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FINAL REPORT

Foam Quality Effects on PFAS Free Foam Firefighting Capabilities: A Demonstration of the Link Between Foam Quality and Extinguishment Capabilities and What's Being Produced by DoD Hardware

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14. ABSTRACT

The leading, commercially available PFAS-Free Foams (PFFs) do not form a film like the legacy Aqueous Film-Forming Foams (AFFFs) and rely solely on the foam blanket as a "mechanical" means for smothering a liquid fuel fire. Most foam approval test standards/protocols (commercial and military) use air-aspirating discharge devices to apply foam to the fire to receive an approval/listing. The current military specification (Mil-Spec) for approving AFFF (MIL-PRF-24385F) uses an air-aspirating foam discharge nozzle during the fire performance approval tests and does not consider or try to replicate the foam quality that will be produced by the various fielded discharge devices. Neither does the draft land-based Mil-Spec currently under development.

Since the new PFFs rely solely on the foam blanket to smother/extinguish the fire, foam quality will be a key consideration/parameter in actual applications that is being overlooked when considering these new PFFs as AFFF alternatives.

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ACRONYMS AND ABBREVIATIONS

AFFF	Aqueous Film-Forming Foam
CBD	Chesapeake Bay Detachment
CVN	Carrier Vessel, Nuclear
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
ft	feet
ft^2	square feet
gpm	gallon per minute
gpm/ft^2	gallon per minute per square foot
IBC	Intermediate Bulk Container (IBC)
in	in
INSURV	Board of Inspection and Survey
JH	Jensen Hughes
Mil-Spec	Military Specification
NAVSEA	Naval Sea Systems Command
NFPA	National Fire Protection Association
NRL	Naval Research Laboratory
NSTM	Naval Ships Technical Manual
PFAS	Per- and Polyfluoroalkyl substances
PFOA	Perfluoroctaneanoic acid
psi	pounds per square inch
PVC	Poly Vinyl Chloride
USN	United States Navy

EXECUTIVE SUMMARY

INTRODUCTION

The leading, commercially available PFAS-Free Foams (PFFs) do not form a film like the legacy Aqueous Film-Forming Foams (AFFFs) and rely solely on the foam blanket as a “mechanical” means for smothering a liquid fuel fire. Most foam approval test standards/protocols (commercial and military) use air-aspirating discharge devices to apply foam to the fire to receive an approval/listing. The current military specification (Mil-Spec) for approving AFFF (MIL-PRF-24385F) uses an air-aspirating foam discharge nozzle during the fire performance approval tests and does not consider or try to replicate the foam quality that will be produced by the various fielded discharge devices. Neither does the draft land-based Mil-Spec currently under development.

Since the new PFFs rely solely on the foam blanket to smother/extinguish the fire, foam quality will be a key consideration/parameter in actual applications that is being overlooked when considering these new PFFs as AFFF alternatives.

OBJECTIVES

The ultimate objective of the WP19-5374 program was to develop the link between the small-scale approval test results and the actual/expected fielded capabilities based on foam quality/aspiration and discharge rate. To make this link, the foam quality produced by the various discharge devices used by DoD needed to be characterized and an understanding of the capabilities of these new PFFs as a function of foam quality needed to be developed.

TECHNICAL APPROACH

The WP19-5374 program consisted of two separate/parallel tasks; a demonstration (and characterization) of the foam quality produced by the various discharge devices used throughout the DoD, and a demonstration of the capabilities of these new PFFs as a function foam quality and flow rate using the Mil-Spec fire tests as the basis of this demonstration. These two tasks are summarized in the following sections.

Foam Quality Measurements

The top four PFFs identified during WP19-5324 were selected for this evaluation. These PFFs included Bio-Ex ECOPOL A3+, Fomtec Enviro USP, National Avio Green and Solberg RE-HEALING RF3. The performance of these PFFs were benchmarked during this effort against a C6 QPL Mil-Spec AFFF (Buckeye Type 3).

The foam quality measurements (i.e., equipment and procedures) made during this program were in accordance with NFPA 412/NFPA 1900 which is incorporated in the current Mil-Spec. An illustration of a foam quality test of a hose line nozzle and the measurement apparatus is shown in Figure 1. Per the requirements, both the expansion ratio and drainage time were measured and recorded for each discharge device. However, the focus of the analysis and discussion is based on the expansion ratio (i.e., the degree of aspiration).

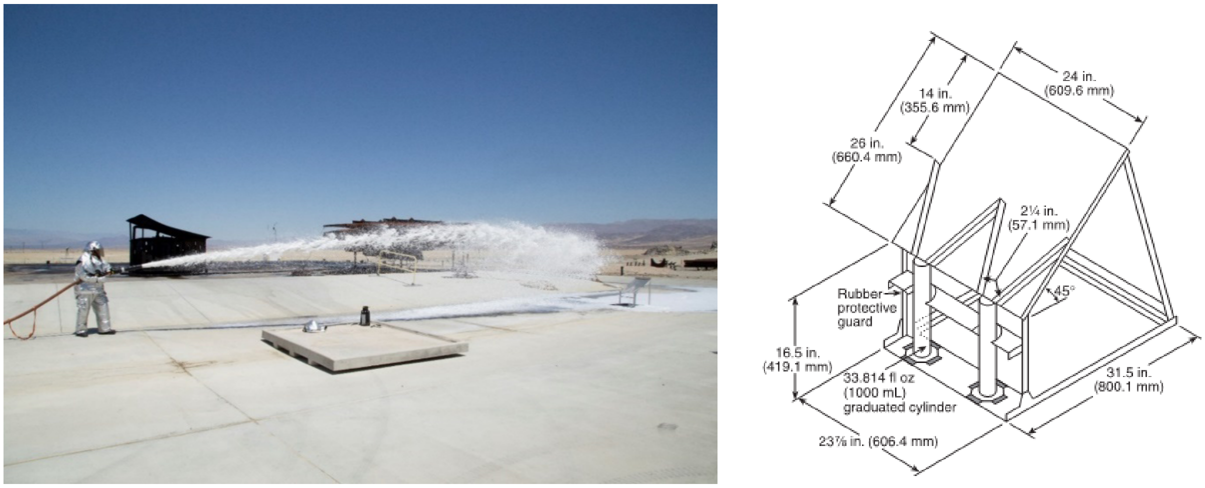


Figure 1. Foam Quality Test Photograph and Collection Backboard

The foam quality of 15 discharge devices was characterized during this program. An illustration of the various types of nozzles is provided in Figure 2.

Fixed Non-Air-Aspirated Nozzles	**Fixed Air-Aspirated Nozzles**	**NAVFAC Hangar Nozzle**
		
Hose Line Nozzles	**Bumper/Roof Turret Nozzles**	**Foam Tubes**
		

Figure 2. Types of Discharge Devices

Firefighting Performance Assessments

The firefighting capabilities (extinguishment and burnback resistance) of the PFFs were determined using the 28 ft^2 pool fire test described in MIL-PRF-24385F as a function of foam quality (expansion ratio). These tests were conducted using the exact same equipment and test personnel that typically perform the MIL-PRF-24385F / QPL approval tests. A photograph of a 28ft^2 pan fire test is provided as Figure 3.

Figure 3. 28ft^2 Pan Fire Test

The firefighting capabilities of each PFF was quantified over a range of expansions (i.e., 2-9 expansion ratios) against two different test fuels (i.e., the legacy unleaded zero alcohol gasoline and Jet A) with two foam solution flow rates 2 gpm and 3 gpm. The degree of foam solution aspiration was varied by partially blocking the aspiration openings on the standard Mil-Spec nozzle. A schematic of the Mil-Spec nozzle is provided as Figure 4.

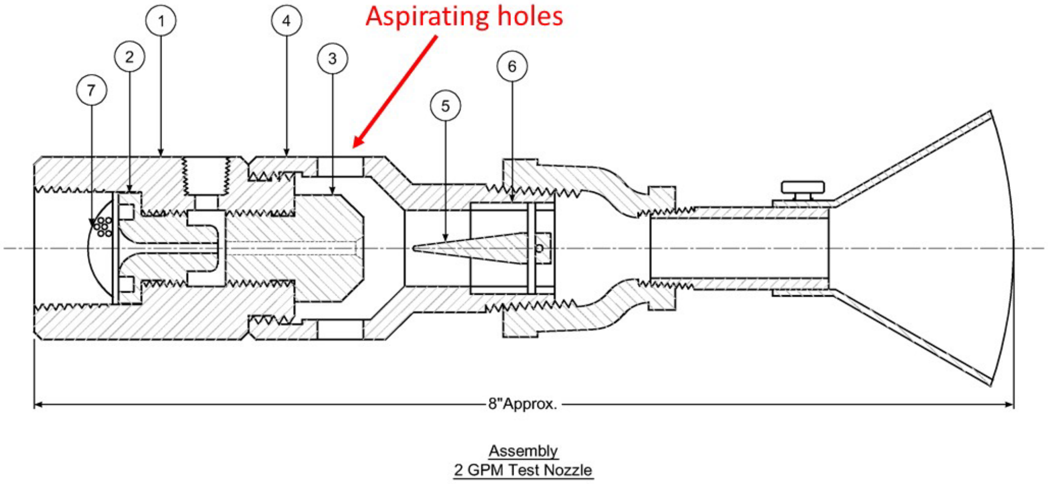


Figure 4. Mil-Spec Nozzle Schematic

RESULTS AND DISCUSSION

Foam Quality Results

As a general statement, all of the commercially available PFFs are "foamier" (i.e., produce better expanded foam solutions) than legacy AFFFs when discharged through the same device. Specifically, the expansion ratios of the PFFs were typically 1-3 expansion points higher than AFFF when discharged through the same device, under the same conditions (i.e., pressure). The drainage times of the Newtonian PFFs are comparable to AFFF while the non-Newtonians have much longer drainage times than AFFF.

With respect to discharge device, the foam quality was typically similar for discharge devices that incorporate the same mechanism to aerate/aspirate the foam solution. For example, typical, non-air-aspirating fire hose nozzles and turret nozzles rely on the sheering of the foam solution stream as it flies through the air to aspirate the foam. As a result, the foam qualities produced by most of fire hose and turret nozzles were similar independent of solution flow rate (e.g., there was little difference between 250 gpm turret nozzles and 500 gpm turret nozzles). As another example, there was little difference between "sprinkler head" type discharge devices since they all rely in the deflector plate to aspirate the foam solution.

Circling back to the discussion on fire hose and turret nozzles, it was determined that the foam quality produced by these devices are a function of spray pattern (i.e., angle). Specifically, a narrow 5-10 degree fog pattern tended to be the best compromise between stream reach and aspiration/expansion and tended to increase the expansion by 2-3 points with only a minimal reduction in stream reach (i.e., about a 10-15% reduction in reach). Conversely, straight stream provided the greatest reach but the lowest foam quality/expansion.

A high-level summary of the foam quality (expansion ratio) produced by the various types of nozzles when discharging the PFFs is provided as follows:

- Fixed system nozzles (non-air-aspirating) used by DoD (between 2-5 exp.)
    - 2-3 expansion for standard orifice nozzles and 4-5 for deflector plate nozzles
- Fixed system nozzles (air-aspirating) used by DoD (between 8-10 exp)
- Fixed system NAVFAC Grate Nozzle (between 6-9 exp)
- Manual firefighting nozzles used by DoD (between 2-6 exp., pattern dependent)
    - 2-4 expansion for straight stream and 4-6 for narrow angle patterns (5-15 degrees)
- Firefighting vehicle nozzles used by DoD (between 2-6 exp., pattern dependent)
    - 2-4 expansion for straight stream and 4-6 for narrow angle patterns (5-15 degrees)
- Foam tubes and legacy protein foam hardware (8-20 flow rate dependent)

As a point worth noting, one of the primary uses of AFFF in land-based applications for DoD is a fixed system used to protect US Navy Aircraft hangars. These hangars are protected using a floor level system consisting of Viking Grate Nozzles (Viking 200 GN nozzles) which are non-air aspirated.

However, during this study, these Grate Nozzles were shown to produce surprisingly good foam quality (expansion ratios in the range of 6-9), much higher than the other non-air-aspirating nozzles.

Firefighting Performance Results

Prior to discussing the fire performance results, it needs to be noted that the extinguishment times are a function of application rate, foam quality (i.e., aspiration/expansion), and application technique. Specifically, reduced foam quality can be compensated for by increased application rate and vise-a-versa. With that said, the focus of the following discussion is to illustrate the effects/trends of foam quality on performance (i.e., both extinguishment and burnback/vapor suppression) to aid in the selection of discharge devices when deploying these products in the near future and/or to identify potential concerns if deploying these products in legacy systems.

Starting with the extinguishment capabilities of the PFFs, the extinguishment times for the four PFFs at an application rate of 0.07 gpm/ft^2 are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.

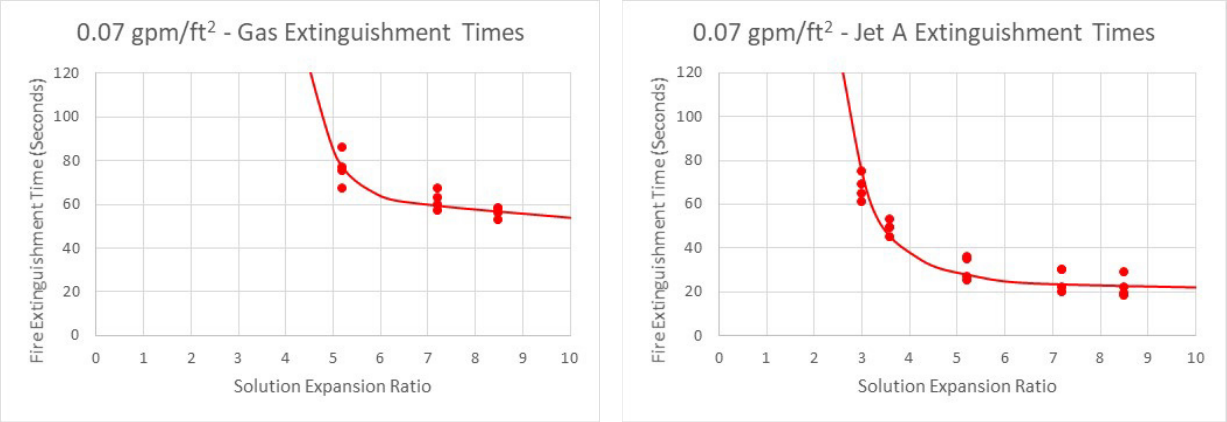


Figure 5. PFF Extinguishment Time versus Expansion Ratio Plots

As shown in Figure 5, the PFF extinguishment times were very similar for the four PFFs (and can be estimated using a single line correlation) but varied significantly between the two test fuels. When extinguishing gasoline (left side plot), the expansion ratio of the PFFs needed to be above 5-6 for the extinguishment times to become fairly consistent requiring about 50-60 seconds to extinguish the fire. Below an expansion of 5, the extinguishment times rapidly increase with decreased expansion.

Similar trends are observed for the PFFs against Jet A but at slightly lower expansion ratios. For Jet A, once the expansion ratio exceeded 4-5, the extinguishment times were fairly consistent requiring about 25-30 seconds to extinguish the fire (right side plot). Below 4, the PFF extinguishment times rapidly increase with decreased expansion.

The 25% burnback times varied between the PFFs as a function of concentrate viscosity. Specifically, the thicker, non-Newtonian products (i.e., Fomtec and Solberg) had much longer burnback times than the thinner, Newtonian products (i.e., Bio-Ex and National). However, the draft land-based Mil-Spec viscosity requirements prevent the approval of these non-Newtonian products channeling the following discussion to focus on the Newtonian PFFs.

The 25% burnback times for the two Newtonian PFFs are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 6 and can be estimated using a single line correlation.

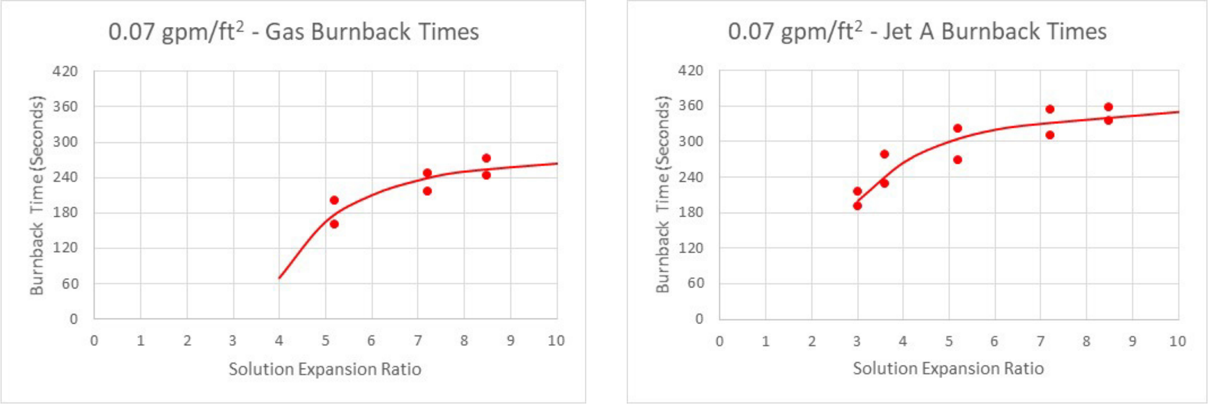


Figure 6. Newtonian PFF Burnback Time versus Expansion Ratio Plots

As shown in Figure 6, the Newtonian PFFs needed to be above 6 for the burnback times to become fairly consistent providing about 4 minutes (240 seconds) of protection against gasoline. Below an expansion ratio of 5, the Newtonian PFF burnback times for gasoline rapidly decreased with decreased expansion to just under 3 minutes (~170 seconds) when the expansion ration was reduced to 5. Similar trends were observed for the Newtonian PFFs against Jet A but at lower expansion ratios. For Jet A, once the PFF expansion ratios exceeded between 4-5 the burnback times became fairly consistent providing about 5-6 minutes (300-360 seconds) of protection. Below an expansion ratio of 4, the Newtonian PFF burnback times for Jet A gradually decreased with decreased expansion to just over 3 minutes (180 seconds) when the expansion ration was reduced to 3.

