Screening Tests for Fluorine-Free Firefighting Foams

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Abstract

An experimental study was performed for the United States Environmental Security Technology Certification Program (ESTCP) and Strategic Environmental Research and Development Program (SERDP) to develop bench-scale test methods and analysis techniques for screening the fire extinguishing performance and burnback (i.e., re-ignition) resistance of new PFAS-free foam formulations. These tests were intended to provide prediction about the ability of novel foams to pass the MIL-PRF-24385F (SH), Amendment 2 (MIL-SPEC) 28 ft², full-strength, fresh-water extinguishment and burnback test [1]. This test is often used as the first evaluator for firefighting performance.

Testing was conducted on nine different foams (five AFFFs and four PFAS-free foams (PFF)) to develop the bench-scale tests and criteria. Testing included measurements of the foam quality (expansion and drainage), the fluidity of the foam over a liquid, vapor retention and stability of the foam on heated fuel, and a reduced scale extinguishing and burnback test.

Recommended bench-scale screening tests include a beaker ignition test of foam over heated fuel and reduced-scale fire extinguishing / burnback. Distinct performance metrics for the beaker ignition and small pool fire tests were developed using machine learning to identify critical parameters and thresholds to predict potential passing foam solutions. A scoring system was developed to analyze the reduced-scale fire results with promise as a predictor of MIL-SPEC 28 ft² (fresh-water, full strength) extinguishing time.

Keywords: Firefighting foam; Aqueous Film Forming Foam; AFFF; Perfluorinated compounds; PFAS-free foam; extinguishing performance;

Introduction

An experimental study was performed to develop bench-scale test methods for screening fire extinguishing and burnback (i.e., re-ignition) resistance of new PFAS-free foam formulations. Data was evaluated for correlation and prediction about the ability of novel foams to pass the

MIL-PRF-24385F (SH), Amendment 2 (MIL-SPEC) 28 ft^2 (2.6 m^2) area, full-strength, fresh-water ethanol free gasoline pool fires as well as a subsequent burnback fire test [1].

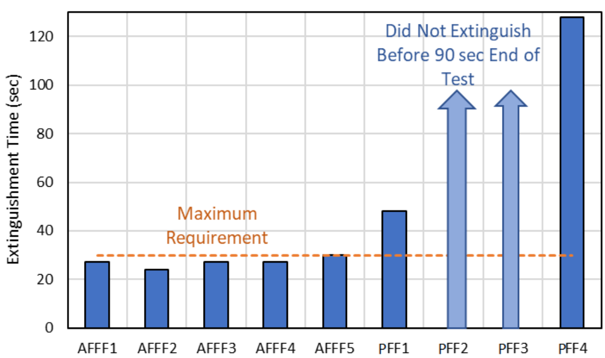
Mounting environmental pressures mounting lead the U.S. Congress to restrict the use of per and polyfluoroalkyl substances (PFAS) in the National Defense Authorization Act (NDAA) for fiscal year 2020. The use of firefighting foams containing PFAS by the military must be phased out by 2024 and an updated military test standard allowing for PFAS-free alternatives is needed, as the current Military Specification (MIL-SPEC) requires fluorinated surfactants. The Federal Aviation Administration (FAA) has also been mandated to stop the use of PFAS in foams by October 4, 2021 in the FAA Reauthorization Act of 2018. PFAS-free firefighting foams (PFFs) need to be formulated for the Department of Defense (DoD) and Civilian Aviation Applications that provide equivalent firefighting performance when compared to AFFF.

Experiments were developed to evaluate, quantify, and compare foam solutions for foam quality, fluidity, stability, and vapor retention. These metrics isolate physical mechanisms used to extinguish and prevent re-ignition of real-world fires [2] [3]. Quantifiable measures of foam performance on the bench intend to provide predictive data for foam manufacturers if chemistry or concentration modifications are required to achieve desired performance.

Tested Foams and MIL-SPEC Performance

Initial testing was conducted on nine different commercially available foams (five AFFF and four PFFs). The AFFF foams had passed or nearly passed the MIL-SPEC fire test while the PPF had failed.

Bench results were compared to MIL-SPEC 28 ft^2, full-strength, fresh-water fire extinguishing and burnback results. There are other MIL-SPEC fire performance tests but the 28 ft^2 test is often used as a first evaluation. Each of nine foams was subjected to this test and the results and criteria are shown in Fig. 1.



