ESTCP

FINAL REPORT

Capabilities Assessment of Commercially Available Fluorine-free Foams

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14. ABSTRACT
The firefighting foams (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. DoD needs to develop and/or identify environmentally acceptable alternatives (fluorine-free (FF)) that can provide equivalent firefighting capabilities as the foams that are currently being used. The first step to solving this problem was to develop an understanding and database of the capabilities of the currently available alternatives.

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ACRONYMS AND ABBREVIATIONS

AFFF	Aqueous Film-Forming Foam
CBD	Chesapeake Bay Detachment
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
in	inches
JH	Jensen Hughes
MILSPEC	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 / PRODUCT DESCRIPTION

Legacy firefighting foams (AFFF) used by the Department of Defense (DoD) are facing increasing regulatory scrutiny throughout the world due to both environmental and human health concerns associated with the fluorinated surfactants (i.e., per and polyfluoroalkyl substances). This WP19-5324 program was a two-year effort to assess the capabilities of PFAS-free AFFF alternatives including both traditional candidates such as fluorine-free and/or PFAS-free foams, and non-traditional options such as wetting agents and other water additives. Overall, the program provided an “apples to apples” comparison of the capabilities of the foams currently used by the DoD (AFFFs) and a range of commercially available PFAS-free alternatives. These results are currently presented as a “blind study” and do not include the names of the products tested (i.e., just generic names associated with the type of product tested). The names of the products will be included in an NRL report (Distribution D) published later this year.

OBJECTIVES / APPROACH

The approach was to quantify the capabilities of the “state-of-the-art” PFAS-free alternatives (PFAS-Free Foams (PFFs) and agents) in use today and provide information on the relationship between the actual fielded capabilities of the foam/agent and the current approval test requirements/results.

The systematic approach developed for this program included the following six tasks:

- Task 1: A literature search on potential PFAS-free AFFF alternatives.
- Task 2: A high-level environmental analysis to down-select agents for testing.
- Task 3: Approval-scale fire performance testing using the tests described in MIL-PRF-24385F with and without modifications.
- Task 4: Data analysis to rank the capabilities of the alternatives and to down-select agents for real-scale testing.
- Task 5: Real-scale fire testing using two representative scenarios.
- Task 6: The development of a database/final report that documents the findings and recommendations for the path forward.

The program was conducted from February 2019 to February 2021. A summary of the finding is provided in the following paragraphs.

PERFORMANCE ASSESSMENT

The initial literature/internet search conducted during Task 1 identified over 60 products that were being marketed as environmentally friendly AFFF alternatives. Upon further investigation, it was determined that at least 20 of these products had no firefighting performance listings or approvals (i.e., no legitimate firefighting pedigrees). Based on this lack of performance data, these products were not considered for this program. The remaining 40 products were assembled into an excel spreadsheet that was uploaded to the SERDP/ESTPC website. The spread sheet includes the links to the manufacturer’s websites, SDS (MSDS), and some of the approval tests reports (where available).

The 40 products include both "foams" and "wetting agents". The difference being that foams are tested and approved using a specific set of standards such as the MILSPEC, UL 162, EN 1568 and ICAO while wetting agents are approved based on NFPA 18. The foam standards are much more challenging than the NFPA 18 requirements and will be discussed in the following paragraphs.

Task 2 was conducted to identify any environmental "showstoppers" that would eliminate the product from further consideration (i.e., fire performance testing). During this screening process, it became obvious that the limited data provided in the SDS (MSDS) was inadequate to properly screen these foams/agents. As a result, the 15 foams/agents that had the greatest depth of listings/approvals applicable to typical DoD hazards were selected for firefighting performance testing. The team of Jensen Hughes (JH) and the Naval Research Laboratory (NRL) continues to test more products and continues to update the performance database. The current database now consists of over 25 products that have been tested due to date (primarily due to the availability of additional/new products and new formulations).

During Task 3, the firefighting capabilities (extinguishment and burnback resistance) of the selected alternatives were evaluated 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 foam/agent was tested 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. Jet A was included in the assessment since it is more representative of the kerosene-based fuels used throughout the DoD. Specifically, the original MILSPEC was developed when the predominant fuels included JP-4 and MOGAS and may need be revised in the future to include a representative kerosene-based fuel. In addition, Jet A (or military variants such as JP-8 for the Air Force and F-24 for the Navy) is the primary fuel used at both DoD and Civilian Airfields which has become the initial focus for the selection of a PFAS-free, AFFF alternative and has become the driver for the development of the new land-based MILSPEC.

The approval scale tests identified a couple of trends associated with fuel type and the general trends in the firefighting capabilities of these new products. The first observation was the ease in extinguishing the Jet A fires as compared to the gasoline fires. Thirteen of the fifteen foam/agents were capable of extinguishing the Jet A fires at 2 gpm (0.07 gpm/ft^2) in about 30 seconds or less. Conversely, only nine of the products were capable of extinguishing the gasoline fires at 2 gpm (0.07 gpm/ft^2) and required significantly longer and more foam/agent to extinguish the fire. As a general statement, the extinguishment times for gasoline (during the tests where the fire was actually extinguished) were typically about twice as long as those observed for Jet A.

With respect to the type of product (i.e., AFFF, PFF and WA), the legacy MILSPEC AFFF provided consistent results and always outperformed the other products included in this assessment. The foams listed and approved using UL 162 or EN 1568–part 3 or ICAO C out-performed the wetting agents (which are approved to NFPA 18). This was expected since foam products are tested and approved at much lower application rates (i.e., between 0.04 gpm/ft^2 – 0.06 gpm/ft^2) than the "wetting agents" which are listed and approved at 0.2 gpm/ft^2 per NFPA 18. There were a limited number of foams that were only tested to either EN 1568-part 2 or ICAO B which fell in between the higher performance foam products and the wetting agents. A summary of the results is provided in the table below (Table 1).

Table 1. 28ft^2 Pan Fire Tests Performance Groupings

Foam/Agent	Gasoline		Jet A	
	2 gpm (.07 gpm/ft^2)	3 gpm (.11 gpm/ft^2)	2 gpm (.07 gpm/ft^2)	3 gpm (.11 gpm/ft^2)
	Ext. (sec)	Ext. (sec)	Ext. (sec)	Ext. (sec)
AFFF	30	24	16	12
Top Five PFFs	49-58	37-52	19-33	15-22
Middle Three PFFs	77-82	55-67	22-27	15-21
One PFF	126	71	22	16
Three PFFs	No	No	26-103	20 -114
Three Wetting Agents	No	104- No	29-No	20-95

Good
OK
Less than OK
Not so good

During Task 4, the alternatives were ranked and grouped based on the firefighting capabilities observed/measured during the approval scale tests as noted by the colors in the previous table. As expected, the legacy MILSPEC AFFF provided consistent results and always outperformed the other products included in this assessment. The top five PFAS-free performers (all PFFs) demonstrated good capabilities against both gasoline and Jet A. These top performers were all able to extinguish the gasoline fires with a 2 gpm discharge rate in less than 60 seconds and the Jet A fires at the 2 gpm discharge rate in less than 30 seconds.

Based on the results of the approval scale tests, the top five PFFs were selected to be further assessed during the representative scale testing. This group included three Newtonian concentrates (lower viscosity concentrates that flow like water or corn syrup) and two non-Newtonian concentrates (higher viscosity concentrates that behave more like molasses and/or jello). These top five PFFs are currently being ECOTOX tested during other SERDP – ESTCP programs.

During Task 5, the firefighting capabilities of the top fluorine free foams/agents were assessed against a real-scale, representative manual firefighting scenario using a fire hose to extinguish a 400 ft^2 pool fire. Most of these tests were conducted with Jet A with a limited number repeated with gasoline for comparative purposes (i.e., the agents that did extremely well against the Jet A were retested using gasoline). The initial tests conducted were conducted with MILSPEC AFFF to provide a baseline for comparison and to allow the firefighting party the opportunity to optimize their procedures and tactics.

During the representative scale tests, the fires were extinguished using a fire hose equipped with a 30 gpm vari-nozzle. The resulting foam solution application rate was 0.07 gpm/ft^2 which is the same as the approval scale tests (i.e., 28ft^2 pan fire tests conducted with a foam solution discharge rate of 2 gpm).

This provided a direct comparison of capabilities for a fixed application rate on two vastly different scales (i.e., provided data that could be used to assess scaling between the approval scale and representative scale scenarios). A second set of tests were conducted with a foam tube attachment for the nozzle that provided higher aspirated foam which could be the key to effectively fielding these products in DoD applications. The results are summarized in the table below (Table 2).

Table 2. Representative Scale Tests Results (Summary)

Foam/Agent	Fuel	STD Nozzle (.07 gpm/ft^2)		Foam Tube (.07 gpm/ft^2)	
		Cont. (sec)	Ext. (sec)	Cont. (sec)	Ext. (sec)
AFFF	Jet A	25	45	15	25
PFF1-5 (AVG)	Jet A	45	60	25	40
AFFF	gasoline	30	50	30	45
PFF1-5 (AVG)	gasoline	100	135	60	105

The tends for the representative scale tests were consistent with the approval scale tests. Namely, the Jet A fires were much easier to extinguish than the gasoline fires and were typically extinguished in half the time it took to extinguish the gasoline fires. Along these same lines, the extinguishment of the gasoline fires was observed to be highly technique dependent. Specifically, the fire continues to burn at the location where the hose stream impinged on the fuel surface/foam blanket. In addition, the force from the hose stream was more than adequate to cause plunging of the solution into the fuel and cause the fuel to splash out of the pan. As a result, the firefighters needed to use a "rain-down" technique (as opposed to direct hose stream impingement) to apply the foams/agents "more gently" to the burning fuel to optimize the product performance.

During the second phase, the use of the foam tube adapter resulted in better foam aspiration and allowed for a "more- gentle" application of the foam to the fuel surface. The net result was a decrease in extinguishment times in all scenarios by about 30-45%. However, the use of the foam tube reduced the stream reach by about 40% (50 ft with the standard nozzle to 30 ft with the foam tube adapter).

From "Apples to Apples" comparison, the top five PFFs (PFF1-5) required about 1.5-2 times longer to extinguish the fires than the legacy MILSPEC AFFF. However, all the fires were quickly controlled and ultimately extinguished with the performance difference measure in seconds or fractions of minutes.

To further assess the capabilities and limitations of these products, "L curves" were developed for the baseline MILSPEC AFFF and the top five PFFs for both Jet A and gasoline. The L curves are a plot of the extinguishment time on the "Y" axis versus the application on the "X" axis.

The "L curves" for the MILSPEC AFFF and the top five PFFs are almost parallel for Jet A fires with the PFFs requiring about one and a half times as long to extinguish the fires as the MILSPEC AFFF as shown in Figure 1 below.

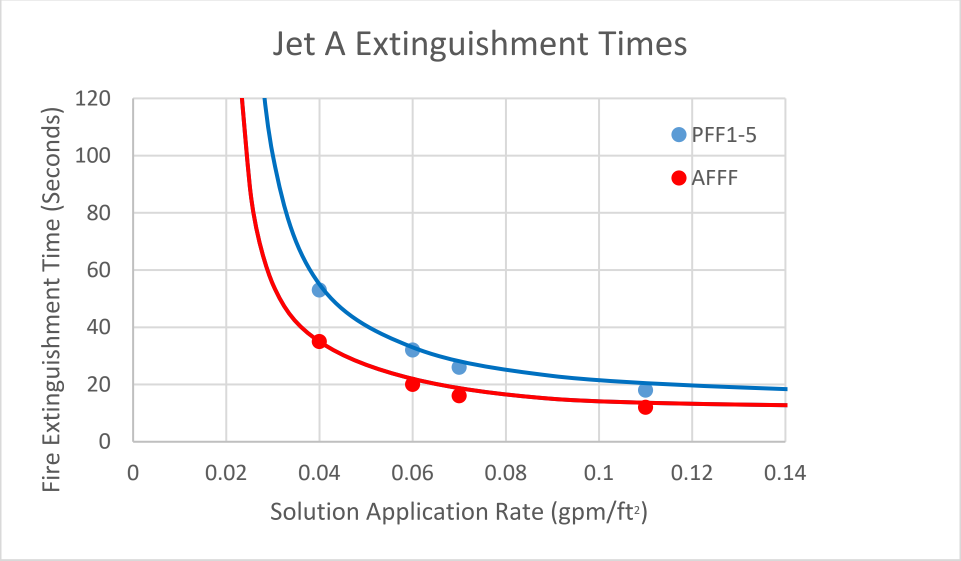

Figure 1. Jet A Fire Extinguishment Times versus Application Rates - "L Curve"

The critical application for the PFFs (i.e., the asymptote for the line) was only about 0.003 gpm/ft^2 higher than the MILSPEC AFFF (0.022 gpm/ft^{2}for the MILSPEC AFFF versus 0.025 gpm/ft^2 for the PFFs). In any case, the plot illustrates the ease in extinguishing Jet A with the extinguishment times being less than 60 seconds for application rates as low as 0.04 gpm/ft^2 and 30 seconds for application rates of 0.06 gpm/ft^2 and above.

The L curves for the MILSPEC AFFF and the top five PFFs for gasoline fires are parallel for the higher application rates (i.e., 0.07 gpm/ft^2 and above) but diverge for application rates less than 0.07 gpm/ft^2 as shown in Figure 2 below.

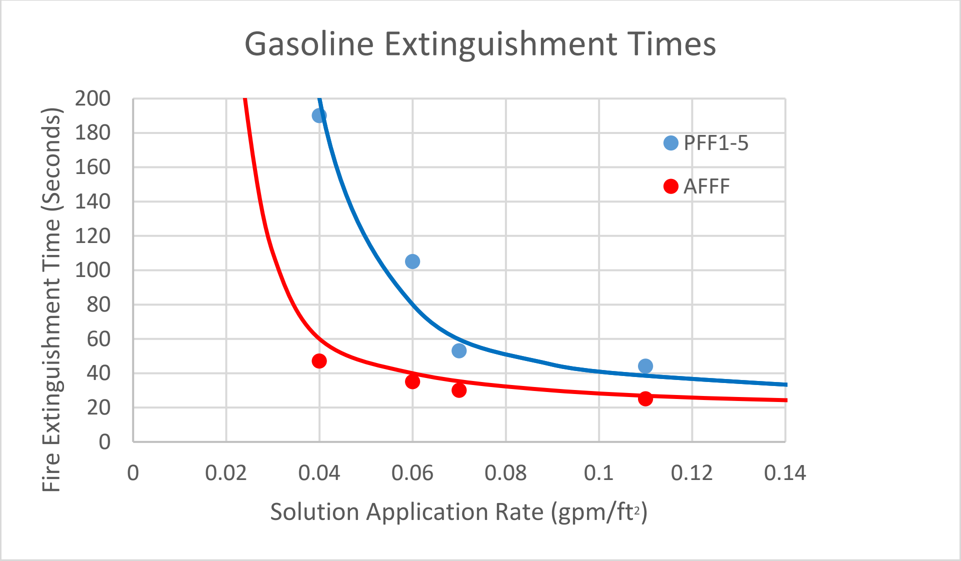

Figure 2. Gasoline Fire Extinguishment Times versus Application Rates - "L Curve"

At applications of 0.07 gpm/ft^2 and above, the top five PFFs require about twice as long to extinguish the fires as the MILSPEC AFFF. The critical application rate for the PFFs was about 0.015 gpm/ft^2 higher than the MILSPEC AFFF (0.024 gpm/ft^{2}for the MILSPEC AFFF versus 0.039 gpm/ft^2 for the PFFs). Variations in the firefighting capabilities of the PFFs in were observed for application rates approaching the critical value. Specifically, the extinguishment times for the gasoline fires for PFF application rates of 0.04 gpm/ft^2 were significantly higher than AFFF (i.e., on average about four times higher than AFFF) and varied significantly between products. In any case, the assessment illustrates the challenging nature of gasoline fires with the extinguishment times for the PFFs never meeting the current 30 second MILSPEC requirements even with application rates above 0.11gpm/ft^2.