The effect of increasing the foam application rate on the PFF capabilities was also quantified and is shown in Figures 7 & 8. As expected, increasing the application rate increased the firefighting capabilities of the PFFs (reduced the extinguishment times and increased the burn back protection) and tended to reduce the critical expansion ratio of the solution. In general, a 50% increase in application rate tended to decrease the extinguishment times by about 20% and shifted the "L" curve to the right by one expansion point. This 50% increase in application rate also tended to increase the burnback times by about 50%.

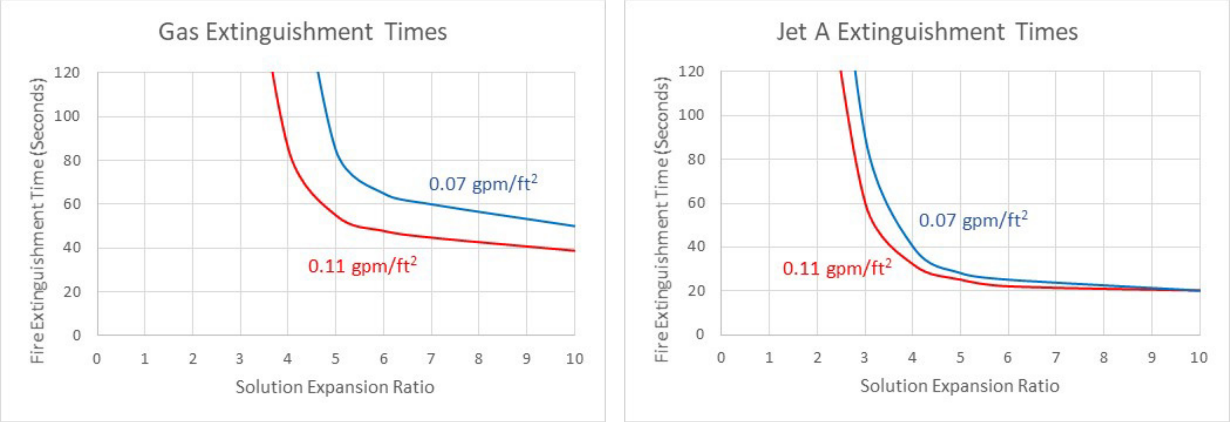


Figure 7. Application Rate Effects on the Extinguishment Capabilities of the PFFs

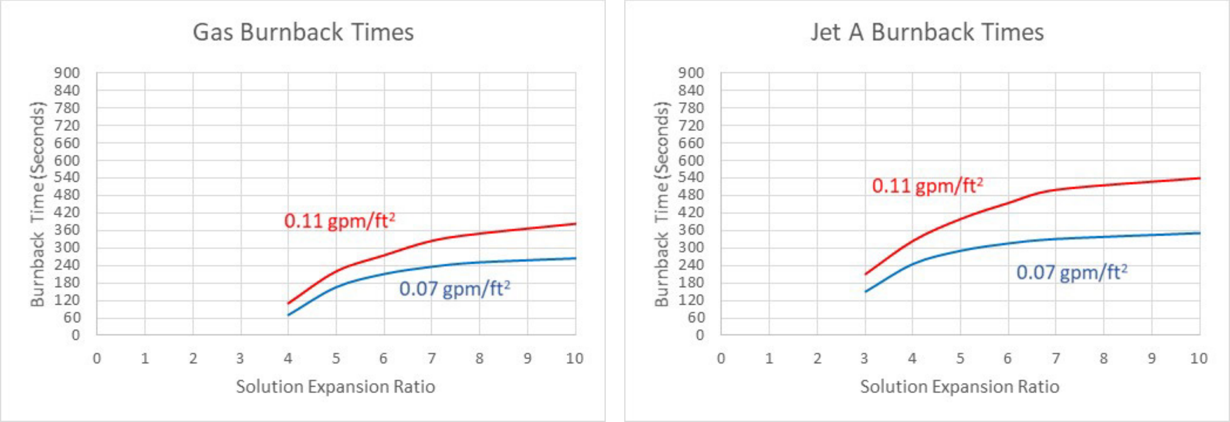


Figure 8. Application Rate Effects on the Burnback Protection Capabilities of the PFFs

IMPLICATIONS FOR DEPLOYING PFFS AS AFFF ALTERNATIVES

Taking a conservative approach to applying the fire performance data to the various discharge devices used by DoD, the critical expansion ratio appears to be about 4 to cover the two fuels used during this assessment. Specifically, gasoline fires are very difficult to extinguish using a PFF if the expansion ratio of the foam solution is below 5. Consequently, any situation where the design application rate is less than 0.11 gpm/ft^2 and the foam expansion is below 5, is potentially problematic and warrants additional consideration/assessment, especially if the hazard is gasoline. If the hazard is a kerosene-based fuel like Jet A/JP-8/F-24, the critical expansion ratio is about 3 for typical design application rates.

For fixed fire suppression systems, potential areas of concern include systems that use straight orifice type discharge nozzles in general and deflector plate discharge nozzles if the hazard being protected is gasoline.

Looking specifically at the NAVFAC hangar fire suppression system consisting of Viking Grate Nozzles, the combination of the good foam quality produced by the nozzles (i.e., 6-9 expansion), the system design application rate (0.1 gpm/ft^2) and the kerosene-based fuel hazard provides a high level of confidence that the system will provide adequate when discharging PFF solution.

With respect to manual firefighting, the data suggests that the use of a straight stream could be problematic unless the foam is “bounced off” of the deck/ground in front of the fire to help agitate the foam. Conversely, the data suggests that the use of a narrow angle fog pattern (i.e., 5-10 degrees) can increase the foam expansion by a few points and lead to faster extinguishment times. This was, to some degree observed during the large-scale validation tests conducted at NAWC-CL in 2021 (WP21-3461 and WP21-3465).

During Phase I of the large-scale tests conducted at Naval Air Warfare Center – China Lake (NAWC-CL), large 2500-2800 ft^2 F-24 spill fires were manually extinguished using a 125 gpm vari-nozzle in various configurations: the standard nozzle without attachments, the standard nozzle with a long (lower aspiration) foam tube, and the standard nozzle with a short (higher aspiration foam tube). The standard nozzle without attachments provided a 75 ft effective reach of foam solution with an expansion ratio in the range of 4-6. The longer foam tube provided a 65 ft effective reach of foam solution with an expansion ratio in the range of 7-9. The shorter foam tube provided a 45 ft effective reach of foam solution with an expansion ratio in the range of 12-23.

In general, the large-scale results were consistent with the findings of this study in that the standard nozzle configuration produced foam quality near the critical values (4-6 expansion range) and the use of the long tube typically resulted in faster extinguishment with expansion ratios 7-9 range. Specifically, the standard nozzle (without attachments) produced foam qualities/expansion ratios near the “knee” of the extinguishment time curves while the foam tube produced foam qualities/expansion ratios in the flat/level region of the curve.

With respect to burnback protection, immediately after the spill fires were extinguished, a small hole was created in the foam blanket and ignited using one of the brush burner propane torches. Although the fuel was still hot, it typically took between 3-5 minutes to ignite (i.e., it was much harder to ignite than the fuel discharged from the fuel truck). In all cases, the fires tended to grow slowly once ignited, but in general, the foam tube typically increased the burnback times by about a minute for all foams.

The take-aways of the large-scale tests as they pertain to foam quality are consistent with the findings of this program. It appears that after an initial attack on the fire with a straight stream, the next steps should be to slightly increase the spray pattern angle to extinguish any remaining small pockets of fire and to blanket the fuel surface with higher aspirated foam (i.e., foam with a higher expansion ratio). An assessment of various discharge approaches, tactics, and potential hardware/nozzle modifications has been proposed and will be conducted as the third phase of the large-scale test program.

SUMMARY AND CONCLUSIONS

The ultimate objective of the WP19-5374 program was to develop the link between the small-scale approval test results and the actual/expected fielded capabilities. When applying the fire performance data to the various discharge devices used by DoD, the critical expansion ratio appears to be about 5 to cover the two fuels used during this assessment. Specifically, gasoline fires are very difficult to extinguish using a PFF if the expansion ratio of the foam solution is below 5. Consequently, any situation where the design application rate is less than 0.11 gpm/ft^2 and the foam expansion is below 4, is potentially problematic and warrants additional consideration/assessment, especially if the hazard is gasoline. If the hazard is a kerosene-based fuel like Jet A/JP-8/F-24, the critical expansion ratio is about 4 for typical design application rates.

For fixed fire suppression systems, potential areas of concern include systems that use straight orifice type discharge nozzles in general and deflector plate discharge nozzles if the hazard being protected is gasoline. With respect to manual firefighting, the data suggests that the use of a straight stream could be problematic unless the foam is "bounced off" of the deck/ground in front of the fire to help agitate the foam. Conversely, the data suggests that the use of a narrow angle fog pattern (i.e., 5-10 degrees) would increase the capabilities to potentially acceptable levels. These concerns were observed during the large-scale validation tests conducted at NAWC-CL in 2021 (WP21-3461 and WP21-3465).

IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

The WP19-5374 data set provides a tool to estimate the capabilities of legacy AFFF systems and hardware during the transition from AFFF to these new PFFs. Additional areas of research that would benefit DoD include the development of new replacement nozzles for the ones that have been identified as potentially problematic during this study. With respect to manual firefighting, there is a need to explore enhancements to delivery equipment and/or improvements to application techniques and tactics to compensate for deployment of less effective agents.

Methods of improving the performance of PFFs as it relates to foam quality and spray characteristics that have been proposed as a Phase III effort to WP21-3461 and WP21-3465 include:

1. Development of novel nozzle designs specifically suited to discharge of PFFs (i.e., variable aspiration while maintaining pattern control).
2. Improvements to application techniques and firefighting tactics/doctrine (aggressive sweep of leading edge with a narrow spray pattern, impacting the foam solution on the deck directly in front of the fire to roll the foam blanket onto the burning fuel, side to side discharge that "rains" the foam solution down on the front edge of the fire, low delivery with a nozzle angle pattern to push foam across fuel surface, as well as others).

1.0 INTRODUCTION

The firefighting foams (Aqueous Film Forming Foam (AFFF)) currently used by the Department of Defense (DoD) and civil aviation are facing increasing regulatory scrutiny throughout the world due to both environmental and human health concerns associated with fluorinated surfactants. In December 2019, Congress passed the FY20 National Defense Authorization Act (NDAA), which prohibits uncontrolled release of AFFF at military installations except in emergency response or in training or testing if complete containment, capture and proper disposal is in place [1]. The NDAA also requires the development of a new land-based foam specification to aid in the phase out of PFAS (Per- and Polyfluoroalkyl Substances) containing AFFF at all land-based military installations by 2024 (with tightly limited extensions totaling up to 2 years). As a result, DoD needed to develop and/or identify environmentally acceptable alternatives that can provide equivalent firefighting capabilities as the foams that are currently being used.

During the SERDP/ESTCP WP19-5324 program, a detailed literature search was conducted to identify all the commercially available PFAS-Free Foams (PFFs). During the approval scale testing, over 25 of the commercially available products were tested against the 28 ft^2 pan fires described in the Mil-Spec (MIL-PRF-24385F) using two fuels (ethanol free gasoline and Jet A) [2,3]. The approval scale test results identified five commercially available PFFs that demonstrated superior firefighting capabilities. However, the tests series demonstrated some potential limitations of these products associated with the need for the discharge device to aspirate the foam to produce good foam quality.

The leading, commercially available PFFs do not form a film like the legacy AFFFs and rely solely on the foam blanket as a "mechanical" means for smothering a liquid fuel fire. Most foam approval test standards/protocols (commercial and military) use air-aspirating discharge devices to apply foam to the test fire to receive an approval/listing. The current military specification (Mil-Spec) for approving AFFF (MIL-PRF-24385F) uses an air-aspirating foam discharge nozzle during the fire performance approval tests and does not consider or try to replicate the foam quality that will be produced by the various fielded discharge devices. Neither does the draft land-based Mil-Spec currently under development [4].

Since the new PFFs rely solely on the foam blanket to smother/extinguish the fire, foam quality is a key consideration/parameter in actual applications that is being overlooked when considering these new PFFs as AFFF alternatives. The WP19-5374 program was established to demonstrate the capabilities of these new PFFs from a mechanistic standpoint (i.e., foam quality) as well as the need to link the small-scale approval test conditions to actual fielded conditions (i.e., determining the foam quality produced by legacy, DoD discharge devices).

2.0 OBJECTIVES

The technical objectives of this effort were to demonstrate (and to develop an understanding of) the effect that foam quality has on the firefighting capabilities of the new PFFs and relate these capabilities to the foam qualities produced by the various discharge devices used throughout the DoD. To develop this relationship, the foam quality produced by the various discharge devices used by DoD needed to be characterized and an understanding of the capabilities of these new PFFs as a function of foam quality needed to be developed.

The main technical questions that were answered during this program are:

- What are the firefighting capabilities of PFFs as a function of foam quality (expansion ratio and drainage time)?
- What foam quality is produced when PFF is discharged through typical DoD hardware?
- And, by combining this information, identify the expected firefighting capabilities of the currently installed DoD hardware if the AFFF is replaced by a PFF?

3.0 TECHNICAL APPROACH

The WP19-5374 program consisted of two separate/parallel tasks:

- Task 1 - Measure the foam characteristics produced by the various discharge devices used throughout the Department of Defense (DoD) as well as legacy protein foam devices.
- Task 2 - Demonstrate how foam quality (expansion ratio and drainage time) effects the capabilities of the newly developed PFAS Free Foams (PFFs).

On completion of the of the two parallel efforts, the information was combined to provide a means of estimating the capabilities of these new AFFF alternatives if discharged through current DoD systems and hardware.

During the WP19-5324 program, five PFFs demonstrated superior firefighting capabilities as compared to the other commercially available products. Two of these products have the same formulations but are made in different countries. As a result, only four PFFs were selected for these evaluations. These PFFs included Bio-Ex ECOPOL A3+, Fomtec Enviro USP, National Avio Green, and Solberg RE-HEALING RF3. During the firefighting performance assessments, the capabilities of these products were benchmarked against an C6 AFFF currently on the Qualified Products List (QPL) (i.e., Buckeye Type 3) [5].

4.0 TASK 1 FOAM QUALITY PRODUCED BY DOD AND LEGACY HARDWARE

4.1 FOAM QUALITY TEST OBJECTIVES

The specific objectives of Task 1 were to characterize/measure the foam quality produced by typical DoD discharge devices at their intended operating pressures/flow rates. An illustration of the "types" of discharge devices assessed during this program is provided as Figure 4.1.

Figure 4.1 Types of Discharge Devices

4.2 TEST SETUP AND DESCRIPTION

4.2.1 Test Facilities

The tests were conducted at numerous facilities including the laboratory at Jensen Hughes (JH), Chesapeake Bay Detachment (CBD) of the Naval Research Laboratory (NRL), and Naval Air Warfare Center, China Lake (NAWC-CL). In addition, previous data collected at Tyndall Air Force Base and Underwriters Laboratories was also included in this assessment.

4.2.2 Foam Concentrates

The four PFFs included in this assessment are listed in Table 4.1. The foam quality tests were conducted with one Newtonian PFF (National Avio Green) and one non-Newtonian (Solberg RE-HEALING RF3), highlighted in yellow below. Based on the foam quality measurement made during the WP19-5324 program, the Newtonian foams produced similar foam qualities and the non-Newtonian foams produce similar foam qualities with only slight variations between the two types of foam concentrates (i.e., the non-Newtonian are slightly foamier and have longer drainage times than the non-Newtonian products). The foam qualities produced by the PFF were were benchmarked against an C6 AFFF currently on the QPL (i.e., Buckeye Type 3).

Table 4.1 PFF Concentrates

Manufacturer	Foam Name	Type	Viscosity
Buckeye	Mil-Spec Type 3	AFFF	Newtonian
Bio-ex	ECOPOL A3+	PFF	Newtonian
Fomtec	Enviro USP	PFF	Non-Newtonian
National	Avio Green	PFF	Newtonian
Solberg	RE-HEALING RF3	PFF	Non-Newtonian

4.2.3 DoD Discharge Devices

A literature search was conducted to identify the types and manufacturers of the discharge devices used in legacy DoD AFFF systems including devices used for manual firefighting (i.e., hose line nozzles and vehicle turrets). The discharge devices selected for this program are summarized in Table 4.3. The operating pressures and flow rates are shown in Table 4.4.

Table 4.2 DoD Discharge Devices (Description)

Manufacturer	Model	Description
Tyco	B1	Air-aspirating nozzle used in hangar bays on USN ship as well as other deluge foam systems
Bete Fog Nozzle	TF29	Open head non-aspirating nozzle used in bilges and generator spaces on USN ship as well as other deluge foam systems
Globe	GL5601	Closed head foam sprinkler nozzles use in numerous applications such as flammable liquid storage configurations
Viking	GN200/360	NAVFAC hangar nozzle
Elkhart	SFL-GN-95	Typical USN Flight Deck hose line nozzle
Akron Brass	3023	Typical USN ARFF hose line nozzle
Task Force	ME1VPGI-125	Commercial 125 gpm hose line nozzle
Akron Brass	3352	Typical DoD 250 gpm ARFF truck bumper turret
Akron Brass	3353	Typical DoD 500 gpm ARFF truck bumper turret
Rosenbauer	RM25	Typical DoD 250 gpm ARFF truck bumper turret

Table 4.3 DoD Discharge Devices (Flow Characteristics)

Manufacturer	Model	Type	Pressure (psi)	K-factor (gpm/psi$^{1/2}$)	Flowrate (gpm)
Tyco	B1	Air-aspirating Sprinkler Nozzle	40	3.0	19
Bete Fog Nozzle	TF29-180-24	Industrial Spray Nozzle	30	3.0	16
Globe	GL5601	Sprinkler Nozzle	10	5.6	18
Viking	GN 200/360	Hangar Nozzle	43	23.4	150
Elkhart	SFL-GN-95	Hose Nozzle	100	9.5	95
Akron Brass	3023	Hose Nozzle	100	12.5	125
Task Force	ME1VPGI-125	Hose Nozzle	100	12.5	125
Akron Brass	3352	Turret Nozzle	100	25.0	250
Akron Brass	3353	Turret Nozzle	100	50.0	500
Rosenbauer	RM25	Turret Nozzle	100	100.0	1000

4.2.4 Legacy Protein Foam Discharge Devices

A literature search was conducted to identify the types and manufacturers of the discharge devices used in legacy protein foam systems including devices used for manual firefighting (i.e., hose line nozzles and vehicle turrets). The protein foam discharge devices selected for this program are summarized in Table 4.5. The operating pressures and flow rates are shown in Table 4.6.

