

FINAL REPORT

Validation of Fluorine-free Fire Suppression Alternatives (FF_FSA) Against Military Specifications

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14. ABSTRACT Thirteen 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 passed biodegradability and corrosion-related specifications, but all failed the spreading coefficient specification. Several PFFs also failed the viscosity specifications. All PFFs failed fire-extinguishment time specification, and most failed the burnback time specifications, but CAF delivery significantly improved both for all PFFs. On average, the extinguishment time was reduced by more than 25%, but still fell short of the specification. The CAF testing at medium-field (315-ft ²) scale and large-field (6,504-ft ²) scale showed that the extinguishment time was not significantly different than at Mil-Spec (28-ft ²) scale. The positive results from the demonstration of UHP technology at 6,504-ft ² scale confirmed the potential of UHP. Both CAF and UHP technologies help to significantly reduce the foam use and associated wastewater volume, and thus the operating costs for extinguishing Type B fires.					
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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
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	Personal 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 project was conducted under the programmatic guidance of Dr. Robin Nissan and Dr. John La Scala of the ESTCP Program Office. Braxton Lewis and Maya Rabinowitz of Noblis provided the primary ESTCP project administration support.

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.

WP20-5335 Team

Name	Organization	Project Activity
Dr. Satya Chauhan (PI)	Battelle	Project planning and execution; reporting
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Andrew McMeans	Battelle	Mil-Spec-scale and medium-size, field-scale fire testing
Steven Wells	Battelle	Large, field-scale fire testing; CAF expert
Kris Cozart	Battelle	Design and integration of CAF and UHP skids
Sue Broxson	Battelle	Physical property testing coordination
Dr. Heather Luckarift	Battelle	Fire testing coordinator; Co-PI; reporting
Dr. Bridgett Ashley (co-PI)	AFCEC	CAF and UHP expert; test site oversight
Keith Bagot	FAA	Advisor
William Kavanaugh	ARMY IMCOM	Advisor; tech transfer
Marc Mills	EPA	Advisor; regulatory review
Jeff Eichler	Navy	Advisor; tech transfer

ABSTRACT

OBJECTIVE

The objectives of this project were to (a) rigorously evaluate commercial off-the-shelf (COTS) and maturing 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. This project was supplemental to previously completed and reported ESTCP WP19-5299 project.

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. By conducting this work, we have been able to comprehensively test and evaluate thirteen 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 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 cost about the same as AFFF concentrates, but the better performing PFFs require about two times as much foam to extinguish gasoline fires, employing aspirating nozzles. However, CAF typically reduces the amount of PFF required by over 30%. So, the real benefit of employing a technology like CAF is in reducing the annual PFF purchase cost and wastewater treatment and disposal costs. It is estimated that the DoD-wide demand for PFF concentrates for FY25 is \$1.12 million gallons per yr, suggesting a potential DoD operational cost savings of as high as \$70M/yr for foam purchase and wastewater treatment and disposal via CAF implementation. The estimated capital cost to implement CAF is \$100M to \$200M, which makes the potential investment worthwhile.

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 key publications resulted from this project:

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. 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.

Chauhan, S., “Demonstration of Compressed Air Foam and Ultra High Pressure Firefighting with PFAS-Free Foams,” presented at SERDP-ESTCP Symposium, Enhancing DoD Mission Capabilities, November 30, 2022.

EXECUTIVE SUMMARY

INTRODUCTION

Aqueous film-forming foams (AFFFs) are robust Class B firefighting foams that have been widely used by militaries, municipal airports, and industrial sites since they were 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 environmental persistence and potential hazards that are comparable to the original AFFF. Increasing concerns over PFAS as a class of chemicals has led 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 to cease the use of AFFF (with the exception of use on maritime vessels) by October 1, 2024. Additionally, as required, the Naval Sea Systems Command (NAVSEA) released an updated version of the Mil-Spec for PFAS-free foams (PFFs) in January 2023.

While many 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 specifications and used CAF and UHP to evaluate their effect on the fire-extinguishment and suppression performance of various PFFs.

OBJECTIVES

The objectives of this project were (a) to rigorously evaluate COTS and maturing PFFs to determine where they fall short of MIL-PRF-24385F specifications; (b) to determine whether commonly available firefighting engineering technology such as CAF or UHP, and/or minor chemical modifications, would allow the foams to meet required standards of extinguishment and burnback times; (c) to demonstrate the CAF and UHP technologies at field scale; and (d) to explore the effect of elevated ambient temperatures on firefighting performance. This project was a companion to the ESTCP WP19-5299 project that was completed in September 2022, to allow testing of more recently available COTS and maturing PFFs.

Performance objectives were based on evaluation against the Mil-Spec, including the engineering evaluation of PFFs with CAF and UHP on Mil-Spec scale (28-ft²) 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	• 7 of 8 passed all • 1 other with partial failure of bronze
	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 specification • All meet COD specification
	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	• 5 of 6 passed precipitation requirements
	Precipitation	Precipitation: 0.05% by volume	

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

The optimal operating conditions for field testing were found via lab-scale and Mil-Spec-scale testing, then 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-ft ² Mil-Spec Scale, Gasoline Fires			
Foamability/ drain time	Expansion ratio (ER)	ER: ≥5	All PFFs pass
	25% foam drain time	25% foam 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 (2 of 10 failed to extinguish) • 24% lower extinguishment time with CAF
Burnback/ cold burnback	Stopwatch	Burnback time: ≥360 s	• 1 of 10 passed with Mil-Spec nozzle • 8 of 9 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 and 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. 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 left). Unlike conventional aspirating nozzles, CAFS inject air into the liquid line carrying the water/foam solution (Figure ES-1 right). There are three main zones in 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.

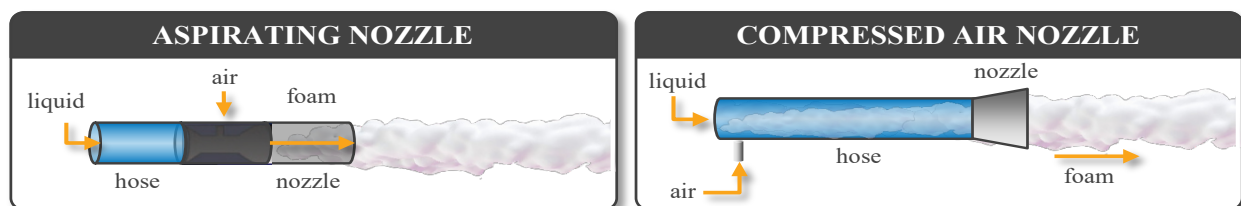


Figure ES-1. Foam Delivery Using an Aspirating Nozzle (Left Panel) vs. CAF (Right Panel)

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 foam delivery has shown 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 foam delivery also allows for a more concentrated layer of AFFF to form at the surface of the fuel layer. 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. PFF Products Tested

COTS PFF Vendor, Product
PHOS-CHEK [®] , 3–6% AFFF (C6) Baseline
PHOS-CHEK [®] , 1% Fluorine Free
Solberg Re-Healing [™] RF3
BioEx, Ecopol A3+
National Foam, Avio [®] Green KHC
BioEx, Prototype 11.2020 3%
Greenfire Fluorine Free Foam (GFFF)
Enforcer [®] , FireBull F3 Fluorine Free
Fire Terminator, FT Slam
Fomtec [®] , Enviro AIR
Molekule, Inc. Molekule Z2
Perimeter Solutions Mil-Spec SFFF
Fomtec [®] , Enviro ARF
Perimeter Solutions Prototype

PERFORMANCE ASSESSMENT

COTS PFFs

A total of 14 COTS and developmental PFFs (foams) shown in Table ES-3 were selected for performance assessments. Each PFF was assigned a number, with C6 AFFF being numbered 0, for discussing results. All PFFs were tested on a consistent basis for whatever performance testing was carried out. For field testing, a total of six PFFs were selected based on their fire-extinguishment performance at Mil-Spec scale (28-ft²) and due to budget limitations.

Environmental Properties (BOD₂₀ and COD)

The BOD₂₀ and COD data for C6 AFFF (Foam No. 0) and 10 PFFs are shown in Table ES-4. All PFFs tested met the COD pass-fail definition. BOD₂₀ values obtained from extended tests using the conditioned inoculum show all PFFs tested also exceed required biodegradability (BOD₂₀/COD) threshold under the Mil-Spec. As shown, 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. To further clarify this, we need to know the elemental composition of the PFFs, which is presently undisclosed by the PFF vendors.

Table ES-4. BOD₂₀ and COD Results (mg/L) for Various COTS PFF Products

PFF No. or Foam No.	COD	BOD ₂₀	Biodeg Index
0 ¹	575,300	514,800	0.890
4	605,000	499,950	0.830
6	521,600	525,300	1.007
8.2	446,300	323,900	0.726
12	894,000	745,200	0.834
13	693,700	NP	NP
14	363,000	402,750	1.110
15.2	488,670	580,873	1.189
16	153,333	NP	NP
19	NP	NP	NP
22	NP	NP	NP

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

NP: Not Planned

Physical Properties

There were two most notable findings. First, the spreading coefficients of the PFFs ranged from about 0.5 to -5.0 compared to 6.95 for C6 AFFF and a Mil-Spec value of at least 3. Thus, the PFFs are not film forming. Second, some PFFs are quite viscous and non-Newtonian, failing the 25°C Maximum-viscosity specification of 20 cp (increased to 300 cp under the recently revised Mil-Spec). Data for various physical properties are shown in Table ES-5.

Table ES-5. pH, Viscosity, RI, and Density Results for Various COTS PFF Products

PFF No.	pH	Viscosity 5°C (cSt)	Viscosity 25°C (cSt)	RI	Density (g/cm ³)
0 (AFFF)	8.01	6.99 (k)	3.29 (k)	1.367	1.01
4	5.94	7.95 (k)	3.99 (k)	1.386	0.96
6	6.76	44,134 (b)	24,135 (k)	1.386	1.04
8.2	8.01	26.20 (k)	11.36 (k)	1.362	1.03
12	8.41	145 (k)	60.10 (k)	1.383	1.00
13	8.15	7.12 (k)	3.57 (k)	1.366	1.06
14	8.59	1,031 (b)	1,011 (b)	1.357	1.05
15.2	6.98	12,785 (b)	11,828 (b)	1.361	1.01
16	8.64	2.37 (k)	1.41 (k)	1.367	1.12
19	NP	NP	NP	NP	NP
22	NP	NP	NP	NP	NP

Key: k=Kinematic viscometer; b=Brookfield viscometer (dynamic); NP=not planned

Corrosion Performance

Only eight PFFs were tested against the corrosion-based requirements set out in the Mil-Spec. All PFFs down-selected for field-scale testing passed all corrosion tests (Table ES-6). Note that PFF 13, which had a partial failure on the bronze coupon, and PFF 16 were tested for corrosion, but were not down-selected for field-scale fire testing, due to their poor firefighting performance at smaller scale.

Table ES-6. 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	0(AFFF)	0.98	0.01	0.00	6.02
	4	0.81	0.98	0.00	85.26
	6	0.18	0.02	0.02	68.80
	8.2	0.34	0.98	0.01	93.13
	12	0.10	0.21	0.00	28.26
	13	0.40	0.88	0.04	118.56
	14	0.13	0.86	0.06	83.34
	16	0.83	0.27	0.09	14.53

Red Values = Failing, Green Values = Passing

CAF Fire Testing

Fire testing with CAF was carried out at three scales: laboratory scale (0.3-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. Previous testing, under the ESTCP WP19-5299 project, indicated that the CAF performance depended on the foam expansion ratio (ER), with ER 12 being near optimum. Therefore, all testing under this project was carried out at ER 12.

Testing with E0 Gas at Mil-Spec Scale. The comparative CAF performance data for various PFFs at the optimum ER 12 are shown in Figure ES-2 (extinguishment time) and Figure ES-3 (burnback time). As seen, the use of CAF resulted in the extinguishment time being reduced by an average of 25% and the burnback time being increased by 115%, compared to use of a Mil-Spec (self-aspirating) nozzle.

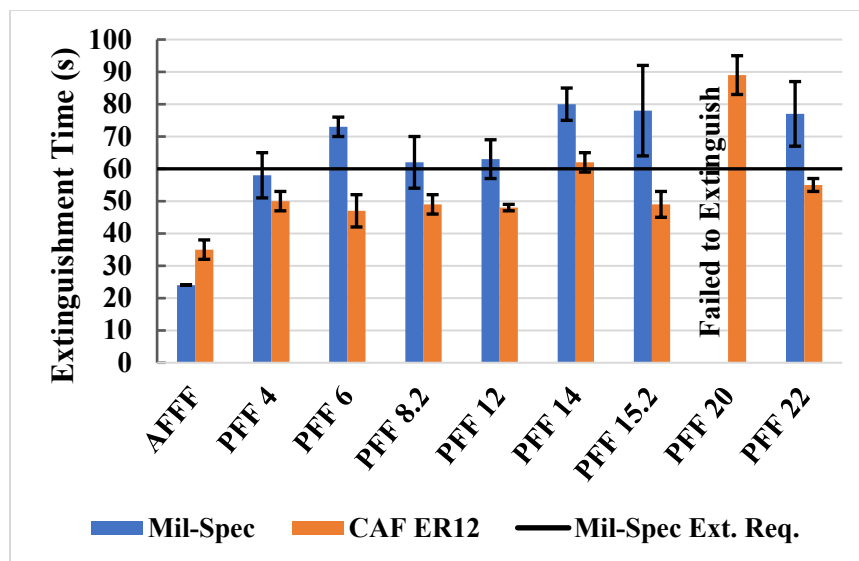


Figure ES-2. Extinguishment Time for 28-ft² E0 Gas Fires for Mil-Spec Nozzle and CAF (at ER 12)

Based on the Mil-Spec-scale testing with E0 gas, the following six PFFs were down-selected for field-scale testing:

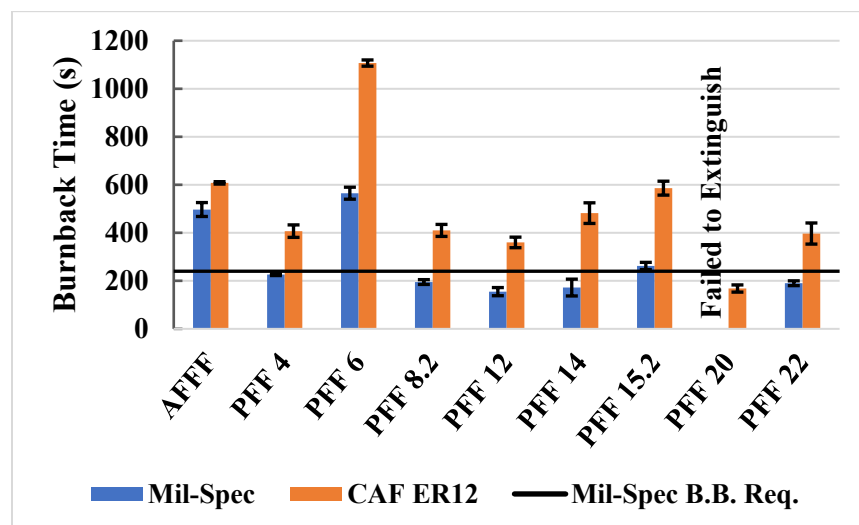


Figure ES-3. 25% Burnback Time with E0 Gas Fires with Mil-Spec Nozzle and CAF (at ER 12)

PFF 4 (315-ft² scale only)

PFF 6 (315-ft² and 6,504-ft² scales); while the viscosity is too high, we selected it due to the extensive amount of CAF data we have from the companion project

PFF 8.2 (315-ft² and 6,504-ft² scales)

PFF 12 (315-ft² and 6,504-ft² scales)

PFF 14 (315-ft² scale only)

PFF 21 (315-ft² scale only).

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-7.

Table ES-7. Summary of 28-ft² E0 Gas Fire Test Data for PFFs Down-selected for Field-Scale CAF Testing

PFF No. or Foam No.	Mil-Spec Nozzle		CAF (at ER 12)	
	Extinguishment Time, s	Burnback Time, s	Extinguishment Time, s	CAF Burnback Time, s
4	58±7	226±4	50±3	407±26
6	73±3	565±25	47±5	1107±13
8.2	62±8	195±10	49±3	410±25
12	63±6	155±17	48±1	360±22
14	80±5	172±35	62±3	482±43

Testing with Jet-A at Mil-Spec Scale. Since the revised Mil-Spec for on-shore applications also specifies testing with Jet-A, tests were also conducted with Jet-A on several down-selected PFFs. The extinguishment times for Jet-A fires at 28-ft² scale are shown in Figure ES-4.

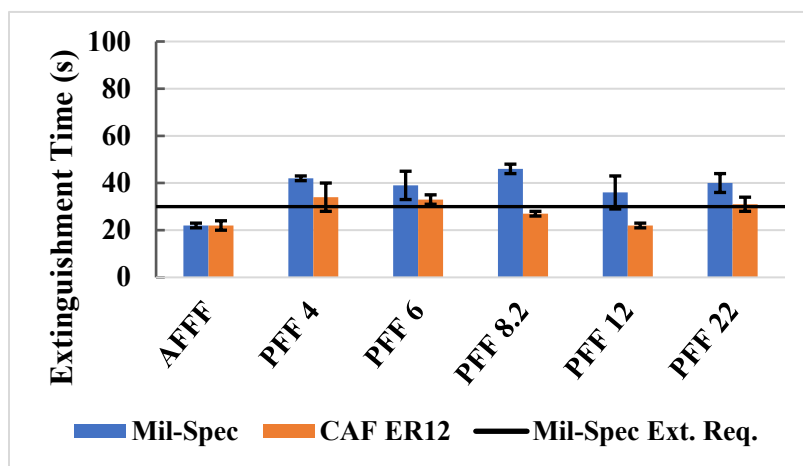


Figure ES-4. Extinguishment Time for 28-ft² Jet-A Fires for Mil-Spec Nozzle and CAF (at ER 12)

Comparison of Fire Performance with E0 Gas vs. Jet-A. As previously reported, Jet-A fires are less of a challenge to extinguish than gas fires, as the fuel is less volatile and not as explosive as gas. Results are shown in Figure ES-5, which shows the specifications for maximum extinguishment times for the two fuels under the new, land-based Mil-Spec.