Although it was not the intent of this effort to assess the adequacy of replacing the legacy AFFFs with any of these new products/formulations, the following discussion is provided as “food for thought” going forward.

The current MILSPEC requirements have evolved over the past 50 years to ensure that military firefighting personnel are given the best products available with the highest probability for success. These requirements were initially established based on the capabilities of the state of the art at the time the initial MILSPEC written (i.e., late 60’s early 70’s). The extinguishment times in the specification have been routinely reduced to match the capabilities of the best products of the day. Specifically, the original extinguishment time requirement for the 28ft^2 pan fire in 1969 was 84 seconds and was reduced to 65 seconds in 1971, 45 seconds in 1977 and to 30 seconds in 1978. The final performance requirements are typically attributed to the time required to prevent cookoff of ordnance and or the burn-thru of a fuselage in the aviation industry. However, the performance requirements evolved to those values more by “happen stance” than most people believe.

Shifting the logic away from the historical events like the fire on the USS Forestall in 1967 or the USS Nimitz in 1981 to typical “land-based” incidents, may allow more flexibility in the use of these new, more environmentally friendly formulations. Considering that, in most situations, these products will be applied at rates toward the right side of the “L curves” (i.e., at application rates above 0.1 gpm/ft^2), the differences in the capabilities of the top five PFFs and the legacy AFFFs are measured in seconds (i.e., 5-10 seconds for Jet A and 15-20 seconds for gasoline). This begs the question of “how good is good enough?”.

This program provides some of the required performance data needed to begin to answer this question and, in some respects, provides a fallback position when the use of AFFF is banned in the near future. If the capabilities of the top commercially available PFAS-free products are deemed adequate, addition research and preparation will be required to identify the non-fire performance properties needed to deploy these in typical DoD applications. Issues such as agent capability and viscosity will need to be re-evaluated and potentially reconsidered going forward (to name a few).

PATH FORWARD / IMPLEMENTATION

The primary performance limitation of these products is associated with the mechanisms of extinguishment and the need to produce aspirated foam to increase the extinguishment capabilities of these products. AFFF extinguishes a fire through the combination of two mechanisms: the formation of an oleophilic fluoro-surfactant film on the fuel surface and a layer of aspirated foam. Both mechanisms combine to seal in the fuel vapors and to prevent the development of a flammable vapor mixture above the fuel surface. Fuel surface cooling may also be a contributor for higher flashpoint fuels.

PFFs rely solely on the development of an aspirated foam blanket to contain the vapors and extinguish the fire. To date, the commercially available PFFs have no oleophilic properties and do not form a film on the fuel surface.

The MILSPEC tests currently used to approve AFFF do not consider the foam quality that will be produced by the fielded system/hardware. In fact, the MILSPEC fire performance tests are conducted with an air aspirating nozzle that produces significantly better foam quality than any of the discharge devices used in actual DoD applications. The WP19-5374program 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. This link should serve as the first step in developing a new foam specification for land-based applications.

The technical objective of the WP19-5374 effort is to demonstrate (and to develop an understanding of) the effects that foam quality has on the capabilities of new Fluorine Free Foams (FFFs) and relate these capabilities to the foam qualities produced by the various discharge devices used throughout the DoD.

The two scales of testing conducted during the WP19-5324 program demonstrated the potential of using PFFs in DoD applications with the understanding that final validation tests would be required against worst case, Maximum Credible Event (MCE) scenarios. WP21-3461 and WP21-3465 were established to validate these capabilities against the MCE test configurations used to assess the capabilities of AFFF 30 to 40 years ago with a focus on aircraft rescue and firefighting (i.e., ARFF, shore-based applications). These include an uncontained fuel spill fire and an obstructed running fuel fire scenario (referred to as debris pile fire scenarios) that includes both an obstructed 3-D component and a growing, uncontained spill/pool fire. The test parameters have been selected to represent shore-based applications (i.e., foam solutions will be made with freshwater) and the fires will be produced using kerosene-based aviation fuels (i.e., F-24 which is the military version of Jet A). As with the previous studies (i.e., WP19-5324), the results will be compared to the performance of a C6, AFFF currently on the QPL list. During the initial test series, the fires will be combatted using a single 125 gpm handline. During the second test series, the fires will be fought using the turrets/monitors mounted on ARFF vehicles. The programs will be performed by The Naval Research Laboratory (NRL), the Naval Air Warfare Center (NAWC), Weapons Division (WD) in China Lake (CL) California and Jensen Hughes (JH).

COST ASSESSMENT

An assessment of the costs to implement PFFs throughout the DoD cannot be performed until the performance requirements have been defined and documented.

IMPLEMTATION ISSUES

The two main implementation issues associated with these PFFs include the limited knowledge on the effects of foam aspiration on the firefighting capabilities of these products, and potential issues with proportioning higher viscosity and potentially non-Newtonian concentrates. The effects of aspiration on the firefighting capabilities of these products are being investigated under WP19-5474. This study will determine whether new discharge devices (i.e., nozzles) will be required when transitioning from AFFF to these PFFs. The issues associated with viscosity are being investigated by both the PFF manufacturers as well as ARFF vehicle manufacturers. This information should be available prior to developing the new shore-based MILSPEC toward the end of the 2021 calendar year.

1.0 INTRODUCTION

1.1 BACKGROUND AND PROBLEM STATEMENT

The firefighting foams (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. DoD needs to develop and/or identify environmentally acceptable alternatives (fluorine-free (FF)) that can provide equivalent firefighting capabilities as the foams that are currently being used. The first step to solving this problem was to develop an understanding and database of the capabilities of the currently available alternatives.

1.2 OBJECTIVES

The ultimate goal of the SERPD & ESTCP efforts is to identify an environmentally acceptable fluorine-free AFFF alternative that can provide equivalent firefighting capabilities as MILSPEC (MIL-PRF-24385F) AFFF.

The specific objectives of this program were to quantify the capabilities of the “state-of-the-art” fluorine-free foams in use today in both approval scale and real-scale applications and to initiate the development of a database for potential alternatives

This required us to answer the following technical questions:

- What are the firefighting capabilities of commercially available fluorine-free firefighting products?
- Are there potential environmental issues associated with these products?
- Are any of them suitable replacements for the foams (AFFF) currently in use by DoD?

1.3 TERMINOLOGY

1.3.1 PFAS versus Fluorine Free

AFFF contains a fluorinated, film forming surfactant (per- and poly- fluoroalkyl substances (PFAS)) to seal the fuel surface during suppression/extinguishment. In the early 2000s, the scientific and regulatory communities developed an increased understanding of the potential environment, safety and occupational health risks associated with continued use of PFAS, which has resulted in evolving, increasingly strict regulations at the federal, state, local and international levels. The historic longer chain (C8) surfactants (i.e., perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA)) were phased out of production in 2002 and replaced with shorter C6 chain PFAS. However, these shorter chain molecules are also being evaluated as emerging contaminants as well. To compound the issue, some fluorinated compounds in general are also being scrutinized/regulated.

Due to the constant influx of new research, regulatory levels are changing across the country almost daily pushing both the fire protection industry and DoD to aggressively pursue fluorine-free alternatives to the legacy AFFF. The fire protection industry (i.e., foam manufacturers) began to develop and market new fluorine free formulations about 15 years ago (i.e., around the time that C8 AFFFs were being replaced by C6 formulations). These new foams are labeled by the manufacturers and marketed as Fluorine Free Foams (FFFs). In addition there are a number of products referred to as “wetting agents” that are being developed and marketed as fluorine free AFFF alternatives.

As a point of clarification, it is generally understood that fluorine free is synonymous with the term PFAS free.

1.3.2 Current Test Standards

With respect to test standards, there are many industry specific test/approval standards used to approve foams for the spectrum of applications. The US military (i.e., Department of Defense (DoD)) uses MIL-PRF-24385 for approve legacy AFFFs (referred to from here on out as the MILSPEC). The petroleum industry uses UL 162 (Underwriters Laboratories – Standard for Foam Equipment and Liquid Concentrates) and/or the European Equivalent EN1568 (British Standard Fire Extinguishing Media – Foam Concentrates). The aviation industry uses ICAO (International Civil Aviation Organization – Test Standards A, B and C). In addition, there are a number of trade organizations such as LASTFire (Large Atmospheric Stationary Tank - Fire) that conducts third part performance assessments of specific products (both foams and hardware) for the petroleum industry.

At the time this program was conducted, there were a number of fluorine-free foams that had been tested to, and or listed/approved to, the legacy commercial foam test protocols and were being marketed and used over a range of applications.

It should be noted that there is no consistency in the performance and test parameters between the various protocols which tends to add confusion to the fire protection industry as a whole.

In addition to the "foams" investigated during this program, a group of products referred to as "wetting agents" and/or water additives were also assessed. These products are designed for a range of fire types (i.e., not specifically for flammable liquids as are the foams) and are tested to lower performance standards (i.e., NFPA 18 Wetting Agents & NFPA 18A Water Additives).

1.3.3 Descriptive Performance Parameters

During the assessments conducted during this program, the performance will be discussed in terms of application rate and extinguishment density. The application rate is defined as the foam/agent solution discharge rate per unit area and is expressed in terms of gallons per minute per square foot of fire area (gpm/ft^2). The metric equivalent has the units of liters per minute per square meter (lpm/m^2). The extinguishment density is the total amount of foam/agent per unit area required to extinguish the fire. This is expressed in terms of gallon per square foot (gal/ft^2) in English units and L/m^2 in metric units. These values are determined by multiplying the application rates times the extinguishment times.

In addition, the foam quality will be expressed in terms of expansion ratio and drainage time. The expansion ratio is the volume of expanded product discharged (i.e., liquid and bubbles) divided by the volume of the liquid solution used to make the product. The drainage time is the time in minutes that it takes for 25 percent of the total liquid contained in the foam sample to drain from the foam.

The fire performance will be expressed in terms of control, extinguishment and burnback time. Control is defined as the time required to reduce the size of the fire to 10% of its original/free burn size. Extinguishment is defined as the time required to eliminate all visual flaming of any size.

And, burnback is defined as the time for the fire to spread to involve an area of 25% of the fuel surface (e.g., 7 ft^2 for the 28 ft^2 pan fire). All of these fire performance times are expressed in term of seconds.

1.4 MECHANISMS OF EXTINGUISHMENT

From a mechanistic standpoint, the commercially available fluorine free products are different than the legacy AFFFs. Specifically, the fluorinated surfactants in AFFF tend to form a film on the fuel surface which aids in the containment of the fuel vapors. As a result, AFFF has two mechanisms that combine to extinguish/suffocate the fire; the foam blanket and the fluorinated surfactant film. PFFs do not form a film on the fuel surface and rely solely on the foam blanket to extinguish/smother the fire. This suggests (as shown in the literature) that the fire performance of the PFFs will be directly related to the quality of foam produced by the discharge device. The current MILSPEC tests are conducted with an air aspirating nozzle that typically produces expansion ratios on the order of 5-8.

In addition to the “foams” investigated during this program, a group of products referred to as “wetting agents” were also assessed. Some of these products use similar extinguishment mechanisms as the PFFs while other claim to work as emulsifiers and/or encapsulators. These potential additional mechanisms were never specifically studied/verified during this program.

2.0 TECHNICAL APPROACH

The program was initiated/designed to quantify the capabilities of the “state-of-the-art” of the commercially available fluorine-free foams and agents in use today and provide information on the relationship between the approval test requirements/results and the actual fielded capabilities of the foam/agent.

The systematic approach developed for this program includes the following six tasks:

> Task 1: A literature search on potential fluorine-free AFFF alternatives;
>
> Task 2: A detailed environmental analysis to down-select agents for real-scale testing;
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> Task 3: Approval-scale fire performance testing using the tests described in the MILSPEC with and without modification;
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> Task 4: Data analysis to rank the capabilities of the alternatives and to down-select agents for approval-scale testing;
>
> Task 5: Real-scale fire testing using two representative scenarios; and,
>
> Task 6: The development of a database/final report that documents the findings and recommendations for the path forward.

It should be noted that the original approach presented to SERDP/ESTCP had Tasks 3 & 5 switched in order. The original approach was concerned that the challenging nature of the MILSPEC test requirements was prematurely eliminating potentially acceptable alternatives. However, due to COVID related delays obtaining the required test equipment to conduct the representative scale tests, the approval scale tests were conducted first. This is explained in more detail later in this report.

3.0 TASK 1 LITERATURE SEARCH

During Task 1, JH and NRL personnel conducted a comprehensive literature review on commercially available fluorine free flammable liquid fire extinguishing foams and agents. As part of the review, each manufacturer was contacted to gather as much information as possible on agent composition, safety data sheets, type approvals and test data/results, and applications/markets where the agent is currently being used (i.e., a few references on their product capabilities will also be collected). JH also reached-out to the end users (i.e., first responders) to inquire their thoughts and opinions on the capabilities of the product. The review also included a search on peer-reviewed journal articles, professional articles, academic publications and incident reports involving alternative agents.

The initial literature/internet search identified over 60 products that were being marketed as environmentally friendly AFFF alternatives. Upon further investigation, it was determined that at least 20 of these products had no listings or approvals (i.e., no legitimate firefighting pedigrees). Based on the lack of any performance data, these products were no considered for this program.

The leading fluorine free foam and agent manufacturers are summarized in Table 3.1. Many of these manufacturers have multiple formulations designed for specific hazards. For example, Angus has products for use in the aviation industry and ones designed for broad spectrum petroleum industry use that are classified as Alcohol Resistant Fluorine Free Foams (AR-FFF).

The complete list has been assembled into an excel spreadsheet that has been uploaded to the SERDP/ESTPC website. The spread sheet includes the links to the manufacturer's websites, SDS (MSDS), and some of the approval tests reports (where available).

Table 3.1. Main Manufacturers of Fluorine Free Foams and Agents

Manufacturer	Type
National (4 FF products)	Foam
Angus (4 FF products)	Foam
Solberg (2 FF products)	Foam
Fomtec (4 FF products)	Foam
Bio-ex (2 FF products)	Foam
Dr. Sthamer (2 FF products)	Foam
vs FOCUM (2 FF products)	Foam
Auxquimia (2 FF products)	Foam
Phos-Chek (4 FF products)	Foam
FireBull PFF (1 FF product)	Foam
3F – Freedol (4 FF products)	Foam
Bristol – EkoSol (2 FF products)	Foam
Orchidee (4 FF products)	Foam
GreenFire (2 FF products)	Both
Amiran (1 FF product)	Wetting
Pyrocool (1 FF product)	Wetting
Novacool (1 FF product)	Wetting
Coldfire (1 FF product)	Wetting
Geltech Solutions – FireIce (1 FF product)	Wetting

Note: FF – Fluorine Free = PFAS Free

4.0 TASK 2 ENVIRONMENTAL SCREENING

During Task 2, Jensen Hughes conducted a preliminary life cycle environmental assessment (i.e., high level - chemical constituent identification and review) for each potential alternative. At a minimum, JH collected available aquatic toxicity, chemical oxygen demand and biodegradability test data required in the MIL-PRF-24385. Jensen Hughes collected the majority of this data from Safety Data Sheets (SDS) and Technical Data Sheets available from the manufacturers for 26 total products, including a collection of fluorine-free foams, gels, and additives (encapsulators, absorbent polymers). This assessment does not include a comparison of one product to another based on available data, only an assessment of what data is available at this time. A heavy emphasis is placed on persistence in the environment due to the unique concerns associated with current aqueous film forming foams non-biodegrability. A summary of these findings is provided below.

Five of these products were deemed to have an acceptable amount of available data, including at least a baseline amount of data for eye irritation, skin irritation, acute toxicity, ecotoxicity and persistence. Additional data may be needed, but based on the SDS, these materials have been evaluated for potential ESOH risks.