Table 4.4 Protein Foam Discharge Devices (Description)

Manufacturer	Model	Description
Angus Fire	K40	Air-aspirating open head used in deluge foam systems
National Foam	JS-10	Legacy 100 gpm hose line nozzle
National Foam	PC-31	Legacy DoD 250 gpm turret nozzle
Task Force Tips	FJ-LX-HM	Multi-purpose foam tube low aspiration
Task Force Tips	FJ-MX-HM	Multi-purpose foam tube high aspiration

Table 4.5 Protein Foam Discharge Devices (Flow Characteristics)

Manufacturer	Model	Type	Pressure (psi)	K-factor (gpm/psi$^{1/2}$)	Flowrate (gpm)
Angus	K40	Fixed Nozzle	15	2.6	10
National Foam	JS-10	Hose Nozzle	100	10.0	100
National Foam	PC-31	Turret	100	26.0	260
Task Force Tips	FJ-LX-HM	Hose Nozzle	100	12.5	125
Task Force Tips	FJ-MX-HM	Hose Nozzle	100	12.5	125

4.2.5 Foam Solution Discharge System

A variety of pumping systems were used to supply the nozzles with foam solution for the foam quality testing. These include:

- The 20-gallon pressure vessel used during Mil-Spec testing at CBD,
- A 150 gpm / 100 psi portable Honda gasoline pump at CBD,
- A 1500 gpm / 150 psi trailer-mounted Darley pump at NAWC-CL, and
- The 500 gpm / 150 psi P-25A USN shipboard firefighting vehicle at NAWC-CL.

In all cases, the foam solutions were premixed, and the concentration verified using a using a Palm Abbe digital refractometer.

4.2.6 Foam Quality Measurements

The foam collection method and measurement procedures used during this test program were in accordance with NFPA 412/NFPA 1900 (also used by the USN to measure foam quality during the Mil-Spec certification process) [3,6]. Per these documents, both the expansion ratio and drainage time were measured and recorded. A photograph of an actual test and an illustration of the foam collection backboard is provided as Figure 4.3.

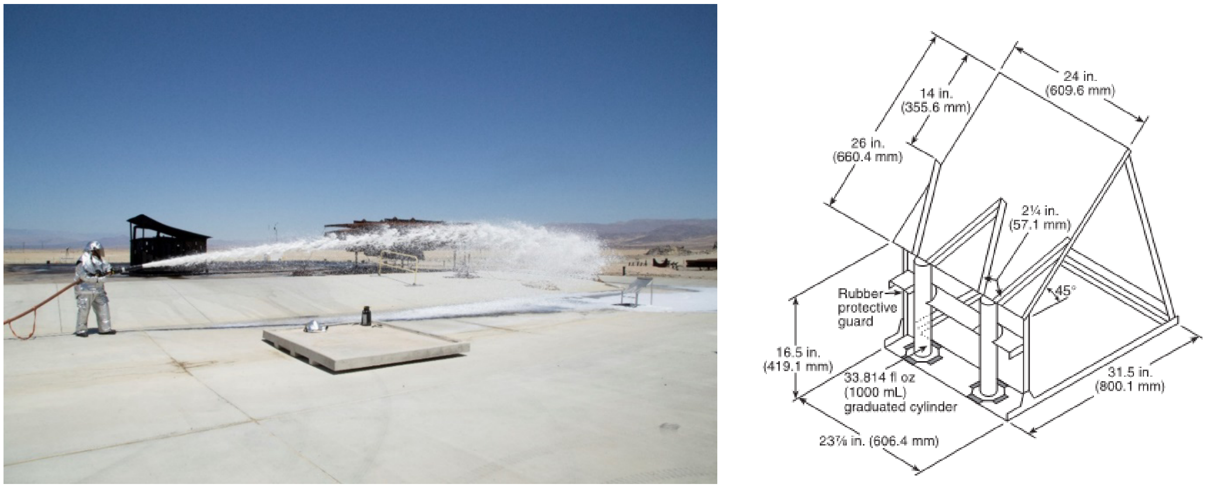


Figure 4.2 Foam Quality Test Photograph and Collection Backboard

During the tests conducted with the fixed nozzles, the foam was initially discharged from the nozzle to determine the appropriate location to place the foam collection backboard to get an accurate measurement. It became a trial-and-error process until the correct location was identified. Photographs showing the foam is charged onto the deck during the pattern test and then the placement of the collection board are shown in Figure 4.4.

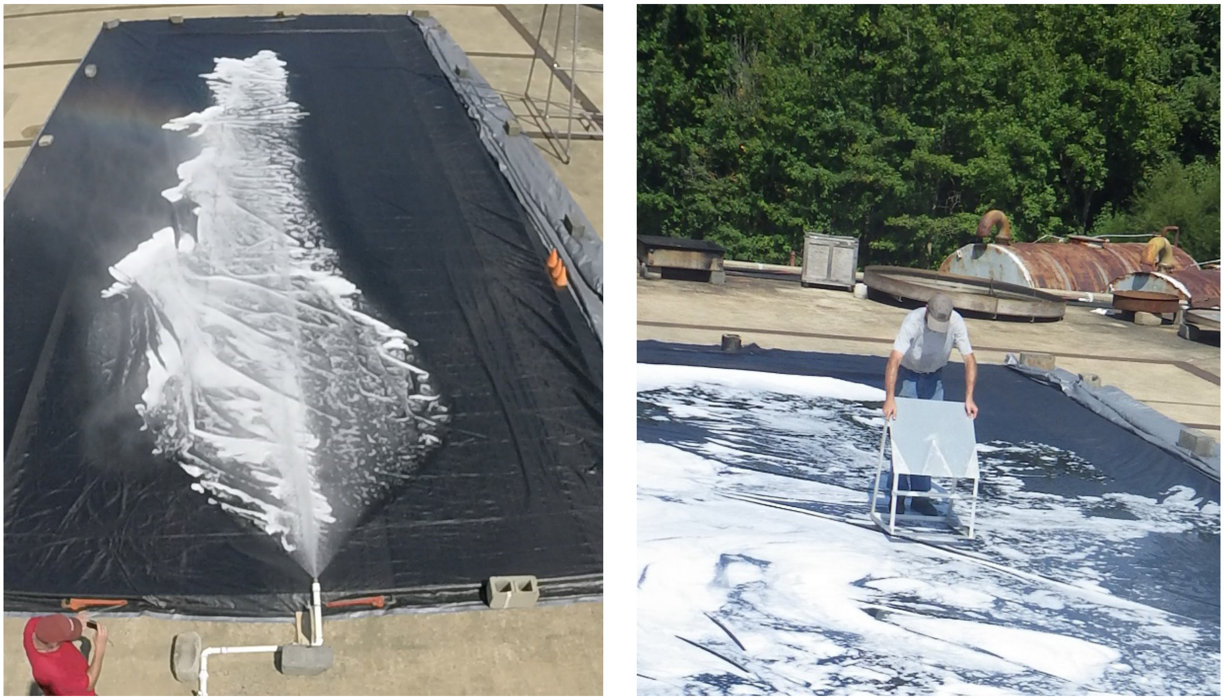


Figure 4.3 Collection Backboard Placement for Fixed Nozzles (Iterative Process)

4.2.7 Foam Quality Test Procedure.

As a high-level description of the test procedures, two, pre-weighed 1000 ml graduated cylinders were placed at the bottom of the collection board such that the foam that hits the board flows down into the cylinders (as shown to the right in figure 4.3). The foam solution was either sprayed onto the collection board or the board was positioned in the spray pattern at a location the is representative of the entire spray (i.e., an aera in the spray pattern with a high density of solution). As soon as the foam sample containers were filled with foam, the discharge nozzle was shut off and the timing of the 25 percent drainage started. The foam sample containers were quickly removed from the base of the foam collector, excess foam struck off the top of the foam containers using a straightedge, and any remaining foam wiped from the outside surface of the containers. Each container was then weighed and placed on a level surface at a convenient height.

At 30-second intervals, the level of accumulated liquid (i.e., non-aspirated solution) in the bottom of the cylinder was noted and recorded. The drainage was recorded until the liquid level reached 100 ml.

The expansion ratio is calculated by dividing 1000 by the weight of the foam solution in grams. The weight of the foam solution in the container was determined by subtracting the weight of the empty container from the weight of the container filled with the foam. So as an example, a 1000 ml graduated cylinder that contains 250 g of solution has an expansion ratio of 4.

The weight of the foam solution in grams was divided by 4 to obtain the equivalent 25 percent drainage volume in milliliters. The 25 percent drainage time was then be interpolated from the drainage data collected at 30 second intervals (or from a liquid volume (ml) versus drainage time (sec) plot).

4.3 FOAM QUALITY RESULTS

As a preface to the following discussion on results, it needs to be noted that measuring foam quality is as much as an "art" as it is a "science". The measurements are highly dependent on technique and timing. As an example, how and where the foam solution impacts the collection backboard is major variable. How fast the graduated cylinder is removed once full is also a factor. Lastly, the backboard itself tends to agitate/aspirate the solution at impact and tends to dry the solution slightly as it flows down the collection board. With that as the understanding, this technique is the industry standard for making these measurements and have been made by literally hundreds of times by our test personnel.

The foam quality test results are shown in Table 4.7. The table includes the measured expansion ratios and 25% drainage times for three foam solutions: the baseline AFFF, National Avio Green, and Solberg RE-HEALING RF3. Both the expansion ratios and the 25% drainage times are the average of the two 1000 ml samples collected during the test. If the measurements varied by more than 10%, the test was repeated.

Table 4.6 DoD Discharge Devices Foam Quality Measurements

Man. / Model	Buckeye AFFF		National Avio		Solberg RF3	
	Exp. Ratio	Drainage (sec)	Exp. Ratio	Drainage (sec)	Exp. Ratio	Drainage (sec)
Tyco / B1	5.1	300	7.7	400	9.8	>2000
Bete / TF29-180-24	2.2	-	2.6	-	3.2	364
Globe / GL5601	3.5	-	4.7	-	5.4	630
Viking / GN 200/360	3.9	-	6.1	180	9.0	>2000
Elkhart / SFL-GN-95*	3.2	-	4.3	90	5.9	742
Akron Brass / 3023*	3.5	-	4.9	80	6.1	712
TFT / ME1VPGI-125*	3.1	-	4.6	-	6.7	723
Akron Brass / 3352*	3.3	-	4.9	-	6.6	765
Akron Brass / 3353*	3.2	-	4.6	-	6.5	732
Rosenbauer / RM25*	3.0	-	4.6	-	5.9	721

"-" below measurable range "*" Spray Pattern Specific (values shown are ~10 degree spray patterns)

As a general statement, the new PFFs are "foamier" than legacy AFFFs. Specifically, the expansion ratios of the PFFs were typically 1-3 expansion points higher than AFFF when discharged through the same non-air-aspirating device, under the same conditions (i.e., pressure). There was also a difference in expansion of the PFFs dependent to the concentrate viscosity. Specifically, the Newtonian PFFs were typically 1-2 point higher than AFFF and the non-Newtonians were 2-3 points higher. This difference was increased to 3-5 expansion points for air-aspirating discharge devices (i.e., Tyco/B1).

With respect to discharge device, the foam quality was typically similar for discharge devices that incorporate the same mechanism to aerate/aspirate the foam solution. For example, typical, non-air-aspirating fire hose and turret nozzles rely on the sheering of the foam solution stream as it flies through the air to aspirate the foam. As a result, the foam qualities produced by most of fire hose and turret nozzles are similar independent of solution flow rate (e.g., there was little difference between 250 gpm turret nozzles and 500 gpm turret nozzles). As another example, there was little difference between "sprinkler head" type discharge devices since they all rely in the deflector plate to aspirate the foam solution.

Circling back to the discussion on fire hose and turret nozzles, it was determined that the foam quality produced by these devices are a function of spray pattern (i.e., angle). Specifically, a narrow 5-10 degree fog pattern tended to be the best compromise between stream reach and aspiration/expansion and tended to increase the expansion by 2-3 points with only a minimal reduction in stream reach (i.e., about a 10-15% reduction in reach). Conversely, straight stream provided the greatest reach but the lowest foam quality/expansion.

The protein foam discharge device foam quality measurements are shown in Table 4.8.

Table 4.7 Protein Foam Discharge Device Foam Quality Measurements

Man. / Model	Buckeye AFFF		National Avio		Solberg RF3	
	Exp. Ratio	Drainage (sec)	Exp. Ratio	Drainage (sec)	Exp. Ratio	Drainage (sec)
Angus K40	6.1	170	7.4	400	8.2	1430
National Foam JS-10	6.2	211	8.3	633	9.5	1635
National Foam PC-31	6.2	236	7.6	549	9.5	1569
Task Force Tips FJ-LX-HM	7.1	354	9.5	703	11.9	>2000
Task Force Tips FJ-MX-HM	8.9	401	16.9	765	20.7	>2000

"-" solution was more than 25% liquid "*" Spray Pattern Specific

The results in Table 4.8 demonstrate how much "foamier" the PFFs are as compared to AFFF, especially for the foam tubes. In general, the legacy protein foam discharge devices produced better aspirated foam by about 2-3 expansion points as compared to their AFFF counterparts. Unfortunately, the primary mechanism for aspirating the foam (i.e., screens, deflector plates or both) tended to significantly reduce the reach and/or spray pattern of the device/nozzle.

The foam tubes did an excellent job of aspirating the foam solutions but not only suffered when it came to reach but were also limited to a straight stream spray. The lack of flexibility in spray pattern selection was shown to be problematic during some of the validation tests conducted at NAWC-CL. Innovative nozzle designs will be assessed during Phase III of the WP21-3465 program [8].

4.4 FOAM QUALITY RESULTS SUMMARY

A high-level summary of the foam quality (expansion ratio) produced by the various types of nozzles when discharging the PFFs is provided as follows:

- Fixed system nozzles (non-air-aspirating) used by DoD (between 2-5 exp.)
    - 2-3 expansion for standard orifice nozzles and 4-5 for deflector plate nozzles
- Fixed system nozzles (air-aspirating) used by DoD (between 8-10 exp)
- Fixed system NAVFAC Grate Nozzle (between 6-9 exp)
- Manual firefighting nozzles used by DoD (between 2-6 exp., pattern dependent)
    - 2-4 expansion for straight stream and 4-6 for narrow angle patterns (5-15 degrees)
- Firefighting vehicle nozzles used by DoD (between 2-6 exp., pattern dependent)
    - 2-4 expansion for straight stream and 4-6 for narrow angle patterns (5-15 degrees)
- Foam tubes and legacy protein foam hardware (8-20 flow rate dependent)

As a point worth noting, one of the primary uses of AFFF in land-based applications for DoD is a fixed system used to protect US Navy Aircraft hangars. These hangars are protected using a floor level system consisting of Viking Grate Nozzles (Viking 200 GN nozzles) which are non-air aspirated. However, during this study, these Grate Nozzles were shown to produce surprisingly good foam quality (expansion ratios in the range of 6-10), much higher than the other non-air-aspirating nozzles.

5.0 TASK 2 FOAM QUALITY EFFECTS ON FIREFIGHTING CAPABILITIES

5.1 FIRE TEST OBJECTIVES

The specific objectives of Task 2 were to quantify the firefighting capabilities of PFFs as a function of foam quality. The final result should be a series of "L" curves that can be used to predict the firefighting capabilities of the foam for a range of foam qualities and application rates.

5.2 FIRE TEST SETUP AND DESCRIPTION

5.2.1 Test Facility

The fire tests were conducted at the Chesapeake Bay Detachment (CBD) of the Navy Research Laboratory (NRL) located in Chesapeake Beach, MD. The tests were conducted in the large burn building (Building 313) during the 2nd and 3rd QTRs of FY21. An aerial view of the test facility is provided in Figure 5.1.

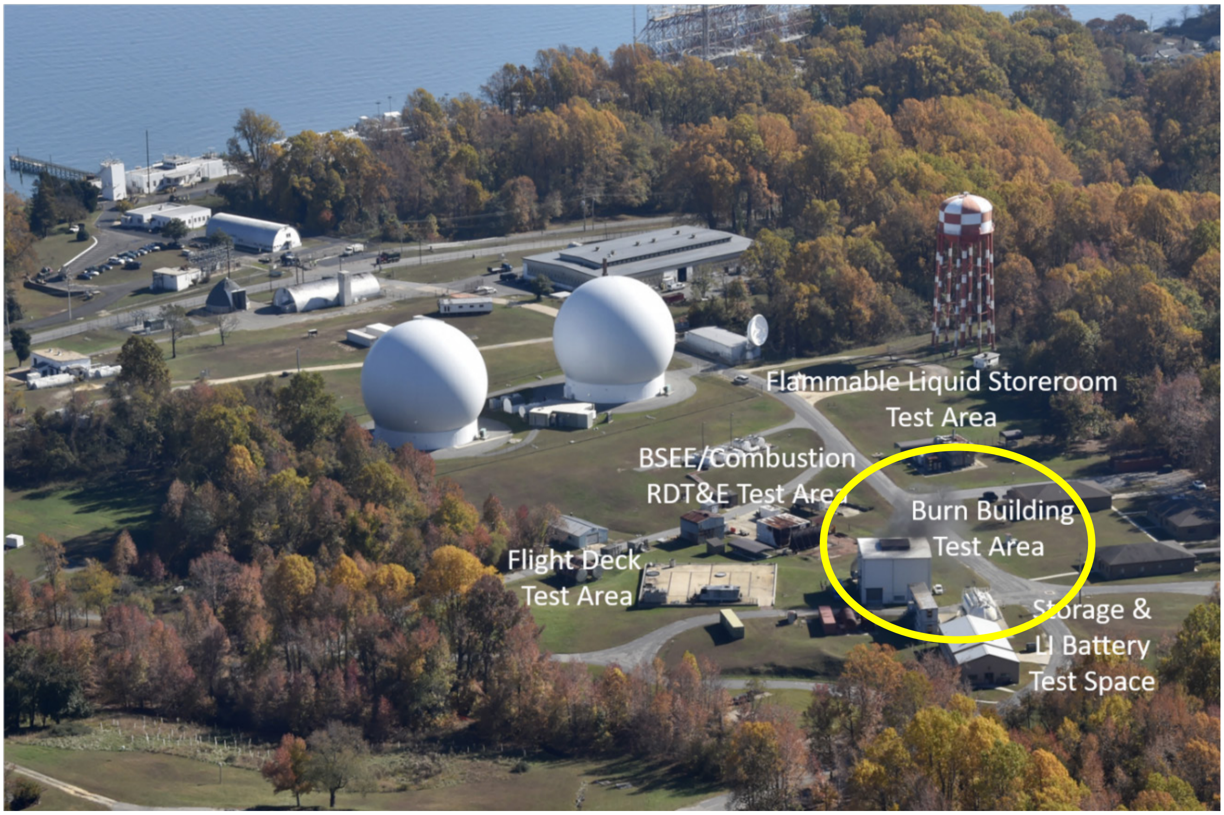


Figure 5.1 Aerial View of CBD Test Facility (with the burn building circled)

5.2.2 Foam Concentrates

The four PFFs included in this assessment are listed in Table 5.1. The firefighting capabilities of all four PFFs were quantified as a function of foam quality during Task 2. The firefighting capabilities of the PFFs were benchmarked against an C6 AFFF currently on the QPL (i.e., Buckeye Type 3).

