

**GUIDANCE DOCUMENT**

# Engineering Fire Suppression Agent Delivery to Augment PFAS-Free Foam (PFF) Performance: Compressed Air Foam (CAF) and Ultra-High Pressure (UHP) Methodologies

---

Satya Chauhan  
Julie Bryant  
Melody Graves  
Heather Luckarift  
Malena Maraviglia  
Melissa Roshon  
**Battelle Memorial Institute**

Bridgett Ashley  
Jeffery Owens  
**Air Force – AFCEC**

Jeff Eichler  
**Naval Surface Warfare Center PCD**

## June 2022

---

This report was prepared under contract to the Department of Defense Environmental Security Technology Certification Program (ESTCP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                        |                                     | Form Approved<br>OMB No. 0704-0188                 |                                                       |                                                              |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|-------------------------------------|----------------------------------------------------|-------------------------------------------------------|--------------------------------------------------------------|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.                                                                                                                                                                                                                                                                                                                                       |                        |                                     |                                                    |                                                       |                                                              |
| 1. REPORT DATE<br>06-15-2022                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                        | 2. REPORT TYPE<br>Guidance Document |                                                    | 3. DATES COVERED (From - To)<br>6/21/2019 - 9/30/2022 |                                                              |
| 4. TITLE AND SUBTITLE<br><br>Validation of Fluorine-free AFFF Against Military Performance Criteria<br><br>Engineering Fire Suppression Agent Delivery to Augment PFAS-Free Foam (PFF)<br>Performance: Compressed Air Foam (CAF) and Ultra-High Pressure (UHP) Methodologies                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                        |                                     | 5a. CONTRACT NUMBER<br>W912HQ19C005                |                                                       |                                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                        |                                     | 5b. GRANT NUMBER                                   |                                                       |                                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                        |                                     | 5c. PROGRAM ELEMENT NUMBER                         |                                                       |                                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                        |                                     | 5d. PROJECT NUMBER WP19-5299                       |                                                       |                                                              |
| 6. AUTHOR(S)<br><br>Chauhan, S.P., Maraviglia, M., McMeans, A., and Luckarift, H., Battelle;<br>Glenn Johnson, ARCTOS; Ashley, B, AFCEC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                        |                                     | 5e. TASK NUMBER                                    |                                                       |                                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                        |                                     | 5f. WORK UNIT NUMBER                               |                                                       |                                                              |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                        |                                     | 8. PERFORMING ORGANIZATION REPORT NUMBER<br>G29520 |                                                       |                                                              |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><br>Battelle Memorial Institute,<br>Columbus, Ohio 43201<br>AFCEC; Tyndall AFB, FL                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                        |                                     | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>ESTCP          |                                                       |                                                              |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br><br>Environmental Security Technology Certification Program<br>4800 Mark Center Drive, Suite 16F16<br>Alexandria, VA 22350-3605                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                        |                                     | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) WP19-5299   |                                                       |                                                              |
| 12. DISTRIBUTION / AVAILABILITY STATEMENT<br>DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                        |                                     |                                                    |                                                       |                                                              |
| 13. SUPPLEMENTARY NOTES<br>See Final Report for more details                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                        |                                     |                                                    |                                                       |                                                              |
| 14. ABSTRACT<br>This document provides guidance on two technologies to enhance the performance of PFAS-free foams (PFFs) against MIL-PRF-24385F specification for Class B fire suppressants. These two technologies were compressed air foam (CAF) and ultra-high pressure (UHP) foam delivery. All PFFs failed fire extinguishment time specification, and a few failed the burnback time specifications, but CAF delivery significantly improved both for all PFFs. On average, the extinguishment time was reduced by about 40%, but still fell short of the specification. The CAF testing at medium-field (315-ft <sup>2</sup> ) scale showed that the extinguishment time was not significantly different than at Mil-Spec (28-ft <sup>2</sup> ) scale. The UHP technology also has shown considerable promise, but the demonstration of its true potential requires larger field-scale testing. Both CAF and UHP technologies help to significantly reduce the foam use, and thus the operating costs for extinguishing Type B fires. The engineering background, test-equipment description, and typical test methods for CAF and UHP are provided. As more data from currently planned testing with CAF and UHP are obtained, this guidance document is expected to be refined. |                        |                                     |                                                    |                                                       |                                                              |
| 15. SUBJECT TERMS<br>AFFF; PFF; Fluorine-free Fire Suppressants; Compressed Air Foam; Ultra High Pressure; Class B Fires                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                        |                                     |                                                    |                                                       |                                                              |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                        |                                     | 17. LIMITATION OF ABSTRACT<br><br>UNCLASS          | 18. NUMBER OF PAGES<br><br>60                         | 19a. NAME OF RESPONSIBLE PERSON<br>Satya Chauhan             |
| a. REPORT<br>UNCLASS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | b. ABSTRACT<br>UNCLASS | c. THIS PAGE<br>UNCLASS             |                                                    |                                                       | 19b. TELEPHONE NUMBER<br>(include area code)<br>614-424-4812 |

# TABLE OF CONTENTS

|                                                                                                                                       | Page        |
|---------------------------------------------------------------------------------------------------------------------------------------|-------------|
| <b>LIST OF ACRONYMS .....</b>                                                                                                         | <b>v</b>    |
| <b>ACKNOWLEDGEMENT.....</b>                                                                                                           | <b>vii</b>  |
| <b>EXECUTIVE SUMMARY .....</b>                                                                                                        | <b>viii</b> |
| GOAL OF THE GUIDANCE .....                                                                                                            | viii        |
| TECHNOLOGICAL CHALLENGE.....                                                                                                          | viii        |
| PHYSICAL MECHANISM, PERFORMANCE AND OPERATIONAL ISSUES OF<br>PFAS-FREE FOAMS .....                                                    | ix          |
| EVALUATING EFFECT OF COMPRESSED AIR FOAM AND ULTRA-HIGH-<br>PRESSURE DELIVERY SYSTEMS ON FIRE EXTINGUISHMENT AND<br>SUPPRESSION ..... | ix          |
| IMPLEMENTATION ISSUES FOR CONSIDERATION .....                                                                                         | x           |
| <b>1.0 INTRODUCTION .....</b>                                                                                                         | <b>1</b>    |
| 1.1 BACKGROUND .....                                                                                                                  | 1           |
| 1.2 OBJECTIVE OF DEMONSTRATION.....                                                                                                   | 2           |
| 1.3 REGULATORY DRIVERS .....                                                                                                          | 2           |
| <b>2.0 PFAS-FREE FOAMS.....</b>                                                                                                       | <b>3</b>    |
| 2.1 BACKGROUND .....                                                                                                                  | 3           |
| 2.2 BENEFITS OF PFF COMPARED TO CURRENT PREDOMINANT<br>PRACTICES .....                                                                | 4           |
| 2.3 TEST PROTOCOLS.....                                                                                                               | 5           |
| 2.3.1 Physical Properties Testing Against MIL-PRF-24385F .....                                                                        | 6           |
| 2.3.1.1 pH (Hydrogen Ion Concentration).....                                                                                          | 6           |
| 2.3.1.2 Refractive Index.....                                                                                                         | 6           |
| 2.3.1.3 Viscosity .....                                                                                                               | 6           |
| 2.3.1.4 Spreading Coefficient .....                                                                                                   | 6           |
| 2.3.2 Corrosivity Testing .....                                                                                                       | 6           |
| 2.3.3 Environmental Impact.....                                                                                                       | 7           |
| 2.3.3.1 Aquatic LC <sub>50</sub> and IC <sub>25</sub> .....                                                                           | 7           |
| 2.3.3.2 BOD <sub>20</sub> and COD .....                                                                                               | 7           |
| 2.3.4 Stability of PFF Concentrate.....                                                                                               | 8           |
| 2.4 RESULTS FROM PHYSIOCHEMICAL CHARACTERIZATION TESTS .....                                                                          | 8           |
| 2.4.1 Physical Properties and Characterization.....                                                                                   | 8           |
| 2.4.1.1 pH, Viscosity, Refractive Index, and Density .....                                                                            | 8           |
| 2.4.1.2 Spreading Coefficient .....                                                                                                   | 9           |
| 2.4.2 PFF Stability .....                                                                                                             | 9           |
| 2.4.3 Corrosion Testing.....                                                                                                          | 10          |
| 2.4.4 Environmental Fate and Toxicity.....                                                                                            | 11          |
| 2.4.4.1 BOD <sub>20</sub> and COD .....                                                                                               | 11          |
| 2.4.4.2 Toxicology -LC <sub>50</sub> and IC <sub>25</sub> for PFF Against Aquatic<br>Vertebrate Animals.....                          | 11          |
| 2.5 DISCUSSION .....                                                                                                                  | 12          |

## TABLE OF CONTENTS (CONTINUED)

|                                                                                                                    | Page      |
|--------------------------------------------------------------------------------------------------------------------|-----------|
| <b>3.0 COMPRESSED AIR FOAM FIREFIGHTING FOR PFAS-FREE FOAMS.....</b>                                               | <b>14</b> |
| 3.1 BACKGROUND .....                                                                                               | 14        |
| 3.2 BENEFITS OVER CONVENTIONAL PRACTICES .....                                                                     | 14        |
| 3.3 TEST PROTOCOLS.....                                                                                            | 16        |
| 3.3.1 Indoor Live Fire Tests.....                                                                                  | 16        |
| 3.3.1.1 Lab-Scale Fire Testing System.....                                                                         | 16        |
| 3.3.1.2 Mil-Spec-Scale (28-ft <sup>2</sup> ) Live Fire Testing.....                                                | 17        |
| 3.3.2 Outdoor Live Fire Tests .....                                                                                | 20        |
| 3.3.2.1 Medium-Size Field- Scale (315-ft <sup>2</sup> ) Pan-Fire Live Fire Testing .....                           | 20        |
| 3.3.2.2 Large-Size Field-Scale (6500-ft <sup>2</sup> ) Live Fire Testing .....                                     | 21        |
| 3.4 RESULTS FROM LIVE FIRE SUPPRESSION TESTS .....                                                                 | 23        |
| 3.4.1 Mini-CAF, Lab scale Tests .....                                                                              | 24        |
| 3.4.2 Mil-Spec Scale Tests (28-ft <sup>2</sup> Fire Ring).....                                                     | 24        |
| 3.4.2.1 Comparison of Air Aspirated- and CAF-nozzles for<br>Suppression of Ethanol-Blend (E10) Gasoline Fires..... | 24        |
| 3.4.2.2 Suppression with Ethanol-Free (E0) Gasoline Fires .....                                                    | 25        |
| 3.4.2.3 Effect of CAF Expansion Ratio (ER) on Foam Characteristics<br>and Fire Suppression.....                    | 26        |
| 3.4.2.4 Further Comparisons of PFF at the Selected CAF ER 12 .....                                                 | 28        |
| 3.4.2.5 Down-selection of PFF for Field Tests.....                                                                 | 28        |
| 3.4.3 Medium-Size Field-Scale—Training-Pit Pan Fire.....                                                           | 29        |
| 3.4.3.1 CAF Suppression of 315-ft <sup>2</sup> Field-Scale Fuel Fires—E0 Gas.....                                  | 29        |
| 3.4.3.2 CAF Suppression of 315-ft <sup>2</sup> Field-Scale Fuel Fires—Jet-A<br>Aviation Fuel .....                 | 30        |
| 3.4.3.3 Baseline Comparison of Fuel Fire Extinguishment – C6 AFFF<br>and Selected PFF .....                        | 31        |
| 3.4.4 Large-Field-Scale – Class IV ARFF Platform .....                                                             | 31        |
| 3.5 DISCUSSION .....                                                                                               | 32        |
| <b>4.0 ULTRA HIGH PRESSURE FIREFIGHTING FOR PFAS-FREE FOAMS.....</b>                                               | <b>33</b> |
| 4.1 BACKGROUND .....                                                                                               | 33        |
| 4.2 BENEFIT OVER CONVENTIONAL PRACTICES .....                                                                      | 33        |
| 4.3 TEST PROTOCOLS.....                                                                                            | 34        |
| 4.3.1 Mil-Spec (28-ft <sup>2</sup> ) Scale Live Fire Tests .....                                                   | 34        |
| 4.3.2 Medium-Size Field-Scale (315-ft <sup>2</sup> ) Pan-Fire Live Fire Testing .....                              | 34        |
| 4.3.3 Large-Size Field-Scale (6500-ft <sup>2</sup> ) Live Fire Testing .....                                       | 35        |
| 4.4 RESULTS FROM LIVE FIRE SUPPRESSION TESTS .....                                                                 | 35        |
| 4.4.1 Indoor Mil-Spec (28-ft <sup>2</sup> ) Scale Tests .....                                                      | 35        |
| 4.4.2 Outdoor Medium-Size Field-Scale (315-ft <sup>2</sup> ) Pan Fire Tests.....                                   | 36        |
| 4.5 DISCUSSION .....                                                                                               | 36        |

## TABLE OF CONTENTS (CONTINUED)

|                                                                                              | Page      |
|----------------------------------------------------------------------------------------------|-----------|
| <b>5.0 TECHNOLOGY TRANSITION AND IMPLEMENTATION .....</b>                                    | <b>37</b> |
| 5.1 ALTERNATIVES TO LEGACY DELIVERY METHODS – CAF AND UHP<br>EFFECT ON PFF PERFORMANCE ..... | 37        |
| 5.2 DEFINING METHODS TO OPTIMIZE PFF PERFORMANCE .....                                       | 37        |
| 5.3 FIREFIGHTER TECHNICAL TRAINING .....                                                     | 38        |
| 5.4 CRITICAL UNDERSTANDING AND INTERPRETATION OF TEST<br>RESULTS .....                       | 38        |
| 5.5 COST ANALYSIS – TRANSITION AND LIFECYCLE.....                                            | 39        |
| 5.6 ADVOCACY – REGULATORY ADVISORS AND STAKEHOLDERS .....                                    | 41        |
| 5.7 TRANSFORMATIONAL MILESTONE – THE NEW MIL-SPEC.....                                       | 41        |
| <b>6.0 CONCLUSIONS.....</b>                                                                  | <b>43</b> |
| <b>7.0 REFERENCES .....</b>                                                                  | <b>44</b> |

### List of Tables

|                                                                                                                                        |    |
|----------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 1. Commercial Products Used in Study .....                                                                                       | 5  |
| Table 2. pH, Viscosity, RI, and Density Results for Various COTS PFF Products .....                                                    | 8  |
| Table 3. Spreading Coefficient Results for Various COTS PFF Products .....                                                             | 9  |
| Table 4. Aging test results for COTS PFFs products.....                                                                                | 10 |
| Table 5. Corrosion Results for COTS PFF Products .....                                                                                 | 10 |
| Table 6. BOD <sub>20</sub> and COD Results for Various COTS PFF Products .....                                                         | 11 |
| Table 7. Toxicity Results for Various COTS PFF Products .....                                                                          | 12 |
| Table 8. Objectives, Collection, and Summary of Foam Properties and<br>Firefighting Performance .....                                  | 23 |
| Table 9. Summary of 28-ft <sup>2</sup> Ethanol-free Gasoline Fire Test Data for PFFs Down-selected<br>for Field-Scale CAF Testing..... | 28 |
| Table 10. Relative Cost Estimates to Extinguish a 28-ft <sup>2</sup> Fire Using Selected PFFs .....                                    | 40 |

## TABLE OF CONTENTS (CONTINUED)

|                                                                                                                                                                                                      | Page |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| <b>List of Figures</b>                                                                                                                                                                               |      |
| Figure 1. Stylized Illustrations Showing Foam Generation in Conventional Air Aspirating Nozzle and the Compressed Air Foam Systems .....                                                             | 14   |
| Figure 2. Lab-Scale “Mini-CAF” System.....                                                                                                                                                           | 17   |
| Figure 3. Mil-Spec Extinguishment Test.....                                                                                                                                                          | 18   |
| Figure 4. Mil-Spec 25% Burnback Test (28 ft <sup>2</sup> pan, SkyX Facility Tyndall AFB).....                                                                                                        | 19   |
| Figure 5. Large Scale Aviation Fuel Fire and ARFF Demonstration - Silver Flag Research Test Pool II (Archival photo, USAF-AFCEC).....                                                                | 20   |
| Figure 6. Dual-Agent CAF Skid for 315-ft <sup>2</sup> Fire Tests .....                                                                                                                               | 21   |
| Figure 7. Manual Ignition of 1000 Gallon Aviation Fuel. Research and Test Pool-II (Silver Flag Test Site, Tyndall AFB).....                                                                          | 22   |
| Figure 8. Extinguishing 28-ft <sup>2</sup> Gasoline with 10% Ethanol (E10) Fires with Mil-Spec Air-Aspirating Nozzle vs. CAF Nozzle (at ER 10).....                                                  | 24   |
| Figure 9. Cold Burnback Times with E10 Gas for PFF Blankets Using Air-Aspirating Mil-Spec Nozzle vs. CAF Nozzle (at ER 10).....                                                                      | 25   |
| Figure 10. Extinguishment Time for 28-ft <sup>2</sup> Fire—E10 vs. E0 Gas for Mil-Spec Nozzle and CAF (at ER 10) .....                                                                               | 25   |
| Figure 11. 25% Burnback time E10 vs E0 Gas for Mil-Spec Nozzle and CAF Nozzle (at ER 10).....                                                                                                        | 26   |
| Figure 12. Effect of CAF ER on Extinguishment Time (28-ft <sup>2</sup> , E0 Gas).....                                                                                                                | 26   |
| Figure 13. 25% Foam Drain Times for CAF at Various ER and the Mil-Spec Aspirating Nozzle .....                                                                                                       | 27   |
| Figure 14. Effect of ER on Burnback Times for 28-ft <sup>2</sup> E0 Gas Fires.....                                                                                                                   | 27   |
| Figure 15. Extinguishment of E0 Gas Fires by Various PFFs—Mil-Spec Nozzle vs. CAF (at ER 12).....                                                                                                    | 28   |
| Figure 16. Burnback Times for Various PFFs for Mil-Spec Nozzle vs. CAF (at ER 12).....                                                                                                               | 28   |
| Figure 17. Extinguishment Times for 315-ft <sup>2</sup> E0 Gas Fires (CAF at ER 12).....                                                                                                             | 29   |
| Figure 18. Extinguishment Time of E0 Gas Fires at Laboratory-, Mil-Spec-, and Field-Scales (CAF at ER 12).....                                                                                       | 29   |
| Figure 19. Extinguishment Time for 315-ft <sup>2</sup> Jet-A Fuel Fires (CAF at ER 12) .....                                                                                                         | 30   |
| Figure 20. Scaling Extinguishment of Jet-A Fuel Fires (28-ft <sup>2</sup> vs. 315-ft <sup>2</sup> , CAF) .....                                                                                       | 30   |
| Figure 21. Effect of Volumetric Application Rate on CAF Extinguishment of Jet-A Fuel Fires (315-ft <sup>2</sup> at 0.07 gpm/ft <sup>2</sup> , 454-ft <sup>2</sup> at 0.05 gpm/ft <sup>2</sup> )..... | 31   |
| Figure 22. C6 AFFF Baselines for CAF at 315-ft <sup>2</sup> (at ER 12; 20 gpm Application Rate).....                                                                                                 | 31   |
| Figure 23. Extinguishment Time for 28-ft <sup>2</sup> E10 Gasoline Fire with Mil-Spec Nozzle vs. UHP Nozzle .....                                                                                    | 35   |
| Figure 24. Extinguishment Time for UHP (Jet-A; 315-ft <sup>2</sup> ; 20 gpm).....                                                                                                                    | 36   |