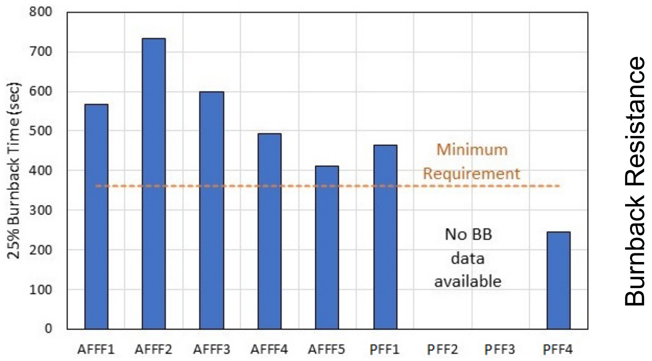


Fig. 1. MIL-SPEC scale results for evaluated foams.

Production of Foam

Foam was generated using a MIL-SPEC 2.0 GPM aerated nozzle. The quality of foam produced by the 2 GPM (7.6 LPM) MIL-SPEC nozzle was critical. This nozzle is an aerated nozzle made from a modified National Foam Systems nozzle with a "wing-tip" spreader.

The foamability (i.e., expansion ratio (ER) and 25 % drainage time (DT)) from the MIL-SPEC and alternative nozzles were measured. Despite exploring numerous nozzle/air architectures the researchers were unable to consistently produce a foam with equal quality to the MIL-SPEC nozzle. The nozzle development effort was abandoned and a foam collector and separator were constructed to distribute foam into two flow paths as shown in Fig. 2.

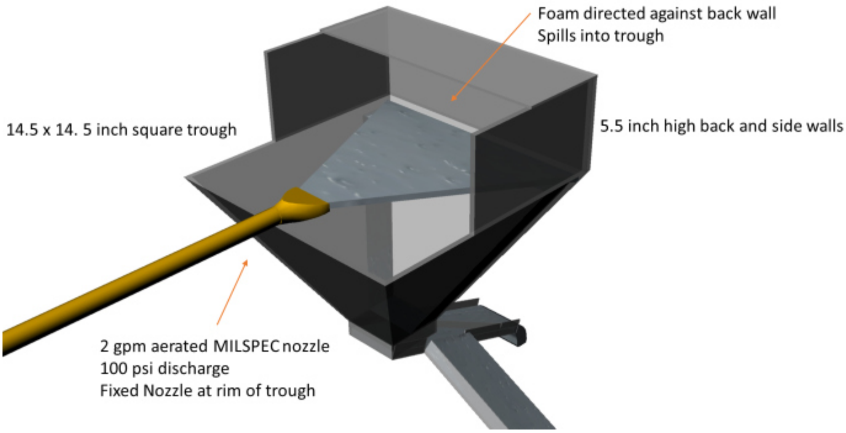


Fig. 2. Spray nozzle and foam collector and separator.

The collector and separator allowed usage of the MIL-SPEC nozzle, ensuring equivalent foamability between the bench and MIL-SPEC testing while minimizing foam consumption. A full set of tests could be conducted with a total of 1.5 gallons (5.7 l) of mixed foam solution (0.045 gallons (0.17 l) of 3 % concentrate).

Fluidity Testing

Fluidity tests measured the rate of area coverage the foam provided across water. Twenty seconds of discharge at 0.66 GPM (2.5 LPM) was applied as shown in Fig. 3. The wetted pan area was 7.07 ft² (0.66 m²), resulting in a foam application density of 0.031 gal/ft² (1.27 l/m²).

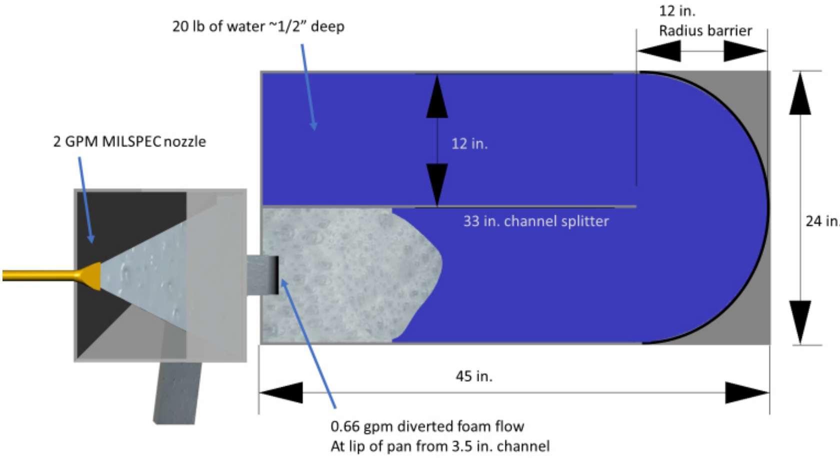


Fig. 3. Foam fluidity test pan and foam distributor.