- Freedol-SF, Alcohol Resistant Synthetic (3F)
- Respondol ATF 3/3, Alcohol Resistant Synthetic (Angus Fire)
- Fomtec Enviro USP, Synthetic (Dafo Fomtec AB)
- F-500, Encapsulator (Hazard Control Technologies)
- Moussol FF 3/6, Alcohol Resistant Synthetic (Sthamer)

Three products were found to have a near complete data set for eye, skin, acute toxicity and ecotoxicity; however, they did not include data for persistence or bioaccumulation. Additional persistence or bioaccumulation data is needed to provide an adequate risk assessment for complete implementation.

- Universal F3 Green, AR – Synthetic (National Foam)
- Pyrocool FEF, Fire Extinguishing Foam (Pyrocool Techinologies)
- LS xMax, Multi-purpose Foam Concentrate (Fomtec)

Four products were found to have minimal data, but did provide an assessment of persistence in the environment. Additional human health and ecotoxicity data is needed to provide an adequate risk assessment.

- Ecopol, Alcohol Resistant Synthetic (Bio – Ex)
- Coldfire, Encapsulator (Coldfire Canada)
- FireIce – Pro, Super Absorbant Polymer (Geltech Solutions)
- Sthamex K 1% F-15, Synthetic (Sthamer)

Six products were found to have limited human health and ecotoxicity data; however, they did not include an assessment of persistence in the environment. Additional persistence and bioaccumulation data is needed to provide an adequate risk assessment.

- Flameout, Synthetic Bio – Surfactant (Amiran Biochemicals)
- Unipol-FF 3/6, Alcohol Resistant Synthetic (Auxquimia)
- Orchidee, Foam Concentrate (Orchidee)
- Phos-Chek 1% Fluorine Free, Synthetic (Perimeter Solutions)
- Phos-Chek 3%/6% Fluorine Free, Alcohol Resistant Synthetic (Perimeter Solutions)
- RE-HEALING RF3, 3% Foam Concentrate Synthetic (Solberg)

Five products did not have a publicly available SDS or technical data sheet providing at least a baseline amount of data.

- Hyfex SF-1, Synthetic (3F)
- EkoSol FF-3-3X6, Alcohol resistant synthetic (Bristol)
- GreenFire, Fluorine free foam (Fire Suppression Innovations)
- Silvara 1, Fluorine free foam Class A,B (VS Focum)
- Silvara APC 3x6, Polivalent (VS Focum)

In total, 17 products also included details on specific ingredients. As expected, many of these ingredients pose a risk for skin and eye irritation, with some anticipated to cause severe, irreversible eye damage upon exposure. Of these, the most toxic material is likely the reaction mass of 5-chloro-2-methyl-4-isothiazolin-3-one and 2- ATP CLP00 methyl-2H -isothiazol-3-one (3:1), which may produce an allergic reaction upon exposure and has been shown to be acutely toxic in mammals and aquatic species. However, this is only used in quantities less than 0.0007% as reported in the final mixture, so it is unlikely to pose a serious threat. Additional materials, as reported on the SDS, did not present significant risk to humans.

At the time of this project, it was determined that additional assessment of environment, safety and occupational health risks for firefighting foams should be conducted as part of an SERDP-wide coordinated effort. Multiple leveraged efforts are developing Life Cycle Assessments (LCAs), toxicity assessments and toxicity data for firefighting foams to provide a quantitative risk score for emerging fluorine-free foams. This project was used to inform potential priority testing for the best performing foams.

5.0 TASK 3 APPROVAL SCALE TESTING

During Task 3, the firefighting capabilities (extinguishment and burnback resistance) of the selected alternatives were evaluated 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 foam/agent was tested against two different fuels (i.e., the legacy unleaded zero alcohol gasoline and Jet A) with two foam solution flow rates 2 gpm and 3 gpm. Jet A was included in the assessment since it is more representative of the kerosene-based fuels used throughout the DoD. Specifically, the original MILSPEC was developed when the predominant fuels included JP-4 and MOGAS and may be unnecessarily eliminating potential alternatives from further consideration. There has been talk about adding a kerosene-based fuel in the land-based revision of the MILSPEC to make the approval tests more representative. In addition, Jet A is the primary fuel used at both DoD and Civilian Airfields which has become the initial DoD focus for the selection and deployment of a fluorine free, AFFF alternative. The details of the test program are provided in the following sections.

5.1 TEST SETUP AND DESCRIPTION

5.1.1 Test Facility

The 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.

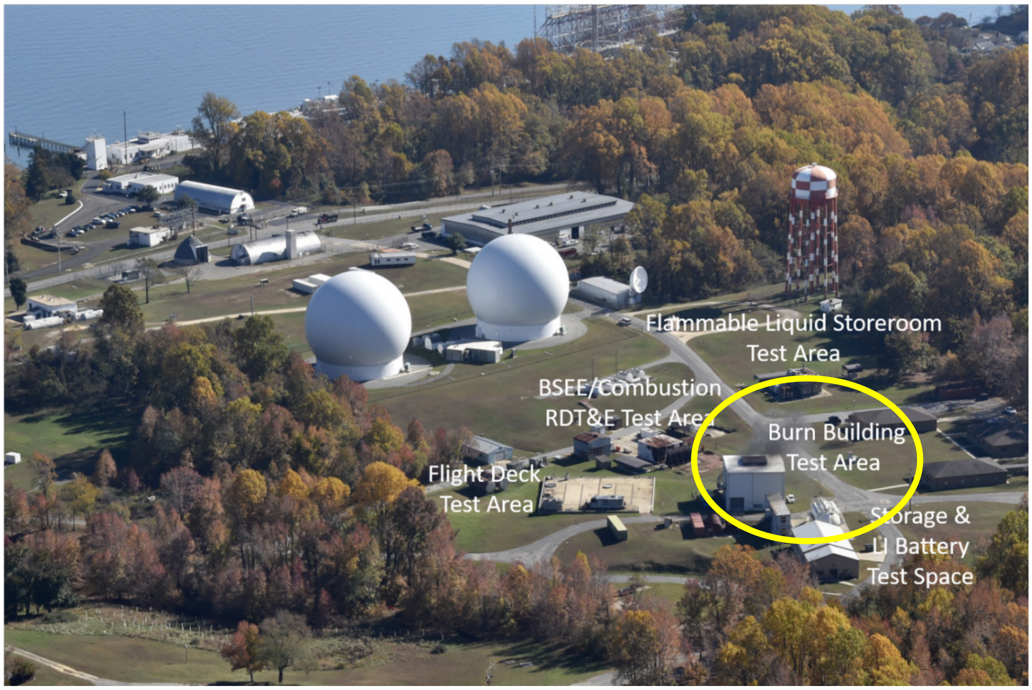


Figure 5.1. Aerial View of CBD Test Facility (with the Burn Building Circled)

Although the original intent was to select 10 candidate foams/agents for testing, the number grew to over 20 as prototype products were developed, and additional products identified.

5.1.2 Fire Scenario(s)

5.1.2.1 Fire Sizes/Pans

The MILSPEC (MIL-PRF- 24385F) includes fire extinguishment tests using both 28 ft^2 pool fires and 50 ft^2 pool fires (i.e., Sections 4.7.13.1 and 4.7.13.2). The focus of this test program was on the 28ft^2 pool fires but a limited number of 50ft^2 pool fires were also conducted.

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 (see Figure 5.2). The 50 ft^2 fire is produced using a circular pan 8 feet in diameter, fabricated from 0.25-in. thick stainless steel with a 4-in. high side. The 28ft^2 pan fires are conducted in the large burn building while the 50 ft^2 pan fires are typically run outdoors on the Flight Deck adjacent to the burn building (reference Figure 5.2).

Figure 5.2. 28ft^2 Pan Fire

5.1.2.2 Measures of Performance

The performance metrics included complete extinguishment and the 25 % burnback time. Since many of these fires were extinguished fairly quickly, it was difficult to identify the control time (i.e., 90% extinguishment time). These metrics were determined real-time by the test director as well as through video analysis after the test was completed.

5.1.3 Test Fuels

The tests were conducted using two fuels; unleaded, zero alcohol gasoline (referred to as MILSPEC 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).

5.1.4 Firefighting Equipment

Prior to the start of each test, the 3% foam solution (i.e., 97% water/3% foam concentrate) was prepared in a clear/white, open top mixing container and then pumped into a pressure vessel for discharge onto the fire. The clear/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 MILSPEC qualification was used during these tests.

5.1.5 Test Procedures

The tests were conducted using the MILSPEC test procedures as basis. The fire pan was first filled with a water substrate to a depth of 1 inch. Ten gallons of fuel were 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. The fire was allowed to preburn for a 10 second period after reaching full involvement.

After the 10 second preburn, 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 (1ft diameter with 2in high sides) containing one gallon of unleaded gasoline was placed in the center of the 28ft^2 pan and a timer started. When it appeared that the fire had spread outside the pan, the pan was removed. The burnback time that was recorded in tables was the time where an estimated 7ft^2 (25 percent) of the total area was involved in flames.

5.1.6 Foam/Agent Concentrates and Test Matrix

Although the original intent was to select 10 candidate foams/agents for testing, the number grew to over 15 as prototype products were developed, and additional products identified. The final 15 tested included 12 Fluorine Free Foams (FFFs - i.e., products with foam approval test pedigrees) and 3 wetting agents (WAs - i.e., products with NFPA/UL 18 & 18A approval test pedigrees). Each foam/agent was tested against two different fuels (i.e., the legacy unleaded zero alcohol gasoline and Jet A) with two foam solution flow rates 2 gpm and 3 gpm. In addition to the candidate foams/agents, tests were also conducted with Buckeye Type 3 (3%) MILSPEC AFFF to provide a baseline for comparison. The test matrix is shown in Table 5.1.

Table 5.1. Approval Scale Test Matrix

Foam/ Agent	Agent Type	Gasoline		Jet A	
		2 gpm	3 gpm	2 gpm	3 gpm
AFFF	AFFF	X	X	X	X
PFF1	Foam	X	X	X	X
PFF2	Foam	X	X	X	X
PFF3	Foam	X	X	X	X
PFF4	Foam	X	X	X	X
PFF5	Foam	X	X	X	X
FFF6	Foam	X	X	X	X
FFF7	Foam	X	X	X	X
FFF8	Foam	X	X	X	X
FFF9	Foam	X	X	X	X
PFF10	Foam	X	X	X	X
PFF11	Foam	X	X	X	X
PFF12	Foam	X	X	X	X
WA1	Wetting	X	X	X	X
WA2	Wetting	X	X	X	X
WA3	Wetting	X	X	X	X

In addition to the tests shown in Table 5.1, there were a half dozen or so prototype formulations being developed during other SERDP / ESTCP programs that were also tested. The results of the tests conducted with prototype formulations will be published in the final reports of the various formulation development programs.

5.2 APPROVAL SCALE TESTS RESULTS

The approval scale test results are summarized in Tables 5.2 and 5.3. Table 5.2 provides the extinguishment and burn back times for the tests conducted with each foam/agent. Table 5.3 provides the measured expansion ratios and drainage times for the two flow rates included during this assessment. These results are currently presented as a "blind study" and do not include the names of the products tested (i.e., just generic names associated with the type of product tested). The names of the products will be included in an NRL report (Distribution D) published later this year.

Table 5.2. Approval Scale Test Results

Foam/Agent	Agent Type	Gasoline		Jet A	
		2 gpm	3 gpm	2 gpm	3 gpm
		Ext (sec)	Ext (sec)	Ext (sec)	Ext (sec)
AFFF	AFFF	30	24	16	12
PFF1	Foam	49	42	19	15
PFF2	Foam	58	37	24	15
PFF3	Foam	57	45	30	20
PFF4	Foam	53	45	33	22
PFF5	Foam	57	52	26	18
FFF6	Foam	77	55	27	15
FFF7	Foam	77	65	25	21
FFF8	Foam	84	67	22	17
FFF9	Foam	126	71	22	16
PFF10	Foam	No	123	26	20
PFF11	Foam	-	No	No	114
PFF12	Foam	No	113	43	31
WA1	Wetting	No	124	29	20
WA2	Wetting	No	104	32	27
WA3	Wetting	-	No	-	95

Table 5.3. Approval Scale Foam Qualities

Foam/Agent	Agent Type	2 gpm		3 gpm	
		Expansion Ratio	Drainage (sec)	Expansion Ratio	Drainage (sec)
AFFF	AFFF	8.0	269	8.2	260
PFF1	Foam	8.5	248	8.0	275
PFF2	Foam	8.2	2574	7.6	2759
PFF3	Foam	7.7	297	7.2	296
PFF4	Foam	8.2	1831	7.2	2182
PFF5	Foam	7.1	192	7.0	187
FFF6	Foam	8.6	202	7.6	215
FFF7	Foam	7.3	560	7.8	527
FFF8	Foam	7.9	790	7.8	811
FFF9	Foam	6.7	193	6.8	210
PFF10	Foam	6.5	380	5.9	180
PFF11	Foam	-	-	7.4	202
PFF12	Foam	7.3	193	7.6	215
WA1	Wetting	6.9	145	6.5	148
WA2	Wetting	7.0	167	6.7	188
WA3	Wetting	-	-	7.7	270

The approval scale tests identified a few obvious trends in the test difficulty and foam/agent capabilities. The first observation was the ease in extinguishing the Jet A fires as compared to the gasoline fires. Thirteen of the fifteen foam/agents were capable of extinguishing the Jet A fires at 2 gpm (0.07 gpm/ft^2) in about 30 seconds or less. Conversely, only nine of the products were capable of extinguishing the gasoline fires at 2 gpm (0.07 gpm/ft^2) and required significantly longer and more foam/agent to extinguish the fire. As a general statement, the extinguishment times for gasoline were typically about twice as long as those observed for Jet A.

With respect to the type of product (i.e., AFFF, PFF and WA), the legacy MILSPEC AFFF provided consistent results and always outperformed the other products included in this assessment. The foams listed and approved using UL 162 or EN 1568–part 3 or ICAO C typically out-performed the wetting agents. This was expected since these “foam products” are tested and approved at much lower application rates (i.e., between 0.04 gpm/ft^2 – 0.06 gpm/ft^2) than the “wetting agents” which are listed and approved per NFPA 18 (i.e., 0.2 gpm/ft^2). There were a limited number of foams that were only tested to either EN 1568-part 2 or ICAO B which fell in between the higher performance foam products and the wetting agents.

In addition to the foams/agents listed in Table 5.2, there were a half dozen or so prototype formulations being developed during other SERDP / ESTCP programs that were also tested. Some of these products showed promise but none of them could compete with the performance observed for the current commercially available products with the exception of one product (i.e., a modified siloxane formulated by Materials Modification Inc.) The results of the tests conducted with prototype formulations will be published in the final reports of the various formulation development programs.

6.0 TASK 4 DATA ANALYSIS AND DOWN SELECTION

During Task 4, the alternatives were ranked and grouped based on the firefighting capabilities observed/measured during the approval scale tests. As stated previously, the legacy MILSPEC AFFF provided consistent results and always outperformed the other products included in this assessment. The top five fluorine free performers (all PFFs) demonstrated good capabilities against both gasoline and Jet A and are highlighted in green in Table 6.1. These top performers were all able to extinguish the gasoline fires with a 2 gpm discharge rate in less than 60 seconds and the Jet A fires at the 2 gpm discharge rate in less than 30 seconds. The next group of products (all PFFs) demonstrated good capabilities against Jet A but produced longer extinguishment times against the gasoline fires (i.e., about 50% longer than the top 5 performers). These are highlighted in yellow in Table 6.1. The remaining group consisted of seven products that had varying degrees of success but typically struggled against the gasoline fires. This group consists of four PFFs and the three wetting agents as highlighted in red in Table 6.1.