## LIST OF ACRONYMS

| Acronym           | Definition                                                            |
|-------------------|-----------------------------------------------------------------------|
| AFB               | Air Force Base                                                        |
| AFCEC             | Air Force Civil Engineer Center                                       |
| AFFF              | Aqueous film-forming foams                                            |
| ARFF              | Aircraft Rescue and Fire Fighting                                     |
| Battelle          | Battelle Memorial Institute                                           |
| BOD               | Biological Oxygen Demand                                              |
| BOD <sub>20</sub> | 20-Day Biological Oxygen Demand                                       |
| CAF               | Compressed Air Foam                                                   |
| CAFS              | Compressed Air Foam System                                            |
| CERCLA            | Comprehensive Environmental Response, Compensation, and Liability Act |
| COD               | Chemical Oxygen Demand                                                |
| COTS              | commercial-off-the-shelf                                              |
| cSt               | centiStoke                                                            |
| DACS              | Data Acquisition Control System                                       |
| DoD               | Department of Defense                                                 |
| DT <sub>50</sub>  | 50% Biodegradation Time                                               |
| E10               | Gasoline with 10% Ethanol                                             |
| EPA               | Environmental Protection Agency                                       |
| ER                | Expansion Ratio                                                       |
| ESTCP             | Environmental Security Technology Certification Program               |
| FF_AFFF           | Fluorine-Free Aqueous Film-Forming Foam                               |
| FAA               | Federal Aviation Administration                                       |
| FIRE              | Fire Integrated Research and Engineering                              |
| IC <sub>25</sub>  | Inhibition concentration 25%                                          |
| ICAO              | International Civil Aviation Organization                             |
| IFT               | interfacial tension                                                   |
| IMCOM             | United States Army Installation Command                               |
| LC <sub>50</sub>  | Lethal Concentration 50%                                              |
| LOEC              | Lowest Observed Effect Concentration                                  |
| Mil-Spec          | Military Specifications                                               |
| NAVSEA            | Naval Sea Systems Command                                             |
| NDAA              | National Defense Authorization Act                                    |
| NFPA              | National Fire Protection Agency                                       |
| NOEC              | No Observed Effect                                                    |
| PFAS              | Polyfluoroalkyl Substances                                            |

| <b>Acronym</b> | <b>Definition</b>              |
|----------------|--------------------------------|
| PFF            | PFAS-Free Foams                |
| PFHxA          | Perfluorohexanoic Acid         |
| PFHxS          | Perfluorohexanesulphonic Acid  |
| PFOA           | Perfluorooctanoic Acid         |
| PFOS           | Perfluorooctanesulfonic Acid   |
| pH             | Hydrogen Ion Concentration     |
| PI             | Principal Investigator         |
| PPE            | Personnel Protective Equipment |
| SDS            | Safety Data Sheet              |
| SFT            | Surface Tension                |
| TRL            | Technology Readiness Level     |
| TSCA           | Toxic Substance Control Act    |
| UHP            | Ultra High Pressure            |
| UL             | Underwriters Laboratory        |
| USAF           | United States Air Force        |

## ACKNOWLEDGEMENT

This project was conducted for the Environmental Security Technology Certification Program (ESTCP) by Battelle Memorial Institute (Battelle). Battelle's co-performer was the Air Force Civil Engineer Center (AFCEC).

The project was conducted under the programmatic guidance of Dr. Robin Nissan of the ESTCP Program Office. Braxton Lewis of Noblis provided the primary 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.

**WP19-5299 Team**

| Name                        | Organization | Project Activity                                                    |
|-----------------------------|--------------|---------------------------------------------------------------------|
| Dr. Satya Chauhan (PI)      | Battelle     | Project planning and execution; reporting                           |
| Malena Maraviglia           | Battelle     | Lab-scale fire and Mil-Spec-scale fire testing; reporting           |
| Andrew McMeans              | Battelle     | Mil-Spec-scale and medium-size, field-scale fire testing; reporting |
| Julie Bryant                | Battelle     | Mil-Spec-scale and medium-size, field-scale fire testing; reporting |
| 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; reporting                                 |
| Dr. Bridgett Ashley (co-PI) | AFCEC        | Co-PI; CAF and UHP expert; test-site oversight                      |
| Jonathon Torres             | FAA          | Advisor                                                             |
| William Kavanaugh           | ARMY IMCOM   | Advisor; tech transfer                                              |
| Marc Mills                  | EPA          | Advisor; regulatory review                                          |
| Jeff Eichler                | Navy         | Advisor; tech transfer                                              |

## EXECUTIVE SUMMARY

### GOAL OF THE GUIDANCE

This guidance document provides background and insight to support the transition from legacy firefighting foams to PFF products, with summaries and interpretation of recent laboratory and field tests. The authors used their knowledge of the field, critical review of available literature, results from active research and development projects, and input from users/stakeholders for document preparation. The result is intended to support decision-makers on formal recommendations and inform firefighter community on application of perfluoroalkyl substance (PFAS)-free foams (PFF) (previously referred as Fluorine-Free Aqueous Film-Forming Foams; (FF\_AFFF)) for class B (liquid fuel) fires. The focus of this document is on compressed air foam (CAF) and ultra-high pressure (UHP) foam delivery methods to enhance the firefighting performance of PFFs. As further experience and data from ongoing CAF and UHP testing are obtained, this guidance document is expected to be refined.

### TECHNOLOGICAL CHALLENGE

The environmental and public health risks due to PFAS release and exposure are not unequivocally resolved. Technical studies clearly show the persistence of these molecules in the environment and the resulting spread throughout the ecosystem. The studies and resulting public sentiment, appear to have pushed regulatory agencies to fall on the side of caution: products using PFAS (in particular the “C-8” and larger molecule) have left the marketplace and environmental regulatory limits in many states are approaching thresholds for current analytical tools. The Department of Defense (DoD) also engaged in proactive steps that addressed the phase-out of PFAS use. The 2020 National Defense Authorization Act (NDAA) dictated that the legacy fire suppression foams that contain perfluorinated surfactants (i.e., the aqueous film forming foams (AFFF)) shall not be used after 1 October 2023. In order to meet the deadline and protect DoD personnel, facilities, and assets, PFF must be identified that will effectively substitute for AFFF. The fundamental challenge, however, is that the physiochemical characteristics of PFF will not support a direct “drop-in” substitution without performance trade-offs.

Several commercial-off-the-shelf (COTS) PFFs are available, but currently none of them meet the very stringent list of MIL-PRF-24385F specifications. The firefighting performance metrics—the extinguishment time (30 seconds maximum) and the burnback time (360 seconds minimum)—are key assessment points for fire suppression. The extinguishment and burnback times are dependent upon the quality of the foam produced. The PFF may be modified by using: 1) chemical means, supplementing PFF with dry agents that augment PFF performance; or 2) physical means, applying agent delivery systems that change foam structure compared to traditional platforms. The CAF and UHP delivery technologies are known to affect foam formation and fire suppression performance. By adjusting the volume of air injection, nozzle pressure, and agent flowrates, one can tailor the foam quality (e.g., its “spreadability” and stability) in order to effectively extinguish a fire. Another practical issue for agent performance is its corrosivity. PFF must be compatible with firefighting equipment so the mixed agent may be safely stored without risk of degrading or disabling the system. In many cases, the issue may be addressed by chemical formula changes, such as adding a corrosion inhibitor, without affecting fire suppression. The MIL-PRF-24385F specifications, also include narrowly defined

physiochemical characteristics for the AFFF that are not necessarily relevant to performance. The PFF fundamental chemistry and make-up are distinct from AFFF, accordingly, the PFF will not meet some of those criteria, for example, refractive index. Ultimately, some of the physiochemical specification criteria will need to be changed in order to correspond to the PFF chemistry.

By using rational engineering to combine the physical and the chemical concepts and augment PFF, the resulting performance could be modified to meet the relevant performance standards of MIL-PRF-24385F, thus allowing the U.S. military to switch to a more environmentally friendly firefighting agent that satisfies the impending NDAA restrictions without significant risk to personnel and assets.

## **PHYSICAL MECHANISM, PERFORMANCE AND OPERATIONAL ISSUES OF PFAS-FREE FOAMS**

The PFF fire suppression mechanism fundamentally differs from AFFF. The PFF surfactants need to maintain a blanket over the burning fuel in order to effectively cool and then extinguish the fire. By comparison, the AFFF surfactants spread over the fuel, forming a film that keeps fuel from vaporizing to suppress and extinguish a fire. In the former, creating the blanket alone is challenging, in the case of liquid fuel fires (class B), the hydrocarbon fuels partition into the foam blanket and break down its structure. As noted, none of the current COTS PFF meet the extinguishment threshold for MIL-PRF-24385F. When foam formulations were applied using conventional air-aspirated nozzle (also referred to as Military Specifications (Mil-Spec) in trial discussions below), 3 of the 12 formulations tested to date failed to extinguish a standardized gasoline-fueled fire, and the others required ca. 60–90 seconds to extinguish the fire. The PFF “burnback” performance (suppression of ignition) is more encouraging, again using the standard application nozzle, 5 of the 11 PFF blankets tested exceeded the required 360 sec suppression threshold in MIL-PRF-24385F. The decision dictated in the 2020 NDAA to eliminate PFAS-based AFFF was rooted in environmental and public health risks. In addition to those intrinsic benefits, the change will yield operational and maintenance cost savings for the DoD. A preliminary economic analysis indicates that PFFs are ~10 to 20% less expensive than equivalent AFFF concentrates. A 2011 study estimated that the DoD expends 157,000 gallons of AFFF concentrate per year, suggesting a potential savings of the DoD between \$1.4 to \$2 million annually in foam purchase costs alone. The change will also lead to reduced costs for waste management, and likelihood of later requirements for site remediation.

## **EVALUATING EFFECT OF COMPRESSED AIR FOAM AND ULTRA-HIGH-PRESSURE DELIVERY SYSTEMS ON FIRE EXTINGUISHMENT AND SUPPRESSION**

Agent delivery methods and technologies may improve PFF blanket structure or other physical aspects of the aqueous fire suppression agent formulations. Conventional aspirating nozzles rely on the venturi effect to create foam. The solution in the delivery line is constricted within the nozzle and forces air into the liquid, upon exit from the nozzle the air rapidly evolves, causing the surfactant to foam. Compressed air foam systems (CAFS) inject air into the liquid line carrying the water/foam solution. The gas liquid mixture then moves toward the nozzle, where the flow through the plumbing of the system alters the foam structure to form a more uniform bubble distribution. The CAFS nozzle does not constrict flow, which helps maintain the foam

expansion and bubble structure developed through earlier stage of system. UHP foam delivery is defined by the National Fire Protection Agency (NFPA) as foam delivered at 1100 psi or above. Typically, a piston-driven pumping system compresses the agent solution to the high pressures for delivery; when released from the nozzle at the high pressures, the liquid agent forms extremely small droplets. The reduced cross section increases relative surface area to increase the cooling rate compared to low pressure droplets. Accordingly, less agent volume is required to achieve the same extinguishment performance. Reports state the UHP improves AFFF performance, depositing a concentrated layer of surfactant film to suppress fuel vapors. No comprehensive evaluations of UHP and PFF are reported to date.

The Environmental Security Technology Certification Program (ESTCP) projects WP19-5299 and its extension, WP20-5335, are designed to evaluate the efficacy of commercially available as well as some developmental/experimental PFFs using CAF and UHP extinguishment systems for fire tests using the framework of MIL-PRF-24385F. The standardized, industry-recognized methodology provides rigor to compare all PFF against one another with clear basis and assess the effect CAF and UHP technologies have when applying the PFF.

## **IMPLEMENTATION ISSUES FOR CONSIDERATION**

The completion of this project should raise the Technology Readiness Level (TRL) for DoD use of PFF for class B fire application to TRL 8/9. The advance addresses a defined requirement, eliminating the use of fire suppression foams containing fluorinated-surfactant molecules. The restrictions were outlined first in the 2017 NDAA seeking alternative fire suppression agents that do not contain perfluorooctanoic acid (PFOA) or perfluorooctanesulfonic acid (PFOS), and then expanded in the 2020 NDAA to eliminate all use of AFFF except on maritime vessels. In addition to the DoD requirement, the technology demonstration/validation may be applied to protect civil aviation assets, further reducing risks and costs due to PFAS-based AFFF.

The approaching release of the Mil-Spec on use of PFF for Class B fire suppression is an inflexible milestone towards implantation of the alternative foams (October 2023). Gaining stakeholder acceptance will be greatly facilitated by identifying and demonstrating that a PFF can achieve firefighting performance that rivals known capabilities, i.e., the AFFF. If there is any question that the technology inadequately protects the user, its implementation may be viewed as a forced deadline by users, regardless of the long-term: cost-, environmental-, and public health benefits.

Preliminary results indicate that CAF, UHP, or a combination of the two, may be required for PFFs to provide adequate fire suppression performance. The United States Air Force (USAF) aircraft rescue and firefighting (ARFF) fleet is widely equipped with UHP vehicles, but CAF capability is less prevalent. Accordingly, there is potential that portions of the fleet will require retrofit updates to include one or both enhanced delivery systems. In future procurements, the updated firefighting fleet could integrate CAF and UHP as standard requirements. Those decisions, however, require extensive lifecycle and sustainment analysis to support the acquisition plan. There are additional challenges even if PFF application may be integrated with existing platforms. Firefighting techniques for the PFF differ from those used with AFFF, thus additional training is necessary for safety of users and effective application. The composition and physical characteristics of PFF may require changes in existing hardware. For example, some PFF formulations are exceptionally viscous, the proportioning systems that measure and dispense

foam concentrates could struggle to obtain working solutions. Lastly all trucks that previously used AFFF will need to be fully refurbished to remove deposits and residual traces of PFAS from systems. The process will add logistic and financial burdens to the transition, but significantly less than a replacement platform.

## 1.0 INTRODUCTION

### 1.1 BACKGROUND

Flammable liquid fires (or Class B fires) pose special challenge to firefighting. The heat from flames generates more volatile vapors, increasing relative fuel volumes, and dangerously propagating the fire. Fire suppression foams overcome the fundamental physics, restricting vapors and stifling propagation. 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 U.S. Navy and the 3M Corp (Maplewood, MN) in the 1960s. The “film” component of AFFF is the key to its effectiveness: the amphiphilic molecules can rapidly form a monolayer on hydrocarbon fuels, holding the volatile vapors in the bulk liquid phase. The foam contains 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 PFOA and 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 chain “C6” foams as opposed to “C8” PFAS in the legacy foam). The replacement molecules in the C6 AFFF products, however, present environmental persistence and potential hazards comparable to the original AFFF [3]. Increasing concerns over PFAS as a class of chemicals has led both public and regulatory agencies to demand that firefighting foam manufacturers discontinue the use of foams containing any perfluorinated compounds in the formulation. As consequence, the PFAS-based AFFF is heavily regulated and its use in most DoD operations will end 1 Oct 2024. However, the fire risks will remain, and alternative approaches are needed to address risks from liquid-fueled fires. Fire suppression foam may comprise numerous naturally occurring and synthetic formulations, excluding use of PFAS to yield PFF. Government and industry are aiming to implement PFF and if possible, maximize use of existing infrastructure and equipment. The physiochemical nature of PFF does not afford the distinctive fire suppression performance of the original AFFF formulation. As the transition to PFF moves forward, technology advances must be found to match AFFF protection—or accepted performance trade-offs.

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. The suppression mechanism of most PFF is fundamentally different from AFFF. PFF rely on a contiguously structured foam to limit flammable vapor levels and suppress fire propagation. Engineered foam delivery methods, such as CAF and UHP, have previously been shown to improve the performance of AFFF [4-6]. Those technologies may enhance physical structure of foams or other relevant profile of the agent and change fire suppression performance. To date, the project has evaluated several COTS PFFs against the MIL-PRF-24385F (Mil-Spec) and then applied the engineered delivery methods to evaluate their effect on the fire extinguishment and suppression performance. There are considerable test and evaluation data for standard methods and CAF system application, the project team found that the UHP tests are not amenable to the small-scale test platform and have been limited to the outdoor field-scale profiles.

## 1.2 OBJECTIVE OF DEMONSTRATION

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

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 corrosivity, aquatic toxicity, biological and chemical oxygen demand, 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 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-ft<sup>2</sup> 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 towards assessing the impact that delivery methods have on fire-extinguishment performance. Standard-strength freshwater 28-ft<sup>2</sup> 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 assessed in outdoor test beds at medium (315-ft<sup>2</sup>, 100 gallons fuel) and large (6,500-ft<sup>2</sup>, 1000 gallons fuel) scales.

## 1.3 REGULATORY DRIVERS

Pressure on the DoD to find a PFAS-free fire extinguishing agent has been increasing since the 2017 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 1 Oct 2024. Additionally, it is required that the Naval Sea Systems Command (NAVSEA) release an updated version of the Mil-Spec for PFFs by 2023.

In April 2021 the Environmental Protection Agency (EPA) established the EPA Council on PFAS to address contamination from this class of chemicals. In October of the same year, they released a “roadmap” encompassing plans to increase research, regulate use, and remediate contamination. The agency is currently in the rule-writing phase to regulate PFAS under the Toxic Substance Control Act (TSCA) and Comprehensive Environmental Response, Compensation CERCLA, 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 [7].

## 2.0 PFAS-FREE FOAMS

### 2.1 BACKGROUND

The first firefighting foams, developed in Russia and reported by Loren in the early 20<sup>th</sup> 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. The early chemical foams also included plant-based surfactants such as saponin and licorice roots that stabilized the mixture [17]. While foams can be used on structural and wildland fires (class A, burning solids), they are essential in fighting class B (liquid and vapor) fires. Water has a higher specific gravity than hydrocarbon fuels, making it an ineffective extinguishing agent for fuel fires, as it simply sinks below the burning liquid. Foam is less dense 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, apart from sodium bicarbonate handheld fire extinguishers, most firefighting foams are made by agitating a surfactant solution, using the mechanical process to introduce air into the liquid agent.

The challenges and understanding of Class B firefighting evolved dramatically since Loren's demonstrations of fire suppression foams. The scale of operations and volume of fuel pose potential for enormous catastrophes in places such as oil fields and refineries, chemical manufacturing and storage facilities, maritime vessels, and aircraft. Materials and technological solutions were sought, developed, and applied to protect facilities and personnel. A large leap in firefighting foam technology was the AFFF patented by the U.S. Navy in the 1960s. AFFF was superior to fire suppressing properties on class B fires by previous chemical foams. AFFF quickly forms a vapor-suppressing film in addition to the wet foam that blankets and cools the fire. AFFF was readily adopted by militaries, airports, and fire departments around the world as the choice "class B foam." The extinguishment performance of AFFF became the standard for firefighting foams. Unfortunately, the highly stable PFAS in the surfactant mix that forms aqueous films persist in the environment, bioaccumulate, and are associated with several health consequences. PFAS have been increasingly regulated over the past two decades. The company that produced one of the predominant PFAS (PFOS) voluntarily ceased its production in 2002 as reports of its health effects became public knowledge [7-9]. Rising concerns regarding the "C8" (8-carbon chain) PFAS, (e.g., PFOS and PFOA) led foam manufacturers to shift to "C6" (6-carbon chain, perfluorohexanoic acid (PFHxA) and perfluorohexanesulphonic acid (PFHxS))—and other so-called "GenX"—surfactants to replace PFOS and PFOA. The change did not, however, ameliorate the risks of PFAS, because the C6 and other molecules persist and bioaccumulate like earlier formulations. A cease-use order for all PFAS-laden AFFF by 1 Oct 2024 is now mandated under the 2020 NDAA. In addition, the EPA is in the process of writing overarching regulations to control the use all PFAS and derivative compounds. The catastrophic risk from hydrocarbon fuel fires will remain, so alternative PFF are in use and also in development to address the risk and reduce long-term environmental impact.

