Effect (E) – localized attack originating at the machined edges of coupons

In the following tables, observations are logged for each of the exposed stainless steel coupons. An orange highlight suggests the localized attack was obvious with the naked eye. A yellow highlight suggests that the localized attack required magnification for confirmation. Pits were confirmed by removal of corrosion product with a dental pick to ensure that metal loss was associated with the adhered corrosion product. All images included in this section are micrographs at 10X magnification.

Table E-2. Tabulated Localized Corrosion Observations for Foam #1.

	<i>Sample #</i>	<i>Visual Inspection by eye</i>	<i>Inspection at 10X</i>	<i>Code</i>
Foam #1	1	No Pits	No Pits	
	2	No Pits	No Pits	
	3	No Pits	No Pits	
	4	No Pits	No Pits	
	5	Pit - Bottom edge under rubber band	Pit - Bottom edge under rubber band	C
	6	No Pits	No Pits	
	7	No Pits	No Pits	
	8	No Pits	No Pits	
	9	No Pits	No Pits	
	10	No Pits	No Pits	

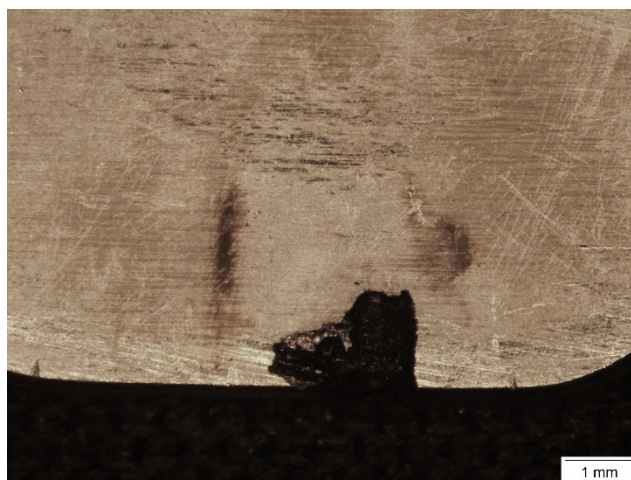


Figure E-17. Crevice Attack Observed on Stainless Steel Sample 5, Foam #1

Table E-3. Tabulated Localized Corrosion Observations for Foam #2

	Sample #	Visual Inspection by eye	Inspection at 10X	Code
Foam #2	11	No Pits	Possible Pit Back Side not under band - below surface	P
	12	No Pits	No Pits	
	13	No Pits	No Pits	
	14	No Pits	No Pits	
	15	No Pits	No Pits	
	16	One large Pit top of front side and extends to the back side under rubber band	One large Pit top of front side and extends to the back side under rubber band	C
	17	One Small Pit - Back side - Not under rubber band	One Small Pit - Back side - Not under rubber band	P
	18	No Pits	No Pits	
	19	Pit Bottom front side under rubber band	Pit Bottom front side under rubber band	C
	20	No Pits	Small Pits on Back side under rubber band under surface	C