The peak rate of coverage was slower for PFFs compared to the AFFF, and the peak amount of area covered per unit mass applied was also lower for PFF. The final coverage and mass applied were consistent between AFFF and PFFs, but the rate PFFs covered the area was slower. The average rate of coverage area is provided in Fig. 4.

All AFFFs spread rapidly at the start of the test (0-2.5 sec, 0-5 sec, and 0-10 sec) compared with the PFFs. The PFF rates were lower than AFFF for the 0-2.5 sec and 0-5 sec increments but similar at the later time increments. The AFFF began spreading quickly and slowed during the test. The maximum area covered by the AFFFs was less than or equal to the PFFs which covered more area per time later in the tests (>5 sec).

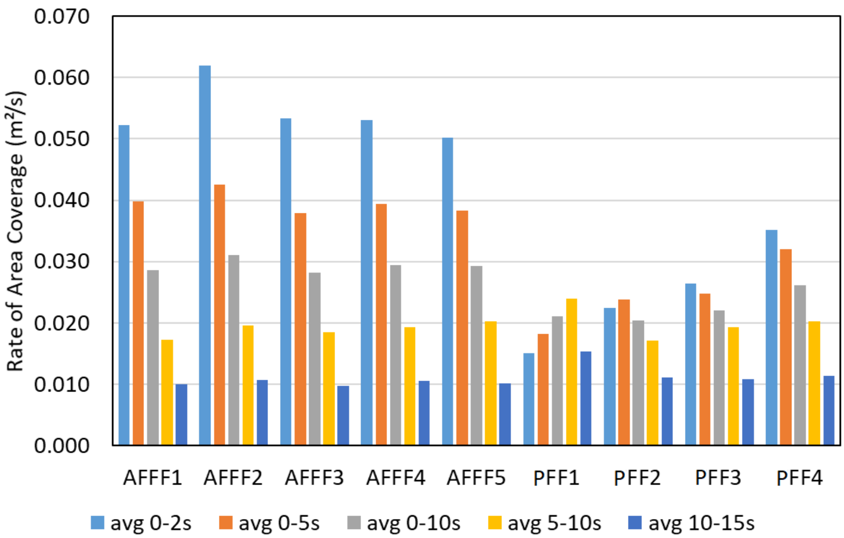


Fig. 4. Foam a) rate of area coverage averaged over different time increments.

Vapor Retention and Foam Stability

Foam was applied to either a preheated water/fuel (50 °C, 0 kW/m² external radiation) or over ambient water/fuel beneath a radiant heater (20 and 40 kW/m²). External radiation exposure is shown in Fig. 5.

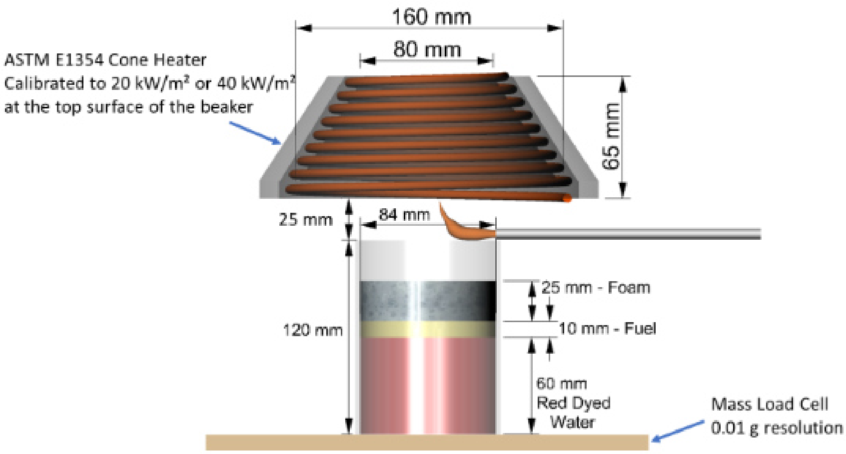


Fig. 5. Test configurations for stability of foam under external radiation.