The PFF, like the original protein-derived firefighting foams, generally do not form the vapor-suppressing films that allow for rapid fire extinguishment provided by AFFF. Although some siloxane-based surfactants show a modest film-forming behavior, none are yet able to meet the performance of traditional PFAS-reliant AFFF [10]. PFFs use a mixture of zwitterionic and anionic surfactants, with higher overall surfactant concentrations than AFFF. The PFF

formulations commonly include diethylene glycol monobutyl ether (CAS number 112-34-5), which is present in most of the products evaluated in this project at concentrations ranging from 2.5–30%. This chemical is known to be an eye irritant and acutely toxic to aquatic life [11]. Many PFF blends also take advantage of thickening agents to form a more stable foam, including pseudo-plastic polymers such as xanthan gum, which contribute to highly non-Newtonian behavior and generally viscous characteristics. The chemical makeup of PFFs does not allow them to spread spontaneously or form films; instead, they achieve extinguishment through heat absorption and by forming a physical barrier between fuel and oxidant. Many PFFs are already available as COTS products. The aerated foams are generally quite stable, demonstrated by their long drain times relative to AFFF [12]. The foam cools the fire and forms a blanket over the liquid fuel to suppress the burning vapors of liquid fuels. The suppression, however, is hindered by fuel uptake into the aqueous solution. As a result, to date, no PFFs have been able to meet the Mil-Spec extinguishment standard. Some of the foams, however, are certified by other standards, such as International Civil Aviation Organization (ICAO).

## **2.2 BENEFITS OF PFF COMPARED TO CURRENT PREDOMINANT PRACTICES**

The fluorinated surfactant-based fire suppression foams rose to dominate application because of their stability and film forming characteristics made them exceptionally effective agents. In the 1960s, the U.S. Navy and the 3M patented AFFF that used PFOS and PFOA as predominant PFAS substituents. In 1967, the United States Ship Forrestal caught fire; 134 sailors died in the blaze. Shortly after this accident, the Navy dictated that all vessels carry AFFF on board for firefighting and automated discharge systems. 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 ICAO standards due to the lower application rate and more volatile fuel type. The DoD and Federal Aviation Administration (FAA) have both adopted the Mil-Spec to validate foam performance. The original version of the Mil-Spec, released in 1969, required a 28-ft<sup>2</sup> fire be extinguished in 84 seconds and a minimum 25% burnback of 240 seconds at an application rate of 0.10 gpm/ft<sup>2</sup>. 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 0.07 gpm/ft<sup>2</sup>. 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. The PFAS-surfactants are amphipathic, 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 towards the fuel, while the hydrophilic head groups align with the aqueous foam solution. Though these characteristics are positive for firefighting, it also makes PFAS nearly impossible to degrade naturally. They cannot be photolyzed, biodegraded, or thermally degraded at near-ambient conditions. Since PFAS are exceptionally stable, they persist in the environment, accumulate in living organisms and spread throughout the ecosystem. These chemicals are not exclusively used in firefighting products: the chemistry of PFAS makes them useful in a variety of consumer products, such as skincare products, grease-resistant paper (often used in food packaging), and non-stick coatings. Due to

the ubiquity of products and the resilient nature of the PFAS, nearly everyone in the United States has detectable concentrations of these chemicals in their bodies [13]. 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.

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 [14]. 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 even better 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 higher than that of AFFF. The environmental impact trade-offs require further evaluation. Also, many PFFs are non-Newtonian and highly shear-thinning fluids; properties that may be incompatible with the pumps and plumbing used in existing systems to proportion the foam concentrate and deliver the solutions.

## 2.3 TEST PROTOCOLS

The Mil-Spec (MIL-PRF-24385F) includes a list of physical and chemical properties criteria specifically related to the PFAS-based AFFF. The profile serves as the definitive methodology to confirm authenticity and guide formulation of AFFF for the DoD. The Mil-Spec also defines functional properties and features that are relevant to their use, material interactions, and environmental/ biological effects. The following sections provide brief background and values for the criteria. The details on method are less relevant to the guidance document but are outlined in detail within other project reports.

The products used in tests for this document are listed in Table 1. Each product has been given a code number, with the C6 being the AFFF standard. Note that PFF 3 is missing from Table 1 and rest of the report as it was an early product, which was discovered to be inapplicable for fighting Class B fires.

**Table 1. Commercial Products Used in Study and Code Numbers**

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

## **2.3.1 Physical Properties Testing Against MIL-PRF-24385F**

### **2.3.1.1 *pH (Hydrogen Ion Concentration)***

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.

### **2.3.1.2 *Refractive Index***

The criterion for refractive index is described in test section 4.7.1. of the Mil-Spec. The refractive index is used as physical standard to check the foam concentration. The range of values determined for AFFF that relates to a proportioned concentration of 3% is at least 1.3580. Considering the chemical composition of AFFF and PFFs are vastly different, it is not surprising (or relevant to firefighting performance) if the PFF are outside the current Mil-Spec requirement.

### **2.3.1.3 *Viscosity***

Viscosity is the physical characteristic of fluids resistance to flow. It is measured by determining the force required to move a defined profile of the fluid (i.e., force/area). Newtonian fluid viscosities do not change as the force applied to the fluid changes. Conversely, for non-Newtonian fluids, viscosities change as force is applied to the fluid. Non-Newtonian fluids can be shear-thickening or shear-thinning, i.e., become more or less viscous as force is applied, respectively. Non-Newtonian PFFs are shear-thinning and in practice, the fluid may be initially resistant to flow, but will flow readily once sufficient force has been applied to overcome resistance. The Mil-Spec was defined to test Newtonian AFFFs. The standard method, essentially the time required for the fluid to flow through the test apparatus (Ubbelohde capillary viscometer), does not effectively determine non-Newtonian fluid viscosities. The viscosity of the non-Newtonian fluids in the demonstration tests were determined using a rotational viscometer, which measures the torque, or angular force, required to move a spindle through the fluid. The Mil-Spec includes a minimum viscosity ( $\geq 2$  centiStoke (cSt)) at standard ambient temperature (25°C) and a maximum viscosity ( $\leq 20$  cSt) at a low temperature (5°C). The parameters account for representative operating conditions.

### **2.3.1.4 *Spreading Coefficient***

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. Surface tension is the quantitation of how a liquid surface resists disturbance. It is a characterization of the cohesive network of molecules in the bulk liquid media. Interfacial tension is the quantitation of force required to break the interface between two non-miscible liquids. A positive spreading coefficient implies that one media will spontaneously spread, or wet, the lower media. Spreading coefficient is an important property for AFFF fire suppression agents, as the film that spontaneously forms is a key factor for extinguishment. The Mil-Spec requires a spreading coefficient  $\geq 3$  dynes for AFFF.

## **2.3.2 Corrosivity Testing**

The corrosivity of a firefighting agent is an important consideration when determining compatibility with the materials in existing systems. The corrosion test, described in section 4.7.7 of the Mil-Spec, requires that metal coupons are held in a 10% solution of foam

concentrate in sea water for 60 days. The stringent sea water solvation reflects that the Mil-Spec was originally written by NAVSEA for naval vessels. The quantitative material losses (e.g., thickness or mass) for four alloys (low carbon steel, two nickel-copper alloys, and bronze) were tested. A qualitative “pitting” test of stainless steel was also completed.

### 2.3.3 Environmental Impact

Fire suppression foams, whether used in an emergency response or tests and training exercises will inevitably enter the ecosystem. In the former, there is no effective containment so the agent will directly diffuse into the site where it was applied. In the latter, the effluent will be held and then processed in some manner. For example, in some instances PFF waste streams may be pre-treated on-site and then transferred to a Municipal Wastewater Treatment Plant and the effluent ultimately released to environments post-processing.

#### 2.3.3.1 Aquatic $LC_{50}$ and $IC_{25}$

Two quantifiable laboratory toxicological assessments were done for each of the PFF and the AFFF (as a standard for comparison). The lethal concentration ( $LC_{50}$ ) is the amount of a material that will result in 50% reduction of a given aquatic population (species death) over a defined period, usually 24 or 96 hours. The inhibitory concentration,  $IC_{25}$ , is the concentration that leads to a 25% reduction in a biological function (usually growth or reproduction). Lower values correspond to higher toxicity, i.e., the biological response is evident at lower concentrations.

#### 2.3.3.2 $BOD_{20}$ and COD

The chemical oxygen demand (COD) is the amount of dissolved oxygen consumed during reaction of a strong oxidant (typically potassium dichromate) and an aqueous sample of test materials. In the current Mil Spec, COD for fire suppression foams cannot exceed 1,000,000. The 20-day biological oxygen demand ( $BOD_{20}$ ) is the total amount of oxygen consumed by microbes during 20-day contact with test sample in defined conditions. The  $BOD_{20}$  is sometimes referred to as ultimate BOD, suggesting that, if material is biodegradable, there will be measurable, and consistent degradation in that timeframe. The values, however, are affected greatly by the composition and physiological state of the microbial seed. The biodegradability index is the ratio of  $BOD_{20}$  and COD. The Mil-Spec calls for value of  $\geq 0.65$  for this ratio, a standard threshold for industrial wastewater in treatment facilities. The index ( $BOD_{20}/COD$ ) is not the same as a true biodegradability test, often reported as disappearance time or biodegradation half-life ( $DT_{50}$ ) in literature. Another rigorous biodegradability assessment determines the amount of carbon dioxide released due to microbial breakdown of a sample. The carbon dioxide quantity reflects extent of actual biomineralization by the microbial processes.

For the present tests, a sample from the Tyndall Air Force Base (AFB) Advanced Wastewater Treatment Plant was used to inoculate mineral media containing a mixture of PFF concentrates as 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  $BOD_{20}$  assays. The selected population was required to represent potential biodegradability in an exposed environment.

### 2.3.4 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, stratification, viscosity, and spreading coefficient of the dilute solution. The tests predict the product “shelf-life” as opposed to stability of the concentrate mixed with water for application. Additional tests of working solutions of the PFF were done, in which the foams were mixed with municipal tap water (3%) and stored to mimic conditions in which the diluted agent is stored in a fire truck or other extinguishment system.

## 2.4 RESULTS FROM PHYSIOCHEMICAL CHARACTERIZATION TESTS

### 2.4.1 Physical Properties and Characterization

#### 2.4.1.1 pH, Viscosity, Refractive Index, and Density

The direct physical measurements are benchmark characteristics noted in the Mil-Spec and will be narrowly exhibited by AFFF products. The PFF product formulations are distinct from AFFF and varied among the product themselves, so it is not remarkable that the values are also different. The summary is shown in Table 2. As noted earlier, PFF 3 was not tested. The pH and refractive index are basic characteristics and no apparent relevance to fire suppression or usability. Density is not a Mil-Spec factor but was used for viscosity conversions of non-Newtonian fluids. The characteristic viscosity of the formulation may affect both usability and the functional performance of the fire suppression foam.

Some PFFs are notably more viscous than AFFF, accordingly they do technically pass the minimum viscosity requirement of the Mil-Spec at 25°C. However, at 5°C the non-Newtonian products fail the maximum viscosity limit of 20 cSt (see Table 2). Many manufacturers are aware of the concerns surrounding the viscosity of these products and

are working to lower them, but due to the nature of their formulations they will likely never be as flowable as AFFF. The characteristic may require changes to platform hardware, in particular proportioning systems and other plumbing components contacting the PFF concentrates. 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. Solutions with higher viscosities

**Table 2. pH, Viscosity, RI, and Density Results for Various COTS PFF Products**

| Foam Product | pH   | Viscosity 5C (cSt) | Viscosity 25 C (cSt) | RI     | Density (g/cm <sup>3</sup> ) |
|--------------|------|--------------------|----------------------|--------|------------------------------|
| AFFF         | 8.05 | 6.99 (k)           | 3.29 (k)             | 1.367  | 1.01                         |
| PFF 1        | 6.66 | 47400 (b)          | 27900 (b)            | 1.335  | 1.04                         |
| PFF 2        | 7.02 | 99.8 (k)           | 47.7 (k)             | 1.3875 | 1                            |
| PFF 4        | 6.76 | 7.95 (k)           | 3.99 (k)             | 1.375  | 0.96                         |
| PFF 5        | 7.38 | 6770 (b)           | 5340 (b)             | 1.3605 | 1.08                         |
| PFF 6        | 7.33 | 45900 (b)          | 25100 (b)            | 1.6875 | 1.04                         |
| PFF 7        | 7.4  | 15400 (b)          | 13200 (b)            | 1.3715 | 1.26                         |
| PFF 8        | 7.95 | 4.12 (k)           | 2.33 (k)             | 1.334  | 0.99                         |
| PFF 8.2      | 8.01 | 26.20 (k)          | 11.36 (k)            | 1.3617 | 1.03                         |
| PFF 9        | 6.86 | 19100 (b)          | 13900 (b)            | 1.3335 | 1.1                          |
| PFF 10       | 7.31 | 4600 (b)           | 4190 (b)             | 1.332  | 1.1                          |
| PFF 11       | 7.74 | 12.7 (k)           | 8.74 (k)             | 1.325  | 1.1                          |
| PFF 12       | 8.33 | 145 (k)            | 60.1 (k)             | 1.3827 | 1                            |

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

experience more drag within the gas phase, which results in more liquid holdup, and correlates with a lower foam drain rate; and as discussed previously, increased drain time correlates with a concurrent improvement of burnback time.

#### 2.4.1.2 Spreading Coefficient

The SFT, IFT, and calculated spreading coefficient for all the PFF and AFFF are shown in Table 3. The positive spreading coefficient is indicative of spontaneous film-formation and is an inherent, functional characteristic of PFAS-based fire suppression foams like AFFF. The physical chemistries of the PFFs (and their fire suppression mechanism) are entirely different. The formulations are designed to form a thick, stable foam blanket to smother the fire. On the molecular level, the behaviors will be very different, that difference is reflected in the results of the assay. The majority of PFF actually show negative spreading coefficients, the only positive value products were well below the Mil-Spec threshold value.

**Table 3. Spreading Coefficient Results for Various COTS PFF Products**

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

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

NA: Not analyzed

#### 2.4.2 PFF Stability

Two of the PFF products tested failed the stratification requirement of the Mil-Spec test (see Table 4). Interestingly, both of these products contained xanthan gum, based on the Safety Data Sheets (SDS). The correlation was not investigated further but is notable. While all the other PFF products were able to pass the aging requirements, none of the remaining products had acceptable spreading coefficients. The results were consistent with known characteristics of the products and was discussed in the previous section. Additional “shelf-life” and “pot-life” assessments of the foam concentrates, and working solutions, respectively are warranted. For example, formation of insoluble complexes with dissolved minerals or other solutes in tap water or seawater could dramatically affect performance. The general performance stability,

(i.e., whether aged samples form stable foams when discharged) is obviously a critical characteristic and needs to be determined to select and then recommend a product to user groups.

**Table 4. Aging test results for COTS PFF Products**

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

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

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

### 2.4.3 Corrosion Testing

Ten of the 12 COTS PFFs evaluated passed corrosion requirements set out in the Mil-Spec, as shown in Table 5. The other four had partial failures, with two (i.e., PFF 1 and PFF 7) only failing on the specific Cu-Ni alloy; this limitation potentially can be addressed by the addition of a corrosion inhibitor. One product (i.e., PFF 2) was corrosive for all metal coupons except for Ni-Cu and may require reformulation to meet corrosion requirements of any current or future Mil-Spec. Another product (i.e., PFF 11) only failed on the bronze coupon. A detailed report is provided in Appendix E.

**Table 5. Corrosion Results for COTS 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 |
|              | AFFF               | 0.98          | 0.01         | 0.00         | 6.02             |
|              | PFF 1              | 0.36          | 0.41         | 0.01         | 45.66            |
|              | PFF 2              | 1.50          | 2.47         | 0.12         | 138.78           |
|              | PFF 4              | 0.81          | 0.98         | 0.00         | 85.26            |
|              | PFF 5              | 0.04          | 0.01         | 0.00         | 38.74            |
|              | PFF 6              | 0.18          | 0.02         | 0.02         | 17.98            |
|              | PFF 7              | 0.12          | 0.84         | 0.01         | 68.8             |
|              | PFF 8              | 0.23          | 0.16         | 0.04         | 56.14            |
|              | PFF 8.2            | 0.34          | 0.98         | 0.01         | 93.13            |
|              | PFF 9              | 0.13          | 0.16         | 0.04         | 30.38            |
|              | PFF 10             | 0.12          | 0.19         | 0.04         | 23.17            |
|              | PFF 11             | 1.02          | 0.84         | 0.01         | 131.84           |
|              | PFF 12             | 0.400         | 0.21         | 0.00         | 28.26            |

*Red Values = Failing, Green Values = Passing*

## 2.4.4 Environmental Fate and Toxicity

### 2.4.4.1 BOD<sub>20</sub> and COD

Table 6 provides the data obtained from assessing biodegradability of selected PFF. The COD and biodegradability index are identified within the Mil-Spec for fire suppression foams. All PFF tested met the COD pass-fail definition. The BOD values obtained from extended test 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 4/5 PFF (Table 6). In most instances, COD is greater than BOD as the chemical oxidant reacts with all dissolve organic matter. In the present sample, there is high concentration of additional nitrogen containing organic molecules that do not react well with the chemical oxidant but do cause BOD signal. Accordingly, the PFF are readily biodegradable by the present criteria (index >> 0.65). Whether that relationship is appropriate assessment of the PFF environmental impact may be subject for further review and consideration.

**Table 6. BOD<sub>20</sub> and COD Results (mg/L) for Various COTS PFF Products**

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

<sup>1</sup>COD and BOD<sub>20</sub> are results from previous work done by AFCEC/CXAE technical team in program.

NA: Not measured.

### 2.4.4.2 Toxicology -LC<sub>50</sub> and IC<sub>25</sub> for PFF Against Aquatic Vertebrate Animals

Material and chemical toxicity tests are done to find the exposure concentration that does not cause adverse effects to the test organism or cell line. In the approach here, the concentrations are noted at which, there is no observed effect (NOEC) and the lowest concentration where there is an adverse effect is observed (LOEC) (Table 7). The inhibition concentration (25%) is the concentration at which reproductive effects were observed in 25% of the subsequent generation of organisms (fathead minnows). With the PFF tested to date, all were more toxic than allowed in the Mil-Spec limit. In fact, most PFFs were found to be more acutely toxic to aquatic life than the legacy AFFF, possibly due to the higher surfactant concentrations. Note that after testing the first 6 PFFs, it was decided that another project, funded under SERDP, was to more thoroughly look at toxicity to various aquatic species.