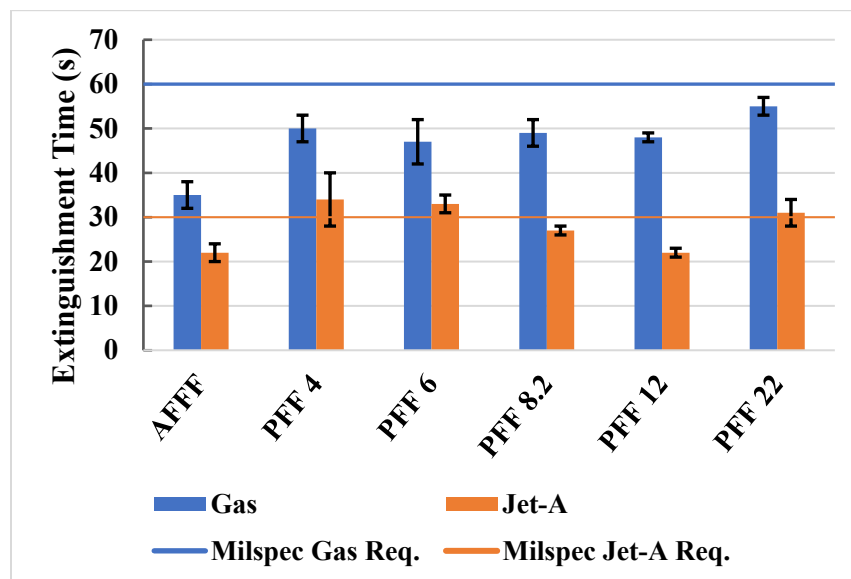


Figure ES-5. Extinguishment of 28-ft² E0 Gas and Jet-A Fires with selected PFFs and CAF (at ER 12)

CAF Testing at Field Scales. A key objective of the project was to determine how the CAF and UHP technologies scale-up from the Mil-Spec scale (28-ft²) up to two orders of magnitude larger fires. These tests were conducted with those PFFs that were down-selected on the basis of promising fire suppression performance at the Mil-Spec scale. 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 three down-selected PFFs, that were tested at various scales, were quite comparable to C6 AFFF. Similarly, CAF performance at 315-ft² on Jet-A for the four down-selected PFFs, that were tested at various scales, was also quite comparable to C6 AFFF.

For the larger (i.e., 6,504-ft²) fires, only Jet-A fuel was used, as it is very difficult to manage gas fires at that scale. These tests used a 3% concentrate and the same delivery rate (0.071 gpm/ft²) as for the Mil-Spec scale, which translates to about 450 gpm of PFF solution. Because of high expense associated with tests at this scale, only one or two tests were performed on each PFF, so the variability could not be adequately assessed, unlike the testing at smaller scales, where three tests were performed for each PFF. All three PFFs (6, 8.2, and 12) performed well. A comparison of extinguishment times for three fire sizes is shown in Figure ES-6. As shown, the extinguishment time remains about the same over a three orders of magnitude range of fire size. These results are very important, as this means that tests at smaller scales can be very good predictors of large-size field-scale performance for CAF.

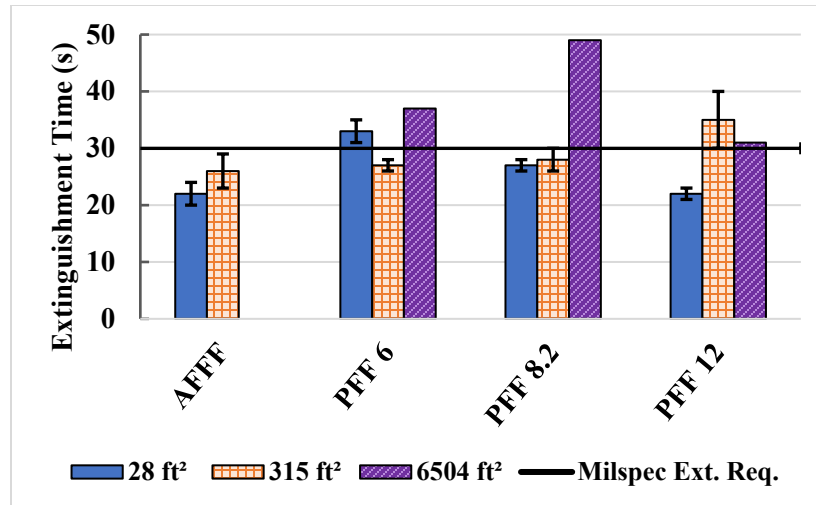


Figure ES-6. Extinguishment Time for Jet-A Fires at Mil-Spec-, Medium-Field-, and Large-Size-Field-Scale with CAF (at ER 12)

The scale-up data for E0 gas, covering the fire size range from 0.3-ft² to 315-ft², are shown in Figure ES-7. Once again, the scale-up relationship for gas fires is relatively flat over three orders of magnitude. This suggests that lab-scale testing can be used as a tool to screen PFFs before conducting much more expensive Mil-Spec scale testing.

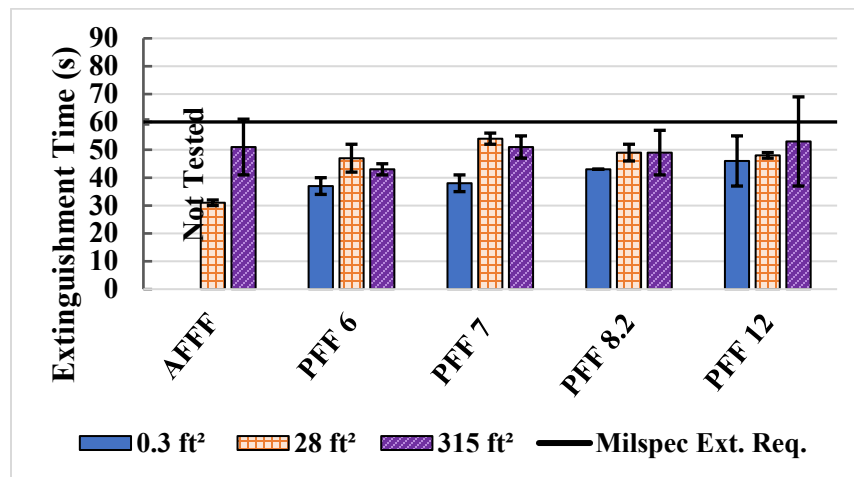


Figure ES-7. Extinguishment Time for E0 Gas Fires at Lab-, Mil-Spec-, and Field-Scale with CAF (at ER 12)

UHP Fire Testing at Field Scales

UHP testing was conducted with Jet-A fuel at 315-ft² and 6,504-ft² scales. PFFs 4, 6, 8.2, 12, and 14 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.

Three PFFs (6, 8.2, and 12) were also tested at 6,504-ft² scale. These tests were carried using a P-19 fire truck, which was limited to 300 gpm and resulted in a 0.046 gpm/ft² PFF solution delivery rate, which is about 35% less than the Mil-Spec rate. Even at this much reduced delivery rate, which is considered too low to extinguish a fire with conventional foam delivery, all three PFFs and the C6 AFFF performed very well. It is believed that, based on early work by AFCEC, UHP can be effective in extinguishing fires at an even lower (below 0.03 gpm/ft²) delivery rate.

The PFFs performed nearly as well as C6 AFFF. A comparison of UHP performance at the two field scales is shown in Figure ES-8.

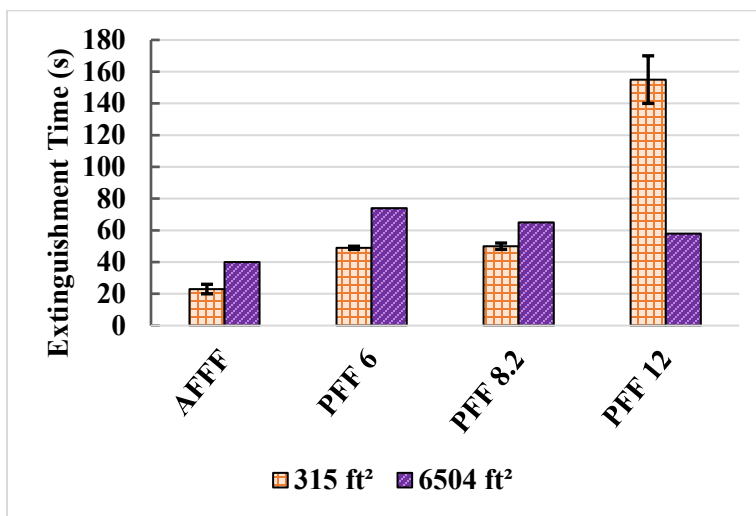


Figure ES-8. Extinguishment Time for Jet-A Fires at 315-ft² Scale (at 0.071 gpm/ft²) and 6,504-ft² Scale (at 0.046 gpm/ft²) with UHP

Exploratory Testing on Effect of Elevated Ambient Temperature

To determine the effect of elevated ambient temperatures on firefighting performance, four PFFs were tested at ambient (25°C) and elevated (40–50°C) temperatures. Ambient temperatures were simulated by preheating the foam solution, since the mass of the liquid is much more than that of air deployed to make foam. The ER for both the baseline and elevated-temperature tests was 12, and tests were conducted at 0.3-ft² fire scale, using CAF delivery and E0 gas fires. The result showed that performance for some of the PFFs gets worse at temperatures above about 45°C, and it may be compounded by longer-term storage for some products. Therefore, more thorough testing under elevated as well as near-freezing conditions for the qualified products is warranted.

Note that even though the ER was controlled at 12 for ambient as well as elevated temperatures, the changes in fire performance suggest that ER alone is not a sufficient indicator of foam quality. We believe that the bubble-size distribution and liquid-film stability at ambient and extreme temperatures needs to be quantified to better understand or predict firefighting performance or degradation.

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 likely to be 10–20% more expensive than a standard platform. Currently, fire trucks can be retrofitted with a customized CAFS for \$50,000–\$100,000, 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 plus a project completed in 2022 show that CAF helped reduce the extinguishment time by an average of over 30%. Data were used to conduct a preliminary analysis of the foam cost and wastewater treatment 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, indicating a selling price of \$28/gallon. For estimating the DoD-wide PFF demand, we utilized an estimate from a life cycle analysis by Noblis, to derive 1.12 gallons/yr procurement of foam concentrate. This estimate assumed that the fire extinguishment time for PFFs with air-aspirating nozzles is roughly two times that for AFFF, which has been reported by other researchers as well as by the fact that the revised Mil-Spec for gasoline fires is 60 seconds compared to 30 seconds for AFFF. This provided an estimated foam concentrate procurement cost of \$31.4M/yr for standard nozzles. According to the Noblis analysis, the associated wastewater treatment and disposal cost is \$201M/yr, which is based on the assumption that the wastewater will have to be treated and concentrated to solidify to allow disposal in a secure landfill. Thus, the annual cost for PFF procurement and wastewater treatment is \$232M/yr.

A payback analysis for DoD-wide CAF implementation was carried out. The data from this project along with from the project completed by Battelle/AFCEC in 2022 shows that the extinguishment time could be reduced by over 30% by employing CAF. If this technology was implemented across DoD, the operational cost savings for foam acquisition and wastewater treatment would be as high as \$70M/yr. It is believed that standard ARFF trucks can be retrofitted with CAF capability at a cost of \$50,000 to \$100,000 per truck, depending on whether pressurized-air bottles or air compressors are used. With an estimated 2,000 ARFF trucks across DoD, the capital cost would be \$100M to \$200M, assuming that it is practical to retrofit every truck. Anyway, the full implementation of CAF is estimated to provide a simple payback period of 1.4 to 2.8 years. This therefore appears to be an attractive investment.

IMPLEMENTATION ISSUES

A few PFFs are expected to meet the new Mil-Spec with conventional foam delivery, however 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, especially the cost of wastewater treatment and disposal, would have to be extensively completed ahead of an acquisition plan.

For trucks currently in the fleet, existing hardware could have some trouble proportioning PFFs, as some of the new formulations are more 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 [1]. 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 [2]. 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 [3]. 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 [4–6]. 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 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, (c) to demonstrate the CAF and UHP technologies at field scale, and (d) to explore the effects of additives and elevated ambient temperatures on firefighting performance. This is a companion to ESTCP WP19-5299 project that was completed in September, 2022, to allow testing of more recently available COTS and maturing PFFs [7].

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.

The fourth objective was to explore the effects of additives and elevated ambient temperature on firefighting performance.

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, as required, the Naval Sea Systems Command (NAVSEA) recently released an updated version of the Mil-Spec (MIL-PRF-32725) for PFFs for shore-based applications [8].

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. 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].

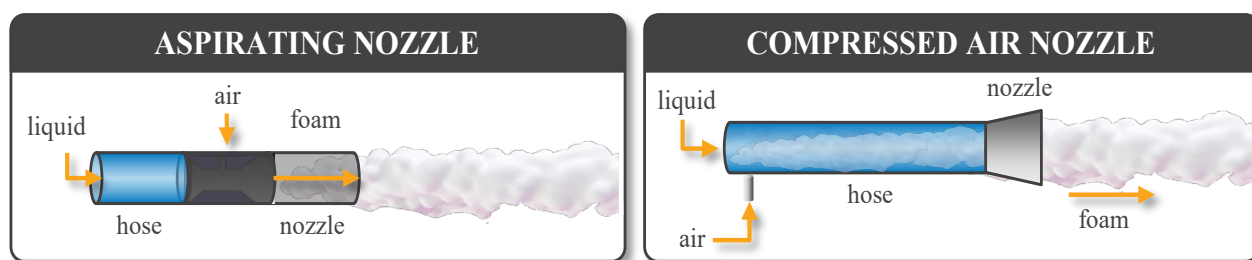


Figure 1. Foam Delivery Using an Aspirating Nozzle (Left Panel) vs. CAF (Right Panel)

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 [17]. 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.

2.1.4 Selected Additives

The PFFs require several critical properties, such as spreading coefficient, driven from the chemistry employed for their formulation. It was theorized that certain functional additives could potentially enhance the firefighting performance of PFFs, by altering these properties. Since this was an exploratory study, we selected three products that by themselves failed as Class B firefighting agents but the vendor claimed these had special functional properties relative to wetting. Two of the products were developed with SERDP funding.

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 [18]. 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 [18].

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 to 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 US has detectable concentrations of these chemicals in their bodies [19]. 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 [20]. 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 [6]. More recently, CAF technology has gained traction in combatting Class B fires, beginning in the mid-90s with use in aircraft hangers [4]. Multipurpose overhead CAFS and their Class B fire suppression performance has also been assessed in locations such as chemical storage facilities [4]. 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 [5]. 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 [21]. Additionally, it has proven to be more effective than foam and water, or water alone, at combatting Class A solid fuel fires [22].

2.2.3 UHP

The use of water mist in combatting fires initially gained interest in the 1990s [23] and is now used in sprinkler systems [24]. UHP firefighting technology is, essentially, a way to create a high velocity water mist [25] (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 [26]. 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.

2.2.4 Additives

Since this was an exploratory study, we selected three products that by themselves failed as Class B firefighting agents but the vendor claimed these had special functional properties relative to wetting. Two of the products were developed with SERDP funding and a third one a COTS products used as a Class A firefighting agent.

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 [27]. 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.

2.3.4 Additives

Unlike AFFF products, which involve essentially the same formulation chemistry, the PFFs vary substantially in their formulation chemistry. It is therefore very likely that a functional additive that works well with some PFFs may not work so well with others.

3.0 PERFORMANCE OBJECTIVES

Performance objectives were based on evaluation against the previous, shore-based 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 [TAFB]). 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. For the sake of completeness, these two tables cover this as well as the companion (WP19-5299) project.

Table 1. Performance Objectives per MIL-PRF-24385F 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	• 7 of 8 passed all • 1 other with partial failure of bronze
	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 specification • All meet COD specification
	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	• 5 of 6 passed precipitation requirements
	Precipitation	Precipitation: 0.05% by volume	

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

Table 2. Performance Objectives per MIL-PRF-24385F 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 (2 of 10 failed to extinguish) • 24% lower extinguishment time with CAF
Burnback/ Cold Burnback	Stopwatch	Burnback time: ≥360 s	• 1 of 10 passed with Mil-Spec nozzle • 8 of 9 passed with CAF
	Heat flux		
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 and 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; this was revised to a range of 6.5 to 9.0 under the new Mil-Spec (MIL-PRF-32725).

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 (revised to 1.3600 under the new Mil-Spec). 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, under the previous Mil-Spec, at 25°C is 2 cSt, and the maximum at 5°C is 20 cSt; the new Mil-Spec specifies a maximum viscosity at 5°C of 300 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.

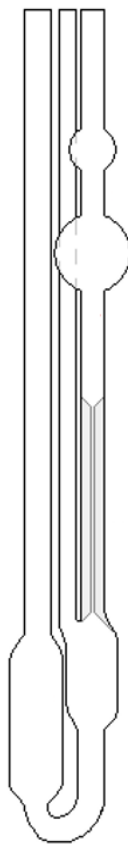


Figure 2. Ubbelohde Viscometer

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 previous Mil-Spec is a spreading coefficient of 3 mN/m. Note that the new Mil-Spec does not have a specification for spreading coefficient.

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 previous 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. Note that the new Mil-Spec also has added another substrate/coupon (Brass; UNS C46400) for corrosion testing.

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 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 previous Mil-Spec are extinguishment in fewer than 30 seconds (raised to 60 seconds under the new Mil-Spec) and 25% burnback resistance greater than 360 seconds (reduced to 240 seconds under the new Mil-Spec). The majority of the tests were done with gasoline fires, following the previous Mil-Spec, with CAF compared to the Mil-Spec nozzle. After the new Mil-Spec was released, tests were also performed on jet fuel fires as this was also specified. Note that, based on the results from the WP19 project, UHP testing was not conducted at this scale; it was only tested at field scale, where it was easier to deploy UHP sprays.

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.