Brief flashing ignitions and eventual sustained ignitions were recorded. Fuel vapors escape through the foam blanket and contact the pilot flame and oxygen. If sufficient vapor escapes, a flash may occur. If this flash consumes all vapor and steady release is insufficient to sustain ignition, the flash flame would extinguish, and the test was continued. If escaping vapor was steady or foam was destroyed by the heat of the flash, the flame was sustained and continued to burn.

The time for fuel vapors to penetrate through the foam blanket and ignite is believed to be an important parameter to both extinguishment and burnback performance. For tests with no flash ignition, the sustained ignition has been reported as the flashing ignition time for comparison. The flash ignition times are provided in Fig. 6.

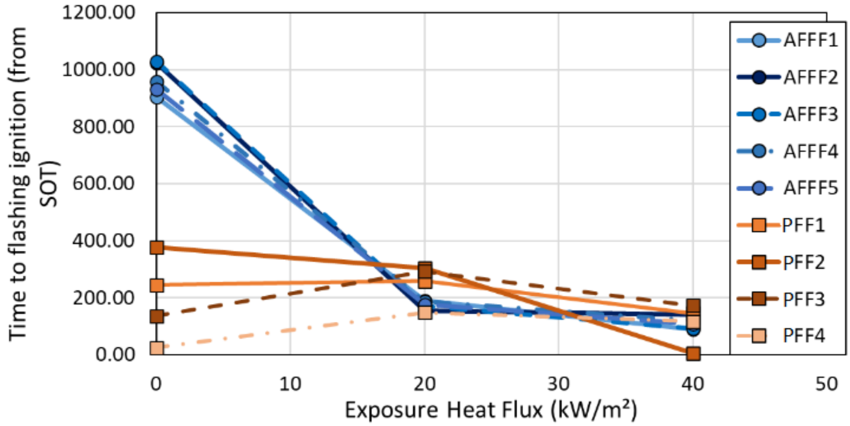


Fig. 6. Flash ignition times at different heat flux levels.

All flash ignition times for the PFFs at 0 kW/m² (with preheated fuel) occur much faster than AFFF. The flash ignition times for PFFs on preheated fuel (0 kW/m²) were approximately equal to ambient fuel heated externally by a 20 kW/m² heat flux. At both 20 and 40 kW/m², flash ignition times for all foams of both AFFF and PFF were similar.

Reduced Scale Extinguishing and Burnback

A set of increasingly challenging extinguishing and burnback tests were conducted on a 1 x 1 ft (30.5 x 30.5 cm) square pan of water and fuel. Ethanol free gasoline in accordance with MIL-SPEC Section 4.7.10.1 conforming to ASTM D4814 [1] was used. A total of 0.13 gal (500 ml) of fuel was placed atop a layer of 0.30 gal (1150 ml) of water (approx. 0.5 in. (12.7 mm) depth) of water in a steel pan 2 in. (50 mm) deep. The fuel burned freely for 10 or 20 seconds then foam was added at fixed mass. Additional foam was added after extinguishing before re-igniting the pool fire. Foam amounts were correlated with the amount of foam applied in 28 ft² and 50 ft² (2.6 m² and 4.7 m²) MIL-SPEC tests.

A scoring system was developed for analysis of the extinguishing tests data based on time to extinguish and level of fire control achieved. Scores for each of the nine foams were combined and compared against the MIL-SPEC 28 ft² (2.6 m²) extinguishment times. The scoring values were selected to provide the best correlation between datasets.

AFFF1-AFFF4 all received perfect scores of 210 for extinguishing all four fires before the threshold times. AFFF5 received a score of 180, losing points for extinguishing Tests B, C, and D slower than the threshold goals. AFFF5 did not pass the MIL-SPEC tests and extinguished the 28 ft² test slowest of the AFFF, at 30 seconds. The exponential fit of MIL-SPEC extinguishment times from the bench-scale scoring is shown in Fig. 4. The PFF are shown as orange triangles and the AFFF are tightly bunched as blue circles. PFF2 and PFF3 are shown as gray triangles as their extinguishing time is calculated from the fit and known from testing only to exceed 90 seconds when the tests were stopped.