**Table 7. Toxicity Results for Fathead Minnows for Various COTS PFF Products**

| PFF | Acute LC <sub>50</sub><br>(mg/L) | Chronic NOEC<br>(mg/L) | Chronic LOEC<br>(mg/L) | Chronic IC <sub>25</sub><br>(mg/L) |
|-----|----------------------------------|------------------------|------------------------|------------------------------------|
| 1   | >120*                            | 120                    | >120                   | >120                               |
| 2   | 56.6                             | 20.0                   | 40.0                   | 37.8                               |
| 4   | 56.4                             | 40.0                   | 80.0                   | 47.6                               |
| 5   | >80.0*                           | 80.0                   | >80.0*                 | >80.0*                             |
| 6   | 66.2                             | 40.0                   | 80.0                   | 52.9                               |
| 7   | 70.7                             | 40.0                   | 80.0                   | 55.1                               |

*NOEC: No Observed Effect Concentration; LOEC: Lowest Observed Effect Concentration; LC<sub>50</sub>: Lethal Concentration 50%; IC<sub>25</sub>: Inhibition concentration 25%. \*=no LOEC was found*

## 2.5 DISCUSSION

The narrowly defined criteria of the AFFF Mil-Spec are not necessarily related to the characteristics of PFF as each comprise very different chemical formulations. Accordingly, assigning a pass/fail basis for some characteristics may be misleading with respect to their potential for use as fire suppression agents. One issue of note was the spreading coefficient. Rapid film formation is critical for the AFFF mechanism but is irrelevant to the PFF mechanical foam structure. The overall framework of the physical characteristic list, however, provides a good basis for internal comparisons, and some of the physical characteristics have relevance to the use in the field.

The viscosity range of products is potentially important. Product flow, delivery, and dispersion in working solutions may all be affected by density and need to be addressed for down-selected products. Stability and corrosion are both relevant to actual use. Materials must remain useable after extended hold times in storage and when in firefighting equipment tanks. In the latter, corrosion issues are another obvious detriment. Although the quantitative measures showed some PFF exceeded corrosion thresholds, those limitations may be addressed with corrosion inhibitor, minor reformulations, or selection and use of resistant materials in the equipment. If the suppression performance of the product is exceptional, the trade-offs may be warranted.

Results of the biodegradability tests were atypical for wastewater and should be considered in the rationale to refine the Mil Spec related to PFF. The legacy Mil Spec intended the AFFF formulations to be maximally susceptible to microbial processes, but that can become muddled in complex product formulations. As noted above, the PFF components appear to elevate biological oxygen demand, suggesting they are readily degraded in typical microbial processes. This characteristic is promising for an engineered management and treatment strategy but can be detrimental when an unintended large release to environment occurs. Excessive BOD in surface and ground water have great consequence to water quality and higher organisms.

The toxicology assays showed that the PFF toxicities are more severe than the Mil-Spec limit. The PFAS-based AFFF have relatively low acute toxicity but do bioaccumulate, as the PFAS do not breakdown in natural processes [15]. By comparison, PFF contain high levels of non-fluorinated surfactants, which can be toxic to aquatic organisms, but are susceptible to microbial breakdown. In addition, the PFF formulations may contain additional components that raise

BOD, also deleterious to the environment when released. To decrease toxicity and bioaccumulation potential, non-fluorinated betaines are used in some PFF, but their environmental impact is not well-known. While PFF and their degradation products are undoubtedly less persistent than those containing the recalcitrant carbon-fluorine bond, PFF require higher concentrations of active ingredients in order to reach fire extinguishing standards[16]. Further investigation would be needed to better understand the toxicity of non-fluorinated surfactants and more extensive research is needed to fully evaluate the trade-off between acute and chronic toxicity of next generation PFF. Nonetheless using the generic EPA acute toxicity guideline, the PFFs tested would only be categorized as “slightly toxic” [17]. Accordingly, effective training and understanding could provide acceptable practices for the use of PFF.

### 3.0 COMPRESSED AIR FOAM FIREFIGHTING FOR PFAS-FREE FOAMS

#### 3.1 BACKGROUND

Fire suppression foams are essentially gas bubbles encased in liquid. When water contains a dissolved surfactant, the surface tension of liquid drops and foam forms more readily. In the most basic applications, air mixes with the solution as it is exiting the hose nozzle, or the solution is agitated as it contacts a surface and the foam builds-up on the wetted surface. In general, the longer the fire suppression foam lasts, it will hold flammable vapors and cool the material, suppressing or possibly extinguishing fires. The stability of foams, however, tempts entropy, which will progressively drive the gas to escape from the liquid. Regardless of the construct, entropy is undefeated, and over time the gas will evolve, and the liquid will fall out of the foam matrix. A skeletal structure of bubbles may remain, but those will also rupture, leaving the liquid behind.

Agent delivery methods and technologies may improve PFF blanket structure or other physical aspects of the aqueous fire suppression agent formulations. An aspirating nozzle flow path and CAFS are illustrated in Figure 1. Conventional aspirating nozzles, rely on the venturi effect to create foam. The solution in the delivery line is constricted within the nozzle, which forces air into the liquid, upon exit from nozzle the air rapidly evolves, causing the surfactant to foam. CAFS inject air into the liquid line carrying the water/foam solution. The gas liquid mixture then moves toward the nozzle, where the flow through the plumbing of the system alters the foam structure to form a more uniform bubble distribution. The CAFS nozzle does not constrict flow, which helps maintain the foam expansion and bubble structure developed through earlier stage of system.

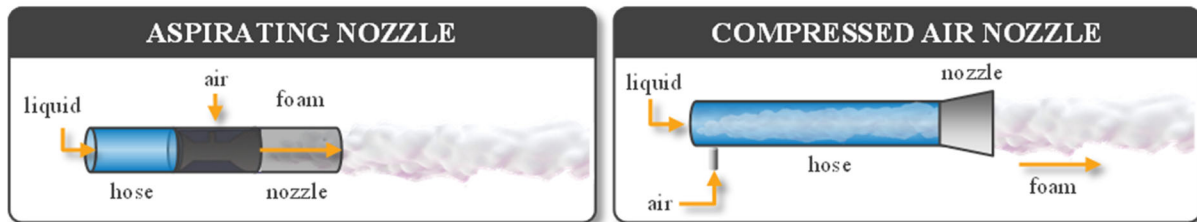


**Figure 1. Stylized Illustrations Showing Foam Generation in Conventional Air Aspirating Nozzle and the Compressed Air Foam Systems**

#### 3.2 BENEFITS OVER CONVENTIONAL PRACTICES

Early work describing the CAF concept for fire suppression was patented by Schnabel in the late 1920s [18]. A series of patents from 1940s started to establish a technology by combining mechanical systems to create and deliver the foam [19-21]. Despite those early advances, CAFS did not see widespread use until the 1970s after firefighters in Texas showed the efficacy of Mark Cummins' CAF system for class A foams to combat wildland and brush fires [22]. The firefighters noted that CAF used less water and adhered to surfaces more effectively than air-aspirated foams. Those same firefighting agencies then used their CAF equipment against class A structural fires when they were called to residential fires in neighboring communities, where

they saw the same firefighting benefits [23]. In recent years, CAF has begun to expand applications into the class B (liquid fuel) firefighting arena, first in sprinkler systems for chemical storage facilities and later into active firefighting scenarios.

The effectiveness of CAF can be attributed to its stabilization of the foam structure compared to foam formed in conventional air-aspirated nozzles. The stabilization maintains coverage over the fuel source, reducing flammability. The blanketing phenomenon is effective for solid materials as well as flammable liquids. The foam stability is quantifiable by its “drainage rate”, i.e., the time required for a predetermined fraction of the liquid to release from the foam matrix. The rate that a foam degrades and drains is controlled by several competing factors. Gravity exerts force on the liquid in the foam matrix causing it to drain. In stronger foam structures, that drainage may be countered by “capillary suction” [24]. The foam will coarsen as the liquid layers between bubbles burst, causing air pockets to merge. As the bubbles merge, the uniform bubble size in that original foam is lost, further diminishing structure. Another complication as the foam degrades is the so-called “liquid-holdup” phenomenon [12]. The surface viscosity of the liquid exerts a drag force between the ascending gas and descending liquid, increasing foam drainage times. The optimal expansion ratio (ER) (the ratio of gas to liquid in the foam structure) varies by foam type and other solution factors. It has been reported that foams at higher initial ER have thinner liquid layers and a smaller distribution of bubble sizes [25]. This characteristic lead to a slower rate of differentiation and drainage.

Foams generated via CAF methods show both smaller bubble size, and the bubble size distribution is narrower, relative to aspirated foam with the same ER. Those physical characteristics increase foam stability, and slow drainage rates. AFFF depends on the liquid drainage to supply and replenish the vapor suppressing film underneath the foam layer; thus, for extinguishment, AFFF has an optimum ER that yields a relatively rapid drainage rate. By comparison, rapid drain time negatively affect PFF performance. PFFs do not form a vapor-suppressing film, instead a stable, high-volume foam structure will hold flammable vapor back in order to extinguish and suppress fire. Accordingly, the primary assessments for foam performance, fire extinguishment, and burnback (ability of the foam blanket to delay the spread of a fire) times are affected by stability and foam drainage times. Delivering PFFs (and other structural foams) using air-aspirating systems will limit their effectiveness, as the foam architecture is deficient compared to the CAF structure.

A CAF system encompasses three main zones: the injection, development, and discharge zones (Figure 1). Air is injected into the liquid agent stream early in the line, generally in the truck mounted system. The foam structure can be manipulated in the injection zone by changing the rate and pressure that the air is introduced to the agent (these are colloquially referred to as “dry,” “wet,” and “medium” settings with respect to ER) and the indirectly proportional liquid content. In the development zone, the foam is coarsened as the bubble size becomes smaller and more uniform through turbulent agitation. The agitation occurs within the fire hose; accordingly, hoses used in CAF systems must be rated to withstand the high pressure injected air and avoid rupture. The discharge zone for CAF must be free of sharp bends, contact points, or other flow constrictions, which may cause bubbles to burst and otherwise degrade the foam quality needed to extinguish and suppress the fire.

Previous tests and their reports indicated that CAF can improve performance of fire suppression agents. 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 [4]. 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 [26]. Additionally, it has proven to be more effective than foam and water, or water alone, at combatting class A solid fuel fires [27]. One objective in work underpinning this guidance document was to establish a rigorous methodology to test whether (and to what extent) CAFS affect the fire suppression performance of PFF in liquid fuel fires. The results from this approach may be used by DoD and civilian agencies to select products that best meet requirements and develop criteria (i.e., a new “Mil-Spec”) that applies specifically to PFF.

### **3.3 TEST PROTOCOLS**

The live fire test parameters were derived from the Mil-Spec protocol. The Mil-Spec uses a standardized raised pan fire (circular, 28-ft<sup>2</sup>) containing 10 gallons of gasoline. In the formal document there is a comprehensive series of tests that comprise 42 different configurations, principally varying agent concentration or flow rate and using freshwater or seawater as diluent for the concentrate. The present project used 3% diluted concentrate in nearly all tests, 2 gallons/min (gpm) for the 28-ft<sup>2</sup> fires, and freshwater diluent. In instances where fire scale was changed, the fuel volumes and flow rates were changed proportional to the area of the fire. The fuel volumes were direct linear extrapolation, and the flow rates were adjusted to match agent delivery per area in the standardized ring fire (i.e., 0.07 gallons/ft<sup>2</sup>/min (270 mL/ft<sup>2</sup>/min). Different liquid fuels were used: commercial gasoline with ethanol, ethanol-free gasoline, and Jet-A aviation fuel.

#### **3.3.1 Indoor Live Fire Tests**

Lab scale and Mil-Spec scale fires were carried out at the SkyX test facility (Tyndall AFB). The building is a concrete reinforced Quonset-style structure with a powered overhead ventilation system to clear smoke following tests. Secondary containment and clean-up processes are used so that all materials and effluent from tests are collected and transferred for processing and treatment.

##### **3.3.1.1 Lab-Scale Fire Testing System**

The lab-scale test apparatus, also referred to as Mini-CAF system, is a down-sized CAFS designed and fabricated by Battelle/AFCEC (Figure 2). It allows the user to manipulate the flow rates of a foam solution and air at low liquid flow rates, in order to match the Mil-Spec application rate relative to area of the pan. It can be used to conduct preliminary screening tests on foam formulations and CAF input parameters. The tests can be completed in rapid succession while using limited quantities of foam. Lastly, because it is a fixed system of limited scale, it does not require the presence of a trained firefighter for effective and safe operation.



**Figure 2. 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*

For the mini-CAF tests (Figure 2), the foam concentrates were premixed with municipal tap water in an open container. The mixture was pumped through a pressure dampener using a peristaltic pump. The flowrate was controlled via a flow meter, controller, and proportioning valve. The liquid then contacted compressed air in a mixing chamber that contained steel wool to coarsen the foam with turbulent flow. The liquid flowrate could be set between 1.0–140.4 mL/min. The air injection rate could be set between 0–2 cubic feet per minute (standard pressure). The foam ER could be manipulated by setting the compressed air flowrate, so the system could create ERs that were typical of both aspirating nozzle and CAFS at larger scales.

Tests were conducted using steel test pan to contain liquid and focus fire (3.5-inch deep, 7.5-inch diameter (0.30-ft<sup>2</sup>)). The foam was delivered at a constant rate (80 mL/min), which corresponds to a delivery rate of 0.07 gpm/ft<sup>2</sup>. The desired outlet ER was set by adjusting the inlet air flow rate 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 manually. There was no supplementary instrumentation (e.g., thermocouple or heat flux) or systematic video collection for later analysis.

### **3.3.1.2 Mil-Spec-Scale (28-ft<sup>2</sup>) Live Fire Testing**

The evaluation of the PFF performance was centered on tests derived from the Mil-Spec standard scale platform. The indoor SkyX test site included all necessary apparatus for the test bed. In addition to the raised fire pan, a “skid” custom system was designed and built by AFCEC/Battelle personnel to deliver foam at the 2 gpm flowrate defined by the Mil-Spec. The system delivered agent using a conventional nozzle (air aspiration) as well as changing configuration for CAF application. The custom platform was required because the testing specifications could not be reliably done using commercially available equipment: in particular, one that would produce and deliver foam using both compressed air or self-aspirating nozzles. The skid used a single tank, and foam formulations were quantitatively prepared, premixed, and

transferred to the tank. The tank was then pressurized with a gasoline-powered air compressor. The air compressor was also plumbed into line in order to inject air when using the CAF configuration. The skid was connected to a digital acquisition and control system (DACS), used to independently manipulate and monitor the liquid and foam pressures and flowrates. The control software monitored and recorded the volume of foam used in each test and the liquid level in the skid tank. Coupling those data, the flow rates, and video recording analysis provided precise determination for performance of the foams, settings (e.g., ER), and the platform.

The custom skid for 28-ft<sup>2</sup> fires (Mil-Spec) used a single pressurized tank for agent. The foams were combined with municipal tap water at working concentration (typically 3% (weight to volume)), stirred with a rotary mixer to disperse concentrate and then transferred to the skid tank. The tank was then pressurized using compressed air to 120–150 PSI and flow adjusted to target rate. For the air aspiration tests, nozzle pressure was adjusted ( $100\pm5$  psi) by tweaking supply tank pressure. When using CAF, the liquid flow rate was established and then compressed air set at a level calculated to attain target ER. For all foams and delivery configurations the drain times and actual ER were determined using methods described in the Mil-Spec (Section 4.7.5). With the CAF configuration the air injection was adjusted in order to fine tune the ER characteristics.



**Figure 3. Mil-Spec Extinguishment Test.**

*Key: A) Fuel ignition, B) Initial foam application post pre-burn, C) Firefighter application, D) 90% suppression, time recorded, application continued, full extinguishment time noted and foam blanket developed for “burnback” assessment*

After finalizing the settings, the live fire tests were evaluated; first, extinguishment and then the burnback assessment. Water was pumped to the 28-ft<sup>2</sup> test pan until the bottom of the pan was completely covered. Ten gallons of fuel was then transferred to the test pan. The gasoline in the test pan was ignited and allowed to pre-burn (10 seconds). During the pre-burn, the DACS was initiated to begin foam flow at desired setting and record instrumentation data. After the pre-

burn, firefighters in full personnel protective equipment (PPE) used test material and equipment to extinguish the fire as expeditiously as possible (Figure 3). The extinguishment time was recorded, but the application continued until foam was discharged into the pan for a total of 90 seconds. Once foam flow was completed, the second burnback test pan (1 gallon fuel) was ignited and placed into the center of the foam blanket (Figure 4). The burnback pan was removed once it was no longer needed to sustain flames inside the 28-ft<sup>2</sup> test pan. The burnback time was recorded as the point when 25% of the pan was covered with flames. As all tests generate hazardous waste, the test effluent was collected, held, and then disposed of according to site handling regulations.

In the event that the fire was not extinguished in 90 seconds, the tests were modified to include an additional “cold burnback” test. As before, the water was used to cover 28-ft<sup>2</sup> test pan, then 10 gallons fuel added to the pan. The foam was applied to the unlit fuel in the pan for 90 seconds, and then the burnback ignition pan (containing 1 gallon of gasoline) was ignited and placed in the center of the foam layer, the burnback time was determined as before for each test configuration. The modified test supported more consistent test conditions for the poor extinguishing configurations. When the fires lasted longer than 90 seconds, there was an excess volume of agent compared to the standard method; additionally, the longer the fire burned the more fuel was consumed, so there were less vapors for subsequent ignition.

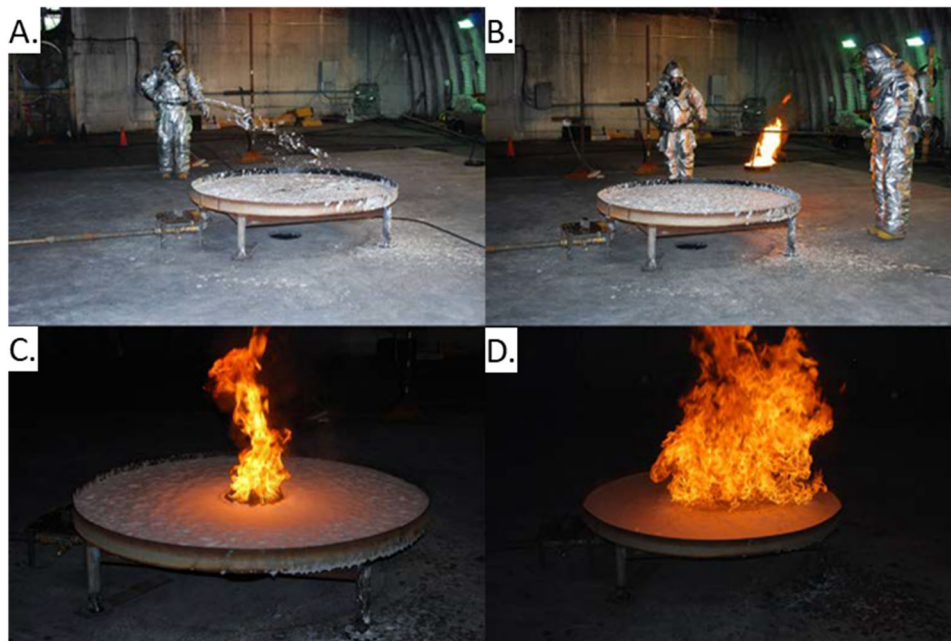


**Figure 4. Mil-Spec 25% Burnback Test (28 ft<sup>2</sup> pan, SkyX Facility Tyndall AFB)**

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

### 3.3.2 Outdoor Live Fire Tests

The Silver Flag fire training facility (Tyndall AFB, FL) has two large diameter (ca. 90-ft dia) pools used for fire training exercises for Air Force firefighters as well as the tests by the AFCEC-Fire Integrated Research and Engineering (FIRE) program. The site has integrated plumbing and delivery systems to safely facilitate fuel transfer to the test pools and complete containment of test effluents.