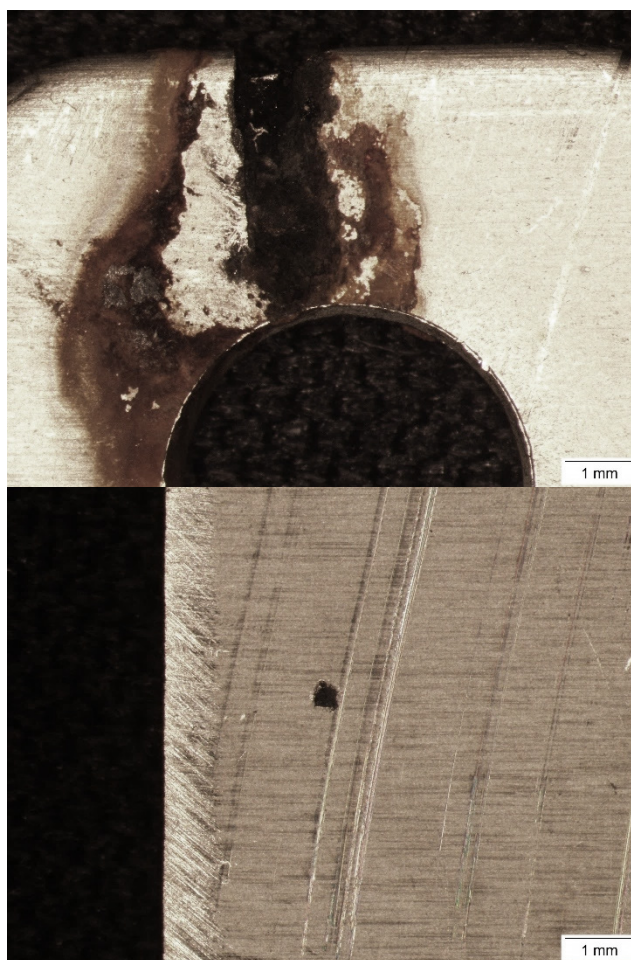


Figure E-18. (L) Crevice Attack Observed on Sample 16, (R) Isolated Pit Observed on Sample 17, Foam #2

Table E-4. Tabulated Localized Corrosion Observations for Foam #4

	Sample #	Visual Inspection by eye	Inspection at 10X	Code
Foam #4	21	No Pits	No Pits	
	22	One Pit on back side - questionable	One Pit on back side - questionable	C
	23	No Pits	Possible pit on back side - below surface under rubber band	C
	24	No Pits	Possible pit on back side - below surface under rubber band	C
	25	No Pits	Possible pit on back side below surface_Not under rubber band - staining from rubber band	P
	26	No Pits	No Pits	
	27	No Pits	No Pits	
	28	No Pits	No Pits	
	29	No Pits	No Pits	
	30	No Pits	2 possible Pits on back edge - below surface	E,P



Figure E-19. Isolated Pitting Observed on Stainless Steel sample 25, Foam #4

Table E-5. Tabulated Localized Corrosion Observations for Foam #5

	Sample #	Visual Inspection by eye	Inspection at 10X	Code
Foam #5	31	No Pits	No Pits	
	32	No Pits	No Pits	
	33	No Pits	No Pits	
	34	No Pits	No Pits	
	35	No Pits	No Pits	
	36	No Pits	No Pits	
	37	No Pits	No Pits	
	38	No Pits	No Pits	
	39	No Pits	No Pits	
	40	No Pits	Possible pit near edge on rough surface from machining - Below Surface	P

Table E-6. Tabulated Localized Corrosion Observations for Foam #6

	Sample #	Visual Inspection by eye	Inspection at 10X	Code
Foam #6	41	No Pits	Possible pit front side near edge - below surface	P
	42	No Pits	No Pits	
	43	No Pits	Possible Pit front side under band - below surface	C
	44	No Pits	No Pits	
	45	No Pits	Possible Pit Back Side not under band - below surface	P
	46	No Pits	No Pits	
	47	No Pits	No Pits	
	48	No Pits	No Pits	
	49	No Pits	No Pits	
	50	No Pits	No Pits	

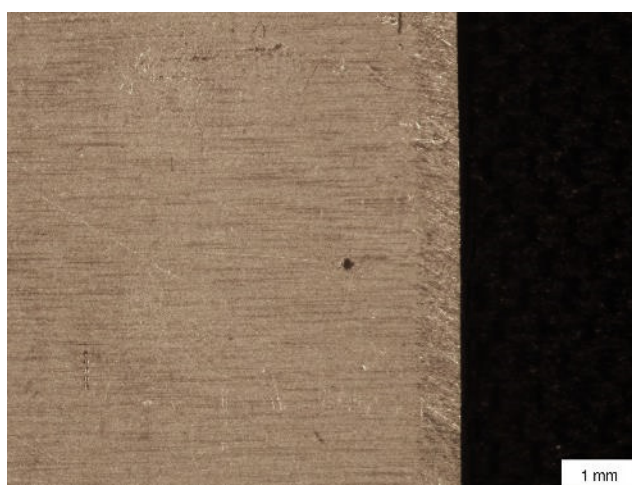


Figure E-20. Isolated Pitting Observed on Stainless Steel Sample 45, Foam #6

Table E-7. Tabulated Localized Corrosion Observations for Foam #7

	Sample #	Visual Inspection by eye	Inspection at 10X	Code
Foam #7	51	No Pits	No Pits	
	52	No Pits	No Pits	
	53	No Pits	One Possible pit - under band - below surface	C
	54	No Pits	Possible pit near edge on rough surface from machining - Below Surface	P
	55	No Pits	No Pits	
	56	No Pits	No Pits	
	57	No Pits	No Pits	
	58	Pit -In middle, not under band - small	Pit -In middle, not under band - small	P
	59	No Pits	Possible Pit Back Side not under band - below surface	P
	60	No Pits	No Pits	