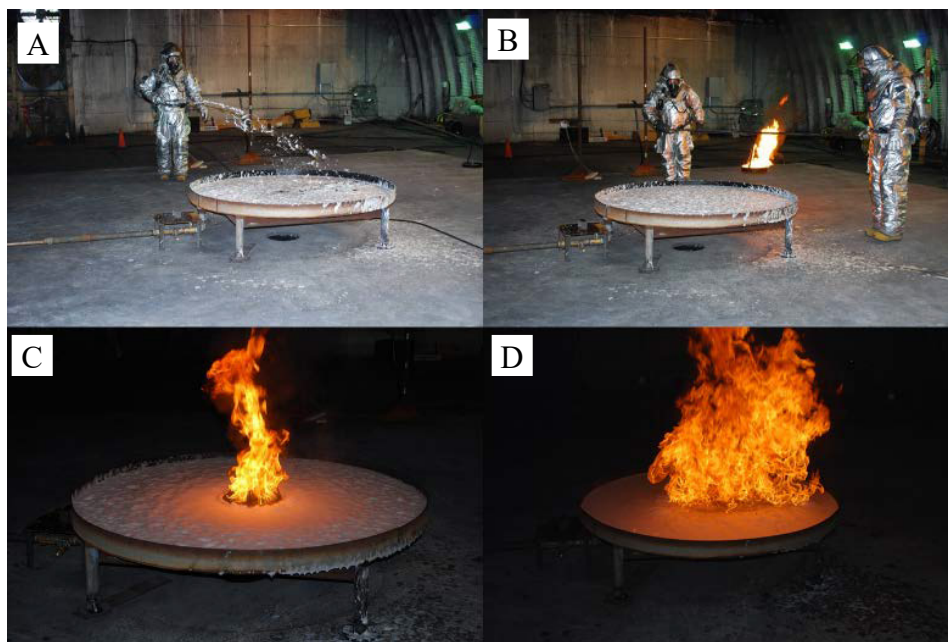


Figure 3. Mil-Spec 25% Burnback Test in SkyX Facility

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-Size 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. 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-19 and 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 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. A certification was therefore acquired to allow for testing and training to occur at Tyndall AFB, with the requirement that effluent is not released into the environment. For comparison purposes, some tests were also performed with AFFF.

5.0 TEST DESIGN

5.1 ECOTOXICITY TESTING

5.1.1 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.

1.1.2 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 [28].

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:

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

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

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

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

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 [29]. 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 de-scaled 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 de-scaling varied for G10100 Steel, by utilizing (undiluted) $\text{HCl} + 20 \text{ g/L SnCl}_2 + 50 \text{ g/L Sb}_2\text{O}_3$ for 1–25 cycles (min). The stainless-steel localized corrosion specimens were not de-scaled 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 personal 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.

6.0 PERFORMANCE ASSESSMENT

6.1 COTS PFFS

The 14 COTS and developmental PFFs (foams) and an AFFF, listed in Table 3, were selected for performance assessments in this project. Numbering is consistent throughout the remainder of the report as well as the publications to date [7, 30–35].

Table 3. PFF Products Tested

PFF Vendor, Product
PHOS-CHEK [®] , 3–6% AFFF (C6) Baseline
PHOS-CHEK [®] , 1% Fluorine Free
Solberg Re-Healing [™] RF3
BioEx, Ecopol A3+
National Foam, Avio [®] Green KHC
BioEx, Prototype 11.2020 3%
Greenfire Fluorine Free Foam (GFFF)
Enforcer [®] , FireBull F3 Fluorine Free
Fire Terminator, FT Slam
Fomtec [®] , Enviro AIR
Molekule, Inc. Molekule Z2
Perimeter Solutions Mil-Spec SFFF
Fomtec [®] , Enviro ARF
Perimeter Solutions Prototype

Brief descriptions of these PFFs, by code names, are provided below:

PFF 0 is C6 AFFF product used for baseline testing.

PFF 4 was previously tested at Mil-Spec scale with gasoline, and results were included in the report for the WP19-5299 project [7]; the testing with Jet-A and field-scale testing is covered in this project. For the benefit of the readers, all test data are included in this report.

PFF 6 and 8.2 were extensively tested at Mil-Spec and 315-ft² scales previously, and results were provided in the previous report [7]; the testing at large-size (6,504-ft²) field scale is additionally covered in this report.

PFF 12 was previously tested at Mil-Spec scale with gasoline, and results were included in the previous report [7]; the Jet-A and field-scale testing is covered in this project. Again, all test data are covered in this report.

PFF 13 was a prototype product, which was later replaced by a better product, PFF 8.2.

PFF 14 is a Class B firefighting product; this vendor also provided a wetting agent product that was tested as an additive.

PFF 15.2 is a newer product compared to PFF 1, tested in the previous project, developed by the same company. It was determined to be above the maximum viscosity under the new Mil-Spec, so testing was limited to lab-scale fires.

PFF 16 is a newer product.

PFF 19 and 22 are new, low-viscosity products from a vendor that had previously provided a high-viscosity product that had excellent performance. The vendor seems to prefer PFF 22, so it was tested more extensively.

PFF 20 is a novel-chemistry product being developed under a SERDP project; it is likely to be replaced by a newer version in the near future.

PFF 21 is a new product from the same vendor, which is likely to be commercialized soon.

PFF 24 is a new, prototype product supplied by the same vendor who supplied PFF 21.

The test results for various PFFs are provided in Appendix B. The PFFs 13 and 16 failed to extinguish gasoline fires are excluded from Appendix B.

In the sections to follow, some measurements of physical properties were not planned (NP) as these were unlikely to be down-selected for field-scale fire testing, based on their poor or marginal fire-fighting performance in smaller-scale tests. In a few cases, some physical properties were not measured (NM) due to technical difficulties with measuring equipment and it was not critical to repeat the tests if the primary purpose of the testing, namely the fire-fighting performance, was adequately met.

6.2 BOD₂₀ AND COD

Table 4 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 two of six PFFs tested (Table 4). 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 4. BOD₂₀ and COD Results (mg/L) for Various PFF Products

PFF No.	COD	BOD₂₀	Biodeg Index
0(AFFF) ¹	575,300	514,800	0.890
4	605,000	499,950	0.830
6	521,600	525,300	1.007
8.2	446,300	323,900	0.726
12	894,000	745,200	0.834
13	693,700	NP	NP
14	363,000	402,750	1.110
15.2	488,670	580,873	1.189
16	153,333	NP	NP
19	NP	NP	NP
22	NP	NP	NP

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

NP: Not Planned

6.3 PHYSICAL PROPERTIES

6.3.1 Spreading Coefficient

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, rather they 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; therefore, it has been eliminated as a requirement in the new Mil-Sec. Since this is an aspect of the previous Mil-Spec, we did measure it, as shown in Table 5.

Table 5. Spreading Coefficient Results for Various PFF Products

PFF No.	0 (AFFF)	4	6	8.2	12	13
SFT n(mN/m) (Non-Aged)	16.34	26.2	27.0	23.81	25.4	16.56
IFT n(mN/m) (Non-Aged)	1.0	1.36	2.42	-0.07	1.35	NP
Spreading Coefficient mN/m (Non-Aged)	6.947	-3.272	-5.133	0.547	-2.463	NP

PFF No.	14	15.2	16	19	22
SFT n(mN/m) (Non-Aged)	22.86	26.93	28.44	NP	NP
IFT n(mN/m) (Non-Aged)	3.26	0.53	NP	NP	NP
Spreading Coefficient mN/m (Non-Aged)	-1.833	-3.173	NP	NP	NP

NP: Not Planned

6.3.2 pH, Viscosity, Refractive Index (RI), and Density

Results for physical properties such as pH, viscosity, RI, and density are provided in Table 6. While some PFFs tested so far are notably more viscous than AFFF, they 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 6). The manufacturers are aware of the concerns surrounding the viscosity of these products and are working to lower them. 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, as previously reported in the companion project [7]. 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.

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

PFF No.	pH	Viscosity 5°C (cSt)	Viscosity 25°C (cSt)	RI	Density (g/cm ³)
0 (AFFF)	8.01	6.99 (<i>k</i>)	3.29 (<i>k</i>)	1.367	1.01
4	5.94	7.95 (<i>k</i>)	3.99 (<i>k</i>)	1.386	0.96
6	6.76	44,134 (<i>b</i>)	24,135 (<i>k</i>)	1.386	1.04
8.2	8.01	26.20 (<i>k</i>)	11.36 (<i>k</i>)	1.362	1.03
12	8.41	145 (<i>k</i>)	60.10 (<i>k</i>)	1.383	1.00
13	8.15	7.12 (<i>k</i>)	3.57 (<i>k</i>)	1.366	1.06
14	8.59	1,031 (<i>b</i>)	1,011 (<i>b</i>)	1.357	1.05
15.2	6.98	12,785 (<i>b</i>)	11,828 (<i>b</i>)	1.361	1.01
16	8.64	2.37 (<i>k</i>)	1.41 (<i>k</i>)	1.367	1.12
19	NP	NP	NP	NP	NP
22	NP	NP	NP	NP	NP

Key: k=Kinematic viscometer; b=Brookfield viscometer (dynamic); NP=not planned

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 6). 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.

Lastly, the pH of some products was slightly out of the range under the previous Mil-Spec (Table 6), but all pass under the expanded range provided in the new Mil-Spec.

6.3.3 PFF Stability Testing

The effect of aging on spreading coefficient and stratification was determined for only the products that were likely to be tested at field scale; the results are provided in Table 7. Only one of the PFF products tested failed the stratification requirement of the Mil-Spec test, three passed with color change, and the remaining four passed without color change. 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 unaged PFF failed the spreading coefficient also (as shown in Table 7).

Table 7. Aging Test Results for Selected PFF Products

PFF No.	0 (AFFF)	4	6	8.2	12	13
SFT n(mN/m)	16.33	26.4	27.46	23.85	24.98	30.08
IFT n(mN/m)	0.59	0.90	3.17	-0.32	1.97	NP
Spreading coefficient	7.37	-3.54	-6.34	0.76	-2.66	NP

PFF No.	14	15.2	16	19	22
SFT n(mN/m)	31.09	26.89	NP	NP	NP
IFT n(mN/m)	3.62	0.69	NP	NP	NP
Spreading coefficient	-5.79	-2.14	NP	NP	NP

NP: Not Planned

Note: All measurements were 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 selected PFFs was completed, and results are shown in Table 8 (unaged concentrates) and Table 9 (aged concentrates and aged solutions)). As shown, aging does not seem to affect the ER, but the 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 8. Foamability Results for Selected, Unaged PFF Products

25% Drain Time and Expansion Ratio (ER)				
PFF No.	Mil-Spec (ER value)	CAF (ER=10)	CAF (ER=12)	CAF (ER=15)
0 (AFFF)	295 (6.9)	NP	519	NP
4	345 (7.0)	NP	364	NP
6	2220 (7.1)	2208	2649	3360
8.2	502 (6.8)	419	620	292
12	247 (6.4)	330	386	NP
14	444 (7.0)	NP	643	NP
15.2	890 (7.7)	NP	1570	NP
20	890 (7.7)	NP	1570	NP

NP: Not Planned

Table 9. Foamability Results for Selected, Aged PFF Concentrates and Aged Solutions

25% Drain Time and Expansion Ratio (ER)		
PFF No.	Aged Concentrate Mil-Spec (ER value)	Aged Solution Mil-Spec (ER value)
0 (AFFF)	NP	NP
4	249 (6.6)	179 (6.4)
6	1253 (8.0)	1138 (7.9)
8.2	195 (6.7)	67 (6.7)
12	238 (7.1)	276 (7.0)
14	278 (7.3)	325 (7.5)
15.2	441 (7.4)	527 (6.1)

NP: Not Planned

6.4 CORROSION TESTING

All PFFs expected to be down-selected for field-scale fire testing, passed the previous Mil-Spec, as shown in Table 10. Detailed reports for PFFs 12, 13, 14, and 16 are provided in Appendix B. Data for other PFFs down-selected for field-scale fire testing, namely PFFs 4, 6, and 8.2, were reported previously [7]. Note that PFF 13, which had a partial failure on the bronze coupon, and PFF 16 were tested for corrosion, but were not down-selected for field-scale fire testing due to their poor firefighting performance at smaller scale.

Table 10. Corrosion Results for Selected PFF Products

		Material Type			
		G10100 Steel	C70600 Cu-Ni	N04400 Ni-Cu	C90500 Bronze
Foam Product	Mil-Spec Max (mpy)	1.5	1	1	100 mg mass loss
	0(AFFF)	0.98	0.01	0.00	6.02
	4	0.81	0.98	0.00	85.26
	6	0.18	0.02	0.02	68.80
	8.2	0.34	0.98	0.01	93.13
	12	0.10	0.21	0.00	28.26
	13	0.40	0.88	0.04	118.56
	14	0.13	0.86	0.06	83.34
	16	0.83	0.27	0.09	14.53

Red Values = Failing, Green Values = Passing

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

6.5.1 CAF Fire Testing with Ethanol-Free (E0) Gasoline (Gas)

The fire performance of PFF products was tested using the Mil-Spec requirements of a self-aspirating nozzle compared to CAF technology using E0 gas. Based on previous CAF-optimization testing, ER 12 was used for all CAF testing. As seen, the use of CAF resulted in the extinguishment time for PFFs being reduced by an average of about 25% when compared to AFFF (Figure 8).

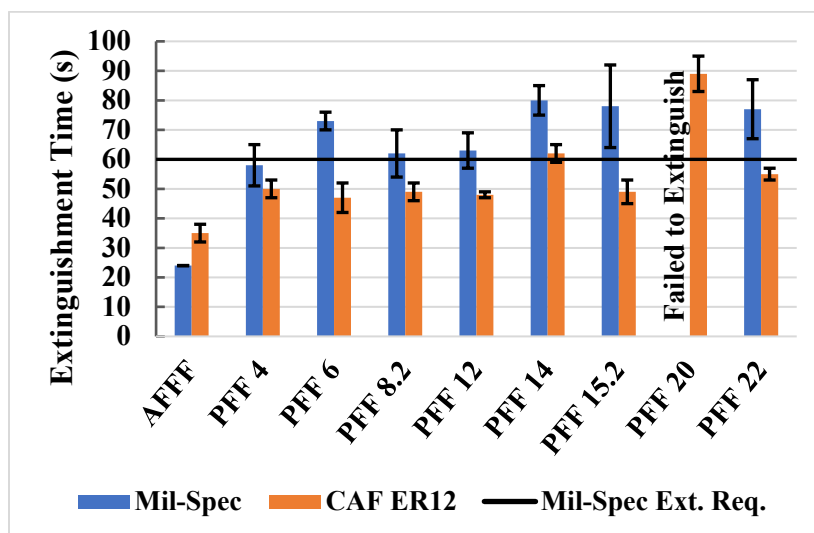


Figure 8. Extinguishment Time for 28-ft² E0 Gas Fires for Mil-Spec Nozzle and CAF (at ER 12)

The data in Figure 9 show that the burnback time for PFFs increased by an average of 105% compared to the use of a Mil-Spec nozzle.

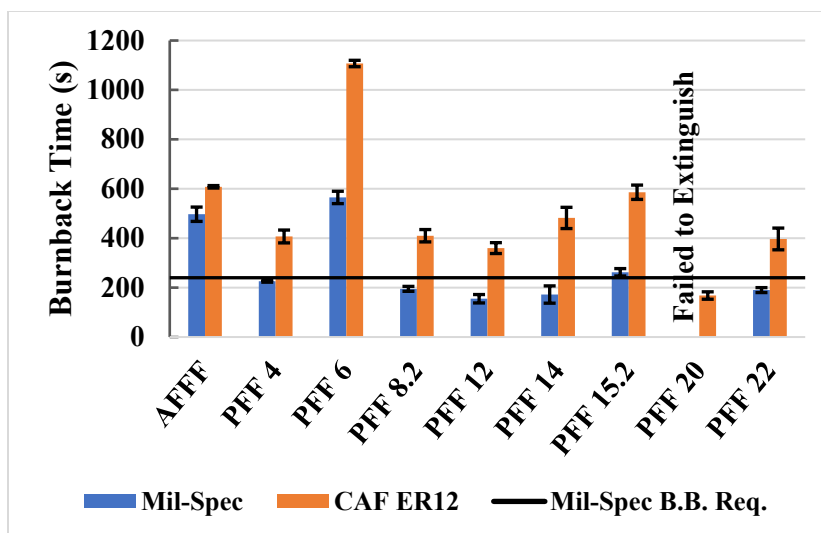


Figure 9. 25% Burnback Time with E0 Gas Fires for Mil-Spec Nozzle and CAF (at ER 12)

These findings confirm those reported in the companion ESTCP project, in that there is no question about the substantial improvement in firefighting performance achieved with CAF technology.

Based on the Mil-Spec-scale testing with E0 gas and being mindful of the revised specifications under the new Mil-Spec, the following six products were selected for field-scale fire testing:

PFF 4 (315-ft² scale only)

PFF 6 (315-ft² and 6,504-ft² scales); while the viscosity is too high, we selected it due to the extensive amount of CAF data we have from the companion project

PFF 8.2 (315-ft² and 6,504-ft² scales)

PFF 12 (315-ft² and 6,504-ft² scales)

PFF 14 (315-ft² scale only)

PFF 21 (315-ft² and 6,504-ft² scales).

The Mil-Spec nozzle and CAF at ER 12 data for these tentatively down-selected PFFs is summarized in Table 11.

Table 11. Summary of 28-ft² E0 Gas Fire Test Data for PFFs Down-selected for Field-Scale CAF Testing

PFF No. or Foam No.	Mil-Spec Nozzle		CAF (at ER 12)	
	Extinguishment Time, s	Burnback Time, s	Extinguishment Time, s	CAF Burnback Time, s
4	58±7	226±4	50±3	407±26
6	73±3	565±25	47±5	1107±13
8.2	62±8	195±10	49±3	410±25
12	63±6	155±17	48±1	360±22
14	80±5	172±35	62±3	482±43

6.5.2 CAF Results for Jet-A Fuel Fires

As mentioned earlier, the previous Mil-Spec provides specifications for extinguishment and burnback times for E0 gas. However, the recently issued, revised Mil-Spec for on-shore applications also includes 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 10 and 11, respectively. While none of the PFFs in this project were able to meet the previous Mil-Spec extinguishment time of 30 seconds with gas at the 28-ft² scale, three of the five PFFs tested were able to extinguish Jet-A fires with CAF in less than 30 seconds.