The test pools may be used for variously scaled fire suppression tests including full field-scale two-dimensional live fire tests (Figure 5). 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. Fuel is pumped directly into test rings via control systems integrated into the Fire Training Facility fuel transfer system. After suppression tests are completed, the remaining fuel in the test pool is typically burned to the self-extinguishment point. Effluent water from tests in the fire pools is sent to an oil/water separator to further limit fuel contamination. The effluent is then transferred and held in a retention pond or other storage assets until processed or disposed according to the AF and site operations requirements.



**Figure 5. Large Scale Aviation Fuel Fire and ARFF Demonstration - Silver Flag Research Test Pool II (Archival photo, USAF-AFCEC)**

The scale of outdoor tests requires additional firefighters and equipment to limit risks compared to the SkyX fire tests. A standby ARFF vehicle is onsite with an operator in event the test platform malfunctions or there is other failure that leads to unsafe operation. Accordingly, the rigorous evaluation of the PFF and the delivery platforms requires access and use of significant infrastructure, equipment, and personnel systems and investments.

#### 3.3.2.1 Medium-Size Field- Scale (315-ft<sup>2</sup>) Pan-Fire Live Fire Testing

For the large-scale air aspiration and CAF testing, a skid platform was designed and built by Burner Fire Control® (Broussard, LA) (Figure 6). The skid includes an 80-gallon CAF foam tank with internal coating, a 100-ft discharge hose, and four nitrogen cylinders (sufficient to completely discharge the system twice). The platform also includes a 200 lb. dry chemical tank, that may be employed to assess how/whether augmenting PFF with dry chemical agent improves fire suppression performance. Two handlines were integrated with the platform and could

accommodate the conventional air aspiration nozzle, a smooth-bore dual-agent handline for CAF and dry chemical (CAF discharge rate of 15–24 gpm), or an adjustable, dual-agent handline (straight stream and fog). A steel ring with raised sides (20 ft diameter) was used to retain fuel for the tests.

In preparation for the live fire tests, water was transferred to the pool until it was above the lower edge of the fire ring. Foam solutions (75 gallons) were pre-mixed at working concentrations (typically 3% in municipal tap water) and then transferred to the skid system tank. The tank was sealed and pressurized with compressed gas to provide agent delivery. As before, it was the sole input for the air aspiration; for CAF there was additional in-line compressed gas injection. The setting required for flow rates and ER for the test materials were determined prior to the bona fide live fire tests. In preparation for tests, the handline nozzle was opened to prime the line and closed again until used for extinguishment. The fuel (100 gal) was pumped to the steel ring, in a manner such that it will float on the water surface and be retained in the ring. The fuel was ignited remotely using an electrical charge to ignite a ball of wood wool shavings or directly by using a propane torch. Once fully involved with flames, the fuel went through a pre-burn stage (15 seconds). The fire was then extinguished as expeditiously as possible by two firefighters; one aimed and discharged the handline, and the other managed the delivery hose to facilitate the nozzle operator movements, which helped to both minimize and replicate consistent extinguishment times. For the data collection the extinguishment time was noted directly and then reviewed on video recordings to confirm. Fuel that remained following a test was burned until self-extinguishment in order to avoid confounding subsequent tests and minimize fuel transfer to the storage and treatment system.



**Figure 6. Dual-Agent CAF Skid for 315-ft<sup>2</sup> Fire Tests**

### ***3.3.2.2 Large-Size Field-Scale (6500-ft<sup>2</sup>) Live Fire Testing***

The Silver Flag ARFF inventory included a Class 4 vehicle (Rosenbauer Panther) that was on loan to AFCEC/CXAE from the FAA as part of a collaborative extramural project. It was a representative ARFF vehicle used on DoD and civilian facilities. The AFCEC/CXAE FIRE team

had broad permissions from the FFA to use the platform for large-scale research and demonstration fires. The Panther included a Rosenbauer R-600 two stage centrifugal pump with an automatic around-the-pump foam proportioning system, a dual-agent handline that could be used for non-aspirated application of PFF and dry chemical. The truck also featured a CAF handline (50–100 gpm, 100 psi), as well as CAF discharge from the bumper turret (600–1200 gpm) and an additional High-Reach Extendible Turret with high volume discharge (500–1000 gpm). The flow rates and compressed gas injection could be adjusted using on-board controls, and delivery conditions could be fine-tuned for tests (and ultimately ARFF emergency response). The working solutions of fire suppression foams were mixed as used by the platform during the discharge. There were separate tanks for the water and foam concentrate. A proportioning pump-controlled flow of foam concentrate, and it combined with the water in-line to obtain the desired concentration. All flow rates and agent consumption amounts were monitored and recorded with the truck's data acquisition system. On-board compressed air storage included six, 400 ft<sup>3</sup> compressed air cylinders, which could be charged using an on-board air compressor or an external gas compressor system.



**Figure 7. Manual Ignition of 1000 Gallon Aviation Fuel. Research and Test Pool-II (Silver Flag Test Site, Tyndall AFB)**

For live fire operation, the water and foam concentrate were pumped from the Rosenbauer's designated tanks at predetermined rates and settings. Prior to tests the flow rates and ER were determined using the rigorous standardized tests. The flow and proportioning rates were then adjusted to match desired test inputs. Once the truck operating parameters were established 1000 gallons of fuel was pumped into the firefighter training pool; as before, the pool contained water to "float" the fuel and provide a heat sink to protect concrete and other components. For ignition, two fire technicians walked around the perimeter of the pit using propane torches to light the fuel (Figure 7). The fuel was allowed to pre-burn for 15 seconds once the full pit was involved. The fire was then extinguished as expeditiously as possible with the equipment on the

ARFF vehicle, and the extinguishment time was recorded. The fuel that remained in the pit was then burned away until self-extinguishment. This step limited waste fuel volume that must be processed in the closed-loop water treatment system.

### 3.4 RESULTS FROM LIVE FIRE SUPPRESSION TESTS

An extensive series of tests examined foam characteristics and fire suppression by selected PFF. The tests compared application of standard air aspirated foams (aka “Mil-Spec” nozzle) and CAF side-by-side with each PFF and comparisons among the foam products. The approach provided a comprehensive, and well-controlled regimen to assess the PFF performance, in particular the effect CAF delivery technology had on the product performance. The overwhelming portion of tests used the 28-ft<sup>2</sup> pan, as that is the “standard” and it is an obvious approach to establish a defensible performance metric.

The high-level summary of tests is shown in Table 8. In short, none of the PFFs met the fire extinguishment time limit. Other aspects of PFF were satisfactory (drain time and standard ER) against the reference criteria (Table 8). The CAF application technology, however, improved performance significantly compared to the standard air aspiration. The improvement was evident for the other “measurables” as well, for example the structural foam formed using CAF surpassed burnback threshold for all foams in the tests to date.

**Table 8. Objectives, Collection, and Summary of Foam Properties and Firefighting Performance**

| Performance Objective                                                                                                  | Data Requirement           | Success Criteria                 | Result                                                                                                                                                                                             |
|------------------------------------------------------------------------------------------------------------------------|----------------------------|----------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Quantitative Performance Objective for 28-ft<sup>2</sup> Mil-Spec Scale, Gasoline Fires</b>                         |                            |                                  |                                                                                                                                                                                                    |
| Foamability/<br>Drain Time                                                                                             | Expansion ratio (ER)       | ER: $\geq 5$                     | All PFFs pass                                                                                                                                                                                      |
|                                                                                                                        | 25% foam drain time        | 25% drain time: $\geq 150$ s     |                                                                                                                                                                                                    |
| 90% Control                                                                                                            | Heat flux                  | N/A to Mil-Spec                  | Measured                                                                                                                                                                                           |
| Fire Extinguishment                                                                                                    | Stopwatch                  | Extinguishment time: $\leq 30$ s | <ul style="list-style-type: none"> <li>No PFF passed with Mil-Spec nozzle (3 of 12 failed to extinguish)</li> <li>40% lower extinguishment time with CAF (1 of 12 failed to extinguish)</li> </ul> |
| Burnback/<br>Cold Burnback                                                                                             | Stopwatch<br>Heat flux     | Burnback time: $\geq 360$ s      | <ul style="list-style-type: none"> <li>6 of 12 passed with Mil-Spec nozzle</li> <li>All 12 passed with CAF</li> </ul>                                                                              |
| <b>Field-scale Performance Objective (315-ft<sup>2</sup> with Gasoline and Jet-A; 6,504-ft<sup>2</sup> with Jet-A)</b> |                            |                                  |                                                                                                                                                                                                    |
| Extinguishment Time Handling/<br>Usability                                                                             | Stopwatch<br>Testing notes | Fire control and extinguishment  | <ul style="list-style-type: none"> <li>Yes, for all 4 PFFs tested so far with CAF</li> <li>Yes, for all 4 PFFs tested so far with UHP</li> </ul>                                                   |

### 3.4.1 Mini-CAF, Lab scale Tests

The mini-CAF platform was used as an initial screen for PFF received for testing. The platform provides a rapid, low-cost, low risk, “gate” to determine how well a new product compared to other PFF products. When these lab-scale tests showed extinguishment or foam structure that had little chance of moving forward in selection, the product could be eliminated from further testing, avoiding time and expense to characterize and test a material that would not compete with other known products.

### 3.4.2 Mil-Spec Scale Tests (28-ft<sup>2</sup> Fire Ring)

#### 3.4.2.1 Comparison of Air Aspirated- and CAF-nozzles for Suppression of Ethanol-Blend (E10) Gasoline Fires

The tests shown in **Error! Reference source not found.** 8 provided direct comparison of the standard and CAF delivery of a series of PFFs. The use of CAF improved the average extinguishment time of the PFFs by an average of 36.6%. However, the extinguishment time improvement provided by CAF was not sufficient for any PFF foam to pass the Mil-Spec extinguishment time of 30 seconds (marked with horizontal line, Figure 8). It was noted that CAF delivery appears to equalize the performance of PFFs; i.e., the difference between lesser-performing PFFs and top-performing PFFs is significantly decreased when using CAF. For PFF10, the extinguishment time dropped from ca. 6 ½ minutes to less than 90 seconds (>85% improvement). The relative standard deviation of the average extinguishment times was 62.6% when using the Mil-Spec air aspirating nozzle. By comparison, the relative standard deviation for extinguishment times decreased to 16.8% for fire tests with CAF. The initial display clearly supported apparent value of CAF for foam delivery in the standardized test. Note that PFF 2 failed to extinguish the fire with either nozzle type.

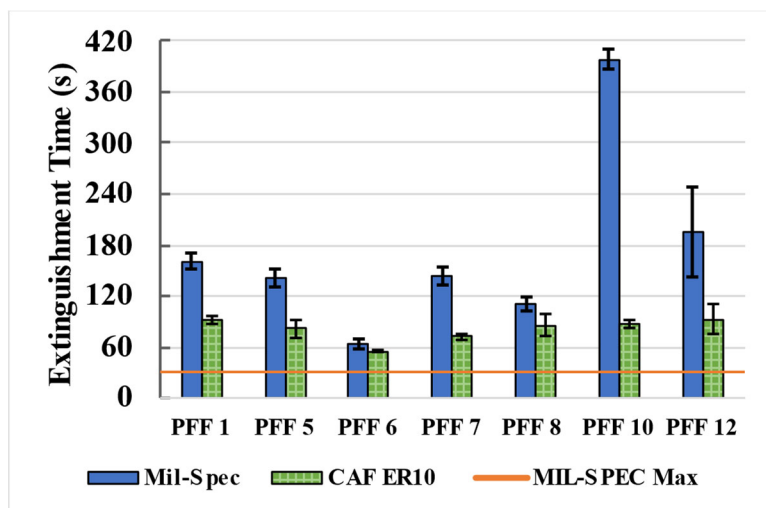


**Figure 8. Extinguishing 28-ft<sup>2</sup> Gasoline with 10% Ethanol (E10) Fires with Mil-Spec Air-Aspirating Nozzle vs. CAF Nozzle (at ER 10)**

The direct comparison of standard nozzle and CAF was extended to the burnback tests. The tests applied the “cold” burnback modification to the standard burnback test. The approach reduced confounding variability that would otherwise occur when examining such a broad range of foam products. Figure 9 data show distinct improvement in burnback time with the use of CAF. The CAF improved burnback across the board, in fact raising two additional PFFs above the Mil-Spec threshold (360-sec, horizontal line, Figure 9). Burnback time increased by an average of 33.6%, ranging from 7.1% to 75.0%. There was not an equalizing effect between PFF foams with burnback time, as seen with extinguishment times. The relative standard deviation of the average burnback time with the Mil-Spec air-aspirating nozzle was 36.5%, while CAF had a relative standard deviation of 32.1%.

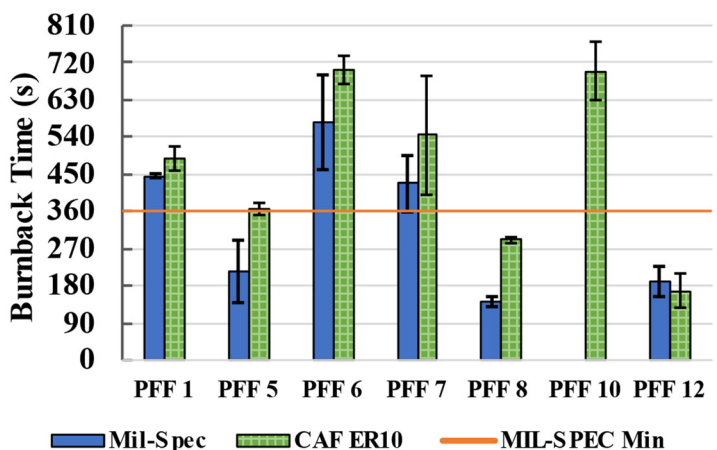


**Figure 9. Cold Burnback Times with E10 Gas for PFF Blankets Using Air-Aspirating Mil-Spec Nozzle vs. CAF Nozzle (at ER 10)**

### 3.4.2.2 Suppression with Ethanol-Free (E0) Gas Fires

Within Class B fires, alcohol (and other polar solvent) fires add to challenges of hydrocarbon liquid fires. In a non-polar hydrocarbon and aqueous foam system, the foam phase and the hydrocarbon phase are immiscible, and there is little mass transfer at the foam-fuel interface. The alcohol, however, will partition within the aqueous foam, possibly affecting the foam-fuel interface and formation of a stable foam blanket, thus inhibiting fire suppression. Some foam formulations are marketed as “alcohol-resistant,” and are specifically designed to fight alcohol-containing fuel fires. PFF products 6 and 7 were tested with the Mil-Spec air-aspirating nozzle at ER 10 with both ethanol-free and ethanol-containing gasoline. As seen in Figure 10, the ethanol-free gasoline fire extinguishment times were slightly lower for 3 of the 4 tests.

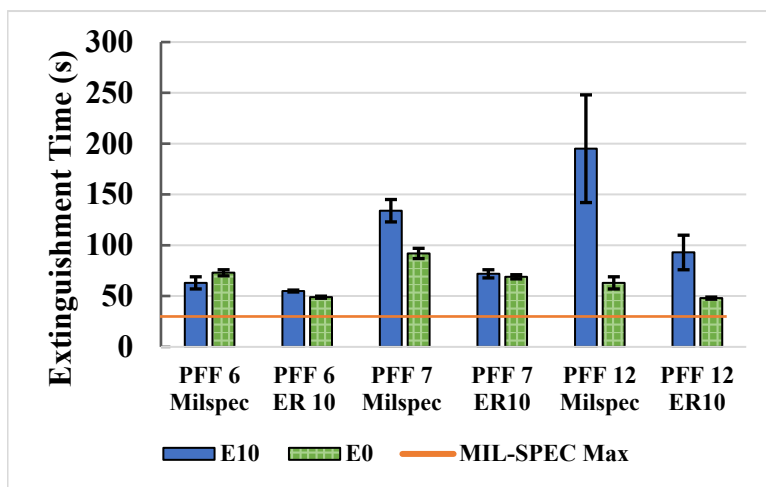


**Figure 10. Extinguishment Time for 28-ft<sup>2</sup> Fire—E10 vs. E0 Gas for Mil-Spec Nozzle and CAF (at ER 10)**

The burnback times improved using the CAF with ethanol-free fuel. The standard nozzle showed no difference or even poorer burnback inhibition for ethanol free fuel (Figure 11).

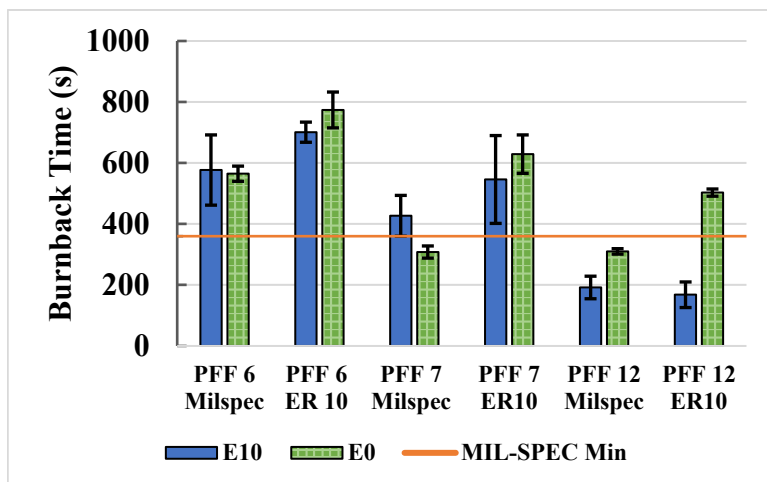


**Figure 11. 25% Burnback time E10 vs E0 Gas for Mil-Spec Nozzle and CAF Nozzle (at ER 10)**

### 3.4.2.3 Effect of CAF Expansion Ratio (ER) on Foam Characteristics and Fire Suppression

The coverage of foam delivered by CAFS undoubtedly affected the fire-extinguishment performance in fuel pool fires, and the coverage rate was governed by the ER of the compressed air foam. Based on the early testing, discussed in the previous section, three different PFFs were selected to determine the effect of ER on performance of CAF. As shown is in Figure 12, the combined average extinguishment time for each of the three foams improved by 30.8% with CAF at an ER 10 compared to the self-aspirating Mil-Spec nozzle. The PFF products 6 and 7 are non-Newtonian, whereas product 8.2 is Newtonian, so the viscosity of the products did not appear to greatly impact the relationship between performance enhancement by CAF and ER.