Table 6.1. Approval Scale Test Performance Groupings

Foam/ Agent	Agent Type	Gasoline		Jet A	
		2 gpm (.07 gpm/ft^2)	3 gpm (.11 gpm/ft^2)	2 gpm (.07 gpm/ft^2)	3 gpm (.11 gpm/ft^2)
		Ext (sec)	Ext (sec)	Ext (sec)	Ext (sec)
AFFF	AFFF	30	24	16	12
PFF1	Foam	49-58	37-52	19-33	15-22
PFF2	Foam				
PFF3	Foam				
PFF4	Foam				
PFF5	Foam				
FFF6	Foam	77-82	55-67	22-27	15-21
FFF7	Foam				
FFF8	Foam				
FFF9	Foam	126-No	71-No	22-No	16 -114
PFF10	Foam				
PFF11	Foam				
PFF12	Foam				
WA1	Wetting	No	104-124	29-32	20-27
WA2	Wetting				
WA3	Wetting	No	No	No	95

🟩 Good
🟨 OK
🟥 Not so good

From a general performance classification standpoint, the capabilities observed during these tests were consistent with the documented pedigrees (i.e., listings and approvals). Specifically, the PFFs with the most/challenging approvals (i.e., UL 162, EN1568-Part 3, and ICAO C) performed the best during this program. Conversely, the wetting agents that are approved to NFPA/UL 18 at a much higher application rate (i.e., 10 gpm for NFPA/UL 18 versus 3 gpm for UL 162/EN 1568 and ICAO C) were toward the bottom of the performance groupings. With that said, the best performing wetting agent (i.e., WA2) was also assess during the representative scale test scenario.

It should also be noted that there are a few reports that indicate that some of these wetting agents may perform better against a three-dimensional running fuel fire than the PFFs and even AFFF. However, none of the current test protocols include this type of scenario in the approval process.

The top five performers, all PFFs, typically produced extinguishment times that were 50-80% longer than the MILSPEC AFFF as illustrated in Figure 6.1 The average extinguishment times and the percent differences are shown in Table 6.2.

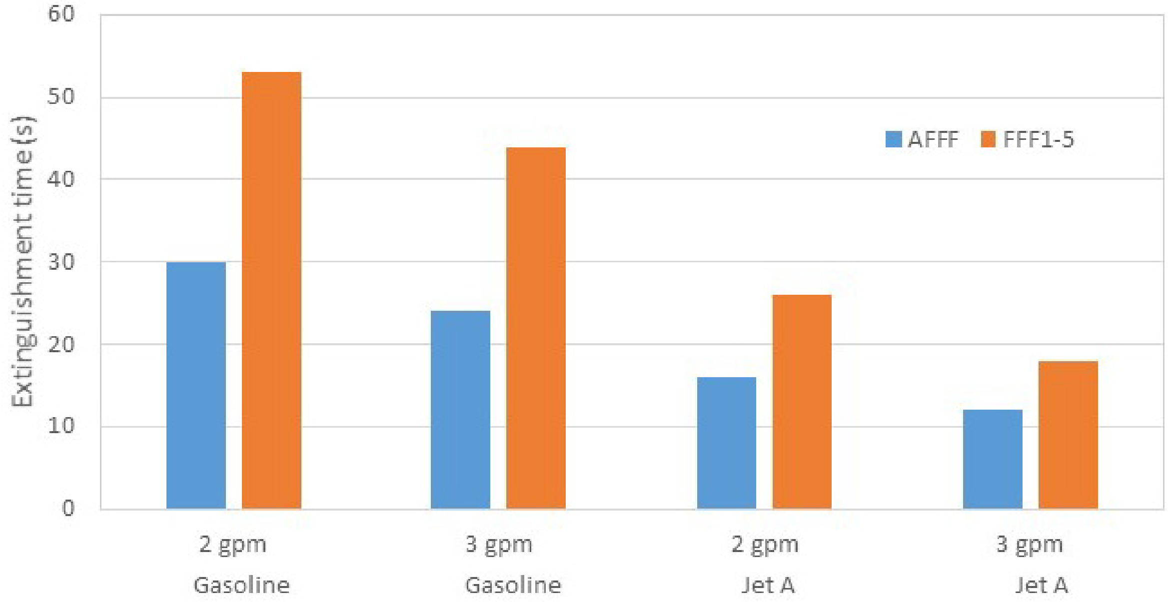


Figure 6.1. Approval Scale Performance Comparison (AFFF vs PFF1-5)

Table 6.2. Approval Scale Performance Comparison (AFFF vs PFF1-5)

Foam/Agent	Gasoline		Jet A	
	2 gpm (.07 gpm/ft^2)	3 gpm (.11 gpm/ft^2)	2 gpm (.07 gpm/ft^2)	3 gpm (.11 gpm/ft^2)
	Ext - sec	Ext-sec	Ext-sec	Ext-sec
AFFF	30	24	16	12
PFF1-5	53	44	26	18
Percent longer	70%	80%	60%	50%

Based on the results of the approval scale tests, the top five PFFs were selected to be further assessed during the representative scale testing. This group included three Newtonian concentrates (lower viscosity concentrates that flow similar to corn syrup) and two non-Newtonian concentrates (higher viscosity concentrates that behave more like molasses and/or jello). As stated in Section 4.0, these top five PFFs are currently being ECOTOX tested during other SERDP – ESTCP programs.

7.0 TASK 5 REPRESENTATIVE SCALE TESTING

During Task 5, the firefighting capabilities of the top fluorine free foams/agents were assessed against a real-scale, representative manual firefighting scenario using a fire hose to extinguish a 400 ft^2 pool fire. Most of these tests were conducted with Jet A with a limited number repeated with gasoline for comparative purposes (i.e., the agents that did extremely well against the Jet A were retested against gasoline). The initial tests conducted were conducted with MILSPEC AFFF to provide a baseline for comparison and to allow the firefighting party the opportunity to optimize their procedures and tactics.

During this series, the fires were extinguished using a fire hose equipped with a 30 gpm vari-nozzle. The resulting foam solution application rate was 0.07 gpm/ft^2 which is the same as the approval scale tests (i.e., 28ft^2 pan fire tests conducted with a foam solution discharge rate of 2 gpm). This provided a direct comparison of capabilities on two vastly different scales (i.e., almost a factor of 15 difference in size). A second set of tests were also conducted with a foam tube attachment to the nozzle that provided higher aspirated foam. The details of the test program are provided in the following sections.

John Farley of the Naval Research Laboratory (NRL) lead the firefighting efforts during this program. John and his assistant were fully suited-out in PPE and typically combatted each fire for a period of 3 minutes (after a 10 second preburn). If the fire was not extinguished after the three-minute period, the fire was extinguished using MILSPEC AFFF discharged from the backup fire hose (and firefighter) located near the northwest corner of the Flight Deck.

7.1 TEST SETUP AND DESCRIPTION

7.1.1 Test Facility

As with the approval scale tests, the representative scale tests were also conducted at CBD located in Chesapeake Beach, MD. The tests were conducted on a 100 ft by 100 ft concrete pad referred to as the Flight Deck during 3rd Qtr of FY21. An aerial view of the test facility is provided in Figure 7.1.

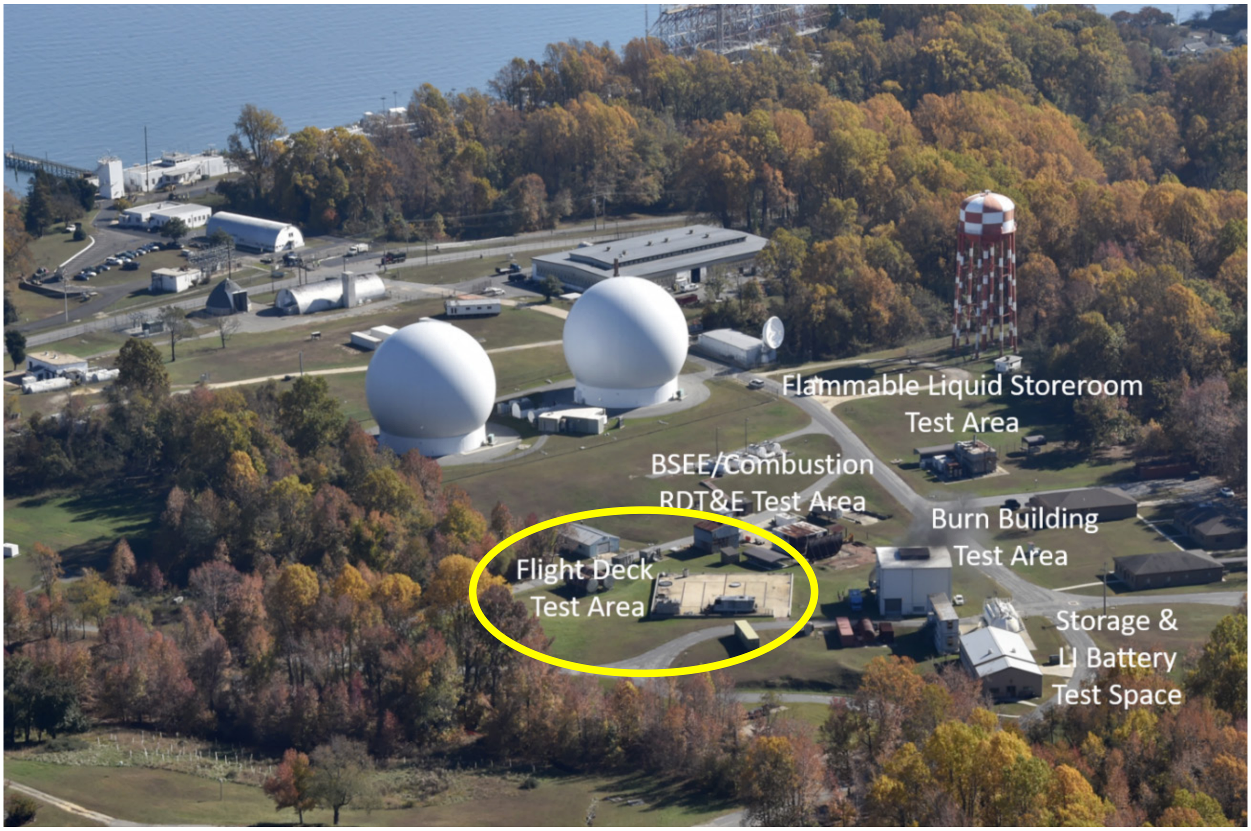


Figure 7.1. Aerial View of CBD Test Facility (with Flight Deck Circled)

7.1.2 Fire Scenario(s)

7.1.2.1 Fuel Pan

A 400 ft^2 (20 ft x 20 ft) steel pan was constructed and place near the center of the flight deck (i.e., slightly shifted toward the northeast corner). The approximate location and scale are shown in Figure 7.2. The pan was constructed of 0.375 in. (3/8 in.) steel plate with an 8 in. lip. All seams were continuously welded to ensure the pan was water/liquid tight. A nominal 2 in. diameter drain was installed at the southeast corner of the pan (bottom of the pan) to aid in the removal of the effluent after each test. The drain was positioned over one of the existing trenches built into the concrete flight deck. The drain was equipped with a ball valve and was connected directly to the Clean Harbors effluent removal system and storage tank located on the deck below.

Figure 7.2. Fuel Pan Relative Size and Location

7.1.2.2 Fire Size

At full involvement, the fire consumed about 40 gallons of fuel per minute and produce a flame height of about 50 ft. A photograph of the fully involved pan is provided as Figure 7.3.

Figure 7.3. Fuel Pan Relative Size and Location

The radiation released from the fire made the entire Flight Deck untenable with exposure values in excess of 5 kW/m^2 at the edges of the deck. To prevent the concrete deck from spalling, a deck cooling system was installed around the perimeter of the pan that sprayed water away from the pan directly on the concrete surface. The system flowed approximately 250 gpm and applied water to the concrete within 20ft of the pan at a rate of about 0.15 gpm/ft^2. The water being sprayed from this system can be seen in Figure 7.3.

7.1.2.3 Measures of Performance

The performance metrics for the representative scale tests included both the 90% control time and the 100% extinguishment time. Due to the size of the burn pan, no burnback tests were conducted at this scale. The control and extinguishment times were determined real-time by the test director as well as through video analysis after the test was complete.

7.1.3 Test Fuels

Most of the tests were conducted with Jet A but a limited number were also conducted with gasoline. Additional information of the fuels was provided in Section 5.1.3 of this report. Approximately 150 gallons of fuel was used during each test which is adequate to provide just under a 5-minute burn time.

7.1.4 Manual Firefighting Equipment / System

The manual firefighting system used to combat the 400ft^2 pool fires consisted of a pre-mixed solution storage tank (i.e., an Intermediate Bulk Container (IBC)), a discharge pump with recirculation capabilities for mixing, and a standard 1 ½ in fire hose equipped with a 30 gpm vari-nozzle. In addition to the primary firefighting system, a backup AFFF system consisting of a pre-mixed solution storage tank (i.e., an Intermediate Bulk Container (IBC)), a discharge pump with recirculation capabilities for mixing, and a standard 1 ½ in fire hose equipped with a 95 gpm vari-nozzle was used in situations where the fire was not extinguished during the allotted discharge time. All of these components were located on the west side of the flight deck behind aluminum heat shields as shown in Figure 7.4.

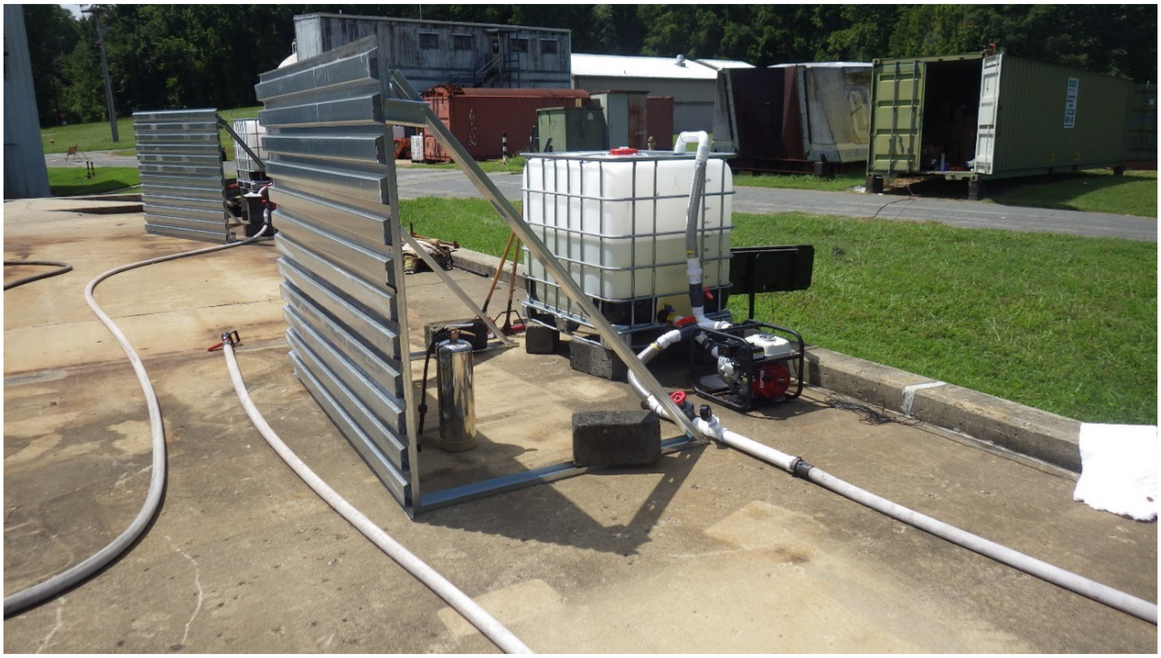
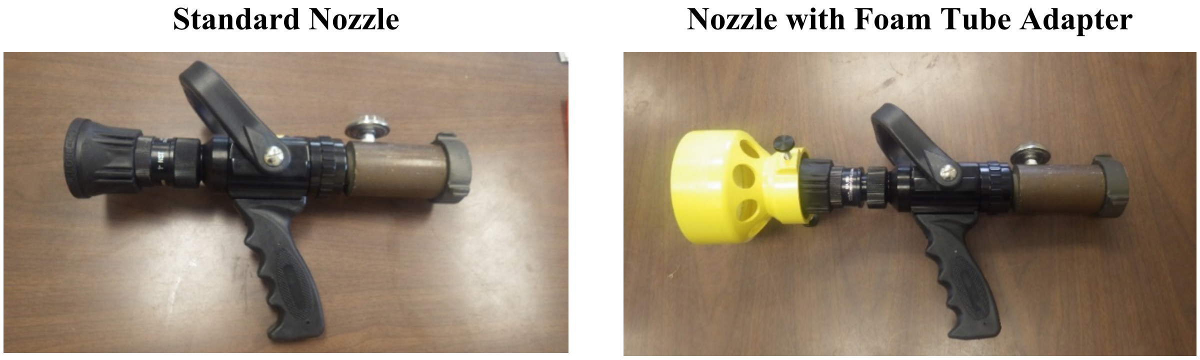


Figure 7.4. Primary and Backup Manual Firefighting Systems

The foam solution for each test was be mixed and stored in a 275-gallon Intermediate Bulk Container (IBC) located on the west side of the Flight Deck. Approximately 165 gallons of foam solution was prepared for each test (i.e., 5 gallons of foam/agent concentrate and 160 gallons of water). The foam solution was pumped from the IBC to the fire hose nozzle using a gasoline engine driven pump manufactured by Honda Corp. The pump has a capacity of 150 gpm at a pressure of 100 psi. The nozzle pressure was regulated by adjusting the speed (i.e., RPM) of the discharge pump and preset prior to the start of each test.