Table E-8. Tabulated Localized Corrosion Observations for Foam #8

	Sample #	Visual Inspection by eye	Inspection at 10X	Code
Foam #8	61	No Pits	Possible Pit Back Side not under band - below surface	P
	62	No Pits	2 Possible Pits - Not under band - below surface	P
	63	No Pits	Possible pit near edge on adjacent to rough surface from machining - Below Surface	P
	64	No Pits	Possible pit back side under band - below surface	C
	65	No Pits	No Pits	
	66	No Pits	No Pits	
	67	No Pits	Possible Pit fron side not under band - Below	P
	68	No Pits	No Pits	
	69	No Pits	No Pits	
	70	Large Crevice under band Lower Front side	Large Crevice under band Lower Front side	C



Figure E-21. Crevice Attack Observed on Stainless Steel Sample 70, Foam #8

Table E-9. Tabulated Localized Corrosion Observations for Foam #9

	Sample #	Visual Inspection by eye	Inspection at 10X	Code
Foam #9	71	No Pits	No Pits	
	72	No Pits	Possible Pit Back side corner not under band - Below surface	P
	73	No Pits	Possible Pit Back Side not under band - below surface	P
	74	No Pits	No Pits	
	75	No Pits	Possible Pit Back Side not under band - below surface	P
	76	No Pits	No Pits	
	77	No Pits	No Pits	
	78	No Pits	2 possible Pits, one near edge and the other in middle under band - both small and below surface	P,C
	79	No Pits	No Pits	
	80	No Pits	No Pits	



Figure E-22. Isolated Pitting Observed on Stainless Steel Sample 72, Foam #9

Additional Observations

Subjective observational notes were made regarding the appearance of the general corrosion coupons after the 60-day exposure prior to chemical de-scaling. Those notes are tabulated in the following table for reference.

Table E-10. General Observations Made of the Matrix of Material Coupons Post-exposure, Prior to Chemical De-scaling.

Material	Sample #	Foam	Physical Description (Prior to cleaning with Acid)
C90500 Bronze	1-5	1	Brown/Green coloring on top half of specimen. Lower half look similar to the start of exposure
C90500 Bronze	6-10	2	Uniform dark brown color, Green/blue tint in localized areas
C90500 Bronze	11-15	4	Uniform dark brown (darker than 6-10) color , Green/blue tint in localized areas
C90500 Bronze	16-20	5	Uniformly darker (yellow/brown) - not as severe as 6-10 & 11-15 - some blue/green areas
C90500 Bronze	21-25	6	Darker (yellow) - areas of red/purple corrosion
C90500 Bronze	26-30	7	Darker - red/purple tint in areas as well as dark brown
C90500 Bronze	31-35	8	Dark Brown and red areas uniform across surface
C90500 Bronze	36-40	9	Localized areas of dark and light corrosion with brown/red colors
CDA706 Cu-Ni	1-5	1	Darkened - Upper half has more darkening than lower. Distinct line in middle of coupon separating light from dark
CDA706 Cu-Ni	6-10	2	Uniform Darkening
CDA706 Cu-Ni	11-15	4	Corrosion product surrounding edges on face
CDA706 Cu-Ni	16-20	5	No corrosion product observed or darkening
CDA706 Cu-Ni	22-26	6	No corrosion product observed or darkening
CDA706 Cu-Ni	26-31	7	Non-uniform darkening - severe discoloration (similar to 6-10) but with a purple tint
CDA706 Cu-Ni	32-36	8	A little darker with a few areas of darker patches
CDA706 Cu-Ni	37-41	9	Uniform darkening - less severe than 6-10
M400 Ni-Cu	2-6	1	No Signs of corrosion
M400 Ni-Cu	7-11	2	Uniform darkening - small change. Looks to be localized pitting on the surface
M400 Ni-Cu	12-16	4	No Signs of corrosion
M400 Ni-Cu	17-21	5	Areas of corrosion - surface is roughened
M400 Ni-Cu	22-26	6	Small amount of staining/darkening
M400 Ni-Cu	27-31	7	No Signs of corrosion
M400 Ni-Cu	32-36	8	Stained/darker evenly across surface
M400 Ni-Cu	37-41	9	No Signs of corrosion
G10100 Steel	1-5	1	Minor Staining
G10100 Steel	6-10	2	Localized areas of severe attack - red/brown rust
G10100 Steel	11-15	4	Localized areas of severe attack - red/brown rust
G10100 Steel	16-20	5	Uniform light rust
G10100 Steel	21-25	6	Uniform light rust - minimal
G10100 Steel	26-30	7	Uniform light rust
G10100 Steel	31-35	8	Localized areas of light rust - minimal
G10100 Steel	36-40	9	Uniform light rust