Table 5.1 PFF Concentrates

Manufacturer	Foam Name	Type	Viscosity
Buckeye	Mil-Spec Type 3	AFFF	Newtonian
Bio-ex	ECOPOL A3+	PFF	Newtonian
Fomtec	Enviro USP	PFF	Non-Newtonian
National	Avio Green	PFF	Newtonian
Solberg	RE-HEALING RF3	PFF	Non-Newtonian

5.2.3 Fire Scenarios

The evaluation was based on the 28 ft^2 pan fire tests specified in the Mil-Spec [3]. The 28 ft^2 fire is produced using a circular pan 6 feet in diameter, fabricated from 0.25-in. thick stainless steel with a 4-in. high side as shown in Figure 5.2.

Figure 5.2 28ft^2 Pan Fire

The tests were conducted using two fuels; unleaded, zero alcohol gasoline (referred to as Mil-Spec gas) and Jet A. Gasoline is a low flash point (about -50° F (-65° C)) petroleum-based fuel consisting of a mixture of hydrocarbons, additives, and blending agents. The composition of gasolines varies widely, depending on the crude oils used, the refinery processes available, the overall balance of product demand, and the product specifications. The typical composition of gasoline hydrocarbons (% volume) is as follows: 4-8% alkanes; 2-5% alkenes; 25-40% isoalkanes; 3-7% cycloalkanes; l-4% cycloalkenes; and 20-50% total aromatics (0.5-2.5% benzene). Additives and blending agents are added to the hydrocarbon mixture to improve the performance and stability of gasoline. These compounds include anti-knock agents, anti-oxidants, metal deactivators, lead scavengers, anti-rust agents, anti-icing agents, upper-cylinder lubricants, detergents, and dyes. At the end of the production process, finished gasoline typically contains more than 150 separate compounds. Jet A is a kerosene-based aviation used for most jet aircraft. It meets stringent international requirements, particularly those of the latest versions of the Aviation Fuel Quality Requirements for Jointly Operated Systems (AFQRJOS), the British DEF STAN 91-91 standard, the ASTM D1655 standard, and the NATO F-35 specification. It has a minimum flashpoint of 100.0 °F (38°C).

5.2.4 Firefighting Equipment

Prior to the start of each test, the 3% foam solution (i.e., 97% water/3% foam concentrate) was prepared in an open top mixing container and then dumped into a pressure vessel for discharge onto the fire. The open top mixing container was used to ensure that the foam concentrates were well mixed prior to the start of the test (i.e., allowed for visual observation of the mixing and final solution). The foam concentrate was measured using a 2000 ml plastic graduated cylinder. Approximately 1135 ml of concentrate (0.3 gal) was required for each 10 gallon increment/batch of 3% foam solution. Once mixed, the foam solution was poured into a 10-gallon or 20-gallon pressure vessel and then pressurized with nitrogen to just over 100 psi (i.e., to produce a 100 psi nozzle pressure). The aspirating nozzle used during Mil-Spec qualification was used during these tests. The degree of foam solution aspiration was varied by partially blocking the aspiration openings on the nozzle using aluminum tape. A schematic of the Mil-Spec nozzle is provided as Figure 5.3.

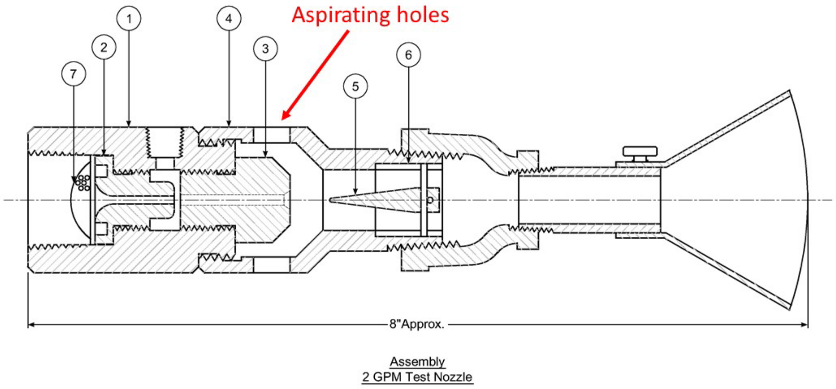


Figure 5.3 Mil-Spec Nozzle Schematic

5.2.5 Measures of Performance

The performance metrics included the time for complete extinguishment and the 25 % burnback time. These metrics were determined real-time by the test director as well as through video analysis after the test was completed.

5.2.6 Test Procedures

The tests were conducted using the Mil-Spec test procedures as the basis. The fire pan was first filled with a water substrate to a depth of 1 inch. Ten gallons of fuel (either gasoline or Jet A) was then dumped into the pan. For the tests conducted with Jet A, a cup of gasoline was also dumped into the pan to aid in ignition of the fuel. Within 30 seconds after the fuel was dumped, the fire was ignited using a propane torch fastened to a 10 ft pole. Foam discharge began 10 seconds after the fire had reached full involvement (i.e., a 10 second preburn time).

The foam solution was discharged onto the fire by a well-trained, experienced firefighter. The foam solution was discharged onto the fire for up to 150 seconds (two and a half minutes). If the fire was extinguished in less than 90 seconds, the foam discharge was stopped at the 90 second mark and then a the burnback test was conducted. If the fire was not extinguished within 90 seconds, no burnback test was conducted.

During the burnback assessment, a burning pan (1 ft diameter with 2 in high sides) containing one gallon of unleaded gasoline was placed in the center of the 28 ft^2 pan and a timer started. Once the fire had spread outside the pan, the pan was removed. Once the fire size reached 7 ft^2 (25 percent of the total area) was involved in flames the time was recorded and the pan was extinguished.

5.3 FIRE TESTS RESULTS

The test results are discussed initially as a function of foam type/manufacturer and then combined to demonstrate the trends in the data as a technology. During this test program, each test was conducted at least twice. If the results of the first two tests were withing 10%, the values were averaged and recorded in the table. If the results varied by more than 10%, a third test was conducted and the two most similar were averaged and recorded in the table.

5.3.1 Baseline C6 AFFF Test Results

The results of the tests conducted with the baseline, C6 AFFF are shown in Table 5.2 for an application rate of 0.07 gpm/ft^2 (i.e., 2 gpm foam solution discharge rate against the 28ft^2 pan fire).

Table 5.2 Baseline C6 AFFF Test Results (0.07 gpm/ft^2)

Aspiration	Drainage Time (sec)	Gasoline		Jet A	
		Ext. Time (sec)	Burnback Time (sec)	Ext. Time (sec)	Burnback Time (sec)
2.1	176	70	576	35	782
3.3	215	36	615	20	835
4.0	224	35	624	16	831
5.2	301	32	661	15	839
6.9	324	28	674	15	879

The extinguishment times are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.4.

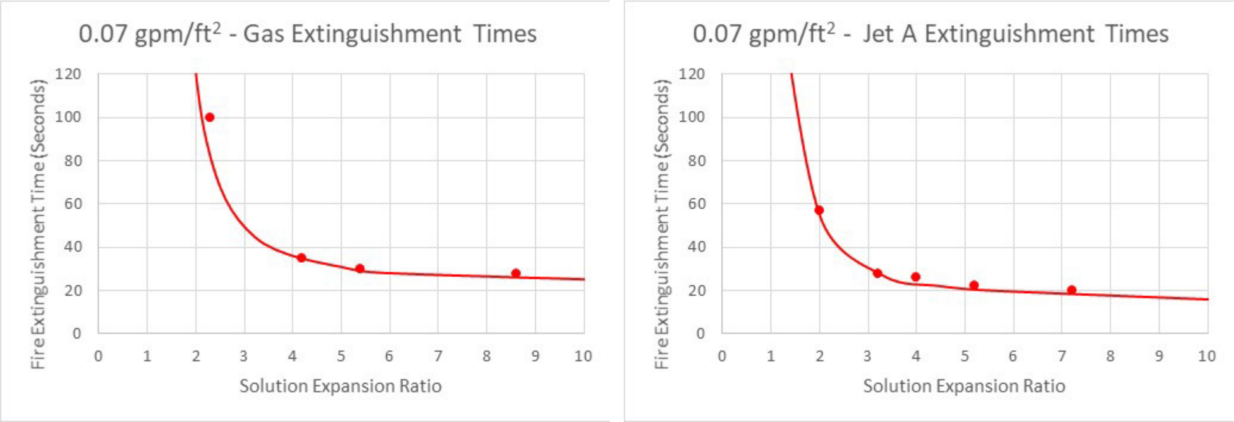


Figure 5.4 Baseline C6 AFFF Extinguishment Time versus Expansion Ratio Plots

As shown in Figure 5.4, the AFFF extinguishment times are similar for the two test fuels. When extinguishing gasoline (left side plot), once the expansion ratio of AFFF exceeds 4, the extinguishment times are fairly consistent requiring about 25 seconds to extinguish the fire. Below 4, the extinguishment times rapidly increase with decreased expansion. Similar trends are observed for AFFF against Jet A but at slightly lower expansions. For Jet A, once the AFFF expansion ratio exceeds 3, the extinguishment times are fairly consistent requiring only 15-20 seconds to extinguish the fire (right side plot). Below 3, the extinguishment times rapidly increase with decreased expansion.

The 25% burnback times are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.5.

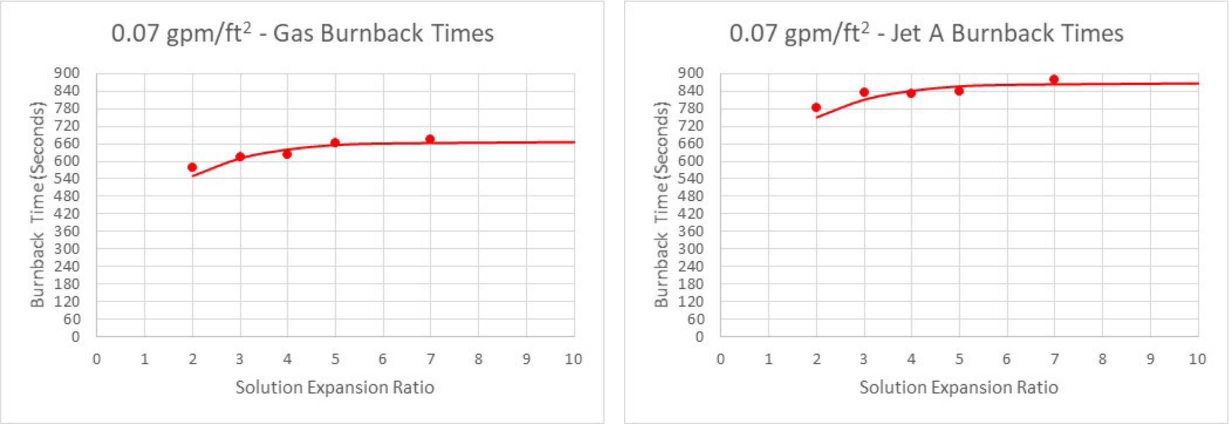


Figure 5.5 Baseline C6 AFFF 25% Burnback Time versus Expansion Ratio Plots

As shown in Figure 5.5, the AFFF 25% burnback times are fairly long (i.e., on the order of 10-14 minutes) and about three minutes longer for Jet A as compared to gasoline. In addition, the 25% burnback times only vary by about one to two minutes over the range of expansion ratios measured during these tests.

The trends in both extinguishment time and 25% burnback time demonstrate the contribution of the firm formation of AFFF for suppressing the fuel vapors. Specifically, even at lower expansion ratios, AFFF is still effective in extinguishing the fires and preventing burnback.

5.3.2 National Avio Green KHC Test Results

The results of the tests conducted with National Avio Green are shown in Table 5.3 for an application rate of 0.07 gpm/ft^2 (i.e., 2 gpm foam solution discharge rate against the 28ft^2 pan fire). National Avio Green is a Newtonian concentrate and should be compatible with legacy US DoD proportioning systems.

Table 5.3 National Avio Green Test Results (0.07 gpm/ft^2)

Aspiration Expansion Ratio	Drainage Time (sec)	Gasoline		Jet A	
		Ext. Time (sec)	Burnback Time (sec)	Ext. Time (sec)	Burnback Time (sec)
2	-	No	NA	No	NA
3	-	No	NA	69	216
3.6	-	No	NA	45	278
5.2	80	86	200	27	321
7.2	185	60	248	20	355
8.5	297	56	273	19	357

"-" below measurable range NA Not Applicable

The extinguishment times are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.6.

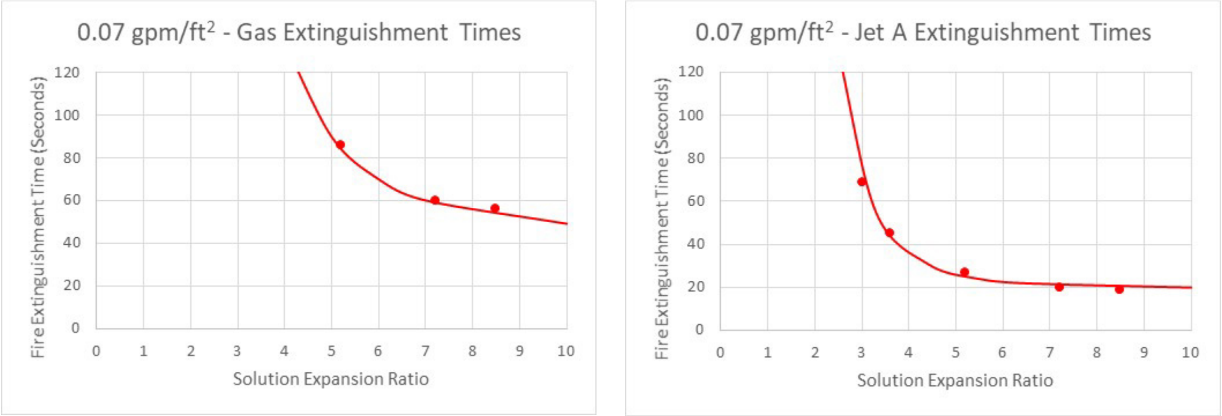


Figure 5.6 National Avio Green Extinguishment Time versus Expansion Ratio Plots

As shown in Figure 5.6, the National extinguishment times varied significantly between the two test fuels. When extinguishing gasoline (left side plot), the expansion ratio of the National needed to be above 7 for the extinguishment times to become fairly consistent requiring about 55 seconds to extinguish the fire. Below 7, the extinguishment times rapidly increase with decreased expansion and could not extinguish the gasoline fire when the expansion ration was below 5 (@ 0.07gpm/ft^2). Similar trends are observed for the National against Jet A but at much lower expansions. For Jet A, once the National expansion ratio exceeded 5, the extinguishment times are fairly consistent requiring about 20 seconds to extinguish the fire (right side plot). Below 5, the extinguishment times rapidly increase with decreased expansion and could not extinguish the Jet A fire when the expansion ration was below 3 (@ 0.07gpm/ft^2).

The 25% burnback times for the National are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.7.

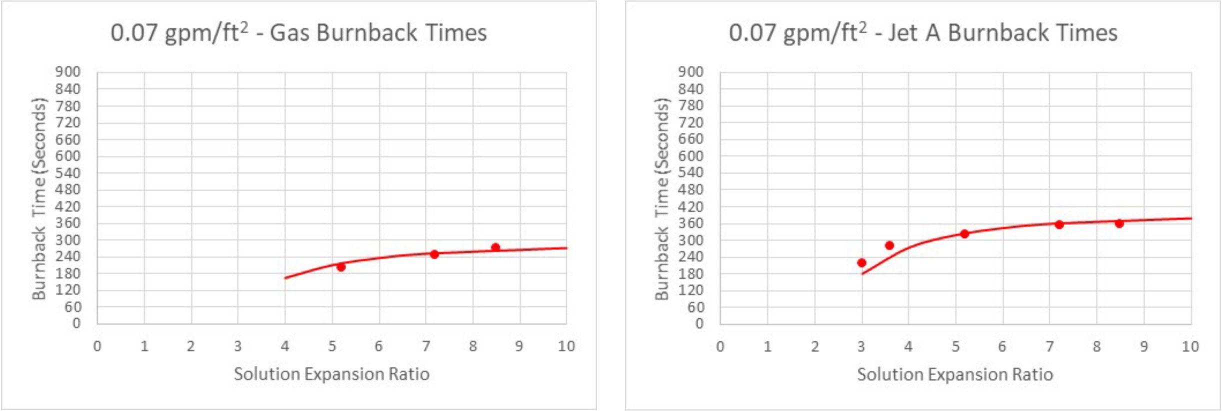


Figure 5.7 National Avio Green 25% Burnback Time versus Expansion Ratio Plots

As shown in Figure 5.7, the National 25% burnback times are much shorter than AFFF (i.e., 3-6 minutes as compared to 10-14 minutes for AFFF) and were about two minutes longer for Jet A as compared to gasoline. In addition, the 25% burnback times only vary by about one to two minutes over the range of expansion ratios from 5 to 8.5 but dropped off significantly below an expansion ratio of 5.