A constant flow rate, 30 gpm pistol grip nozzle was used to extinguish these fires (CS Supply Inc., Model VB 1560 body and Model 130 tip). The nozzle is designed to flow 30 gpm at a pressure of 100 psi over the range of spray patterns from zero degrees (straight stream) to 120 degrees (fog pattern). In addition, an air-aspirating foam tube adapter manufactured by Mad Dog Corp. was also tested during this program. Photographs of the discharge nozzle, with and without the foam tube adapter are provided as Figure 7.5.



Standard Nozzle

Nozzle with Foam Tube Adapter

Figure 7.5. 30 gpm Nozzle with and without the Foam Tube Adapter

Prior to conducting the actual fire tests, the firefighters conducted a series of “mock tests” to develop an optimal technique for fighting the fires using the standard nozzle and the nozzle with the foam tube adapter.

One of the first variables investigated was nozzle spray pattern. During these mock tests, it was determined that the optimal spray pattern for the standard nozzle (i.e., without the foam tube) was 15 degrees. At 15 degrees, the nozzle provided a stream reach of about 50 ft and foam aspiration in the 5-6 range (i.e., the expansion ratio for the AFFF was approximately 5 and the expansion ratio of the PFFs was approximately 6). Narrower spray patterns (i.e., straight stream) increased the reach to over 80 ft but provided minimal aspiration (i.e., 1-2 range). The straight stream pattern also had a tendency to plunge into the fuel and splash the fuel out of the pan making it difficult to “gently” apply the foam to the fuel surface. Wider spray patterns (i.e., greater than 15 degrees) tended to reduce the reach, but did not increase the foam aspiration and tended to overshoot the pan edges resulting in less than optimal foam application (i.e., the spray pattern was wider than the fire pan reducing the actual delivered application rate). A photograph of the fire being extinguished used the standard nozzle with a 15-degree spray pattern is provided as Figure 7.6.

Figure 7.6. Standard 30 gpm Nozzle at 15 Degree Spray Pattern

When repeating the same assessment with the foam tube adapter, it was determined that the optimal spray pattern was about 5 degrees. At 5 degrees, the nozzle provided a stream reach of about 30 ft and a foam aspiration in the 20 range (i.e., the expansion ratio for the AFFF was approximately 18 and the expansion ratio of the PFFs was between 20-24). Narrower spray patterns (i.e., straight stream) increased the reach to over 40 ft but produced a nonhomogeneous spray (i.e., lower aspirated foam in the center of the pattern and higher aspirated foam at the edges). As with the standard nozzle without the foam tube adapter, the straight stream pattern also had a tendency to plunge into the fuel and splash the fuel out of the pan making it difficult to “gently” apply the foam to the fuel surface, especially when close to the pan. Wider spray patterns only tended to reduce the reach and did not increase the foam aspiration. A photograph of the fire being extinguished used the nozzle equipped with the foam tube adapter with a 5-degree spray pattern is provided as Figure 7.7.

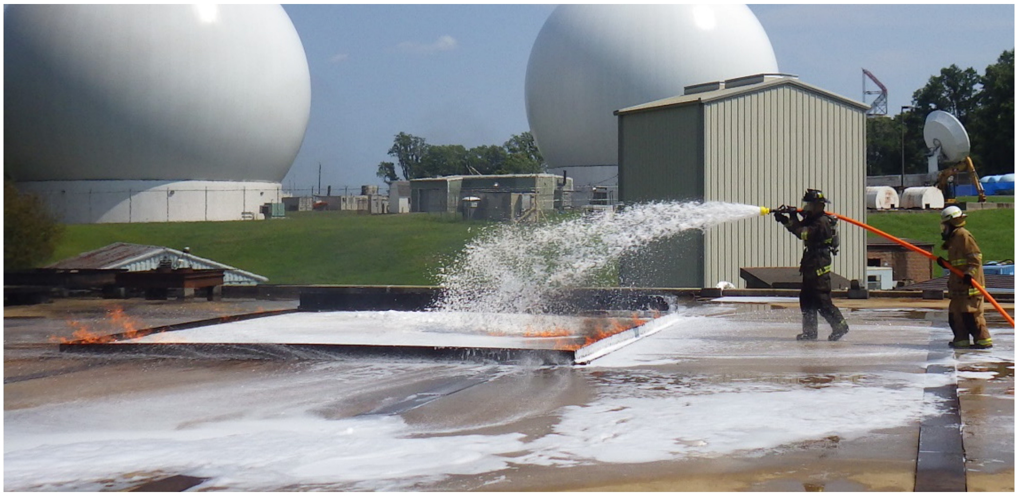


Figure 7.7. 30 gpm Nozzle with Foam Tube at 5 Degree Spray Pattern

7.1.5 Foam/Agent Concentrates and Test Matrix

The top 5 PFFs identified during the approval scale tests were then evaluated against the 400 ft^2 pool fire. In addition, the top performing wetting agent was also included in the evaluation. As with the approval scale tests, the agent capabilities were baselined to the Buckeye Type 3 (3%) MILSPEC AFFF. These products along with their approval scale test results are listed in Table 7.1.

Table 7.1. Selected Fluorine Free Foams and Agents

Foam/ Agent	Agent Type	Gasoline		Jet A	
		2 gpm	3 gpm	2 gpm	3 gpm
		Ext (sec)	Ext (sec)	Ext (sec)	Ext (sec)
AFFF	AFFF	30	24	16	12
PFF1	Foam	49	42	19	15
PFF2	Foam	58	37	24	15
PFF3	Foam	57	45	30	20
PFF4	Foam	53	45	33	22
PFF5	Foam	57	52	26	18
WA2	Wetting	No	104	32	27

7.2 REPRESENTATIVE SCALE TEST RESULTS

The representative scale test results for Jet A are summarized in Tables 7.2 and 7.3. Table 7.2 provides the control and extinguishment times for the tests conducted with each foam/agent. Table 7.3 provides the measured expansion ratios and drainage times for the two nozzle configurations (i.e., with and without the foam tube adapter) used during this assessment. As with the approval scale tests, these results are currently presented as a "blind study" and do not include the names of the products tested (i.e., just generic names associated with the type of product tested given during the approval scale testing).

As shown in Table 7.2, the legacy MILSPEC AFFF produced the fastest control an extinguishment times during this program. The AFFF extinguished the Jet A fire in 45 seconds with the standard nozzle configuration and in 25 seconds with the foam tube adapter. The PFFs took about 60 seconds to extinguish the Jet A fires using the standard nozzle and about 40 seconds with the foam tube adapter. These results are consistent with the approval scale tests in terms of relative differences (i.e., the PFFs required about 50% longer to the extinguish the Jet A fires as compared to the MILSPEC AFFF).

Table 7.2. Representative Scale Tests Results (Jet A)

Foam/ Agent	Agent Type	Fuel	Fire	STD Nozzle		Foam Tube	
				Control	Ext	Control	Ext
AFFF	AFFF	Jet A	400 ft^2	25	45	15	25
PFF1	Foam	Jet A	400 ft^2	40	60	20	35
PFF2	Foam	Jet A	400 ft^2	40	52	25	45
PFF3	Foam	Jet A	400 ft^2	30	49	20	35
PFF4	Foam	Jet A	400 ft^2	45	60	20	35
PFF5	Foam	Jet A	400 ft^2	50	65	35	55
WA2	Wetting	Jet A	400 ft^2	60	90+/No	60	102

Table 7.3. Representative Scale Foam Qualities

Foam/ Agent	Agent Type	Fuel	Fire	STD Nozzle		Foam Tube	
				Expansion	Drainage	Expansion	Drainage
AFFF	AFFF	Jet A	400 ft^2	4.8	40	18.0	50
PFF1	Foam	Jet A	400 ft^2	5.9	70	26.0	70
PFF2	Foam	Jet A	400 ft^2	6.1	66	28.2	62
PFF3	Foam	Jet A	400 ft^2	5.9	313	21.5	+300
PFF4	Foam	Jet A	400 ft^2	5.8	288	24.3	+300
PFF5	Foam	Jet A	400 ft^2	5.4	40	19.3	81
WA2	Wetting	Jet A	400 ft^2	5.3	30	15.9	102

The wetting agent that showed the best capabilities in the approval scale tests (WA2) was also in the assessment. During the first test conducted WA2 using the standard nozzle configuration, the wetting agent was able to control the fire but could not completely extinguish it with a 3-minute discharge. As with the foam products (AFFF and PFFs), the use of the foam tube adapter increased the firefighting capabilities of the wetting agent (WA2). During the test conducted with WA2 using the foam tube adapter, the fire was controlled in 60 seconds and extinguished 42 seconds later (i.e., 102 second total discharge). These times were about three times longer than the AFFF and double the PFFs.

The results of the tests conducted with gasoline are summarized in Table 7.4. During the tests conducted gasoline, the AFFF extinguished the fire in 50 seconds with the standard nozzle configuration and in 45 seconds with the foam tube adapter. The PFFs took about 135 seconds to extinguish the gasoline fires using the standard nozzle and about 105 seconds with the foam tube adapter. It should be noted that there were significant variations in extinguishment times between the PFFs (i.e., extinguishment times varied by over a factor of two for both nozzle configurations). These variations were attributed more to the technique used to extinguish these fires (and the difficulty in extinguishing the flames around the edges) as they were to the capabilities of the products (i.e., the error bar in the test results was greater than the differences in the capabilities of the top 5 PFFs).

Table 7.4. Representative Scale Tests Results (gasoline)

Foam/ Agent	Agent Type	Fuel	Fire	STD Nozzle		Foam Tube	
				Control	Ext	Control	Ext
AFFF	AFFF	Gas	400 ft^2	30	50	30	45
PFF1	Foam	Gas	400 ft^2	135	190	80	135
PFF2	Foam	Gas	400 ft^2	150	200	60	105
PFF4	Foam	Gas	400 ft^2	50	75	45	70

A summary of the representative scale test results is provided in Table 7.5 and is shown in Figure 7.7. As a general description on how these fires were typically extinguished, as the foam began to buildup on the fuel surface, the center of the pan was typically extinguished first while fire continued to burn around the perimeter of the pan (i.e., edge effects). These edge effects were much more pronounces for gasoline than for Jet A.

Table 7.5. Representative Scale Tests Results (Summary)

Foam/Agent	Fuel	STD Nozzle (.07 gpm/ft^2)		Foam Tube (.07 gpm/ft^2)	
		Cont (sec)	Ext (sec)	Cont (sec)	Ext (sec)
AFFF	Jet A	25	45	15	25
PFF1-5 (AVG)	Jet A	45	60	25	40
WA2	Jet A	60	No	60	102
AFFF	gasoline	30	50	30	45
PFF1-5 (AVG)	gasoline	100	135	60	105

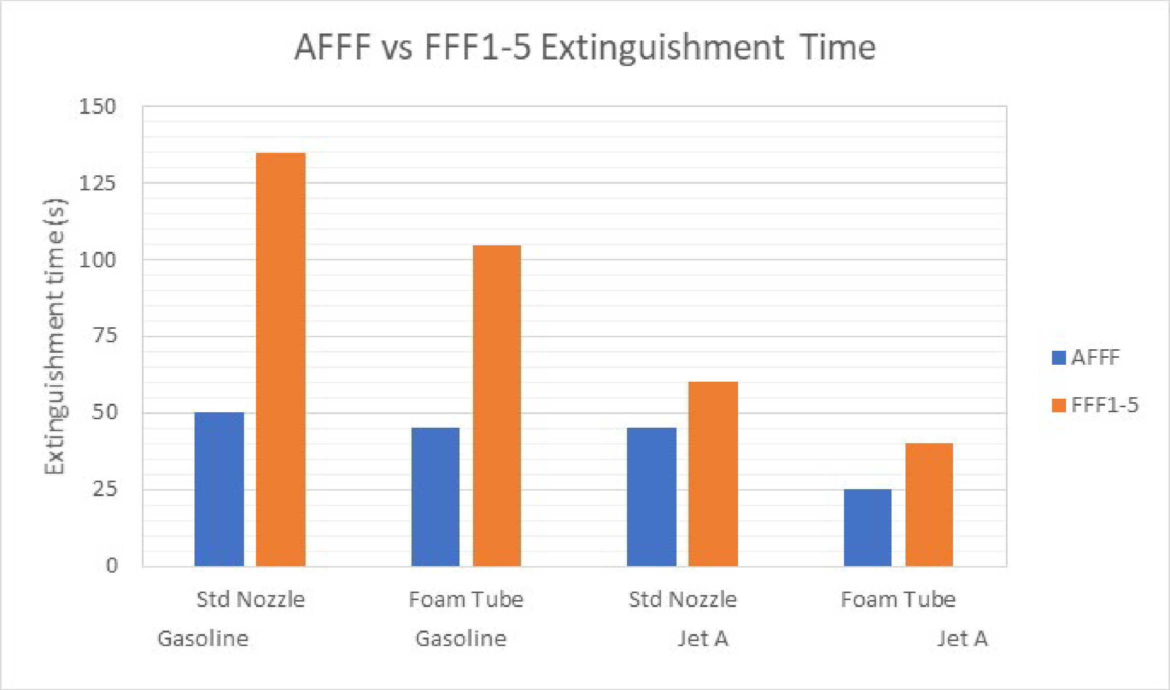


Figure 7.8. Representative Scale Tests Results (Summary)

The trends for the representative scale tests were consistent with the approval scale tests. Namely, the Jet A fires were much easier to extinguish than the gasoline fires and were typically extinguished in half the time it took to extinguish the gasoline fires. Along these same lines, the extinguishment of the gasoline fires was observed to be highly technique dependent. Specifically, the fire typically continued to burn at the location where the hose stream impinged on the fuel surface (i.e., made openings in the foam blanket at the impact location). In addition, the force from the hose stream was more than adequate to cause plunging into the fuel and cause the fuel to splash out of the pan. As a result, the firefighters needed to develop techniques to “more gently” apply the foams/agents to the burning fuel to optimize the product performance.

The use of the foam tube adapter resulted in better foam aspiration and allowed for a “more-gentle” application of the foam to the fuel surface. The net result was a decrease in extinguishment times in all scenarios by about 30-45%. However, it needs to be restated that the use of the foam tube reduced the stream reach by about 40% (50 ft with the standard nozzle to 30 ft with the foam tube adapter).

From “Apples to Apples” comparison, the top five PFFs (PFF1-5) required about 1.5-2 times longer to extinguish the fires than the legacy MILSPEC AFFF. However, all the fires were quickly controlled and ultimately extinguished with the performance difference measure in seconds for the Jet A fires and in minute (or fractions of minutes) for the gasoline fires.