Certain foam solutions also exhibited some change over the 60-day exposure. There were color changes likely associated primarily with the dissolution of metal ions into solution. There was also phase separation witnessed in some foam solutions and examples of coagulation on the metal sample surfaces. A few examples are included in the follow set of photographs.

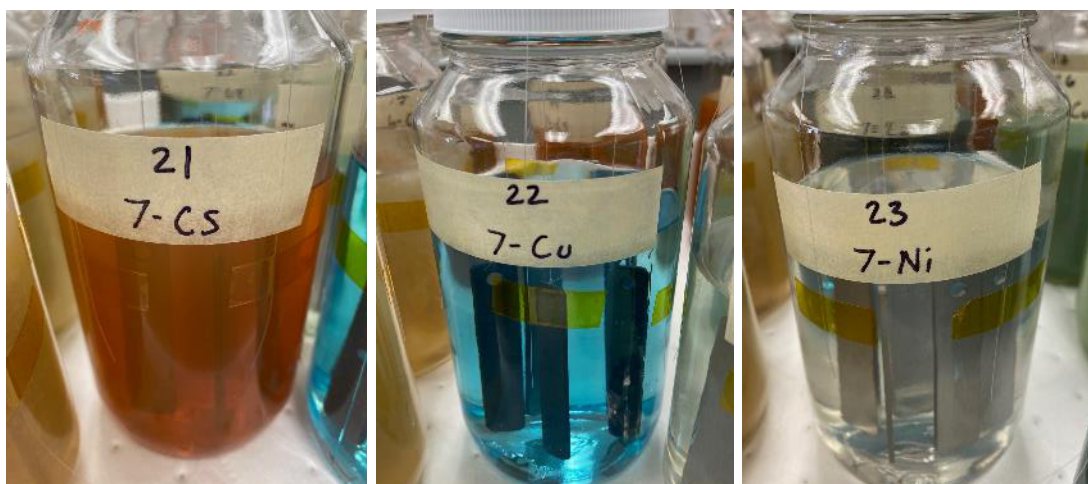


Figure E-23. Foam #7 Exposures. L to R – G10100 Steel, C70600 Cu-Ni,

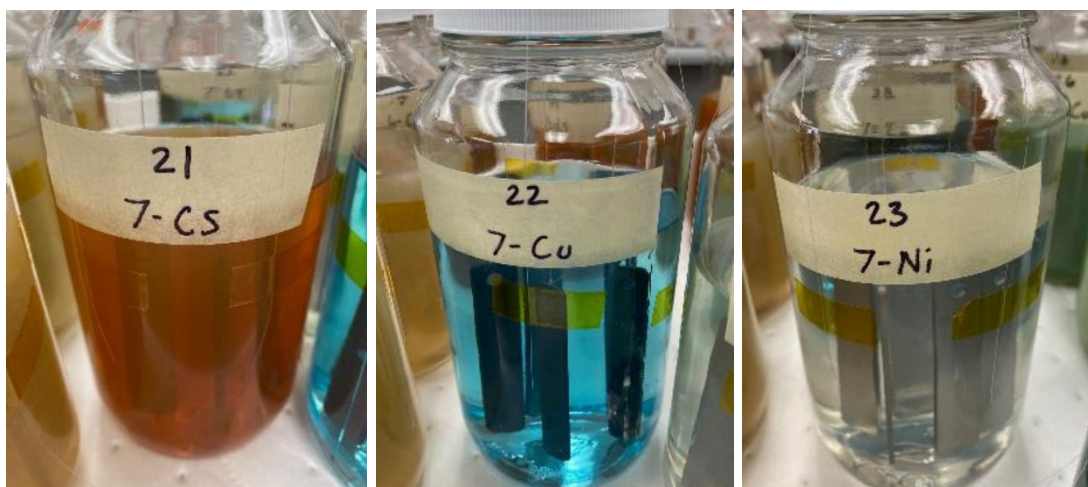


Figure E-23 depicts the color change associated with alloy type exposed. The foam solution began the exposure relatively colorless and changed with the dissolution of metal ions from the coupons. The next two images are examples of the phase separation and gelation/coagulation.



Figure E-24. Foam #1 Exhibiting a Phase Separation into a Milky Blue Low-density Phase and the Native Pink Foam Solution.



Figure E-25. Foam #8 Example of Coagulant Collecting at the Solution Surface and Along the Length of the C90500 Specimens.

CONCLUSIONS

The Mil-Spec provides coarse guidelines for allowable general corrosion rates. For C90500, the specification calls for a maximum allowable weigh loss rather than a mils per year corrosion rate. Those are outlined below.

G10100 Steel – 1.5 milli-inches per year (mpy)

C70600 Cu-Ni – 1.0 mpy

N04400 Ni-Cu – 1.0 mpy

C90500 Bronze – 100 mg gross mass loss

Based on the Mil-Spec qualification, the following reference table contains a pass/fail ranking of each material per foam solution.

Table E-11. Summary of Mil-Spec Pass/Fail Ranking.