Since these new PFFs are not film formers like AFFF (or to the degree of AFFF), their capabilities degrade faster as expansion ratio is reduced, especially for higher vapor pressure fuels like gasoline. The previous two figures (Figures 5.6 and 5.7) suggest that National needs to be discharged through nozzles that produce expansion ratios on the order of 5 to be effective at application rates on the order of 0.07 gpm/ft^2. Higher applications can compensate for some of this limitation and will be discussed later in this report.

5.3.3 Bio-Ex ECOPOL A3+ Test Results

The results of the tests conducted with Bio-Ex ECOPOL A3+ are shown in Table 5.4 for an application rate of 0.07 gpm/ft^2 (i.e., 2 gpm foam solution discharge rate against the 28ft^2 pan fire). Bio-Ex ECOPOL A3+ is a Newtonian concentrate and should be compatible with legacy US DoD proportioning systems.

Table 5.4 Bio-Ex ECOPOL A3+ Test Results (0.07 gpm/ft^2)

Aspiration Expansion Ratio	Drainage Time (sec)	Gasoline		Jet A	
		Ext. Time (sec)	Burnback Time (sec)	Ext. Time (sec)	Burnback Time (sec)
2	-	No	NA	No	NA
3	-	No	NA	75	190
3.6	-	No	NA	49	228
5.2	65	77	160	35	268
7.2	225	63	216	30	311
8.5	395	58	244	18	335

"-" below measurable range NA Not Applicable

The Bio-Ex extinguishment times are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.8.

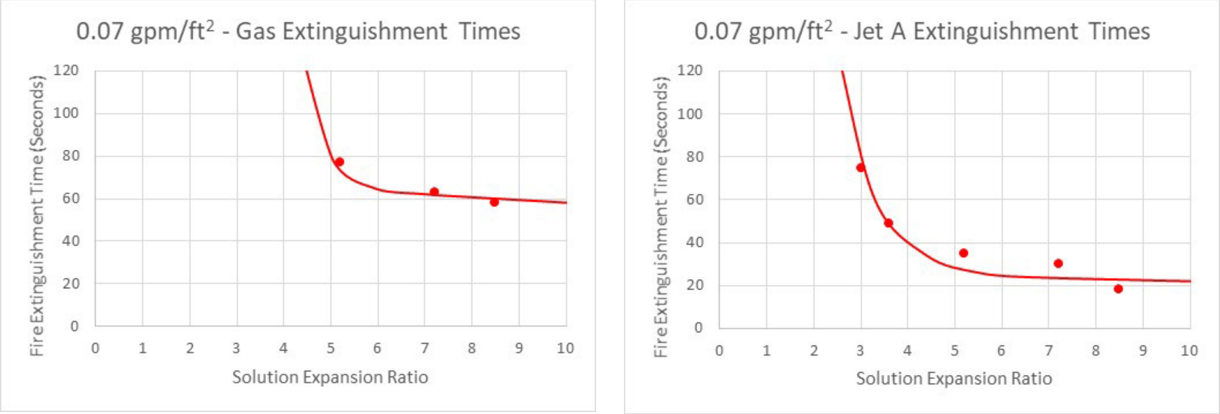


Figure 5.8 Bio-Ex ECOPOL A3+ Extinguishment Time versus Expansion Ratio Plots

As shown in Figure 5.8, the Bio-Ex extinguishment times varied significantly between the two test fuels. When extinguishing gasoline (left side plot), the expansion ratio of the Bio-Ex needed to be above 6 for the extinguishment times to become fairly consistent requiring about 55 seconds to extinguish the fire. Below 6, the extinguishment times rapidly increase with decreased expansion and could not extinguish the gasoline fire when the expansion ration was below 5 (@ 0.07gpm/ft^2). Similar trends are observed for the Bio-Ex against Jet A but at lower expansion ratios. For Jet A, once the Bio-Ex expansion ratio exceeded 5, the extinguishment times are fairly consistent requiring about 25 seconds to extinguish the fire (right side plot). Below 5, the extinguishment times rapidly increase with decreased expansion and could not extinguish the Jet A fire when the expansion ration was below 3 (@ 0.07gpm/ft^2).

The 25% burnback times for the Bio-Ex are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.9.

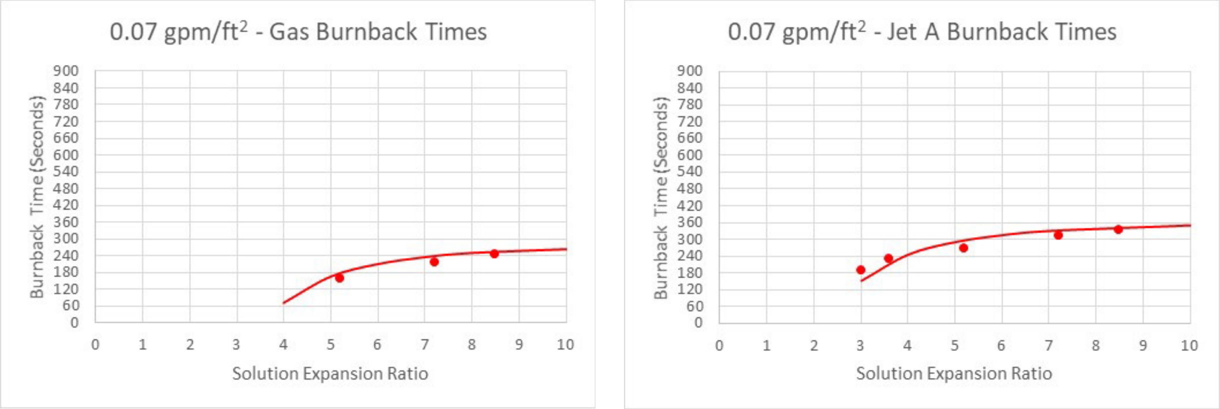


Figure 5.9 Bio-Ex ECOPOL A3+ 25% Burnback Time versus Expansion Ratio Plots

As shown in Figure 5.9, the Bio-Ex 25% burnback times are much shorter than AFFF (i.e., 3-6 minutes as compared to 10-14 minutes for AFFF) and were about one minute longer for Jet A as compared to gasoline. In addition, the 25% burnback times only vary by about one to two minutes over the range of expansion ratios from 5 to 8.5 but dropped off significantly below an expansion ratio of 5 for gasoline and an expansion ratio 3-4 for Jet A.

Since these new PFFs are not film formers like AFFF, their capabilities degrade faster as expansion ratio is reduced, especially for higher vapor pressure fuels like gasoline. The previous two figures (Figures 5.8 and 5.9) suggest that Bio-Ex needs to be discharged through nozzles that produce expansion ratios on the order of 5 to be effective at application rates on the order of 0.07 gpm/ft^2. Higher applications can compensate for some of this limitation and will be discussed later in this report.

5.3.4 Fomtec Enviro USP Test Results

The results of the tests conducted with the Fomtec Enviro USP are shown in Table 5.5 for an application rate of 0.07 gpm/ft^2 (i.e., 2 gpm foam solution discharge rate against the 28ft^2 pan fire). Fomtec Enviro USP is a non-Newtonian concentrate and requires additional attention when premixing the foam solution for testing (i.e., requires more mixing/stirring to ensure that the concentrate has completely dissolved in the water).

Table 5.5 Fomtec Enviro USP Test Results (0.07 gpm/ft^2)

Aspiration Expansion Ratio	Drainage Time (sec)	Gasoline		Jet A	
		Ext. Time (sec)	Burnback Time (sec)	Ext. Time (sec)	Burnback Time (sec)
2	-	No	NA	No	NA
3	-	No	NA	61	500
3.6	-	No	NA	49	551
5.2	615	75	375	25	589
7.2	>1000	67	406	22	618
8.5	>1000	58	434	22	630

"-" below measurable range NA Not Applicable

The extinguishment times for the Fomtec are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.10.

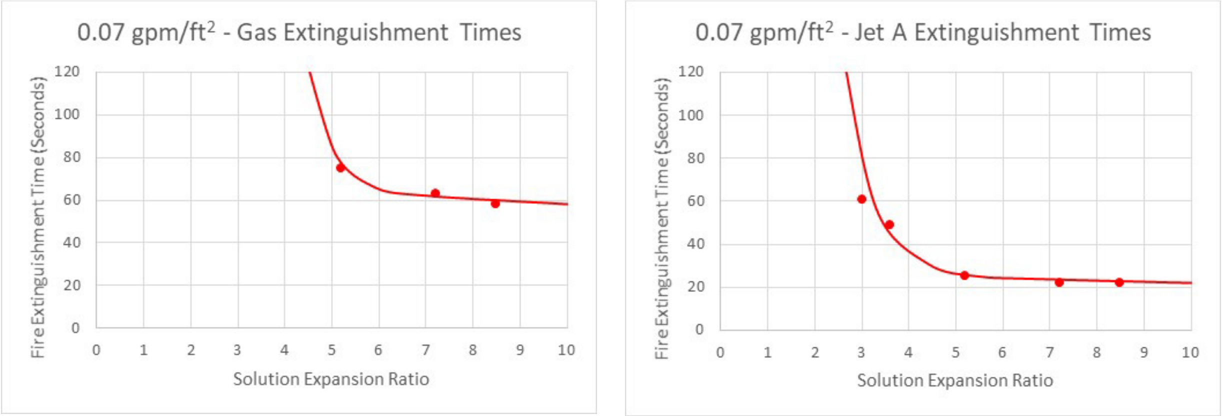


Figure 5.10 Fomtec Enviro USP Extinguishment Time versus Expansion Ratio Plots

As shown in Figure 5.10, the Fomtec extinguishment times varied significantly between the two test fuels. When extinguishing gasoline (left side plot), the expansion ratio of the Fomtec needed to be above 6 for the extinguishment times to become fairly consistent requiring about 60 seconds to extinguish the fire. Below 6, the extinguishment times rapidly increase with decreased expansion and could not extinguish the gasoline fire when the expansion ration was below 5 (@ 0.07gpm/ft^2). Similar trends are observed for the Fomtec against Jet A but at slightly lower expansion ratios. For Jet A, once the Fomtec expansion ratio exceeded 5, the extinguishment times are fairly consistent requiring about 25 seconds to extinguish the fire (right side plot). Below 5, the extinguishment times rapidly increase with decreased expansion and could not extinguish the Jet A fire when the expansion ration was below 3 (@ 0.07gpm/ft^2).

The 25% burnback times for the Fomtec are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.11.

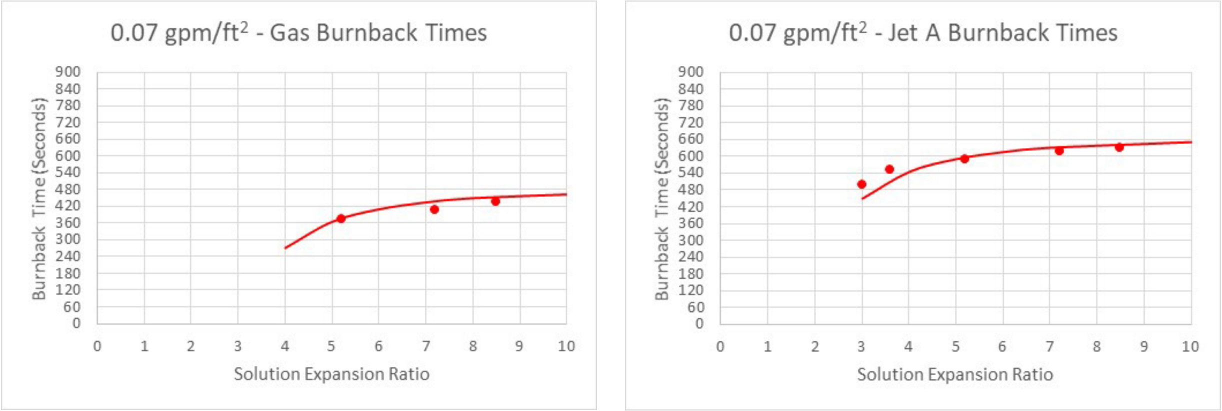


Figure 5.11 Baseline C6 AFFF 25% Burnback Time versus Expansion Ratio Plots

As shown in Figure 5.11, the Fomtec 25% burnback times are much shorter than AFFF (i.e., 6-8 minutes as compared to 10-14 minutes for AFFF) but are nuch longer than the Newtonian PFFs (i.e., 6-8 minutes as compared to 3-6 minutes for the Newtonian PFFs). With respect to fuel type, the burnback times were about three minutes longer for Jet A as compared to gasoline. In addition, the 25% burnback times only vary by about one to two minutes over the range of expansion ratios from 5 to 8.5 but dropped off significantly below an expansion ratio of 5 for gasoline and an expansion ratio 3-4 for Jet A.

Since these new PFFs are not film formers like AFFF, their capabilities degrade faster as expansion ratio is reduced, especially for higher vapor pressure fuels like gasoline. The previous two figures (Figures 5.10 and 5.11) suggest that Fomtec needs to be discharged through nozzles that produce expansion ratios on the order of 5 to be effective at application rates on the order of 0.07 gpm/ft^2. Higher applications can compensate for some of this limitation and will be discussed later in this report.

5.3.5 Solberg Re-Healing RF3 Test Results

The results of the tests conducted with the Solberg Re-Healing RF3 are shown in Table 5.8 for an application rate of 0.07 gpm/ft^2 (i.e., 2 gpm foam solution discharge rate against the 28ft^2 pan fire). Solberg Re-Healing RF3 is a non-Newtonian concentrate and requires additional attention when premixing the foam solution for testing (i.e., requires more mixing/stirring to ensure that the concentrate has completely dissolved in the water).

Table 5.6 Solberg Re-Healing RF3 Test Results (0.07 gpm/ft^2)

Aspiration Expansion Ratio	Drainage Time (sec)	Gasoline		Jet A	
		Ext. Time (sec)	Burnback Time (sec)	Ext. Time (sec)	Burnback Time (sec)
2	-	No	NA	No	NA
3	-	No	NA	65	514
3.6	-	No	NA	53	561
5.2	>1000	67	586	36	689
7.2	>1000	56	644	30	748
8.5	>1000	53	686	29	770

“-“ below measurable range NA Not Applicable

The extinguishment times for the Solberg Re-Healing RF3 are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.12.

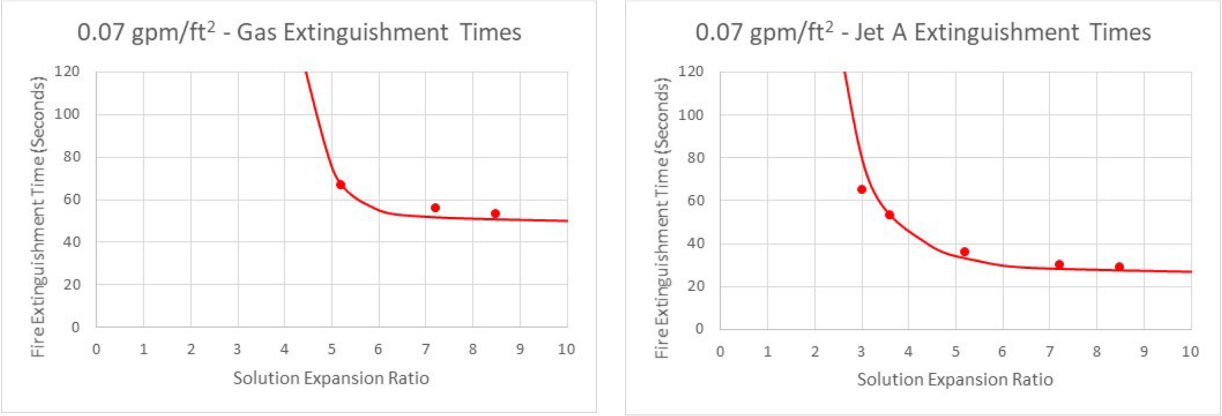


Figure 5.12 Solberg Re-Healing RF3 Extinguishment Time versus Expansion Ratio Plots

As shown in Figure 5.12, the Solberg extinguishment times varied significantly between the two test fuels. When extinguishing gasoline (left side plot), the expansion ratio of the Solberg needed to be above 6 for the extinguishment times to become fairly consistent requiring about 50 seconds to extinguish the fire. Below 6, the extinguishment times rapidly increase with decreased expansion and could not extinguish the gasoline fire when the expansion ration was below 5 (@ 0.07gpm/ft^2). Similar trends are observed for the Solberg against Jet A but at a slightly lower expansion ratio. For Jet A, once the Solberg expansion ratio exceeded 5, the extinguishment times are fairly consistent requiring about 30 seconds to extinguish the fire (right side plot). Below 5, the extinguishment times rapidly increase with decreased expansion and could not extinguish the Jet A fire when the expansion ration was below 3 (@ 0.07gpm/ft^2).

The 25% burnback times for the Solberg are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.13.

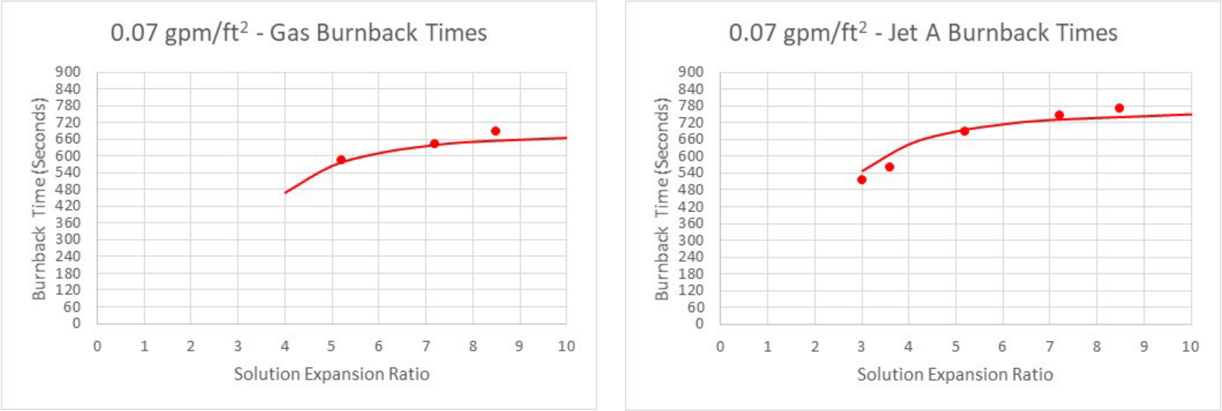


Figure 5.13 Solberg Re-Healing RF3 25% Burnback Time versus Expansion Ratio Plots

As shown in Figure 5.13, the Solberg 25% burnback times are shorter than AFFF (i.e., 8-12 minutes as compared to 10-14 minutes for AFFF) but are much longer than the Newtonian PFFs (i.e., 8-12 minutes as compared to 3-6 minutes for the Newtonian PFFs). With respect to fuel type, the burnback times were about two minutes longer for Jet A as compared to gasoline. In addition, the 25% burnback times only vary by about one to two minutes over the range of expansion ratios from 5 to 8.5 but dropped off significantly below an expansion ratio of 5 for gasoline and an expansion ratio 3-4 for Jet A.