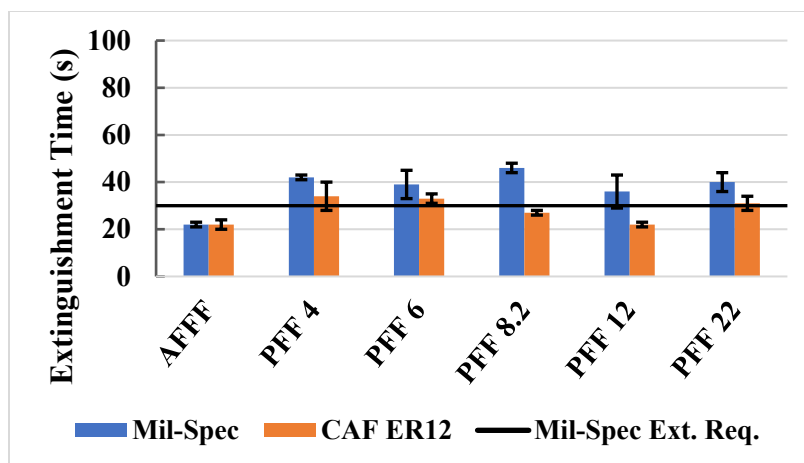


Figure 10. Extinguishment Time for 28-ft² Jet-A Fires for Mil-Spec Nozzle and CAF (at ER 12)

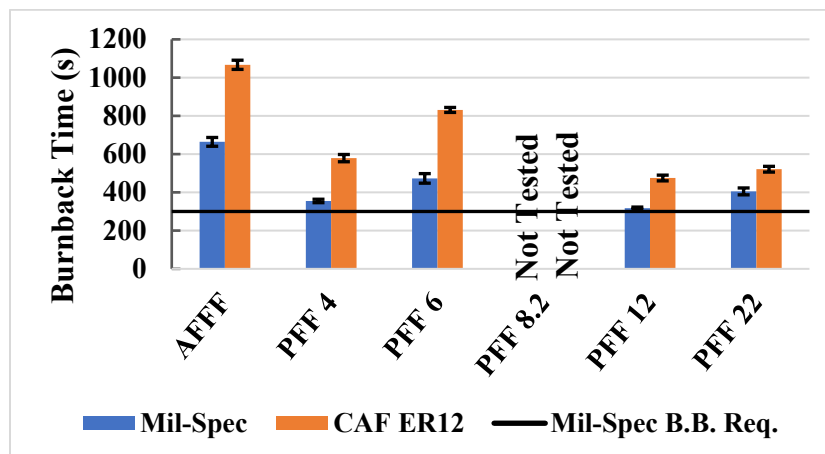


Figure 11. 25% Burnback Time for 28-ft² Jet-A Fires for Mil-spec Nozzle and CAF (at ER 12)

The Mil-Spec nozzle and CAF at ER 12 data for these tentatively down-selected PFFs are summarized in Table 12. The average reduction in fire-extinguishment time was 29% and the average increase in the 25% burnback time was 65%.

Table 12. Summary of 28-ft² Jet-A 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	42±1	355±9	34±6	579±19
PFF 6	39±6	473±25	33±2	831±13
PFF 8.2	46±2	NP	27±1	NP
PFF 12	36±7	317±6	22±1	475±15
PFF 14	NP	NP	NP	NP

NP: Not Planned

As reported previously, the extinguishment times for gasoline are considerably higher than for Jet-A fuel [7]. Jet-A is a less challenging fuel to extinguish than gas, as it is less volatile and not as explosive as gas, and because it has a much higher surface tension than gas, which may make some PFFs film forming. 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 12 (extinguishment time).

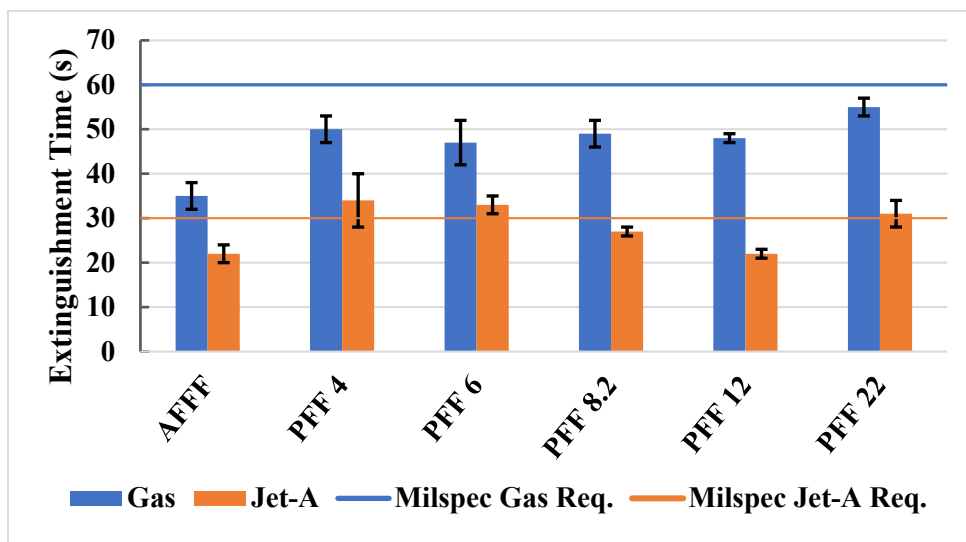


Figure 12. Extinguishment of 28-ft² E0 Gas and Jet-A Fires with selected PFFs and CAF (at ER 12)

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 4, 6, 8.2, 12, 14, and 21 were selected for medium-size field-scale CAF testing. A CAF skid was set up to deliver foam at ER 12 and 20 gpm, which corresponds to the same application rate (0.071 gpm/ft²) as the Mil-Spec requirement. All of these PFFs were tested with Jet-A, but only a few were tested with E0 gas because of the relative difficulty in handling gas fires at field scale.

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

The extinguishment time results for the five PFFs are shown in Figure 13. All six products successfully extinguished the fire in 27–40 seconds. Three tests for each PFF were conducted, with fairly good reproducibility, and results being comparable to C6 AFFF.

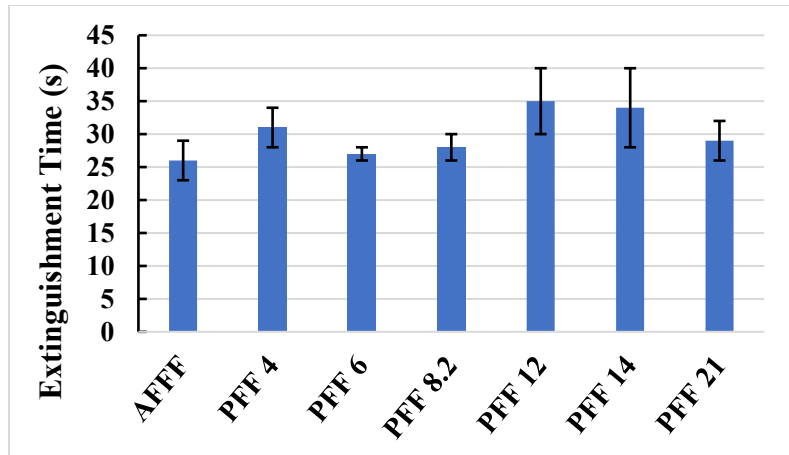


Figure 13. Extinguishment Time for 315-ft² Jet-A Fires with CAF (at ER 12)

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

CAF testing at medium-size field scale was conducted with PFFs 6, 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 14. Extinguishment times for PFFs were comparable to C6 AFFF.

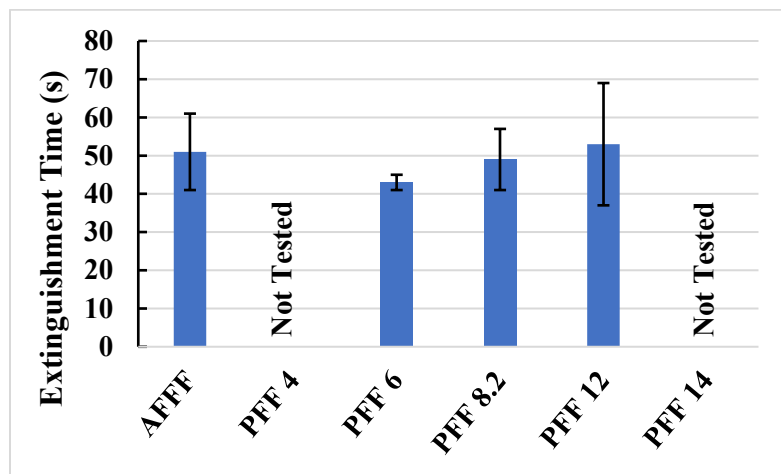


Figure 14. Extinguishment Time for 315-ft² for E0 Gas Fires with CAF (at ER 12)

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

PFFs 4, 6, 8.2, 12, and 14 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. The results are shown in Figure 15.

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 Figure 15. The C6 AFFF 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.

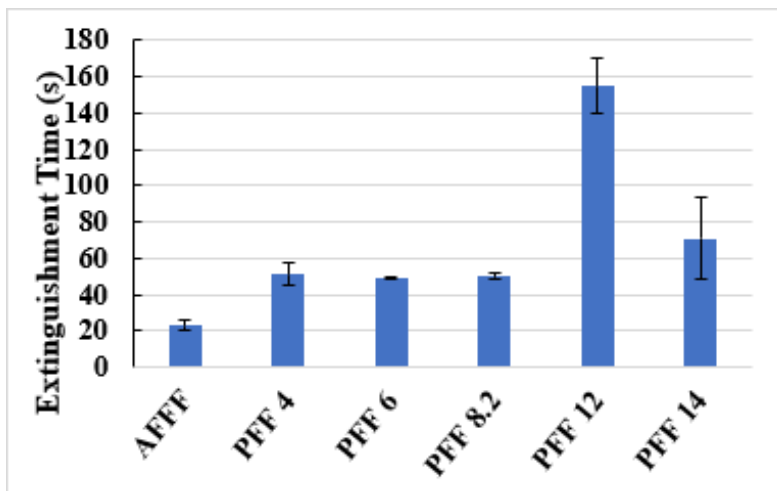


Figure 15. Extinguishment Time for 315-ft² Jet-A Fires with UHP

6.6.3 Large-Size Field Scale (6,504-ft²) Jet-A Fire Testing with CAF and UHP

To further evaluate the down-selected PFFs' fire performance, large-size field-scale testing was conducted with PFFs 6, 8.2, and 12 utilizing both CAF and UHP delivery technologies. Testing was conducted in the research pit located at Test Range I, TAFB. This pit has an approximate diameter of 91-ft, resulting in an approximate area of 6,504-ft². The pit's construction is such that a concrete floor is approximately 2-ft below the surrounding surface, with a berm of rock built around the circumference.

Two separate fire trucks were utilized for large-scale testing, a UHP P-19 Rosenbauer Panther and an FAA-furnished research Rosenbauer Panther capable of producing CAF. Prior to full-scale fire suppression testing, a series of preliminary flow tests, utilizing the bumper turret, were conducted with each truck to quantify the flow rate and foamability of each foam mixed at a 3% solution. Additional testing with the CAF truck was required to set specific foam solution flow and ER. To avoid any issues/concerns with inducing foam concentrate at precisely 3% (due to differences in viscosity), all foam solutions regardless of delivery technology were premixed at 3%. UHP tests were conducted at 300 gpm, which is the maximum capacity of the P-19, resulting in an application rate of 0.046 gpm/ft², and utilized a center-stemmed variable stream nozzle set to straight stream. CAF tests, on the other hand, were conducted at 455 gpm, with an ER 12, resulting in an application rate of 0.071 gpm/ft², which is the same as in the Mil-Spec. To achieve this desired ER, a series of smooth-bore nozzles were utilized, ranging in aperture opening of 2.0-in to 2.5-in.

During test preparation, water was pumped into the pit by a series of pumps to cover and protect the concrete floor, water/fuel piping, and valves. This resulted in a water level of 3-in to 6-in during testing. Jet-A fuel was then pumped into the pit and floated on top of the water. To achieve full coverage of Jet-A fuel, approximately 1,200 gallons of fuel were utilized per test.

Fuel usage is directly correlated to weather conditions during testing, as winds as low as 2–3 mph will cause fuel to accumulate on the downwind side of the pit. Therefore, testing is only conducted when average wind speeds are below 2–3 mph. While the truck’s distance to the pit remained constant throughout testing, the orientation of the truck was determined on the day of test to ensure the apparatus remained upwind of the fire.

Ignition of the Jet-A fuel was conducted by two firefighters in full Self Contained Breathing Apparatus (SCBA) and PPE with the use of propane torches. The two firefighters began on the upwind side of the pit (closest to the apparatus) and walked approximately 1/4 the circumference of the pit each igniting the fuel, before gathering ignition materials and moving a safe distance away for the duration of the test. The fire was then allowed to naturally propagate to full involvement and free-burn for 10 seconds before suppression began. Flow from the bumper turret was initiated at full involvement but directed into a containment area adjacent to the fire to ensure proper flow rate prior to commencing suppression of the fire. Both the 90% control time and extinguishment time were recorded during testing and later verified from thermal and standard imaging cameras. Data obtained during large-size field-scale testing are presented in Table 13.

Table 13. Summary of 6,504-ft² Jet-A Fire Test Data for Down-Selected PFFs Utilizing both CAF and UHP Technologies

Technology	AFFF		PFF 6		PFF 8.2		PFF 12	
	90% Control Time (s)	Ext. Time (s)	90% Control Time (s)	Ext. Time (s)	90% Control Time (s)	Ext. Time (s)	90% Control Time (s)	Ext. Time (s)
UHP	25	40	58	74	47	65	44	58
CAF	NP	NP	26	37	34	49	21	31
NonCAF	NP	NP	32	44	64	72	25	37

NP: Not Planned

During UHP testing, it was observed that the foam produced by the UHP apparatus appeared less expanded than with the CAF apparatus. At the conclusion of suppression with UHP technology, the foam did not fully cover the pit, rather it accumulated on the downwind side of the pit opposite the apparatus. At the conclusion of suppression with CAF technology, the foam fully covered the pit. Re-ignition of the pit (to burn off extra fuel) was observed to be exceedingly more difficult for the CAF tests when compared to the UHP tests due to the foam expansion and coverage. Even with these differences in foam expansion and pit coverage between the two technologies, candling flames (like those observed in Mil-Spec testing) were not observed. In addition, during fire suppression application of foam on top of an already formed foam blanket did not appear to break the foam’s seal at that location, thus avoiding re-ignition of vapors (as observed in Mil-Spec testing).

Most observations during large-scale testing were related to firefighting efforts in this pit with these specific apparatuses rather than foam fire performance. One of these observations is the “reach” or discharge distance of the bumper turret. To ensure the flow of agent reaches the full area of the pit, the truck must typically be moved closer to the pit’s edge during suppression. Another observation is the method of application of foam onto the fire. Neither bank-down nor rain-drop methodologies were utilized, rather the bumper turret was directed parallel to the fuel surface to apply agent at the base of the flames without disturbing the fuel surface for both UHP and CAF.

This type of attack involves sweeping the bumper turret across the fuel spill to extinguish most of the flames. Final extinguishment, if the reach of the bumper turret was not sufficient, employed a roll-on method of extinguishment.

Some of these large-scale demonstration were performed for several visitors from ESTCP stakeholders during October 2022. PFF 8.2 was tested with both UHP and CAF technologies during the demonstration.

The results with CAF and UHP were compared to NonCAF, which were carried out at an application rate of 0.071 gpm/ft², using a fogging (non-aspirating) nozzle. As shown in Table 13, CAF was more effective than NonCAF, as also observed in testing with smaller fires. The data also suggest that UHP at a 35% lower application rate is nearly as effective as NonCAF at the Mil-Spec application rate. Further testing of UHP at yet lower application rate should be performed in the future.

6.6.4 Effect of Fire Size on Performance of PFF and UHP

6.6.4.1 Effect of Fire Size for CAF with Gas

CAF fire testing with gas was conducted at three separate scales, from 0.3-ft² to 315-ft², with PFFs 6, 7, 8.2, 12, and 15.2. Each set of tests was conducted in triplicate at ER 12. Figure 16 shows a graphical comparison of extinguishment times. Data from these tests are also summarized in Table 14. The data so far suggest, as also reported in the companion ESTCP project [7], that lab-scale testing can be used as a tool to screen PFFs before going to the much more expensive Mil-Spec-scale testing. We will know more about further scale-up of gas-firefighting performance when testing is carried out in another, ongoing ESTCP project (WP21-7556).