RED = greater than max allowable; GREEN = under the max allowable.

Material Type	1- FireAde	2- Novacool	4- Phos Check 1%	5- Phos Chek 3-6%	6- Solberg	7- Fomtec	8- BioEx A	9- BioEx B
G10100 Steel	0.36	1.50	0.81	0.04	0.18	0.12	0.23	0.13
C70600 Cu-Ni	0.41	2.47	0.98	0.01	0.02	0.84	0.16	0.18
N04400 Ni-Cu	0.01	0.12	0.00	0.00	0.02	0.01	0.04	0.00
C90500 Bronze	45.66	138.78	85.26	38.74	17.98	68.80	56.14	30.38

Foam #2 - Novacool UEF is the most corrosive medium of the eight foams studied. This held true for all material types exposed. The relative resistance of materials to attack by individual foams varied with foam chemistry. As can be seen in Table E-11, often the highest corrosion rates were experienced by the C90500 bronze, but because of the aggressivity of Foam #2, C70600 Cu-Ni alloy exhibited the highest overall GCR. Foam #5 and #6 appeared to be the most benign across the field of materials.

Localized attack was not prevalent. The most severe examples were the result of crevice formation and occurred in Foam #1, #2 and #8. Pitting was generally isolated and infrequently exhibited.

APPENDIX F DATA ON EXPANSION RATIO (ER) AND 25% FOAM DRAINAGE TIME

Table F-1. ER and 25% Foam Drainage Time

Expansion Ratio and 25% Drain Time				
PFF Product	Mil-Spec (ER value)	CAF (ER=10)	CAF (ER=12)	CAF (ER=15)
1	1,020 (7.7)	1,260	-	-
4	345 (7)	-	364	-
5	465 (6.8)	840	-	-
6	2,200 (7.1)	2,208	2,649	3,360
7	1,380 (6.2)	4,548	3,909	975
8	165 (6.6)	910	-	-
8.2	402 (6.8)	419	620	292
9	556 (7.5)	-	1,890	
10	>3,600 (6.9)	>7,200	-	-
11	259 (6)		335	
12	248 (6.4)	330	-	-