7.3 FIXED FIRE SUPPRESSION SYSTEM RESULTS AND DISCUSSION

The initial proposal included an assessment of the capabilities of these fluorine free products when discharged through fixed systems (i.e., sprinkler type systems).

During the development and testing of aircraft hangar AFFF sprinkler systems, Factory Mutual Research Corporation (FMRC) conducted a series of tests for the U.S. military to establish appropriate design parameters using both standard sprinklers (i.e., non-aspirating nozzles) and air-aspirating old-style upright sprinklers. The tests consisted of 900 ft2 JP-4 pool fires in a 60 ft high space. The results showed that the standard sprinklers were 1.3 to 1.6 times more effective in achieving extinguishment compared to air-aspirating foam-water sprinklers at application rates of 0.16 gpm/ft2 (i.e., the foam sprinkler application rate used to design overhead foam sprinkler systems).

The superior performance of the standard sprinklers was attributed to more effective plume penetration by higher density foam particles (liquid and bubbles). Specially, the lower aspirated foam produced by the standard sprinklers are about twice as dense as air-aspirated particles, the terminal velocities are greater. Greater velocities allow greater penetration of the fire plume. Conversely, the aspirated foam particles/droplets near the centerline never reached the fire. This result supports the theory that extinguishment occurs from the outside perimeter inward.

The superior performance of standard sprinklers compared to air-aspirating sprinklers is reflected in the criteria of NFPA 409, Standard on Aircraft Hangars. If standard sprinklers are used with AFFF, the design application rate for overhead deluge systems may be reduced to 6.6 L/min/m2 (0.16 gpm/ft2) from 8.2 L/min/m2 (0.20 gpm/ft2) required for air-aspirated sprinklers. This decrease represents a 20 percent reduction in foam required when standard sprinklers are used. However, PFFs rely strictly on the foam blanket (i.e., aspirated foam) to extinguish the fire, forcing them to be designed at the higher rates with aspirating nozzles.

Two scoping tests were conducted during this SERDP/ESTCP program with fixed nozzles against the Jet A 400ft^2 pan fire. The tests were conducted with a standard non-aspirating nozzle (i.e., the Bete Model TF29) and then repeated with an aspirating sprinkler nozzle (i.e., the Tyco B-1 nozzle). The nozzles were sized to flow 30 gpm at a pressure of 50 psi. The 30 gpm flow rate is the same as used during the manual firefighting tests resulting in the same foam application rate of 0.07 gpm/ft^2.

During both tests, the foam solution discharged by the nozzle was carried away in the plume and never reached the fuel surface. As a result, the foam/sprinkler system had no effect on the fire and the tests had to be terminated.

Based on this very preliminary assessment and the need to discharge the PFFs through aspirating nozzles, additional research and considerations/precautions will need to be implemented for fixed system applications. Specifically, although the tests demonstrated a significant limitation of these products, the problem may be solvable through the use of higher application rates and/or lower level nozzles. The low-level nozzles should minimize the interaction of the foam particle with the plume by applying the agent near the fuel surface. In any case, additional research on fixed systems that discharge the foam solution high in the space is warranted.

8.0 ANALYSIS AND DISCUSSION

8.1 FUEL TYPE

As expected, the gasoline fires were significantly more challenging than the Jet A fires. As a general statement, the extinguishment times for gasoline were about double that of Jet A. However, there were some foams/agents that could not extinguish the gasoline fires, even at higher application rates.

The difficulty in extinguishing the gasoline fires was attributed primarily to the lower flashpoint of the fuel which is also related to the vapor pressure. Lower flashpoint fuels have higher vapor pressures which makes them more difficult to contain the vapors below the foam blanket (i.e., vapor pressure for gasoline at 50ºC ~ 110 kPa versus ~1.5 kPa for Jet A). In addition, the boiling point for gasoline is much lower than Jet A (i.e., gasoline boils near 85ºC versus Jet A at ~176ºC) which makes the fires located around the edges of the pan much more difficult to extinguish. Specifically, the edges of the pan are heated by the fire which results in localized boiling at this location.

A bar-chart showing a comparison of the extinguishment times between gasoline and Jet A is provided as Figure 8.1.

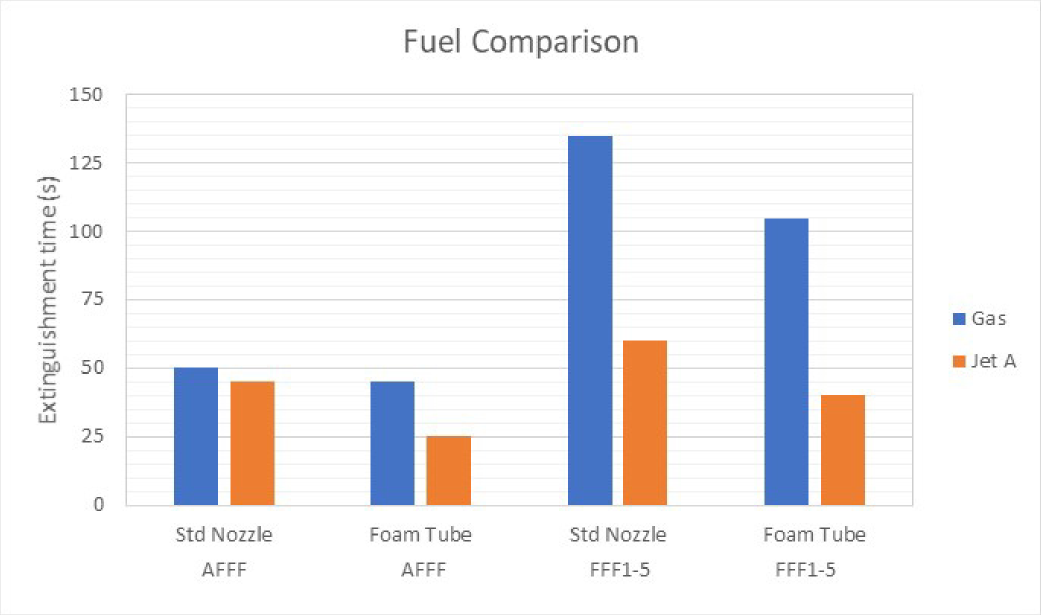


Figure 8.1. Fuel Type Extinguishment Time Comparison

8.2 SCALING

Between the approval scale and the representative scale tests, the fire size was increased by a factor of 15 (28 ft^2 versus 400 ft^2) but the application rate was held constant at 0.07 gpm/ft^2. This increase in fire size caused the extinguishment density (i.e., the gallons of solution per square foot needed to extinguish the fire) to increase by about factor of 2 (or more). These extinguishment densities are listed in Table 8.1.

Table 8.1. Extinguishment Density Comparisons

Foam/Agent	Extinguishment Densities (gal/ft^2)			
	Jet A		Gasoline	
	28 ft^2	400ft^2	28 ft^2	400 ft^2
AFFF	0.02	0.05	0.035	0.06
PFF1-5 (AVG)	0.03	0.07	0.06	0.16

There are at least three variables that may have contributed to the increases in the extinguishment densities for the larger scale tests. To start, during the larger scale tests (400 ft^2 fires), the firefighters had to standoff about 50 ft from the pan during the preburn to minimize their radiant exposures and to prevent their turnout gear from heating-up prior to the initial attack on the fire. The time for the firefighters to approach the fire could easily be on the order of 5-10 seconds as opposed to a “zero-time delay” for the approval scale fires (28 ft^2). Specifically, during the approval scale tests, the firefighter is within a few feet of the pan when at the start of discharge and all of the foam/agent is applied in the pan. During the approach on the large-scale fires, the firefighting party has to drag the hose while simultaneously aiming the nozzle at the fire (i.e., which can be challenging).

The second variable is associated with the application (i.e., gentle application) of the foam on the fire. As stated previously, the “gentle” application of the foam on the fire is very technique depended for the 30 gpm nozzle. Conversely, it is almost impossible to plunge the foam solution discharged from the aspirating MILSPEC nozzle below the fuel surface.

The third/final variable is the continued burning around the edges of the pan during the latter stages of the tests. Specifically, during the tests conducted with the 28 ft^2 pan, the firefighter can reach the entire pan from one location. During the 400 ft^2 pan fire tests, the firefighters have greater distances to travel in order to gently apply the foam near the edges of the pan. If the firefighter tried to reach these locations from a greater distance, the foam/agent stream would tend to splash the fuel out of the pan adding to difficulty in extinguishing the fire. As a result, during the larger tests, the firefighters needed to walk around the perimeter of the pan (at least on two of the four sides) to effectively apply foam/agent and to extinguish the flames near the edges of the pan.

With those three variables as potential contributors, the agreement in the extinguishment densities is not that disconcerting.

8.3 PERFORMANCE COMPARISON (L CURVES)

During a study conducted for the FAA in the mid-90s, the firefighting capabilities of foam extinguishing agents (i.e., control and extinguishment times) were typically shown to follow an “L Curve”. The “L Curve” is a plot of the extinguishment time (seconds) on the Y-axis and the application rate (gpm/ft^2) on the X-axis. An example L curve for AFFF is shown in Figure 8.2.

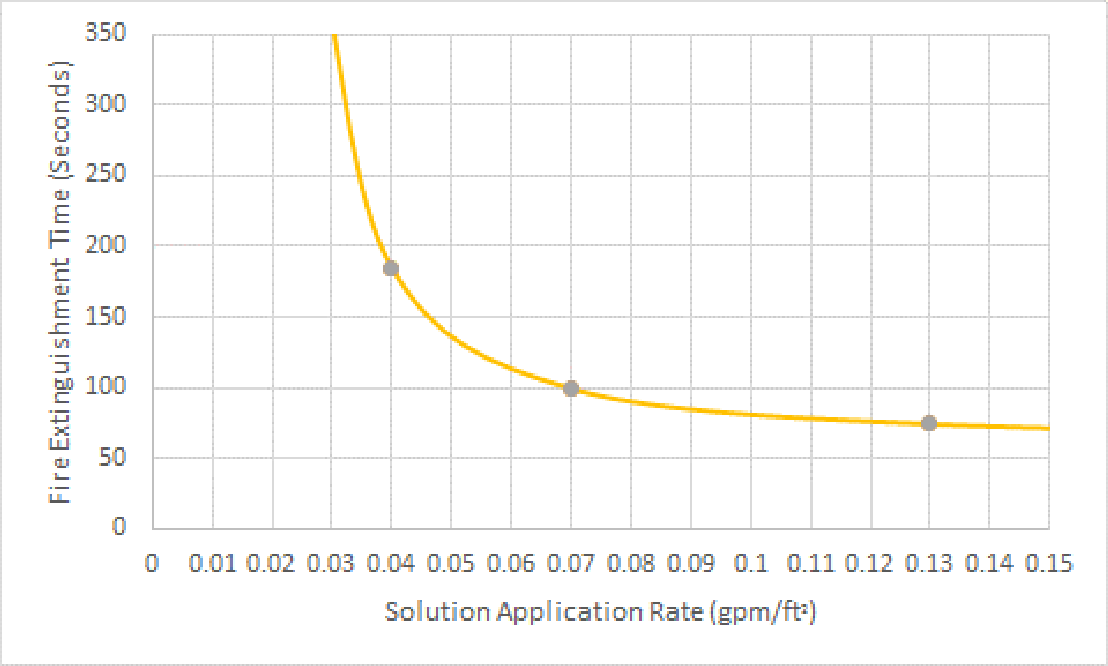


Figure 8.2. **Typical Extinguishment Time versus Application Rate "L Curve"**

The shape of the curve is directly associated with the extinguishment mechanisms. As a simple explanation of the curve (moving from right to left on the figure), when the foam is applied at a high rate, the fire is quickly controlled and extinguished. This is illustrated by the right side of the plot where the performance levels off even though the foam is being applied at higher rates. As the application rate is reduced, the times tend to increase as the rate approaches a critical value. Specifically, the times asymptotically approach the rate where the foam is being consumed by the fire as fast as it is being applied. In the plot above (Figure 8.2), this asymptotic value is approximately 0.03 gpm/ft^2. Below this rate, the foam has virtually no effect on the fire.

The approval scale tests provided two data points to begin the production of the "L curves" for the baseline AFFF and the top five PFFs (PFF1-5). Specifically, the extinguishment times for the 0.07 gpm/ft^2 and the 0.11 gpm/ft^2 application rates were determined during the 28 ft^2 fire tests at 2 gpm and 3 gpm respectively. To acquire additional data, tests were repeated using the 50 ft^2 MILSPEC fire test at same solution flow rates (i.e., 2 gpm and 3 gpm). These tests provided the data for the 0.04 gpm/ft^2 and the 0.06 gpm/ft^2 application rates respectively. The final dataset used to develop the L curves for this assessment is provided in Table 8.2. The values shown for PFF1-5 are the average of the five extinguishment times for each scenario.

Table 8.2. **Extinguishment Times for Various Application Rates**

Agent Type	Gasoline				Jet A			
	0.04 gpm/ft^2	0.06 gpm/ft^2	0.07 gpm/ft^2	0.11 gpm/ft^2	0.04 gpm/ft^2	0.06 gpm/ft^2	0.07 gpm/ft^2	0.11 gpm/ft^2
	sec	sec	sec	sec	sec	sec	sec	sec
AFFF	47	35	30	24	35	20	16	12
PFF1-5	190	105	53	44	53	32	26	18

The L curves for the baseline MILSPEC AFFF and the top five PFFs (PFF1-5) for the Jet A fires are shown in Figure 8.3.

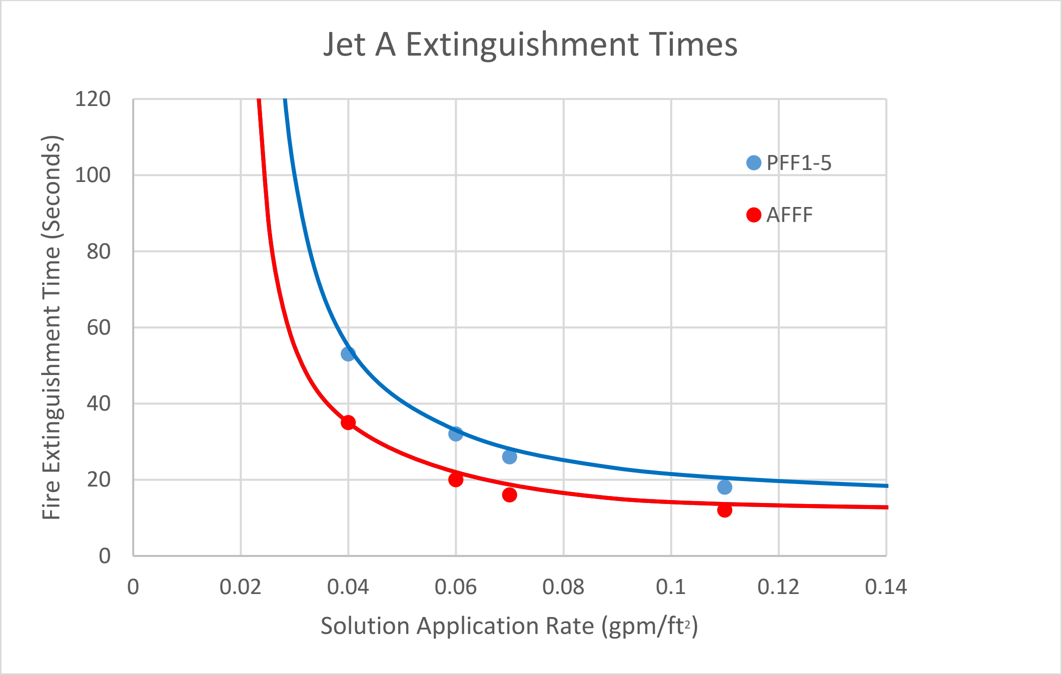


Figure 8.3. Jet A Fire Extinguishment Times versus Application Rates - "L Curve"

As shown in Figure 8.3, the L curves for the MILSPEC AFFF and the top five PFFs are almost parallel with the PFFs requiring about one and a half times as long to extinguish the fires as the MILSPEC AFFF. The critical application for the PFFs (i.e., the asymptote for the line) against Jet A was only about 0.003 gpm/ft^2 higher than the MILSPEC AFFF (0.022 gpm/ft^2 for the MILSPEC AFFF versus 0.025 gpm/ft^2 for the PFFs).