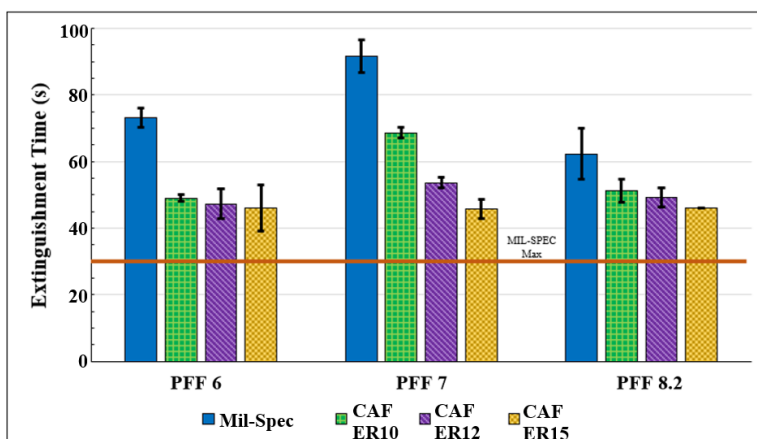


**Figure 12. Effect of CAF ER on Extinguishment Time (28-ft<sup>2</sup>, E0 Gas)**

The general shift in improved fire suppression with CAF vs Std was obvious at the first step (ER 10). Increasing the ER further from ER 10 to ER 12, only provided marginal improvement and then from ER 12 to ER 15, exhibited a similar small improvement. A conclusion that the “optimum” ER is 15 or greater is misguided because at the higher ER, there are negative effects on foam structure, for example, the demonstrated shift in drain time (Figure 13). The optimum ER varies between foams, but ER 12 provided a combination of satisfactory tradeoffs. The changes found above ER12 are attributed to the fact that over-expanding the foam eventually destabilized the mixture. The test results highlighted the tradeoffs at higher ERs with respect to a foam’s ability to spread on the fire. Highly expanded foams may have problems in larger scale fires that are less apparent at Mil-Spec-scale. Highly expanded foam is less dense, since the foams capture more air per unit volume. The foam may be disrupted by wind or updrafts created during large fire events and may be more buoyant on the fuel layer.

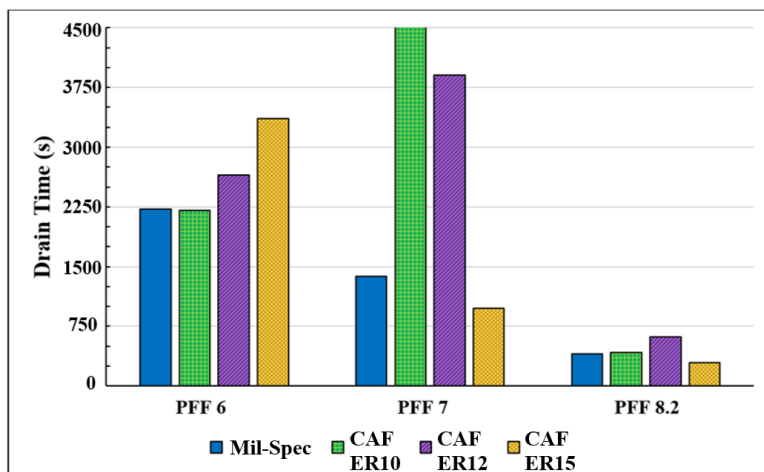


**Figure 13. 25% Foam Drain Times for CAF at Various ER and the Mil-Spec Aspirating Nozzle**

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

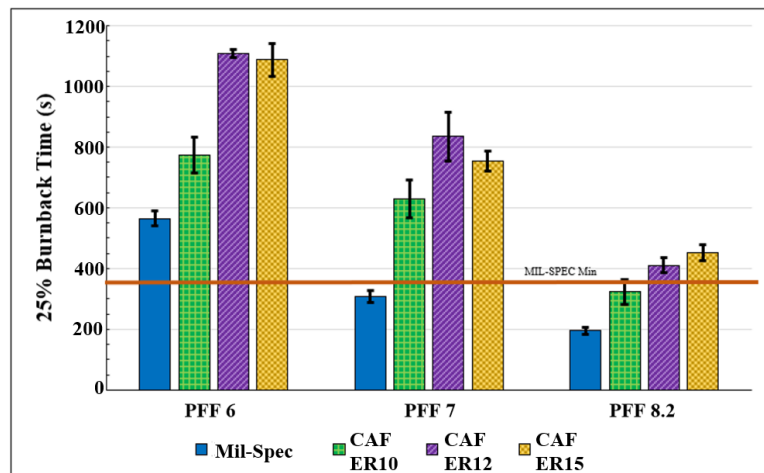


**Figure 14. Effect of ER on Burnback Times for 28-ft² E0 Gas Fires**

### 3.4.2.4 Further Comparisons of PFF at the Selected CAF ER 12

The proposed ER12 trade-off was used in standardized tests for PFF for further edification. The CAF performance data for ER 12 and the Mil-Spec air aspiration nozzle are shown in Figure 15 (extinguishment time) and Figure 16 (burnback time). The pattern found in previous tests holds, and CAF improved both extinguishment and burnback times.

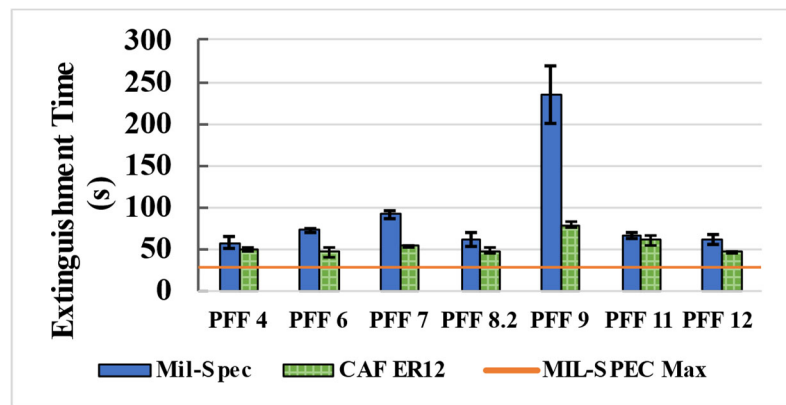


Figure 15. Extinguishment of E0 Gas Fires by Various PFFs—Mil-Spec Nozzle vs. CAF (at ER 12)

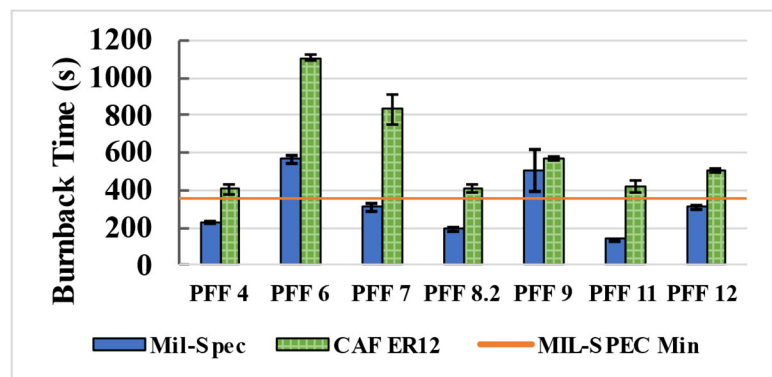


Figure 16. Burnback Times for Various PFFs for Mil-Spec Nozzle vs. CAF (at ER 12)

### 3.4.2.5 Down-selection of PFF for Field Tests

Using results of the characterization and Mil-Spec-scale testing, the following PFFs were down-selected for field-scale testing: PFF numbers 4, 6, 7, 8.2 and 812. The selected products are those showing relatively better fire suppression than other PFF and include Newtonian and non-Newtonian fluids for assessment and comparison at the operational scales. The relevant quantitative fire suppression data are Summarized in Table 9.

Table 9. Summary of 28-ft<sup>2</sup> Ethanol-free Gasoline Fire Test Data for PFFs Down-selected for Field-Scale CAF Testing

| Product | Mil-Spec Nozzle        |                  | CAF                    |                      |
|---------|------------------------|------------------|------------------------|----------------------|
|         | Extinguishment Time, s | Burnback Time, s | Extinguishment Time, s | CAF Burnback Time, s |
| PFF 4   | 58±7                   | 226±4            | 50±3                   | 407±26               |
| PFF 6   | 73±3                   | 565±25           | 47±5                   | 1107±13              |
| PFF 7   | 92±5                   | 308±20           | 54±2                   | 835±80               |
| PFF 8.2 | 62±8                   | 195±10           | 49±3                   | 410±25               |
| PFF 12  | 63±6                   | 310±9            | 48±1                   | 503±12               |

### 3.4.3 Medium-Size Field-Scale—Training-Pit Pan Fire

#### 3.4.3.1 CAF Suppression of 315-ft<sup>2</sup> Field-Scale Fuel Fires—E0 Gas

The initial field-scale CAF trials showed results consistent with the Mil-Spec scale trials. All PFFs successfully extinguished the gasoline fires, and the rates were internally comparable. The average extinguishment times, based on three tests for each PFF, are shown in Figure 17.

Notably, using the same platform and fire fighters, the extinguishment time for AFFF was also comparable to the PFF. As seen, the CAF extinguishment times with PFFs 6 and 8.2 were about the same as with AFFF.

More importantly, both AFFF and all the three PFFs performed much better (44-52 seconds) with CAF than with an aspirating nozzle, the later requiring about 94 seconds for extinguishment with PFF 12.

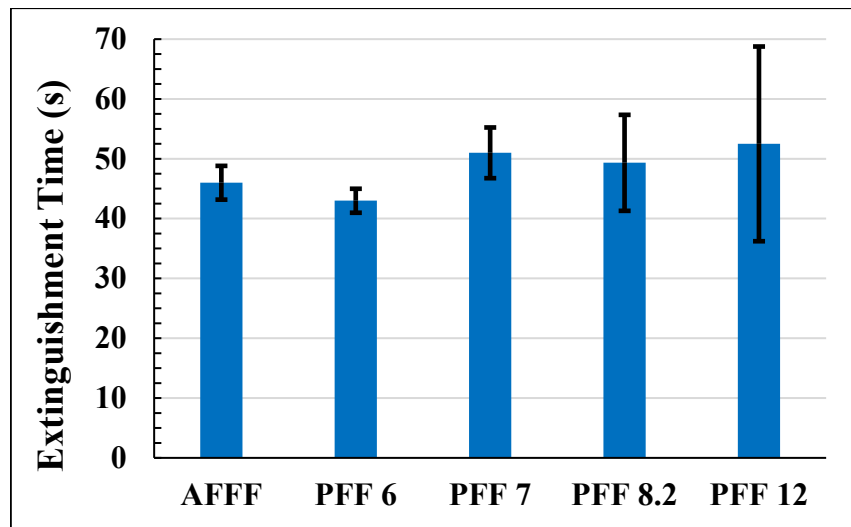


Figure 17. Extinguishment Times for 315-ft<sup>2</sup> E0 Gas Fires (CAF at ER 12)

The field-scale testing so far showed that individual practices undoubtedly affect outcome. The firefighter suggested that the best PFF application technique is slightly different from that with practiced use of AFFF, and with that platform and scale, extinguishment time could drop to the Mil-Spec rate (<30 sec).

The extinguishment times for gasoline fires scaled remarkably well for the tested “pan” scenarios. CAF fire testing with gasoline was conducted at three separate scales with PFF 6, 7, 8.2, and 12. Each set of tests was conducted in triplicate at ER 12. By using the identical volumetric application rate (0.7 gal/min/ft<sup>2</sup>) and ER, the extinguishment time for a PFF was comparable regardless of scale (see Figure 18). The Mil-Spec

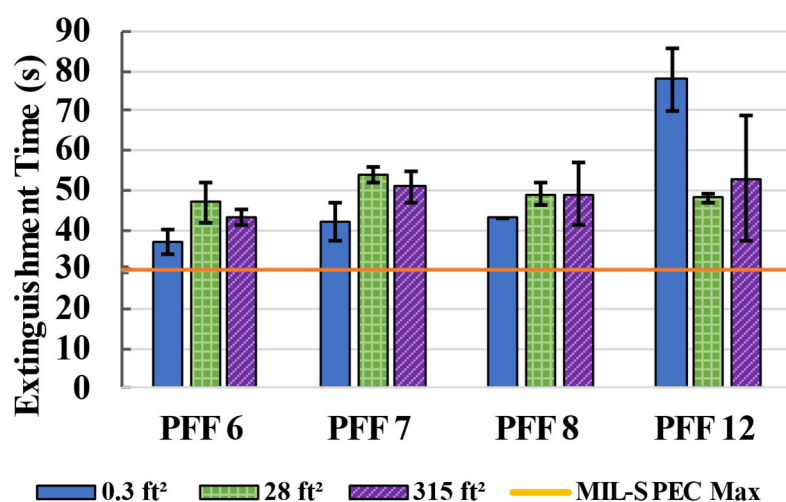


Figure 18. Extinguishment Time of E0 Gas Fires at Laboratory-, Mil-Spec-, and Field-Scales (CAF at ER 12)

and field-scale tests were statistically identical for all 4 PFF tested. The “mini-CAF” platform showed more variance, but still validated its use as an effective screening tool.

### 3.4.3.2 CAF Suppression of 315-ft<sup>2</sup> Field-Scale Fuel Fires—Jet-A Aviation Fuel

Additional tests were done to evaluate suppression of a representative aviation fuel fire. Although the aviation fuel is more energetically dense (watts/volume) it is less volatile, which, facilitates suppression. The extinguishment time for tests done with Jet-A fuel using the five PFFs are shown in Figure 19. All four products successfully extinguished the fire in 25–35 seconds with good reproducibility.

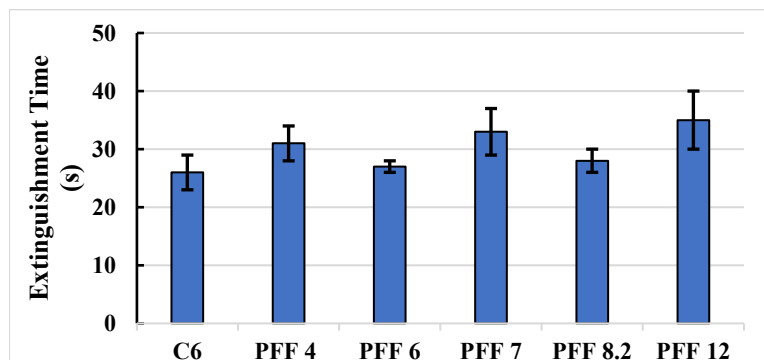


**Figure 19. Extinguishment Time for 315-ft<sup>2</sup> Jet-A Fuel Fires (CAF at ER 12)**

Similar to results with gasoline fires, the PFF performance (Jet-A extinguishment) scaled well between Mil-Spec- and the field-scale pan fires (see Figure 20). Both the C6 AFFF and 4 PFFs were tested at ER 12 at this larger scale. At the 28-ft<sup>2</sup> scale, PFF 6 and 7 were tested at ER 15 and PFF 8.2 was tested at ER 12. The difference in ER may have contributed to the difference for PFF6 performance, although there the extinguishment times for PFF 7 matched at the two scales and different ER. Other differences between scales included the force at which the foam lands in the pan, the relative distance that the firefighters must cover, and of course the weather conditions of each test. The volatility of the fuel was largely dependent on temperature, and the stability of the foam blanket could be affected by wind gusts. In order to accurately determine relationship, more tests would need to be conducted in multiple weather conditions.

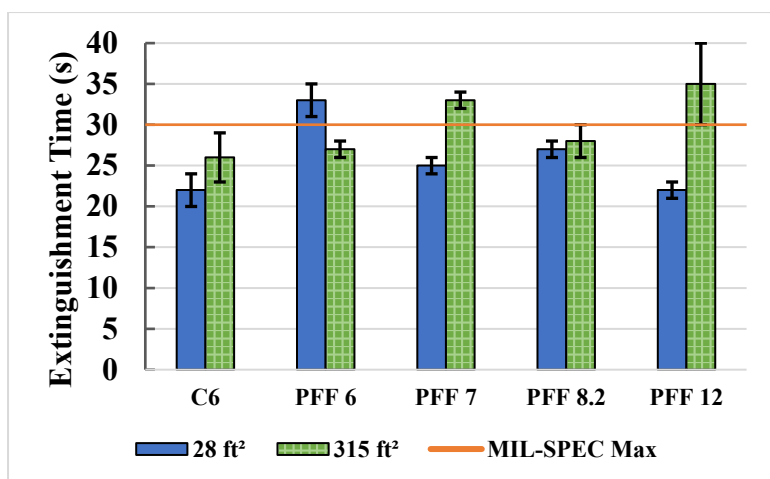


**Figure 20. Scaling Extinguishment of Jet-A Fuel Fires (28-ft<sup>2</sup> vs. 315-ft<sup>2</sup>, CAF)**

An additional set of scaled tests with Jet-A fuel fires examined the effect of volumetric application rate. Two series of field-scale pan fires were done (454-ft<sup>2</sup> and 315-ft<sup>2</sup>). The ER and total flow rates for the tests were identical (ER 12 and 20 gpm) but with larger area the relative application rates differed significantly (0.05 gpm/ft<sup>2</sup> and 0.07 gpm/ft<sup>2</sup>). The extinguishment times were not significantly affected by the changed volumetric rates (see Figure 21). The result suggests that the structural foam blanket was sufficient to suppress vapors and extinguish fire even at decreased total volume.

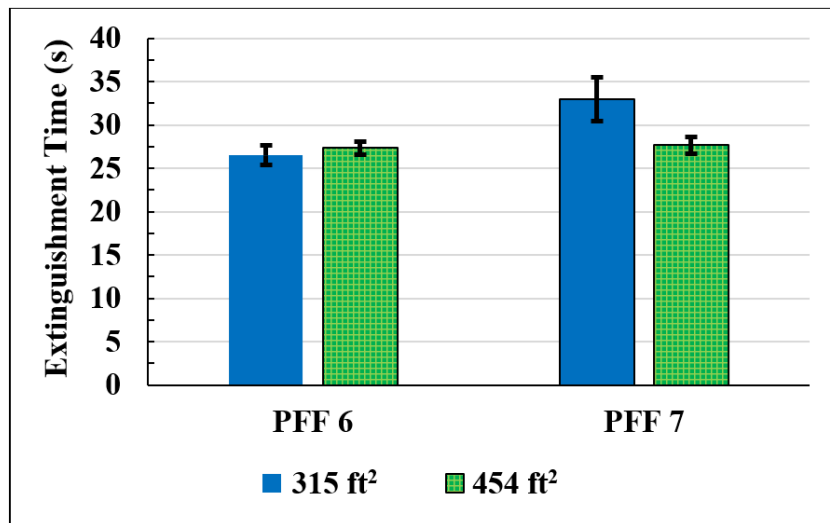


**Figure 21. Effect of Volumetric Application Rate on CAF Extinguishment of Jet-A Fuel Fires (315-ft<sup>2</sup> at 0.07 gpm/ft<sup>2</sup>, 454-ft<sup>2</sup> at 0.05 gpm/ft<sup>2</sup>)**

### 3.4.3.3 Baseline Comparison of Fuel Fire Extinguishment – C6 AFFF and Selected PFF

AFFF (C6) performance was compared directly to the PFF at the medium-size field-scale and CAF skid delivery platform. PFFs 6 and 8.2 performed as well as AFFF, with CAF and Jet-A fuel (Figure 22). Though the firefighters indicated that the AFFF burnback was better than PFF, the rigorous Mil Spec-like test was not done. But when the remaining fuel was burned off between tests, it was more difficult to ignite the remaining fuels after AFFF tests compared to PFF.