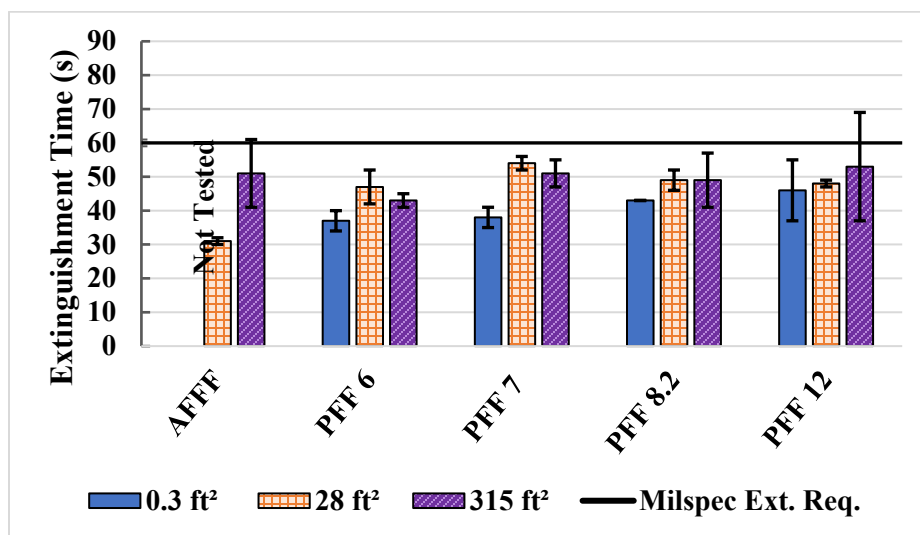


Figure 16. Extinguishment Time for E0 Gas Fires at Lab Scale, Mil-Spec Scale, and Field Scale with CAF (at ER 12)

Table 14. Average Extinguishment Time for E0 Gas Fires for Selected PFFs with CAF (at ER 12) Tested at Lab Scale, Mil-Spec Scale, and Medium-Size Field Scale

Fire Scale	AFFF	PFF 6	PFF 7	PFF 8.2	PFF 12	PFF 14	PFF 15.2
Lab scale (0.31-ft ²)	NP	37±3	38±3	43±0	46±9	NP	44±2
Mil-Spec scale (28-ft ²)	31±1	47±5	54±2	49±3	48±1	62±3	48±4
Medium-size field scale (315-ft ²)	51±10	43±2	51±4	49±8	53±16	NP	NP

NP: Not Planned

6.6.4.2 Effect of Fire Size for CAF with Jet-A

PFFs 6, 8.2, and 12 were tested at three scales (28-ft², 315-ft², and 6,500-ft²) utilizing CAF technology, at ER 12, on Jet-A fuel; extinguishment time results are presented in Figure 17. Due to monetary expense, there was only one repetition at the largest scale (6,500-ft²). Extinguishment times at this scale are more accurately represented by the 90% control time rather than full extinguishment. The 90% control times are presented in Table 15. While a comparison of 90% control time and extinguishment times across all three scales indicates no direct correlation across PFFs, it can be observed that extinguishment was relatively similar across all three scales for each individual PFF. This indicates that small-scale results can be a good predictor of large-scale results for extinguishment time with CAF.

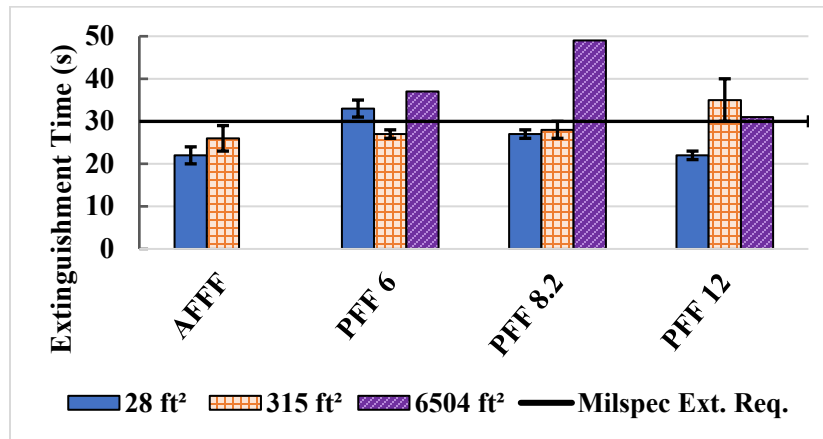


Figure 17. Extinguishment Time for Jet-A Fires at Mil-Spec Scale, Medium-Size Field Scale, and Large-Size-Field Scale with CAF (at ER 12)

Table 15. Extinguishment Time for Jet-A Fires for Three PFFs with CAF (at ER 12) Tested at Mil-Spec Scale, Medium-Size Field Scale, and Large-Size Field Scale

Fire Size	AFFF	PFF 6	PFF 8.2	PFF 12
Mil-Spec scale (28-ft ²)	22±2	33±2	27±1	22±1
Medium-size field scale (315-ft ²)	26±3	27±1	28±2	35±5
Large-size field scale (6,500-ft ²) 90% Control Time (s)	NP	26	34	21
Large-size field scale (6,500-ft ²) Extinguishment Time (s)	NP	37	49	31

NP: Not Planned

For PFFs 6 and 8.2, extinguishment times were about the same at the 28-ft² and 315-ft² scales. However, the large-scale extinguishment time for PFFs 6 and 12 were about the same as the one of the two smaller scales.

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.

6.6.4.3 *Effect of Fire Size for UHP with Jet-A*

PFFs 6, 8.2, and 12 were tested at two scales (315-ft² and 6,504-ft²) utilizing UHP technology, on Jet-A fuel; extinguishment time results are presented in Figure 18. Due to monetary expense, there was only one repetition at the largest scale (6,504-ft²). Extinguishment times at this scale are more accurately represented by the 90% control time rather than full extinguishment. The 90% control times are presented in Table 16. While a comparison of 90% control time and extinguishment times across both scales again indicates no direct correlation across all PFFs, it can be observed that extinguishment was relatively unaffected by ~20X scale-up in fire size, despite a 35% lower foam application rate at the larger scale. This indicates that small-scale results can generally be a good predictor of large-scale results for extinguishment time with UHP. Note that, for PFF 12 the performance at 6,504-ft² scale was much better than at 315-ft², which once again suggests that the full potential of UHP is better realized at the larger scales because of the difficulty in landing foam from UHP systems at the desired spots when the target area is small.

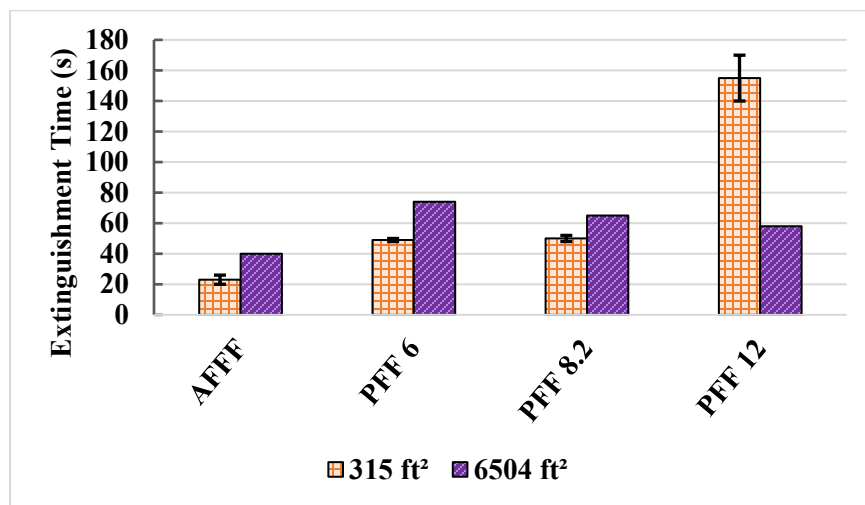


Figure 18. Extinguishment Time for Jet-A Fires at 315-ft² Scale (at 0.071 gpm/ft²) and 6,504-ft² Scale (at 0.046 gpm/ft²) with UHP

Table 16. Average Extinguishment Time for Jet-A Fires for Three PFFs with UHP Tested at Medium-Size Field Scale and Large-Size Field Scale

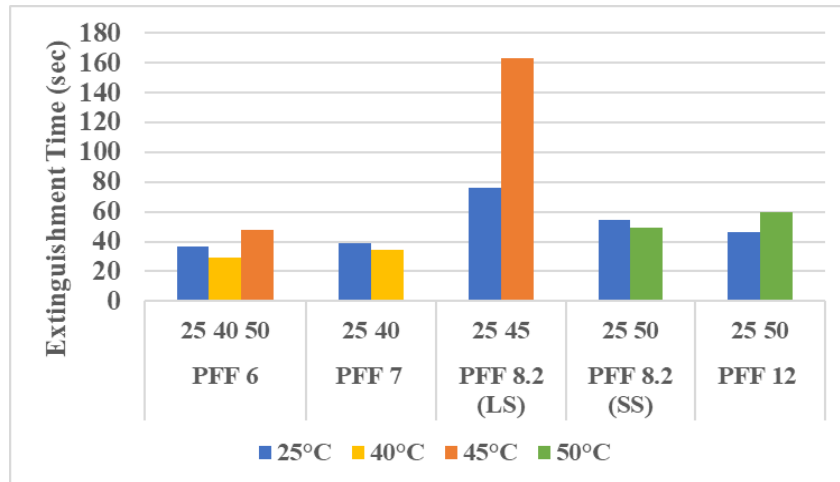
Fire Size	AFFF	PFF 6	PFF 8.2	PFF 12
Medium-size field scale (315-ft ²)	23±3	49±1	50±2	155±15
Large-size field scale (6,500-ft ²) 90% Control Time (s)	25	58	47	44
Large-size field scale (6,500-ft ²) Extinguishment Time (s)	40	74	65	58

6.7 EXPLORATORY TESTING WITH ADDITIVES

This project briefly explored testing some products that failed as Class B firefighting agents as additives to some down-selected PFFs to determine whether their performance could be enhanced. Three products (i.e., Nu Element, PNS, and Greenfire Wetting Agent) were tested with PFFs 6 (Solberg), 7 (Fomtec), and 8 (BioEx A). Only the Greenfire Wetting Agent product showed some potential for improvement, based on mini-CAF scale testing, as the extinguishment time was reduced by 30%. This and other additives are being explored thoroughly in the ongoing SERDP WP22-3103 project.

6.8 EXPLORATORY TESTING ON EFFECT OF ELEVATED AMBIENT TEMPERATURE

To determine the effect of elevated ambient temperatures on firefighting performance, four PFFs were tested at ambient (25°C) and elevated (40–50°C) temperatures. The ambient temperatures were simulated by preheating the foam solution, since the mass of the liquid is much more than that of air deployed to make foam. The ER for both the baseline and elevated-temperature tests was ER 12, and tests were conducted at 0.3-ft² fire scale, using CAF delivery. As shown in Figure 19, the extinguishment time for the PFF 6 product was unchanged on heating to 40°C, but increased significantly upon increasing the temperature to 50°C. The PFF 7 product did not show any change at 40°C. The first set of results for the PFF 8.2 product were a bit puzzling, as the extinguishment time more than doubled, with high degree of variability among the three tests. We then tested a newer sample of the PFF 8.2 product, and it showed that the ambient temperature extinguishment time was lower than for the aged sample (>1-year old); the extinguishment time for the elevated temperature (50°C) for the newer sample was about the same as for the ambient temperature test. The PFF 12 product also showed significant increase in the extinguishment time at 50°C. Therefore, more thorough testing under elevated as well as near-freezing conditions for the qualified products is warranted.



Key: Long storage (LS), Short storage (SS)

Figure 19. Effect of Foam Solution Temperature on the Extinguishment Time of Selected PFFs

Note that even though the ER was controlled at ER 12 for ambient as well as elevated temperatures, the changes in fire performance suggest that ER alone is not a sufficient indicator of foam quality. We believe that the bubble-size distribution and liquid-film stability at ambient and extreme temperatures needs to be quantified to better understand or predict firefighting performance or degradation.

6.9 SUMMARY OF PERFORMANCE ASSESSMENT

The performance testing with 13 PFFs against MIL-PRF-24385F specifications has provided similar observations as previously reported under the companion ESTCP project WP19-5299:

- (1) None of the PFFs tested so far meet the Mil-Spec
Viscosity of some products is still high, even under the revised Mil-Spec (MIL-PRF-32725); these may have to be reformulated to reduce viscosity.

All products pass corrosion tests.

All products pass the biodegradability specification.

- (2) All PFFs fail fire-extinguishment time requirement and most fail the 25% burnback time requirement of MIL-PRF-24385F (though at least two are likely to pass the new Mil-Spec)
Extinguishment times for gasoline fires are reduced with CAF by an average of 25% (the products tested under the previously completed project showed a decrease close to 40%, with considerable variation across the type of product, with poorly performing products showed higher reductions). The reduction in extinguishment time for Jet-A fires was 29%.

The 25% burnback times increased with CAF by an average of 115% for gasoline and by 65% for Jet-A, making all marginal PFFs meet the revised Mil-Spec.

- (3) Based on testing at Mil-Spec-scale, six PFFs (4, 6, 8.2, 12, 14, and 21) were down-selected for field-scale testing at 315-ft² and 6,504-ft². All were successful in extinguishing fires with CAF, UHP, and NonCAF (non-aspirating) foam delivery methods, with projected advantages of CAF and UHP over NonCAF being confirmed.
- (4) There was no significant change in observed extinguishment times for the down-selected PFFs on scale-up of CAF to 6,504-ft² size, which is a very encouraging result. Additional testing at 960-ft² scale, currently ongoing under ESTCP WP21-7556, will provide a better correlation between extinguishment time and fire size for both Jet-A and E0 gas.
- (5) UHP testing at 6,504-ft² scale was very effective in extinguishing Jet-A fires, even at a 35% lower application rate compared to Mil-Spec rate of 0.071 gpm/ft². Testing confirmed that UHP testing be conducted above about 315-ft² fire size to demonstrate the true potential of UHP technology. Additional testing at yet lower application rates is recommended.

7.0 COST ASSESSMENT

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 [36]. 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 produces up to 64 gpm per unit and are intended for handlines [37]. Fire truck manufacturers also offer their services to retrofit trucks [38, 39].

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 [40]. 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-BENEFIT ANALYSIS (CBA)

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 CAF technology. 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 focus of this cost-benefit analysis was the reduction in extinguishment time, therefore the reduction in foam concentrate use and generation of wastewater, achieved with implementation of CAF technology. The details are provided below.

7.2.1 Reduction in Foam Acquisition Costs

A life cycle analysis (LCA), including a life cycle cost analysis was prepared for SERDP/ESTCP by Noblis; this report is currently unpublished, but some estimates from it were used in this CBA. This report assumed, partly on the basis of a 2011 report by Darwin on estimated DoD-wide inventory of AFFF [41], an AFFF demand across DoD of 507,782 gallons for 2020. Based on the data obtained by Battelle/AFCEC, the projected FY25 demand is roughly double of that, assuming several PFFs are qualified by NAVSEA and all are used, yielding a requirement of 1.12 million gallons/yr. This assumption is supported by data obtained by NRL and Jensen Hughes, which were cited in the Noblis report; it is further supported by the fact that the revised Mil-Spec for gasoline-fire extinguishment time was doubled to 60 seconds from the 30 seconds for AFFF.

In a recently completed project, Battelle checked the market prices for several PFFs in 2022[7]. Since prices in bulk quantities were not available, the prices of 5-gallon pails were used. The average price was about \$28/gallon. For the purposes of CBA, the same price for FY25 was assumed, on a bulk basis. Thus, the annual foam-concentrate (PFF) procurement cost was projected to be \$31.4M/yr, assuming standard foam-delivery technology.

The results from a previous Battelle/AFCEC project [7] showed that the gasoline-fire extinguishment time, and thus the PFF concentrate requirement, was reduced by an average of 44%. This project showed that, for PFFs down-selected for field-scale testing, the reduction in extinguishment time for CAF foam delivery was 25% (average) for gasoline fires and 29% (average) for Jet-A fires. For CBA purposes a 30% reduction was assumed for DoD-wide implementation of CAF. Thus, the potential savings with full CAF implementation in PFF procurement cost are \$9.4M/yr, on FY25 year basis.

7.2.2 Reduction in Wastewater Generation Costs

The LCA by Noblis shows that the 20-yr life cycle costs for treatment and disposal of wastewater associated with firefighting is about 6-7 times more than the 20-year life cycle costs for the procurement of PFFs. A reference is made to a 2020 NAVFAC project [42] that examined the costs on the basis that the wastewater needs to be solidified and then the solids need to be disposed in a secure landfill. This is likely because of the cleanout of current equipment that would release enough AFFF into wastewater from PFF solutions. Battelle back-calculated the wastewater disposal cost to be about \$180/gallon of concentrate, which translates to \$2.68/gallon of wastewater, based on Battelle/AFCEC data that one gallon of concentrate typically produces about 67 gallons of wastewater. The annual wastewater treatment costs, based on the Noblis report, was estimated by Battelle to be \$201M/yr. So, the potential cost savings from DoD-wide implementation of CAF technology is estimated to be 30% of that, i.e., \$60.4M/yr.

The AFCEC at Tyndall AFB currently operates a wastewater treatment/solidification plant for handling all firefighting activities at the training site, where all PFF testing is done by Battelle/AFCEC. Our data show that the treatment cost, excluding the concentrated waste disposal, is about \$0.60/gallon, which number yields a cost savings of \$13.5M/yr plus an unknown amount related to solids/concentrate disposal, which is to be handled by DLA. The solids/concentrate is currently stored at Tyndall.

The combined, DoD-wide, operational cost savings from full adaptation of CAF are somewhere in between \$23M/yr and \$70M/yr. This is clearly a large range, so it is recommended that the wastewater treatment requirements and processes be looked at carefully.

7.2.3 Capital Investment for Implementing CAF Technology

A fire truck with CAFS is 10–20% more expensive than a standard platform. To eliminate the need to replace the entire inventory of an estimated 2,000 ARFF trucks across DoD, it might be more cost effective to replace retiring assets to be replaced with new CAF trucks and retrofit others. A more detailed analysis of the current fleet will reveal what portion of it is suited to retrofit. But, for the purposes of CBA, it was assumed that all could be retrofitted. The primary expense in such a retrofit is the capability to provide compressed air. Two options were considered: adding a compressor and associated power supply, etc. vs adding compressed-air bottles. The cost could range from \$50,000 (for adding compressed-air bottles) to \$100,000 (for adding a compressor), for a total capital investment of \$100M to \$200M.

7.2.4 Simple Payback Analysis for CAF Implementation

A simple payback analysis was performed for the two wastewater treatment costs and two capital expenses (CAPEX) or investments. The results are shown in Table 17.

Table 17. Payback Periods (in Years) for Various Scenarios for DoD-wide CAF Technology Implementation

Wastewater Treatment Cost Basis	CAPEX \$100M	CAPEX \$200M
AFCEC/Tyndall AFB	4.3 yrs	8.7 yrs
NAVFAC (Used in Noblis LCA)	1.4 yrs	2.8 yrs

Based on this payback analysis, it seems attractive to retrofit ARFF trucks with CAF capability. The retrofit costs can be easily firmed up by actually converting a couple of trucks.