Since these new PFFs are not film formers like AFFF, their capabilities degrade faster as expansion ratio is reduced, especially for higher vapor pressure fuels like gasoline. The previous two figures (Figures 5.12 and 5.13) suggest that Solberg needs to be discharged through nozzles that produce expansion ratios on the order of 5 to be effective at application rates on the order of 0.07 gpm/ft^2. Higher applications can compensate for some of this limitation and will be discussed later in this report.

5.3.6 PFF Comparison

This section briefly discusses the difference in capabilities between the four selected PFFs. A comparison of the PFFs to AFFF is provided in Section 5.3.7.

The extinguishment times for the four PFFs are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.14.

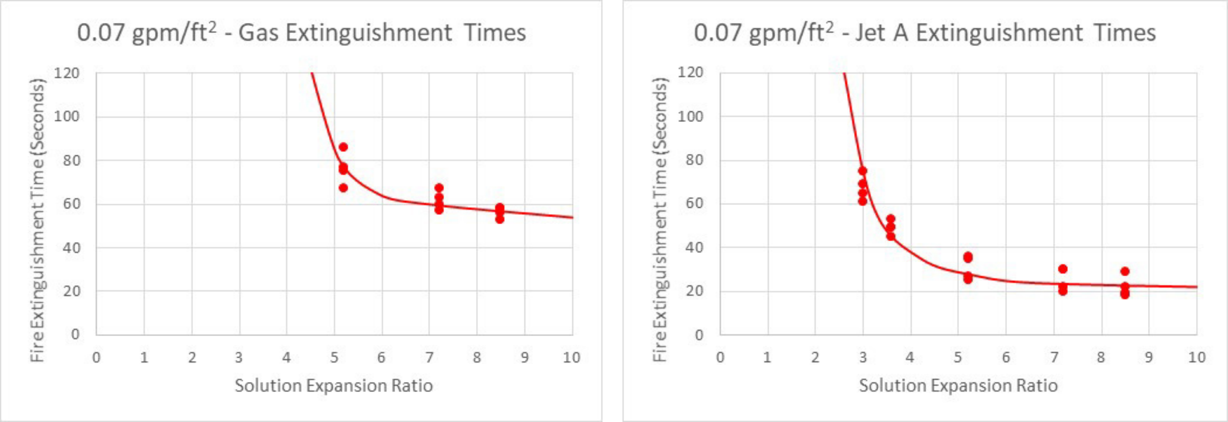


Figure 5.14 PFF Extinguishment Time versus Expansion Ratio Plots

As shown in Figure 5.14, the PFF extinguishment times were very similar for the four PFFs (and can be estimated using a single line correlation) but varied significantly between the two test fuels. Generally speaking, when extinguishing gasoline (left side plot), the expansion ratio of the PFFs needed to be above 5-6 for the extinguishment times to become fairly consistent requiring about 50-60 seconds to extinguish the fire. Below 6, the extinguishment times rapidly increase with decreased expansion and could not extinguish the gasoline fire when the expansion ration was below 5 (@ 0.07gpm/ft^2). Similar trends are observed for the PFFs against Jet A but at a slightly lower expansion ratio. For Jet A, once the expansion ratio exceeded 4-5, the extinguishment times were fairly consistent requiring about 25-30 seconds to extinguish the fire (right side plot).

Below 5, the PFF extinguishment times rapidly increase with decreased expansion and could not extinguish the Jet A fire when the expansion ration was below 3 (@ 0.07gpm/ft^2).

The 25% burnback times varied between the PFFs as a function of concentrate viscosity. Specifically, the thicker, non-Newtonian products (i.e., Fomtec and Solberg) had much longer burnback times than the thinner, Newtonian products (i.e., Bio-Ex and National).

The 25% burnback times for the four PFFs are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 5.15 and can be estimated using a single line correlation. The red dots/line corresponds to the Newtonian concentrates and the blue dots/line corresponds to the non-Newtonian concentrates.

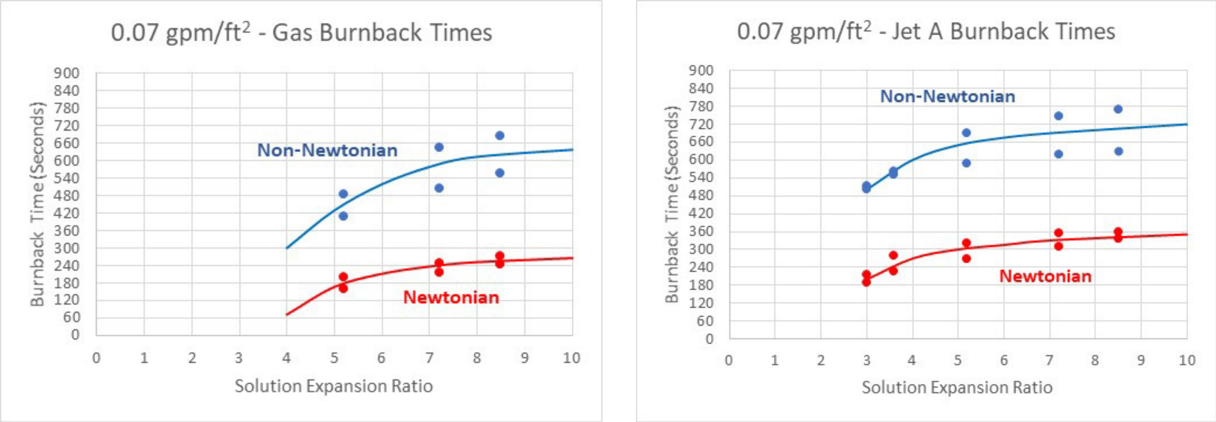


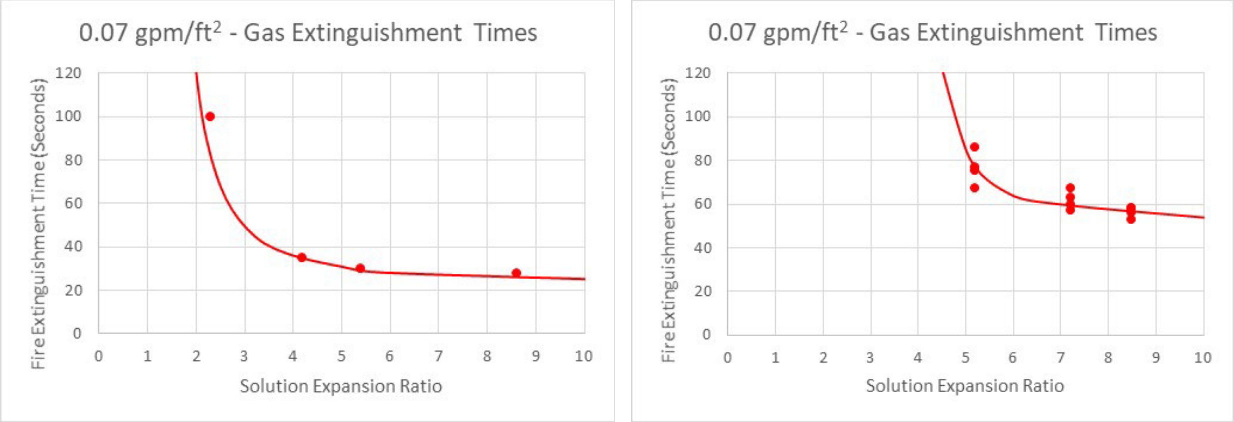
Figure 5.15 PFF Burnback Time versus Expansion Ratio Plots

As shown in Figure 5.15, the non-Newtonian PFF burnback times are much longer than the Newtonian PFFs (i.e., 8-12 minutes as compared to 3-6 minutes for the Newtonian PFFs).

However, since the industry is trending towards Newtonian concentrates to ensure compatibility with legacy AFFF proportioning systems/equipment, the non-Newtonian concentrate manufacturers are reformulating to lower viscosity products. In addition, the new Land-Based Mil-Spec (MIL-PRF-XX727) viscosity requirements (i.e., test parameters and required limits) eliminates the non-Newtonian from meeting the specification. As a result, the analysis and discussion in the following section (Section 4.4) will focus on the Newtonian PFFs.

5.3.7 AFFF/PFF Comparison

The extinguishment times of the baseline C6 AFFF and the PFFs as a function of expansion ratio are shown in Figures 5.16 and 5.17 for gasoline and Jet A respectively.

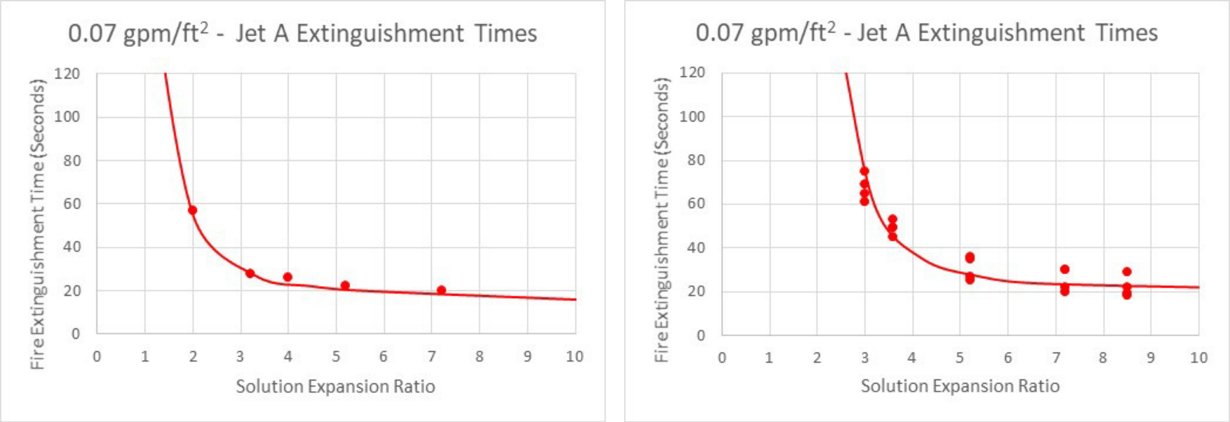

0.07 gpm/ft² - Gas Extinguishment Times

0.07 gpm/ft² - Gas Extinguishment Times

AFFF

All PFFs

Figure 5.16 AFFF / PFF Gasoline Extinguishment Time Comparison


0.07 gpm/ft² - Jet A Extinguishment Times

0.07 gpm/ft² - Jet A Extinguishment Times

AFFF

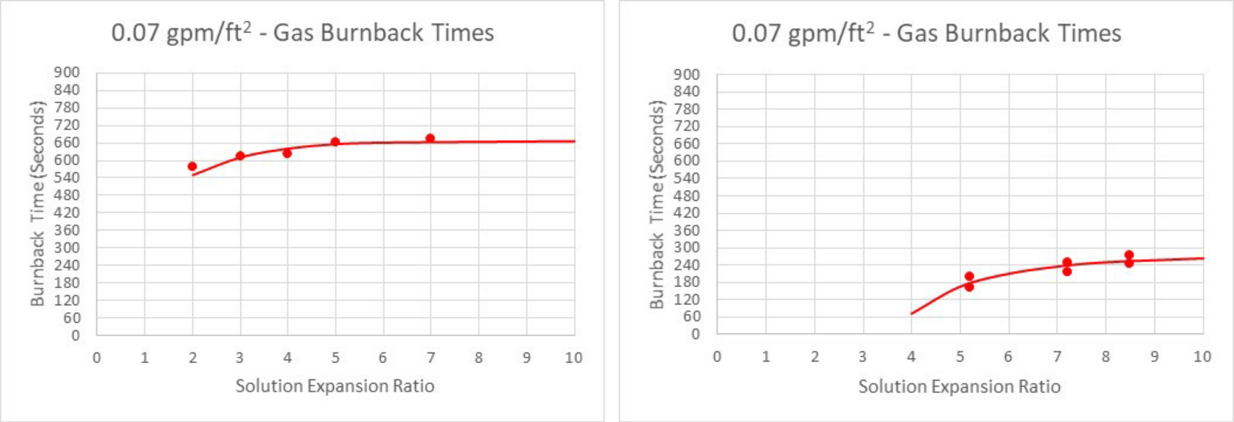
All PFFs

Figure 5.17 AFFF / PFF Jet A Extinguishment Time Comparison

As shown in Figure 5.16, the PFF extinguishment times were about a factor of two longer than AFFF and required better aspiration to achieve these times. When extinguishing gasoline, the expansion ratio of the PFFs needed to be above 6 for the extinguishment times to become fairly consistent requiring about 55 seconds to extinguish the fire as compared to 30 seconds for AFFF in the same aspiration range. Below an expansion ratio of 6, the PFF extinguishment times for gasoline rapidly increase with decreased expansion and could not extinguish the gasoline fire when the expansion ration was below 5 (@ 0.07gpm/ft^2). This is compared to AFFF which was able to extinguish the gasoline fires with an expansion ratio between 2 and 3.

As shown in Figure 5.17, similar trends were observed for the PFFs against Jet A but at lower expansion ratios. For Jet A, once the PFF expansion ratio exceeded between 4-5, the extinguishment times were fairly consistent requiring about 25 seconds to extinguish the fire as compared to less than 20 seconds for AFFF. Below 5, the PFF extinguishment times rapidly increase with decreased expansion and could not extinguish the Jet A fire when the expansion ration was below 3 (@ 0.07gpm/ft^2). This is compared to AFFF which was able to extinguish the gasoline fires with an expansion ratio of 2.

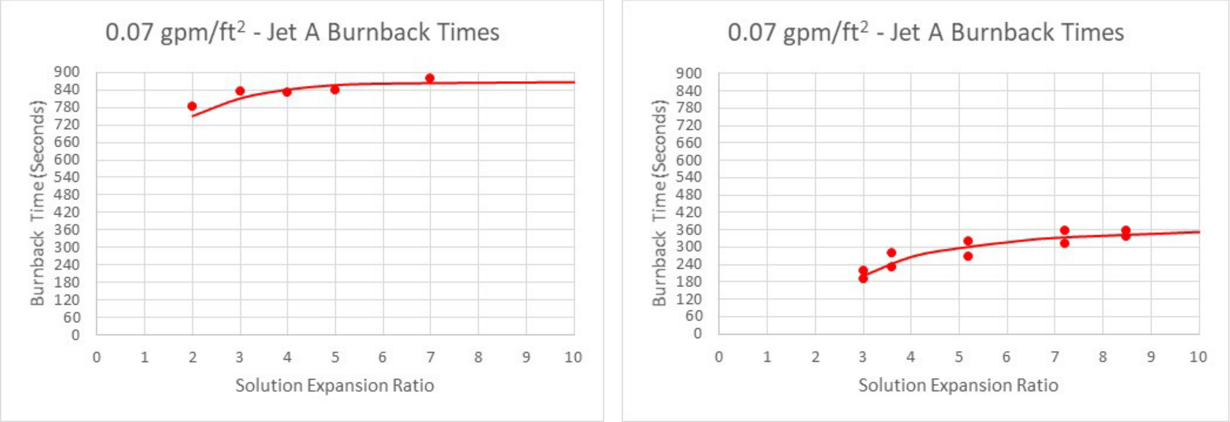
The burnback (and vapor suppression) capabilities of the baseline C6 AFFF and the Newtonian PFFs as a function of expansion ratio are shown in Figures 5.18 and 5.19 for gasoline and Jet A respectively.



AFFF

Newtonian PFFs

Figure 5.18 AFFF / PFF Gasoline 25% Burnback Time Comparison



AFFF

Newtonian PFFs

Figure 5.19 AFFF / PFF Jet A 25% Burnback Time Comparison

As shown in Figure 5.19, the Newtonian PFF 25% burnback times were almost a factor of three shorter longer than AFFF and required better aspiration to achieve these times. When extinguishing gasoline, the expansion ratio of the PFFs needed to be above 6 for the burnback times to become fairly consistent providing about 4 minutes (240 seconds) of protection as compared as compared to about 11 minutes (~660 seconds) for AFFF in the same aspiration range. Below an expansion ratio of 5, the Newtonian PFF burnback times for gasoline rapidly decreased with decreased expansion to just over 3 minutes (180 seconds) when the expansion ration was reduced to 5. This is compared to AFFF which still provided about 10 minutes (600 seconds) of protection at expansion ratios just below 3.

As shown in Figure 5.19, similar trends were observed for the Newtonian PFFs against Jet A but at lower expansion ratios. For Jet A, once the PFF expansion ratios exceeded between 4-5 the burnback times became fairly consistent providing about 5-6 minutes (300-360 seconds) of protection as compared as compared to about 14 minutes (~840 seconds) for AFFF in the same aspiration range. Below an expansion ratio of 4, the Newtonian PFF burnback times for Jet A gradually decreased with decreased expansion to just over 3 minutes (180 seconds) when the expansion ration was reduced to 3. This is compared to AFFF which still provided about 13 minutes (780 seconds) of protection at expansion ratios just below 3.