Another notable test issue was that the sustained winds were relatively high during the C6 tests compared to PFF. Wind speeds were a sustained 10 mph and gusts were several mph higher, the conditions may have affected the fire extinguishment times, though the reproducibility within the data set was good (Figure 22).

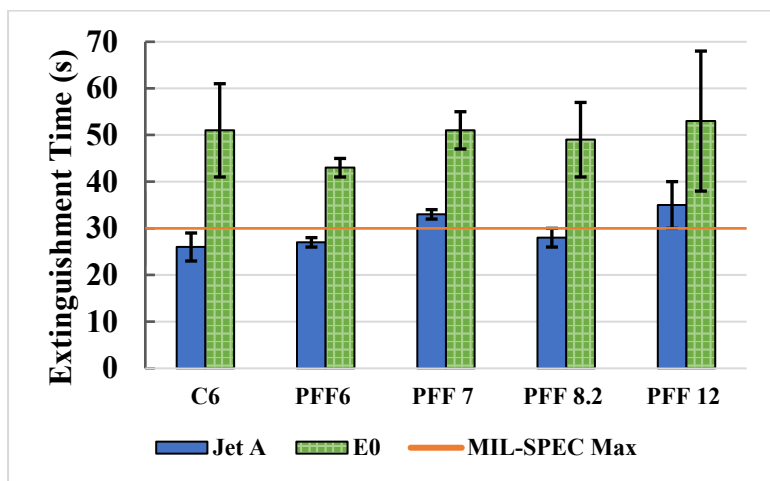


**Figure 22. C6 AFFF Baselines for CAF at 315-ft<sup>2</sup> (at ER 12; 20 gpm Application Rate)**

### 3.4.4 Large-Field-Scale – Class IV ARFF Platform

The full field-scale tests have not been completed to date. Those trials will be critical to examine scalability of the CAF delivery and use of PFF. The representative ARFF platform will also

provide key practical assessment of foam “usability,” for example compatibility with proportioning systems, establishing flowrates and ER at large-field-scale (6,500-ft<sup>2</sup>), and foam stability.

### **3.5 DISCUSSION**

The CAF technology clearly shows promise for improving performance of PFF against liquid fuel fires. The extensive series of Mil-Spec scale tests provided rigorous support of the approach. The 40% decrease in extinguishment times for the foams tested to date bears that out. The effect was evident even at the lowest ER tested, suggesting that the structural stability played a predominant role. Although the extinguishment time limit was not achieved to satisfy Mil-Spec, the products showed good burnback performance. The foams inhibited re-ignition of vapors, especially the CAF-delivered foams. The physical mechanism was not explored here but uniform bubble structure and other features could drive the stability and improved drain times, which affect both extinguishment and burnback.

The volumetric scaling was also encouraging. The transition to PFF for actual application will need to go beyond the well-controlled tests done to date. Demonstration at relevant scale and performance that approaches the legacy AFFF will be invaluable to facilitate transition and user acceptance.

## **4.0 ULTRA HIGH PRESSURE FIREFIGHTING FOR PFAS-FREE FOAMS**

### **4.1 BACKGROUND**

Ultra-high pressure (UHP) technology was, like CAF, not initially designed for use on class B fires. Early, and current, use of UHP was mainly intended for producing water mist for structural firefighting, especially in enclosed spaces like ships and submarines. The U.S. Air Force initially conducted high pressure extinguishment tests to maintain CO<sub>2</sub> in liquid form to deliver it as a firefighting agent to combat both two- and three-dimensional class B fires. Fire trials showed that the presence of CO<sub>2</sub> at high pressures made less of an impact than the high pressures alone. The result indicated that the key influence was the water droplet dispersal under pressure [28]. This method of firefighting used with AFFF can suppress fires that the foam alone could not typically combat and would require a gaseous suppressing agent such as Halon to extinguish.

UHP foam delivery is defined by the NFPA as foam delivered at 1100 psi or above. Water droplets formed and dispersed at high pressures become atomized; measurement of UHP droplets released from apparatus at 1200 to 1500 psi were 80 to 90 microns in diameter [29]. By comparison, the average diameter of a raindrop is 2000 microns. The increase in surface to volume ratio with atomized droplets dramatically increase relative cooling, and in turn, fire suppression. Additional trials extended tests using UHP to deliver AFFF on liquid fuel fires. At large scales, UHP technology consistently extinguished liquid hydrocarbon fires faster and with less agent than the standard low pressure high flow delivery method. Controlled trials showed UHP reducing the amount of AFFF needed to extinguish a fire by up to 33% compared to standard ARFF delivery methods [29]. The UHP may enhance AFFF dispersal, improving deposition of the vapor stifling film. Those test results supported an advanced demonstration to modify a standard P-19 truck platforms and fit it with UHP technology. The fire suppression performance led to broader integration of UHP within the USAF ARFF fleet [30].

### **4.2 BENEFIT OVER CONVENTIONAL PRACTICES**

The commercialization and user acceptance of UHP are still in developmental stage. It should be noted the UHP technology referenced here and applied in the present program is distinct from the mid-20th century “John Bean” pump systems often confused in trade literature and colloquial discussions as UHP. Those early high pressure firefighting systems nozzles operate at ca. 600 psi; the operating pressure of modern UHP is more than twice that (typically 1200-1500 psi) [31]. The physics supporting UHP efficacy are irrefutable: the droplet surface:volume ratio provides cooling effect that is not matched by standard pressure or historic high-pressure applications [32]. Another prime advantage is the limited volume of agent (and water) needed when using UHP. At delivery rates typically less than 20 gallons per minute, UHP can offer long on-site response time with a modestly scaled platform. Additionally, the low water volume used means less waste and runoff generated from training and use in an emergency response. There are numerous manufacturers of firefighting platforms incorporating UHP as an agent delivery option. It is not, however, a dominant platform in the marketplace. There is a combination of factors that likely contributes to adopting the technology: cost, understanding, emotional inertia from users, and limited demonstrations of its utility compared to entrenched products. There are limited background studies of UHP with fire suppression foams. The fire extinguishment with AFFF is reportedly enhanced by UHP [33]; the process, however, will definitely strip some of

the air dissolved in the agent mix and ER will be minimal. The structure of the foam will likely be minimized, and its effect on burnback is unknown. There are no widely-reported studies of UHP with PFF fire suppression agent mixes—the present study provides an opportunity to establish practices and complete rigorous evaluation of the combination.

## **4.3 TEST PROTOCOLS**

### **4.3.1 Mil-Spec (28-ft<sup>2</sup>) Scale Live Fire Tests**

A custom-designed UHP platform was used to test the technology at the indoor Mil-Spec scale (28-ft<sup>2</sup>) pan fires. The system used a handline that delivered flow rates proportional to the ARFF settings, and discharge pressure was greater than 1200 psi. The set-up was similar to previous ones with fuel layered onto the water in the pan. Ignition, pre-burn, and extinguishment practices followed standard methods.

### **4.3.2 Medium-Size Field-Scale (315-ft<sup>2</sup>) Pan-Fire Live Fire Testing**

The AFCEC FIRE team had two UHP-capable ARFF platforms for research and test purposes: a class III Oshkosh model P-19 (Oshkosh Defense, Oshkosh WI), and a Class II Rosenbauer model P-34 (Rosenbauer America, Wyoming MN). The 315-ft<sup>2</sup> pan fires used the P-34 platform for suppression tests. The P-34 UHP truck could deliver foam at legitimate UHP discharge (>1100 psi). The truck included 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. The platform hand-line was used for tests to provide best comparison to the CAF and air-aspiration trials.

As noted, the P-34 had a separate water and proportioning system to allow preparation of the agent mixtures as needed during use. In the test procedures, however, the foam concentrates and water were premixed and then transferred to water tanks for direct use. This approach was done to minimize variability in materials between tests. This approach was critical for proportioning the highly viscous PFFs. The system was designed to proportion Newtonian agents like AFFF, but the hardware was not certified for the viscous agent concentrates. Identical to the previous tests, the prepared foam mixtures were subject to a series of flow tests so the system could be calibrated and set for live fire tests. The general test parameters were identical to CAF and standard nozzle tests. Water was added in the training pool to allow fuel to float and remain in fire ring. The handline nozzle was opened to prime the line and closed again until use for extinguishment. The fuel (100 gal) was pumped to the steel ring, in a manner that it will float on water surface and be retained in the ring. The fuel was ignited remotely using electrical charge to ignite a ball of wood wool shavings or directly by using a propane torch. Once fully involved with flames, the fuel went through a pre-burn stage (15 seconds). The fire was then extinguished as expeditiously as possible by two firefighters; one aimed and discharged the handline, and the other managed the delivery hose to facilitate the nozzle operator movements, which helped to both minimize and replicate consistent extinguishment times. For the data collection, the extinguishment time was noted directly and then reviewed on video recordings to confirm. Fuel that remained following the test was burned until self-extinguishment in order to avoid confounding subsequent tests and minimize fuel transfer to the storage and treatment system.

### 4.3.3 Large-Size Field-Scale (6500-ft<sup>2</sup>) Live Fire Testing

Field-scale tests will be done using the Rosenbauer P-19 platform. The system has capacity and output to respond to the 1000-gal scale liquid fuel fires as it has been used extensively in previous demonstrations for comparable tests using AFFF. The proportioning system has not been evaluated for the various PFF or similar chemical formulations; accordingly, it may be appropriate to pre-mix concentrate and water for most replicable methods. The flow and pressure quantitation and setting, ignition, pre-burn, and recording will be done as described above (3.3.2.2). To date, the none of the full field-scale fires have been done using UHP for PFF delivery.

## 4.4 RESULTS FROM LIVE FIRE SUPPRESSION TESTS

### 4.4.1 Indoor Mil-Spec (28-ft<sup>2</sup>) Scale Tests

UHP testing presented a challenge for testing at the small scale (28ft<sup>2</sup>). The velocity of the agent stream disrupts the fuel surface and literally pushed the fuel and foam outside of the capture pan, confounding determination of extinguishment times for individual foam formulations. As a result, at this scale, UHP extinguishment times were actually longer than the Mil-Spec extinguishment times for most foams tested (see Figure 23). When using UHP, there was virtually no difference in extinguishment time among the PFF products tested. In fact, extinguishment time with water alone was statistically similar to the extinguishment times using PFF. These equivocal results indicated that the project should shift focus with UHP to larger-sized, field-scale tests to examine whether UHP potential matches literature reports.

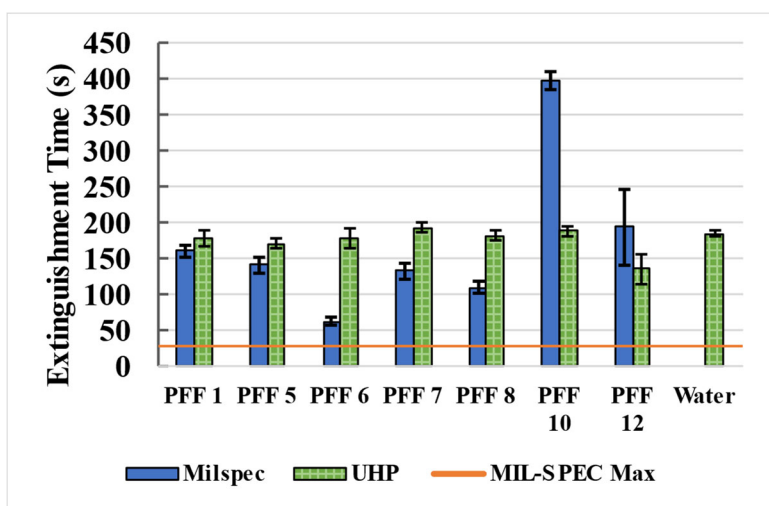


**Figure 23. Extinguishment Time for 28-ft<sup>2</sup> E10 Gasoline Fire with Mil-Spec Nozzle vs. UHP Nozzle**

#### 4.4.2 Outdoor Medium-Size Field-Scale (315-ft<sup>2</sup>) Pan Fire Tests

The extinguishment of Jet A fires with AFFF (C6) and the five down-selected PFFs using UHP were directly compared in the medium-size, field-scale (315-ft<sup>2</sup>) pan-fire tests. This method showed UHP was exceptionally effective for the AFFF; the extinguishment time averaged 23 seconds (see Figure 24), slightly outperforming CAF (26 seconds extinguishment time). The next best PFF was more than twice that time. Similar to the CAF tests with AFFF, the sustained winds were higher than PFF tests (10 mph vs. <5 mph), but with UHP the performance advantage was clear.

During the post-test burn-off, it was clear that none of the PFFs provided any noticeable burnback prevention when delivered with UHP. The film provided by AFFF from UHP still provided burnback protection, even with the low-quality UHP foam.

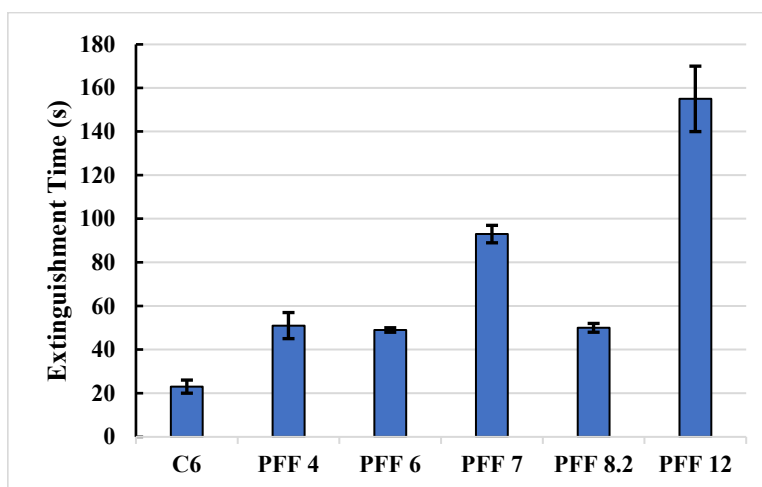


**Figure 24. Extinguishment Time for UHP (Jet-A; 315-ft<sup>2</sup>; 20 gpm)**

#### 4.5 DISCUSSION

The results from the 315-ft<sup>2</sup> testing showed that the extinguishment times for PFFs with UHP were much lower, as hypothesized, at the larger scale compared to the 28-ft<sup>2</sup> scale. For example, the extinguishment time for PFF 6 dropped from ~180 seconds at 28-ft<sup>2</sup> scale to ~50 seconds at 315-ft<sup>2</sup> scale. The extinguishment time with CAF was significantly better, at ~28 seconds. It is believed that the full potential of UHP technology for PFFs can be further demonstrated at a yet larger field-scale, as also suggested by a previous AFCEC testing at 6,500-ft<sup>2</sup> scale with AFFF [33]. Therefore, tests with selected PFFs are planned for UHP testing at the 6,500-ft<sup>2</sup> scale, and the results will be incorporated in an updated version of this document.

One reason for a significantly better UHP performance with AFFF is that AFFF does not require the structurally stable blanket like PFF, instead the fluorosurfactants rapidly forms a thin film, which suppresses the flammable vapor. By using UHP, minimal air is dissolved in the agent. To overcome this drawback with PFFs, alternative UHP nozzle designs, including use of a dual-nozzle to control the fire with lower ER, followed by a higher-ER nozzle setting are suggested.

## **5.0 TECHNOLOGY TRANSITION AND IMPLEMENTATION**

The transition from AFFF to PFF as a primary fire-suppression foam for the DoD will require several steps and rational considerations before full and confident implementation. The broad commercialization of PFF for domestic and international markets provides something of a head-start, in that there is both a manufacturing base and serviceable products. The breadth of options (and market competition), however, also requires a significant investment by DoD agencies to perform due diligence, define an impartial methodology for assessment, and then execute that assessment. Applying the parameters from MIL-PRF-24385F as strict criteria provides a clear set of objectives but one must appreciate that the Mil-Spec is finely tuned to the chemistry and performance of AFFF. Accordingly, it can only be an holistic guide to assess fire suppression foam and products ultimate applicability for the DoD requirements.

### **5.1 ALTERNATIVES TO LEGACY DELIVERY METHODS – CAF AND UHP EFFECT ON PFF PERFORMANCE**

The CAF and UHP technologies have significant history, trade, and technical literature that show advantages over conventional firefighting applications, especially those using AFFF. The past performance provided rationale for the tests with PFF in the present project.

The tests have generated extensive data comparing CAF and conventional aspiration nozzle delivery of PFF. The results are both compelling in their rigor and promising with respect to performance. The CAF application method provided measurable improvement in fire suppression performance for all PFFs tested, as shown by decreased extinguishment times and increased re-ignition (burnback) times in 28-ft<sup>2</sup> pan fires. Subsequent large-scale tests (315- and 454-ft<sup>2</sup>) corroborated those results with extinguishment times essentially matching the small pan fires. Moreover, side-by-side comparisons of AFFF and four representative PFFs had statistically matching extinguishment times for gasoline fires at the 315 ft<sup>2</sup> scale.

The tests using UHP for agent delivery (at 315-ft<sup>2</sup> scale) showed a clear distinction between AFFF and PFF performance. The extinguishment times for AFFF decreased slightly compared to CAF application at same scale, pointing to the potential of UHP. The PFF extinguishment times with UHP increased compared to CAF application. However, the UHP performance with PFF improved dramatically on scaling from 28-ft<sup>2</sup> scale to 315-ft<sup>2</sup> scale, suggesting that testing at full field-scale tests (6500-ft<sup>2</sup>) may demonstrate improved performance with PFF using UHP.

### **5.2 DEFINING METHODS TO OPTIMIZE PFF PERFORMANCE**

Tests in the present project were done by a single firefighting team. This approach provided for the most consistent, replicable results for the inherently dynamic live-fire tests. The minimal standard deviation found with many of the foams tested clearly showed that consistency. The repeated tests with an experienced, competent firefighter also provided a template for developing “best practices.” By performing the exhaustive number of standardized tests, the firefighters consciously (and perhaps subconsciously) learned nuanced practices to effectively extinguish the liquid-fueled fires. The firefighters shared their perceptions directly and through standardized questionnaire reviews. Another approach can be the meticulous, critical review of the video recordings that document the live fire tests. Compilation, analysis, and interpretation of the human factor data can then be applied for building recommendations and the training regimen.

### 5.3 FIREFIGHTER TECHNICAL TRAINING

The moratorium on use of AFFF has undoubtedly affected firefighter readiness and, in turn, increased risk to DoD personnel and assets. Currently, AFFF can be used to combat class B fires in emergency scenarios. It has not been widely used for firefighter training since July 2019, except when allowed under a special operational use certification. As a result, there are many DoD firefighters that have never actually used AFFF against a live fire.

Studies have repeatedly shown that the CAF and UHP technologies improve the performance of AFFF, decreasing suppression times and water use compared to legacy platforms. Both types of systems are commercially available options from firefighting truck manufacturers. The application of firefighting foams using those systems is not broadly used across the DoD, but the equipment is growing in the DoD firefighting inventories (as well as civilian) and the techniques are being implemented in ARFF and structural firefighting response procedures. The results in the present work demonstrated that the alternative methods, especially CAF, improve PFF performance, and should be implemented as part of the transition from AFFF to PFF agents.