8.0 IMPLEMENTATION ISSUES

8.1 STAKEHOLDERS AND TECHNOLOGY ACCEPTANCE

The initial step in stakeholder acceptance of any PFF is being qualified under the new Mil-Spec, which is based on use of conventional foam delivery, employing air-aspirating nozzles. However, 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 widely equipped with CAF.

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, especially the cost of wastewater treatment and disposal, would have to be extensively completed ahead of an acquisition plan.

8.3 PLANNED TECHNOLOGY TRANSFER EFFORTS

Battelle/AFCEC has prepared a Guidance Document on implementation of PFF and that provides recommendations on how CAF and UHP may be added to training schedules for ARFF. Documentation consists 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 groups are advisors to Fire and Emergency Services Working Group, AF Fire Panel/Major Air Commands (MAJCOMS) and FAA.

As part of this effort, the following presentations/publications have resulted so far from this ongoing project.

- (1) 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.
- (2) 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.

- (3) 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.
- (4) Bryant, J. and Chauhan, S., “Firefighting Performance of PFAS-Free Foams at Mil-Spec and Field-Scale, presented at AFCEC/Tyndall AFB ESTCP Fire Demo and Workshop, November 8, 2022.
- (5) Chauhan, S., “Demonstration of Compressed Air Foam and Ultra High Pressure Firefighting with PFAS-Free Foams”, presented at SERDP-ESTCP Symposium, Enhancing DoD Mission Capabilities, November 30, 2022.

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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
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
Keith Bagot	FAA	Phone: N/A E-mail: Keith.Bagot@faa.gov	Advisor
William Kavanaugh	ARMY IMCOM	Phone: +49-(0)611-9744-2975 E-mail: william.j.kavangh@usace.army.mil	Advisor; tech transfer
Jeff Eichler	Navy	Phone: N/A E-mail: Jeffery.eichler@navy.mil	Advisor; tech transfer

APPENDIX B PFF-SPECIFIC PRODUCT DETAILS AND RESULTS

APPENDIX B-1: MIL-PRF-24385F TEST RESULTS FOR PFF 4

1.0 Firefighting Agent Details

Light green, low-viscosity, 1% concentrate; UL 162/ULC S654 Listed, ANSI/NFPA 18 Approved, EN1568-3:2018 Approved, LASTFIRE Batch Tested.

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	5.94
Viscosity 5°C (cSt); <20 cSt	7.95
Viscosity 25°C (cSt); >2 cSt	3.99
RI; >1.3630	1.3863
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	Some pitting
Stability	
Spreading coefficient; > 3	N/A
Stratification; No visible evidence	Pass
Precipitation: 0.05% by volume	Pass

3.0 Firefighting Performance

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

- (1) Mil-Spec nozzle, listed as “Mil-Spec”
- (2) Compressed Air Foam (CAF)
- (3) 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, 3%				
Mil-Spec	7	345	58±7	226±4
CAF	12	365	50±3	407±26
28-ft² Jet-A Fuel; 2 gpm, 3%				
Mil-Spec	6.3	295	42±1	318±10
CAF	11.7	491	34±6	561±25
28-ft² Jet-A Fuel; 2 gpm, 1%				
Mil-Spec	6.2	713	Failed	NA
CAF	12	1097	57±3	332±27
315-ft² Jet-A Fuel; 20 gpm, 3%				
CAF	11.7	NM	31±3	NA
UHP	NA	NM	51±6	NA

Failed: Failed to extinguish fire within Mil-Spec requirement; NM: Not Measured; NA: Not Applicable

4.0 Testing Observations

This product was a low-viscosity product. It was down-selected for field-scale testing at 3% concentration. No further testing beyond 315-ft² scale was however carried out as the vendor did not recommend testing at 3% concentration and the 1% is not recommended for Type B fires.

APPENDIX B-2: MIL-PRF-24385F TEST RESULTS FOR PFF 6, 3% FOAM CONCENTRATE

1.0 Firefighting Agent Details

UL 162, FM Standard 5130, EN Standard 1568, ICAO B/C; Thick, brown non-Newtonian Concentrate.

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	6.76
Viscosity 5°C (cSt); <20 cSt	44,134
Viscosity 25°C (cSt); >2 cSt	24,135
RI; >1.3630	1.3857
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	N/A
Stratification; No visible evidence	Pass
Precipitation; 0.05% by volume	Pass

3.0 Firefighting Performance

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

- (1) Mil-Spec nozzle, listed as “Mil-Spec”
- (2) Compressed Air Foam (CAF)
- (3) 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	757	180±10	3±1
28-ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	7	NM	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	11.9	2134	47±5	688±8
28-ft² ethanol-free (E0) gasoline; 3 gpm				
CAF	11.6	2361	36±3	788±94
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	NM	43±2	NA
315-ft² Jet-A fuel; 20 gpm				
UHP	NA	NM	49±1	NA
454-ft² Jet-A fuel; 20 gpm				
CAF	12	NM	27±1	NA

NA: Not Applicable; NM: Not Measured

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	90% Control Time (s)
6504-ft² Jet-A fuel; 455 gpm				
CAF	10.3	850	35	24
NonCAF	NM	NM	43	24
UHP @ 300gpm	NA	NA	75	58

NA: Not Applicable; NM: Not Measured

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.

APPENDIX B-3: MIL-PRF-24385F TEST RESULTS FOR PFF 8.2

1.0 Firefighting Agent Details

ICAO and EN1568-3 certified; Light green, Newtonian, 3% Concentrate.

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	0.55
pH; 7.0<pH<8.5	8.01
Viscosity 5°C (cSt); <20 cSt	26.20
Viscosity 25°C (cSt); >2 cSt	11.36
RI; >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	NA
Stratification; No visible evidence	Pass
Precipitation; 0.05% by volume	Pass

3.0 Firefighting Performance

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

- (4) Mil-Spec nozzle, listed as “Mil-Spec”
- (5) Compressed Air Foam (CAF)
- (6) Ultra-High Pressure (UHP)

This PFF was also 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	402	62±8	195±10
CAF	10	420	51±4	323±40
CAF	12	620	49±3	410±25
CAF @ 2X Conc.	12	NM	61±1	422±40
CAF @1/2X Conc.	12.3	245	60±3	383±34
CAF	15	292	46±0	451±26
28-ft² ethanol-free (E0) gasoline; 3 gpm				
CAF	11.9	302	41±6	286±6
28-ft² Jet-A fuel; 2 gpm				
Mil-Spec	6.3	520	46±2	NM
CAF	12	NM	27±1	NM
315-ft² E0 gasoline; 20 gpm				
CAF	11.9	630	51±7	NA
NonCAF	4.1	156	225	NA
315-ft² Jet-A fuel; 20 gpm				
CAF	11.5	240	27±1	NA
NonCAF	4.6	156	43±4	NA
UHP	NA	NA	50±2	NA
454-ft² Jet-A fuel; 20 gpm				
UHP	NA	NA	132±71	NA

NA: Not Applicable; NM: Not Measured

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	90% Control Time (s)
6504-ft² Jet-A fuel; 455 gpm				
CAF	10.9	292	49	39
NonCAF	2.5	<150	77	43
6504-ft² Jet-A fuel; 300 gpm				
CAF	NM	NM	41	30
NonCAF	2.5	<150	66	48
UHP	NA	NA	66±11	43±14

NA: Not Applicable; NM: Not Measured

4.0 Testing Observations

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

APPENDIX B-4: MIL-PRF-24385F TEST RESULTS FOR PFF 12

1.0 Firefighting Agent Details

ICAO Level C certified, Passes Boeing D6-17487. Clear, Newtonian, 3% Concentrate.

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	8.41
Viscosity 5°C (cSt); <20 cSt	145
Viscosity 25°C (cSt); >2 cSt	60.1
RI; >1.3630	1.3827
Corrosion	
UNS G10100: < 1.5 milli in/yr	0.40
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	N/A
Stratification; No visible evidence	Pass
Precipitation; 0.05% by volume	Pass

3.0 Firefighting Performance

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

- (1) Mil-Spec nozzle, listed as “Mil-Spec”
- (2) Compressed Air Foam (CAF)
- (3) 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	247	195±53	192±37
CAF	9.9	330	93±17	168±42
UHP	1.6	140	137±21	9±8
28-ft² ethanol-free (E0) gasoline; 2 gpm				
Mil-Spec	7.0	190	63±6	155±17
CAF	12	386	48±1	360±22
28-ft² Jet-A Fuel; 2 gpm				
Mil-Spec	6.7	190	36±7	317±6
CAF	11.6	386	22±1	475±15
315-ft² E0 gasoline; 20 gpm				
CAF	12.6	342	129	NA
NonCAF	7.8	170	196	NA
315-ft² Jet-A Fuel; 20 gpm				
CAF	12.6	342	34±9	NA
NonCAF	7.8	170	36±7	
UHP	NA	NA	155±15	NA

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	90% Control Time (s)
6504-ft² Jet-A fuel; 455 gpm				
CAF	11.8	265	32±1	25±5
NonCAF	18.3	180	37	25
UHP @ 300gpm	NA	NA	68	44

NA: Not Applicable

4.0 Testing Observations

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

APPENDIX B-5: MIL-PRF-24385F TEST RESULTS FOR PFF 14

1.0 Firefighting Agent Details

Clear, Newtonian, 3% Concentrate.

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	363,000
BOD ₂₀ (mg/L)	402,750
Biodegradability (BOD ₂₀ /COD); >0.65	1.11
Other Physical Properties	
Spreading coefficient; > 3	-1.83
pH; 7.0<pH<8.5	8.59
Viscosity 5°C (cSt); <20 cSt	1,031
Viscosity 25°C (cSt); >2 cSt	1,011
RI; >1.3630	1.3567
Corrosion	
UNS G10100; < 1.5 milli in/yr	0.13
UNS C70600; <1.0 milli in/yr	0.86
UNS NO4400; <1.0 milli in/yr	0.06
UNS C90500; <100 mg	83.34
CNS S30400; no pitting	No pitting
Stability	
Spreading coefficient; > 3	N/A
Stratification; No visible evidence	Pass
Precipitation; 0.05% by volume	Pass

3.0 Firefighting Performance

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

- (1) Mil-Spec nozzle, listed as “Mil-Spec”
- (2) Compressed Air Foam (CAF)
- (3) 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-free (E0) gasoline; 2 gpm				
Mil-Spec	7.0	444	80±5	172±35
CAF	12	643	62±3	482±43
315-ft² Jet-A Fuel; 20 gpm				
CAF	12	NM	34±6	NA
UHP	NA	NA	71±23	NA

NA: Not Applicable; NM: Not Measured

4.0 Testing Observations

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

APPENDIX B-6: MIL-PRF-24385F TEST RESULTS FOR PFF 15.2

1.0 Firefighting Agent Details

ICAO Level B 6% certified, NFPA 11 compliant, and EN1568:3/EN1568:1 certified. Clear, Newtonian, 3% Concentrate.

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	488,670
BOD ₂₀ (mg/L)	580,873
Biodegradability (BOD ₂₀ /COD); >0.65	1.189
Other Physical Properties	
Spreading coefficient; > 3	-3.173
pH; 7.0<pH<8.5	6.98
Viscosity 5°C (cSt); <20 cSt	12,785
Viscosity 25°C (cSt); >2 cSt	11,828
RI; >1.3630	1.3614
Corrosion	
UNS G10100: < 1.5 milli in/yr	
UNS C70600: <1.0 milli in/yr	
UNS NO4400: <1.0 milli in/yr	
UNS C90500: <100 mg	
CNS S30400: no pitting	
Stability	
Spreading coefficient; > 3	N/A
Stratification; No visible evidence	Pass
Precipitation; 0.05% by volume	Pass

3.0 Firefighting Performance

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

- (1) Mil-Spec nozzle, listed as “Mil-Spec”
- (2) Compressed Air Foam (CAF)
- (3) 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-free (E0) gasoline; 2 gpm				
Mil-Spec	7.7	890	65±4	293±21
CAF	12.5	1570	48±4	745±13
315-ft² Jet-A Fuel; 20 gpm				
CAF	12	NM	40±5	NA
UHP	NA	NA	49±3	NA

NA: Not Applicable; NM: Not Measured

4.0 Testing Observations

This product was selected for field-scale evaluations because of its good firefighting performance with CAF at the Mil-Spec scale. However, its viscosity is too high to meet the new Mil-Spec.

APPENDIX B-7: MIL-PRF-24385F TEST RESULTS FOR PFF 21

1.0 Firefighting Agent Details

Proprietary new formulation. Clear, Newtonian, 3% Concentrate.

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.

3.0 Firefighting Performance

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

(1) Mil-Spec nozzle, listed as “Mil-Spec”

(2) Compressed Air Foam (CAF)

This PFF was also selected for field-scale testing at 315-ft² scale, the results are listed below.

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	6.6	218	86±4	156±19
CAF	12.8	857	68±6	368±54
28-ft² Jet-A Fuel; 2 gpm				
Mil-Spec	6.5	218	46±4	349±25
CAF	11.5	857	33±2	501±53
315-ft² Jet-A Fuel; 20 gpm				
Non-CAF	8.5	158	36±4	NA
CAF	12.6	317	29 ±3	NA

NA: Not Applicable

4.0 Testing Observations

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

APPENDIX B-8: MIL-PRF-24385F TEST RESULTS FOR PFF 22

1.0 Firefighting Agent Details

Proprietary new formulation. Clear, Newtonian, 3% Concentrate.

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	889,667
BOD ₂₀ (mg/L)	1,536,900
Biodegradability (BOD ₂₀ /COD); >0.65	1.728
Other Physical Properties	
Spreading coefficient; > 3	0.547
pH; 7.0<pH<8.5	7.78
Viscosity 5°C (cSt); <20 cSt	21.18
Viscosity 25°C (cSt); >2 cSt	9.30
RI; >1.3630	1.3949
Corrosion	
UNS G10100; < 1.5 milli in/yr	
UNS C70600; <1.0 milli in/yr	
UNS NO4400; <1.0 milli in/yr	
UNS C90500; <100 mg	
CNS S30400; no pitting	
Stability	
Spreading coefficient; > 3	N/A
Stratification; No visible evidence	Pass
Precipitation; 0.05% by volume	Pass

3.0 Firefighting Performance

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

(1) Mil-Spec nozzle, listed as “Mil-Spec”

(2) Compressed Air Foam (CAF)

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	6.6	225	77±10	176±4
CAF	12.7	546	55±2	382±49
28-ft² Jet-A Fuel; 2 gpm				
Mil-Spec	5.9	335	40±4	377±25
CAF	12.2	546	31±3	521±15

4.0 Testing Observations

This product was not selected for field-scale evaluations because the vendor is planning to make improvements to the formulation so it performs within specifications for fire extinguishment.

APPENDIX B-9: MIL-PRF-24385F TEST RESULTS FOR PFF 24

1.0 Firefighting Agent Details

Prototype product; proprietary new formulation. Clear, Newtonian, 3% Concentrate.

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.

3.0 Firefighting Performance

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

(1) Mil-Spec nozzle, listed as “Mil-Spec”

(2) Compressed Air Foam (CAF)

This PFF was also selected for field-scale testing at 315-ft² scale, the results are listed below.

Delivery Method	Expansion Ratio	25% Drain Time (s)	Extinguishment Time (s)	25% Burnback Time (s)
28-ft² Jet-A Fuel; 2 gpm				
Mil-Spec	7.7	1044	41±12	344±54
CAF	12.0	1400	31±3	602±15
315-ft² E0 Fuel; 20 gpm				
Non-CAF	7.1	159	152±44	NA
CAF	11.5	299	62±17	NA
315-ft² Jet-A Fuel; 20 gpm				
Non-CAF	7.1	159	65±27	NA
CAF	11.5	299	32±2	NA

NA: Not Applicable

4.0 Testing Observations

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

APPENDIX C 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 numbers assigned to each foam (also referred to as PFF) tested:

Foam 0 (PFF 0)
Foam 8.2 (PFF 8.2)
Foam 10 (PFF 10)
Foam 11 (PFF 11)
Foam 12 (PFF 12)
Foam 13 (PFF 13)
Foam 14 (PFF 14)
Foam 16 (PFF 16)

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 G10100, C70600, N04400, and S30400 coupons were 3"L x ½"W x 1/16"T. The C90500 nominal dimensions were 3"L x ½"W x 3/16"T, per the Mil-Spec.

All coupons were cleaned with acetone and DI water followed by air drying prior to recording an initial weight. Per the Mil-Spec, the stainless-steel coupons were passivated in a 10% HNO₃ solution for five minutes prior to introduction to the exposure environments. Each general corrosion coupon was suspended in the foam solutions by a nylon string attached to the containment cell lid (Figure C-1). These tethers were spaced apart to prevent the contact of metal surfaces during the 60-day exposure.



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

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 500 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.



Figure C-2. AFFF Exposure Containment Cells –General and Localized 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 C-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.