Test Severity	Pre-burn Time (s)	Foam Added for Ext. (g)	Foam Added After Ext. (g)	MIL-SPEC Test Basis
A (Least)	10	405	None	90 seconds of 2 GPM foam applied to 28 ft² pool fire
B	10	136	269	30 seconds of 2 GPM foam applied for extinguishment and 60 seconds applied for burnback of 28 ft² pool fire
C	10	125	98	50 seconds of 2 GPM foam applied for extinguishment and 40 seconds applied for burnback of 50 ft² pool fire
D (Most)	20	125	98	50 seconds of 2 GPM foam applied for extinguishment and 40 seconds applied for burnback of 50 ft² pool fire

The curve fit matches the known extinguishing times for all 5 AFFF and PFF1 (Score – 127 → MIL-SPEC 48 seconds) and PFF4 (Score – 0 → MIL-SPEC 128 seconds). The exact MIL-SPEC extinguishing times for PFF2 and PFF3 are not known, but they did not extinguish in the 90 seconds the tests were conducted. With extinguishing scores of 32 and 40, PFF2 and PFF3 are predicted by calculation to have extinguishing times of 99 and 93 seconds, respectively. These values both fall above the 90 seconds failed tests, and so are in generally good agreement.

Recommendations and Further Study

Statistical analysis and machine learning were used to identify the most relevant bench-scale data for predicting MIL-SPEC fire performance. The beaker ignition test of foam over heated fuel and the reduced-scale pool fire suppression / burnback test provide the strongest correlations. For experimental and unproven foams, it is recommended to conduct the full suite of tests. For commercially available foam formulations, focused testing should indicate MIL-SPEC fire test performance for fresh-water, full-strength 28 ft² fires.

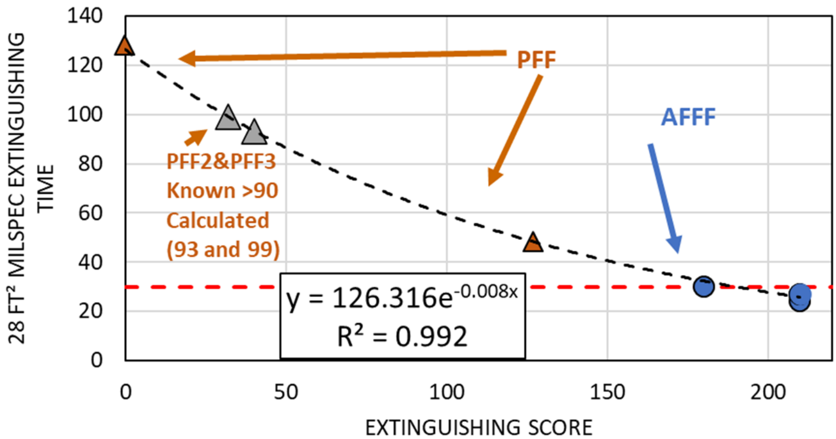


Fig. 7. Comparison between bench-scale extinguishing score and MIL-SPEC 28 ft² extinguishing time.

The primary limitation to testing is the use of the 2 GPM MIL-SPEC nozzle. Each test requires a small amount of foam and simultaneous foam capture was used to minimize waste, but this requires several staff members working together.

Matching exact foamability of multiple foams is challenging. It is unrealistic to think that alternate discharge would match the MIL-SPEC foam in expansion ratio, drainage time, bubble characteristics, and other parameters for all formulations tested. If bench results are not overly sensitive to these exact parameters reduced foam production could produce equivalently correlated performance. A series of tests conducted on several concentrates utilizing alternative foam production methods could identify if performance correlations are preserved.

The bench-scale tests can provide good distinction between the fire performance of foams. The tests can distinguish between foams of equal performance to existing AFFF, foams that meet the highest existing PFF performance, foams that meet the lower performance of existing PFF, and foams that are not close to providing MIL-SPEC performance. There is evidence that the tests can provide an approximation for MIL-SPEC 28 ft² full-strength, fresh-water extinguishing time.

Further refinement and improvement of these tests could rapidly accelerate the evaluation and production of new foams toward the goal of meeting the existing MIL-SPEC fire performance requirements.

Acknowledgements

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