The noted deficiencies and proposed emphasis on CAF use underscore the need for increased technical education and training for firefighters. The lessons learned to date provide a starting point for developing the firefighting techniques and the training approach for CAF delivery of PFF. There is no DoD restriction on use of PFF in training or tests; this accessibility provides ample opportunity compared to the present issue with AFFF. The opportunity will have significant logistic and direct costs, which will need to be examined, estimated, and then prioritized. A reasoned strategy will help overcome the noted training deficiencies. The resulting increased user expertise may be a trade-off that balances the less effective fire suppression mechanism for the new class of foams.

### 5.4 CRITICAL UNDERSTANDING AND INTERPRETATION OF TEST RESULTS

The physiochemical characterization and qualification testing under this ESTCP project provided a rigorous, defined basis to comprehensively test and evaluate available PFFs against the “standards” (MIL-PRF-24385F), as well as side-by-side performance against the other products. A practical objective was to identify an existing product that best fills the DoD needs for fire suppression foam. As noted, none of the PFFs met the Mil-Spec extinguishment threshold or satisfied all of its physical or physiochemical criteria. The results are valuable in that they provide clear quantitative and descriptive characterizations of the products. Accordingly, the differences should not be strictly weighed as “pass/fail” but used as reference point for the state of the technology or a specific physical or chemical characteristic of the material.

Consider the fire suppression results first. The PFF burnback values are quite strong, particularly when CAF was used for agent delivery. Two of the eight representative PFFs satisfy the Mil-Spec burnback using a standard air aspiration nozzle, all eight exceed the burnback threshold when a CAF system was applied. The extinguishment times did not meet the Mil-Spec target (30 sec) in the standardized 28 ft<sup>2</sup> pan test, but performance of PFF did not appear to be far from target. Subsequent side-by-side comparisons of AFFF and selected PFFs in large-scale pan fires showed comparable extinguishment rates for the AFFF and PFFs when using CAF. Some follow-on work is recommended to tease out discrepancies with the AFFF performance observed here. The CAF approach may be detrimental to AFFF as done in tests. Trials will be done using

AFFF to extinguish gasoline fires at standardized Mil-Spec scale using the air aspiration nozzle and CAF system for delivery. The standardized protocol will reveal whether the AFFF meets strict Mil-Spec target, if there is a systematic issue with the Sky X test bed or methodology that limits effectiveness—the PFF may even be closer to satisfying performance hallmarks.

The environmental fate and toxicity assessments for PFFs showed promise in comparison to the Mil-Spec. The present biodegradability results were equivocal. The completed assays indicated that all samples (including the AFFF) fell below the biodegradability index. Additional ongoing analyses (not shown) indicate that the PFF are readily broken down biologically once a microbial population develops through selection with extended exposure to the fire suppression agents (10 to 20 days). Commercial literature, along with results of the ongoing trials, suggest that a PFF formulation that transitions to DoD inventory will meet biodegradability requirement for its use.

## **5.5 COST ANALYSIS – TRANSITION AND LIFECYCLE**

The NDAA mandate dictated that the shift to a PFF will be made regardless of cost. Accordingly, it is critical to estimate the extent to which the shift to PFF will affect operating and equipment budgets. Initial projections have been made using the present costs of the commercially available foams, as discussed below, and estimated costs for retrofitting or replacing firefighting equipment. There is potential for significant cost changes from the estimates. As demand expands, costs may be reduced by economies of scale or market competition. The approach and assumptions for the present cost estimates and projections are discussed below.

Both CAF and UHP have been previously shown to substantially reduce the amount of AFFF product needed to extinguish a fire. The testing with PFFs in this project showed that CAF helped reduce the extinguishment time by an average of 44% compared to standard air aspiration. The data were used to do a preliminary analysis of the operational cost savings from use of CAF over conventional nozzles. The bulk price for PFFs (e.g., 300-gallon tote) are not readily available; for comparison the published prices of 5-gallon pails were used for calculations. Market checks showed the C6-based AFFF is \$127 for a 5-gallon pail. Using that price and the extinguishment times from trials, relative costs for using PFF with CAF and conventional (air aspiration) were calculated and are summarized in Table 10. The first estimates reveal an initial materials cost increase. The absolute cost is dependent on a combination of the product price and the effectiveness. But the present values indicate that material cost for PFF will increase compared to the Mil-Spec AFFF.

**Table 10. Relative Foam-Cost Estimates to Extinguish a 28-ft<sup>2</sup> Fire Using Selected PFFs**

| PFF     | Price/<br>Unit | Relative<br>Price | Relative<br>Quantity<br>-CAF | Relative<br>Quantity<br>-Air Asp. | Relative<br>Cost<br>-CAF | Relative<br>Cost<br>-Air Asp. |
|---------|----------------|-------------------|------------------------------|-----------------------------------|--------------------------|-------------------------------|
| 1       | \$118.75       | 0.94              | 1.64                         | 2.60                              | 1.54                     | 2.43                          |
| 4       | \$166.50       | 1.31              | 1.67                         | 1.94                              | 2.19                     | 2.55                          |
| 5       | \$95.00        | 0.75              | 2.84                         | 4.88                              | 2.13                     | 3.65                          |
| 6       | \$120.00       | 0.94              | 1.58                         | 2.44                              | 1.49                     | 2.31                          |
| 7       | \$214.00       | 1.69              | 1.79                         | 3.06                              | 3.02                     | 5.15                          |
| 8.2     | \$128.30       | 1.01              | 1.64                         | 2.08                              | 1.66                     | 2.10                          |
| Average | \$140.43       | 1.11              | 1.86                         | 2.83                              | 2.00                     | 3.03                          |

Additional extrapolation of the data can be applied to rationalizing the transition to CAF on DoD platforms. A 2011 report estimated that the USAF used 2,826,000 gallons of AFFF per year at a cost of \$18 per gallon (\$22.32 in 2022 dollars, for total cost of ca. \$66 million). Applying the relative costs from Table 10, the foam cost using CAF is twice that and standard air aspiration three times that total. Realizing that savings would mean all platforms need to have that technology; the upgrade through retrofitting and replacing platforms is a complex and expensive proposition. As an illustration, the USAF fields six core sets of fire and emergency response vehicles, each set includes structural pumpers, rescue vehicles, water tankers, crash trucks, rapid intervention vehicles, and HazMat vehicles [34]. Four of the platforms could be upgraded to CAF by using retrofits kits, 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. A 1994 report stated that a wide-ranging retrofit was feasible when a universal kit was available for upgrading platform inventory [**Error! Reference source not found.**]. Though nearly 30 years have passed since the proposal, no product has provided the versatility to approach the requirement. The class of fire truck (e.g., P-22 and P-34) is not indicative of uniformity. Rather, different manufacturers, produce makes, and models of trucks that fit the performance requirements are designated against that “class” of vehicle. The platforms’ dimensions and other specifications differ enough that a common retrofit system has not been available to market; perhaps it is not technically or economically practical.

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

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 conducted. 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. The cost to retrofit and/or replace

existing ARFF trucks with CAF (or UHP) platforms should be carried out in future when the costs for retrofitting are more narrowly defined and the performance tradeoffs decided.

The main savings provided by the shift from AFFF to PFFs will be reduced waste management burden and the associated long-term environmental restoration or remediation costs. The DoD currently treats any emergency response where AFFF is used as a hazardous material release. Hazardous waste remediation following a single crash rescue response costs ca. \$5 million to clean up after AFFF dispersal. This category applies to the legacy C8-based product *and* the C6 replacement; the transition to the more environmentally friendly PFF will save the DoD tens of millions annually in those instances. Current reports show that the Air Force spent \$974 million on PFAS-related actions to date [35]. Preliminary studies outline details for these great costs from management and remediation of PFAS contaminated sites and waters. The Air Force alone is expected to spend more than \$2 billion to clean up PFOS and PFOA contamination and safely dispose of waste; accordingly, the DoD responsibilities will be even greater. Any estimates, however, are highly speculative. There are no technologies to practically address full remediation at the scales and scope of the problem. In addition, the endpoint (acceptable level of exposure/contamination) has not been consistently defined, so the extent of treatment or number of sites that ultimately will require remediation is presently unknown and costs may be even higher.

## **5.6 ADVOCACY – REGULATORY ADVISORS AND STAKEHOLDERS**

Top level decision makers and regulatory advisors must rationally support the PFF transition in order to effectively promote change to stakeholders and users. The product rationale must be broad enough to apply across multiple agencies—principally DoD and FAA—but other federal agencies such as the Department of the Interior (wildfires), EPA, and the Center for Disease Control (public health) have responsibilities and interests that overlap with the transition outcome. State and local agencies likewise have requirements and concerns that will benefit from effective transition. In order to promote dialog and apply expertise of firefighters, notes on the perception of product usability and performance were taken at every opportunity throughout this project. Physical characteristics, such as miscibility and pumping requirements for the concentrates, were noted. Firefighters conducting the actual tests and provided immediate feedback, particularly on their observations of product performance and handling and any difficulties noted during the firefighting operation. 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. Another opportunity used the field-scale (315-ft<sup>2</sup>) firefighting demonstration: experienced stakeholders in the ARFF community observed series of test fires with different foams and delivery methods. The group included leaders and ad hoc advisors to Fire and Emergency Services Working Group, AF Fire Panel/Major Air Commands (MAJCOMS), and FAA representatives. The senior observers had the breadth of experiences and perspectives that can provide feedback and effective critique to examine and refine the transition strategy.

## **5.7 TRANSFORMATIONAL MILESTONE – THE NEW MIL-SPEC**

Rigorous, independent, and quantitative tests of PFF are the critical basis for developing physical criteria and performance standards for the fire suppression agents. The U.S. Navy is the agency responsible for the formal Mil-Spec on PFF agents (due January 2023). The draft of proposed amendments to MIL-PRF-24385F is expected to be released Summer 2022. The transition to

PFF products will include certification by NAVSEA and additions to the QPL-24385 documentation. The revised Mil-Spec will provide a keystone for transition. The physiochemical criteria will guide the formulation: e.g., viscosity, toxicity, and stability will be clearly defined targets. The performance thresholds will focus on commercial landscape. Products that do not meet extinguishment or burnback requirement that may have been previously marketed under environmentally friendly guise, will likely be held back from production until performance criteria are met.

## 6.0 CONCLUSIONS

The objective statement is straightforward—obtain a PFF that performs comparably to present fire suppression agents and can be used in present emergency response platforms and equipment without modification. Reaching that practical objective, however, is fundamentally challenged by physiochemical and mechanistic differences between AFFF and PFF. Providing information that helps users and stakeholders understand the advantages and present shortcomings of PFF will manage expectations and smooth the transition from the PFAS-based foams.

The revised requirements for the new Mil-Spec and other formal documents will use the physical characteristics and performance data of the PFF, rather than contemporary standard for AFFF that evolved over 50 years of refined formulations and firefighting practices. As an illustration, if one were to hold PFFs to a standard comparable to AFFF at a similar level of maturity, revision C of the Mil-Spec (released 1989) may be an appropriate guide. Revision C was released 20 years after AFFF was phased into DoD use, comparable to the approximately 15-year-old PFF technology. In revision C, the pass/fail limit for extinguishing the gasoline fires was 45 seconds, matching the performance of PFF when using CAF delivery platform. Continued work on delivery technologies and agent formulations will likely improve PFF and may rival contemporary AFFF suppression performance.

The test data revealed that delivery technology, specifically CAF and UHP, significantly improved PFF fire suppression performance. By coupling upgrades to firefighting platforms with the transition to PFF, the performance trade-offs are minimized. The cost of the transition due to equipment and training expenditures will be significant. The preliminary cost estimates for upgrades are highly speculative; the economics are vague because there is not a standardized platform for modification and the timeline for fleet replacement is not known. Decisions by DoD and other user groups (on the timeline in particular) will allow industry to take opportunity to shift more production of CAF and UHP technologies. The change may provide price relief that facilitates transition.

## 7.0 REFERENCES

1. *PFAS Explained*. 5/17/2022; Available from: <https://www.epa.gov/pfas/basic-information-pfas>.
2. *Risk Management for Per- and Polyfluoroalkyl Substances (PFAS) under TSCA*. 5/17/2022; Available from: <https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-and-polyfluoroalkyl-substances-pfas#tab-3>
3. Carol F. Kwiatkowski, D.Q.A., Linda S. Birnbaum, Thomas A. Bruton, Jamie C. DeWitt, Detlef R. U. Knappe, Maricel V. Maffini, Mark F. Miller, Katherine E. Pelch, Katherine E. Pelch, Anna Reade, Anna Soehl, Xenia Trier, Marta Venier, Charlotte C. Wagner, Zhanyun Wang, and Arlene Blum, *Scientific Basis for Managing PFAS as a Chemical Class*. Environmental Science and Technology Letters, 2020. 7(8): p. 532-543.
4. Crampton, G.P., & Kim, A. K. Comparison of the Fire Suppression Performance of Compressed-Air Foam with Air Aspirated and Unexpanded Foam Water Solution, in 8th Fire Suppression and Detection Research Application Symposium. 2004: Orlando, FL.
5. Kim, A.K., & Dlugogorski, B. Z. *Multipurpose overhead compressed-air foam system and its fire suppression performance*. Journal of Fire Protection Engineering, 1996. 8(3): p. 133-150.
6. Kim, A.K., & Crampton, G. P. Evaluation of the fire suppression effectiveness of manually applied compressed-air-foam (CAF) system. Fire Technology, 2012. 48(3): p. 549-564.
7. R., R., *Growing Concern Over Perfluorinated Chemicals*. Environmental Science & Technology, 2001. 35(7): p. 154A-160A.
8. Thorpe, B., Scoping Per- and Polyfluoroalkyl Substances Releases from the Recycling of Paper and Textiles and their Implications for the Great Lakes-St Lawrence River Ecosystem.
9. US Department of Health and Human Services, Agency for Toxic Substances and Disease Registry-ATSDR 1999.
10. Hetzer, R.H., Kuemmerlen, F., & Blunk, D. *Fire Testing of Experimental Siloxane-Based AFFF: Results from New Experiments*. Munster, Germany: Bundeswehr Research Institute for Protective Technologies and NBC-Protection.
11. National Library of Medicine. *Diethylene glycol monethyl ether*. Available from: <https://pubchem.ncbi.nlm.nih.gov/compound/Diethylene-glycol-monoethyl-ether#section=Safety-and-Hazards>.
12. Magrabi, S.A., Dlugogorski, B. Z., & Jameson, G. J. *Bubble size distribution and coarsening of aqueous foams*. Chemical engineering Science, 1999. 54(18): p. 4007-4022.
13. Centers for Disease Control and Prevention Prevention, *National Biomonitoring Program - Per- and polyfluorinated substances (PFAS) factsheet*. Available from: [https://www.cdc.gov/biomonitoring/PFAS\\_FactSheet.html](https://www.cdc.gov/biomonitoring/PFAS_FactSheet.html).
14. Hinnant, K.M., Giles, S. L., & Ananth, R. *Measuring fuel transport through fluorocarbon and fluorine-free firefighting foams*. Fire Safety Journal, 2017. 90: p. 653-661.
15. Hekster, F.M., Laane, R. W., & De Voogt, P. *Environmental and toxicity effects of perfluoroalkylated substances*. Reviews of Environmental Contamination and Toxicology, 2003: p. 99-121.

16. Dubocq F, W.T., Yeung LWY, Sjöberg V, Kärrman A. Characterization of the Chemical Contents of Fluorinated and Fluorine-Free Firefighting Foams Using a Novel Workflow Combining Nontarget Screening and Total Fluorine Analysis. *Environ Sci Technol*, 2020. **54**(1): p. 245-254.
17. United States Environmental Protection Agency. *Technical overview of ecological risk assessment-analysis phase, ecological effects characterization*. 2019. Retrieved 5/17/2022 from <https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/technical-overview-ecological-risk-assessment-0>
18. Schnabel, R., Process for producing foam from foam developing substances. US Patent 1874209A. 1927.
19. Bedford, H., *Fire-foam producing apparatus*. 1945. US Patent 2373009A
20. Tirrel, LL. Method and means for extinguishing fires. 1944. US Patent 23611980A
21. Urquhart RM, U.G., Method for generating and distributing fire extinguishing foam. 1940. US Patent 2198585A
22. Cummins, MA., *Foam generating firefighting device*. 1982. US Patent 4318443A
23. Wang X, L.Y., Zhang Y, Liao G., Experimental Study On Pool Fire Extinguishing With Multi-Component Compressed Air Foam. *Fire Safety Science*, 2007. **7**: p. 99.
24. SA Magrabi, B.D., GJ Jameson, A comparative study of drainage characteristics in AFFF and FFFP compressed-air fire-fighting foams. *Fire Safety Journal*, 2002. **37**(1): p. 21-52.
25. Sarma, D.S.R., & Khilar, K. C., *Effects of initial gas volume fraction on stability of aqueous air foams*. *Industrial & engineering chemistry research*, 1988. **27**(5): p. 892-894.
26. Chen, T., Fu, X.-cheng, Bao, Z.-ming, Xia, J.-jun, & Wang, R.-ji., Experimental study on the extinguishing efficiency of compressed air foam sprinkler system on Oil Pool Fire. *Procedia Engineering*. *Procedia Engineering* 2018. **211**: p. 94-101.
27. Kim, A.K., & Crampton, G. P. Application of a Newly-developed compressed-air-foam fire suppression system. in *Proceedings of INTERFLAM*. 2001
28. Grosskopf, K.R., & Kalberer, J. L. Potential Impacts of Ultra-High-Pressure (UHP) Technology of National Fire Protection Agency (NFPA) Standard 403. 2007.
29. Grosskopf, K.R., & Kalberer, J. L. *Potential impacts of ultra-high-pressure (UHP) technology on NFPA Standard 403*. *Fire Safety Journal*, 2008. **43**(4): p. 308-315.
30. Menchini, C.P., Dierdorf, D., Kalberer, J. L., McDonald, M. J., Cozart, K. S., Casarez, A., & Carr Jr, V. J., *The Development and Design of a Prototype Ultra High Pressure P-19 Firefighting Vehicle* 2007.
31. C., M., *Ultra-High Pressure: The Nuts and Bolts*. *Fire Apparatus & Emergency Equipment Magazine.*, 2014. **19**(7).
32. Clawson, C.C. *Does Ultra High Pressure Work?* 2022; Available from: <https://www.dyess.af.mil/News/Article-Display/Article/3027178/does-ultra-high-pressure-work/>
33. Schroeder, J.L., McDonald, M.J., Hawk, J.R. and Mellerski, R.C., *Field Demonstration of a Centrifugal Ultra High Pressure (UHP) P-19*. 2010.
34. <https://media.defense.gov/2018/Aug/23/2001957748/-1/-1/1/NFPA%20403%202018%20EDITION%20TIG.PDF>

35. Duncan, S, *Evaluation of NDI compressed air foam system (cafs) applied as a retrofit*. Final report, 1994, Web. <https://www.osti.gov/biblio/6877829> [osti.gov]
36. Department of the Air Force. *PFAS Snapshot*. 2022; Available from: [www.afcec.af.mil](http://www.afcec.af.mil).