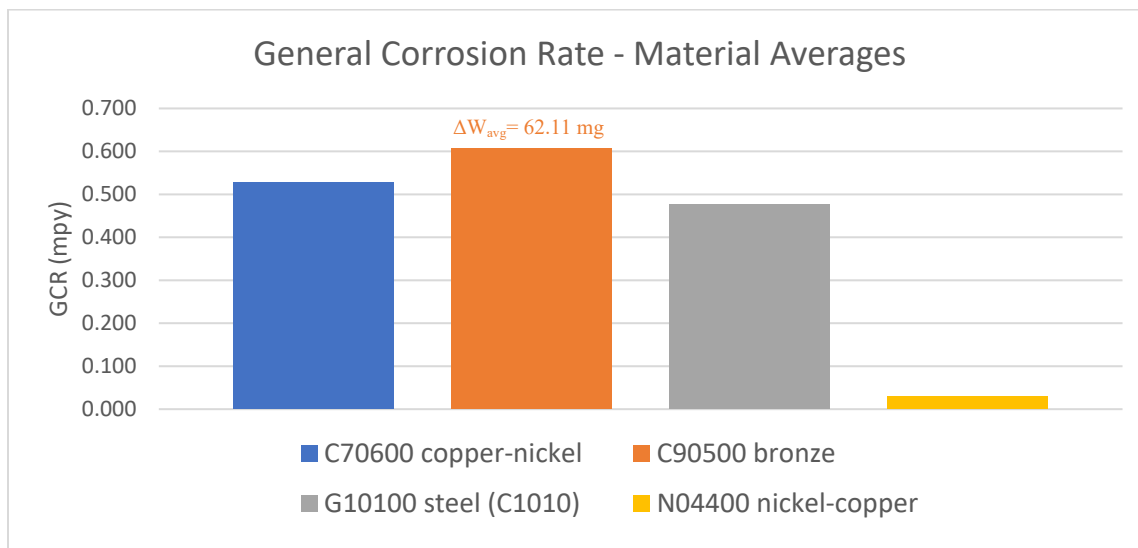


Figure C-3. Average Corrosion Rates Summed over the Entirety of the Field of Coupons Regardless of Foam# Exposure.

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.

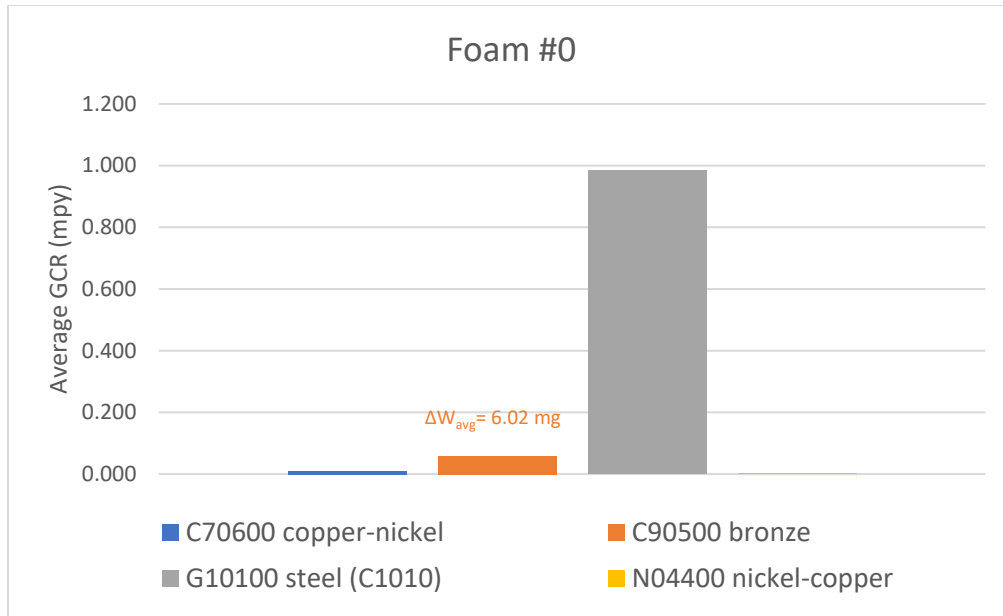


Figure C-4. Average Corrosion Rate by Material with Respect to Foam #0 Exposure.

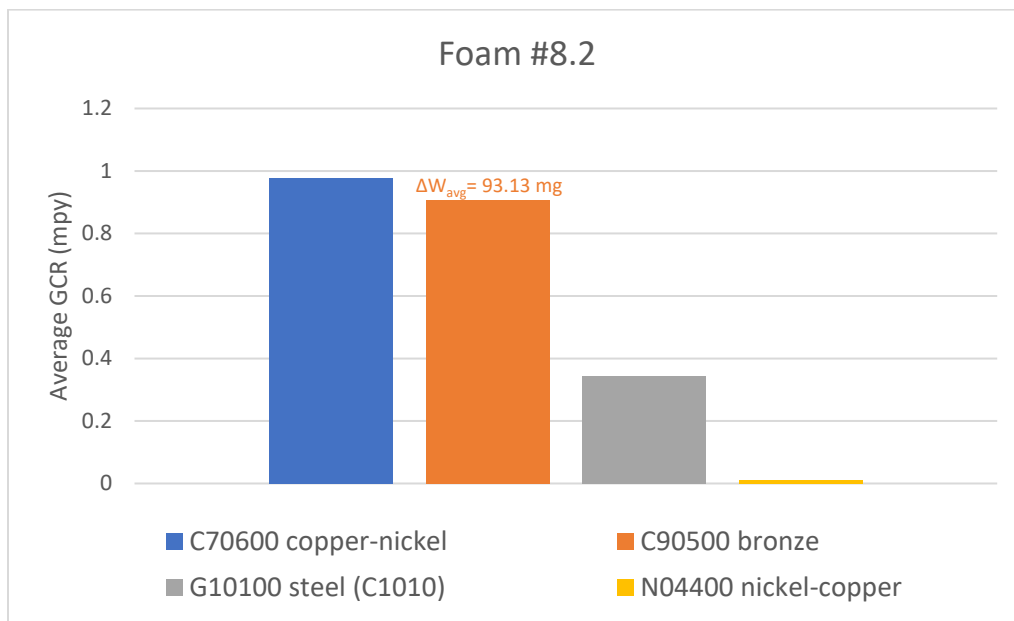


Figure C-5. Average Corrosion Rate by Material with Respect to Foam #8.2 Exposure.

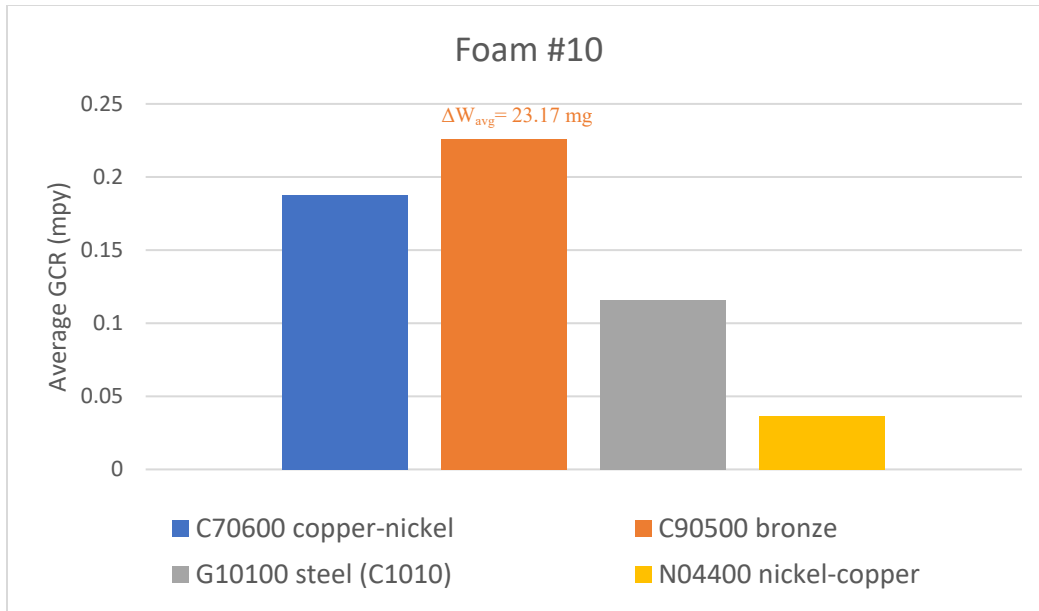


Figure C-6. Average Corrosion Rate by Material with Respect to Foam #10 Exposure.

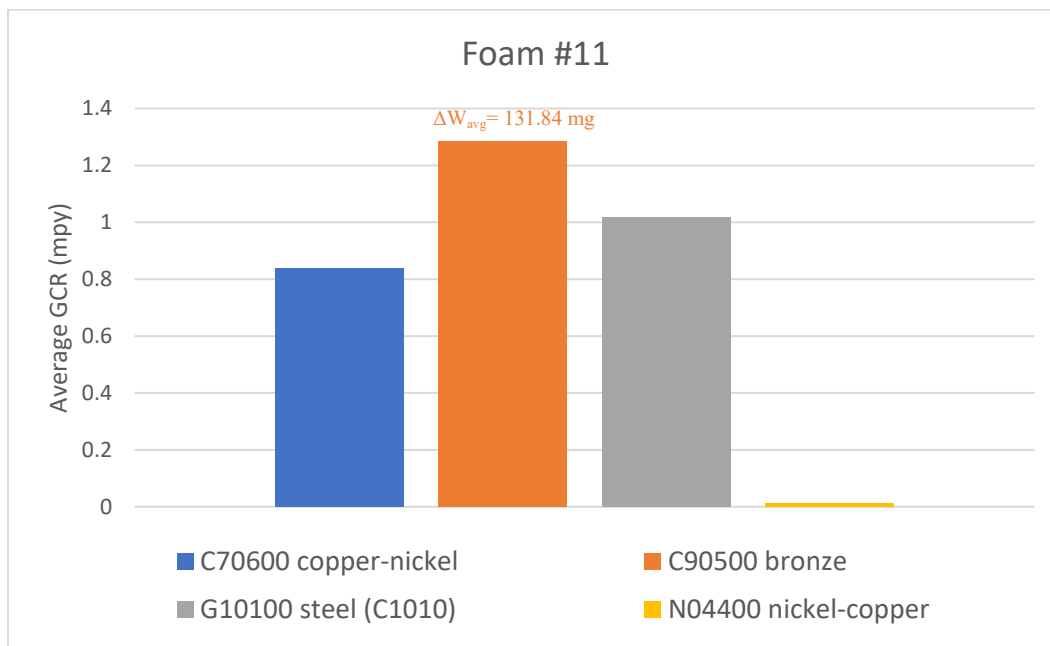


Figure C-7. Average Corrosion Rate by Material with Respect to Foam #11 Exposure.

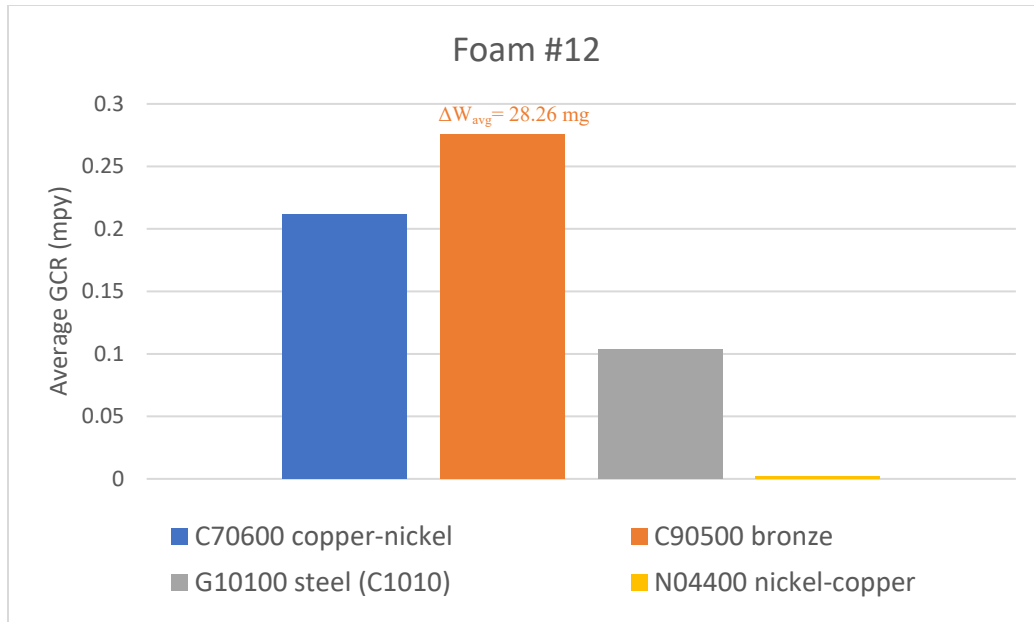


Figure C-8. Average Corrosion Rate by Material with Respect to Foam #12 Exposure.

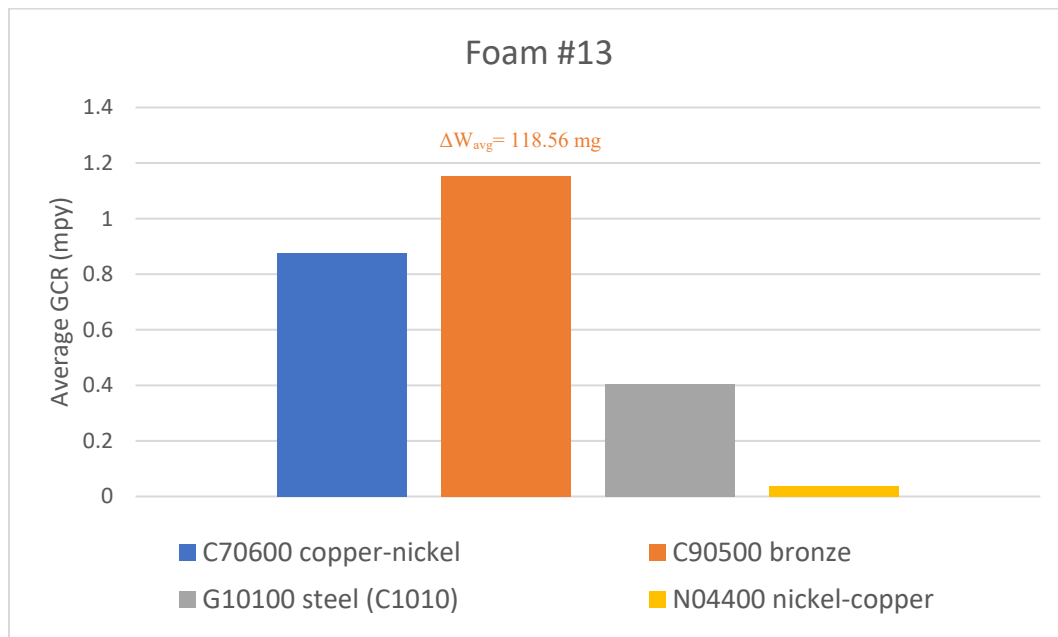


Figure C-9. Average Corrosion Rate by Material with Respect to Foam #13 Exposure.

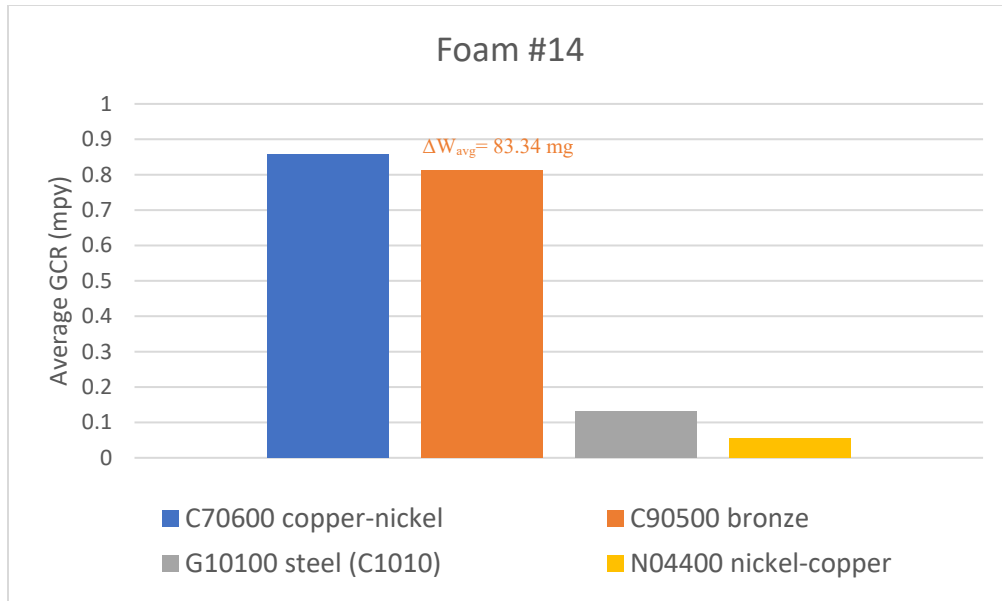


Figure C-10. Average Corrosion Rate by Material with Respect to Foam #14 Exposure.

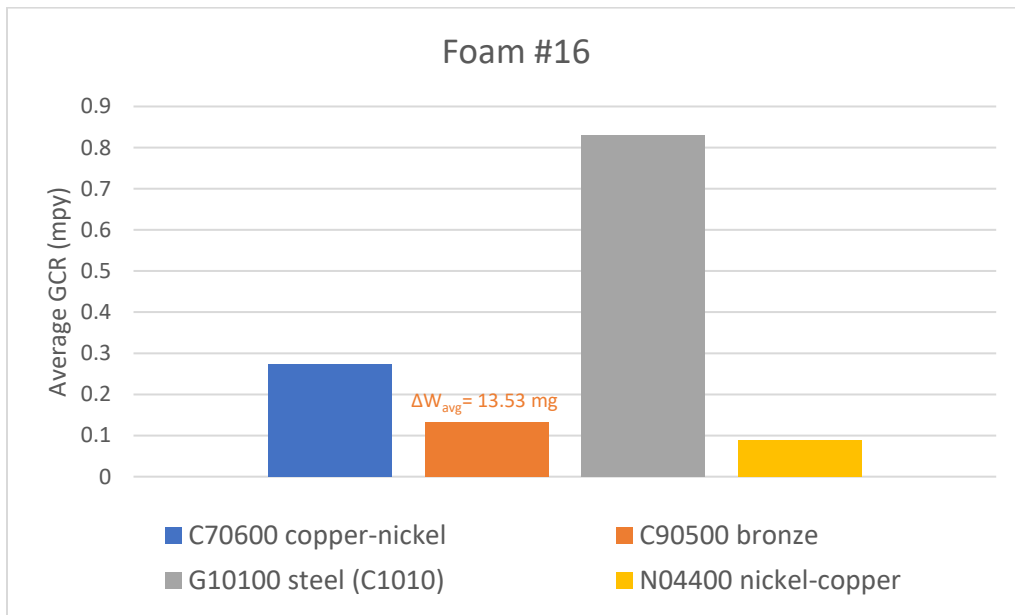


Figure C-11. Average Corrosion Rate by Material with Respect to Foam #16 Exposure.