5.4 ANALYSIS AND DISCUSSION

Prior to discussing implications of the data, it needs to be noted that the extinguishment times are a function of application rate, foam quality (i.e., aspiration/expansion), and application technique. Specifically, reduced foam quality can be compensated for by increased application rate and vise-a-versa. In addition, this data was conducted on an approval scale where the foam was “rained down” onto the fuel surface providing a gentle application of the foam and does not require the foam blanket to flow (or be pushed) to remote/obstructed areas in the pool. In addition, there is minimal fuel pickup in the foam blanket due to the gentle application of foam to the fuel surface. During an actual incident, hose streams tend to be much more forceful resulting in fuel pickup in the foam blanket. Some of the application technique issues will be discussed later in the report. The focus of the following discussion is to illustrate the effects/trends of foam quality on performance (i.e., both extinguishment and burnback/vapor suppression) to aid in the selection of discharge devices when deploying these products.

5.4.1 Foam Quality Effects on Extinguishment Times/Capabilities

The extinguishment times of the PFFs as a function of expansion ratio are shown in Figures 5.20 for both the gasoline and Jet A fires.

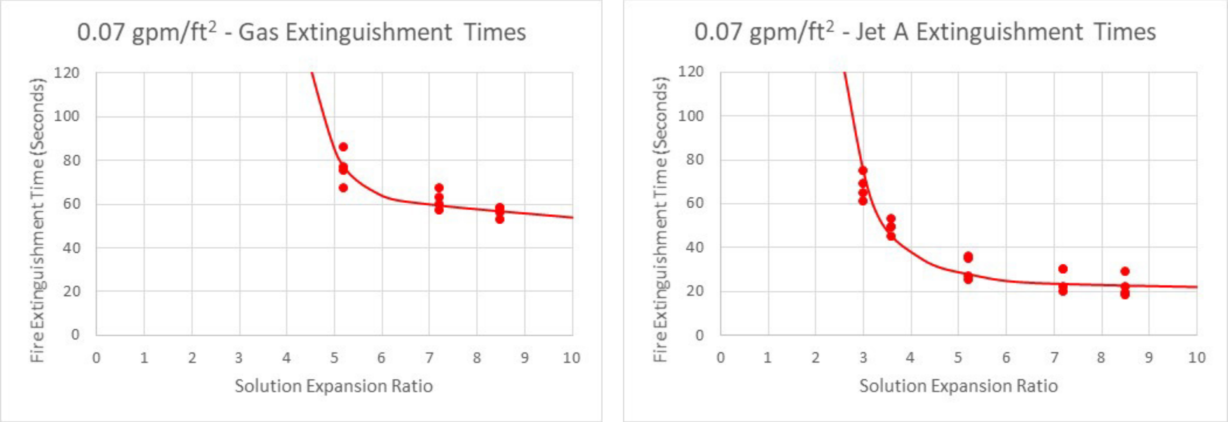


Figure 5.20 Critical PFF Expansion Ratios for Extinguishment

As shown in Figure 5.20, the PFF extinguishment times varied significantly between the two test fuels. Generally speaking, when extinguishing gasoline (left side plot), the expansion ratio of the PFFs needed to be above 5-6 for the extinguishment times to become fairly consistent requiring about 50-60 seconds to extinguish the fire. Below 6, the extinguishment times rapidly increase with decreased expansion and could not extinguish the gasoline fire when the expansion ration was below 5 (@ 0.07gpm/ft^2). Similar trends are observed for the PFFs against Jet A but at a slightly lower expansion ratio. For Jet A, once the expansion ratio exceeded 4-5, the extinguishment times were fairly consistent requiring about 25-30 seconds to extinguish the fire (right side plot). Below 5, the PFF extinguishment times rapidly increase with decreased expansion and could not extinguish the Jet A fire when the expansion ration was below 3 (@ 0.07gpm/ft^2).

5.4.2 Foam Quality Effects on Burnback Times/Capabilities

The burnback and vapor suppression capabilities of the Newtonian PFFs as a function of expansion ratio are shown in Figures 5.21 for both the gasoline and Jet A fires.

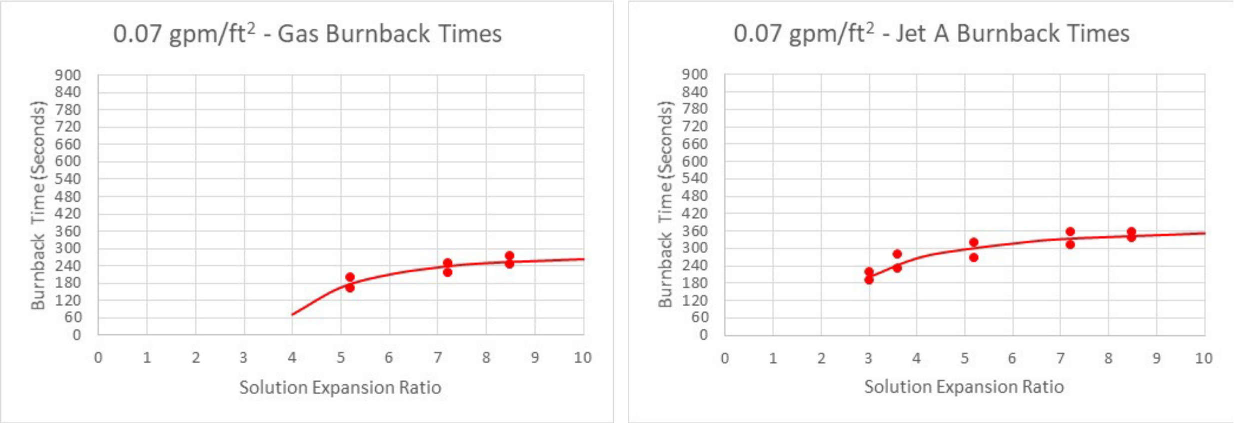


Figure 5.21 Critical PFF Expansion Ratios for Burnback

As shown in Figure 5.21, the Newtonian PFFs needed to be above 6 for the burnback times to become fairly consistent providing about 4 minutes (240 seconds) of protection against gasoline. Below an expansion ratio of 5, the Newtonian PFF burnback times for gasoline rapidly decreased with decreased expansion to just over 3 minutes (180 seconds) when the expansion ration was reduced to 5. Similar trends were observed for the Newtonian PFFs against Jet A but at lower expansion ratios. For Jet A, once the PFF expansion ratios exceeded between 4-5 the burnback times became fairly consistent providing about 5-6 minutes (300-360 seconds) of protection. Below an expansion ratio of 4, the Newtonian PFF burnback times for Jet A gradually decreased with decreased expansion to just over 3 minutes (180 seconds) when the expansion ration was reduced to 3.

5.4.3 Increased Application Rate Effects

As mentioned previously, the extinguishment and burnback times are a function of application rate, foam quality (i.e., aspiration/expansion), and application technique. To investigate the effects of application rate on these capabilities, some of the previous tests were repeated with the discharge nozzle configured to flow 3 gpm against the 28ft^2 pan fires. This corresponds to an application rate of 0.11 gpm/ft^2. The tests were only conducted with the Newtonian foam concentrates (i.e., National and Bio-Ex). The results of the test conducted with National and Bio-Ex are shown in Table 5.7 and 5.8 respectively.

Table 5.7 National Avio Green Test Results (0.11 gpm/ft^2)

		Gasoline		Jet A	
Aspiration	**Drainage Time (sec)**	**Ext. Time (sec)**	**Burnback Time (sec)**	**Ext. Time (sec)**	**Burnback Time (sec)**
2	-	No	NA	No	NA
4	-	57	120	38	265
5.2	81	47	190	27	310
7.2	188	45	244	20	507

"-" below measurable range NA Not Applicable

Table 5.8 Bio-Ex ECOPOL A3+ Test Results (0.11 gpm/ft2)

Aspiration Expansion Ratio	Drainage Time (sec)	Gasoline		Jet A	
		Ext. Time (sec)	**Burnback Time (sec)**	**Ext. Time (sec)**	**Burnback Time (sec)**
2	-	No	NA	No	NA
3	-	58	120	33	281
5	55	40	190	17	297
7.6	215	37	244	15	476

"-" below measurable range NA Not Applicable

The effect of increased application rate on the extinguishment capabilities of the Newtonian PFFs as a function of expansion ratio are shown in Figure 5.22 for both the gasoline and Jet A fires. The red lines are a curve-fit of the higher application rate data (i.e., 0.11 gpm/ft^2) and the blue lines are a curve-fit of the lower application rate data (i.e., 0.07 gpm/ft^2).

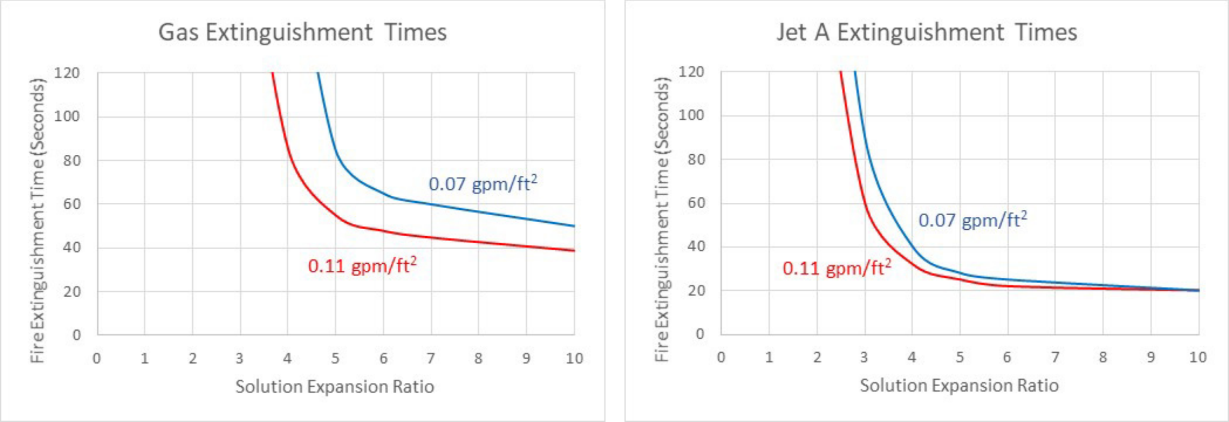


Figure 5.22 Application Rate Effects on Extinguishment Capabilities of Newtonian PFFs

As shown in Figure 5.22, increasing the application rate had a greater impact on the capabilities of these products against gasoline than it did against Jet A. The 50% higher application rate tended to decrease the extinguishment times by about 20% and shifted the “L” curve to the right by one expansion point. In other words, the critical expansion ratio was about 4 for the higher application rate versus 5 for the lower application rate. As one word expect, this demonstrates that poor foam quality can compensated for by increasing the application rate for a narrow, but representative range of parameters.

With respect to Jet A, the extinguishment times are already fairly short with limited room for improvement. However, the increased application rate still tended to reduce the extinguishment times by about 20% in the 3-6 expansion range but provided only a minimal shift in the critical expansion ratio (i.e., about a 0.3 expansion point reduction).

The effect of increased application rate on the burnback protection and vapor suppression capabilities of the Newtonian PFFs as a function of expansion ratio are shown in Figure 5.23 for both the gasoline and Jet A fires. The red lines are a curve-fit of the higher application rate data (i.e., 0.11 gpm/ft^2) and the blue lines are a curve-fit of the lower application rate data (i.e., 0.07 gpm/ft^2).

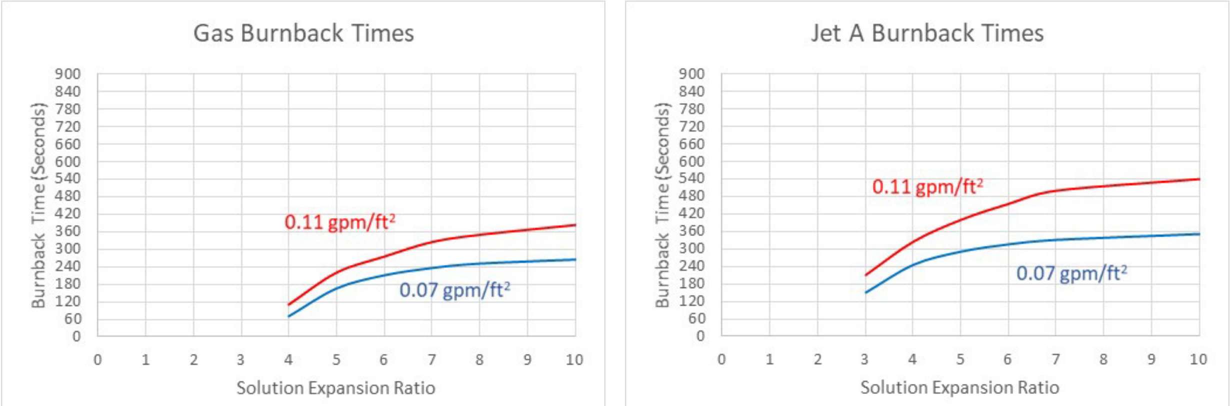


Figure 5.23 Application Rate Effects on Burnback Protection Capabilities of Newtonian PFFs

As shown in Figure 5.23, increasing the application rate tended to increase the burnback protection for both fuels. Although the two plots look somewhat different, the increase in application rate tended to increase the burnback protection consistently, for each expansion value by about 50%, for both fuels. These trends suggest that after a fire is extinguished and/or there is a fuel spill of a flammable liquid requiring vapor suppression, higher aspirated foam would be more effective.

5.5 REPRESENTATIVE SCALE DATA

The following discussion provides a high-level comparison between the approval scale findings and conclusions and the observations recorded during a series a representative scale tests.

During the WP21-3461 & WP21-3465 Phase I efforts, a total of 35 fire tests were conducted to validate the capabilities of five commercially available PFFs against two large scale ARFF fire scenarios (i.e., debris pile and fuel spill fire scenarios)[7,8]. The debris pile fire scenario was developed during the Nimitz tests series and represents an extremely challenging fuel spill fire and obstructed three-dimensional running fuel fire combination. The fuel spill fires were produced by discharging 400 gallons of F-24 onto the Mini Deck surface. All fires were combatted manually using a 125 gpm hose line. Both fire scenarios were conducted with F-24 as the fuel (i.e., the military version of Jet A). Photographs of the two fire large scale fire scenarios are provided in Figure 5.24.

Debris Pile **Spill Fire**

Figure 5.24 WP21-3261 & WP21-3465 Phase I Fire Scenarios

The fuel spill fires were combatted with three nozzle configurations: the standard nozzle without attachments, the standard nozzle with a long (lower aspiration) foam tube, and the standard nozzle with a short (higher aspiration foam tube). The standard nozzle without attachments provided a 75 ft effective reach of foam solution with an expansion ratio in the range of 4-6. The longer foam tube provided a 65 ft effective reach of foam solution with an expansion ratio in the range of 7-9. The shorter foam tube provided a 45 ft effective reach of foam solution with an expansion ratio in the range of 12-23. These parameters are shown in Figure 5.25.

Task Force Tip – Metro 1 (TFT-STD), 75ft Effective Reach, 4-6 Expansion

Task Force Tip – Metro 1 with Long Foam Tube (TFT-LFT), 65ft Effective Reach, 7-9 Expansion

Task Force Tip – Metro 1 with Short Foam Tube (TFT-SFT), 45ft Effective Reach, 12-23 Expansion

Figure 5.25 Stream Reach and Spray/Foam Characteristics Photographs

The spill fire test results are shown in Table 5.9.

Table 5.9 Spill Fire Test Results (Extinguishment Times)

Fire Scenario	Nozzle	AFFF Ext. Time (min:sec)	National Ext. Time (min:sec)	Fomtec Ext. Time (min:sec)	Bio-Ex Ext. Time (min:sec)	Solberg Ext. Time (min:sec)
Spill	TFT- STD	0:33	1:19	1:17	0:55	0:42
Spill	TFT- LFT	0:27	0:53	0:39	0:41	0:52
Spill	TFT- SFT	-	0:43	0:45	0:42	1:05

"-" = not tested

As shown in Table 5.9, the baseline C6 Mil-Spec AFFF was able to extinguish the fuel spill fires in about 30 seconds, independent of the discharge nozzle. All five PFFs were also able to extinguish the spill scenarios but the extinguishment times were typically about 1.5-2.5 times longer than the AFFF (but typically in less than a minute).

With respect to the discharge device and foam quality/aspiration, there were trade-offs associated with using standard nozzles versus foam tubes. The standard nozzle provides more reach and pattern control but with limited foam aspiration. This provided the firefighters with flexibility with respect to how they fight the fire. The foam tubes produced higher aspirated foams but were limited to a set spray pattern and reduced reach. However, the higher aspirated foam produced by these tubes was applied more gently to the fuel surface, had better extinguishment and vapor sealing capabilities but required more technique and faster advancement (i.e., the firefighting party had to advance through the spill in order to reach the other side/completely extinguish the fire).

In general, the results are fairly consistent with this investigation in that the standard nozzle configuration produced foam quality near the critical values (4-6 expansion range) and the use of the long tube typically resulted in faster extinguishment with expansion ratios 7-9 range. Specifically, the standard nozzle produced foam qualities/expansion ratios near the "knee" of the extinguishment time curves while the foam tube produced foam qualities/expansion ratios in the flat/level region of the curve.

Changing the discussion to burnback protection, immediately after the spill fires were extinguished, a small hole was created in the foam blanket and ignited using one of the brush burner propane torches. Although the fuel was still hot, it typically took between 3-5 minutes to ignite (i.e., it was much harder to ignite than the fuel discharged from the fuel truck). If the fire did not ignite within five minutes of flame impingement, the burnback test was terminated and "No Ignition" was noted/recorded.

In all cases, the fires tended to grow slowly once ignited. This slow growth is illustrated by the series of photographs shown in Figure 5.26. The burnback time was defined as the time from ignition until the fire had grown to 100 ft^2. The results of the burnback tests are summarized Table 5.10.

1:00 after ignition ~ 10ft^2

3:00 after ignition ~ 20ft^2

3:00 after ignition ~ 60ft^2

4:00 after ignition ~ 100ft^2

Figure 5.26 Example Burnback Sequence/Timing

Table 5.10 Spill Fire Test Results (Extinguishment Times)

Nozzle	AFFF BB Time (min:sec)	National BB Time (min:sec)	Fomtec BB Time (min:sec)	Bio-Ex BB Time (min:sec)	Solberg BB Time (min:sec)
TFT - STD	3:00	2:30	4:30	2:30	4:00
TFT - LFT	4:00	3:00	No ign.	3:30	7:00

BB time is time to burn back to 100 ft^2: non-Newtonian

As shown in Table 5.10, the burnback time for AFFF was three minutes when discharged through the standard nozzle and four minutes when discharged through the foam tube. In general, the foam tube typically increased the burnback times by about a minute for all foams. When comparing the PFFs to AFFF, the burnback times were typically about 30-seconds shorter (i.e., the fire burned back slightly faster) for the Newtonian PFFs (National, Bio-Ex) but were slightly better (i.e., longer burnback times) for the non-Newtonian PFFs (Fomtec and Solberg). These results are consistent with the approval scale test results presented earlier.