In any case, the plot illustrates the ease in extinguishing Jet A with the extinguishment times being less than 60 seconds for application rates as low as 0.04 gpm/ft^2 and 30 seconds for application rates of 0.06 gpm/ft^2 and above.

The L curves for the baseline MILSPEC AFFF and the top five PFFs (PFF1-5) for the gasoline fires are shown in Figure 8.4.

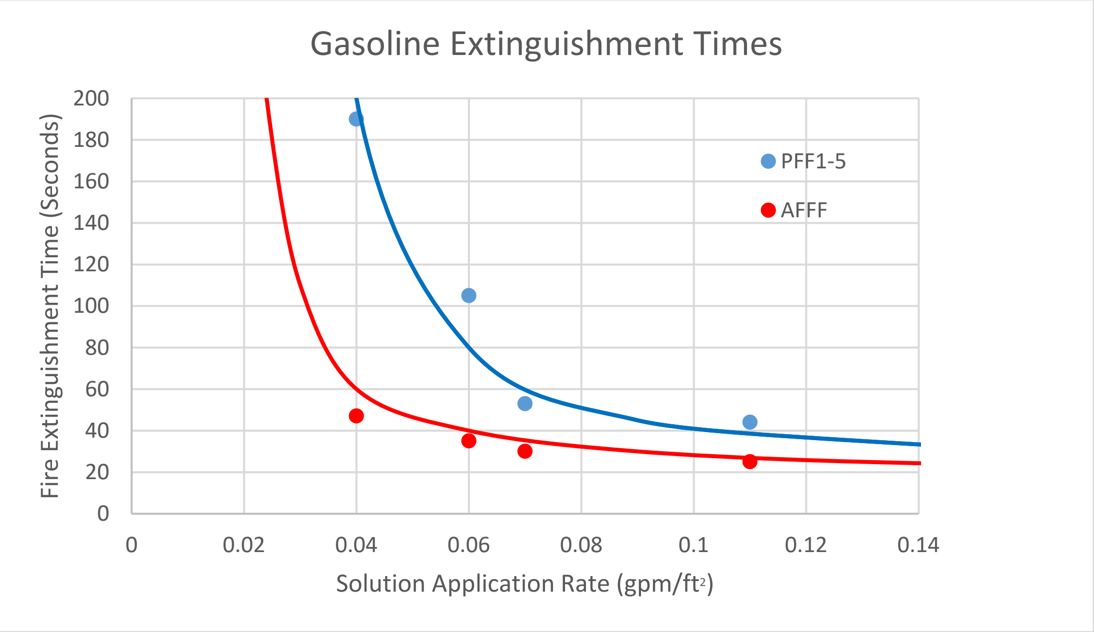


Figure 8.4. Gasoline Fire Extinguishment Times versus Application Rates - "L Curve"

As shown in Figure 8.4, the L curves for the MILSPEC AFFF and the top five PFFs are parallel for the higher application rates (i.e., 0.07 gpm/ft^2 and above) but diverge for application rates less than 0.07 gpm/ft^2. At applications of 0.07 gpm/ft^2 and above, the PFFs require about twice as long to extinguish the gasoline fires as the MILSPEC AFFF. The critical application rate for the PFFs against gasoline was about 0.015 gpm/ft^2 higher than the MILSPEC AFFF (0.024 gpm/ft^2 for the MILSPEC AFFF versus 0.039 gpm/ft^2 for the PFFs). Variations in the firefighting capabilities of the PFFs in general were observed for application rates approaching the critical value. Specifically, the extinguishment times for the gasoline fires for PFF application rates of 0.04 gpm/ft^2 were significantly higher than AFFF (i.e., on average about four times higher than AFFF) and varied significantly between products (i.e., as much as a factor of two).

In any case, the plot illustrates the challenging nature of gasoline fires with the extinguishment times for the PFFs never meeting the 30 second MILSPEC requirements even with application rates above 0.11gpm/ft^2.

Although it was not the intent of this effort to assess the adequacy of replacing the legacy AFFFs with any of these new products/formulations, the following discussion is provided as "food for thought" going forward.

The current MILSPEC performance requirements have evolved over the past 50 years to ensure that military firefighting personnel are given the best products available with the highest probability for success. These requirements were initially established based on the capabilities of the state of the art at the time the initial MILSPEC written (i.e., late 60's early 70's). The extinguishment times in the specification have been routinely reduced to match the capabilities of the best products of the day. Specifically, the original extinguishment time requirement for the 28ft^2 pan fire in 1969 was 84 seconds and was reduced to 65 seconds in 1971, 45 seconds in 1977 and to 30 seconds in 1978.

The final performance requirements are typically attributed to the need (i.e., time required) to prevent cookoff of ordnance and or the burn-thru of an aircraft fuselage in the aviation industry. However, the performance requirements evolved to those values more by "happen stance" than most people believe.

Shifting the logic away from the historical events like the fire on the USS Forestall in July of 1967 to typical "land-based" incidents, may allow more flexibility in the use of these new, more environmentally friendly formulations. Considering that, in most situations, these products will be applied at rates toward the right side of the "L curves" (i.e., at application rates above 0.1 gpm/ft^2), the differences in the capabilities of the top 5 PFFs and the legacy AFFFs are measured in seconds (i.e., 5-10 seconds for Jet A and 15-20 seconds for gasoline). This begs the question of "how good is good enough?".

This program provides some of the required performance data needed to begin to answer the question "how good is good enough?", and in some respects, provides a fall-back position if/when the use of AFFF is banned. If the capabilities of the top commercially available fluorine free products are deemed adequate, addition research and preparation will be required to identify the non-fire performance properties needed to deploy these in typical DoD applications. Issues such as agent capability and viscosity will need to be re-evaluated and potentially reconsidered going forward (to name a few).

9.0 DATABASED DEVELOPMENT

The database consists of two parts; the literature search conducted during Task 1 (Excel Spread Sheet) with the associated links to both the MSDS/SDS and the approval test reports and a separate Excel Spread Sheet that includes the test results conducted during this program. The Task 1 document that has been uploaded to the SERDP/ESTCP website includes the names of the various products and manufacturers. The performance database will not be made public at this time but will become the property of NRL and will be continuously updated as addition products are identified and tested.

10.0 SUMMARY AND CONCLUSIONS

Legacy firefighting foams (AFFF) used by the Department of Defense (DoD) are facing increasing regulatory scrutiny throughout the world due to both environmental and human health concerns associated with the fluorinated surfactants. The WP19-5324 program was a two-year effort to assess the capabilities of fluorine free / PFAS free AFFF alternatives including both traditional candidates such as fluorine-free/PFAS-free foams, and non-traditional options such as wetting agents and other water additives. The program provides an "apples to apples" comparison of the capabilities of the foams currently used by the DoD (AFFFs) and the commercially available fluorine-free alternatives.

Our approach was to quantify the capabilities of the "state-of-the-art" fluorine-free/PFAS-free foams (and agents) in use today and provide information on the relationship between the actual fielded capabilities of the foam/agent and the current approval test requirements/results.

The systematic approach developed for this program includes the following six tasks:

- Task 1: A literature search on potential PFAS-free AFFF alternatives;
- Task 2: A high-level environmental analysis to down-select agents for testing;
- Task 3: Approval-scale fire performance testing using the tests described in the MILSPEC with and without modification;
- Task 4: Data analysis to rank the capabilities of the alternatives and to down-select agents for real-scale testing;
- Task 5: Real-scale fire testing using two representative scenarios; and,
- Task 6: The development of a database/final report that documents the findings and recommendations for the path forward.

It should be noted that the original approach presented to SERDP/ESTCP had Tasks 3 & 5 switched in order. The original approach was developed based on the concern that the challenging nature of the MILSPEC test requirements was prematurely eliminating potentially acceptable alternatives. However, due to COVID related delays obtaining the required test equipment to conduct the representative scale tests, the approval scale tests were conducted first.

The initial literature/internet search conducted during Task 1 identified over 60 products that were being marketed as environmentally friendly AFFF alternatives. Upon further investigation, it was determined that at least 20 of these products had no listings or approvals (i.e., no legitimate firefighting pedigrees). Based on the lack of any performance data, these products were no considered for this program.

The remaining 40 products were assembled into an excel spreadsheet that was uploaded to the SERDP/ESTPC website. The spread sheet includes the links to the manufacturer's websites, SDS (MSDS), and some of the approval tests reports (where available).

Task 2 was conducted to identify any environmental "showstoppers" that would eliminate the alternative from real-scale testing (and further consideration). During this screening process, it became obvious that the limited data provided in the SDS (MSDS) was inadequate to properly screen these foams/agents. As a result, the 15 foams/agents that had the greatest depth of listings/approvals applicable to typical DoD hazards were selected for firefighting performance testing. This value has grown to over 25 foams/agents tested due to the availability of additional products and new formulations but only 15 are documented in this report. The team of JH and NRL continues to test more products and contuse to update the performance database.

During Task 3, the firefighting capabilities (extinguishment and burnback resistance) of the selected alternatives were evaluated 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 foam/agent was tested 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. Jet A was included in the assessment since it is more representative of the kerosene-based fuels used throughout the DoD. Specifically, the original MILSPEC was developed when the predominant fuels included JP-4 and MOGAS and may need be revised in the future to include a representative kerosene-based fuel. In addition, Jet A is the primary fuel used at both DoD and Civilian Airfields which has become the initial focus for the selection of a fluorine free, AFFF alternative and has become the driver for the development of the new land-based MILSPEC.

The approval scale tests identified a few obvious trends in the test difficulty and foam/agent capabilities. The first observation was the ease in extinguishing the Jet A fires as compared to the gasoline fires. Thirteen of the fifteen foam/agents were capable of extinguishing the Jet A fires at 2 gpm (0.07 gpm/ft^2) in about 30 seconds or less. Conversely, only nine of the products were capable of extinguishing the gasoline fires at 2 gpm (0.07 gpm/ft^2) and required significantly longer and more foam/agent to extinguish the fire. As a general statement, the extinguishment times for gasoline were typically about twice as long as those observed for Jet A.

With respect to the type of product (i.e., AFFF, PFF and WA), the legacy MILSPEC AFFF provided consistent results and always outperformed the other products included in this assessment. The foams listed and approved using UL 162 or EN 1568–part 3 or ICAO C typically out-performed the wetting agents. This was expected since these "foam products" are tested and approved at much lower application rates (i.e., between 0.04 gpm/ft^2 – 0.06 gpm/ft^2) than the "wetting agents" which are listed and approved per NFPA 18 (i.e., 0.2 gpm/ft^2). There were a limited number of foams that were only tested to either EN 1568-part 2 or ICAO B which fell in between the higher performance foam products and the wetting agents.

During Task 4, the alternatives were ranked and grouped based on the firefighting capabilities observed/measured during the approval scale tests. As expected, the legacy MILSPEC AFFF provided consistent results and always outperformed the other products included in this assessment. The top five fluorine free performers (all PFFs) demonstrated good capabilities against both gasoline and Jet A. These top performers were all able to extinguish the gasoline fires with a 2 gpm discharge rate in less than 60 seconds and the Jet A fires at the 2 gpm discharge rate in less than 30 seconds.

Based on the results of the approval scale tests, the top five PFFs were selected to be further assessed during the representative scale testing. This group included three Newtonian concentrates (lower viscosity concentrates that flow similar to corn syrup) and two non-Newtonian concentrates (higher viscosity concentrates that behave more like molasses and/or jello). These top five PFFs are currently being ECOTOX tested during other SERDP – ESTCP programs.

During Task 5, the firefighting capabilities of the top fluorine free foams/agents were assessed against a real-scale, representative manual firefighting scenario using a fire hose to extinguish a 400 ft^2 pool fire. Most of these tests were conducted with Jet A with a limited number repeated with gasoline for comparative purposes (i.e., the agents that did extremely well against the Jet A were retested using gasoline). The initial tests conducted were conducted with MILSPEC AFFF to provide a baseline for comparison and to allow the firefighting party the opportunity to optimize their procedures and tactics.

During this series, the fires were extinguished using a fire hose equipped with a 30 gpm vari-nozzle. The resulting foam solution application rate was 0.07 gpm/ft^2 which is the same as the approval scale tests (i.e., 28ft^2 pan fire tests conducted with a foam solution discharge rate of 2 gpm). This provided a direct comparison of capabilities on two vastly different scales (i.e., provided data that could be used to assess scaling between the approval scale and representative scale scenarios). A second set of tests were also conducted with a foam tube attachment for the nozzle that provided higher aspirated foam which may be the key to effectively fielding these products in DoD applications.

The tends for the representative scale tests were consistent with the approval scale tests. Namely, the Jet A fires were much easier to extinguish than the gasoline fires and were typically extinguished in half the time it took to extinguish the gasoline fires. Along these same lines, the extinguishment of the gasoline fires was observed to be highly technique dependent. Specifically, the fire continues to burn at the location where the hose stream impinged on the fuel surface/foam blanket. In addition, the force from the hose stream was more than adequate to cause plunging of the solution into the fuel and cause the fuel to splash out of the pan. As a result, the firefighters needed to develop techniques to “more gently” apply the foams/agents to the burning fuel to optimize the product performance.

The use of the foam tube adapter resulted in better foam aspiration and allowed for a “more-gentle” application of the foam to the fuel surface. The net result was a decrease in extinguishment times in all scenarios by about 30-45%. However, it needs to be restated that the use of the foam tube reduced the stream reach by about 40% (50 ft with the standard nozzle to 30 ft with the foam tube adapter).

From “Apples to Apples” comparison, the top five PFFs (PFF1-5) required about 1.5-2 times longer to extinguish the fires than the legacy MILSPEC AFFF. However, all the fires were quickly controlled and ultimately extinguished with the performance difference measure in seconds or fractions of minutes.

To further assess the capabilities and limitations of these products, “L curves” were developed for the baseline MILSPEC AFFF and the top five PFFs for both Jet A and gasoline.

The “L curves” for the MILSPEC AFFF and the top five PFFs are almost parallel for Jet A fires with the PFFs requiring about one and a half times as long to extinguish the fires as the MILSPEC AFFF. The critical application for the PFFs (i.e., the asymptote for the line) was only about 0.003 gpm/ft^2 higher than the MILSPEC AFFF (0.022 gpm/ft^{2}for the MILSPEC AFFF versus 0.025 gpm/ft^2 for the PFFs). In any case, the plot illustrates the ease in extinguishing Jet A with the extinguishment times being less than 60 seconds for application rates as low as 0.04 gpm/ft^2 and 30 seconds for application rates of 0.06 gpm/ft^2 and above.

The L curves for the MILSPEC AFFF and the top five PFFs for gasoline fires are parallel for the higher application rates (i.e., 0.07 gpm/ft^2 and above) but diverge for application rates less than 0.07 gpm/ft^2. At applications of 0.07 gpm/ft^2 and above, the PFFs require about twice as long to extinguish the fires as the MILSPEC AFFF. The critical application rate for the PFFs was about 0.015 gpm/ft^2 higher than the MILSPEC AFFF (0.024 gpm/ft^{2}for the MILSPEC AFFF versus 0.039 gpm/ft^2 for the PFFs). Variations in the firefighting capabilities of the PFFs in general were observed for application rates approaching the critical value. Specifically, the extinguishment times for the gasoline fires for PFF application rates of 0.04 gpm/ft^2 were significantly higher than AFFF (i.e., on average about four times higher than AFFF) and varied significantly between products. In any case, the assessment illustrates the challenging nature of gasoline fires with the extinguishment times for the PFFs never meeting the 30 second MILSPEC requirements even with application rates above 0.11gpm/ft^2.