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.

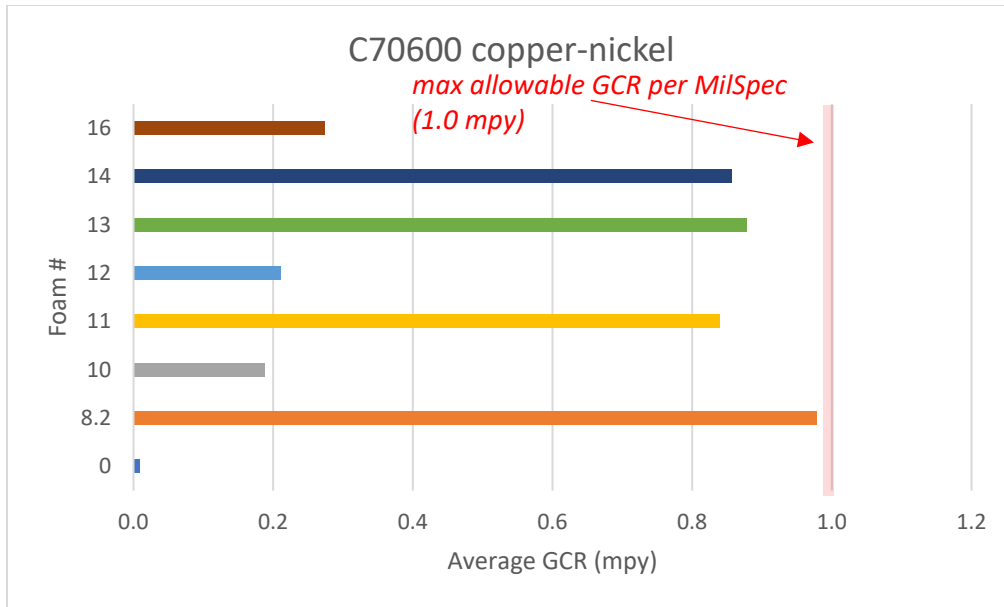


Figure C-12. Average Corrosion Rate of C70600 with Respect to Foam #.

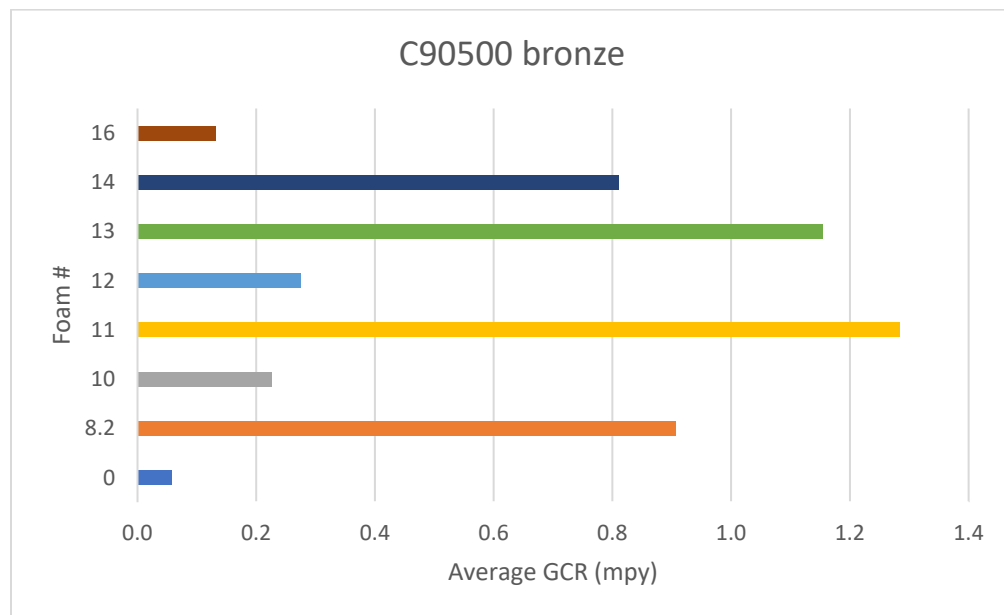


Figure C-13. Average Corrosion Rate of C90500 with Respect to Foam #.

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.

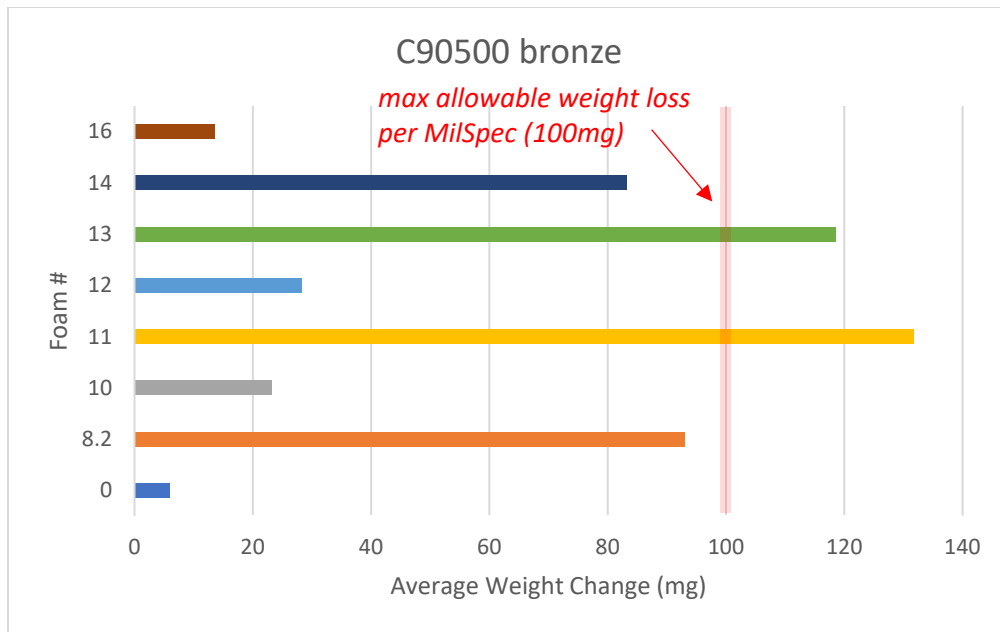


Figure C-14. Average Change in Weight of C90500 with Respect to Foam #.

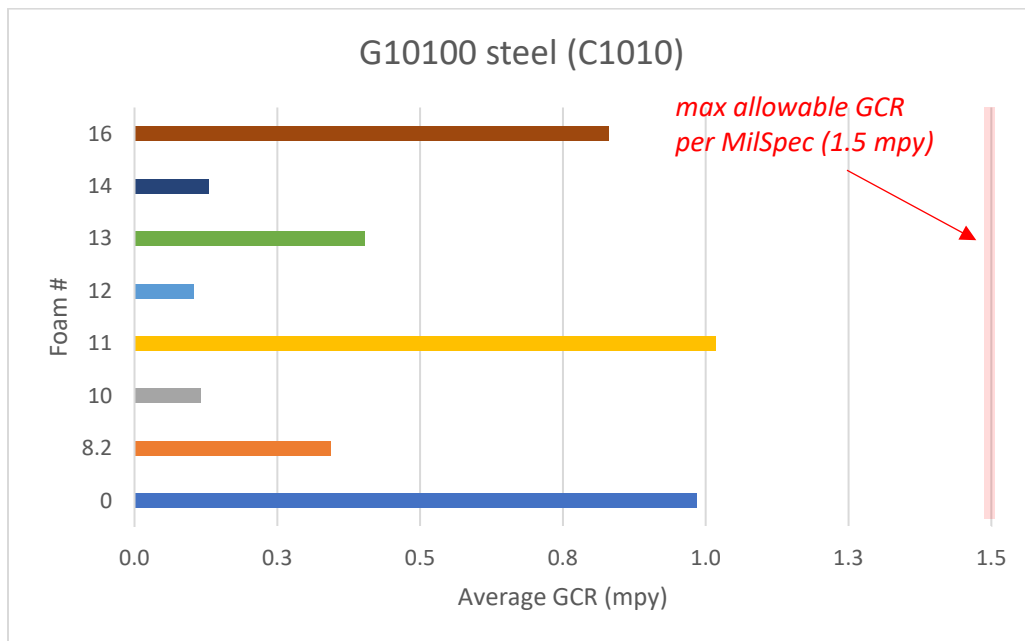


Figure C-15. Average Corrosion Rate of G10100 with Respect to Foam #.

For the N0400 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.

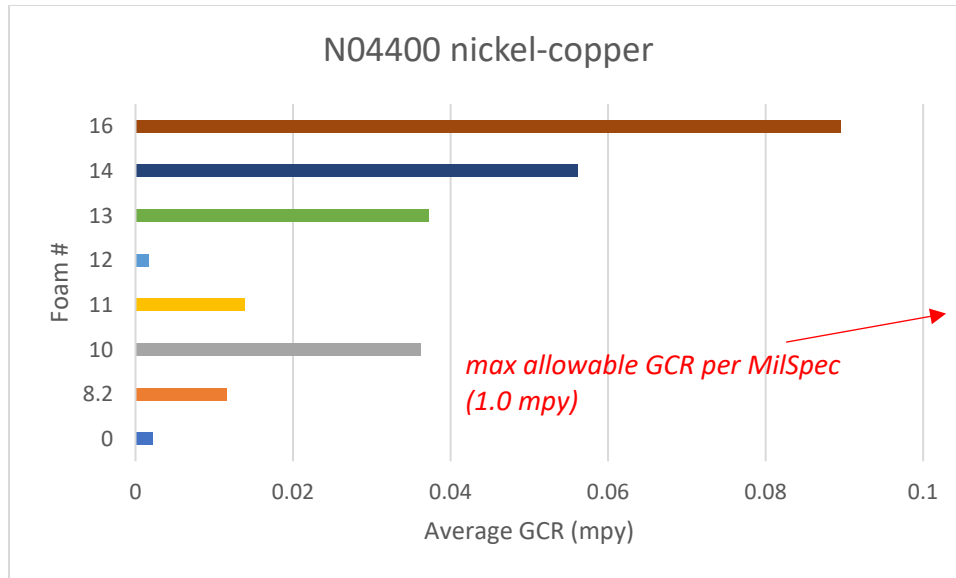


Figure C-16. Average Corrosion Rate of N04400 with Respect to Foam #.

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 C-2. Tabulated Localized Corrosion Observations for Foam #0.

	Sample Label	Visual Inspection by Eye	Inspection at 10X	Code
Foam 0	1	No Pits	No Pits	NA
	2	No Pits	No Pits	NA
	3	No Pits	No Pits	NA
	4	No Pits	No Pits	NA
	5	No Pits	No Pits	NA
	6	No Pits	No Pits	NA
	7	No Pits	No Pits	NA
	8	No Pits	No Pits	NA
	9	No Pits	No Pits	NA
	10	No Pits	No Pits	NA

Table C-3. Tabulated Localized Corrosion Observations for Foam #8.2

	Sample Label	Visual Inspection by Eye	Inspection at 10X	Code
Foam 8.2	39	No Pits	No Pits	NA
	40	No Pits	No Pits	NA
	43	No Pits	No Pits	NA
	52	No Pits	No Pits	NA
	54	No Pits	No Pits	NA
	82	No Pits	No Pits	NA
	102	No Pits	No Pits	NA
	115	No Pits	No Pits	NA
	116	No Pits	No Pits	NA
	120	No Pits	No Pits	NA

Table C-4. Tabulated Localized Corrosion Observations for Foam #10

	Sample Label	Visual Inspection by Eye	Inspection at 10X	Code
Foam 10	21	No Pits	No Pits	NA
	22	No Pits	No Pits	NA
	23	No Pits	No Pits	NA
	24	No Pits	No Pits	NA
	25	No Pits	No Pits	NA
	26	No Pits	No Pits	NA
	27	No Pits	No Pits	NA
	28	No Pits	No Pits	NA
	29	No Pits	No Pits	NA
	30	No Pits	No Pits	NA

Table C-5. Tabulated Localized Corrosion Observations for Foam #11

	Sample Label	Visual Inspection by Eye	Inspection at 10X	Code
Foam 11	21	No Pits	No Pits	NA
	22	No Pits	No Pits	NA
	23	Pit under crevice former at bottom edge	Pit under crevice former at bottom edge	E
	25	No Pits	No Pits	NA
	26	No Pits	No Pits	NA
	29	Pit under crevice former at bottom edge	Pit under crevice former at bottom edge	E
	31	No Pits	No Pits	NA
	32	No Pits	No Pits	NA
	33	No Pits	No Pits	NA
	34	No Pits	No Pits	NA



Figure C-17. Crevice Attack Observed on Stainless-steel Sample 23, Foam #11



Figure C-18. Crevice Attack Observed on Stainless-steel Sample 29, Foam #11

Table C-6. Tabulated Localized Corrosion Observations for Foam #12

	Sample Label	Visual Inspection by Eye	Inspection at 10X	Code
Foam 12	35	No Pits	No Pits	NA
	36	No Pits	No Pits	NA
	37	No Pits	No Pits	NA
	38	No Pits	No Pits	NA
	39	No Pits	No Pits	NA
	42	No Pits	No Pits	NA
	44	No Pits	No Pits	NA
	45	No Pits	No Pits	NA
	46	No Pits	No Pits	NA
	47	No Pits	No Pits	NA

Table C-7. Tabulated Localized Corrosion Observations for Foam #13

	Sample Label	Visual Inspection by Eye	Inspection at 10X	Code
Foam 13	27	No Pits	No Pits	NA
	28	One small pit under rubber band	One small pit under rubber band	C
	40	No Pits	No Pits	NA
	41	No Pits	No Pits	NA
	48	No Pits	No Pits	NA
	49	No Pits	No Pits	NA
	50	No Pits	No Pits	NA
	117	No Pits	No Pits	NA
	118	No Pits	No Pits	NA
	119	No Pits	No Pits	NA



Figure C-19. Crevice Attack Observed on Stainless-steel Sample 28, Foam #13

Table C-8. Tabulated Localized Corrosion Observations for Foam #14

	Sample Label	Visual Inspection by Eye	Inspection at 10X	Code
Foam 14	93	No Pits	No Pits	NA
	94	No Pits	No Pits	NA
	95	No Pits	No Pits	NA
	96	No Pits	No Pits	NA
	97	No Pits	No Pits	NA
	98	No Pits	No Pits	NA
	99	No Pits	No Pits	NA
	100	No Pits	No Pits	NA
	103	No Pits	No Pits	NA
	104	No Pits	No Pits	NA

Table C-9. Tabulated Localized Corrosion Observations for Foam #16

	Sample Label	Visual Inspection by Eye	Inspection at 10X	Code
Foam 16	24	No Pits	No Pits	NA
	30	No Pits	No Pits	NA
	31	No Pits	No Pits	NA
	32	No Pits	No Pits	NA
	33	No Pits	No Pits	NA
	34	No Pits	No Pits	NA
	35	No Pits	No Pits	NA
	36	No Pits	No Pits	NA
	37	No Pits	No Pits	NA
	38	No Pits	No Pits	NA

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

Material	Foam	Physical Description (Prior to cleaning with acid)
G10100 Steel	0	Small pits across sample and areas of brown rust
G10100 Steel	8.2	Darker – no red rust
G10100 Steel	10	Corrosion product near top of samples
G10100 Steel	11	Corrosion product around edges and surfaces darker
G10100 Steel	12	Localized areas of brown corrosion product
G10100 Steel	13	Small amount of rust near top
G10100 Steel	14	Darker but no red rust observed
G10100 Steel	16	Bluish/green pattern formed on surface that was difficult to remove
C70600 Cu-Ni	0	No visible change
C70600 Cu-Ni	8.2	Darker/Reddish
C70600 Cu-Ni	10	Darker in color
C70600 Cu-Ni	11	Dark brown surface
C70600 Cu-Ni	12	Darker/reddish color
C70600 Cu-Ni	13	Dark color
C70600 Cu-Ni	14	Darker in color
C70600 Cu-Ni	16	Looks etched, Light in color
N04400 Ni-Cu	0	No visible change
N04400 Ni-Cu	8.2	No visible change
N04400 Ni-Cu	10	Staining observed - Darker
N04400 Ni-Cu	11	No visible change
N04400 Ni-Cu	12	No visible change
N04400 Ni-Cu	13	Slightly darker
N04400 Ni-Cu	14	Darker
N04400 Ni-Cu	16	Darker/Stained
C90500 Bronze	0	Small localized green spots; most of the surface observed no change
C90500 Bronze	8.2	Darker/ reddish color
C90500 Bronze	10	Top ~10% of coupon was darker; otherwise, no change
C90500 Bronze	11	Uniformly darker surface
C90500 Bronze	12	Darker/Red in color
C90500 Bronze	13	Dark purple color
C90500 Bronze	14	Darker in color
C90500 Bronze	16	Some green corrosion scale

CONCLUSIONS

The Mil-Spec provides coarse guidelines for allowable GCRs. 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 C-11. Summary of Mil-Spec Pass/Fail Ranking.

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

Material Type	Foam 0	Foam 8.2	Foam 10	Foam 11	Foam 12	Foam 13	Foam 14	Foam 16
<i>G10100 Steel</i>	0.98	0.34	0.12	1.02	0.10	0.40	0.13	0.83
<i>C70600 Cu-Ni</i>	0.01	0.98	0.19	0.84	0.21	0.88	0.86	0.27
<i>N04400 Ni-Cu</i>	0.00	0.01	0.04	0.01	0.00	0.04	0.06	0.09
<i>C90500 Bronze</i>	6.02	93.13	23.17	131.84	28.26	118.56	83.34	13.53

Foam #11 and Foam #13 were both outside the corrosion rate requirements for bronze based on the MIL-F-24385 requirements. All other materials met the general corrosion requirements for each foam. Localized attack was not prevalent. The most severe examples were the result of crevice formation and occurred in Foam #11 and #13. Pitting was generally isolated and infrequently exhibited.