But the main take-away of the representative scale tests was that all of the foams tested during the program demonstrated reasonable burnback capabilities against the F-24 spill fire scenarios.

6.0 SUMMARY AND CONCLUSIONS

The current military specification for approving AFFF (MIL-PRF-24385F) uses an air-aspirating foam discharge nozzle during the fire performance approval tests and does not consider or try to replicate the foam quality that will be produced by the various fielded discharge devices. Unlike AFFF, the new PFFs rely solely on the foam blanket to smother/extinguish the fire making foam quality a key consideration/parameter in actual applications.

The WP19-5374 program was initiated to develop the link between the small-scale approval test results and the actual/expected fielded capabilities. To make this link, the foam quality produced by the various discharge devices used throughout DoD need to be characterized and an understanding of the capabilities of these new PFFs as a function of foam quality needed to be developed.

The top four PFFs identified during WP19-5324 were selected for these evaluations. These PFFs included Bio-Ex ECOPOL A3+, Fomtec Enviro USP, National Avio Green and Solberg RE-HEALING RF3. The performance of these PFFs were benchmarked against a C6 QPL Mil-Spec AFFF (Buckeye Type 3).

The foam quality measurements (i.e., equipment and procedures) made during this program were in accordance with NFPA 412/NFPA 1900 which is incorporated in the current Mil-Spec. Per the documents, both the expansion ratio and drainage time were measured and recorded for each discharge device. However, the focus of the analysis and discussion is based on the expansion ratio (i.e., the degree of aspiration). As a point worth noting, all of the commercially available PFFs are “foamier” (i.e., produce better expanded foam solutions) than legacy AFFFs when discharged through the same device. The drainage times of the Newtonian PFFs are comparable to AFFF while the non-Newtonians have much longer drainage times than AFFF.

The foam quality produced by 15 discharge devices was characterized during this program. In general, the foam quality is similar between discharge devices that incorporate the same mechanism to aerate/aspirate the foam solution. For example, typical, non-air-aspirating fire hose nozzles and turrets rely on sheering of the foam solution stream as it flies through the air to aspirate the foam. As a result, the foam quality produced by most of these nozzles is similar independent of solution flow rate and was determined to be a function of spray pattern (i.e., angle). Specifically, a narrow 5-10 degree fog pattern tended to be the best compromise between stream reach and aspiration/expansion. Other examples include “sprinkler heads/nozzles” that use a deflector plate to create a desired spray pattern all tend to produce foam with similar characteristics. A high-level summary of the foam quality (expansion ratio) produced by the various types of nozzles is provided as follows:

- Fixed system nozzles (non-air-aspirating) used by DoD (between 2-5 exp.)
    - 2-3 expansion for standard orifice nozzles and 4-5 for deflector plate nozzles
- Fixed system nozzles (air-aspirating) used by DoD (between 8-10 exp)
- Fixed system NAVFAC Grate Nozzle (between 6-9 exp)
- Manual firefighting nozzles used by DoD (between 2-6 exp., pattern dependent)

  - 2-4 expansion for straight stream and 4-6 for narrow angle patterns (5-15 degrees)
- Firefighting vehicle nozzles used by DoD (between 2-6 exp., pattern dependent)
  - 2-4 expansion for straight stream and 4-6 for narrow angle patterns (5-15 degrees)
- Foam tubes and legacy protein foam hardware (8-20 flow rate dependent)

The firefighting capabilities (extinguishment and burnback resistance) of the PFFs as a function of foam quality (expansion ratio) were determined using the 28 ft^2 pool fire test described in MIL-PRF-24385F. These tests were conducted using the exact same equipment and test personnel that typically perform the MIL-PRF-24385F / QPL approval tests.

Each PFF was tested over a range of expansions (2-9 expansion ratios) against two different test fuels (i.e., the legacy unleaded zero alcohol gasoline and Jet A) with two foam solution flow rates 2 gpm and 3 gpm. The degree of foam solution aspiration was varied by partially blocking the aspiration opening on the standard Mil-Spec nozzle.

Prior to further discussion, it needs to be noted that the extinguishment times are a function of application rate, foam quality (i.e., aspiration/expansion), and application technique. Specifically, reduced foam quality can be compensated for by increased application rate and vise-a-versa. With that said, the focus of the following discussion is to illustrate the effects/trends of foam quality on performance (i.e., both extinguishment and burnback/vapor suppression) to aid in the selection of discharge devices when deploying these products and/or to identify potential concerns with legacy hardware.

Starting with the extinguishment capabilities of the PFFs, the extinguishment times for the four PFFs at an application rate of 0.07 gpm/ft^2 are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 6.1.

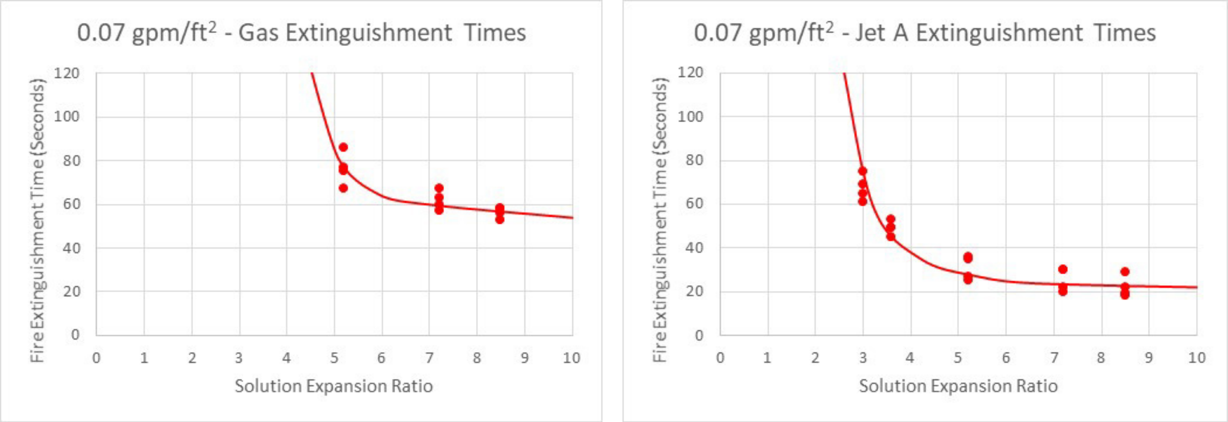


Figure 6.1 PFF Extinguishment Time versus Expansion Ratio Plots

As shown in Figure 6.1, the PFF extinguishment times were very similar for the four PFFs (and can be estimated using a single line correlation) but varied significantly between the two test fuels.

Generally speaking, when extinguishing gasoline (left side plot), the expansion ratio of the PFFs needed to be above 5-6 for the extinguishment times to become fairly consistent requiring about 50-60 seconds to extinguish the fire. Below an expansion of 5, the extinguishment times rapidly increase with decreased expansion.

Similar trends are observed for the PFFs against Jet A but at slightly lower expansion ratios. For Jet A, once the expansion ratio exceeded 4-5, the extinguishment times were fairly consistent requiring about 25-30 seconds to extinguish the fire (right side plot). Below 4, the PFF extinguishment times rapidly increase with decreased expansion.

The 25% burnback times varied between the PFFs as a function of concentrate viscosity. Specifically, the thicker, non-Newtonian products (i.e., Fomtec and Solberg) had much longer burnback times than the thinner, Newtonian products (i.e., Bio-Ex and National). However, the draft land-based Mil-Spec viscosity requirements prevent the approval of these non-Newtonian products channeling the following discussion to focus on the Newtonian PFFs.

The 25% burnback times for the two Newtonian PFFs are plotted as a function of expansion ratio for the two tests fuels (i.e., gasoline and Jet A) in Figure 6.2 and can be estimated using a single line correlation.

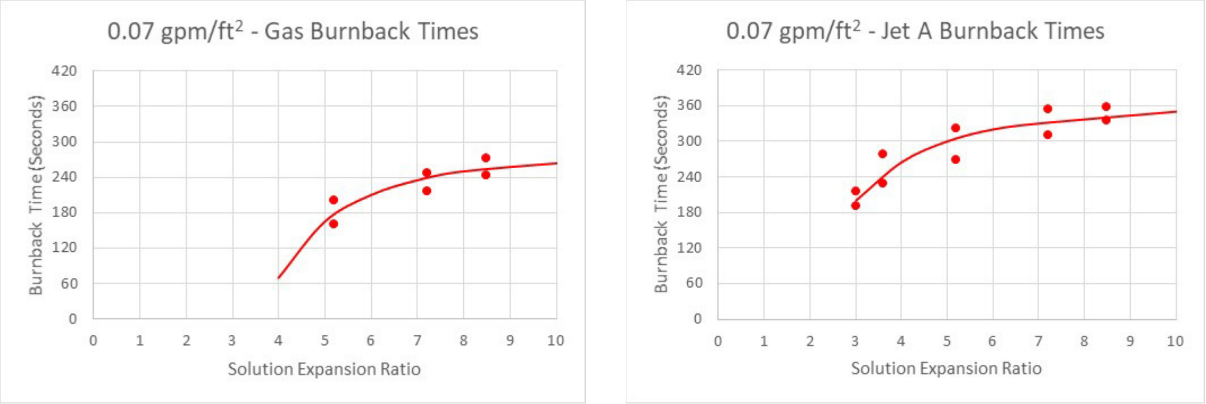


Figure 6.2 Newtonian PFF Burnback Time versus Expansion Ratio Plots

As shown in Figure 6.2, burnback trends are somewhat consistent with the extinguishment time trends, specifically for the expansion ratios near the critical value. In that range, the burnback time tends to increase fairly rapidly (by over a minute per each expansion point increase) up until the extinguishment times begin to level-out. Once in the region where the extinguishment times have become fairly constant, the burnback protection slowly increases with increased expansion ratio (i.e., by about 10 seconds per each expansion point increase).

The effect of increasing the foam application rate on the PFF capabilities was also quantified. As expected, increasing the application rate increased the firefighting capabilities of the PFFs (reduced the extinguishment times and increased the burn back protection) and tended to reduce the critical expansion ratio of the solution. In general, a 50% increase in application rate tended to decrease the extinguishment times by about 20% and shifted the “L” curve to the right by one expansion point. This 50% increase in application rate also tended to increase the burnback times by about 50%.

Taking a conservative approach to applying this information to the various discharge devices used by DoD, the critical expansion ratio appears to be about 5 to cover the two fuels used during this assessment. Specifically, gasoline fires are very difficult to extinguish using a PFF if the expansion ratio of the foam solution is below 5. Consequently, any situation where the design application rate is less than 0.11 gpm/ft^2 and the foam expansion is below 5, is potentially problematic and warrants additional consideration/assessment, especially if the hazard is gasoline. If the hazard is a kerosene-based fuel like Jet A/JP-8/F-24, the critical expansion ratio is about 4 for typical design application rates.

For fixed fire suppression system, potential areas of concern include systems that use straight orifice type discharge nozzles in general and deflector plate discharge nozzles if the hazard being protected is gasoline.

As a point worth noting, one of the primary DoD uses of AFFF in land-based applications is to protect US Navy Aircraft hangars. These hangars are protected using a floor level system consisting of Grate Nozzles (Viking 200 GN nozzles) designed with a 0.010 gpm/ft^2 application rate. During this study, the Grate Nozzles were shown to produce surprisingly good foam quality (expansion ratios in the range of 6-9). The combination of the good foam quality produced by the nozzles, the design application rate and the kerosene based fuel hazard provides a high level of confidence that the system will provide adequate when discharging PFF solution.

With respect to manual firefighting, the data suggests that the use of a straight stream could be problematic unless the foam is "bounced off" of the deck/ground in front of the fire to help agitate the foam. Conversely, the data also suggests that the use of a narrow angle fog pattern (i.e., 5-10 degrees) can increase the foam expansion by a few points and lead to faster extinguishment times. This was, to some degree observed during the large-scale validation tests conducted at NAWC-CL in 2021. During those tests, a large 2500-2800 ft^2 F-24 was using

Three, 125 gpm hose line nozzle configurations: the standard nozzle without attachments, the standard nozzle with a long (lower aspiration) foam tube, and the standard nozzle with a short (higher aspiration foam tube). The standard nozzle without attachments provided a 75 ft effective reach of foam solution with an expansion ratio in the range of 4-6. The longer foam tube provided a 65 ft effective reach of foam solution with an expansion ratio in the range of 7-9. The shorter foam tube provided a 45 ft effective reach of foam solution with an expansion ratio in the range of 12-23.

In general, the validation test results were fairly consistent with the findings of this study in that the standard nozzle configuration produced foam quality near the critical values (4-6 expansion range) and the use of the long tube typically resulted in faster extinguishment with expansion ratios 7-9 range. Specifically, the standard nozzle (without attachments) produced foam qualities/ expansion ratios near the "knee" of the extinguishment time curves while the foam tube produced foam qualities/ expansion ratios in the flat/level region of the curve.

Changing the discussion to burnback protection, immediately after the spill fires were extinguished, a small hole was created in the foam blanket and ignited using one of the brush burner propane torches. Although the fuel was still hot, it typically took between 3-5 minutes to ignite (i.e., it was much harder to ignite than the fuel discharged from the fuel truck).

In all cases, the fires tended to grow slowly once ignited, but in general, the foam tube typically increased the burnback times by about a minute for all foams.

The take-aways of the large-scale tests as they pertain to foam quality are consistent with the findings of this program. It appears that after an initial attack on the fire with a straight stream, the next steps should be to slightly increase the spray pattern angle to extinguish any remaining small pockets of fire and to blanket the fuel surface with higher aspirated foam (i.e., foam with a higher expansion ratio). An assessment of various discharge approaches, tactics, and potential hardware/nozzle modifications has been proposed and will be conducted as the third phase of the large-scale test program.

The ultimate objective of the WP19-5374 program was to develop the link between the small-scale approval test results and the actual/expected fielded capabilities. When applying the fire performance data to the various discharge devices used by DoD, the critical expansion ratio appears to be about 5 to cover the two fuels used during this assessment. Specifically, gasoline fires are very difficult to extinguish using a PFF if the expansion ratio of the foam solution is below 5. Consequently, any situation where the design application rate is less than 0.11 gpm/ft^2 and the foam expansion is below 4, is potentially problematic and warrants additional consideration/ assessment, especially if the hazard is gasoline. If the hazard is a kerosene-based fuel like Jet A/JP-8/F-24, the critical expansion ratio is about 4 for typical design application rates.

For fixed fire suppression systems, potential areas of concern include systems that use straight orifice type discharge nozzles in general and deflector plate discharge nozzles if the hazard being protected is gasoline. With respect to manual firefighting, the data suggests that the use of a straight stream could be problematic unless the foam is “bounced off” of the deck/ground in front of the fire to help agitate the foam. Conversely, the data suggests that the use of a narrow angle fog pattern (i.e., 5-10 degrees) would increase the capabilities to potentially acceptable levels. These concerns were observed during the large-scale validation tests conducted at NAWC-CL in 2021 (WP21-3461 and WP21-3465).

7.0 PATH FORWARD

The WP19-5374 data set provides a tool to estimate the capabilities of legacy AFFF systems and hardware during the transition from AFFF to these new PFFs. Additional areas of research that would benefit DoD include the development of new replacement nozzles for the ones that have been identified as potentially problematic during this study. With respect to manual firefighting, there is a need to explore enhancements to delivery equipment and/or improvements to application techniques and tactics to compensate for deployment of less effective agents.

Methods of improving the performance of PFFs as it relates to foam quality and spray characteristics that have been proposed as a Phase III effort to WP21-3461 and WP21-3465 include:

1. Development of novel nozzle designs specifically suited to discharge of PFFs (i.e., variable aspiration while maintaining pattern control).
2. Improvements to application techniques and firefighting tactics/doctrine (aggressive sweep of leading edge with a narrow spray pattern, impacting the foam solution on the deck directly in front of the fire to roll the foam blanket onto the burning fuel, side to side discharge that "rains" the foam solution down on the front edge of the fire, low delivery with a nozzle angle pattern to push foam across fuel surface, as well as others).

8.0 REFERENCES

1. Congress. *National Defense Authorization Act for Fiscal Year 2020*. Washington, D.C., 20 December 2019. (Public Law 116-92.) https://www.congress.gov/bill/116th-congress/senate-bill/1790

2. Strategic Environmental Research and Development Program/Environmental Security Technology Certification Program. *WP19-5324, Capabilities Assessment of Commercially Available PFAS-Free Foams and Agents – Final Report*. Alexandria, VA, SERDP/ESTCP, January 2021. https://www.serdp-estcp.org

3. MIL-PRF-24385F (SH) Amendment 3, "Fire Extinguishing Agent, Aqueous Film-Forming Foam (AFFF), Liquid Concentrate, for Fresh and Sea Water," Naval Sea Systems Command, 07 May 2019.

4. MIL-PRF-XX727, "Fire Extinguishing Agent, Fluorine-Free Foam (F3) Liquid Concentrate, For Land-Based, Fresh Water Applications", Naval Sea Systems Command, in preparation (April 2022 draft).

5. "Qualified Products List." Qualified Products Database (QPD) at https://assist.dla.mil. (QPL No. 24385.)

6. National Fire Protection Association, "NFPA 412, Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment – 2020 Edition" Quincy, MA, 2020.

7. National Fire Protection Association, "NFPA 403, Standard for Aircraft Rescue and Fire-Fighting – 2019 Edition" Quincy, MA, 2020.

8. Strategic Environmental Research and Development Program/Environmental Security Technology Certification Program. *WP21-3465, Validation Testing of the Leading Commercially Available PFAS-Free Foams (Phase I and Phase II – Final Report)*. Alexandria, VA, SERDP/ESTCP, April 2022. https://www.serdp-estcp.org