Although it was not the intent of this effort to assess the adequacy of replacing the legacy AFFFs with any of these new products/formulations, the following discussion is provided as “food for thought” going forward.

The current MILSPEC requirements have evolved over the past 50 years to ensure that military firefighting personnel are given the best products available with the highest probability for success. These requirements were initially established based on the capabilities of the state of the art at the time the initial MILSPEC written (i.e., late 60’s early 70’s). The extinguishment times in the specification have been routinely reduced to match the capabilities of the best products of the day. Specifically, the original extinguishment time requirement for the 28ft^2 pan fire in 1969 was 84 seconds and was reduced to 65 seconds in 1971, 45 seconds in 1977 and to 30 seconds in 1978.

The final performance requirements are typically attributed to the time required to prevent cookoff of ordnance and or the burn-thru of a fuselage in the aviation industry. However, the performance requirements evolved to those values more by “happen stance” than most people believe.

By shifting the logic away from the historical events like the fire on the USS Forestall in July of 1967 to typical “land-based” incidents, may allow more flexibility in the use of these new, more environmentally friendly formulations. Considering that, in most situations, these products will be applied at rates toward the right side of the “L curves” (i.e., at application rates above 0.1 gpm/ft^2), the differences in the capabilities of the top 5 PFFs and the legacy AFFFs are measured in seconds (i.e., 5-10 seconds for Jet A and 15-20 seconds for gasoline). This begs the question of “how good is good enough?”.

This program provides some of the required performance data needed to begin to answer the question "how good is good enough?", and in some respects, provides a fall-back position if/when the use of AFFF is banned. If the capabilities of the top commercially available fluorine free products are deemed adequate, addition research and preparation will be required to identify the non-fire performance properties needed to deploy these in typical DoD applications. Issues such as agent capability and viscosity will need to be re-evaluated and potentially reconsidered going forward (to name a few).

The database developed during this program consists of two parts; the literature search conducted during Task 1 (Excel Spread Sheet) with the associated links to both the MSDS/SDS and the approval test reports and a separate Excel Spread Sheet that includes the test results conducted during this program. The Task 1 document that has been uploaded to the SERDP/ESTCP website includes the names of the various products and manufacturers. The performance database will not be made public at this time but will become the property of NRL and will be continuously updated as addition products are identified and tested.

11.0 PATH FORWARD

The WP19-5324 program provides some of the required performance data needed to begin to answer the question "how good is good enough?", and in some respects, provides a fallback position if/when the use of AFFF is banned. If the capabilities of the top commercially available fluorine free products are deemed adequate, addition research and preparation will be required to further understand the limitations of these products and to validate their capabilities against a selected Maximum Credible Event (MCE).

The primary performance limitation of these products is associated with the mechanisms of extinguishment and the need to produce aspirated foam to increase the extinguishment capabilities of these products. AFFF extinguishes a fire through the combination of two mechanisms; the formation of an oleophilic fluoro-surfactant film on the fuel surface and a layer of aspirated foam. Both mechanisms combine to seal in the fuel vapors and to prevent the development of a flammable vapor mixture above the fuel surface. Fuel surface cooling may also be a contributor for higher flashpoint fuels. Fluorine Free Foams (FFFs) rely solely on the development of an aspirated foam blanket to contain the vapors and extinguish the fire. To date, the commercially available PFFs have no oleophilic properties and do not form a film on the fuel surface.

The effects of foam quality on the firefighting capabilities of PFFs was demonstrated during a program conducted by JH and NRL for the NFPA Research Foundation a few years ago. During that study, the extinguishment capabilities of these products were shown to significantly decrease with lower aspirated foam. The "L Curves" for a specific PFF showing this decrease are provided as Figure 11.1.

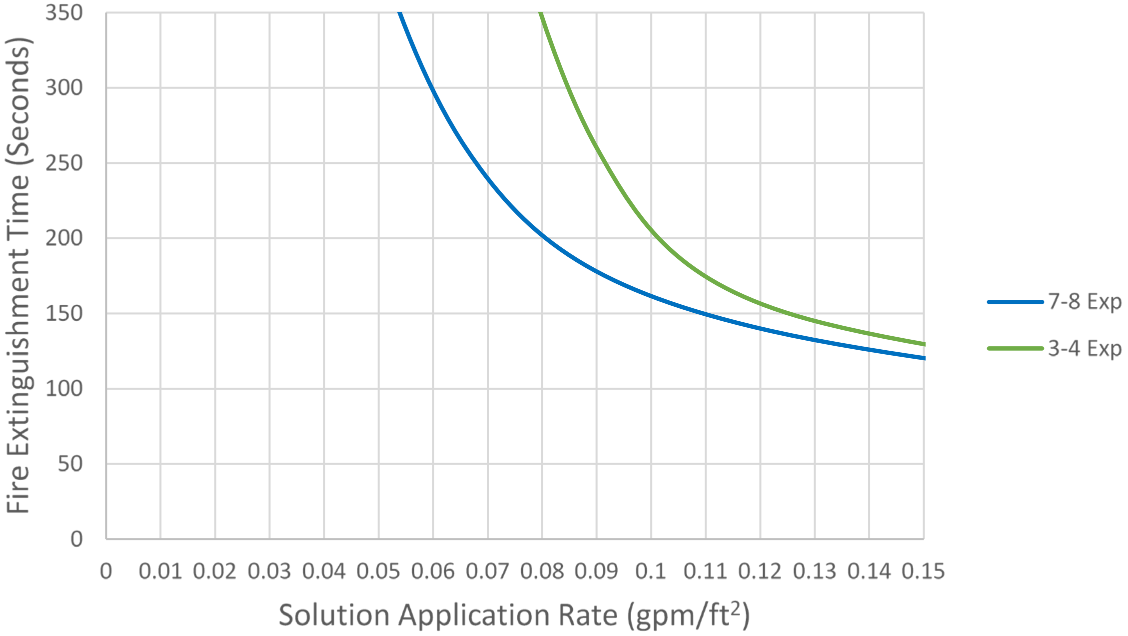


Figure 11.1. Variations in Firefighting Capabilities as a Function of Foam Quality (Aspiration)

A program to assess and quantify this limitation is described in Section 11.1 and has already been funded under WP19-5374.

Prior to fielding these PFFs in DoD applications, the final validation of these products needs to be performed using a representative MCE. During the development and testing of AFFF back in the late 70s early 80s, the MCE was defined as a highly obstructed debris pile fire with a three-dimensional running fuel component. In Section 11.2, a new demonstration program is proposed to validate the capabilities of these fluorine free products against the MCE used to validate the capabilities of AFFF some 40 years ago.

11.1 FOAM QUALITY EFFECTS ON FIREFIGHTING CAPABILITIES

The firefighting capabilities of these new PFFs have been shown to be highly dependent on the characteristics of the foam blanket (i.e., foam quality). The foam blanket serves to contain the fuel vapors and prevent the production of a flammable fuel vapor mixture above the fuel surface. The foam quality effects were demonstrated during this program (WP19-5324) through the 30-45% reductions in extinguishments times gained using the foam tube against the 400 ft^2 fire.

The MILSPEC tests currently used to approve AFFF do not consider the foam quality that will be produced by the fielded system/hardware. In fact, the MILSPEC fire performance tests are conducted with an air aspirating nozzle that produces significantly better foam quality than any of the discharge devices used in actual DoD applications. This proposed program will begin 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. This link should serve as the first step in developing a new foam specification for land-based applications.

The technical objective of this effort is to demonstrate (and to develop an understanding of) the effects that foam quality has on the capabilities of new Fluorine Free Foams (FFFs) and relate these capabilities to the foam qualities produced by the various discharge devices used throughout the DoD.

The main technical questions that will be 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 using a PFF as the agent?

To achieve these objectives, two separate/parallel tasks will be performed; characterization of the foam quality produced by the various discharge devices used throughout the DoD (using PFF as the agent), and, the development of the understanding of the capabilities of these new PFFs as a function foam quality and flow rate.

During initial phase of Task 1, the foam quality produced by the fixed system nozzles used throughout DoD (between 4-6), manual firefighting nozzles used throughout DoD (between 2-4) and firefighting vehicle nozzles used throughout DoD (between 2-3) will be assessed/measured to identify typical foam qualities produced by legacy AFFF hardware. During the foam quality assessment, three of the top five PFFs identified during WP19-5324 will discharged through each devise.

During the second phase of Task 1, the foam quality produced by discharge devices that were developed for Protein Foam (PF) over 50 years ago will also be assessed/measured. Since PF also relies solely on the foam blanket to extinguish a fire (i.e., does not produce a film on the fuel surface), the PF devices were designed with the intent to make aspirated foam (i.e., good foam quality). These devices could potentially serve as replacements for the non-air aspirating discharge devices used in DoD AFFF systems today (if required).

As a parallel effort, the firefighting capabilities of the three selected PFFs will be assessed as a function of foam quality and discharge rate (during Task 2). The tests will be conducted using the MILSPEC 28 ft^2 and 50 ft^2 pan fires and discharge nozzle as the basis of the assessment. The series will assess the capabilities of the two foams over the range of foam qualities (expansion ratios) from 0 to 12 (i.e., 0, 3, 6, 9 and 12). These foam qualities will be produced by blocking or adding the aspirating holes in the body of the MILSPEC nozzle. The tests will be conducted at bot 2 gpm and 3 gpm for each foam quality to develop "L curves" for each foam quality similar to the data set shown in Table 8.2 and the plots shown in Figure 8.3 and 8.4.

The WP19-5374 program will demonstrate (and develop an understanding of) the firefighting capabilities of these new PFFs using the foam qualities produced by the various discharge devices used throughout the DoD. The understanding of the capabilities should allow an analytical assessment of various applications in an attempt to define "How good is good enough?"

11.2 REPRESENTATIVE FIRE SCENARIO VALIDATION TESTS

During the WP19-5324 program, the commercially available fluorine free foams and agents were identified and documented in a spread sheet with links to MSDS/SDS, approvals/listings, performance test data and end user testimonials. During the program, 15 commercially available products were tested against the 28 ft^2 MILSPEC pan fire tests using two fuels (the legacy gasoline and Jet A). The five top fluorine free products were then tested against a 400ft^2 pan fire to assess scalability and to provide an initial assessment of how foam quality/aspiration effects the firefighting capabilities of these products. Both series demonstrated the potential of using these products in DoD applications with the understanding that final validation tests would be required. Specifically, the capabilities of the legacy AFFFs have been assessed and validated over a wide range of fire sizes, fire types, fuel types, and event scenarios over its 50-year legacy as the premier flammable liquid extinguishing agent. Most of the large-scale research was conducted in the 1980's at China Lake Weapon Center in Ridgecrest CA.

During this proposed follow-on effort, the capabilities of the top five fluorine free products will be assessed and validated against the test configurations used to assess the capabilities of AFFF 30 to 40 years ago. These include large unconstrained spill fires (i.e., over 2000 ft^2) and obstructed running fuel fire scenarios (referred to as debris pile fire scenarios) that include both an obstructed 3-D component and a growing, uncontained spill/pool fire.

This research/validation will be performed by Jensen Hughes (JH), The Naval Research Laboratory (NRL) and the Naval Air Warfare Center (NAWC), Weapons Division (WD) in China Lake (CL) California.

In the late ‘70s and early ‘80s, JH/NRL/NAWC-WD personnel developed a debris pile fire test scenario to assess firefighting equipment and agents, and to develop firefighting doctrine and training for aircraft carrier flight deck crash scenarios. A majority of this research and doctrine has been incorporated into the NATOPS manual.

The debris pile fire scenario was designed to represent the Maximum Credible Event (MCE) that could occur on the flight deck of aircraft carrier during peacetime operations (i.e., an aircraft crash with all ship’s systems an crew functional). The initial debris pile fire test scenario consisted of a 30 gpm running fuel fire that flowed down numerous steel trays that served to heat the fuel and to obstruct the fire as it flowed into a large pile of broken cinderblocks. Many of the tests were conducted with instrumented mock-ordnance located in the debris. Over the years, the debris pile fire scenario has been conducted using a range of fuels and has been modified during numerous test programs to simulate obstructed, 3D running fuel fires for a range of scenarios and applications including evaluations of fixed fire suppression systems and manual firefighting equipment and techniques (both handlines and turrets/monitors).

During “Desert Storm,” JH and NRL personnel assessed the difficulty in extinguishing debris pile type fire scenarios (i.e., aircraft crash type scenarios) as a function of the flashpoint of the fuel using the original debris pile fire configuration. During the same program, JH and NRL personnel quantified the flame spread rate across various fuel surfaces as a function of fuel flashpoint. The flame spread rate plays into both the difficulty in extinguishing the fire as well as the likelihood for reflash. JH personnel have also conducted research on spill fire scenarios and expected spill area size as a function of fuel quantity, fuel type and substrate. Most of this information has been published by JH in the SFPE handbook.

During this program, the top five fluorine free products will be assessed against the legacy debris pile fire on the Mini Deck at China Lake Warfare Center, using the same exact configuration and location where all the legacy AFFF testing was conducted. As with the previous studies (i.e., WP19-5324), the results will be compared to the performance of a C6, AFFF currently on the QPL list.

The Mini Deck is an 80ft by 80ft concrete pad constructed of high temperature concrete. The Mini Deck is equipped with a flush deck fire suppression system (the one used on USN aircraft carriers) installed in the trench drains built into the deck. The deck construction allows the fuel to be dumped or flowed directly onto the concrete surface representative of an actual crash type scenario. The deck is equipped with an effluent drainage and waste collection system for waste disposal. An areal photograph of the Mini Deck is provided as Figure 11.2 below.

Figure 11.2. Mini Deck

There is also a legacy debris pile fire setup located on the north end of the deck (Figure 11.3). An array of wind machines are installed on the south of the deck if specific wind conditions need to be assessed. The spectrum of typical DoD firefighting equipment is available for use at this facility including, but not limited to, handlines, fixed nozzle systems and crash trucks (i.e., turrets/monitors). A photograph of a crash truck extinguishing a fire on the Mini Deck is shown in Figure 11.4.

Figure 11.3. Legacy Debris Pile Constructed with Steel Walls and Roof

Figure 11.4. P25 Tests on the Mini Deck

The use of the Mini Deck provides the ability to spill the fuel directly onto the concrete surface without the need for any type of containment which is representative of an actual crash type scenario on the flight deck of an aircraft carrier or on the tarmac of military airfield. Actual spill fires can be significantly different than pan or burn pit fires for a number of reasons. First, as noted during the 400ft^2 pan fire tests conducted during the WP19-5324 program, the fires are first extinguished in the center of the pan but require additional time and effort to extinguish the flames around the edges/sides of the pan. In many respects, these edge effects make these fires more challenging and less representative of an actual even. The use of a burn pit can also adversely alter the fire scenario. For example, most burn pits have significant water depth below the fuel surface to protect the plastic liners from the heat of the fire. During the actual test, since the foams/agents are being discharged from above the fuel surface with the agent being spraying downward into the pit, the force of the spray impacting the fuel surface can drag the fuel below the surface of the water making the fires unrealistically easier to extinguish.

At a minimum, 40 tests will be conducted during this program. Specifically, a baseline C6 MILSPEC AFFF and the top five fluorine free products will be tested against an unconstrained spill fire and the debris pile fire scenario using manual application of the agent via handlines and then using application of the agent via an ARFF truck turret/monitor. The first phase will be conducted with handlines and the second phase with turrets/monitors. Both phases will include assessments of aspirated discharge devices such as aspirating handline/turret nozzles or foam tubes and well as standard nozzle configurations.

These initial tests will be conducted using Jet-A as the fuel. A limited number of tests may be conducted using other fuels such as gasoline if time and funding permits.

After each test, the test team and firefighting party will meet to discuss and document the lessons learned from a technique/procedural perspective. This information may be used to tweak the current approaches and techniques used to extinguish fires using the legacy AFFF.

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